International Workshop on Advanced Materials for Marine Construction

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Table of Contents

Keynote Address and Special Topics Presentations

Theme Papers

Working Group Reports

Workshop Critiques

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List of Participants

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Executive Summary

The last three decades has seen a tremendous national investment by corporations and government in the research and development of many new material systems and significant improvement of the traditional materials. Most of these materials were destines for complex technical assemblies of high performance machine, i.e. aircraft, combatant ships, weapon systems, electronics, etc. With the advent of east-west peace new challenges and opportunities have arrived to make significant improvements in commercial systems by effective introduction of these new materials.

This workshop was designed to promote communication between the users of materials and the producers of materials. It is essential that producers understand the users requirements and users are aware of the materials properties and fabricability of these new materials. Besides the need for greater interactions between designers and material producers, also just as significant is the need for communication between ship and offshore structure fabricators and regulatory and certification bodies.

The designer and fabricator may limit their materials options based on previous experience. For example: a new material may be considered and then rejected as choice for superstructure fabrication simply because the shipyard does not have the necessary experience with the material. Similarly, the use of composites may be limited because of the low melting point of the matrix and the fact that the core may burn. However, slight alteration of the regulations to focus on the structure to contain a fire may result in composites being favored because of the insulating effect the carbon in the balsa core provides when it slowly chars. Increased communication between these few groups will result in more knowledgeable material choices as well as increased safety of the structures. Finally, as more importance is placed on the life cycle cost of a structure rather than the initial expenditure, the use of advanced materials which are higher in price but have better corrosion resistance and maintainability will be more widespread.

There are several roadblocks that sometimes prevent the use of higher alloy alternative solutions. These roadblocks are the lack of knowledge about the materials. There is a need for more data on these materials to fill in the blanks on the materials properties so that they can be used confidently. Another roadblock is the lack of codes and standards for the materials. There is a need to upgrade or develop the codes and standards that facilitates the use of the materials. Finally there is very little experience in the use of many of the materials. Many fabricators shy away from using some of these materials because of their ignorance on the weldability and fabricability of these new materials. The lack of experience generally add a lot to the cost, even though the problems are not great.

The workshop promoted interactions between material producers designers, fabricators and regulators to identify the needs to accelerate the use of these new materials. The first section of this report describes state-of-the-art information about the various materials systems available for utilization in marine structures. The workshop report contains in the second section recommendations based a consensus from working group contributors.

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Minerals Management Service
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Washington, D.C.
1997

Introduction

With the fast approaching of the XXI century, the search of energy and material resources intensifies. Exploration and production of petroleum and gas products have successfully extended into the oceans. With that, the transportation of oil and gas products from the oil fields to mainland also heightened. Direct pipeline links of hundreds of miles have been established. Oil and gas tankers traveling between oceans have grown in capacity to meet the increasing transportation demands. All the exciting development in oil and gas production also brought in substantial demands on the materials used in the marine environment. Deeper water drilling and exploration, oil reservoir rich in CO_2 and sulfur, larger capacity platforms and ocean vessels are some of the applications that challenge materials suppliers, users, equipment fabricators, regulating agencies, and certification agencies.

It was with these ideas in mind that the International Workshop on Advanced Materials for Marine Construction was organized. An organizing committee consisting of recognized experts from around the world was established in late 1995 to put together a program that will:

- define current use of advanced materials in marine engineering
- identify barriers to more widespread use of advanced materials in marine engineering
- provide an international forum for participants from all aspects of materials production and use
- promote the cost effective use of advanced materials in marine structures
- produce an archivable record of current usage and future opportunities for advanced materials in marine engineering

Workshop Overview

The Workshop took place in the Double Tree Hotel, New Orleans, Louisiana between February 5 and 7, 1997, with a total of around 140 participants. The meeting opened with a series of short supporting remarks by several government and industry leaders. They all emphasized the importance and increasing needs for advanced materials in the marine field and encouraged the participants to actively contribute to the workshop. Following the supporting remarks, several key industrial experts were invited to speak on the requirements and expectation of advanced materials applied in the oil exploration and transportation business. A special economic outlook of marine construction and projected trends of demands of materials was also presented. The program followed with eight theme presentations that provided the attendees with current state-of-the-art information on materials for marine applications. The presentations included all major material groups:

- Structural steels
- Titanium alloys
- Copper alloys
- Stainless steels and nickel alloys
- Aluminum alloys
- Elastomers and polymers
- Composite materials, and
- Concrete

The manuscripts of these presentations are included in this volume.

One of the major goals of the workshop was to promote interchange of technical information among producers, designers, engineers, fabricators, inspectors, and users of marine materials.

Eight working group sessions were planned to review and revise position papers (prepared by groups of experts prior to the workshop and distributed to all participants at registration). The Working groups focused on:

- Moorings
- Risers
- Floating structures
- Fixed structures
- Harbors
- Process equipment
- Pipeline/flowline, and
- Secondary structures

Due to the interest of a number of participants present, a ninth working group was requested and established:

- Requirements for Ship Hulls.

The addition of this working group clearly demonstrates the dynamics of the working group format and the intensity of the interaction of the participants.

The activities of each working group were based on the presentation of a white paper which identified the research and development needs of materials with unique properties required for marine applications. The position papers also discussed opportunities and important ongoing projects, and barriers to the progress and application of advanced materials in marine construction. During the working group period, the participants were encouraged to visit more than one session to maximize their contributions to the different material groups used in marine environment. For the final session of the working groups, the participants were charged to prepare lists of prioritized action items for the final workshop assembly.

On the morning of February 7, 1997, the working group leaders came back to report to the full group on their conclusions and recommendations. These important discussions are included in this volume. Two independent materials experts, Dr. Yoshifumi Nakano, Kawasaki Steel Corporation and Commander Bill Sharp, U.S. Coast Guard, presented their critics and assessment of the workshop during the last session of the workshop. The feed back from the two experts and other attendees were excellent, positive and upbeat, finding this workshop extremely worthwhile for information exchange on future trends in materials research and development.

Acknowledgment

The organizing committee would like to extend their most sincere gratitude to the Department of Interior - Minerals Management Service (MMS) and American Bureau of Shipping for sponsoring this event. The major industrial sponsors are also acknowledged for contributions which made this event possible. The industrial participants with booth exhibitions are greatly appreciated for their effort in bringing their specific information to share with the participants of the workshop. In particular, the Ship Structures Committee chose to release their CD-ROM version of their reports (50 years of report) at the workshop. It was the right occasion for the release of such a wonderful product. Finally, the organizing committee congratulates each of the participants for their active participation in the working group sessions with questions, comments, and suggestions.

RECOMMENDATIONS TO ACCELERATE THE USE OF ADVANCE MATERIALS IN MARINE CONSTRUCTION

The message from many of the user sectors involved in the workshop was that the dominant material for the future will still be steel. Steel has served the offshore and shipping industry well in routine and very demanding applications. It has the tremendous advantage of a large experience base and well establish communication links between producers, designers, fabricators and regulators.

However, alternative materials such as titanium alloys, aluminum alloys and polymeric composites are becoming increasingly attractive as offshore development proceeds into greater water depths. Justifications for using alternative materials include system cost-savings, improve performance and ultimately, technical enablement. In order to gain acceptance by the marine industries, these emerging materials must be cost-effective, fabrications, and must not compromise the integrity of the overall system of which they are a part.

The specific system recommendations for acceleration of the use of new emerging materials are listed in the following.

Mooring Systems

1. Design standards need to be updated and unified to accommodate taut mooring systems. There is also a need to develop engineering guidelines for synthetic ropes and composite strands. Developing a system design methodology that includes the coupling with risers is essential to exploiting the full potential of advanced material for mooring systems.

2. Design optimization of mooring systems requires the development of reliability based safety factors and a coupled hull-mooring dynamic analysis methods. There is also a need to develop a strategy to apply CFD analysis to predict coupled platform-mooring-riser response in lieu of model testing which is becoming scale limited as the water depth increases.

3. Very sparse cyclic and static fatigue data exist on synthetic ropes; there is a need to develop time-temperature-load degradation data base and prediction model for both ropes and their terminations. The degradation model should account for issues such creep, stiffness under different load frequencies, and potential damage during installation and service.

4. Because of the criticality of mooring systems, field calibration of synthetic mooring concepts is essential to verify mooring system response, validate degradation model, develop installation procedures, assess potential damage mechanisms, and build-up confidence.

5. A reliable quality assurance program for synthetic ropes and composite strands is an area where developments need to be pursued. Such a program should include manufacturing & quality control specifications, in-service inspection methods, on-line integrity monitoring techniques, and discard/retirement criteria.

6. The three most common terminations are eye spliced, zinc or resin potted, and spike in socket. Although potted and spike in socket terminations have performed well for small diameter ropes, their application for large diameter ropes is far from satisfactory and need to be developed. Eye splices for large ropes (up to 1500 tonne

NBL) have been found to function properly but the details of the eye to pin area has been found to greatly influence the long term integrity of the rope.

7. Preliminary results on developed carbon fiber ropes have demonstrated attractive properties, such as light weight, high axial stiffness and excellent fatigue properties, for potential use as TLP tendons. Assessment of damage resistance and fabrication characteristics, and verification of properties using large scale testing would be required before actual use.

8. Fatigue strength of steel ropes is an important parameter for deepwater installations. Limited data is available today; most obtained by testing small size ropes under bending. The use of these data for the design of large diameter ropes is questionable.

Riser Systems

1. To facilitate and expedite increased use of advanced materials for riser applications, collaborative development and qualification efforts involving end-users, manufacturers, material suppliers, academia, regulatory agencies, etc., must be encouraged and cultivated. Such collaborative efforts will help to pull together resources to overcome the high initial development cost of such risers, and to ensure that commercially viable products meeting the needs of the offshore industry will be developed.

2. System cost-saving must be investigated and emphasized when advanced materials are considered for new riser applications. Cost-savings bases on direct material substitution alone, though present for some special applications, might not provide sufficient incentive for using advanced material for risers.

3. A Joint Industry Project should be conducted to develop an industry-accepted database for the design of risers using composites. Emphasis should be placed on long-term material performance of composites in marine environments.

4. Standardized simple design methods should be developed to facilitate preliminary riser designs for cost, size and weight estimates. Standardized advanced design methods should also be developed and utilized for all final designs of risers.

5. Innovative riser designs should be promoted to reduce material, manufacturing, fabrication, installation and other costs.

6. Promote and standardize composite-to-metal joint designs to reduce the cost and need for qualifying and re-qualifying products of different designs.

7. Develop cost-effective butt-welding methods and fatigue resistant threaded connectors for titanium-alloy tubulars.

8. Develop appropriate NDE/NDT methods to aid composite-product acceptance/rejection.

9. Minimize the need for extensive inspection of composite risers by developing computer-controlled manufacturing processes with on-line monitoring of the fabricated product to ensure product quality and uniformity.

10. Accelerate the development of continuous, reelable composite tubulars. Such reelable tubular will minimize the need for "costly" metallic connectors, will facilitate riser installation and will facilitate the installation of integral sensors for monitoring the integrity of the risers through their service life.

Floaters

1. The recommended development of steel.
    - Materials with higher tensile strength capacity combined with good fracture toughness
    - More efficient methods to protect steel against corrosion
    - Continued improvements of other material properties, weldability, fabrication, quality control, corrosion resistance, etc.

2. The recommended development of concrete.
    - More efficient construction methods, using less manning
    - More efficient quality control methods
    - Light weight concrete, also efficient to fabricate

3. The recommended development of composites
    - Cost efficient fibers, resins and fabrication methods
    - General qualification of composites as construction material
    - General qualification of composites in fire and toxicity safety perspectives

4. The recommended development of aluminum
    - Alloys with higher structural capacities (ultimate strength, fatigue, crack propagation)
    - More efficient welding methods providing good properties also after welding

5. The recommended development of titanium
    - Better alloys with respect to crack propagation
    - More cost efficient materials in general

Fixed Structures

The following questions must be answered in order to further expand the utilization of aluminum alloys in marine structures:

1. What are the technical barriers to increased use of aluminum structural alloys?

2. Is high cost the primary reason why these alloys have been used only in certain applications?

3. Do design codes exist for aluminum structures in offshore applications? (AWS may address primarily welding/fabrication requirements, but not design.)

4. Are the yards equipped for structural fabrication using aluminum alloys and composite materials?

Secondary Structures

This discussion assumes a plate beam structure for all of the materials except composites. For some materials, particularly titanium, nickel alloys, and certain stainless steels, their relatively high strength and cost lend themselves to sandwich construction similar to that used for composites. The use of a corrugated or honeycomb core between two thin skins would reduce the amount of material used, and therefore reduce both the cost and the weight. In addition, because of the increased strength of the materials and the geometry of the sections, the structural integrity of the structure would not suffer. In addition, new and improved joining techniques for these materials, not necessarily limited to welding, can result in the cost effective production of large, complex, three-dimensional structures in a shipyard environment.

The material available for use in secondary structures for the marine environment are continually evolving, as are the methods for their fabrication. In some cases, increasing their use may mean overcoming cultural as well as technological boundaries. However, by taking advantage of these advanced materials today, it is possible to realize greater knowledge gained from the use of these materials will result in the advanced materials of tomorrow.

Hulls

With so many different hull arrangements and purposes, it is impossible to define a single "perfect" material. Clad materials, metallic composites, or other hybrid materials may provide the best solution for all of these scenarios, but even those hybrids would not be the same for each situation. It is important to realize that the best application of an advanced material may not lie in a single sector of the materials industry. It is recommended that cooperation among the manufacturing industries may result in the best arrangement for each of the classes suggested. In addition, hybrid design should be investigated further to utilize the best material(s) for each situation. Together this approach will maximize the benefits and minimize the risks of the use of advanced materials for ship hull construction.

Pipeline

1. Recommendations: Codes and Standards
    - Update current codes to include limit state design
    - Develop an API Standard for welding of solid and clad CRA pipelines
    - Specify yield strength ranges instead of only minimum yield strength for line pipe steels
    - Mechanized ultrasonic testing should be introduced as an acceptable alternative to radiographic testing in pipeline construction codes

2. Recommendations for Research and Development
    - Clarify effects of H_2S in CO_2-containing environment
    - Clarify LP requirements for deep water and shallow water pipeline installations and LP consequences for high strength steels, like X100 steels
    - Develop suitable flanges, fittings, welding procedures, etc. for X100 steels
    - Develop automated intelligent pigging for clad pipelines
    - Clarify advantages and disadvantages of hydro-testing new pipelines
    - Establish H2S limits for weldable 13% Cr steels

Offshore Processing Equipment

There are many considerations that must be taken into account when using some of the alternative materials because many of these alloys are new and untested. These considerations are: 1) design issues, 2) manufacturing/fabrication/operations issues, and 3) costs issues.

Several strategies can be developed to overcome the roadblocks to the use of these materials. Technical data searches are needed to increase the knowledge now available. Testing of materials should be encouraged to facilitate the needed material property information and the updating of codes and standards to include the allowable stressed for the new materials. Finally, new material prototypes should be used and evaluated to establish the experience base for fabrication, and the service history for the materials.

Research and Development is another issue. Funding is essential for R & D to demonstrate the longevity of any new materials proposed for these systems. The transfer of the knowledge to industry should be made through publications or technical meetings.

Harbors

Concrete, steel and timber have been discussed as effective materials in a marine environment. Deterioration and its causes have been discussed, along with various repair/replacement and mitigation strategies. Various research requirements have been discussed. In general, there is a need for a comprehensive database of failures and repair methodologies, in order to evaluate success, in terms of long-term durability.

Structures as Systems

In designing marine structures, the temptation is to view the design challenge as limited to selecting the best material for the structure. In fact, a structure can and should be viewed as a system The performance criteria do not have to be met by a single material. This is acknowledged inherently when a large ship hull is a steel with a hull coating. That is a system where two materials combine together to meet all the performance criteria. Design professionals are encouraged to view the incorporation of advanced materials in marine structures in the same way. Rather than simply desiring a structural material to substitute for another, review all of the features of the structure and seek to exploit the performance of the advanced materials as well as the features of the structure.

Supporting Remarks

Chris C. Oynes, Regional Director
Minerals Management Service
Gulf of Mexico, OCS Region

Robert D. Somerville, President
American Bureau of Shipping

Robert H. Rawle, Vice President and Group Executive
North, South and Central America and West Africa
J. Ray McDermott

Paul Prokop, Captain
United State Coast Guard
[Oral Presentation at Workshop]

Advanced Materials for Marine Construction
International Workshop
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Chris C. Oynes
Regional Director, Minerals Management Service
Gulf of Mexico OCS Region

Minerals Management Service (MMS) is also very interested in the ongoing work of adapting composites and other advanced materials to the production system. To date there has been limited application of such materials in the Gulf of Mexico, with their primary use being applied to nonpressurized and firefighting systems. There are definite design optimization and operating incentives for applying advanced materials to the produced fluid system. Both corrosion and erosion remain major concerns for marine operations. Weight is a key factor for deep water drilling and production facilities. With operations now moving into the ultra-deepwater areas of the world, floating production facilities will become more critical to success. Light-weight, high strength materials will play an increasing role. One specific area that MMS has been tracking closely is the development of composite drilling and production risers, and how the industry is designing these systems to address erosion, corrosion, and environmental loading concerns. An area in which composite and advanced materials have been successfully employed is in the flex joints of tension leg platform (TLP) tethers. Titanium has been used due to its high strength properties, and laminated steel and rubber joints have also proven to be reliable as part of the tethering system. Further, synthetic "Kevlar" mooring lines have been effectively employed as part of taut line anchoring systems in various offshore areas. As the experience base in their use grows, and assuming that their long-term reliability is eventually established, such synthetic mooring lines could conceivably replace conventional steel cable and anchor chain for certain offshore applications on the OCS.

While composite material has not yet enjoyed widespread use in fabrication of the structural elements of offshore structures, their expanded use in topsides facilities construction is certainly a good possibility. The same can be said for higher strength steels as costs and welding problems decrease over time. Industry has demonstrated that cost, not technology development, is the most serious impediment to moving into even deeper waters. Therefore, development of cost effective new materials for use in deepwater production systems will become increasingly more important in both the near and distant future.

Associated with the potential application of advanced materials to the offshore production system are concerns within the MMS regarding the maintenance of adequate levels of safety and environmental protection. The MMS regulations allow for the use of new or alternative techniques, procedures, equipment, or activities other than those prescribed in the regulations if they afford a degree of protection, safety, or performance equal to or better than that intended to be achieved by the MMS offshore regulations. Prior approval of their use is required by MMS. Therefore, any operator planning to integrate advanced materials into the production system in a manner that has not been previously addressed should initiate discussions with MMS at an early stage in order to avoid unwanted delays in the project timing. Appropriate information must be provided during such discussions so that proper MMS evaluation can be carried out in a timely manner.

As mentioned in the workshop brochure, the high cost of materials, lack of expertise in many areas of the manufacturing and fabrication process, and differences in design philosophy continue to present significant barriers to wide-scale application of the so-called advance materials. In some cases, a limited history of application of such materials can have the same effect. We should view these as challenges that can be met with cooperative research efforts and an open dialogue such as is provided by this workshop. The MMS encourages industry to continue with its momentum to seek solutions to these challenges.

SUPPORTING REMARKS FROM A U.S. CERTIFICATION AGENCY

Robert D. Somerville

American Bureau of Shipping

I would like to thank Dr. Olson and the Colorado School of Mines for inviting the American Bureau of Shipping to participate in this International Workshop on Advanced Materials for Marine Construction, and for inviting me to speak before this distinguished group. We look forward to the discussions and interchange of opinion over the next several days, and particularly to the conclusions and direction that the Workshop will provide in the area of advanced materials. These will undoubtedly be a great value to the marine and offshore industries.

As you are probably aware, ABS is one of the leading classification societies in the world with long experience in both the shipping and offshore sectors. It has as its mission promoting the security of life and property at sea, and the protection of the natural environment. ABS does this by setting standards for the design, construction and operation of principally surface vessels and also many other kinds of marine structures and systems. These standards include rules and guidance for material requirements and material selection used in the construction of marine structures and equipment. Those rules relate directly to the topics under discussion at this Workshop.

Just a little history at this point may be useful in explaining the strength of our interest in and development of materials. More than fifty years ago, during World War II, ABS, together with the U.S. Navy and other government agencies, investigated the very serious hull cracking problems that plagued the vast fleet of Liberty ships which were built as part of the war effort. The investigation showed that the combination of the use of welding for hull construction and the use of steel with a lower manganese content than normal had contributed to the cracking.

It was found that a completely welded hull structure afforded a continuous path for fracture propagation, while the lower-manganese steel had an inherently low level of toughness which facilitated initiation and propagation of the fractures. It was these early efforts, and the close inter-agency cooperation which developed during the investigations, that led to the organization of the Ship Structure Committee, which is still, today, directing and funding valuable research in the marine field.

Subsequently, ABS developed material requirements for hull structural steel. And we also developed related material selection criteria for oceangoing merchant vessels. These early developments have been adopted and updated by the eleven-member International Association of Classification Societies of which ABS is a charter member and now form the standards to which the international shipping industry must comply.

Since that time, the hull structure of oceangoing vessels has been fabricated principally by welding of carbon manganese steels. The method and the material are economical while providing the necessary properties. Understandably there have been modifications to the specifications over the years. For example, the introduction of microalloying elements, such as vanadium and columbium, has led to a class of higher-strength hull structural steel with yield strengths increasing from 46ksi to 51ksi to 57ksi.

The introduction of advanced rolling methods such as thermo-mechanical control processing has led to leaner chemistry versions of hull structural steel with increased weldability. And special grades are now being considered for laser welding applications. Today, the behavior of structural carbon manganese steel during fabrication and service is well understood and predictable. But challenges still remain. One such area is the potential application of even higher strength steel within the main structure and, in this regard, we look forward to the workshops dealing with Floating Structures and Fixed Structures.

In contrast to the hull structure, many of the supporting systems place such severe service demands on materials that carbon-manganese steel is no longer a viable option. These systems may involve high or low temperature extremes, or challengingly high pressures, or perhaps exposure to corrosive environments where carbon manganese steel cannot give satisfactory performance.

Typical applications include main propulsion systems, seawater systems and cargo-related containment. Typically the materials chosen for this service have been alloy steels, copper alloys, nickel-based alloys or aluminum alloys. It is fitting that theme papers addressing each alloying system are to be presented to the Workshop.

Many times advancements in materials application have been driven by the United States military since their priority is vessels and systems performance. The concerns of the commercial ship operators are performance related only as they apply to the economics of procurement, fabrication and operation. So, while advanced materials may exist in a proven military application, they cannot be utilized by the commercial industry until the economics are right.

For example, material selection for the propulsion systems in military vessels have always been more advanced than those of commercial vessels. The historical advancement to cupronickel, higher chromium-molybdenum steel, and austenitic stainless steel is a result of successful application demonstrated by the military. However, adoption by the commercial industry has trailed the military use by many, many years. During the discussions which follow, the participants to this Workshop must keep in mind the strong influence of economics upon material selection and application in addition to the properties of the materials themselves.

More exotic materials occasionally are used for quite specific applications. ABS has approved titanium alloy components made from 6Al-4V titanium alloy, which is commonly used by the areospace industry. This alloy possesses a special combination of strength, low density and corrosion resistance not found with stainless steel, aluminum alloys or copper-based alloys. The applications are related principally to the high strength-to-weight ratio and to the corrosion resistance.

For example, since the late 1970s 6Al-4V titanium has been approved by ABS for structural components and shafting in hydrofoils, a light craft with wing-like structures that support the vessel during high speed operation. In more recent years, approved uses have been stress joints for deep water production risers, and unalloyed titanium for seawater pumps and piping. We believe that further innovative uses of titanium and alloys are forthcoming and we look forward to the discussions in the workshop on Risers and on Production Equipment.

Composite materials that have been used in the marine industry are glass reinforced plastic for small boats, typically private yachts. To achieve the needed structural stiffness and strength in the shell, deck and internals, the composites are used as sandwich constructions that provide low weight structural elements with resistance to the seawater environment. Superior mechanical properties are attained by reinforcing with carbon fiber or other materials that are stiffer than glass and also by controlling the orientation of uni-directional fibers.

Composite piping materials are also used for certain applications. A principal disadvantage of composite resin materials is the low flammability rating. Where these materials are proposed for use in commercial vessels, structural fire protection issues must be considered. We trust that discussions in the Workshops dealing with composite materials will address potential solutions to the disadvantages which relate to the threat and consequences of fire.

On the offshore side there is strong interest in production from reserves in much deeper water than in the past, leading to new design approaches and the necessary consideration of advanced materials. Floating production systems have become quite popular for tapping these reserves, but will place severe demands upon the mooring systems which must become larger to accommodate the greater water depth. Non-metallic mooring lines are attractive for these deeper water applications. Thus it is timely that one workshop is to discuss Moorings and one theme paper is to address Elastomers & Polymers.

ABS strongly advocates technology transfer and supports these workshop activities. The bringing together of the materials developers and manufacturers with the marine vessel and systems designers will lead to the interchange of knowledge that will help to implement innovative materials solutions and applications. Comprehensive advancement in ship design must consider the integration of novel materials with the first principles engineering approach. This Workshop is an important means to bring the two together. A review of the topics chosen for the workshop activity and the subjects for the theme papers shows that this Workshop will address the major application and challenge areas for advanced materials in marine construction.

ABS fully supports the ongoing efforts in materials development and encourages everyone here to actively participate, so that this Workshop will develop useful guidance for the future direction of materials application. The commercial marine sector will benefit greatly from improved guidance and recommendations for the use of new and novel materials.

It has been a pleasure to speak before you this morning to share our enthusiasm for this Workshop, and to briefly describe ABS' interest, experience and desired improvements in the application of advanced materials.

Supporting Remarks

Robert H. Rawle
Vice President and Group Executive
North, South and Central America and West Africa
J. Ray McDermott

Good morning and welcome to New Orleans. McDermott has been a fixture in New Orleans for many, many years. We are glad to have you in our city and happy to be a sponsor of this event. Listen closely to what is said today, but then go out and have a good time. There is no other place in the world like New Orleans, so enjoy it. But please be careful.

McDermott has been in the marine construction business since its beginning. We got our start many, many years ago building plank roads into the swamps of South Louisiana. In 1947, we completed the first offshore platform in the Gulf of Mexico. Today, we work in every offshore oil and gas region in the world.

Over the years, we've developed a good relationship with the MMS. These workshops are important to the exchange of ideas and the development of our industry, which takes on unique challenges every day.

The ocean out of sight of land is not an ideal place for a fixed structure. It is exposed to loading from wind, current and severe storm waves. In some places, it may be subject to earth quakes or low temperatures and even ice. The action of the waves is continuous, varying from mild day-to-day chop to huge storm waves, and creates fatigue. To top it off, the structure sits in highly corrosive salt water. Finally, take into account that offshore platforms are built at competitive costs and on short schedules and you'll see the challenge of marine construction.

The first fixed structures to produce oil and gas in the Gulf of Mexico were built 50 years ago in 20 feet of water. The industry was new and so it borrowed and adapted from related industries such as harbor and in-shore construction. The sizes and selection of grades of steel were limited in those days. In fact, one of the first platforms in the Gulf was supported by 10-inch H-beam pilings driven through 14-inch diameter jacket legs. But despite this awkward beginning, the Gulf of Mexico turned out to be a good place to start because it allowed offshore construction technology to develop in a orderly manner.

Those early platforms were fabricated from conventional low carbon steels such as ASTM A-7 and other mild steels such as the various API grades available as pile. When ASTM A-36 was introduced around 1960, the offshore industry made the switch to take advantage of a 10 percent increase in strength--and almost no additional cost.

Over the next few years, the industry moved into deeper water and technology improved. It soon became apparent that the extreme design event--the Gulf of Mexico hurricane--could be considerably more severe than predicted. As platforms were designed to resist larger forces, it became obvious that the "weak link" in platform construction was not structural members but the connection or "joint" where the bracing members were welded to the jacket leg.

In most structural applications, members are welded together either at the ends or on the edges. But the joints in an offshore structure are welded into the sides in a third direction called "through-thickness," which increases the importance of strength and other properties. Steel used for conventional applications doesn't require special properties for this third direction and usually it is not even tested. But as development moved to deeper waters and offshore structures grew larger, we needed steel with better through-thickness. The need was met by the development of API 2-H, a stronger, tougher steel.

Today, ASTM A-36 and API 2-H are still the primary metal grades used in the construction of most offshore platforms. Frequently, other intermediate strength (50 ksi) steel is used in place of 2-H where the thorough-thickness properties are not required. In instances requiring extra thickness or for more highly stressed or critical applications, special quenched and tempered steels such as API 2-Y have been utilized.

We've only talked about steel because most offshore platforms, both fixed and floating, are fabricated from steel. But other materials have been used in the past and are being used today. In the early days of coastal waters and shallow offshore waters, hundreds of concrete platforms were installed in the Gulf of Mexico. In fact, it wasn't until the mid-1950s that we opened the first fabrication yard for steel structures. While concrete is no longer used in the Gulf, concrete and steel construction is still used in some sectors of the North Sea.

In the late 1950s, McDermott installed almost 100 platforms with aluminum jackets in Lake Maracaibo in Venezuela. The lake's low salt content and high dissolved oxygen content created a corrosive condition that precluded the use of steel. The platforms required the development of an entirely new technology to design, fabricate and install, and they performed satisfactorily until they were removed when the oil fields were depleted. But for obvious reasons, aluminum had only limited applications.

So, here we are 50 years after the first offshore platforms were installed in the Gulf of Mexico. We've increased water depths from 20 feet to 3,000 feet, but a revolutionary advance in materials is yet to come. It is reasonable to ask: Why? Certainly, higher strength steels with good welding characteristics are available and suitable for the fabrication of offshore platforms. In fact, some of these steels have been used offshore for very specialized applications such as the tendons that anchor a floating tension-leg platform.

It's choice, not lack of knowledge, that keeps traditional materials in use. Except in unusual cases, intermediate grades of steel offer many advantages for offshore platforms. For example, a thin-walled high-strength steel is not as practical or as cost effective as an intermediate grade with thicker walls. Thicker walls generally have better buckling characteristics and structural stiffness, two factors that are very important in the design of a fixed offshore structure.

As you meet this week, our industry is at a critical juncture. Deepwater development in the Gulf of Mexico and other areas of the world present us with a challenge typical of those we've faced periodically over the past 50 years. Most often, we've responded to such challenges with absolutely fabulous structures. Yet we are an industrial adolescent when compared to bridge and building construction--both of which have benefited from new materials. As we move to a new generation of structures, our industry would no doubt benefit from higher strength materials with improved corrosion resistance and better fatigue and toughness characteristics.

Will these materials be developed? One of the purposes of this workshop, of course, is to ask that question and suggest answers. Possibly the discussions here will result in some new technology. Perhaps they will lead to new materials or applications of materials we currently don't use. However, you must remember this: we use the tried and true by choice--in our world, improvement seldom comes unless it makes price more competitive.

I thank you for your attention.

Keynote Address

Diderik Schnitler and Ole Martin Moe
Kvaerner ASA

Mark Matovich
Shell Corporation
[Oral Presentation at Workshop]

Kensuke Taniguchi
Mitsui & Co. Ltd.

Special Topics Presentations

Gregory Woods (Naval Sea Systems Command)
Anthony J. Furio (Naval Surface Warfare Center)
Natale S. Nappi (N.S. Nappi Associates Inc.)
John Volf (Designers and Planners, Inc.)
Mark Smith (M.A. Smith, Consulting)

Yogi Ogawa (Shikoku National Industrial Research Institute)
Shozaburo Nakano (Technological Research Association of Mega-Float)

Donald E. Brunner (Naval Facilities Engineering Service Center)

Keynote Address:

"Material Requirements for Ships"

Authors:

Diderik Schnitler
Ole Martin Moe

Material Requirements for Ships.

1. Introduction

Shipbuilding is a major industry world-wide. The total capacity for shipbuilding is in the order of 14 million Compensated Gross Tons. Of this Kværner stands for approximately 600.000 CGT. The majority of the ships totally build are bulk carriers and tankers. One large VLCC represents approximately 200.0000 CGT while a Panmax cruise liner represents 250-300.000 CGT

The main material in shipbuilding is steel and mainly the mild steel quality. The use of high tensile steel has however, increased during the last 10 - 15 years and is now used for approximately 75% of the steels in Japan and Korea. In Europe the use of high tensile steel is much more limited and only 10-15% of the total steel volume is high tensile steels.

What is mild steel and high tensile steel in the shipbuilding industry ? In shipbuilding, the governing design requirements are given in the Classification societies Rules and Regulations. These rules defines the requirements to the materials in the different groups in terms of chemical composition and a minimum yield strength. In DNV the NVA to NVE is the lowest quality with a minimum yield strength of 235 MPa. High tensile steel is defined in several groups from NV27 to NV40. The qualities NV32 and NV36 are the most commonly used which means a minimum required yield strength of 315 MPa and 355 MPa. Extra high strength steels are defined as steel qualities with a minimum yield strength from 420 MPa up to 690 MPa

Materials other than steel are only used to a very limited amount, and the reason for using these materials is based on weightsaving, or special requirements from the load itself. Examples are Aluminium, Stainless steel and GRP.

2. State-of-the-art for use of materials within Kværner Shipbuilding group

The Kværner Shipbuilding group comprises totally 9 yards in northern part of Europe. Kværner is Europe's largest shipbuilder and among the three largest in the world. The Kværner yards are focused on special ships, often one-of-a-kind, or small series ships. None of our yards are building large bulkers or tankers which is the main volume in shipbuilding. The special ships have normally stricter requirements to use of materials and the cost pr. ship is significantly higher than for conventional ship types.

Within the Kværner group there are yards which are specialised in building ships not only in steel but also in aluminium and GRP. High speed catamarans are totally built in aluminium to save weight. Minehunters to the Norwegian Navy is totally built in GRP sandwich due to operational requirements. These ship types are, however, small and the material tonnage is very limited compared to steel ships.

The steel shipyards within Kværner has a steel consumption annually of approximately 150.000 tonnes. Of this amount approximately 80% is plates and 20% stiffeners. High tensile steels are used only in limited areas and only 15-20% of the steel volume is HT-steel.

Stainless steel is used in chemical carriers. The annual throughput of stainless steel within the group is approximately 7000 tonnes.

The aluminium used for fabrication of fast car/passenger catamarans is approximately 800 tonnes annually. Aluminium is also used in the spherical tanks on the LNG ships. A total of 3600 tonnes of aluminium is used in each ship. Aluminium is used in the tank system du to the extremely low cargo temperature of - 163 °C. Aluminium have good material properties at low temperatures, and the properties are actually improving as temperatures drops.

Further, aluminium is used in the top deck structure for cruise liners, car ferries and coastal liners. Weight savings due to stability problems is the major reason for using aluminium in these areas, but normally the cost increases when steel is substituted with aluminium to save weight. The groups total annual throughput of aluminium excluding the LNG tank fabrication is approximately 1100 tonnes

Glassfibre Reinforced Polyester is used for the construction of the minehunters and mine sweepers for the Norwegian Navy. GRP is used because of the operational requirements to the ships. The maximum annual throughput of GRP is approximately 350 tonnes. The sophisticated ships for the Norwegian Navy also includes some titanium in the piping system. This adds up to approximately 9 tonnes annually.

As can be seen also for the Kværner group who is focusing on specialised ships, steel is the by far the most important material.

3. Material requirements in traditional shipbuilding

Building of large volume structures for slow speed ships are extremely efficient. The major requirement to the materials are that the forming and joining can be done in a very effective way. The weight of the ship structure is not of any significant importance because the steel weight itself is only 15-20% of the total ship displacement. Normal steel and lower degrees of high tensile steels are the only materials used in this business. Large ships operating in the displacement mode is rather insensitive to weight. This can be illustrated by an example, a conversion of an ULCC made by Sumitomo. The displacement of the ship was increased by 140.000 tonnes, or approximately 30%, and the speed dropped only 1.6 knot with the same machinery.

The fabrication processes developed for these materials and this kind of ship structures are very effective. A labour effort of 10-15 man-hours per tonne is normally obtained for these ships. The competing edge is low cost. Introduction of new materials in these ships must hence reduce the total cost of the ships.

There has, however, been a turn towards high tensile steels also for these ships. The reason is that the cost of high tensile steel is almost the same as for mild steel. By using NV36 steels rather than the mild steel a reduction in the steel weight of 10% is normally obtained. This means a direct reduction in the material cost of 10%. One obstacle against the use of HT-steel is reduced weldability due to increased carbon content. Improving the strength of the material normally means increased alloying elements and the carbon equivalent increases.

The new TMCP-steels represent a solution to this problem. These steels have the same carbon equivalent as the mild steels and the strength of the high tensile steels. This is obtained by the so called Thermo Mechanically Controlled Process (TMCP). The material temperature during the rolling process is controlled and improved cooling with water is introduced if necessary. The material temperature at last rolling is normally rather low.

In Europe the cost of the TMCP steels are somewhat higher than the cost of standard HT-steel, indications of 5-10% higher cost is given by the steel manufacturers. This is not the fact in Japan and Korea as far as we know, and can be one of the reasons for why HT-steel is used more frequent in those countries.

Fatigue related problems have not been a separate issue in the shipbuilding industry. The fatigue resistance is normally taken care of by the rule requirements to plate and stiffener scantling. The introduction of the HT steels in tankers and bulkers lead to an increased stress level in areas with high fatigue loads. Severe fatigue damages have occurred for these shiptypes and the shipowners are based on this somewhat reluctant in introducing to much HT steel in the ships.

Still there are no requirements in the classification rules to document the fatigue capacity of the structures. The focus is however now more towards the fatigue related problems. Guidelines and recommendations for how the fatigue capacity shall be calculated and documented are developed for all the major Classification Societies.

Understanding the fatigue related problems will be a key area when higher tensile steels shall be utilised

4. Material requirements for specialised ships

Specialised ships is a market were the cost level is significantly higher than for the standard ships. The requirements either from the cargo or from the operation of the ship leads to material selections other than the traditional shipbuilding steel.

Requirements stemming from the cargo properties can be extremely low temperatures, corrosive environment, local increased strength and increased space with same weight. The transportation of LNG (Liquefied Natural Gas) at -163°C sets among the toughest requirements to the material in the cargo containment system. Two materials are normally used, Aluminium alloy and Ni-steels. These materials retain their structural properties at the actual low temperatures. The cost of the materials is however high.

Chemical carriers are examples of where corrosive environment and the requirement to be able to transport nearly any fluid has lead to the selection of higher qualities of steel in the cargo containment system. Stainless steel is quite often used in the sophisticated chemical carriers.

Local requirements to increased strength as in the main deck structure of open hatch container ships and LNG ships will also lead to stricter material requirements. The section area in way of large openings in the main deck is too small to render necessary strength with normal steel.

On cruise liners the requirement will be to offer a largest number of passengers an optimum amount of space within given beam and depth restrictions. Stability requirements will often lead to a selection of materials with higher strength/weight properties than the normal steel in the upper decks of the superstructure. Normally the superstructure is dimensioned based on minimum thickness and those are the same for steel and HT-steel, hence aluminium is used in these areas.

Common to all these cases are that the requirements from the transported cargo have given the shipbuilder and the shipowner no other possibility than to select more sophisticated materials although they are much more expensive.

Requirements from operation

Several ship types will also have requirements to the material selection from the point of operating the ships. Among the most extreme examples of material requirements from the operation is the minehunters under construction at Kværner Mandal in Norway. The ships should have as low magnetic emittance as possible and hence the antimagnetic GRP sandwich was selected. The Surface Effect Ship (SES) concept selected for the minhunters is also excellent with respect to explosions in water with a very small wetted surface in operation. This is an example of a ship where the operational requirements have been the leading edge in all stages of the development of the ships.

Icebreakers are another example of a ship type where the requirements to local strength of the hull in icebreaking mode leads to selection of materials with higher strength properties. For these ships high tensile steels are used. Icebreakers with steels where the yield strength is up to 500 MPa have been built. As the strength in these areas is only due to local loads, the fatigue related problems can be omitted. The use of stainless steel in the "ice belt" reduces the friction towards the ice.

Increased service speed may also lead to requirements of improved strength/weight properties for the materials used in the hull girder. This has however, not been a major issue up till now in the shipbuilding industry. Only in the catamaran and high speed monohull car and passenger ferries, this is focused.

5. Future prospects

What is the future of the shipbuilding and shipping industry:
- Major volume will continue to be in the tanker and bulker ship types
- More specialised ships
- Requirements for higher transportation speeds

The major volume in shipbuilding at a global basis will also in the future be on the large conventional tankers and bulkers. Stricter material requirements for these ship types is normally a result of a wish for lower investment cost. New and improved materials will only be used if the material cost and/or the fabrication cost is reduced due to the new material. The TMCP steels have showed to be a step in this direction, at least in the Far East where the cost of the TMCP steels are comparable to the cost of mild steels. Indications have even showed that in some cases the high strength TMCP steel is cheaper than the traditional mild steel. The development in the future will go towards higher tensile steels, and combined with the TMCP technique the weldability is maintained. Projects utilising steel qualities with minimum yield strength of 400 MPa is now launched.

The major problem will be the fatigue properties and how to improve the welded details in this respect. The focus has already turned to the design of detalis and how to improve the fatigue capacity of the welds by post weld treatments.

High speed ships

The requirements to higher service speed for specialised ships will increase the requirements to the materials used in the future. The new materials will first be introduced in these ships and these ships will always be in the front line of the technology. I will hence focus on these shiptypes in the rest of the paper.

The two main markets for high speed ships ar the car/passenger catamarans and monohulls. The largest catamarans built are the two Stena Catamarans, Stena Explorer and Stena Voyager. These ships have a displacement of 4000 tonnes, a length of 125 metres and service speed of 40 knots. For the monohulls, the Tirrenia 1 and 2 now under construction at Fincantieri are the largest with a displacement of 3000 tonnes, a length of 145 metres and a service speed of 40 knots.

The high speed ships are weight sensitive, and a major part of the displacement is used by the hull structural weight. The reduction of the hull structural weight will hence give a direct positive effect on the payload capacity or the service speed/power requirement. The strength to weight ratio of the materials should be improved. Reduced weight means:

- Increased investment cost
- Increased payload capacity
- Reduced power installation
- Reduced fuel consumption

In order to have a competitive concept the sum of these factors must end up in higher margins for the owner or reduced ticket price for containers/car or passengers. This will give the operator a competitive edge. As a matter of fact, high speed ferry services have been identified tha only can be feasible if the relative large ships can be built in weight effective materials.

The high speed ships should be divided into two categories, the monohulls and the catamarans. the monohulls are normally operating in the displacement mode which means a Froude number below 0.5. While the catamarans are operating in the semi planing mode with typical froude numbers between 0.7 and 1.

For the catamarans the weight is extremely important. With only 15-20% of the displacement available at present for the payload, the weight estimates and weight control is important and if weight can be saved it will be done.

In the displacement mode the weight is still very important but not in the same magnitude as for the catamarans. the payload capacity for the monohulls are typically in the magnitude of 25% of the displacement or even higher.

High strength materials are based on this important. There are however several structural strength requirements that has to be fulfilled. The three governing criteria of the material will be :

- Yield strength
- Buckling strength
- Fatigue capacity

The different materials will act different in the three design modes. The state-of the-art figures and potential improvements for the three material requirements will be addressed in the following.

Yield strength

The state-of-the-art shipbuilding materials have the following strength to weight ratios based on the allowable yield strength:

• Mild Steel	0.030
• High tensile steel NV36	0.046
• Aluminium	0.054
• GRP	0,074

Aluminium

As can be seen the aluminium has a better strength to weight ratio based on the yield strength than steel. However, a steel with a yield strength of 420 MPa will have the same strength to weight ratio as today's aluminium. Our belief is that also the aluminium strength properties will be improved in the coming years. Kværner have actually joined forces with Hydro Aluminium and DNV to investigate the possibilities of improving the aluminium material and develop efficient fabrication methods and ship designs to take these new material properties into account. The project is called "Aluminium in Ships".

The project was launched in the summer of 1996 and will be a three year program. The application of such a material will be in catamarans and large fast monohulls mainly, and also for the superstructures of the large cruise liners. There are aluminium alloys available to day with much higher yield strength than what is accepted by the classification societies. For instance the Russian alloy 1561 is reported to have yield strength as welded in the range of 180-200 MPa. This material is however not yet approved by the major western Classification Societies. The AA7108 alloy which is used by Hydro Aluminium for car decks to catamarans have also very good strength performances but the allowable stress level is kept at the same level as the standard alloys by the Classification societies. The corrosion resistance of this alloy is not yet fully documented.

One of the major problem areas associated with aluminium is the soft zones due to welding. The allowable design stresses are based on the allowable stresses in the welded zone as these are the weakest part of the structure. The use of more extruded panels and improved joining methods will reduce the effect of the softening of the material in the weld zones. Joining methods for aluminium structures is hence a major area in our development project. In fact three of a total of six PhD candidates within the "Aluminium in Ships" project are working on joining technologies for aluminium.

High Strength Steel

In parallel with the improvement of the aluminium material the steel industry works in the same direction. We have in the shipbuilding industry seen that the use of 36-steels are quit common especially in the Far East. Also steels with even higher yield strength are now being used. In the offshore industry in Norway steels with yield strength of 420 MPa is common and even higher strength steels are used. Ongoing projects are focusing on steels with yield strength up to 690 MPa.

The weld zones in steel are not that big a problem. (For the aluminium, this is the crucial point.) The requirement to efficient welding methods leads to high heat input in the welds which will reduce the Charpy -V impact toughness of the heat affected zones. On the other hand low heat input will increase the problems with hydrogen cracking. As the material yield strength are improving the area of safe welding conditions are reduced. The reason for the reduced weldability is the Carbon Equivalent (CEV) which is given as:

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

The Carbon content represents the major problem. Other alloying elements add also up to the total CEV. Typical CEV for normalised ship steels with yield strength of 240 MPa are approximately 0.3, while with a yield strength of 360 MPa the CEV is approximately 0.4. This means that preheating of the weld zones may be needed. The TMCP steels combine reduced CEV with improved yield strength. A TMCP material with yield strength of 360 MPa has nearly the same CEV as the normalised steel with 240 MPa yield strength.

A lot of effort is put into how the high strength and extra high strength steels can be made more weldable and how the welding methods can be improved to be able to weld these materials effectively.

Fibre Reinforced Plastic (FRP)

For the FRP the yield strength will simply be what is needed by the structure. Yield strength for such materials is also hard to define. The fibres have a very high strength while the resin is normally softer. Further the material can have different capacities in different directions according to fibre direction. Fibres with very high strength properties as Carbon and Kevlar fibres are available on the market, but at a very high cost. On this basis it is not likely that these types of fibres will be used in commercial shipbuilding until the price is reduced significantly.

The standard fibre in shipbuilding today is glass with polyester as resin. The material is relatively cheap but the strength properties are also quit modest. The weight is however low an the material has the highest strength to weight ratio of the materials. The cost of the material and the fabrication of the hull is today significantly higher than comparable vales with aluminium. One of the major obstacles for improved use of GRP in shipbuilding is the lack of automated fabrication processes which will ensure the quality and reduce the cost. Non Destructive testing of GRP structures is also a major problem area.

The FRP materials is an interesting possibility for future high speed ships but it seems that both the material cost and the fabrication cost must be reduced significantly to have an competitive edge.

Buckling strength

The buckling strength of a structure is mainly coupled to the material Elasticity Modulus. The E-Modulus for the different materials are as follows:

• Steel	210.000,	MPa
• Aluminium	72.000,	MPa
• GRP	25.000,	MPa

Steel has the by far highest E-modulus close to three times higher than aluminium.

It is also found that the E-modulus of the materials will differ very little when the yield stress is improved. This means that the buckling problem is increasing with increasing stress level.

As there is very little that can be done with the material to improve the buckling strength the focus is put on the design side. Ship structures are plate/stiffener structures and are subject to several modes of buckling. Plate buckling, stiffener buckling, global buckling and local buckling are all modes that have to be checked. A typical plate field is carefully designed to obtain sufficient buckling strength in all modes and reduce the number of stiffeners to a minimum. Increased number of stiffeners means increased welding work, but normally reduced weight. In steel shipbuilding the welding cost is significant and will always be reduced as far as possible. Normal steel, HT-steel and

EHT-steel have all the same E-modulus which mean that if the governing design requirement is buckling there is no effect in using higher strength steels.

Aluminium

For Aluminium where extruded panels can be used the design freedom is much higher and the fabrication cost may not increase by increased number of stiffeners. The use of extrusions combined with efficient panel fabrication can improve the buckling strength of the structure by adding more stiffeners without increasing the cost of the panel. The use of extrusions and efficient panel fabrication will be focused also in the "Aluminium in Ships" project.

The Russian Aluminium supplier Samara Works actually delivers plates up to 1820 mm width with 90 mm high stiffeners. These plates are extruded in huge presses as a pipe and split afterwards. For such panels the designer is left free to design the panel with an optimum buckling capacity and lowest possible weight.

FRP

For FRP again the freedom of selecting fibres and fibre direction can improve the buckling strength of the structure. The material might not be isotropic and can hence have better buckling capacity in one direction than in the other main directions. The necessary E-modulus will be determined and applied.

The method of using an-isotropic materials is complicated and costly, and the stresses in the ship structure must be defined in detail. This gives a costly design phase and the construction of the material must be carefully followed. The ships built today in GRP are hence designed from materials which are close to isotropic and have an E-modulus in the range of 25.000 MPa.

Fatigue capacity

The fatigue capacity of a structure is defined as the structures ability to withstand cyclic loading. Improving the yield strength of the material will as for the E-modulus not improve the fatigue capacity of the materials.

The most important tool in defining the fatigue capacity of a structure is the SN-curves which gives number of cycles until a damage occur at a given dynamic stress level. SN-curves are normally worked out for parent material, and a set of welded structural details. The parent material SN-curves are much better than the SN-curves for welded details. The reason for this is mainly the changed geometry due to weldconnections.

High Tensile Steel and Aluminium

For steel there is a given lower limit for dynamic stresses where fatigue damage will not occur. A corresponding limit in the SN-curves for aluminium is not found. This means that for steel fatigue can be avoided if the dynamic stress level is below the given limit but for aluminium fatigue will always be a possibility.

As the SN-curves for the steel and aluminium materials respectively are almost the same for the different qualities, this favours the use of the lower qualities. The use of higher strength materials increases the static and dynamic stress level and the structure will be more exposed to fatigue loads.

In high speed ships where the weight is very sensitive and the use of high strength materials is needed to realise the projects, fatigue will be one of the major problem areas. Fatigue is on this basis included in the "Aluminium in Ships" project as an important item.

The fatigue capacity of a structure is design dependant and hence the focus is put on optimised designs. Especially the local design as plate/stiffener connections etc. are important. It also seems that the knowledge obtained for one material is relevant for other metallic materials.

Post treatment of welds may also improve the fatigue capacity of the structure. R&D projects within these fields are launched and especially the effect of grinding and hammer peening is promising. SN-curves close to the parent material curves have been reported from some of these projects.

Fibre Reinforced Plastic

For FRP the fatigue capacity can be defined in the same way as for the metallic materials. However as the materials can change very much the need for special fatigue testing is obvious. Such testing is expensive and time consuming and can be a further obstacle in using sophisticated high strength fiber materials.

Fatigue data for the normally used GRP are to some extent available but the material is in no way as mature as the metallic materials. The fatigue capacity of the individual fibres is normally very good but combined with the different fibre directions and the resin the fatigue capacity is reduced and can only be established by fatigue testing.

Based on the statements given above we believe that Aluminium and steel will be the dominating materials in the high speed shipbuilding industry in the near future. FRP represents an interesting alternative but is today too expensive and with too much uncertainties in the material properties.

6. Concluding Remarks

Requirements to the materials in shipbuilding is dependant on the ship types. The major volume of materials will also in the future be on large tankers and bulk ships. These ships are entirely built of steel. Only moderate grades of high tensile steels will be used.

Special ships will increase their market share of the shipbuilding market when ship value is considered. These ships have higher and more specific requirements to the materials used than the standard ships. The cost of these ships are also significantly higher and the material cost is hence less important.

High speed ships will also be an increasing market. These ships are extremely weight sensitive and high strength materials are hence needed. In order to be able to develop cost effective high speed cargo ships new high strength materials must be introduced either steel or aluminium. Combination of these materials is also a possibility.

We believe that high speed cargo liners will be realised in the future with a service speed of 35-40 knots and a length above 200 metres. These ships will require high strength materials and effective fabrication methods in order to reduce the power consumption and keep the fabrication cost down.

The success of such ship projects are strongly dependant on further development on material properties, design and fabrication processes. Aluminium or steel is the materials that are most likely to be used. FRP is an interesting material with very good strength to weight properties but the fabrication cost is today more expensive. Combination of the different materials utilising the best properties from each material in different parts of the ship might be a promising solution.

The material requirements from the shipbuilding industry will increase in the future for special and high speed ships, but the major volume of material will still be steel with moderate strength properties.

Keynote Address

Economic Implications of Marine Construction

Kensuke Taniguchi

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Japan

The remarks will address the development of demand for oil & gas, the challenge of bringing oil & gas from remote areas, the significance of new technologies for future business growth especially focusing on advanced materials of steel for marine construction and the necessity of contracting strategies to enhance the project viability.
(From 20 years experience in steel business, the main focus is on to steel which contributed to the economics of today's marine construction technology.)

Oil & Gas Demand

Energy demand in the United States has increased by 17.5% in the past decade, and the demand for oil & gas shares 65.4% on average of this total demand, proving to be the most stable energy resources. The remarkable figure is natural gas consumption which shows a 33.2% increase over the last 10 years. On the other hand, the production of oil & gas shared 52.6% in 1995 which means that the domestic production is not catching up with the rapid demand for energy. Here, we can find the background of the needs for more production, especially in natural gas.
When we look around the world, a lot of oil & gas development projects are being planned and implemented in the Middle East, Asia, Australia besides USA, being accelerated by the recent steady oil price in range of \$20-\$25/brl and natural gas price over \$3.00 per mmbtu.

Hydrocarbon Reserves

World gas reserves increased by about 50% over the last 10 years despite strong growth of gas production. At the current rate of production, gas reserves would last for about 60years and oil reserves would last for about 45years. The continuation of this favorable trend in reserve growth is expected. However, future oil & gas fields are expected to be more remote, hostile and more difficult to develop.

Those examples are "Arctic Field", "Deep Water", "Far from Market", "Sour Environment" and "Higher Carbon Dioxide".

Economics are critical for bringing oil & gas to the markets from remote area and from those difficult field to develop.

Technico-Economic Evolution for Ocean Development & Offshore Production

Despite the difficulties of development, ocean development has been accelerated because more than 50% of undeveloped deposits are under the ocean and 23% of world oil reserve and 14% of gas are in the ocean.

The characteristics of recent offshore production are:

1) The aggravation of operating conditions linked, in particular, to an increase in water depth. (Remote)
2) The decrease in the size of fields discovered (Marginal field)
3) The greater distance between consumption centers and new discoveries. (Remote)

Technical developments have a great influence on the economic condition of offshore production. New technologies being introduced or developed concerning offshore production are, respectively,

1) Deep Water Development
    - TLP (--5,000ft)
    - Compliant Tower (600-2,000ft)
    - Production Spar (3,000ft)
    - Floating Production
    - TBT

  - Mini-TLP
  - Subsea Completion
- 2) Marginal Field Development
  - SPM
  - FPSO (with subsea flexible riser)
  - Sub-sea completion
  - Two-phase production system
  - Monopod/Tripod
- 3) Greater Distance
  - Long Tie-Back
  - Long Natural Gas Trunk Line (vs. LNG)

Floating systems with flexible risers offer numerous economic advantages, particularly for medium-size or marginal fields -- especially as the result of the relatively smaller investment, faster speed of implementation, easier retrieval and possibility of being used again. SPM and FPSO have been most commonly introduced for the areas where the minimum Capex. is needed and/or projects requiring cash generation as early production for the future full development scheme. But, they always require the on-site availability of crude-oil separation and processing equipment before the evacuation of oil and gas and therefore subsea two-phase production systems can be expected. This should enable crude oil to be piped directly through a single flowline from subsea wellheads to the shore where the processing equipment would be installed, thus eliminating any permanent support on the field site.

East Spar field of Western Australia in 1996 was a good example.

Some economic simulations show;

a) With a few exceptions, the rate of return is negative if conventional developments with fixed structures are used.

b) The optimization of fixed structures, i.e., weight reduction and total automation, is a source of great savings, but the concept remains the same and the rate of return decreases in time as a result of the increase in environmental difficulties.

c) Floating production systems are always advantageous even with a crude oil price of $20/bbl or more and hence make up a firmly established trend for the future.

d) Subsea Production systems with gradual spread through satellite developments, especially in their ultimate phase of two-phase production could achieve new economic conditions for deep water.

Where offshore development is a great distance from the consumption area, Trans-Asia Natural Gas Pipeline (all the way from Australia to Japan) is the typical idea because the laying of pipelines at a maximum depth of 1,000meters of water is possible in such areas. Pipeline is always economical compared with the LNG transportation of which Capex. is huge. There would be a competition between 'how to lower the pipeline cost' and 'how to lower the cost of LNG equipment and LNG tankers' in the future.

However, transforming natural gas into liquid hydrocarbons is obviously an ambitious goal and this technology have already been developed by a major oil company.

Technology Contribution to Deep Water Development

The chronicle of recent deep water production is shown in the Figure.

Names of the fields with the type of production facility (Fixed Type, Floating and Subsea Completion) are given at each water depth. Fixed steel jacket for Bullwinkle in 1988 used more than 100,000M/T of steel but Floating TLP for Jolliet in 1989 used approx. 10,000M/T of steel excluding the topside facilities.

Again, the economics are critical and vital for all those deep water projects to materialize and the crowd of deep water projects in the late 90's is proof of their economic success.

An oil company who has been successfully installing TLPs in the Gulf of Mexico says "We can achieve improved production rates, earlier production and lower costs".

We have to add further that the technology has lowered risk exposures besides costs.

Lower finding, development and production costs make some of the Gulf's longer reservoirs in very deep water competitive with many other offshore prospects.

Examples of technologies for such finding, development and production are;

1) Exploration costs are being trimmed with 3D seismic technology

2) Better drilling capabilities are lowering deepwater drilling cost derived from such as Top drives, horizontal drilling, extended long reach wells

3) Recent advances in deep water production systems such as TLP, Compliant Tower, Spar and Sub-sea completion associated with the long subsea tie-back are supported by the remarkable contribution of advanced materials.

Advanced Materials - Steel Innovation

Steel is a vital building materials for all parts of the hydrocarbon development and its delivery chain. Various modern technologies as above mentioned have contributed the economy of offshore oil & gas production, but the contribution from material side,
especially steel, is equally important as other technologies.
Just like today's success of car industries being supported by the innovation of lighter and tougher steel, many of offshore production tools and facilities are supported by the
innovation of steel. Let me introduce some of those examples.
Premium Jointed OCTG has contributed Top drives, Horizontal wells and long reach wells of deepwater.
Hi-collapse OCTG has contributed deep well production and furthermore Hi-Collapse
ERW Casing made it more cost-effective.
Non-Mag Drillcollar is inevitable for horizontal drilling.
High Strength/Lighter weight pipes are used for deepwater drilling risers of 6,000ft.
Subsea Completion has been successful with the super-duplex umbilicals, production risers such as flexible pipe catenary riser/hybrid steel riser.
Development of hi-collapse linepipes are used for long subsea tie-back and trunk line.
Even good quality ERW pipe had been used for over 1,600ft water depth pipeline in Viosca Knoll field.
The deepest tie-back of 5,412ft Mensa field is another step-up for future prospects.
The R&D for heavy wall, accurate ovality and minimal dimensional tolerance linepipe was seriously studied for 10,000ft ultra deep water of the Arabian Sea as well as its laying method.
Weldable high-strength steel is the biggest contribution to the cost effective marine construction.
The increase in strength to weight ratio and the associated savings in material cost is the key-word for deepwater floating structures and ultra-long pipelines.
Due to the lean chemistry (low carbon, smaller alloying elements) and finer grain structure,

TMCP steel has greater cleanliness than Quenched/Tempered steel and such modern H.S. steel has improved weldability, strength and fracture performance.

High toughness steel for Weld and HAZ was established to meet high heat input welding for higher strength and heavy thickness. Consequently, the application of .H.S.

steel for fixed steel structure was dramatically increased for 8% share in 1998 to 40% share in 1995.

Furthermore, the accumulated data for hydrogen cracking and fatigue performance gives more credit to those steels to be aged for floating structures.

Efforts are still continued by steel manufacturers on ultra length crack arrestability steel developed by ultra fine grain, ferrite microstructure of surface layer.

Weldable High Strength steel will contribute to the economics of long pipeline, enabling the transpiration of highly compressed natural gas by means of reduced diameter of pipeline and lighter wall-thickness. The market will be reached with lower cost pipelines even from far remote locations.

Other challenges of steel to the hostile surroundings are such as;

low temperature toughness steels for Arctic service of -60/-70deg.c. and cryogenic temperature for CO2 separation, anti-sour service steels and crack arrestability steels.

Optimization of weldable High Strength in low temp., sour service is the ultimate goal.

Contracting Strategies

The economics of marine construction will not necessarily be affected by the advances in materials engineering itself. The goal is to focus those technical advances to addressing the customers' specific needs, both technical and commercial.

No technology will be attractive if its not packed in the right way at the right price.

To develop simpler and lower cost systems for technology development, team work research on technology sharing and co-operative research was effective.

Likewise, the concept of alliancing and partnering in the contracting area will provide innovative solutions to both technical and procedural problems while still meeting safety, schedule and cost objectives. Getting away from the conventional contracting philosophies of job owner - contractor - supplier to a more cooperative and less protagonist approach will be the key. Even for the Buyer-Seller relationship, the advantages of alliance are, that within a flexible framework, the elements of price, delivery, quality and quantity can be protected over time.

It also lets the supply side see the picture earlier and this enables a commitment to be made to your project in preference to all others as to who will line-up for their slice of materials allocation in the market.

Partner's ability to develop a compatible and responsible alliance culture is vital for the well-being of the project.

The strategic alliance is the adding of value to your project.

Conclusion

Technology and competitiveness are always the essence of industrial activities.

Sound economics and new technologies will be the key element of success and the advanced materials supported by adequate contracting strategy will maximize clients' return on investment.

LIGHTWEIGHT METALLIC SANDWICH PANELS FOR MARINE CONSTRUCTION - U. S. NAVY EXPERIENCE

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SUMMARY

Budget constraints are necessitating the drive for more affordable structures. Operational goals are requiring more survivable and capable structures. Recognized internationally and considered "the new design approach" by naval architect and marine engineers, lightweight metallic sandwich panels feature several advantages for marine construction. Although not widely publicized nor completely "certified" for primary loaded ship structures, lightweight metallic sandwich panels continue to evolve as a viable alternative to conventional plate beam construction. While the content of this paper is pimarily applicable to marine construction, it is considered equally applicable to land base construction. Years of at-sea services for a select number of U. S. Navy ship structures serve as testimony. Metallic sandwich construction technology (advanced by the U. S. Navy) is being pursued to address structural survivability issues, reduce construction and life cycle costs, reduce outfitting costs and improve ship compartment appearance by providing more orderly runs of marine systems. Survivability features include, increased structural stiffness (including higher natural frequencies) and improved ballistic, blast, fire, RCS (very flat surfaces) and IR (reduced heat transfer). Potential cost reduction items include less structural material weight, large flat surfaces with reduced number of angle and tee beam stiffeners, less fire and thermal insulation and easier installation on flat surfaces, no straightening of structure, reduced backup structure for foundations and fewer structural members to protect or paint. Improved habitability features include increased compartment volume (large flat surface areas without stiffeners) and orderly runs of marine systems which improves the appearance of compartment spaces.

GENERAL HISTORY

The U. S. Navy continues to look for new structural materials and configurations which improve warship structural performance and integrity and provide life cycle cost benefits. One such metallic sandwich construction as referred to by the U. S. Navy is LASCOR (LASer welded corrugated CORe). LASCOR is a metallic corrugated core panel made of two metallic face sheets separated by a corrugated core and welded together in a sandwich configuration (Figure 1).

The U. S. Navy began research and development of metallic sandwich construction in the late 1970's to reduce ship's topside weight. Three structural configurations were compared with conventional plate beam structures. They were:

1. Optimized conventional steel plate and tee beam using high strength steel,
2. Lightweight metallic sandwich panels, and
3. Nonmetallic composite panels.

The lightweight metallic sandwich panels consisted of three different core concepts (Figure 2). They were:

1. Corrugated core,
2. Honeycomb core, and
3. Pyramidal Truss core

Preliminary investigation of these three concepts considered flexure, shear, fatigue, and axial compression characteristics. A tradeoff between the concepts was performed after which one metallic and one nonmetallic concept were selected for further investigation based on weight, cost, strength, producibility, repair, fire, and corrosion resistance characteristics. Initially, spot welded corrugated core sandwich panels were selected as potentially the most promising structural concept to pursue for shipboard construction (Figure 3). The spot welded panels were developed by the aerospace industry which used a proprietary spot welding process. The corrugated core was formed using a male and female press break or stamping process (Figure 4). Further investigation and advances in laser welding technology propelled the U. S. Navy into the next generation of metallic sandwich panels, LASCOR. Some of the advantages of laser welding as compared with spot welding are: 1) continuous welds for superior structural integrity, 2) ability to weld thicker and different materials, and 3) potentially cheaper manufacturing process. By the mid-1980's, a series of U. S. Navy research efforts transitioned the sandwich panel construction into "real" applications. Four metallic sandwich panel structures are currently aboard U. S. Navy ships (Figures 5a - 5d). Three of the four applications are constructed of spot welded panels. The fourth application is constructed of LASCOR. From a physical appearance, the only difference between spot welded and LASCOR panels is in the weld process used to join the face sheets to the corrugated core. Additionally, specifications for two new warship classes specify that their helicopters hangar doors be constructed of "metallic panels."

The very first U. S. Navy lightweight sandwich panel construction was a Close In Weapon System (CIWS) deckhouse installed onboard DD-981 (*USS John Hancock*) in March 1982.
The deckhouse is 24 ft. long, 8 ft. wide, 8 ft. high, and constructed of ferallium 255 (stainless steel) spot-welded, corrugated-core panels. This deckhouse application achieved 20 percent weight savings over an aluminum design. The second application was a 64 ft. long, 45 ft. wide, and 9 ft. high 316L stainless steel Avionics Repair and Maintenance Shop Complex installed in November 1986 on CV-41 *(USS Midway) (Retired)*. This module of decks and bulkheads was constructed from spot welded panels. Engineers achieved a weight savings of 20 percent over a steel plate beam design. Approximately 15 percent of additional weight was added due to a lack of full-scale structural tests and verification data at the time.

The third spot welded panel application is a set of deck edge elevator doors installed aboard CV-66 (*USS America*) in August 1987. The doors are 33 ft. wide, 25 ft. high, and 7 inches thick, and are fabricated of 316L stainless steel ¾ inch thick spot welded panels. The weight savings was 46 percent over conventional steel doors. Finally, the latest metallic sandwich panel applications in the fleet are two antenna foundation platforms. Each platform is 33.5 ft. long, 12.5 ft. wide, and approximately 3 ft. deep. The platforms are comprised of 316L stainless steel 2 inch core depth LASCOR panels. They saved 33 percent of the weight of the platform and supporting structure and increased the natural frequency by a factor of 4 over a conventional steel plate and tee-beam design. The platforms were installed onboard LCC 20 (*USS Mount Whitney*) in January 1994.

WHAT ARE THE PRO's AND CON's FOR METALLIC SANDWICH PANELS?

Pro's?

Lightweight metallic sandwich construction offers several technical advantages in comparison with steel plate beam construction designed to the same load requirements. The major advantages are:

1. **Panels Construction Cost.** Panel construction cost is predicted equal to or less than that of conventional plate beam due primarily to fewer pieces to assemble and install, faster production rate, and a more efficient fabrication process. [1]*[2]

2. **Decreased Ship Integration & Outfitting Cost.** No fairing of lightweight panels required, flat surfaces for insulation and outfitting, less painting due to fewer or no external stiffeners.[3][4]

3. **Reduced Weight.** Metallic corrugated core sandwich panels offer a 30-45% savings because of their high stiffness-to-weight ratio. [5]

4. **Increased Ship Structural Stiffness.** The measured modal results of an 86 inch by 45 7/8 inch thick LASCOR panel was compared with finite element analyses of conventional steel plates over a range of thicknesses. The finite element model plates were analyzed with pinned and fixed end conditions. Since the end constraints of the LASCOR panel was between pinned and fixed end constraints, the finite element results are considered comparable. Based on this comparison, LASCOR is significantly stiffer than conventional plate beam construction.

5. **Reduced Need for Fire Thermal Insulation to Satisfy Requirements.** Fire and heat transfer test results reveal that the heat transfer rate through a LASCOR panel is lower than through steel decks. LASCOR panels inherently improve fire protection due to their hollow construction.

6. **Improved Fragmentation Protection.** Panels improve ballistic and fragmentation protection due to required piercing of multiple spaced metallic sheets.

7. **Decreased IR Signature.** Less heat transfer through LASCOR due to hollow construction.

Cons ? Solutions?

With any construction material there are disadvantages or limitations. The metallic sandwich panel is no exception. The most significant, yet surmountable, "cons" as viewed by the authors, are listed below.

1. **Completion of Material Certification.** All U. S. Navy ship structures comprised of corrugated core sandwich panels were installed on a trial basis. Nevertheless, the assumed technical risks

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[ ]* - Refer to references

and benefits gained, triumph over conventional construction. The authors mention this not to discount the need to certify lightweight sandwich panels for ship structures, in fact just the opposite. The principle motivation for certifying lightweight metallic sandwich panel construction is for the expediency of the end users. Certification is essential for designers to take full advantage of the material not only during "backfits" or "overhauls" but also during the early design phase.

At the time of this paper, the authors developed a program which included a proposal to certify lightweight metallic sandwich panels. The details and the scope of the proposal is not the subject of this paper and therefore are not included. However, the central focus/essence/feature of the certification proposal is the full scale testing and evaluation of representative struuctural components to be correlated with design and analytical equations. The following outline list the proposed tasks identified to certify metallic sandwich for ship primary loaded topside structures and internal decks.

TASK 1: Identify: Risks, Design Criteria, Requirements
TASK 2: Design/Analysis - Test / Evaluate
TASK 3: Complete Design Guidance Documents
TASK 4. Complete Fabrication, Inspection, & Repair Documents
TASK 5: Develop Cost Estimating Prediction Program
TASK 6: Technology Transfer

2. **Characterized Ruggedness.** Inherent ruggedness of LASCOR, which is made from steel sheets, has been questioned.. Ruggedness has not been defined quantitatively nor in terms of what is the acceptable. It is acknowledged that some criteria or minimum acceptance limit is necessary. An attempt to characterize "ruggedness" without jeopardizing weight savings should be determined by actual damage assessment or simulation and then correlated with current analytical techniques.

3. **Inaccessible Void Areas.** The hollow construction, raises concern over internal corrosion potential of the inaccessible void areas. Preliminary test results of internal corrosion protection systems applied (i.e., non-toxic foam, standard Navy "fill-and-drain," or rust inhibitors) show that this problem can be eliminated or controlled within an acceptable level. Another important factor to be considered is the trade-off of material selection (e.g., stainless steel versus carbon steel.)

4. **Full Production.** Although metallic sandwich panel construction has matured since the 1980's it is not in full production. At the time of this paper, there has been significant interest expressed by industry in full production of LASCOR. The industrial base includes: Astech, Inc., Santa Ana, CA, Praxair Surface Technologies, Newcastle, PA, and Johnstown Welding and Fabrication, Inc., Johnstown, PA. U.S. Navy facilities with both LASCOR construction experience and production capabilities are Puget Sound Naval Shipyard and Norfolk Naval Shipyard. We expect that the list will grow commensurate with the market.

GENERAL CONSTRUCTION SEQUENCE / SCENARIO

The following provides a general description of recommended practices, techniques, and processing sequence associated with sandwich panel construction:

1. **Producibility and Training for Ship Structural Subassembly.** Because sandwich panel construction within the shipbuildering community is relatively new, it is advisable that some level of producibility training be accomplished before actual construction begin. Producibility training will usually include certification of welders, and concurrently, help to establish the best weld procedures and practice.

Preliminary recommended guidance are already developed for which to help train personnel for handling, welding, assembly, and shipboard integration and outfitting of LASCOR structures. Such guidance is accumulated from over 15-years of experience with training personnel (i.e., welders, shipfitters, and outfitters) aboard U. S. Navy warships.

2. **Panel Fabrication.** As mentioned earlier, the first corrugated core panels were manufactured by a spot welding process. A quality product is produced by this process, however due to advances in metal joining technology, laser welding is currently the preferred process for panel construction. Absolutely crucial to the panel fabrication process is the appropriate jigging and fixturing used during the manufacturing process. Equally important is the proper sequencing of welding to control any potential welding distortion. Due to low heat energy input, high dilution rates, and speed, laser welding is a most efficient and effective process to minimize weld distortion. Rapid advances in laser welding technology and other manufacturing techniques have driven down the panel manufacturing costs without sacrificing quality. This trend is expected to continue.

3. **Panel Cutting.** Recommended methods and tools for cutting holes and penetrations in the panels include using a band saw with hardened metal teeth, an abrasive saw band, a portable hand guided saw with hardened metal teeth or abrasive blade or machine milling. Sawing with a non-portable power saw with hardened metal teeth or abrasive blade, laser, and flame or plasma arc cutting are also recommended. LASCOR faces sheets can be cut by flame and plasma arc cutting. Conditions of the face sheets after flame and plasma cutting require edge prep to deburr edges to limit potential injuries to personnel and for desirable fit up. High pressure water jets can also be used for cutting face sheets. However, cutting of the corrugated core is performed by mechanical tools. Figures 6a and 6b, 7a and 7b, and 8a and 8b illustrate cutting methods. Circular holes can be drilled or cut using circular saws with suitable hardened teeth or an abrasive edge. It should be noted that laser cutting leaves a straight edge with few burrs and the cut edge is nearly perpendicular to the surface.

4. **Welding on Panels.** For best results, it is recommended that all welding be performed by certified welders of sheet metals. Because panels are constructed of thinner gauge sheets (vs plates), there are opportunities for innovative joining and integration techniques. We recommended that all hand welding be done using the MIG and TIG processes. Rapid advancement in laser welding technology (i.e. application of fiber optic Nd-YAG lasers) [6] certianly makes it an attractive and feasible process for metal joining at he work site. Plate doublers are installed locally when welding subassemblies or equipment to panel structures. Plates doublers are also used to evenly distribute the loaded area (Figures 9a and 9b).

5. **Structural Assembly.** Conventional shipfitting techniques, modified slightly, are used to construct structural assemblies. As is the case in panel fabrication, adequate fixturing and jigging is necessary to construct LASCOR structures. Figures 10a and 10b illustrate typical fixturing of panels into a structural assembly. Proper fixturing allows access to both sides of the subassembly so that shipfitting techniques such as commonly used tack and sequence welding can be accomplished.

6. **Handling and Movement of LASCOR Structures.** All structural assemblies must be evaluated or assessed to establish the best method for handling. LASCOR is no different. Weight and center of gravity must be established and the appropriate (structural shapes) utilize to prevent damage during handling. Figures 11a and 11b show an example of handling a structural subassembly.

7. **Painting of Structures.** Metallic sandwich structures can be prepped and painted following guidance established in Naval Ships' Technical Manual (NSTM) S9086-VD-STM-010/CH-631 V1. However, we caution against the use of power tools when removing paint, primer, rust, etc., from the panel surfaces. Hydroblasting may be used to remove foreign material. Lightweight metallic sandwich panel construction generally requires fewer exterior stiffening members resulting in less painting of

unrestricted surface area. Application of corrosion protection systems is also appropriate, depending on the material selected. Non-adherence to prescribed corrosion protection measures can adversely affect the maintenance and performance life of the structure.

8. **Shipboard Integration of LASCOR Subassemblies.** Integration of LASCOR into conventional metallic plate beam construction poses no serious risk or complications. However, inherent stiffness of the panel can the "Achilles' heel" if details are not carefully considered. The panels are usually very stiff and extremely flat which leaves little room for misalignment. However, LASCOR construction lends itself very well to both standard and innovative construction details. Figures 12a - 12f show a progressive sequence of a LASCOR structure integrated with conventional ship structure for the LCC-20 Antenna Platform (see Figure 5d).

9. **Outfitting of LASCOR Structures.** Although not necessary, as a precautionary measure during the outfitting process, plywood may be placed over the LASCOR areas to protect the surface from routine and undesirable outfitting activities (e.g. weld spatters, dropped objects, etc.). Plate doublers are welded to the LASCOR face sheet for equipment foundations and load spreading. Figure 11 shows a typical load spreading detail for equipment foundation attachment.

LASCOR FOR MARINE AND LAND CONSTRUCTION - AUTHOR'S ADVOCACY

For simplification, the structural components of a ship hull can be divided into three areas:

1. Primary structures consist of all structural components which resist hull girder longitudinal bending loads. These elements form a box girder, reinforced inside with a number of bulkheads, decks, and an arrangement of beams and girders forming the framework.

2. Secondary structures consist of horizontal platforms, transverse bulkheads, deckhouse, and miscellaneous lightweight bulkheads, etc., that are not a factor in primary hull girder resistance loads. They are usually subjected to lateral loads, such as hydrostatic pressures, plane or wheel loads, etc. Hence, if the secondary structure sustains a structural failure the strength of the primary hull is not adversely affected.

3. Miscellaneous structures consist of all structures which are not primary and secondary structures.

The following secondary structures represents the most significant candidate applications for lightweight metallic sandwich panels construction for military and commercial ships:

Deckhouse/superstructure (e.g. side walls and decks)*
Ramps
Platforms
Bulkheads
Foundations
Conflagration stations
Escape trunks
Large hatches
Doors (e.g. helo hangar, deck edge elevator, & hangar bay division)
Movable decks
Helo landing platforms

*Deckhouse/Superstructure application can be considered either primary or secondary. It is considered to be primary when it contributes to the hull girder bending load resistance, and considered to be secondary if it "stands alone".

Currently, the most promising candidate commercial structural applications for metallic sandwich panel construction are:

Bridge decking
Oil Rigs platforms
Fortified shelters
Railroad car decks & sidewalls
Building blast walls
Internal shear walls for buildings
Helo landing decks

CURRENT LASCOR ACTIVITY - A SYNOPSIS:

United States Coast Guard (U.S.C.G.) - The U. S. Coast Guard is determining the feasibility of a LASCOR deckhouse for their 278 ft. "High Endurance Class Cutter". Requirements for a steel deckhouse with minimal life cycle cost are factors motivating the consideration of LASCOR as the candidate deckhouse construction. The level of effort for this effort is approximately 0.75 man years.

Naval Air & Warfare Center (NAVAIR) - NAVAIR is investigating the feasibility of applying LASCOR titanium jet blast deflectors for aircraft carriers. The preliminary design and analysis of the deflectors are complete. Fabrication, testing , and evaluation of the deflectors remains to be performed. This level of effort is approximately 2.0 man years. The goals are reduced life cycle and maintenance costs.

United States Navy (U.S.N.) - The U.S.N. is investigating several new technologies which will have some immediate impact and application to military and commercial ship construction under the Mid-Term Sealift Ship Technology Development Program (MTSSTDP). LASCOR is one such technology identified as the structural construction for ships' large hatch cover/movable decks. The design and analysis of a prototype LASCOR hatch cover has been completed. The hatch cover will be fabricated and subjected to full scale tests and evaluation. This is a 3 year program.

Ministry of Defence (MOD), United Kingdom - MOD is investigating the feasibility of LASCOR for their New Carrier 2000 flight deck. The flight deck test section designed by will be tested and evaluated by MOD and the U. S. Navy. Large test sections are currently being manufactured in the U. S. and UK, for in-plane compression and lateral and patch load testing and evaluations.

Helsinki, Finland - Under a U.S.C.G. Memorandum of Understanding (MOU) established between the Helsinki University and NSWCCD, LASCOR technology is being investigated for icebreaker deckhouse structural application. Preliminary investigation of the panels has been completed in the following areas: panel design, fire, static strength, weld fatigue, and acoustic. Future work will be in the area of joint fatigue studies.

SUMMARY:

The U.S. Navy continues to develop lightweight metallic panel technology for marine construction. Successful at-sea experience of selected applications (e.g., doors) is "commendable." [7] Considering the extensive experience of the Navy and collaborating developments in the design, analysis, and fabrication of LASCOR structures, and their level of maturity; this marine construction technology should be made available to designers/engineers for consideration during early stages of ship design. However, to make this possible, it is recognized that elementary yet necessary design "tools" must be made available for easy access to the constructions ship designer. The authors would like to add in closing that this paper by no means addresses every pertinent aspect of LASCOR; rather, it is intended to acquaint the reader with an alternative approach--one which has advanced beyond the feasibility stage and possesses both proven and potential advantages over conventional marine construction.

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Figure 6a, Panel Cutting, Reciprocating Saw

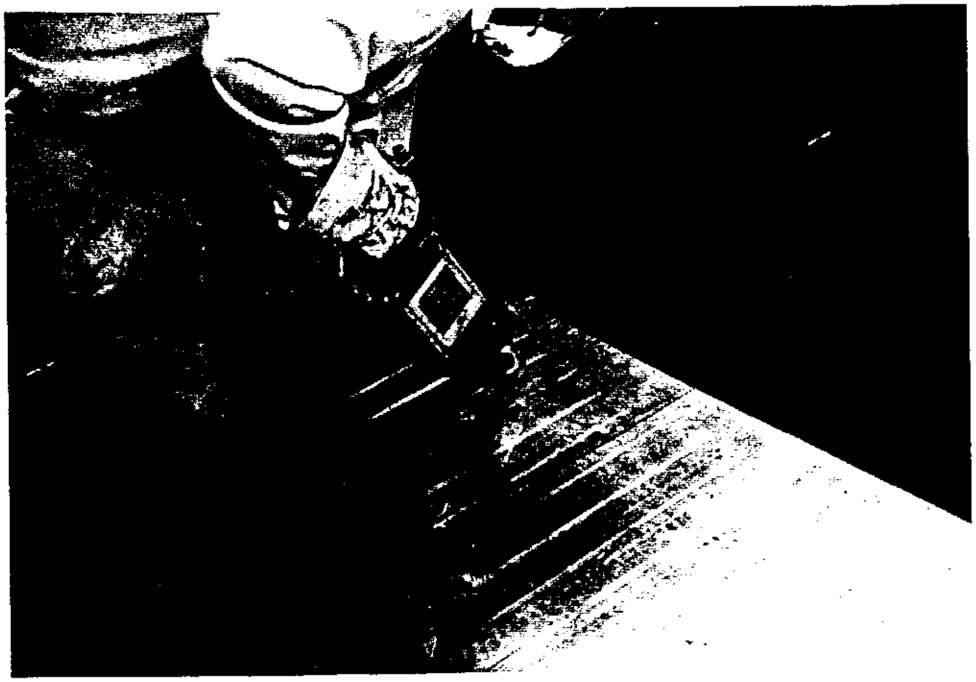

Figure 6b, Panel Cutting, Reciprocating Saw (cont.)

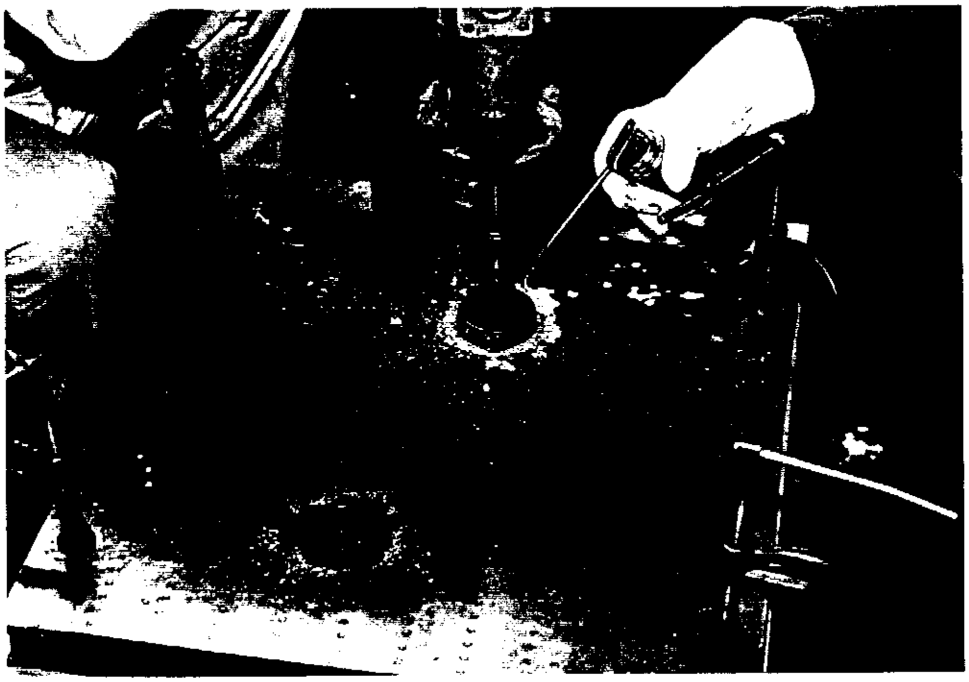

Figure 7a, Hole Drilling

Figure 7b, Drilled Hole

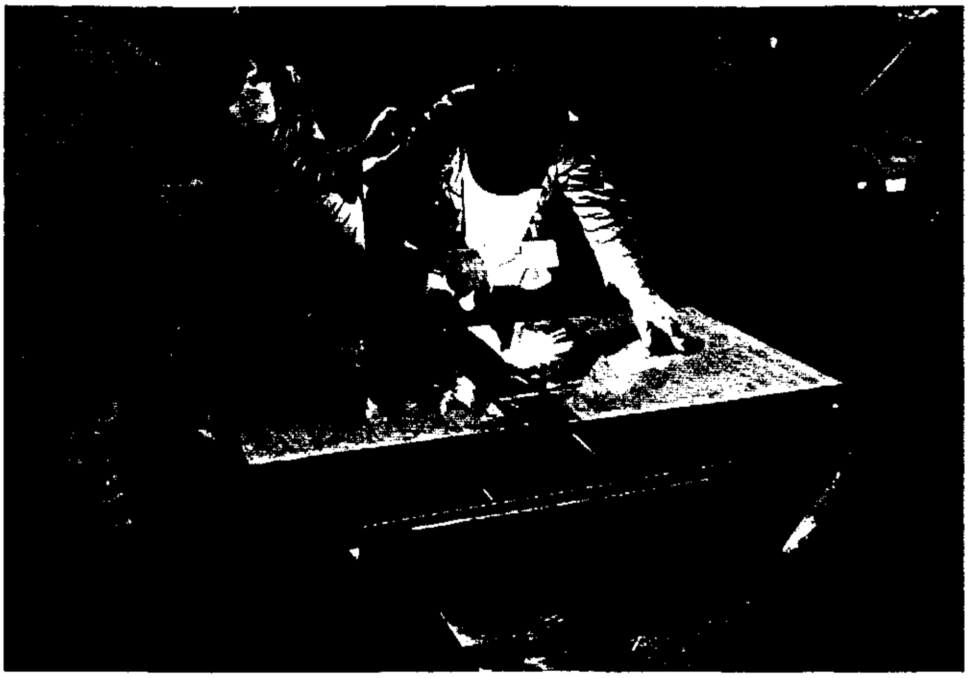

Figure 8a, Panel Cutting, Plasma Arc

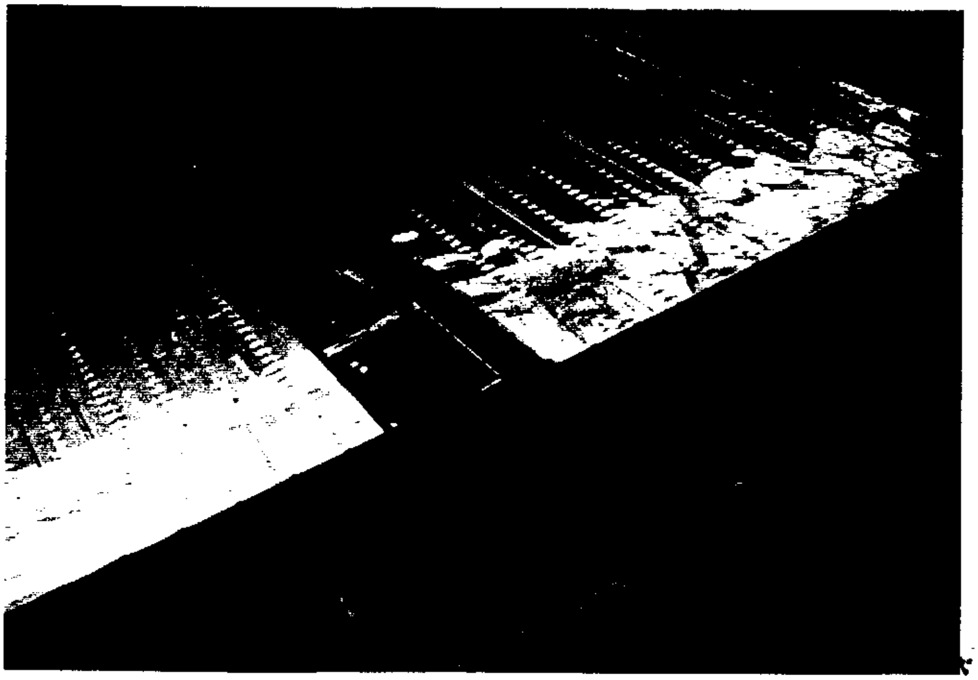

Figure 8b, Panel Cutting, Plasma Arc (cont.)

Figure 9a, Bulkhead Load Spreading Plate

Figure 9b, End View Bulkhead Load Spreading Plate

Figure 10a, LASCOR Panel Assembly

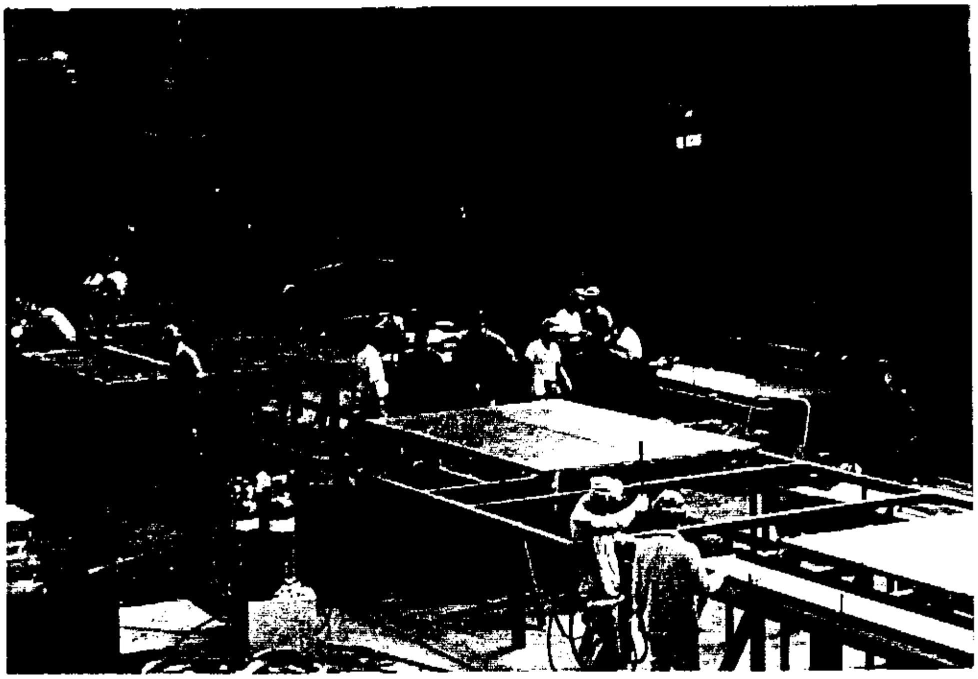

Figure 10b, LASCOR Panel Assembly (cont.)

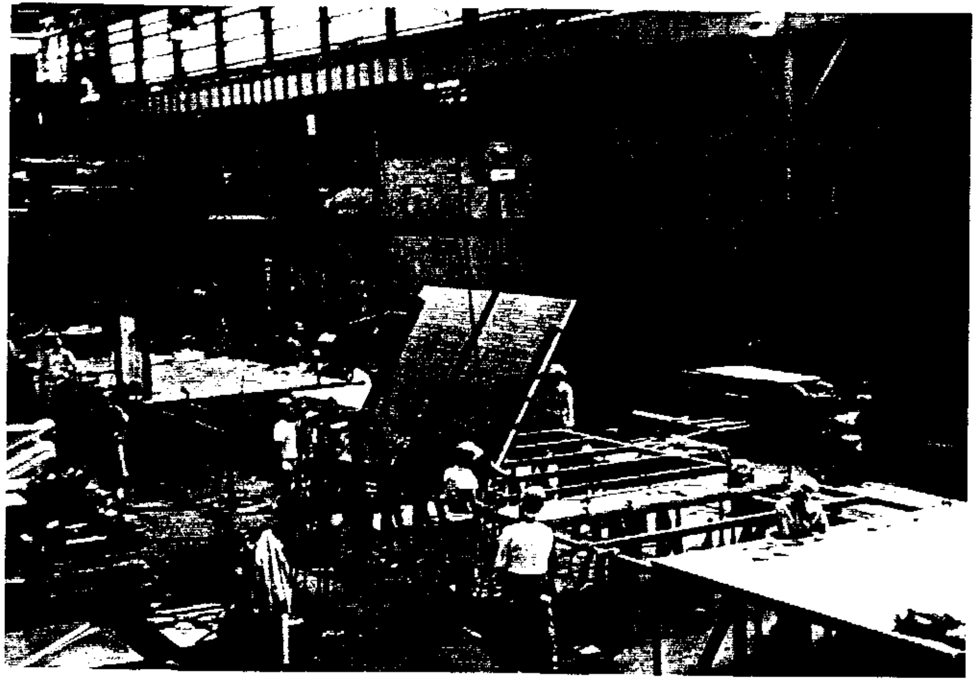

Figure 11a, LASCOR Structure Handling

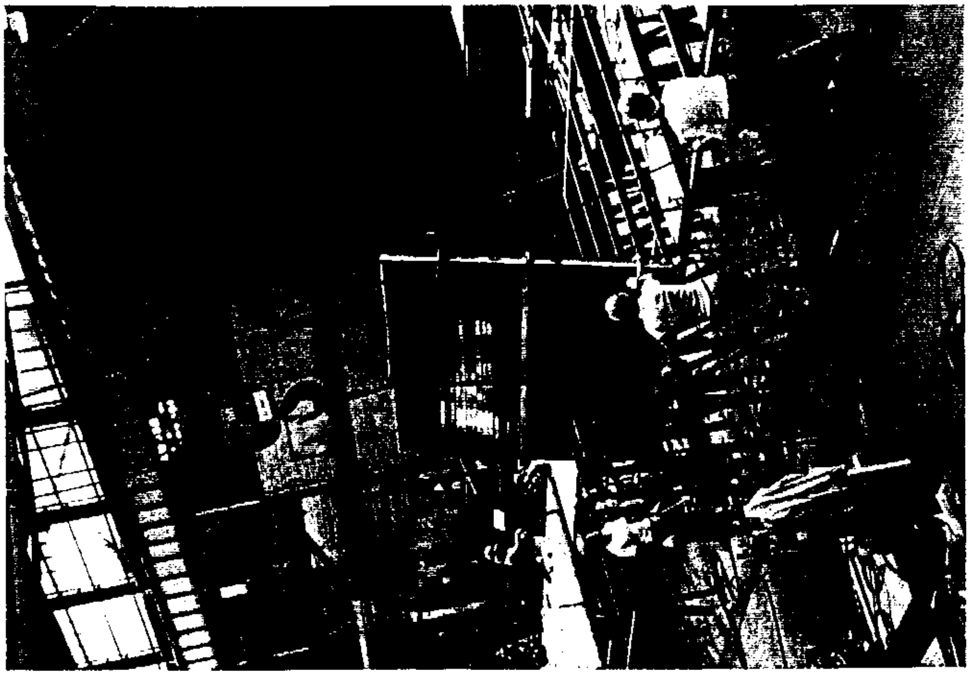

Figure 11b, LASCOR Structure Handling

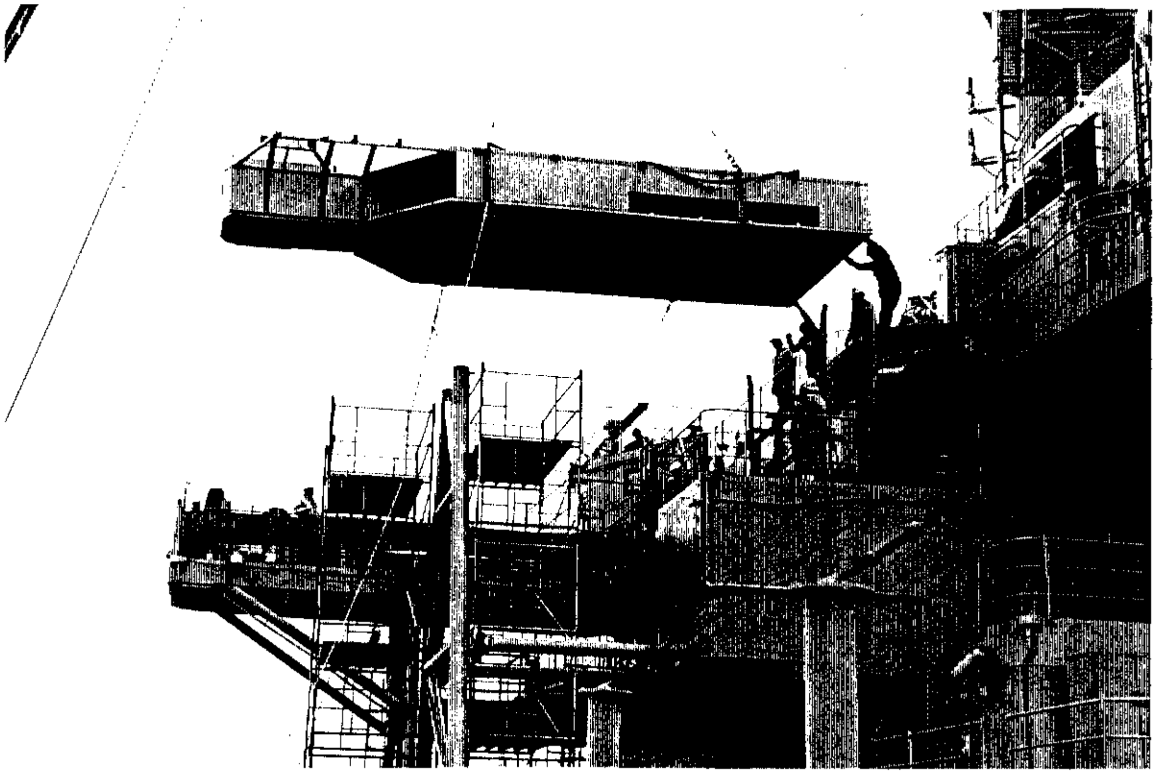

Figure 12a, LASCOR Ship Integration

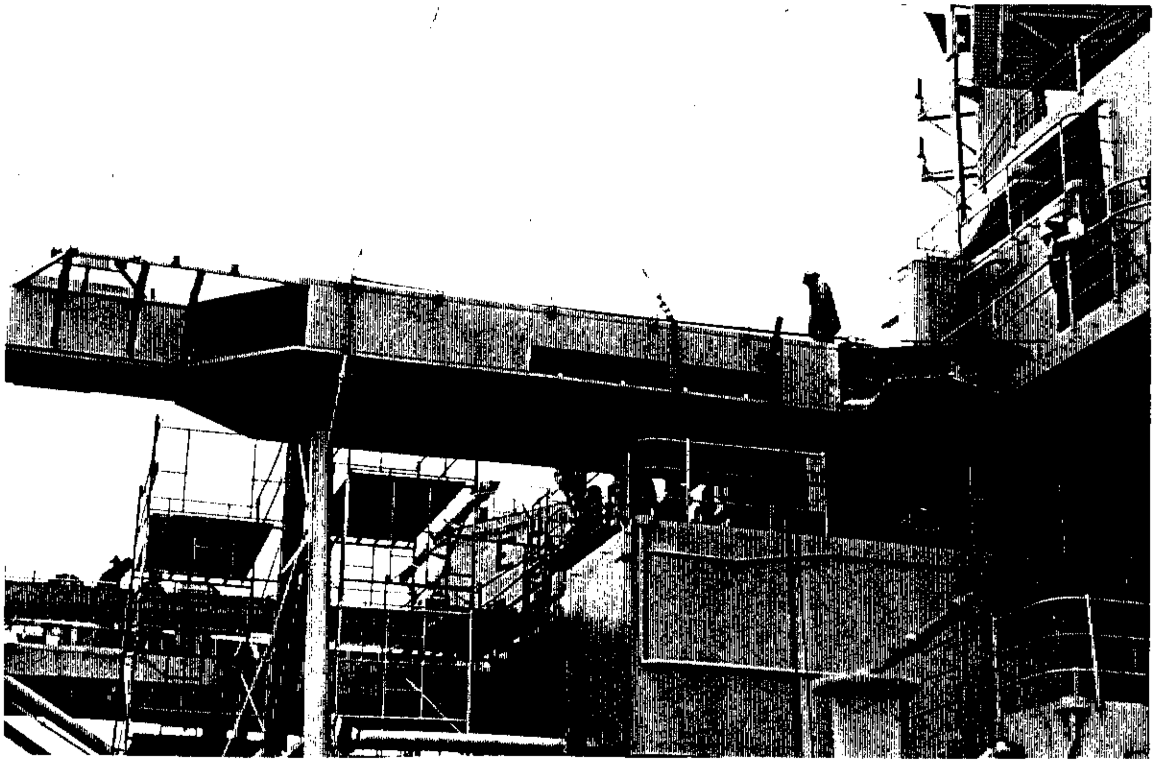

Figure 12b, LASCOR Ship Integration (cont.)

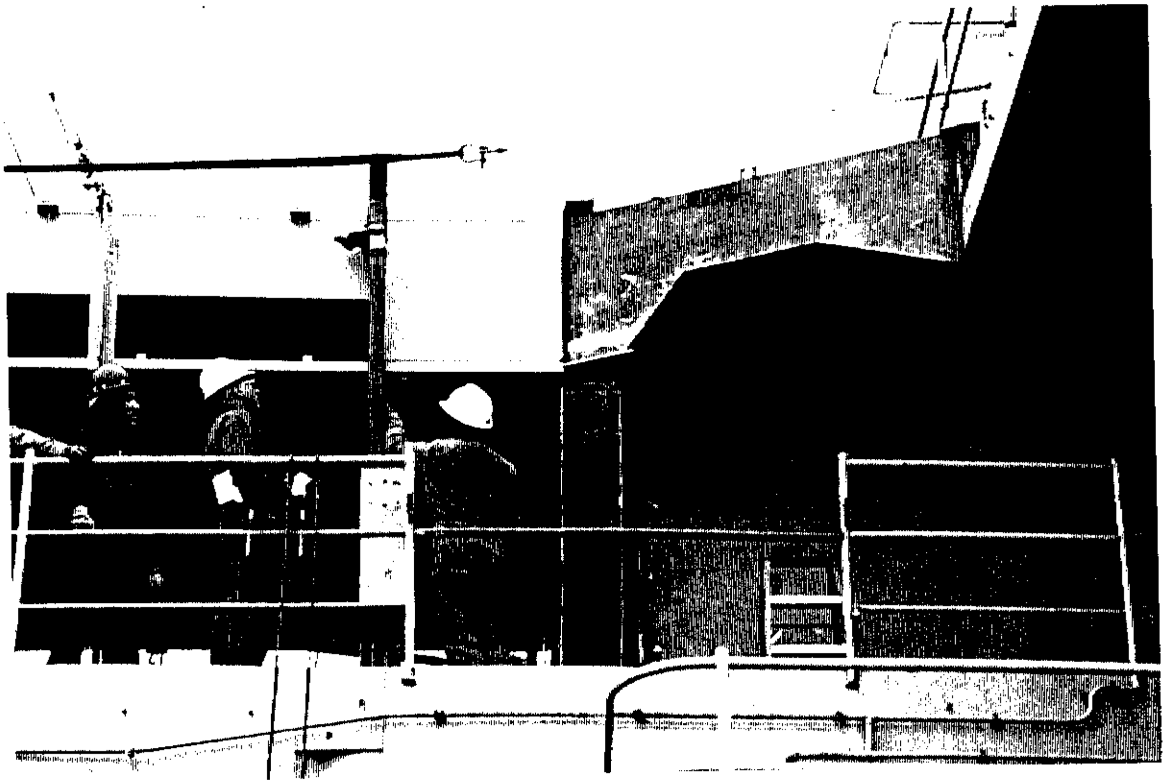

Figure 12c, LASCOR Ship Integration (cont.)

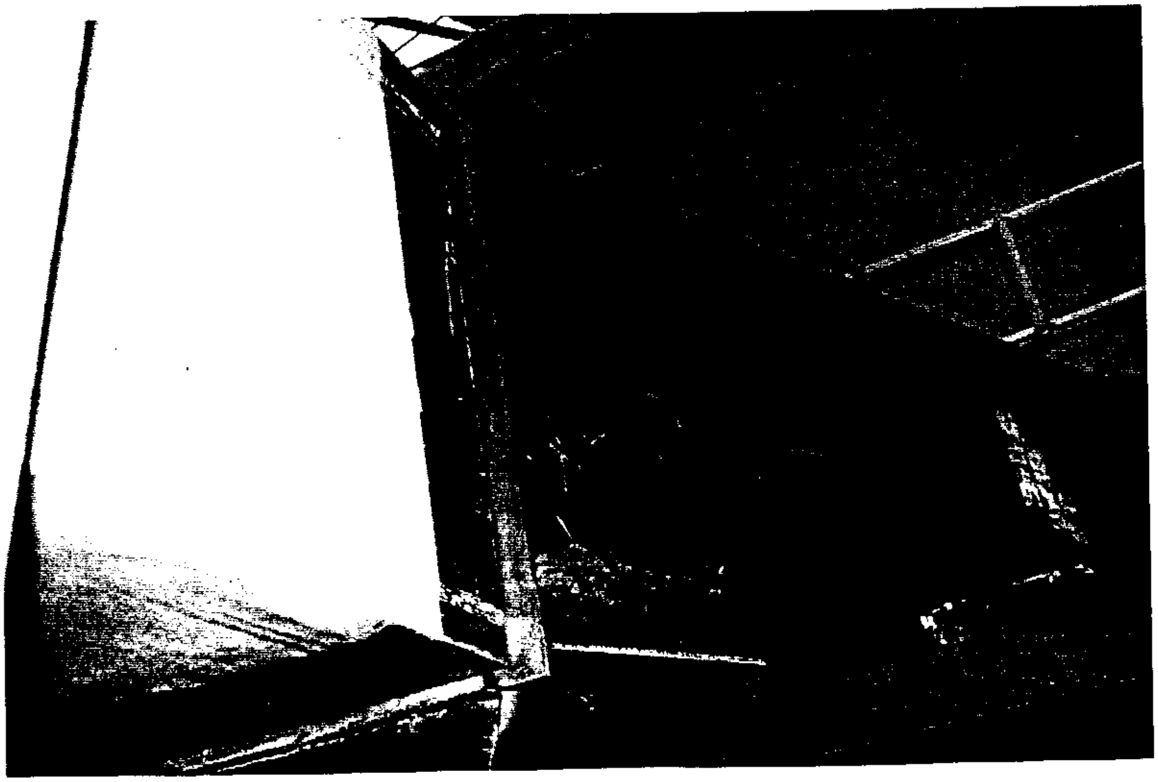

Figure 12d, LASCOR Ship Integration (cont.)

Figure 12e, LASCOR Ship Integration (cont.)

Figure 12f, LASCOR Ship Integration (cont.)

KEYNOTE ADDRESS

MEGA-FLOAT PROJECT IN JAPAN

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SUMMARY

There has been a keen interest for efficient ocean space utilization such as international airport and power generating plant near huge cities. Many city people want their convenient lives without unpleasant feeling. But Japan has little space to fit that demand except sea area. Many shallow coastal zone have been already reclaimed. A large scale floating structure has been closed up as a base for above mentioned utilities. But the experience about that is not enough for realization of a very large floating structure(VLFS), then the Mega-Float project was started in 1995 to obtain technological experiences on VLFS.

A Mega-Float test model which size is 300m in length, 60m in width and 2m in height was successfully constructed in July 1996. The purpose of this construction is a survey for further construction of VLFS, then considerable technological processes were tried as many as possible. The advantages and disadvantages of these applied processes have been analyzed and accumulated for real operation or next step of this project.

INTRODUCTION

The inherent interest for utilization of coastal sea surface has been excited in Japan. The Japan islands is narrow and mountainous, then many people have lived in a restricted plain area. Therefore, ocean space utilization has been considered as one of the most important subjects in the government policies concerning ocean development and a lot of artificial islands have been practically constructed by means of reclamation. Then the remained coastal area for economical reclamation is now limited.

The idea to construct a very large floating structure(VLFS) as a base for recreation and industrial activities instead of reclamation had proposed many years before. One typical promotion was a proposal for Kansai International Airport(KIA) by VLFS. Unfortunately, it was rejected by technological and economical reasons at that time. But the disaster around Kobe by earthquake in 1995 pointed out the advantage for VLFS. Many reclaimed coastal facilities had gotten serious damage by the earthquake. However, floating structures are basically seismic isolation, then VLFS was considered as a realistic method.

At the first stage of KIA project, semi-submergible type of floating structure was proposed. But the construction cost for this kind is too expensive, then the box-shaped pontoon type structure with breakwaters was considered for the second project of KIA to reduce the construction cost in order to compete against the land reclamation. The Technological Research

Association(TRA) of Mega-Float had been established by shipbuilders and steel manufacturers to build-up fundamental technologies for realization of VLFS. The TRA was established in April 1995 after a one-year preparatory period. It is supported financially and politically by the Ministry of Transport and the Nippon Foundation.

OUTLINE OF MEGA-FLOAT PROJECT

The Mega-Float research project of phase one continues three years from 1995FY to 1997FY. The total budget for the phase one is 7.5 billion yen. The first priority of this R & D project is to construct reasonable size of Mega-float structure by offshore joining. Nine divided floating units, each size is 100m in length, 20m in width, 2m in height and 0.5m in draught, were fabricated in shipyards and a manufactory. They were transported to the area for offshore tests at Yokosuka harbor. This area is located between the outfitting pier of Oppama shipyard of Sumitomo Heavy Industries Co.Ltd. and the East Breakwaters. Four units were joined in November 1995 for the first demonstration of offshore joining. The experience of this joining activity was fed back to the second joining activities of remained five units in June and July of 1996. As a result of these offshore joining operations, a box-shaped floating structure of 300m in length, 60m in breadth and 2m in height was constructed.

This structure is moored by gum dampers and rubber mold chains from four dolphins. Three dolphins are arranged along the longitudinal side, and one is arranged at the lateral side. Sea conditions such as waves, wind and tidal currents are measured. The dynamic behavior of the Mega-Float is also measured for future consideration.

The main research tasks of the Mega-float project are as follows:

(1) Technology of design for VLFS.
(2) Technology for offshore construction.
(3) Technology for operational functions of facilities.
(4) Technology for long-term durability.
(5) Technology for environmental assessment.

OFFSHORE CONSTRUCTION

Structure of Mega-Float

The ratio of the depth to the total length of the floating structure is very small, therefore this structure plays as an elastic body by surrounding waves. Then general dynamic response characteristics should be clarified for long-term durability of it. Desirable rigidity and strength of the structure are required to understand for realization of the Mega-Float. The structural reliability for fatigue strength under nonlinear and irregular wave induced load should be considered numerically and experimentally.

The safety and easiness on the construction stage is also important. Many divided units those are fabricated in shipyards simultaneously will be joined at the appropriate offshore site. Japan has the capability to build over 100 units a year which is able to fabricate with acceptable tolerance in dimensions. In this project, nine units were fabricated in eight shipyards under the participation of twelve ship builders and four steel makers. The nine is typical number for offshore construction of VLFS. One unit is entirely enclosed by the other units in this case. Then all occasional situation for offshore joining can be considered.

Dimensions of one unit are 100m in length, 20m in width, 2m in height, and 0.5m in draught. The weight is about 680 - 770 tones and fabrication cost is about 130 million yen. Materials used is rolled steel for ships which is equivalent to SM400. The thickness of upper

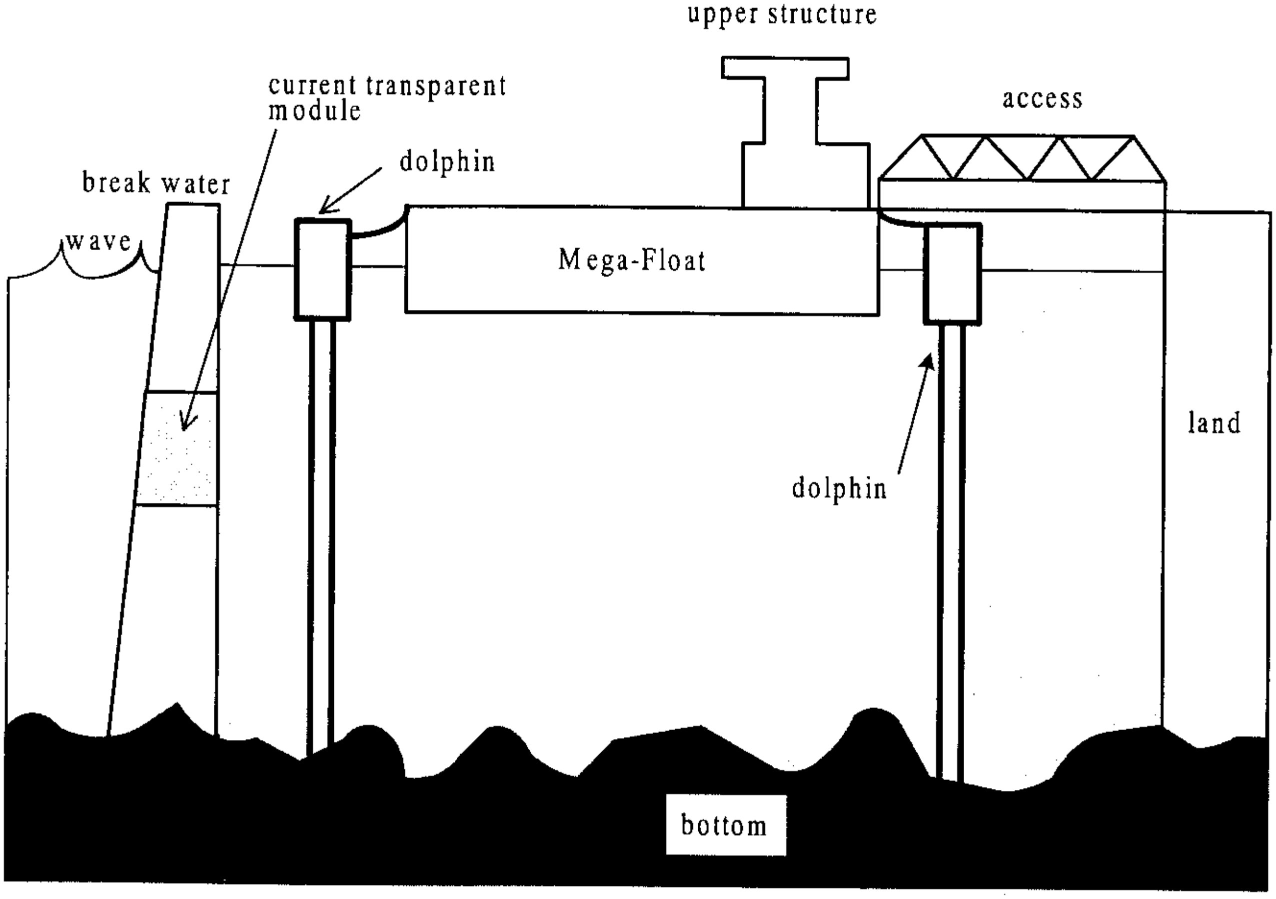


Fig.1 Schematic illustration of floating airport(Mega-Float).

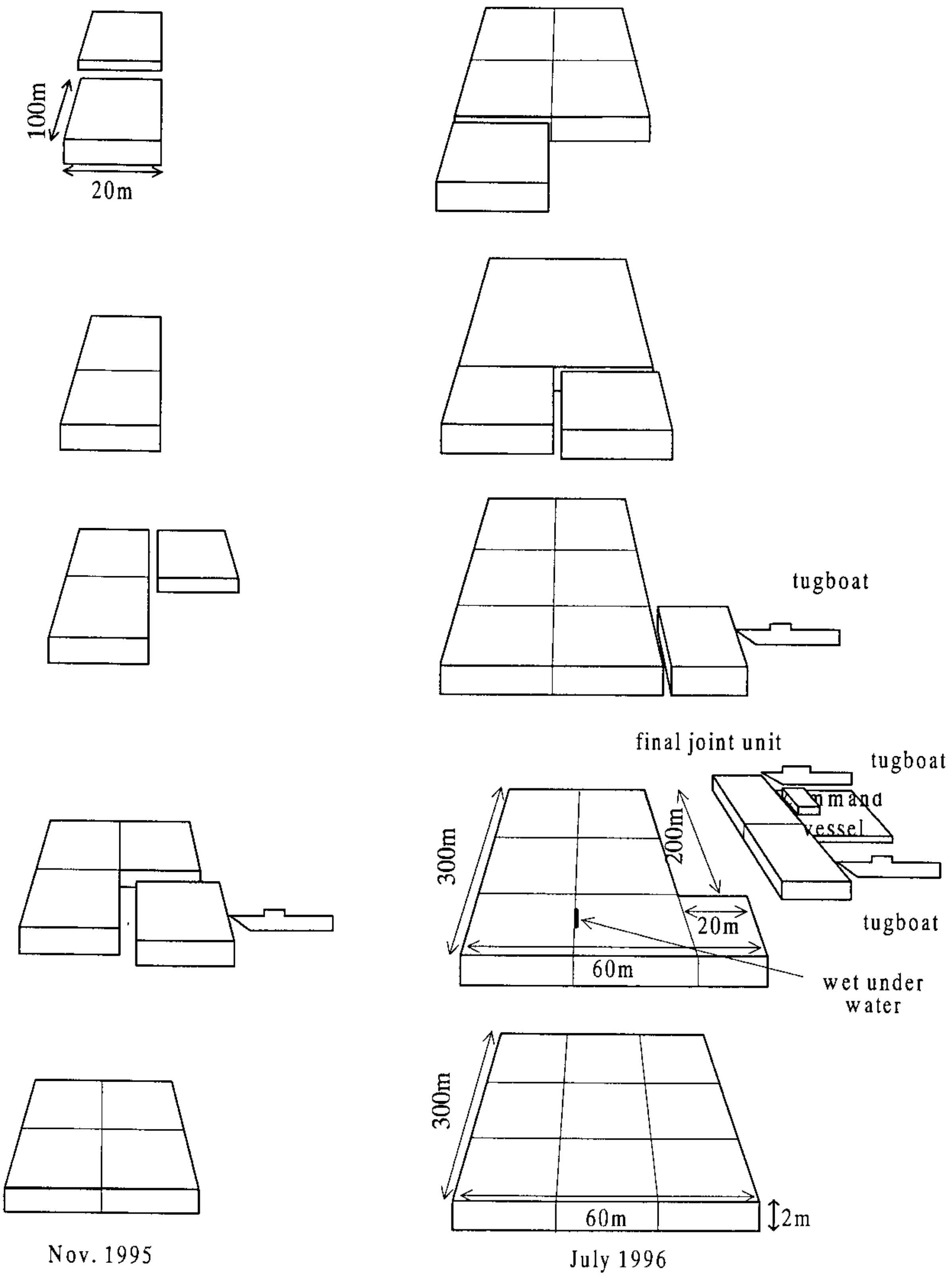


Fig.2 Flow chart of offshore joining.

deck and bottom plate are 12.5mm and 15mm. The inside of this unit is divided by many longitudinal and transverse bulkheads those thickness are about 9mm. Angle stiffeners of 200x90x8x14 are used as deck and bottom longitudinal and girder stiffener for longitudinal bulkhead. Steel strips of 50x9 are used as floor stiffeners.

Transportation

Eight units were transported to the site by wet towing, and one was transported by dry shipping. The design strength of each unit has mainly been decided by the weather condition at the installation site which is covered by wave breakers. The environmental load on the unit during towing is more severe than that after completion in the installation site. Then the dynamic behavior of floating units during towing from the dockyard to the installation site has been estimated and measured during this project. The first unit was towed in a calm condition in November 1955. This was towed from Chiba to Oppama. The route was inside of the Tokyo Bay.

The long towings were carried out in June 1966. The longest towing was from Kitakyushu and the next longest was from Mizushima to Oppama. The approximate lengths of these towings were 900 km and 700 km, respectively, and they took three to four days. The wave height during towing was relatively high, mean wave height was about 1m. The towings were safely completed, and it was appeared that strain due to towing can be estimated by theoretical calculation.

Mooring to dolphin

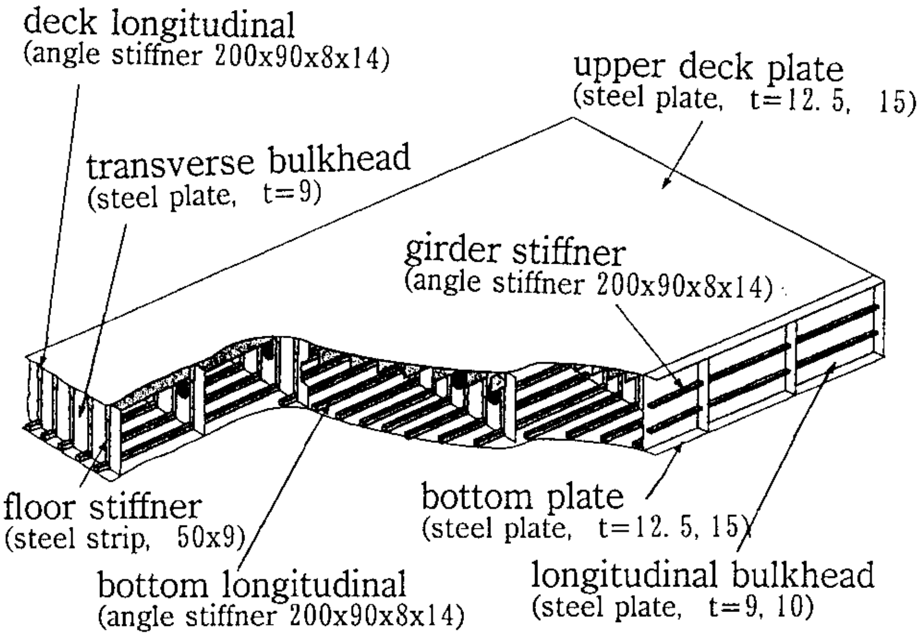
The Mega-Float is expected to have little response by waves and winds. and it is also expected to be moored with small force compared against its huge masses. Then wave breakers are expected to construct around the Mega-Float. Four dolphins were installed to moor the Mega-Float to satisfy theses requirements in this project. Mooring chains those are molded by rubber are used. The mooring force during normal condition is due to the elasticity of these molded chains. At the critical condition, it is moored by the chains themselves. Rubber fenders were installed between dolphins and the Mega-Float to prevent collision.

Drawing and locking

A new coming unit is required to fix in the appropriate position of the already assembled structure of the Mega-Float. Tug-boats are used for primary positioning. Final drawing is carried out by winch operations from the control barge which equips several winches and their controllers. When the final drawing is finished, the unit will be locked by several steps of connecting procedures. This stage is very important for offshore joining of the Mega-Float. This process is required to complete within a short duration even in a rough sea condition. The fixing of the unit to the exact position is closely related with the quality of final completion by welding. If the setup error is out of tolerant value, mechanical properties of weld joint will not be guaranteed.

The following procedures were adopted for quick and reliable connecting and locking methods.

1. New unit was brought toward the main body until the primary mating jig came into contact. While the approaching to the main body, the mutual vertical displacement by waves was reduced by "pelican" jigs those shapes are looked like pelicans.



Dimensions of float unit : 100mL x 20mW x 2mD
Weight : 680-770 tons
Fabrication cost : about 130 milion yen
Material : rolled steel for ships equivalent to SM400

Fig. 3 Cross-sectional view of one float unit.

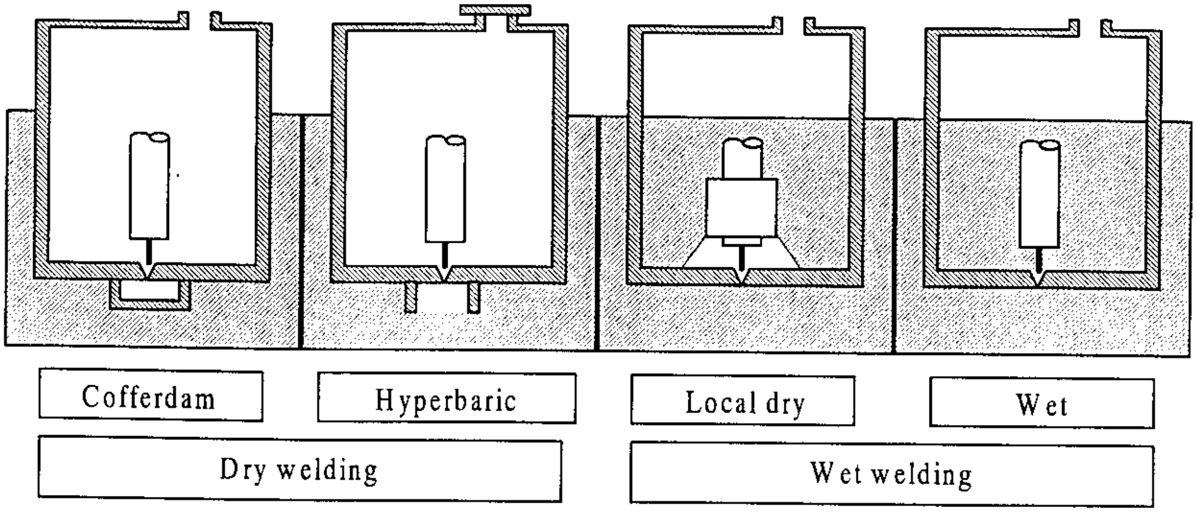


Fig. 4 Classification of underwater welding.

2. Mating jigs attached on both units were fastened together by bolts. The upper decks were tightly fastened by this operation, but the bottom sections are still remained in unconnected situation. The gap between two units at the bottom is oscillating by the wave.
3. The PC wires were inserted into the arched hollow steel tube from the upper deck. The outlet of this tube is located near the bottom deck. The same arched hollow steel tube is also settled in the opponent unit. Then the PC wires were reached to the upper deck of the opponent unit. One side of these wires were fixed, so the wires at the free side were pulled by winches, then the bottom of the units were contacted each other. The bottom side was also fastened by bolts.
4. Minute correction of miss-alignment was carried out by using of oil pressure jacks. Then both units are precisely fixed by tack welding of stoppers and strong back jigs to prevent the deformation during welding.
5. After these operations, the joint part between two units was so tightly locked that the welding could be carried out without any defects while the drifting motion by waves was existed.

Underwater welding

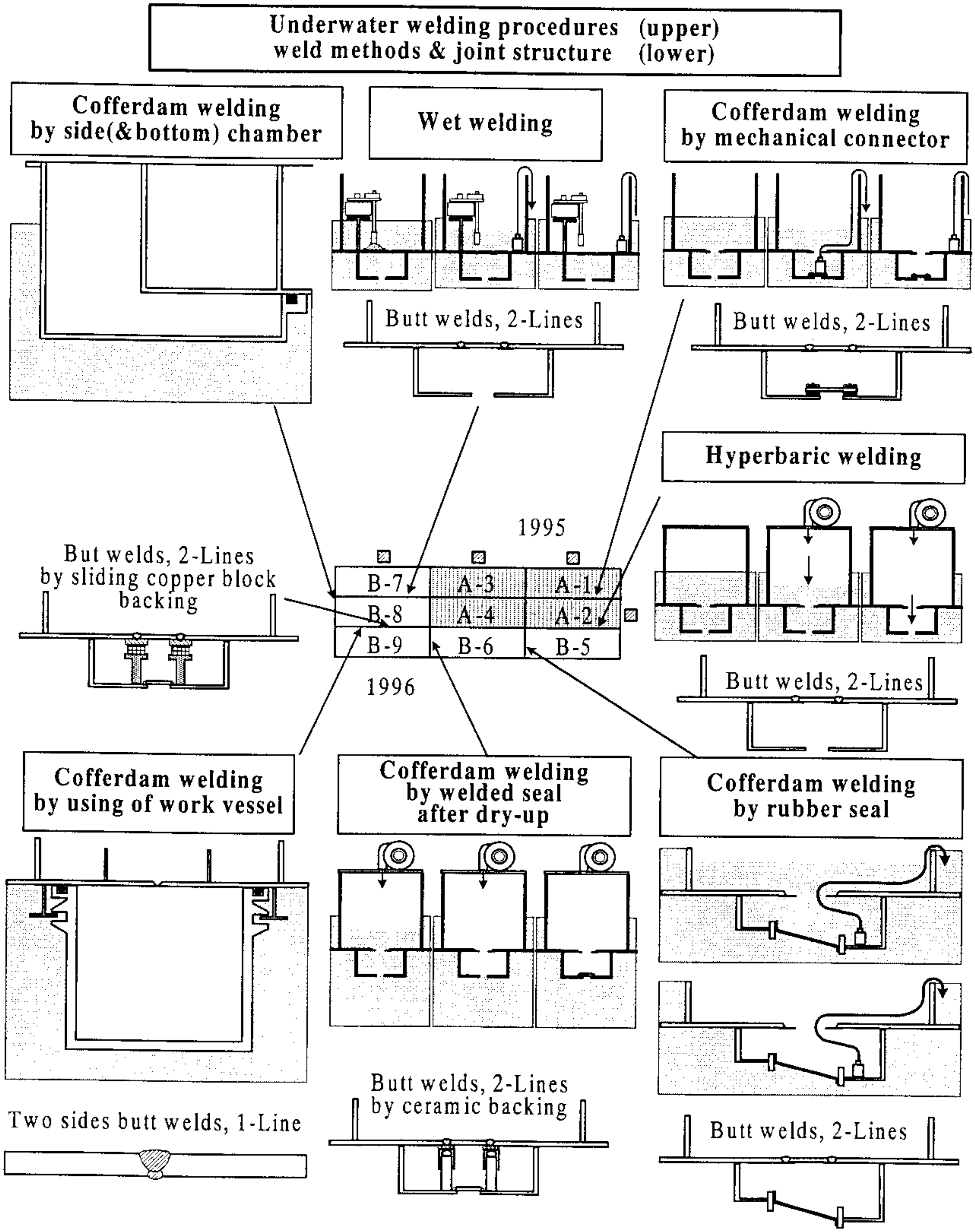
Welding is the most economical method to fabricate steel structures. Welding is also useful for underwater applications and the progress of the underwater welding technique has increased the quality and improved mechanical properties. But there are still many problems to overcome. The influence of the hyperbaric environment on the quality and the efficiency of the welding operation is a hard obstacle to be solved. There is also an urgent need for advanced development of automation of joining and testing methods under the reasonable operating cost.

Welding is considered for final joining of these units because of its economical aspect, strength, reliability and abundant experience. But the working underwater is a lot more difficult than working above water or on land. Therefore the incentives to do so must be found in some aspects of project realization, such as reduced cost, advantageous schedule, and improved technology. One of the purpose of this project is evaluation and development of technologies for offshore construction of the Mega-Float. Then the various underwater welding methods were considered to improve and evaluate each methods. Almost all parts were welded by semi-automatic CO2 welding in dry condition, because the usual welding processes in surface is superior in efficiency compared to wet welding. And the total length of weld line is quite long for the joining of pontoon structures. One part was welded in wet condition for future consideration.

1. Cofferdam welding

Air welding is possible below the water line by introducing a cofferdam around the weld part with direct access from surface. The main advantage is that the welding and testing personnel do not need to be experienced divers. The inside of this pontoon type structures are divided into many rooms which can isolate the ventilation, then it is relatively easy to obtain cofferdam condition compared to the ordinal offshore structures those are formatted by pipe structures. Then, cofferdam welding was carried out for offshore joining operation of the first year. A small bottom box which was attached during fabrication of each units in shipyards was sealed by divers to evacuate water from the welding part.

Rubber strip sealing was tried for the next year. Well formed rubber strip was attached on the one side of the bottom box. This rubber was pressed onto the bottom box plate of another side by the drawing operation of the unit. After locking of two units, this rubber seal acts as an



B-7	A-3	A-1
B-8	A-4	A-2
B-9	B-6	B-5

Fig. 5 Schemtic illustration of underwater welding trials.

insulation agent against bottom water. The water inside the locked units were pumped out entirely. Then, cofferdam welding was successfully proceeded.

Another trial was proceeded by using of the side and bottom chamber for welding of side plates. The cofferdam application by small box is unrealistic for side wall. And cladding operation of thin titanium plate for corrosion free surfacing in splash zone had to be carried out in dry condition, then this technique was considered.

Two lines welding by using of insert plate was carried out for almost all weld line. The benefit of this technique is an easiness to obtain accurate butt groove joints. The miss-alignment and root gap width can be reduced within an allowable values easily for this technique. Then this technique was carried out instead of doubled weld line length.

All weld was carried out by one-side welding for this two line technique. The eternal backing plates with the same steel was used for one-side welding by practical reason. But this eternal backing has possibility to act as a crack initiation for alternative stress due to elastic deformation of the structure by waves. Therefore two one-side welding techniques without eternal backing plate were tried. One was ceramic backing and another was copper backing.

The simplified cofferdam methods mentioned above have the same drawback that the surface treatment of the bottom side was very difficult after welding. The work vessel process was considered to overcome this problem. The work vessel which has enough space for manual welding operation from back-side was constructed. Then both-side welding of the bottom plate and painting of outside of the bottom plate became applicable in cofferdam condition. But special access man-holes from the upper deck to the bottom plate are required for this technique.

The scale of this work vessel is designed big enough for efficiency of working process, then the sealing for water tight needs more careful preparation. Marine growth attached on the sealing plate must be removed before connection of the work vessel, otherwise tight sealing cannot be guaranteed.

2. Hyperbaric welding

Cofferdam is obtained by pumping out of water from inside. On the contrary, hyperbaric condition is obtained by using of compressed air from the upper deck. When the pressure inside the unit is slightly higher in relation to the ambient hydrostatic pressure, the water inside the unit is discharged, and the welding portion becomes dry. The draught is only about 0.5m in this project, then the required hyperbaric pressure to discharge the water around the welding portion is small. Therefore the welding operation is almost the same for cofferdam welding except that the welding portion is locked out from surface. The tight sealing at the bottom is not necessary for this case, but additional air lock room to enter the welding part is necessary.

Hyperbaric condition can be obtained by small electric fun placed on the upper deck. This technique proved its economical and useful ability. The problem to be improved for this technique is the hot and isolated working circumstance. The temperature inside the working area is relatively hot especially during and after gouging operation. The temperature was much raised up by the produced heat from gouging operation and adiabatic compression to obtain hyperbaric condition. Well designed ventilation system is required for this technique.

3. Wet welding

The quality achieved by wet welds was so poor that this procedure was rejected for the repair of structural members of offshore structures about ten years before. But recent remarkable progress on weldment quality by wet welding has pushed this wet welding technique in the applicable one for the structural repair. This process is very cheap and convenient, if highly skilled welder/diver is engaged. But welding speed of this process is quite low for offshore joining of the Mega-Float. Then manual wet welding is expected as for a repair process.

Local dry welding is another option for offshore joining of the Mega-Float. If the stable local dry cavity around the weld zone is guaranteed, good mechanical properties can be obtained. Mechanization of this process is essential in the case of continuous welding and seam tracking technique have to be developed. Fundamental research on CO2 wet welding with warier curtain assist has been carried out to apply this technique on offshore joining of the Mega-float. The results in laboratory test had shown the good ability. Then open field demonstration of this mechanized wet CO2 welding was carried out on two blocks of the Mega-Float. This result showed that it can be applicable.

LONG-TERM DURABILITY

If the suitable maintenance is not executed, a life time of VFLS is limited because of corrosion of materials under the sea water environment. A study on maintenance procedure to guarantee a 100 year service life is an important task for the Mega-float project. Some surface area of the splash zone is covered by thin titanium plate to evaluate its anti-corrosion ability. The fatigue stress is also applied during its life time, because the body plays as an elastic plate by surrounding waves. Hydroelastic behavior of the VLFS is estimated by many theoretical models, then the result should be considered with the real dynamic behavior of the Mega-Float which has been measuring since its construction. A model test in the experimental basin is also carried out.

ENVIRONMENTAL ASSESSMENT

The floating structure has following characteristics in comparison with reclamation land. (1)A floating structure has an advantage for cost and time where it is applied in the rather deep region. (2)A floating structure has an advantage where it is applied on the soft ground. (3)A floating structure can be constructed in a short duration. (4)A floating structure is movable, and it is also removable. (5)A floating structure affects small effect on current around installation area. (6)A floating structure creates huge shaded space under itself.

The VLFS is quite different from ordinal reclamation process, then it is required to create a new technology for environmental assessment. One typical example is the creation of huge shaded area under the VLFS. The penetration of sunshine under the sea is cut by the main body of the VLFS. The primary production by photosynthesis, water temperature, and the kinds of fish offer different behaviors between in the shaded space and in the un-shaded space. Then the ecological model to evaluate an water quality should be modified this effect.

CONCLUSION

The very large scale model of the floating structure(Mega-Float) was successfully constructed in July 1996. This construction was a survey for further construction of very large floating structures(VLFS), then considerable technological processes were tried as many as possible. The advantages and disadvantages of these applied processes have been analyzed and accumulated for next step of this project. The reasonable way for improvement and/or modification on these processes are being studied fundamentally.

ADVANCED WATERFRONT TECHNOLOGY TEST SITE

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ABSTRACT

The Advanced Waterfront Technology Test Site (AWTTS) was established at Port Hueneme by the Navy to enable testing of advanced concepts and materials for waterfront construction that can reduce the construction and maintenance cost of marine facilities to the Navy. The site affords a controlled natural setting for half and full scale model exposure and load testing. A variety of projects involving carbon fiber prestressed concrete, various organic composites and reinforcing metals are currently under evaluation. Although primarily intended for Department of Defense (DOD) waterfront Research Development Test & Evaluation (RDT&E) needs the AWTTS can be made available for projects with private sector sponsorship or cooperative efforts that involve concepts that are of benefit to the Navy

INTRODUCTION

Today's presentation will address the Navy's test facility located at Port Hueneme California, its capabilities and the on going experimental evaluations at this unique facility. But first let me tell you a little about the Naval Facilities Engineering Service Center and our mission for the Navy.

The Naval Facilities Engineering Service Center (NFESC) was established in the Fall of 1993 as a result of a realignment of Navy Shore Activities under the Base Realignment and Closure Commission (BRAC). The NFESC was formed from the consolidation of the Naval Civil Engineering Laboratory (NCEL), the Naval Energy and Environmental Support Activity (NEESA) and other smaller entities, including the Naval Facilities Engineering Command's Chief Engineers Office. The NFESC is the Navy's center for specialized facilities engineering technology. As an arm of the Naval Facilities Engineering Command (NAVFAC) we provide world wide support to NAVFAC Headquarters, Engineering Field Divisions and Public Works Centers as well as to Fleet and Shore Activities including the Marine Corps. Our support efforts are directed at shore, ocean and waterfront facilities, amphibious and expeditionary operations, energy, utilities and environment. We provide a complete range of engineering services from design, construction, test and evaluation, and technology implementation.

It is our mission in facilities for waterfront construction that I wish to address today, particularly our role in testing, evaluation and implementation of advanced technology and materials.

BACKGROUND

The Navy has a huge investment in waterfront facilities and equally large requirement for operation and maintenance of these facilities. A majority of facilities date back to World War II era. About 75% of all Navy piers and wharves are 45 years old and require increased repair and maintenance dollars to maintain their operability. In fiscal year 1991 critical waterfront facilities deficiencies amounted to over $1.3 billion. Since that time actions have been taken to reduce the extent of Navy facilities through the same BRAC actions that resulted in the establishment of the NFESC. Examples include the closing of facilities such as the Long Beach and Mare Island Naval Shipyards in California. But still, even with fewer numbers of facilities to deal with, the downsizing of the DOD and Navy has put a severe strain on the budget to maintain critical facilities and has also limited the dollars available for constructing new waterfront infrastructure. Clearly new approaches and materials were needed to reduce the cost of maintaining current infrastructure, as well as for building new infrastructure with both lower initial cost and long term maintenance requirements.

Towards this end in 1994, the NFESC established and dedicated the Advanced Waterfront Technology Test Site (AWTTS) to enable U.S. researchers to test and demonstrate their state of the art materials and concepts for upgrading, repair and life extension of existing waterfront structures as well as concepts for new facilities [1-5].

AWTTS DESCRIPTION

The AWTTS is a 150 foot long, 18 foot wide structure in the Port Hueneme harbor consisting of test bays defined by permanently installed pile bents to which half and full scale test specimens can be attached (Figures 1, 2). These specimens could be deck sections or components placed for short term destructive testing or long term weathering and durability evaluation. The intent was to create a flexible test bed that would enable evaluating a number of concepts and materials simultaneously, and then be easily reconfigured for a new generation of concepts. As built, the AWTTS consists of fourteen bents each consisting of four piles driven into the harbor floor and a pile cap. The structure can accommodate up to thirteen deck sections. The majority of bents are on ten foot centers and consist of 10 inch square prestressed concrete piles and cast in place pile caps. For structural purposes these bents simulated a half scale structure. Three internal bents are on 20 foot centers and consist of concrete decks prestressed with carbon fiber strands with pile caps post-tensioned with encapsulated fiber glass strands. These are full scale pile bents which represent the initial evaluation conducted on the AWTTS, during the construction phase. This work was a result of a collaborative effort with the USACERL and the Army's CPAR contractor team.

Functionally the AWTTS is divided in four sections which accommodate various structural concepts and materials. The first section consisting of five bays is being used to evaluate the upgrade of half-scale reinforced concrete decks using bonded carbon fiber reinforced plastic (CFRP) sheets. A vertical jacking mechanism allows deck sections installed on these bays to be mechanically loaded with up to 120,000 pounds focused on a square area in the center of the deck. The next two bays which define the section include a control deck and an access ramp. The third section is defined by bays eight and nine. The eighth span is a full-scale demonstration project for precast planks prestressed with carbon (graphite) FRP tendons, in coordination with the South Dakota School of Mines and Technology (SDSM&T) and the US Army Corps of Engineers Construction Engineering Research Laboratory (CERL) (Figure 3). The ninth span features a Composites Institute sponsored full-scale all-composite deck section (Figure 4). Finally, the last four spans which define the last functional section are being used for Navy testing of conventional repair materials, and cathodic protection systems for steel reinforcement.

INITIAL CONCEPTS AND MATERIALS

GFRP Prestressed Piles

The relatively low modulus of elasticity of composites (compared to steel) makes them well suited for prestressing applications. The low modulus reduces the prestressing losses, and the strengths are similar to that of steel. Graphite fibers are particularly well suited for reinforced concrete applications due to their resistance to alkaline environments and resistance to moisture. The tendons used in this application are composed of T300 fibers embedded in a Bisphenol A resin matrix, with a volume fraction of 67%, an ultimate strength of 2.17 GPa, and a modulus of 155 GPa. The concrete piles used in pile caps 8, 9 and 10 are prestressed using these graphite tendons. Their cross-section is 0.355 x 0.355 m with 8 tendons each. The lateral reinforcement is a 6.4 mm diameter graphite spiral. These piles were driven with conventional equipment without damaging the graphite tendons [1,2].

GFRP precast prestressed planks

Recent pier construction technology has focused on the use of precast prestressed planks. These planks are set between pile caps (Figure 3), then, if required, an additional concrete layer can be poured on top. In the latter case the planks are used both as forms and as the tension side of the deck. The eighth span of the AWTTB features a full-depth plank where the steel tendons are replaced by graphite FRP tendons resulting in similar strength and stiffness characteristics [1,2].

All composite deck

An all composite deck using currently available composite structural members was installed in the ninth span [1,2]. The first prototype was designed for a load of 267 kN (Figure 4). An all composite deck provides the following advantages:

- a lightweight structure (3 to 4 times lighter than a reinforced concrete one),
- ease of transportation and installation,
- excellent resistance to corrosion.

This first design is intended to show current capability with off-the-shelf products, and was not optimized for this application due to project time restraints. Significant improvements are expected in load ratings and material savings for successive, optimized designs.

CURRENT CONCEPTS

Evaluation of 1/2 scale deck upgrades using CFRP sheets

Four 1/2 scale reinforced concrete slabs were tested [4,5] (Figure 5). These slabs were simply supported on two edges and subjected to a single 38 by 38 cm (15 by 15 in) patch load at midspan. The slabs dimensions were 3 m (10 ft) by 5.5 m (18 ft) with a thickness of 23 cm (9 in). They were reinforced top and bottom with #5 bars (1.6 cm diameter, ASTM A615 Grade 60). Top bars were spaced at 15 cm (6 in) each way, whereas bottom longitudinal and transverse bars were spaced at 10 and 20 cm (4 and 8 in) on centers, respectively. The measured 28 day compressive strength of the concrete was 43.2 MPa (6260 psi). The four test specimens included two control slabs, and two slabs with four layers of unidirectional CFRP reinforcement, three longitudinal and one transverse. Increases in load carrying capacity of up to 50% can be obtained depending on the amount of CFRP.

Pile wraps

Preliminary three-point bend tests on square prestressed reinforced concrete piles wrapped with CFRP sheets confirmed the ability of the wraps to increase the pile's ductility [6] (Figure 6). Three additional systems are currently being evaluated, one uses a wrapped CFRP sheet, while the other two use cured GFRP (glass fiber reinforced plastic) cylindrical jackets which are installed around the pile, and then filled with grout. Three AWTTS piles are being wrapped from the pile cap to the lowest tide level, to upgrade both the pile to pile cap connection and the splash zone. In addition, three-point bend tests representing the pile to cap connections are being carried out to evaluate the upgrade effectiveness.

Dual-phase steel reinforcement

Our ONR funded R&D effort is also addressing the evaluation of a Dual Phase steel reinforcing bar for concrete. Low carbon, low alloy reinforcing bars heat treated and quenched to obtain a dual phase micro structure are being tested. Steels containing the martensite phase have exhibited very low corrosion when embedded in concrete specimens tested at UC Berkeley. This dual phase steel may serve as a comparable cost replacement for the black bar predominantly in use today as reinforcing steel in waterfront construction. While the Navy has worked with industry to develop criteria and specifications for improved epoxy coated rebar that can meet the demands of the severe marine environment, these new coated bars carry with them an approximate 100% cost premium over conventional uncoated rebar. Therefore our objective here with the dual phase steel is a rebar material that costs nearly the same as conventional bar. Our comparison testing involves four deck panels, 6'x10'x10''" thick, made with various combinations of dual phase steel reinforcement and black rebar. The panels are flooded with seawater every 30 minutes to accelerate chloride contamination, wetting and drying. Corrosion current measurements are made periodically.

Utility hangers

As an alternative to ordinary steel utility pipe hangers, fiber reinforced polymer (FRP) hangers and also stainless steel and galvanized steel have been tested for durability and strength [7]. Three types of FRP were tested: polyester, vinylester, and nylon. All FRP showed significantly higher weathering resistance than plain carbon steel or zinc galvanized steel. Comparative cost data was also collected. Based on the weathering and cost data the reinforced polymer hangers were considered a better buy than plain or galvanized steel. Stainless steel was of course very durable in the long term exposure tests, but the cost were three times that of the polyester and vinylester hangers.

Composite exposure tests

Although FRP materials are typically more resistant to weathering or chemical attacks than steel, some durability concerns still arise in the presence water, concrete, or ultra-violet rays [8]. Exposure testing of several types of FRP materials was started at several locations (where?). Most specimens are placed in the splash zone which typically shows the highest deterioration rates. Accelerated weathering tests are also being conducted to catalogue the comparative durability of six different structural composite materials by generic class. These are glass reinforced orthopolyester, iso-polyester, vinylester, phenolic, polyurethane and bis-phenol/polyamide based epoxy. Strips of these composites are being exposed under controlled temperature, UV, and other environmental conditions. Results will be used as an aid in setting performance standards and specifications for composite materials for Navy construction.

FUTURE PROJECTS

As we work with advanced materials and concepts those that have proven themselves to offer cost and performance advantages will be further demonstrated at operational Navy waterfront installations. We have some limited funding from the Navy to look at specific systems.

Advanced Fendering Concepts

As an example, plans for developing advanced fendering system concepts are currently being implemented that will address fender piles, camels, whalers and chocks. These systems will focus on the use of virgin and recycled plastics, composites and engineered timber to develop less costly systems compatible with major surface combatants and submarines. From 1994 through 1996 the NFESC and the Army jointly investigated with industry and academia a number of composite pile concepts under the CPAR program. This work was sponsored by the U. S. Army Civil Engineering Research Laboratory (USACERL). The fender piling results from the CPAR effort will serve as the starting point for focusing efforts under this new project. We will be working with the product manufactures to define these new systems and then come up with generic specifications for cost competitive procurement. The initial concepts will be first evaluated at the AWTTS and then prototype systems demonstrated at selected Navy shore installations.

The efforts on going at the AWTTS indicate the direction we are headed for that is, evaluating the performance of new promising materials that offer potential for longer life and very low maintenance. We are therefore also open to ideas and material concepts that industry may have that can further this goal. The AWTTS can be made available for evaluating commercial products through direct industry sponsorship or through development of cooperative research and development agreements (CRADA).

FUTURE VISION

Mobile Offshore Basing System (MOBS)

The MOBS as conceived is a large offshore platform unique to any floating structure ever built. It is based on a needs statement of the Navy that dictates the following characteristics:

a) length up to two kilometers
b) low wave induced bynamics to support fixed wing cargo aircraft operations up to seastate 6
c) large volume required for storage
d) large deformation platform dynamics based on probable configuration of either individual modules connected hinge connectors or by long elastic connectors, or a continuous elastic hull
e) long term station keeping in a hurricane or typhoon
f) open ocean ship to ship cargo transfer through sea state 3
g) personnel safety issues associated with supporting a full Army brigade, including platform survivability
h) multiple mission role
i) survivability of 40 years between overhauls

The design and construction of such an unprecedented floating structure is not with out its challenges and DARPA and ONR have considerable research efforts going on involving critical technologies such as connectors, cargo handling systems and advanced composites which will contribute to the MOBS thrust. The need for extremely low maintenance requirements for the MOBs is a critical factor in the selection of materials

Zero maintenance waterfront

FRP materials can be structurally optimized to provide an alternative to most waterfront infrastructure applications. With proper care and design, their durability should significantly exceed that of traditional construction materials, such as steel and wood. It has been shown that whole piers could be constructed with such materials. Under this project, waterfront infrastructure would make use of these advanced materials to provide for durable alternatives to conventional construction requiring little or no maintenance during the design life.

CONCLUSIONS

NFESC has teamed with industry and academia to apply advanced construction materials for waterfront infrastructure applications. The new materials provide viable alternatives and will help reduce maintenance costs. The AWTTS represents a unique resource for large scale structural and durability testing.

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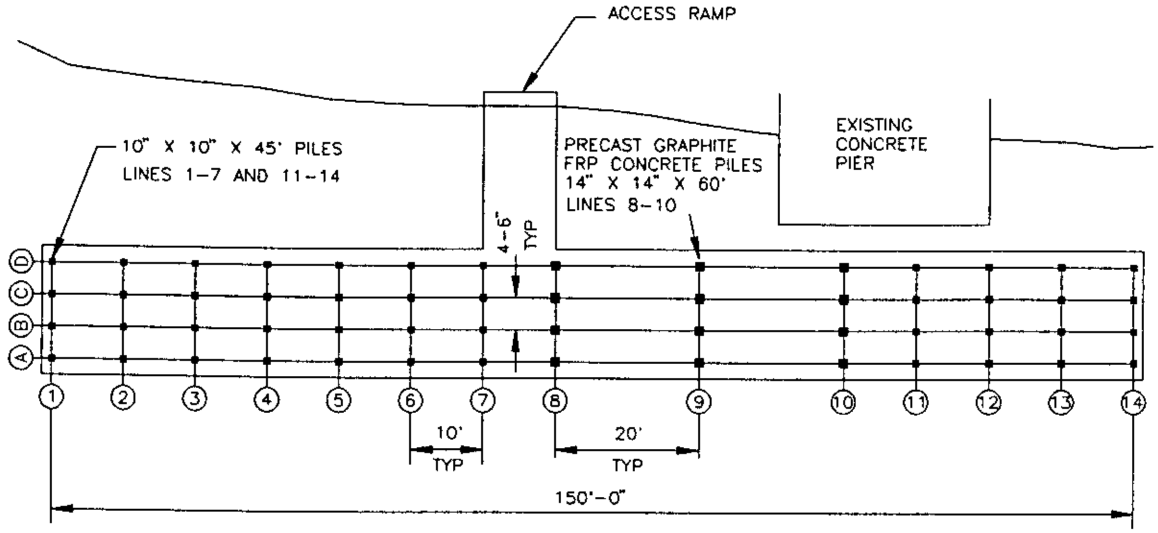


Figure 1. AWTTS plan view

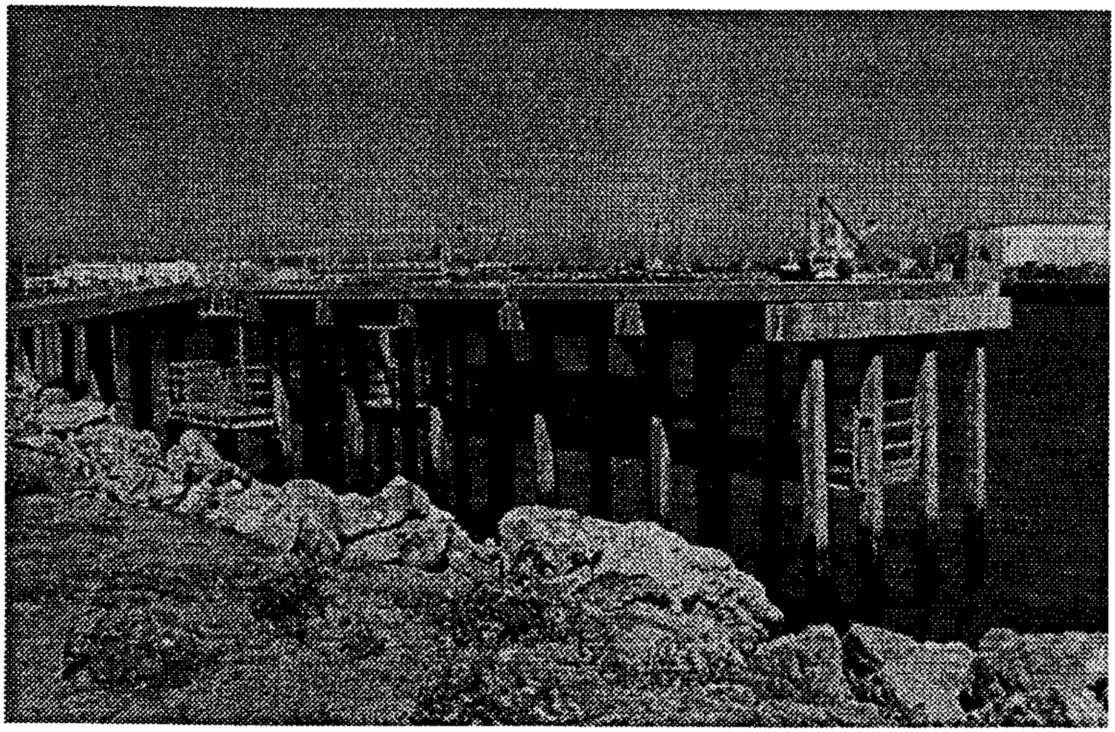


Figure 2. AWTTS: shore view of bents 1 through 6.

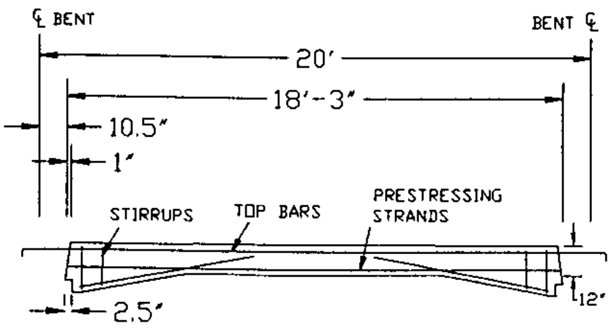


Figure 3. Standard precast plank.

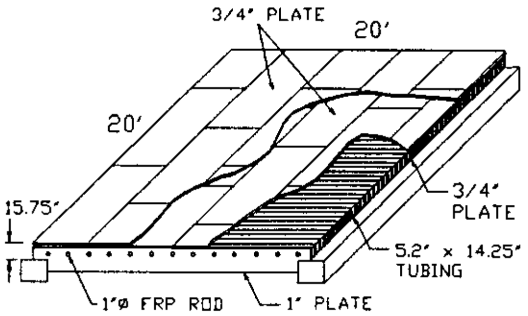


Figure 4. All composite deck

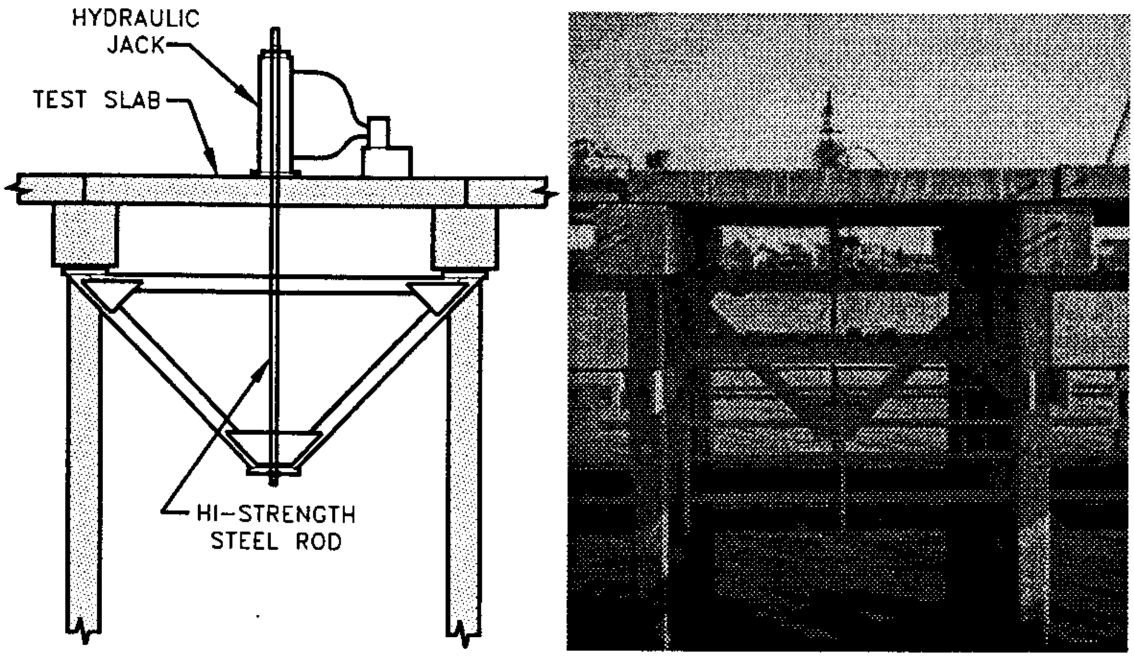
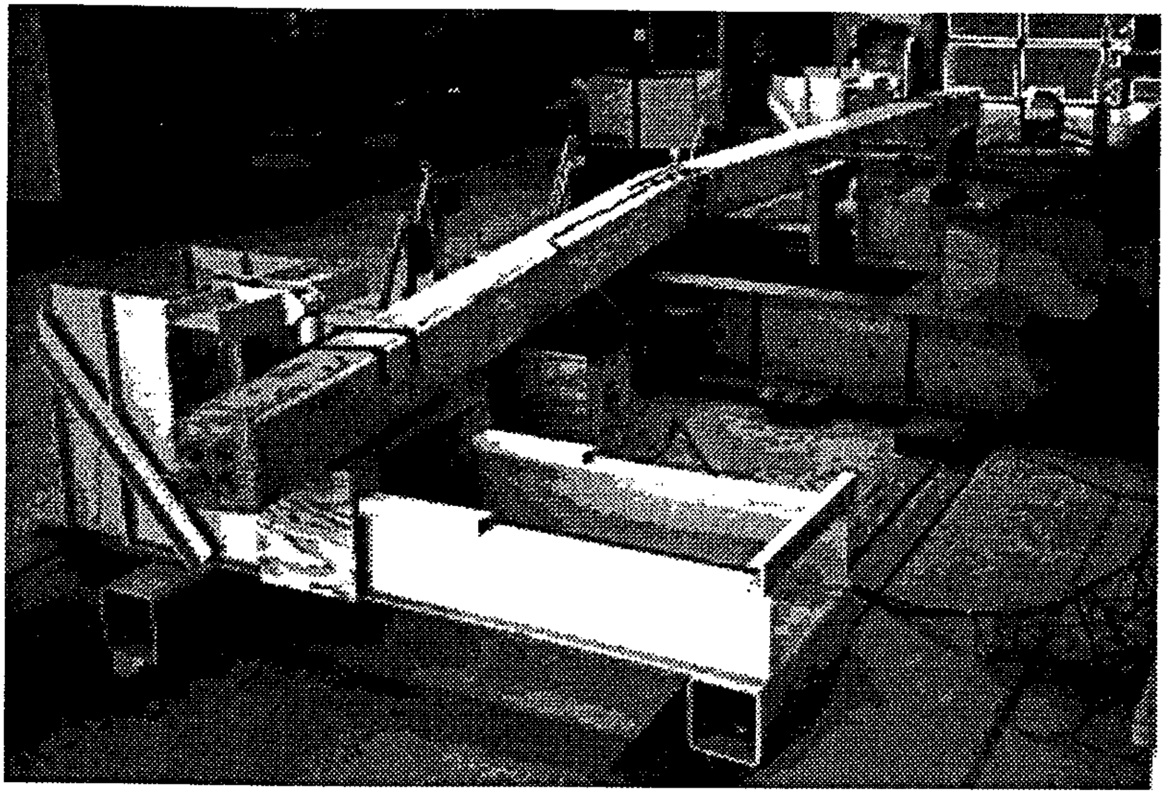


Figure 5. Large scale tests of reinforced concrete decks upgraded with CFRP sheets.



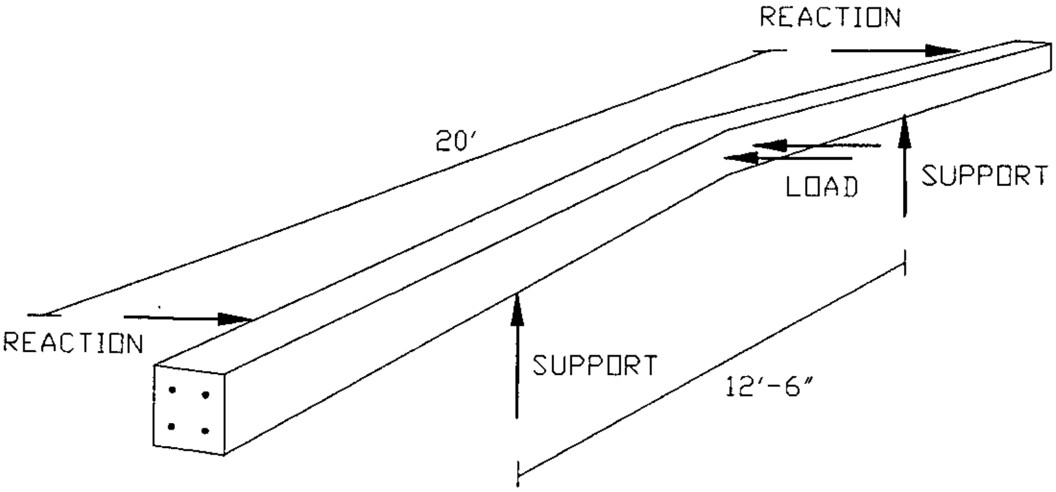


Figure 6. Four point bend tests of wrapped piles.

Theme Papers

Grunner Wold (Det Norske Veritas)
Ole Martin Moe (Kvaerner ASA)
Bjorn Andreas Hugaas (Det Norske Veritas)
Hans Bratfor (Det Norske Veritas)
Steel for Marine Construction

John C. Monsees (International Titanium Association)
Titanium for Marine Construction

John A. Mountford, Jr. (Titanium Metals Corporation)
Basics and Benefits of Titanium for Sea Service - A Review

John G. Banker (Clad Metal Products, Inc.)
Milton R. Scaturro (Consultant)
Titanium for Secondary Marine Structures

R. W. Erskine (Ingalls Shipbuilding Division - Litton Industries)
Shipyard Fabrication of Titanium Piping Systems

Carol A. Powell (Consultant)
Dale R. Peters (Copper Development Association, Inc.)
Copper Alloys for Marine Construction

James F. Jenkins (Nickel Development Institute)
Stainless Steel and Nickel Alloys for Marine Construction

Alex Cho (Reynolds Metals Company)
Chester H. Holtyn (Reynolds Metals Company)
Aluminum Alloys for Marine Construction

Andrew Stevenson (Materials Engineering Research Laboratory, U.K.)
Polymers for Marine Construction

Mamdouh M. Salama (Conoco Inc.)
Steve Borleske (DuPont Advanced Materials)
Jerry G. Williams (Conoco Inc.)
Composites for Marine Construction

Ben C. Gerwick, Jr. (Ben C. Gerwick, Inc.)
Concrete for Marine Construction

Steel for marine construction

Gunnar Wold[1], Ole Martin Moe[2], Bjørn Andreas Hugaas[1], Hans Bratfos[1]

Abstract

This paper presents the present status and future trends related to the application of steel for loadcarrying structures in shipbuilding and the offshore industry. Normalised steel as well as higher strength grades made by TMCP and QT processing routes, are presented with the aim of providing an understanding of the materials performance relevant for engineers responsibel for design and materials selection.

Finally fabrication aspects are discussed, including considerations related to the application of cast and forged components.

1. Introduction

For the purpose of the present paper, marine constructions are taken to comprise loadcarrying structures in ships and offshore installations.

Structural steels as a group, offer several advantages for such structures. Some of the more important ones are:

- Excellent/good availability in plate and other product forms.
- Comprehensive accumulated service experience is available, except for the most high strength grades.
- The materials can readily and economically be joined by welding
- The strength/cost ratio is favourable.
- Efficient methods for corrosion control can be applied to these steels.

For reasons like the above there is little doubt that steel will remain the major structural material in the foreseeable future.

The marine industry is known to be relatively conservative with regard to utilising "new" high strength materials in their products. This is an understandable attitude, considering the great economic consequences that may be encountered should problems or even failures arise during fabrication or service. The industry will therefore tend to settle for the use of materials which have a well-proven, positive record of fabrication and service. Still, it has been a notable trend in later years that an increasing number of companies representing the marine industry are contemplating to utilise "high strength steels" in a number of their products. The reason is the substantial economic gains that may result - particularly for offshore structures - mainly related to weight reductions and general cost savings due to shorter fabrication lead times.

A comment with regard to the frequently used expression "*high strength steel*" should be made, since this is not a well defined term. Firstly, the meaning varies with the field of

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application, as illustrated in Table 1. Secondly, it also tends to change with time; what was high strength steel some years ago may be regarded as normal strength steel today. In this paper the term "*high strength steel*" is taken to mean structural steel with SMYS in the range 420 - 500 MPa, while the term "*extra high strength steel*" is utilised for the structural steels with SMYS ~ 690 MPa.

Table 1. Typical strength levels for "high strength steel" for some different types of application

Some examples of applications of steel with higher strength	**SMYS, MPa**	**Process of manufacture/heat treatment of steel**
Aircraft industry, casing pipe for oil/gas wells	690 - 1000	QT[1)]
Legs for jack-up platforms, submarines	690	QT
More general application in welded structures. Increased use in offshore structures, pipelines and also bridges and high-rise buildings	420 - 500	QT (full strength range) TMCP[2)] (SMYS ≤ 460 MPa)
Shipbuilding. The indicated strength range covers by far largest tonnage and most general range of application of structural steel	265 - 355	Normalised TMCP

1) QT: Quenched and Tempered

2) TMCP: Thermo-Mechanical Controlled Processing = Controlled rolling often followed by accelerated cooling

This paper will predominantly be focusing on the C-Mn type structural steels with good weldability and a specified minimum yield strength (SMYS) in the range 235 - 500 MPa. However, reference is also made to steels with SMYS up to 690 MPa.

2. Application of materials today

2.1 Shipbuilding

The dominant material used for shipbuilding is structural steel.

However, some other materials are also used due to specific operational requirements, or requirements from the cargo in the case of ships. This can be illustrated by the following typical figures for material consumption in advanced shipyards.

Steel:	94.0%
Stainless steel:	4.4%
Aluminium:	1.3%
Glass fibre Reinforced, Polyester:	0.3%

Conventional ship yards focusing on large tankers and bulkers will have close to 100% steel materials in their production.

The steel materials used in the shipbuilding in Europe is mainly mild steel with a SMYS of 235 MPa. Higher strength steels are used when necessary, but in limited amount and mainly up to SMYS 355 MPa. Typical figures for use of high strength steels are in the range 10 - 15 % of the steel volume. Out of this part only a small part is TMCP steel.

In the Far East the situation is quite different. Approximately 70% of the steel materials used for shipbuilding are high strength steel, and mainly TMCP steels. SMYS 355 MPa is most common, but even higher grades are used.

The materials selection in traditional shipbuilding is cost driven, because the effect of a weight saving is minimal. If higher strength materials should be used, this must therefore lead to reduced fabrication cost.

2.2 Offshore structures

In the offshore industry the picture is more complex. The offshore structures are normally more weight optimised and the effect of saving weight by applying high strength materials usually has a value in itself. Steel grades with SMYS in the range 420 - 500 MPa are becoming increasing common, and ongoing research programs investigating the possibilities of using steels with a SMYS of 690 MPa (see also section 9) are being undertaken worldwide..

Also, TMCP steels are more commonly used in the European offshore industry than in the shipbuilding industry.

3. Normalised steel

Normalised steel with SMYS 235 - 355 MPa is sometimes referred to as "the working-horse of the structural steels". This type of material covers the widest range of applications and also constitute by far the largest volume of structural steels used world wide, including marine structures. Most of the fabrication and service experience accumulated for structural steels are related to normalised steel.

Due to the relatively slow heating and cooling rates involved in the normalising heat treatment, the properties of such materials are relatively insensitive to the material thickness, and favourable combinations of strength and toughness can be attained throughout thickness sections of several hundred millimetres. This is a unique feature of the normalised steels. Modern versions of normalised steels have relatively lean chemistry, low carbon equivalent values and hence excellent weldability. Fabrication problems related to this type of structural steel are rarely encountered.

The most notable trends in the development of normalised steels in the last ten to fifteen years are:

Table 2. Trends in the development of normalised steels

Effect aimed at	**Means**
Improved weldability	Lowering of the carbon content.
More isotropic properties	Lowering of sulphur content, Ca-treatment, generally cleaner steels.
Maintaining yield stress up to SMYS 355 MPa	Minor additions of copper, nickel and microalloying elements (vanadium and niobium)

	to compensate for lower carbon content.
Improved toughness in weld heat-affected zones (HAZ)	Lower carbon and phosphorus contents, better control of the use of niobium and vanadium as strengthening elements and titanium as fine grain element. /1/

The normalised steels are considered to be good and reliable steels with an extensive history of successful service experience. However, their strength is limited, and usually restricted to SMYS of 355 MPa.

4. Motivation for using higher strength steel

During the last few years there has been a rising interest world-wide in utilising higher strength structural steels, and the use of such materials is increasing for a range of different types of welded structures. This type of development is primarily based on the fact that the marine industry has realised that providing these materials are used correctly and in an "intelligent" manner significant economic gains may be achieved. Some of the most obvious benefits are listed below:

- Reduced steel weight. Less steel needs to be bought, transported, handled, cut to size, formed and welded.
- A lighter structure is by itself usually economically advantageous (not so relevant for ships, except for high speed ships).
- Reduced volume of weld metal in butt joints due to reduced plate thickness can significantly reduce fabrication costs.

Another important factor is that the high strength steels are exposed to an ongoing enhancement with regard to critical properties such as weldability, toughness and also the uniformity (reducing the amount of scatter) of the various properties.

Finally, positive fabrication experience and also service experience are steadily accumulating, giving confidence in the market.

From a materials engineering point of view the main points where caution must be exercised when fabricating in high strength steels are:

- The fatigue strength of a welded structure is not improved by increasing the strength of the steel. Therefore, if a fatigue loaded structure is slimmed down in connection with the use of high strength steel, and welded as usual without duly considering the implications of the higher stress level in the structure, fatigue problems may arise.
- As steel strength increases the selection of welding consumables becomes more critical, both with regard to toughness properties and risk of hydrogen cracking in the weld metal.

5. The two main types of high strength structural steel

5.1 General

Metallurgically, the modern high strength structural steels are of two main kinds: QT steel and TMCP steel. Several variants in processing routes exist under the two main types, however, it is beyond the scope of this paper to discuss the various routes in depth.

The modern QT and TMCP steels have important metallurgical features in common:

- A well controlled chemical composition which is suited to the desired response of the material during its manufacture (rolling, heat treatment) and fabrication (welding) /2/.
- A low content of non-metallic inclusions and impurity elements, which contributes to good ductility and toughness properties.

QT steels are delivered as rolled plate, rolled profiles, pipe (welded and seamless) and as forged and cast products.

TMCP steels, however, which rely heavily on the details of the rolling process for achieving their properties, are typically supplied as plate or products made from plate, such as seam-welded pipe, although sections are also produced by this method. In some cases it is possible to control the forging processes sufficiently well to consider this as a TMCP process, however, it is more common to conduct a standard forging procedure followed by Direct Cooling (DQ), or accelerated cooling (fan and spray cooling) /3/. The main advantages of converting from a conventional QT forging grades to a forging steel which allows DQ ("third generation forging steels") are listed below:

- No additional heat treatment is required after forging.
- Increased productivity.
- Easy to incorporate in continuous production lines.

5.2 Quenched and tempered steel (QT-steel)

Typical strength range: SMYS 420 - 500 MPa.

Quenching and tempering, as the name implies, is a two-stage heat treatment consisting of quenching from the austenite region, often about 920 °C, (depending on the carbon content) followed by tempering at lower temperatures, typically in the range 580 - 680 °C.

It has been known since the beginning of the century that such a heat treatment produces a particularly favourable combination of strength and toughness /4/. In early versions of QT steels, however, the weldability was severely limited due to the content of alloying elements used to obtain the desired hardenability, and hence the mechanical properties.

In recent years a significant development has taken place regarding both alloying and heat treatment of QT steels. In particular the development of more efficient quenching techniques for plate materials has been important since the more rapid cooling now available enables through-hardening of a certain material thickness with a lower alloying content of the steel.

This has led to QT plates now being available up to 70 - 80 mm thickness, and with weldability comparable to that for normalised steel.

5.3 TMCP-steel

Typical strength range: SMYS 355 - 460 MPa.

As opposed to the QT steels, the TMCP steels represents a relatively new development in steel metallurgy.The TMCP processes builds on a further development of so-called *controlled rolling,* which is briefly outlined below /5, 6, 7, 8/.

For normalised and also QT materials, plate rolling is carried out at high temperatures (1250 - 1000 °C), and the purpose is primarily to get the slab, bloom, or billet from the continuous casting machine, down to the desired plate thickness as quickly and cheaply as possible. The relatively poor properties in the as rolled condition are not a problem, since the desired properties are introduced during the subsequent heat treatment, normalising or quenching and tempering as the case may be.

However, heat treatment takes time and costs money. Steelmakers have therefore tried to develop controlled rolling procedures which could produce properties equal or superior to those of normalised steel in the as rolled condition. These efforts have successfully led to the development of *controlled rolling* or *thermomechanical rolling.*

Thermomechanical rolling is a complex matter. Its most prominent feature is *finish rolling at lower temperatures*, typically down to or a little below the austenite-to-ferrite transformation temperature (Ar_3, often in the range 750 - 700 °C, depending on thickness and chemical composition). In this way a very fine grain size is achieved, which markedly improves toughness and also contributes to increasing the yield strength.

The microalloying elements titanium (Ti) and niobium (Nb) play particularly important roles in the thermomechanical rolling processes. Ti (in the form of fine titanium nitride precipitates) prevents austenite grain growth during slab and bloom reheating prior to rolling. Nb will impede recrystallization (increase the recrystallization stop temperature) of the deformed austenite grains due to formation of Nb(C,N) during rolling in the low temperature regime, thereby promoting ferrite nucleation from heavily deformed austenite, resulting in a very fine ferrite grain size.

In the last decade this technique has been further developed - initially by Japanese steelmakers - to include accelerated cooling from the finish rolling temperature. This gives a significant contribution to strength via several strengthening mechanisms, including some transformation hardening, further refinement of ferrite grain size and increased dislocation density.

Overall, the main benefits from TMCP process are:

- Increased yield and tensile strength
- Reduced alloy content
- Improving weldability
- Increased toughness providing the most ideal microstructure has been achieved

Production of TMCP products requires a high degree of process control during rolling and the subsequent controlled cooling, and computer control of the many variables is a necessity.

TMCP steels commonly possess excellent combinations of strength, toughness and weldability. In particular the high toughness at low temperatures makes these materials attractive for arctic applications.

5.4 QT vs. TMCP-steel

When selecting high strength steel for welded structures QT and TMCP steel can often be considered equivalent alternatives in the strength range where they overlap (SMYS about 420 - 460 MPa). For some steel producers there is a tendency for TMCP steel to have lower carbon equivalent values than QT steels of similar strength. However, a detailed evaluation of weldability should be based on information about the specific chemical composition of the candidate materials.

6. Differences and similarities between high strength and the common normalised structural steels

By far the largest part of the accumulated experience regarding fabrication and operation / service of steel structures applies to normalised steel with SMYS in the range 235 - 355 MPa and with a microstructure consisting of ferrite and pearlite.

High strength steels have been made by rather different processing routes and therefore have other types of microstructures:

- QT steels: Tempered martensite
- TMCP steels: Fine grained ferrite + small amounts of pearlite and bainite

They have higher yield strength, commonly a higher yield strength to tensile strength ratio (Re/Rm), and there are some, albeit small, differences in chemical composition.

It is therefore only natural that designers and steel users sometimes ask what technologically important differences there are between the modern high strength steels and the more familiar normalised steels. In the following some of the points most often questioned are briefly discussed.

6.1 Strength properties

6.1.1 Elastic modulus

The elastic modulus (E modulus) is the same for high strength as for normalised steel (210 000 MPa at room temperature).

6.1.2 Increased yield strength

It should be noted that the higher yield strength of QT and TMCP steel must often be taken into account when cold forming operations are planned, due to the higher forces required. This is an important consideration, which, for example, may have implications for the maximum length of pipe that can be manufactured with a given pipe mill equipment.

6.1.3 Yield strength to ultimate tensile strength ratio (Re/Rm)

As compared to normalised steel, in high strength steel the yield strength (Re) has increased more than the ultimate tensile strength (Rm), thus the Re/Rm ratio is higher in high strength steel. Naturally there is a limit to how high a value for the Re/Rm ratio can safely be used in a structural steel. It is always necessary that the material has sufficient ability to plastically deform and strain harden to allow redistribution of stresses.

For the high strength steel discussed here a maximum value of Re/Rm ≤ 0.90 for actual tensile test results is recommended.

6.2 Fatigue

For smooth base material test bars (no weld) the fatigue strength will increase with increasing strength of the material. It is, however, well known that the fatigue properties of a welded structure are not significantly improved by using steel of higher strength. This is because stress concentrations due to the local geometry in the toe region of the weld leads to early crack initiation. Thus the major part of the fatigue life is spent on crack growth, and this phase of the fatigue life is relatively insensitive to material strength. This means that for welded structures the fatigue design rules used for normalised steels may also be applied for high strength steel (SMYS 420 - 500 MPa)

When the designer chooses to use high strength steel the purpose is to reduce the material thickness, which generally leads to a higher stress level. It is therefore clear that *the use of high strength steel in fatigue loaded structures requires special attention.*

Some points that may be useful to consider for improving the fatigue performance of a structure are:

- Conscious design of the structure to achieve smooth stress flow through the structural details.
- Deliberate location of welds away from areas with high dynamic stresses.
- Possible improvement of fatigue life by using cast or forged components.
- Fatigue is a local phenomenon. All factors leading to a reduction of *local* stress concentrations will improve the fatigue life of that region. To this end several types of post weld treatment are available, an important example is the grinding weld toe regions.

6.3 Corrosion

Both regarding atmospheric and marine corrosion the high strength steels under discussion behave in the same manner as normalised steel.

However, for a high strength steel member that is fully utilised with regard to strength a possible corrosion allowance naturally constitutes a relatively greater proportion of the total thickness than for a corresponding lower strength normalised steel.

For steels with SMYS up to about 550 MPa, the recommended potentials for cathodic protection are the same as those for normalised steel of lower strength. The likelihood of environmentally induced cracking (from hydrogen) is negligible under these conditions.

6.4 Weldability

There are only minor differences in chemical composition between modern versions of normalised steel and the high strength steels discussed here. It is therefore to be expected that there will not be any great differences in weldability.

Typical carbon equivalent values for normalised, QT and TMCP steels in the thickness range 10 - 40 mm are indicated in Table 3. It should be pointed out that deviations from the values shown can be considerable. In particular this may be so for the mild steels where less stringent control of the chemical composition is usually required.

Table 3. Examples of carbon equivalent values (data from a major European steel producer)

Steel type	**SMYS, MPa**	**CE**[1]		**Pcm**[2]	
		ship	**offshore**	**ship**	**offshore**
Normalised mild steel	235	0.38	0.38	-	-
Normalised	355	0.40	0.37	0.24	0.20
QT	460	0.38	0.34	0.21	0.17
TMCP	420	0.36	0.34	0.20	0.17

High strength steels can be welded with all the common welding methods in use for normalised steel.

The general experience from welding of high strength steels with SMYS in the range 420 - 500 MPa covers a wide range of applications including offshore primary deck structures, module support frames, jackets, ice breakers, bridges and high rise buildings. Practical experience shows that there are few problems associated with welding.

It can be argued that due to their higher yield strength the high strength steels will have a higher level of residual stresses after welding, which may contribute to somewhat larger weld deformations, and under otherwise equal conditions, increase the risk of hydrogen cracking (cold cracking). Such tendencies will, however, tend to be counteracted by the reduced material thickness most often associated with the application of high strength steel, and only very few incidents of hydrogen cracking in the weld heat affected zone have been reported for the high strength steels discussed here.

As a rule of thumb the following can be said:

Provided that,

the hydrogen content in the weld is ≤ 5 ml/100 g,
Pcm ≤ 0.22,
CEIIW ≤ 0.39,

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[1] $CE = C + Mn/6 + (Cr+Mo+V)/5 + (Cu+Ni)/15$

[2] $Pcm = C + Si/30 + (Mn+Cr+Cu)/20 + V/10 + Mo/15 + Ni/60 + 5B$

then up to ca 30 mm plate can be welded with no or low (50 °C) preheat, and up to ca 80 mm plate can be welded with preheating in the range 50 - 100 °C

It is important to note that the above applies to avoidance of hydrogen cracking in *the weld heat affected zone*, and that in connection with welding of high strength steel the greatest risk of cold cracking is often in the *weld metal*. For weld metal cracking methods for predicting necessary preheat temperatures are also less reliable.

To avoid weld metal hydrogen cracking the best strategy is usually to keep hydrogen content under stringent control, and, whenever possible, to use robust welding procedures, that is procedures with adequate margins with respect to the essential welding variables.

6.5 Fracture toughness, acceptable defect sizes

6.5.1 Unstable fracture - general

The term *unstable fracture* is generally used to denote fracture starting from a crack or crack-like defect under an extreme load situation[1]. The resistance of a material to unstable fracture is normally referred to as its *fracture toughness*. Unlike the impact toughness (Charpy V-notch), fracture toughness is defined in terms of fracture mechanics and may be applied as a parameter in quantitative assessments in order to evaluate the significance of weld defects, applied loads, local geometry and material properties as a whole.

The classification societies give requirements to impact toughness (Charpy-V) for the whole range of strength classes including SMYS of 690 MPa. These requirements are mainly based on experience, most broadly gained from the use of normalised ship steel grades in moderate thicknesses.

When heavy thickness steel plates (>50 mm) became commonly used for offshore structures during the seventies, fracture toughness testing and fracture mechanics assessments was introduce in the this industry in order to compensate for the lack of experience. Today, fracture mechanics plays a similar role when going to higher strength steels.

The fracture toughness is commonly expressed in terms of either:

- the critical stress intensity factor, $K_{Ic.}$
- the critical crack tip opening displacement, CTOD.
- the critical J-integral, J_{Ic}.

Since the validity of K_{Ic} is restricted to linear elastic situations, CTOD and J are the most relevant parameters for modern ductile structural steels. Very briefly; CTOD is a measure (in mm or inch) reflecting the stretching of the material in the crack tip region, while J is a measure of the deformation energy absorbed by the material in the vicinity of the crack tip.

An important difference between the fracture toughness tests and the CharpyV-notch test is that the fracture toughness test specimen size is not fixed, but is made as large as possible in order to reflect the actual material thickness in each case. The beneficial effect on fracture

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[1] Also the term *brittle fracture* is used in this context, but an unstable fracture may also be of a ductile nature.

toughness resulting from a reduction of material thickness made possible by increasing material strength, is thus inherent in the fracture toughness concept.

6.5.2 Fracture toughness requirements

The required fracture toughness is generally recommended to be determined by a fracture mechanics assessment. Several fracture mechanics models are available for assessing the risk for unstable fracture. BSI's publication PD6493:1991 is probably the most widely used guideline in the marine industry /9/.

As a rule of thumb for normalised steels (SMYS < 355 MPa), CTOD-values above 0.15 mm for the weld metal and HAZ usually gives a positive outcome of a fracture mechanics assessment. To achieve this, the target CTOD-value for the parent material is recommended to be at least 0.1 mm higher in order to allow for a relative drop in toughness in the HAZ. However, when the material strength is increased, and this strength is utilised in way of higher stress levels, the CTOD-value should be increased proportionally (as for Charpy-V) in order to maintain the same level of safety. For the higher strength steel classes this represents a challenge to the steel manufacturers and welding engineers.

Alternatively, a moderate fracture toughness requirement may be justified by other means, such as:

- Reducing the likelihood of large weld defects by better welding procedures and improved workmanship and inspection.
- Reducing the stress concentrations by choosing better local design details.
- reducing the residual stresses by post weld heat treatment or other means.
- improving the weld toe geometry by grinding (most effective with regard to avoiding fatigue initiation).

7. Fabrication in shipbuilding

The fabrication of steel structures in shipbuilding today is a very efficient process with a low manhour consumption. The process is based on steel grades that can be readily formed and welded with high energy input processes.

Single sided welding of butt welds with high heat input is common practice at the yards today. In order to have safe welding conditions, carbon equivalents must be at a relatively low level.

The TMCP steels typically have a somewhat lower CE than normalised steels. This is particularly so for for large thicknesses, for which TMCP grades will be beneficial to use in combination with single sided high energy welding.

Submerged arc welding is the most commonly used welding method. For thicker joints tandem electrodes are used.

The typical division of weld lengths for a tanker is given below

Flat horizontal fillet welds:	74 %
Vertical fillet welds:	18 %
Flat butt welds:	4.8 %
Vertical butt welds:	1.7 %

The traditional shipbuilding consists mainly of plane panels fit together. The necessary forming of the plates and stiffeners are done by cold forming prior to welding. The shipbuilding process can be divided in the following main steps:

- Plain plates are welded together into large panels. Single sided automatic welding is normally used in this stage. Panel sizes up 24x24 meters are used
- Stiffeners in transverse and longitudinal direction are attached and welded to the panels. This process can either be automatic or manual, but the welding is usually automatic.
- The panels are then joined together in sections. This process is manual but the welding can be either manual or automatic.
- The sections are normally joined together into large modules. This process is mainly a manual process, with some automatic welding
- The large modules are erected in a dry dock and joined together into a complete ship. The process is mainly manual, with some automatic welding.

Single sided one path welding will be used as far as possible as this gives the highest productivity and also gives the least weld defects. The necessary heat input will however increase and problems with reduced fracture toughness may occur.

The use of higher strength steel materials in general means a reduction of the operational window for the joining processes. This increases the requirements to the equipment and the operators at the yard.

In a typical modern steel shipyard the modules are outfitted to a maximum extent before they are located in the dry dock. Also painting is performed indoors on the large modules. This improves the overall productivity for the yard and the quality for the ship owner.

8. Cast and forged components

8.1 General

By far the greatest volume of structural steel is used in the form of rolled plate, or products derived from plate materials. However, high quality castings and forgings have been on the market for some time, and in some cases technically and economically favourable solutions can be obtained by utilising such components /10/.

8.2 Castings

Casting steel to shape is the most direct way of producing components near to their final form. The flexibility regarding geometrical form and a favourable strength to weight ratio are important reasons why castings may represent realistic alternatives for structural components of more complicated shape. In particular, the streamlined shape of a casting with generous radii at fillet and junctions contributes to good fatigue performance.

There seems to have been some hesitation in the market in taking full use of cast structural components. This is apparently due to the desire to maintain the freedom of making changes for as long as possible in a project, and also a concern about the occurrence of imperfections /

defects in cast components, and the related aspect of non-destructive testing (NDT) and the interpretation of NDT results.

For high strength castings it is necessary to use a quenching and tempering heat treatment, and the chemical composition must then be adjusted to provide sufficient hardenability for the material thicknesses involved. There is generally a somewhat higher alloying content in QT cast components as compared to QT plate materials in corresponding thickness. This is because the high cooling rates now available during plate quenching can not be obtained for the more complex shapes of castings. Since alloying tends to impair weldability while improving hardenability, in a practical case a balance must be struck which does not involve too much penalty for any of these two important factors.

8.3 Forgings

Forging also offer a considerable freedom to select shape, although to a lesser degree than casting. On the other hand the hot deformation inherent in the forging process has advantages regarding the refinement and uniformity of the microstructure, grain flow, reduction of microsegregations and closing of possible internal voids. As for castings the chemical composition of high strength structural forgings must be chosen to produce a satisfactory balance between hardenability, weldability and mechanical properties for the dimensions in question.

8.4 When should castings or forgings be considered?

8.4.1 Castings

Due to the many variables involved it is difficult to compare the final cost of a component made by different manufacturing routes. Nevertheless it can be said that as a guidance that casting is often competitive when:

- Relatively small numbers of components are required and the cost of forging dies or fabrication by welding would be excessive.
- The cast design would significantly reduce component weight.
- A casting could be used to replace a complicated / difficult forged welded or bolted structural component.
- A complicated component requiring high fatigue strength is needed.
- When placement of welds out of hot-spot regions is desirable for optimising fatigue properties and making joints easily accessible for inspection.

8.4.2 Forgings

Apart from the above latter two points which are also very much valid for forgings, the following can be mentioned as situations where forgings should be considered:

- When there are requirements to, or good reasons to prefer, a favourable pattern of grain flow in the component.
- When a sufficiently large number of like components justifies the cost of initial equipment.

- When the maximum degree of homogeneity and absence of internal imperfections are of importance.

9. Extra high strength steel, SMYS 690 MPa

9.1 Weldability and toughness

The use of steel with SMYS 690 MPa has so far been fairly limited. Typical marine applications are legs for jack-up platforms and hulls for sub-marines. For steel of this strength level a higher alloying content must be used, which somewhat impairs weldability. Typical carbon equivalent values are: CE ~ 0.55 and Pcm ~ 0.27. Correspondingly, greater attention must be given to the factors influencing hydrogen cracking during fabrication, both in the HAZ and the weld metal. Smooth fabrication in thicknesses up to 60 mm has been reported for submarine hulls. In some cases initial problems have been encountered with hydrogen cracking, usually in the weld metal, but these appear to have been satisfactorily solved, and followed by problem-free fabrication.

It should be noted that while the Charpy impact toughness for these steels is in general satisfactory the same situation does not apply to CTOD fracture toughness, which is usually lower than that of lower strength structural steel. Typically, this also applies to HAZ and weld metal.

9.2 Corrosion

In general, the corrosion rates of extra high strength steels, are no different from those of the lower strength grades.

Where corrosion control is effected by a corrosion allowance, the same wall thickness addition must be used irrespective of strength. Such a corrosion allowance thus represents an increasing proportion of the wall thickness as strength is increased, and can outweigh the advantage of the extra strength. This observation justifies evaluation of other approaches to corrosion control, possibly at increased cost.

Cathodic protection may be an economical approach to steel surfaces that are submerged. However there is still some debate about the reliability of compatibility of extra high strength with cathodic protection. Cathodic protection generates hydrogen on the protected surface, some of which may enter the steel and lead to cracking. The susceptibility to such hydrogen damage increases with increasing strength and hardness.

There is limited practical experience with extra high strength and cathodic protection, but there have been isolated occurrences of cracking in jack-up legs. Even though these incidents are now considered as "past experience", they do illustrate the increased sensitivity of these materials to hydrogen damage.

The behaviour of these materials under cathodic protection is still being investigated, and understanding of the phenomena is increasing.

9.2.1 Developments

At present it appears that an extensive deployment of SMYS 690 MPa is not imminent. The strength of these materials implies considerable potential, but there are a few drawbacks as discussed above.

For the moment it appears that more extensive use of SMYS 690 MPa steel awaits more complete information becoming available for the following topics:

- Weldability, and CTOD fracture toughness in HAZ and weld metal
- Fatigue properties in sea water under cathodic protection
- Possible adverse effects from hydrogen from cathodic protection

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Titanium For Marine Construction

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ABSTRACT

Titanium is currently used throughout the world in marine construction. The effective use of the material requires the recognition, understanding and correct application of the combination of useful and unique physical, mechanical and corrosion resistant properties of titanium and its alloys. The following two papers provide an overview and guidance on the design and fabrication using available products and cost effective manufacturing methods for two of titanium's most important applications.

INTRODUCTION

Titanium applications in a marine environment are driven by a number of factors. The following two papers effectively describe the important aspects of successful implementation of titanium for a cost effective application. The principal factors to be considered in successful and effective use of titanium are its basic physical and mechanical properties, corrosion resistance, and practical aspects of fabrication and installation. Titanium is light weight, being little more than half the density of steel, and its alloys are available to match or exceed the strength of steels commonly used. The modulus of titanium is also about half that of steel. This may require some change of design, but is a positive factor both in the high damage tolerance and shock resistance of titanium alloys, and their suitability for flexible risers, flowlines, piping and general construction.

Most importantly, titanium is highly resistant to corrosion in seawater, brines and brackish waters, and to almost all conditions encountered subsea, in oil and gas extraction. Applications for titanium are quite varied because of this and other important factors.

Titanium marine applications to be considered for include; heat exchangers, ball valves, process piping, hull materials for topside as well as deep submersible vessels, naval armor, hatches, fittings, fasteners, yacht fittings, oil and gas platform risers flowlines and many more items.

Experience for titanium in a marine construction date back more than thirty years and is available to guide both existing and new users to the best alloys and manufacturing processes for each application.

Titanium for Marine Applications

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INTRODUCTION

Titanium and its alloys, over the last 25 years, have become recognized as one of the best engineering metals for use in marine applications. Titanium and its alloys were first commercially developed in the 1950's, but did not see much use in marine environments until the mid-1960's. The realization that titanium exhibits remarkable corrosion resistance in natural waters of all kinds led to the first applications, such as tubing for sea water power plant condensers. The first fully tubed condenser went on-line in 1972 at Con Ed's Arthur Kill #3 unit. In short order, titanium was recognized as the best tube material for sea water condensers; in the last 25 years, over 400 million feet of titanium condenser tubing has been installed. To date, there has never been a single corrosion failure of this tubing. The market today for titanium tubing is ever expanding due in no small part to the increasing use of condenser tubing in non sea water cooled condensers. This has been due to titanium's immunity to MIC (microbiologically influenced corrosion) attack and ever stricter EPA regulations for cooling water contamination. Titanium, along with its corrosion immunity, also offers the advantage of being non-toxic to fish and mammals.

Overall, many factors exist for the increasing usage of titanium in marine applications. The primary reason being titanium's immunity to attack by all natural waters, including brackish, salt, and polluted. However, other benefits exist for the design engineer that utilizes titanium in place of more traditional metals. Significant weight savings are derived as the result of titanium's favorable density, zero corrosion allowance (leading to reduced wall thickness), and its excellent erosion resistance (leading to reduced diameters). As a result of reduced wall thickness, heat transfer rates can be maintained and in some instances, improved, over the materials being replaced with titanium. Lastly, decreased maintenance costs are observed when using titanium. This is due to the absence of corrosion and decreased biofouling due to higher flow rates. These benefits are more difficult to quantify; rather, they become evident on an individual basis as the titanium acquires service history.

The "exotic" label given to titanium years ago was due more to lack of exposure than a true understanding of the metals' characteristics. Nowadays, metallurgists and corrosion engineers coming out of college are more cognizant of the metal, and there is an ever-expanding base of knowledge and service experience concerning the metal that was just not available 30 years ago. Today there is a International Titanium Association dedicated to the growth and understanding of the metal. As more fabricators became experienced with titanium, the myth that titanium could not be welded or worked with gradually vanished. Titanium in fact, is easily welded, as most any experienced welder will confirm. Field welding of titanium is commonplace, as it should be, allowing users maximum flexibility in repair options.

Most recently, the use of life-cycle costing has added immensely to the attractiveness of titanium. Although up-front costs may be higher than for most non high-performance materials, these are almost always recouped (usually several fold) in a life-cycle analysis, due to decreased maintenance and increased production time. Often times increased production rates can also be achieved due to the metal's withstanding harsher operating conditions than the previous materials of construction.

Titanium and its alloys often times offer unique combinations of physical, mechanical, and corrosion properties, which, when properly applied, produce unexcelled performance. This paper is intended to assist the marine design engineer in selecting the sea water applications that are not only appropriate, but also justifiable for titanium. The basic outline of this paper will include:

Physical/Mechanical Properties
Corrosion Behavior
Weight Savings
Heat Transfer Comparisons
Marine Applications, Present and Future
Summary

A bibliography will be appended to allow the reader more comprehensive information if desired.

PHYSICAL/MECHANICAL PROPERTIES OF TITANIUM

Table I lists the nominal compositions of the most commonly used titanium metal and alloys. Throughout this article, titanium and its alloys will usually be referred to by their ASTM grade designation, since most design engineers are familiar with ASTM. The first seven grades listed (1, 2, 7, 11, 16, 17,and 12) comprise probably 95% of the titanium use in sea water. Of these, the most widely used is unalloyed (or commercially pure) titanium grade 2. This grade is the workhorse of the titanium family, possessing a good blend of mechanical strength and corrosion resistance. A more complete listing of grades and compositions can be found in the ASTM B265 specification for titanium strip, sheet, and plate.

Table I
Titanium Metal and Alloy Nominal Composition (wt%)

Common Name	ASTM Grade	UNS Designation	O	Fe	Al	Cr	Mo	Ni	Pd	V
Unalloyed	1	R50250	0.06	0.06						
	2	R50400	0.10	0.12						
Ti-Pd	7	R52400	0.10	0.12					0.15	
	11	R52250	0.06	0.06					0.15	
Ti-Pd Lean	16	---	0.10	0.12					0.05	
	17	---	0.05	0.05					0.05	
TI-CODE 12®	12	R53400	0.12	0.15			0.3	0.8		
Ti-3-2.5	9	R56320	0.12	0.15	3.0					2.5
Ti-6-4 ELI (Extra Low Interstitials)	23	R56402	0.13 max.	0.15	6.0					4.0

Table II lists certain physical properties of the more common grades. A quick glance at the table will highlight several distinctions about titanium. Density-approximately half that of ferrous, nickel, and copper alloys. Thus, titanium is best viewed on a per unit area basis when considering weight and cost, often two of the most critical components. Thermal conductivity for unalloyed titanium (and the Pd containing grades) is about 30% higher than the 300 series stainless steels, and over 60% higher than the superaustenitics. In addition, when compared against copper alloys, often times significantly reduced wall thickness for titanium will more than compensate for its lower conductivity. These distinctions are dealt with in detail in the sections on weight savings and heat transfer. The low elastic modulus is of significance in determining the proper fabrication method, and in compensating for increased vibration through additional tube supports (when dealing with heat exchangers or piping). In addition, its low modulus and density make it

Table II
Physical Properties of Titanium

Property	Grades 1,11,17	Grades 2,7,16	Grade 9	Grade 12	Grade 23
Density (lb/cu.in.)	0.163	0.163	0.162	0.163	0.160
Beta Transus (°F)	1630	1675	1715	1630	1800
Thermal Conductivity (Btu/hr.-ft.^{2}-°F/ft.) @ RT	12.5	12.5	4.4	13.2	4.2
Specific Heat (Btu/lb/°F) @ R.T.	0.13	0.13	0.13	0.13	0.135
Coefficient of Expansion (10^{-6}/°F) 32-600°F	5.1	5.1	5.1	5.3	5.3
Electrical Resistivity (microhm-in.) @ R.T.	22	22	49	20	67

Elastic Modulus (10^6 psi) in tension	14.9	14.9	14.9	15.0	16.5
Poisson's Ratio	0.34	0.34	0.34	0.34	0.34

an ideal shock resistant material. Titanium has a relatively low thermal expansion coefficient, which makes it very compatible with glass and ceramics, and is something that should be considered when coupling to other metals. Lastly, titanium is virtually non magnetic, making it ideal to use for applications sensitive to electro-magnetic interference, such as electronic housing equipment.

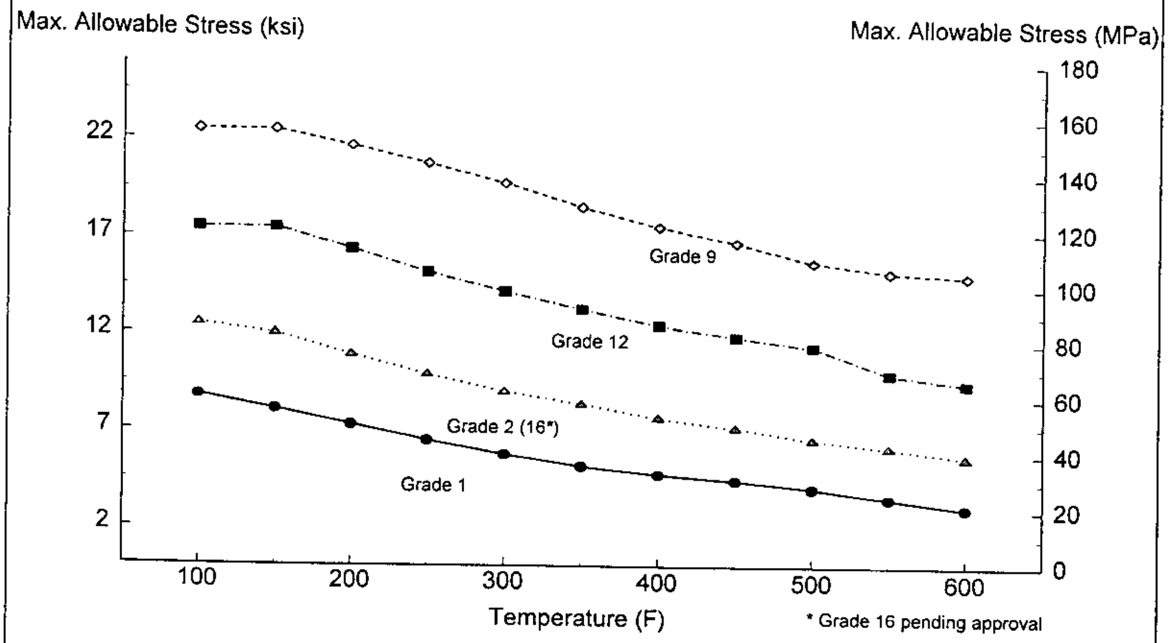
Selection of the proper titanium grade for sea water service will generally be governed by either mechanical properties (usually strength or formability) or corrosion resistance, and sometimes both. Table III gives the minimum (per ASTM) mechanical properties for the grades listed in Table I (again, a more extensive listing can be found in ASTM B265). The grades comprise an almost continuous spectrum from low strength, highly ductile commercially pure metal, to high strength, lower ductility alloys. Grades 1 and 2 differ only in their oxygen and iron content. Grade 1, having the lowest oxygen and iron content, is the lowest strength grade of titanium. However, its attributes include excellent cold formability, allowing this grade to be used for deep press applications like plate and frame heat exchangers or complex geometric designs. Grade 2 is a medium strength unalloyed titanium that has led the way for titanium marine applications. Its strength is similar to common stainless steels, yet it still possesses good cold formability. It is, perhaps, the easiest grade to work with, lending itself more towards fabricability and weldability, allowing users to easily replace stainless steel or nickel equipment without extensive re-designing.

Grades 9, 12, and 23 are alpha/beta titanium alloys; the percent beta phase (and strength level) increasing with higher levels of alloying additions. These alloys each have their own unique characteristics that can be utilized in sea water environments. Grade 12 has been used successfully for many years in high temperature coolers on offshore platforms because of its excellent sea water crevice corrosion resistance. Grades 9 and 23 have been used for erosion resistance in applications such as shafts and impellers. Grade 9 is also the highest strength titanium alloy approved by ASME, allowing use of titanium in very high temperature/pressure heat exchangers.

Table III
Titanium Metal and Alloy Mechanical Properties

ASTM Grade	**Min. Tensile Strength**		**Min. 0.2% Yield Strength**		**Min. Elong. in 2" %**	**Minimum Bend Radius**	
	ksi	**MPa**	**ksi**	**MPa**		**< 0.070" Gage**	**0.070-0.185" Gage**
1, 11, & 17	35	240	25	170	24	3T	4T
2, 7, & 16	50	345	40	276	20	4T	5T
12	70	483	50	345	18	4T	5T
9 and 18	90	620	70	483	15	5T	6T
5	130	895	120	828	10	9T	10T
23	120	828	110	759	10	9T	10T

Several titanium grades are qualified for use as ASME code approved materials. These include grades 1, 2, 7, 9, and 12. As of this writing, grade 16 is being balloted for approval. Figure 1 presents a chart of ASME allowable stresses at various temperatures for these grades. Tensile strengths gradually fall off with temperature until at about 600°F titanium becomes creep limited. The fall off is not as dramatic for grades 9 and 12, making these alloys the preferred (and cost effective) grades for high temperature code-approved equipment.



* Grade 16 pending approval

Figure 1- ASME Allowables for Titanium

CORROSION BEHAVIOR OF TITANIUM

Corrosion resistance of titanium has been the driving force for its use in the marine industry. Table IV offers a quick comparison between titanium and other common metals with regards to sea water corrosion behavior. Titanium is classified as a reactive metal, relying on the formation of a protective oxide film for corrosion resistance. The film is titanium dioxide, which forms

Table IV
Sea Water Corrosion Resistance Comparison

	Cu-Ni Alloys	**316 SS**	**Unalloyed Titanium**
General Corrosion	Resistant/Susceptible	Resistant	Immune
Pitting Attack	Susceptible	Susceptible	Immune
Crevice Corrosion	Susceptible	Susceptible	Immune (< 180°F)
Stress Corrosion Cracking	Resistant	Susceptible (> 140°F)	Immune
Erosion Corrosion	Susceptible	Resistant	Resistant
Galvanic Attack	Susceptible	Resistant	Immune
MIC Attack	Susceptible	Susceptible	Immune

Weld/HAZ Corrosion	Susceptible	Susceptible	Immune

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instantaneously upon contact with air or moisture, and is stable over a wide range of pH and potentials. By studying the nature and stability of the oxide film, one understands much of the corrosion behavior of titanium metal. The scope of this paper does not allow for an in-depth perspective on titanium's sea water corrosion behavior, but rather a general overview. Excellent sources are listed in the bibliography for a more detailed examination of the corrosion behavior of titanium and its alloys.

GENERAL OR UNIFORM CORROSION

Titanium is immune to general corrosion attack in all natural, cooling tower, and high purity waters to temperatures in excess of 600°F including sea water and brackish water. Contaminants, such as metal ions, sulfides, sulfates, carbonates, and chlorides do not affect the passivity of titanium in marine environments. Exposure of titanium for years at various ocean depths has shown it to be immune to corrosion in ambient temperature sea water (rates < 0.01 mpy). Utilities have, over the last 25 years, installed over 400 million feet of titanium tubing in sea water cooled condensers without a single incidence of corrosion. There has also never been a reported incidence of microbiologically influenced corrosion (MIC) attack on titanium. It is widely regarded as the only common structural metal to be immune to MIC attack. Continued high temperature (> 200°F) exposure of titanium to water or steam may produce a slight discoloration of the surface. This is caused by surface oxide growth, and does not damage the integrity of the metal. On the contrary, enhanced oxide films on titanium have been shown to be beneficial in lowering corrosion rates.

The hard, adherent oxide film on titanium also gives the metal outstanding resistance to erosion corrosion. In the absence of suspended solids, sea water velocities as high as 120 ft./sec. cause no appreciable attack of titanium grade 2. Even with sand laden sea water, flow rates can be as high as 15 ft./sec. with no erosion. This is in sharp contrast to many other materials, which are very sensitive to process stream flow velocities and turbulence.

Titanium's inherent corrosion resistance can be enhanced by several methods if necessary. The most common method is through alloying. Many years ago, it was discovered that noble metal additions to titanium were quite effective in extending the range of useful corrosion resistance, particularly in reducing acid environments. Molybdenum and nickel are also useful in this regard. Unalloyed titanium with palladium, grade 7, offers the identical physical and mechanical properties as grade 2, yet its corrosion resistance can be significantly better, especially when very low pH levels are encountered. Alloying with molybdenum and nickel enhances both the mechanical and corrosion properties of titanium, as can be seen with grade 12.

LOCALIZED CORROSION

Titanium exhibits superior localized corrosion resistance when compared to other metals such as stainless steels and nickel alloys. Evidence of this is clear in the over 400 million feet of titanium tubing in sea water condenser service without a single incidence of corrosion. However, crevice corrosion of titanium can occur in sea water given sufficiently severe conditions. Thus, conservative guidelines have been developed for all of the common titanium grades, as seen below. Proper grade selection is important since rapid degradation of the metal can occur within a crevice, leading to premature and undetected failures. Crevice attack is also very random with regards to incubation time and area involved. The nature of crevice corrosion does not lend itself to precise guidelines for avoiding attack, as is the case for general corrosion. Duplication of crevice geometry, gasket material, metal surface condition, dissolved oxygen, and identical solution chemistry is critical if comparative testing is to be done. In reality, all these conditions are never duplicated, allowing only for the use of general guidelines. Years of testing has shown that the most important variables for crevice corrosion are pH and temperature. Brine chemistry is a secondary issue, assuming chloride (or other halide or sulfate) concentration is above the threshold level for titanium, which is about 1000 ppm.

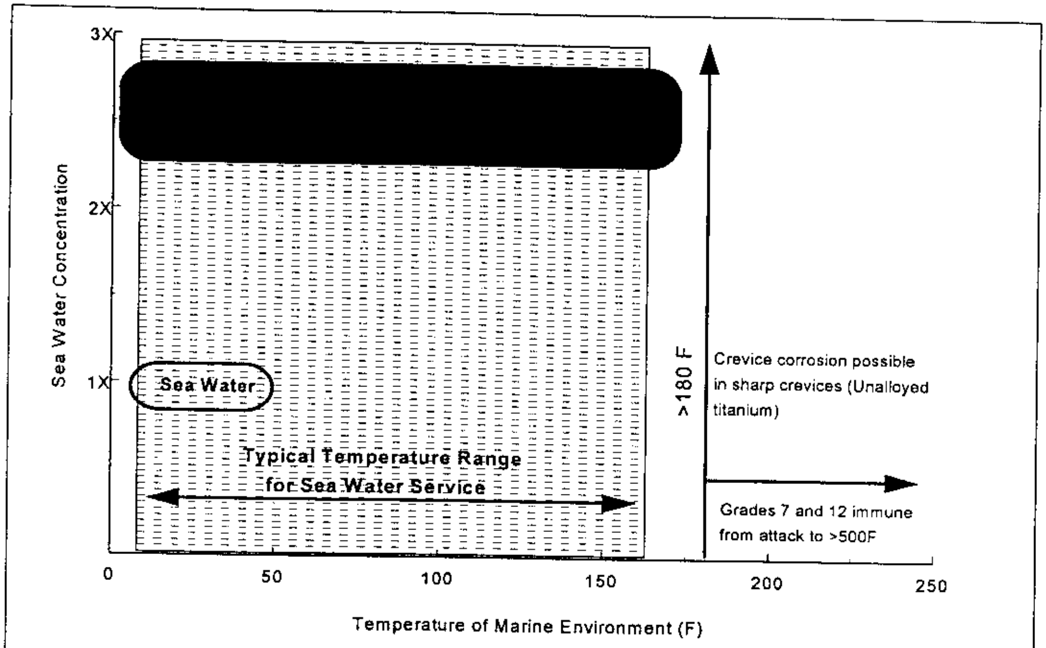

Figure 2- Sea Water Corrosion Diagram for Titanium

Susceptibility to crevice corrosion varies with the different titanium grades. Figure 2 illustrates this for the most common industrial grades in sea water. As stated earlier, brine concentration is of less concern, allowing these guidelines to apply to all concentrations, as the chart reflects. The threshold temperature for crevice corrosion in sea water is about 180°F. Grade 2, as well as the other unalloyed titanium grades, can be subject to crevice corrosion in sea water when temperatures exceed about 180°F. Grade 7 (Ti-.15 Pd) exhibits remarkable crevice corrosion resistance, and is suited for even the most aggressive of environments. Lower cost options, such as grade 16 (Ti-.05 Pd) and grade 12 (Ti-.3Mo-.8Ni), offer nearly the performance of grade 7. These grades (16 or 12) allow the engineer to select a more conservative (i.e. corrosion resistant) titanium grade if crevice corrosion is a possibility, without a substantial cost penalty. Options other than alloy selection are also available to prevent crevice corrosion. These include grade mixing (i.e. use of more corrosion resistant and costly grade only in susceptible areas), gasket selection and/or impregnation, among others.

Pitting attack on titanium is not normally a concern in chloride media, unlike most stainless steel and nickel alloys, because of the excellent oxide stability in halide environments. Very high anodic potentials are required to cause breakdown of the TiO_2 film. Because of this, spontaneous pitting of titanium is almost never observed. Pitting potentials for titanium range from about +5 to +10 volts in sea water. Increasing temperatures will act to push these values somewhat lower, however, pH has very little influence on the pitting potentials.

HYDROGEN

The oxide film on titanium is an excellent barrier to hydrogen gas intrusion. Hydrogen absorption is possible in high pressure/temperature anhydrous gas streams, but the presence of small quantities (2%) of moisture or oxygen will prevent absorption. Once absorbed onto the titanium surface, hydrogen will only cause problems when diffusion into the base metal takes place. Titanium reacts with atomic hydrogen to form TiH_2, titanium hydride. Titanium hydride has limited solubility in titanium (< 150 ppm). Once the solubility limit is exceeded, titanium hydride precipitates form in the metal. These appear as dark, acicular needle-like structures in the metal microstructure. As the concentration of hydrogen reaches about 500-800 ppm loss of ductility begins to occur. At still higher concentrations, full embrittlement of titanium will occur, usually resulting in fracture of the metal. However, if the hydride remains at the titanium surface (no diffusion), the underlying base metal retains its full ductility, even with the presence of several thousand ppm of hydrogen. In this case, the metal can continue in-service indefinitely. As an example, one utility has been operating with extensively hydrided titanium tubing (caused by errant cathodic protection) for more than ten years without failures since the operating temperature of the condenser is sufficiently low to maintain the hydride on the titanium surface.

Overall, very few cases of hydrogen absorption leading to embrittlement have been observed in the CPI. The reason for this is that experience has shown that several factors must simultaneously be present in order for hydrogen related problems to occur:

1. Metal temperature must be above about 176°F. Diffusion of hydrogen into titanium only occurs to a significant degree above this temperature. Below this temperature, hydrogen will remain on the surface, leaving the base metal mechanical properties unaffected.
2. Solution pH of less than 3 or greater than 12, or impressed potentials on the metal more negative than -0.7 volts (vs Ag/AgCl).
3. A mechanism for generating nascent, or atomic, hydrogen at the metal surface must be present. This could occur through galvanic couples, impressed cathodic current, corrosion of the titanium, or constant mechanical abrasion of the metal.

Hydrogen embrittlement is avoided by elimination of one of the three factors listed above. Detrimental galvanic couples and overzealous cathodic protection probably account for the majority of hydrogen absorption problems observed for titanium. Titanium should not be coupled to active metals such as aluminum , zinc, and magnesium in the presence of sea water, at temperatures above 176°F. Lastly, despite the need to refrain from overzealous cathodic protection, experience has shown that impressed potentials as low as -1.0 volt (vs Ag/AgCl) are usually acceptable for cathodic protection systems.

STRESS CORROSION CRACKING (SCC)

SCC is an environmentally assisted fracture, requiring the presence of a corrodent as well as a tensile stress on the metal. Stress factors that can induce SCC would include residual stress from cold work, forming, or welding, and externally applied stress. Typically, the corrodent will not produce measurable gage loss on the metal prior to cracking. Sometimes, however, cracking will be preceded by slight localized attack. Temperature, pH, and metallurgical condition can affect SCC susceptibility. Prevention of SCC can often be obtained by modifying any one of the above conditions.

The majority of titanium alloys used in marine environments are very resistant to stress corrosion cracking. These include titanium grades 1, 2, 7, 9, 12, 16, and 17. These grades exhibit immunity to SCC in all but a few very specific environments. These environments are absolute methanol, red fuming nitric acid, nitrogen tetroxide, and cadmium metal. Chloride induced SCC is not a consideration for these grades, allowing most equipment to be used without stress relief anneals despite the presence of cold worked, formed, or welded components.

GALVANIC CORROSION

Titanium tends to exhibit very noble equilibrium potentials in most common chloride environments. As such, when considering galvanic couples between titanium and other materials, titanium will almost always be the cathode. Thus, galvanic corrosion of titanium has rarely, if ever, occurred in the CPI. Even if titanium were the anode, corrosion would most likely not occur due to the passive film formation titanium exhibits under oxidizing potentials. There are, however, two areas of concern when titanium is galvanically coupled to a less noble material. Depending on the material, there could be an acceleration of attack to the anode, and also excessive hydrogen generation and absorption onto the titanium (cathodic reaction by-product). This could have the effect of reduced service life for both components of the galvanic couple. Table V lists a galvanic series for materials exposed to ambient flowing sea water.

No concern exists when titanium is coupled to materials close to it in the galvanic series. This includes passive stainless steels, nickel and nickel alloys, and some copper alloys. Active stainless steels, carbon steel, aluminum, zinc, and possibly some copper alloys can exhibit accelerated attack when coupled to titanium. The extent of any effects will be determined by several factors including, surface area ratios, degree of aeration, temperature, velocity, and solution makeup, including pH. In addition to the possible acceleration of corrosion of the active metal, the titanium can experience increased hydrogen absorption, which, given the right circumstances, could lead to embrittlement of the titanium (see section on hydrogen absorption). The best recommendation to follow when facing possible active galvanic couples is to use insulating (nonconductive) materials to break the galvanic couple. When this is not possible or feasible, mitigation of the effects of the couple can be achieved by controlling some of the factors listed above, or through the use of transition sections, which utilize short sections of compatible materials between the titanium and the active metal. Lastly, the use of a more galvanically compatible material with the titanium can be implemented, up to and including an all titanium design.

Table V. Galvanic Series in Flowing Sea Water

Material	**Steady State Electrode Potential, volts** (vs saturated calomel half-cell)
Graphite	+0.25
Platinum	+0.15
Zirconium	-0.04
316 Stainless Steel (passive)	-0.05
304 Stainless Steel (passive)	-0.08
Monel 400	-0.08
Hastelloy C	-0.08
Titanium	-0.10
Silver	-0.13
410 Stainless Steel (passive)	-0.15
316 Stainless Steel (active)	-0.18
Nickel	-0.20
430 Stainless Steel (passive)	-0.22
Alloy 715 (70-30 cupro-nickel)	-0.25
Alloy 706 (90-10 cupro-nickel)	-0.28
Alloy 442 (admiralty brass)	-0.29
G Bronze	-0.31
Alloy 687 (aluminum brass)	-0.32
Copper	-0.36
Alloy 464 (Naval rolled brass)	-0.40
410 Stainless Steel (active)	-0.52
304 Stainless Steel (active)	-0.53
430 Stainless Steel (active)	-0.57
Carbon Steel	-0.61
Cast Iron	-0.61
Aluminum 3003-H	-0.79

Zinc	-1.03

CLEANING OF TITANIUM EQUIPMENT

The passive film on titanium will often provide for a more smooth, slick surface, inhibiting chemical buildup and providing for extended periods between cleaning. In marine environments, titanium is subject to biofouling, which is sometimes controlled with chlorine injection. This process is totally innocuous to the titanium. In addition, chemical cleaning of titanium with acid media can be performed on titanium when proper inhibition is utilized. Carbon steel implements should not be used to mechanically clean titanium. Introduction of embedded iron could pose corrosion problems once the equipment is put back on-line. Stainless steel or titanium cleaning implements should be used.

WEIGHT SAVINGS

Due to its virtual immunity to seawater corrosion and its high erosion/corrosion resistance, higher water velocities can be used in conjunction with titanium tubes (as opposed to Copper Nickel alloys) and piping systems commonly found throughout a ship or offshore platform with no loss of wall or metal carryover.

Substitution of smaller schedule sizes and thinner wall titanium tubing and pipe is being designed in for both weight and cost savings. With the density of titanium at half that of the copper alloys (.163 lbs/in^3 versus .323 lbs/in^3), weight savings of over 70% can be attained for pipe systems. As an example, a 2" SCH 5 (2.375" O.D. X .065" wall) titanium pipe substituted for a 2" Class 200 Cu-Ni pipe (2.375" X .083" wall) has an effective weight savings of 60%. A study by the Auxiliary Systems Group of the Naval Sea Systems Command (NAVSEA) shows weight savings as high as 78%.

In actuality, lighter walls in sub-schedule sizes can be used for even greater weight savings. In the above example, this translates to a pipe sized 2.375" X .050" wall at a weight of .7144 lbs/ft. versus a Cu-Ni weight of 2.3380 lbs/ft.

Charts of typical real weight saving comparisons are shown under the following figures:

"Pipe Wall Thickness (Inches)" is depicted in Fig. 3; "Weight Savings for Titanium Pipe Versus Class 200 Cu-Ni Piping" is shown in Fig. 4, while "Weight Comparisons Titanium Versus Cu-Ni SCH 10 Pipe" is shown in Fig. 5.

Opportunities will exist where a current nominal O.D. size can be reduced for titanium pipe (as replacement for the next higher O.D. schedule size in Cu-Ni) due to the ability to withstand higher velocities with no erosion effects and the overall zero corrosion allowance of titanium. This greatly increases the weight savings as is exemplified in Fig. 6, "Weight Savings."

These examples are representative of many of the current typical pipe sizes used and substitutions that can be made using titanium.

TITANIUM VERSUS CLASS 200 CU-NI				
PIPE DIAMETER NOMINAL (Inches)	PIPE DIAMETER ACTUAL (Inches)	WALL CLASS 200 CU-NI (Inches)	WALL GRADE 2 TI (PER ASME CODE)*	WALL GRADE 2 TI SCH 5
2	2.375	0.083	0.019	0.065
3	3.500	0.095	0.028	0.083

6	6.625	0.135	0.053	0.109
12	12.750	0.250	0.101	0.156

* Allowable

Figure 3- **PIPE WALL THICKNESS (INCHES)**

PIPE DIAMETER NOMINAL (Inches)	PIPE DIAMETER ACTUAL (Inches)	WEIGHT CU-NI PIPE (Lbs/100 Ft)	WEIGHT GRADE 2 TI (Lbs/100 Ft)	WEIGHT SAVINGS SCH 5 TI %
2	2.375	232	92	60
3	3.500	394	174	56
6	6.625	1060	436	59
12	12.750	3805	1207	69

Figure 4- WEIGHT SAVINGS FOR TI PIPING VERSUS CLASS 200 CU-NI PIPING

O.D. Nominal (Inches)	O.D. Actual (Inches)	WALL Nominal (Inches)	WEIGHT Cu-Ni (Lbs/100 Ft)	WEIGHT Grade 2 Ti (Lbs/100 Ft)	WEIGHT SAVED (Lbs/100 Ft) @49.5%
2	2.375	0.109	301	152	149
3	3.500	0.120	493	249	244
4	4.500	0.120	640	323	317
5	5.563	0.134	886	447	439
6	6.625	0.134	1,058	534	524
8	8.625	0.148	1,527	771	757
10	10.750	0.165	2,126	1,073	1,053
12	12.750	0.180	2,754	1,390	1,364

Figure 5- WEIGHT COMPARISONS TITANIUM VERSUS CU-NI SCH 10 PIPE

CU-NI		TITANIUM			
PIPE SIZE	WEIGHT (Lbs/100 ft)	PIPE SIZE	WEIGHT (Lbs/100 ft)	WEIGHT SAVINGS Lbs.	%
4" SCH 10	640	3" SCH 10	249	391	61
6" SCH 10	1,058	5" SCH 10	447	611	58

10" SCH 10	2,126	8" SCH 10	771	1,355	64

Figure 6- WEIGHT SAVINGS

DECREASED WATER VOLUME EFFECT

In addition to the above material weight savings, consideration must also be given to the reduction in the volume of water inside the piping (directly related to the area difference between titanium and Cu-Ni pipe sizes and their varying pipe I.D.'s).

For the example shown, contained water in a 5" SCH 10 titanium pipe is 30% less than that of a 6" SCH 10 Cu-Ni pipe, thus increasing the beneficial weight savings over and above the smaller size and density factors.

Total weight savings <u>per foot of pipe</u> containing water = 10.32 lbs. using titanium (in this example). See Fig. 7 "Weight Comparison - Water Contained Piping" below:

CU-NI	TITANIUM
6" SCH 10 10.58 Lbs/Ft	5" SCH 10 4.47 Lbs/Ft
6.625" O.D.	5.563" O.D.
0.134" WALL	0.134" WALL
6.357" I.D.	5.295" I.D.
31.74 in^2 AREA	22.02 in^2 AREA
Water Volume = 13.76 lbs/ft *	Water Volume = 9.55 lbs/ft *
TOTAL WEIGHT Water Contained Pipe = 24.34 lbs/ft	TOTAL WEIGHT Water Contained Pipe = 14.02 lbs/ft

* @0.4335 lbs/in^2 for 1 foot of water.

Figure 7- WEIGHT COMPARISON (Water Contained Piping)

After approximately nine years of study, the Auxiliary Systems Group of NAVSEA has confirmed these approaches; and during the last few years, the U.S. Navy has designed in the use of titanium pipe systems for both retrofit on existing ships and for firemain and machinery cooling water systems for new LPD-17 shipsets to be contracted for within the next two years.

HEAT TRANSFER COMPARISONS

In 1992, the Rochester Institute of Technology (RIT), Rochester, New York, sponsored by EPRI (Electric Power Research Institute and ESEERCO (Empire State Electric Energy Research Corp.), performed state-of-the-art tests to determine the true values for the thermal conductivities of titanium, stainless steels, and copper alloys. This study has been long overdue as for years the performance of titanium tubed condensers and testing has shown results to have been far above rated capacities. Also, as a result of these tests, it was determined that the differences in the ability to transfer heat among differing metals was based only on the metal resistance due to their thermal conductivities with no differences in any of the other parameters related to metal types.

The Heat Transfer formula ($U = C\sqrt{V}\ x\ F_t\ x\ F_m\ x\ F_c$) developed long ago by the Heat Exchanger Institute (HEI) is based on the following parameters:

U = Overall Heat Transfer Rate (BTU/Hr-Ft^{2}-°F)
C = Diametral tube constant
V = Velocity of water inside the tube (ft/sec)
F_t = Inlet Water Temperature Correction Factor
F_m = Metal Correction Factor
F_c = Cleanliness Factor
(Copper = .85 Stainless and Titanium = .90)

Based on the work done at the Rochester Institute of Technology, comparisons between materials can now be made by using the differences in metal resistance's (through the wall of the tube) of the various metals, all compared against the HEI standard [Admiralty Brass @7/8" X .049" (18 BWG)].

The Thermal Conductivity values developed as a result of this study are shown in Table VI. (The Cu-Ni alloys were either not tested or unchanged.)

TABLE VI			
	BTU/Hr-Ft^{2}-°F/in	K/cm^{2}-Hr-°C/m	% Change
Titanium	150	18.6	+32
Ferritic Stainless	118 118	14.6 14.6	-14 * - 1 *
Austenitic 304 Stainless	104	12.9	- 8
6% Mo Super Austenitic	77	9.5	-19

* Dependent on supplier chemistry.

For relativity, the Thermal Conductivity values for 90-10 Cu-Ni are 348 BTU/Hr-Ft^{2}-°F/in (43.2 K/cm^{2}-Hr-°C/m) and 70-30 Cu-Ni at 204 BTU/Hr-Ft^{2}-°F/in (25.3 K/cm^{2}-Hr-°C/m).

Calculations of U -- the overall Heat Transfer Rate -- indicate titanium versus the Cu/Ni alloys to be very close to or better in overall heat transfer performance due to lighter walls and a higher cleanliness factor. Against all stainless steels, titanium has higher heat transfer rates due to lighter walls and higher Thermal Conductivity (BTU/Hr-Ft^{2}-°F/in) values.

Results of typical comparisons (using the Resistance Method) between titanium versus stainless steels and a Cu/Ni alloy in real situations are shown in Table VII. This comparison would be typical of tubing for condensers or general heat exchanger service.

Due to the thinner walls for titanium, the area of the I.D. is increased which lowers the velocity at constant pump pressure and reduces the effective gain in heat transfer. By maintaining a constant velocity, however, heat transfer can be increased significantly. [Note both conditions in the first comparison.]

TABLE VII					
Comparison Materials	Size	V	Inlet Temp	U (BTU/Hr-Ft^2-°F)	Titanium (Gain/Loss)
90/10 Copper/Nickel	7/8" X .049"	7.0	65°F	544	
Titanium	7/8" X .028"	6.3	65°F	533	(-1.9%)
Titanium	7/8" X .028"	7.0	65°F	560	+3.0%
6% Mo Super Austenitics	1" X .028"	7.5	70°F	531	
	1" X .028"	7.5	70°F	595	+12.0%
Ferritic Stainless	1" X .035"	7.0	65°F	598	
Titanium	1" X .028"	7.0	65°F	643	+7.4%

The Comparison of Heat Transfer Rates by the Resistance Method for Titanium versus 90/10 Cu/Ni in condenser service is shown in the example indicated in Fig. 8.

The Comparison of Heat Transfer Rates for Titanium versus 70/30 Cu/Ni in condenser service is shown in the example indicated as Fig. 9 and Titanium versus 316 Stainless Steel as Fig. 10.

1.000" x .028" (22 BWG)			**1.000" x .028" (22 BWG)**	
TIMETAL 50A		U' = C x sq.root V x Ft	316 S.S.	
$263\sqrt{7.0}\ (.97)$ =	675.0 =	U' (BTU/hr. sq.ft. deg.F)	= $263\sqrt{7.0}\ (.97)$ =	675.0
1/675.0 =	0.00148157 =	R'	= 1/675.0 =	0.00148157
-	0.00006767 =	7/8 X 18 BWG ADMIRALTY	= -	0.00006767
	0.00141391 =	REMAINING RESISTANCE	=	0.00141391
+	0.00019210 =	TIMETAL 50A 316 S.S.	= +	0.00030331
	0.00160601 =	R"	= =	0.00171722
	622.7 =	U"	= =	582.3
622.7 X .90 =	560.4 =	U CLEAN SERVICE	= 582.3 X 0.90 =	524.1
		REDUCTION IN SERVICE RATE =		**-6.9%**

1.000" x .028" (22 BWG)			1.000 " x .050" (18 BWG)	
TIMETAL 50A		U' = C x sq.root V x Ft	90/10 CU/NI	
263$\sqrt{6.36}$ (.968)	642.2	U' (BTU/hr. sq.ft. deg.F)	263$\sqrt{7.00}$ (.968)	673.6
1/642.2	0.00155722	R'	1/673.6	0.00148464
	- 0.00006767	7/8 X 18 BWG ADMIRALTY		- 0.00006767
	0.00148955	REMAINING RESISTANCE		0.00141697
	+ 0.00019210	TIMETAL 50A 90/10 CU/NI		+ 0.00015143
	0.00168165	R"		0.00156840
	594.7	U"		637.6
594.7 X .90	535.2	U CLEAN SERVICE	637.6 X 0.85	542.0
	-1.2%	**REDUCTION IN SERVICE RATE**		

1.000" x .028" (22 BWG)		VELOCITY CONSTANT	1.000 " x .050" (18 BWG)	
TIMETAL 50A		U' = C x sq.root V x Ft	90/10 CU/NI	
263$\sqrt{7.00}$ (.968)	673.6	U' (BTU/hr. sq.ft. deg.F)	263$\sqrt{7.00}$ (.968)	673.6
1/673.6	0.00148464	R'	1/673.6	0.00148464
	- 0.00006767	7/8 X 18 BWG ADMIRALTY		- 0.00006767
	0.00141697	REMAINING RESISTANCE		0.00141697
	+ 0.00019210	TIMETAL 50A 90/10 CU/NI		+ 0.00015143
	0.00160907	R"		0.00156840
	621.5	U"		637.6
621.5 X .90	559.3	U CLEAN SERVICE	637.6 X 0.85	542.0
		REDUCTION IN SERVICE RATE		**-3.1%**

Figure 8- Comparison of Heat Transfer Rates for Titanium and 90/10 CuNi

1.000" x .028" (22 BWG)				1.000" x .049" (18 BWG)
TIMETAL 50A		U' = C x sq.root V x Ft	70 - 30 CU - NI	
263√5.934 (1.05) =	672.72 =	U' (BTU/hr. sq.ft. deg.F)	= 263√6.500 (1.05) =	704.05
1/672.72 =	0.00148650 =	R'	= 1/704.05 =	0.00142036
	- 0.00006767 =	7/8 X 18 BWG ADMIRALTY	=	- 0.00006767
	0.00141883 =	REMAINING RESISTANCE	=	0.00135269
	+ 0.00019210 =	TIMETAL 50A 70 - 30 CU - NI	=	+ 0.00025280
	0.00161093 =	R"	=	0.00160549
	620.8 =	U"	=	622.9
620.8 X .90 =	558.7 =	U CLEAN SERVICE	= 622.9 X .85 =	529.4
		REDUCTION IN SERVICE RATE	=	**-5.2%**

1.000" x .028" (22 BWG)		VELOCITY CONSTANT		1.000" x .049" (18 BWG)
TIMETAL 50A		U' = C x sq.root V x Ft	70 - 30 CU - NI	
263√6.500 (1.05) =	704.05 =	U' (BTU/hr. sq.ft. deg.F)	= 263√6.500 (1.05) =	704.05
1/704.05 =	0.00142036 =	R'	= 1/704.05 =	0.00142036
	- 0.00006767 =	7/8 X 18 BWG ADMIRALTY	=	- 0.00006767
	0.00135269 =	REMAINING RESISTANCE	=	0.00135269
	+ 0.00019210 =	TIMETAL 50A 70 - 30 CU - NI	=	+ 0.00025280
	0.00154479 =	R"	=	0.00160549
	647.3 =	U"	=	622.9
647.3 X .90 =	582.6 =	U CLEAN SERVICE	= 622.9 X .85 =	529.4
		REDUCTION IN SERVICE RATE	=	**-9.1%**

Figure 9- Comparison of Heat Transfer Rates for Titanium and 70/30 CuNi

The Resistance Method calculates "U" as: $U = C \times \sqrt{V} \times F_t$

In the examples above (Figs. 8-10):

- For 7/8" - 1" O.D. C = 263 (per H.E.I.)
- The baseline V is taken as that for either Cu/Ni or S.S. For the same tube sizes, V is identical in comparisons. For thinner wall comparisons, V is lower due to the Area Difference for flow (larger Area = lower Velocity).
- For assumed Inlet Water Temperatures of 65°F (Fig. 8 and Fig. 10), $F_t = .97$.
  For 80°F (Fig. 9), $F_t = 1.05$.
- The Metal Resistance r_m for the standard - 7/8" O.D. X 18 BWG (.049" wall) Admiralty is 0.00006767.
- The Metal Resistances of 1" O.D. X .028" wall titanium is 0.00019210 (*TIMETAL*®50A = Grade 2 titanium).

In determining Metal Resistances for any metal, the following formulas are used. (See Fig. 11 below.)

Metal Resistance $r_m = \dfrac{1}{BTU/hr\text{-}ft^2\text{-}°F} = \dfrac{1}{U}$

With U unknown $r_m = \dfrac{w \times d_o}{K \times d_m}$ $d_m = \dfrac{d_o - d_i}{\ln(d_o - d_o)}$

w = Tube Wall Thickness (inches)
d_o = Tube O.D. (inches)
d_i = Tube I.D. (inches)
K = Tube metal thermal conductivity (BTU/hr-ft^2-°F/inch)
$\ln$ = Natural Logarithm

Figure 11- METAL RESISTANCE EQUATIONS

In each example the effect of keeping the velocity constant is shown to drive the heat transfer rate more in favor of titanium. It is interesting to note that in cases where 70/30 Cu/Ni has been used to replace 90/10 Cu/Ni (in possibly trying to affect added corrosion resistance), corrosion aside, the heat transfer for 70/30 Cu/Ni is less than titanium's thinner wall substitute tube even at lower velocities. Again, where velocities can be increased even higher heat transfer rates can be attained.

Replacements with titanium tubes affect a virtual corrosion free system having only a slight loss to an actual gain in heat transfer in heat exchanger service when compared against Cu/Ni; and always a gain when compared against stainless steels. The net effect in substitution with titanium tubing would be heat exchanger systems with essentially the same heat transfer rate and/or size to potentially smaller units and/or higher heat transfer rates (where stainless steel tubes are currently in place). In all cases, however, weight would be reduced.

APPLICATIONS

Many areas currently exist where titanium is used aboard ship as heat exchanger tubing. A list of several of these applications along with several applications on offshore (oil) platforms which may have relevance to additional potentials for on-board sea service is shown in Fig. 12.

SHIPBOARD

- Ship service turbine generator condenser (S/T)
- Racer steam condenser (S/T)
- Radar electronic cooler (S/T and P/F)
- De-Salination Units (S/T)
- Other electronic coolers (P/F)
- Air conditioning freon condenser (S/T)
- Distillation unit brine heater and preheater (P/F and S/T)
- Lube oil and engine jacket coolers for TAO oilers (P/F)
- Low pressure air compressor cooler (S/T)

OFFSHORE

- Lube oil cooler (S/T)
- Engine jacket cooler (P/F)
- Compressor cooler (P/F)
- Central exchanger (P/F)
- Direct low pressure crude oil service cooler (P/F)
- Discharge cooler (S/T)
- Quench water cooler (S/T)
- Propane condenser (S/T)
- Gas Dehydrator cooler (S/T)
- Natural gas cooler (S/T)
- Glycol cooler (S/T)
- Flash gas compressor
- Intercooler (S/T)
- Interstage oil cooler (S/T)

P/F = Plate/Frame Exchanger
S/T = Shell/Tube Exchanger

Figure 12- **TITANIUM HEAT EXCHANGER APPLICATIONS ON NAVY SHIPS AND OFFSHORE PLATFORMS**

Areas that are being considered or would be ideal candidates for titanium pipe for shipboard sea service are indicated in Fig. 13.

Firemain Systems
Seawater Ballast Systems
Aegis Radar Cooling Water Systems
Oily Waste Systems
Deck Draining Systems
Magazine Sprinkling Systems
HVAC (Ducting)
Seawater Service System
Feedwater to Distilling Plants
Seawater Compensated Fuel Oil Systems
Bilges
Countermeasure Washdown Piping
Missile Deluge Systems
Stanchions

Figure 13- TITANIUM APPLICATIONS FOR SHIPBOARD PIPING

In addition to pipe and tubing of C.P. Grade 2, there are other titanium alloys being used or considered for many other shipboard applications; i.e., Grade 9--3Al-2.5Va strip for uptakes in DDG-51 destroyers, while other alloys are being tested and proven for other uses; i.e., Near-Alpha Alloy for fastener stock. Also, other forms of C.P. Grade 2, etc., such as bar, plate, and sheet are available for numerous other potentials.

SUMMARY

In terms of corrosion immunity for marine service, titanium is unsurpassed. Coupled with its low density, high strength/weight ratio, and erosion resistance, titanium offers unexcelled performance in terms of service life, weight savings, and reduced maintenance costs for the marine design engineer. Titanium provides the necessary and desired solution to problems that have traditionally plagued sea water applications. It is and will continue to be the prime candidate material in these harsh water environments.

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CRITICAL DESIGN ASPECTS OF DYNAMIC TITANIUM ALLOY RISERS

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ABSTRACT

Titanium alloys offer a unique, attractive combination of physical, mechanical, and corrosion properties for design of dynamic, compliant offshore risers. The Ti-6A1-4V ELI alloy, in a beta-transformed condition and with minor ruthenium or palladium additions for chloride resistance above 80°C, represent logical "base-case" metallic materials for compliant risers. All of the technology and components needed to produce a complete, viable titanium alloy compliant riser system, including pipe, termination designs, joining methods, and coatings are available, and are reviewed in this paper.

INTRODUCTION

Offshore oil and gas production has entered a new phase of development recently typified by increasing water depths, often in association with high product temperatures and pressures. This is particularly true in the Gulf of Mexico and Norwegian sectors of the North Sea. Economic exploitation of these new areas has been made possible by the use of floating production systems mainly based on tanker-like vessels or semi-submersible platforms. Such floating structures require production and export riser systems compliant enough to cope with the motions of the platform in extreme environmental conditions while remaining connected to the subsea production system. This entails a compliant or "dynamic" riser system.

Traditional flexible risers comprising a composite of steel reinforced, non-bonded elastomer/polymer layers have been used in catenary configurations for several years as compliant riser systems. However, as water depth increases stiffer materials can be used as a viable, economic alternative to flexible piping. Secondly, current flexible risers have difficulty coping with temperatures exceeding 100°C, and several failures have even been reported in the Norwegian Sector at temperatures below 100°C.

These factors have led to a growing interest in developing alternatives to flexible piping, of which titanium alloy tubulars are technically and economically the correct choice for many applications.

REQUIREMENTS OF DYNAMIC RISER MATERIALS

In selecting materials for compliant risers, there are certain key design attributes to be considered, as listed below. These attributes are not in order of importance since their relative significance can vary with a particular application and are often interrelated.

- Strength: Strength is critical in minimizing the material required for pressure containment since it is the deciding factor for determination of wall thickness for most of the length of a given riser. As water depth increases, it also contributes to collapse resistance when a riser is depressurized.
- Flexibility: Platform motions are accommodated by bending of the riser. Therefore, low stiffness accommodates these motions without generating high bending moments.
- Weight: It may be thought at first consideration that light weight would be an obvious advantage to a riser system in reducing hang-off loads on the platform, minimizing use of added buoyancy and reducing stress in the riser due to weight loading. In practice, a certain amount of weight is required to control the shape and dynamic response of the riser. It is particularly important to keep a relatively high axial tensile load in the section of riser from immediately below the platform to well below the water surface. However, lightweight is still an advantage overall in that weight can be added as and where required to adjust the dynamic response of the riser.
- Seawater Corrosion Resistance: A material that is inherently corrosion resistant to seawater and the marine environment does not require an external corrosion protection system or corrosion allowances on wall thickness.
- Resistance to Well Fluids: More fields are being developed which exhibit hotter, higher pressure and, often, more sour well flows.
- Pressure Integrity: Metal risers can be made absolutely pressure tight and will not suffer gas permeation.
- Durability: Metals do not suffer from chemical aging or property degradation with time. Risers also require a material that has a good fatigue life and fatigue crack propagation characteristics in seawater, as well as high fracture toughness for high damage tolerance.
- Inspectability: Risers produced from a single metal are readily inspectable both during manufacture using established NDT techniques, and in service using intelligent pigs.
- Availability: Any material proposed for riser use must be available in the quantities required within a project time scale. This entails high volume production methods using proven, consistent processes, along with proven techniques of welding where required. It is also an advantage, from the oil producer's point of view, that the material be standardized to maintain competition among suppliers.

OVERVIEW OF RISER MATERIAL TYPES

Currently, compliant risers in service are made from either reinforced flexible piping (bonded and non-bonded types) or steel tubulars.

Historically, flexible piping has been the material of choice for dynamic risers. This is because modest water depths in which fields have previously been developed using catenary moored platforms put a severe requirement for flexibility on the pipe: a typical flexible production riser will have a minimum bend radius of about 2 to 3 meters. The small bend radius also makes flexible piping easy to install since it can be laid from a reel. These flexible risers have given satisfactory service in moderate water depths (100 to 300 meters) and at low well temperatures, and are inherently thermally insulated. Primary disadvantages of flexibles are their heaviness, which limits their potential for deep-water use where their self-weight becomes a design issue, and their very high cost. As well fluid temperatures have risen towards 100^0C, problems have been encountered with the materials of construction in flexible piping, and service failures have been reported in the Norwegian Sector over the past few years. The multitude of materials and complex construction involved make the effects of fatigue, aging and gas permeation extremely difficult to predict, and it has been stated[1] that "established procedures for fatigue design are lacking" for this type of riser. Furthermore, the complex wall construction practically precludes inspection by conventional means although considerable work continues to be aimed at developing inspection methods for in-service monitoring.

A compliant steel riser was first installed by Shell in the Auger field in the Gulf of Mexico. The water depth is 870 meters and the riser is attached to a tension leg platform (TLP). The large water depth, together with the restrained motions of a large TLP, enabled steel with its high elastic modulus, to be used. Pipeline steel, for example API 5L-X65, is a very cheap material for dynamic risers where it can be used. It is also lighter (typically half the weight) than flexible piping of equivalent size and pressure rating. For many applications, however, steel is too stiff to consider. Furthermore, well fluids may dictate the use of more exotic (high Cr + Mo) steels, such as super-duplex stainless steels eroding the price advantage of steel.

Consideration of the limitations of riser materials described above has led to an interest in developing riser designs using alternative materials. The two main materials of interest are composites (fiber-reinforced plastics) and titanium alloys. Neither of these materials are new: only the application is new. Composites for risers are in an early stage of development and will not be discussed here.

Titanium alloys are obvious contenders for dynamic risers, possessing all the positive attributes listed in the prior section. Particularly attractive qualities as a riser material include their lower density and elastic modulus (both about half that of steel), elevated strength-to-density and strength-to-modulus ratios for enhanced flexibility and lighter weight, and their exceptional resistance to both seawater and produced well fluids[2,3].

The foregoing brief review indicates there are gaps in the market that are not satisfied by either flexible piping or steel tubulars. It is these where titanium alloys, in addition to being competitive with other riser materials in many applications, may provide the only solution. Just where titanium alloys can be most profitably employed needs to be assessed on a case by case basis. However, it can be stated that for typical (15-25 cm) production risers, titanium alloys can operate successfully in water depths of more than 250 meters. Berge et al[4] studied free hanging risers from a catenary moored platform in water depths from 300 to 2000 meters and found that steel risers were not feasible. Titanium alloys, on the other hand, provided a satisfactory solution with the added advantage of less than half the hang-off load on the platform compared to steel for most of the cases studied.

TITANIUM ALLOY SELECTION FOR RISERS

The family of commercially available titanium alloys can be simply categorized into three fundamental types: alpha, alpha-beta, and beta alloys. The alpha alloys primarily include the unalloyed (commercially pure) alloys, which are on the low side in strength; and some medium strength (all-alpha or near-alpha phase) alloys primarily containing aluminum and/or tin or zirconium, along with minor amounts of vanadium and/or molybdenum. With increased beta stabilizing element additions (e.g., V, Mo, Cr) and higher alpha stabilizing element content (e.g., Al), alpha-beta titanium alloys exhibit medium to high strength derived from higher alloy content and their duplex phase structure. The beta and near-beta alloys offer moderate to elevated strengths derived from a high beta stabilizer content as well as age-hardenability in most cases. Some common commercial titanium alloys offering a yield strength above 450 MPa which may be considered for offshore riser applications are listed in Table 1.

Titanium alloy characteristics and properties are generally highly dependent on alloy composition, phase type and volume function, and grain size and morphology. As a result, these three basic types of titanium alloys exhibit significant differences in many engineering properties and attributes. A relative comparison of engineering attributes of these titanium alloy types that are relevant to offshore riser application is presented in Table 2. For dynamic riser application, it is desirable to have the first three attributes (i.e., density, modulus, and cost) rated toward the "lower" side and all the remaining attributes listed rated toward the "higher" side. Based on the selection criterion, it is logical to focus on alpha-beta alloys as the most attractive initial candidates for consideration in riser application.

Attributes of Alpha-Beta Alloys

As Table 2 suggests, the commercial alpha-beta alloys offer the desirable synergistic combination of lower density and medium to high strength (i.e., elevated strength-to-density ratio), high S-N fatigue life and fracture toughness, excellent fabricability (including weldability) and producibility in basic product forms, at a minimum cost premium. Due to their duplex phase structure, mechanical and physical properties can be widely varied and controlled via microstructure development (i.e., thermomechanical processing). This permits achievement of a more favorable balance in alloy tensile and fatigues strength, ductility, and fracture resistance for a given application.

The highest volume, most readily available commercial titanium alloy falls within this alloy group: the Ti-6Al-4V alloy (Grade 5 titanium). As the historical titanium alloy leader in the aerospace industry, this alloy has been most-widely studied and characterized, offering an extensive metallurgical property database for design of critical offshore components. With the aim to maximize riser damage tolerance, weld joint properties, ductility, and fracture resistance in air and aqueous chloride environments, it is logical to specifically focus on the extra-low-interstitial (ELI) version of the Ti-6Al-4V alloy (i.e., Grade 23 titanium). The fracture resistance of this alloy (K_{1c} (air), K_{1scc} (saltwater), and fatigue crack growth resistance) can be further optimized by beta-processing and/or beta-annealing to produce a fully transformed beta microstructure[3,5]. The synergistic influence of the ELI formulation and a beta-transformed microstructure on Ti-6Al-4V alloy fracture toughness in air and saltwater is indicated in Fig. 2.

Base-Case Riser Alloy

Based on the foregoing considerations, the following base-case titanium riser alloys are selected:

	ASTM Grade	UNS No.	Nominal Composition
Ti-6Al-4V (ELI)	23	R56401	TI-6Al-4V (0.13% max. O)
TI-6Al-4V-Pd (ELI)	*	--	Ti-6Al-4V-0.06Pd(0.13%max.O)
Ti-6Al-4V-Ru (ELI)**	29	R56404	TI-6Al-4V-0.1Ru (0.13% max. O)

*A modified lower oxygen (ELI) version of ASTM Gr. 24 titanium.
**Currently pending approval under NACE MR-01-75 Standard for sour service use.

Riser components in these alloys should be specified in the fully beta-transformed microstructural condition for maximum resistance to fracture and fatigue crack growth in air and seawater. As discussed in the following sections, the minor ruthenium or palladium alloy additions enhance resistance to chloride crevice and stress corrosion in seawater and produced fluids when metal temperatures exceed ~80^0C.

Typical properties of Ti-6-4 ELI and Ti-6-4-Ru/Pd alloy products in the beta-transformed condition are presented in Table 3. Note that the minor addition of ruthenium or palladium does not significantly influence the mechanical or physical properties of the alloy. It should also be recognized that one can expect a wide range in ductility values depending on alloy product/component size and form. For example, the heavier section forgings (i.e., flanges, stress taper joints) and joint weldments will naturally exhibit lower elongation and reduction in area values than thinner section tubulars with more refined grain structures. As a result, specified ductility minimums will vary depending on product form.

ENVIRONMENTAL RESISTANCE

Offshore risers must resist a multitude of corrosive environments in service which include seawater on OD surfaces, and produced fluids and various workover fluids on ID surfaces, at maximum well temperatures. The incentive for utilizing titanium alloys is predicated on its superior resistance to all these diverse corrosive conditions.

Seawater Resistance

Titanium alloys are virtually immune to almost all forms of corrosion attack in ambient seawater, as indicated in Table 4. This exemplary resistance stems from the formation of an extremely thin, but highly stable, chemically resistant, and highly adherent and protective titanium oxide surface film[2,3]. This oxide film (primarily TiO_2), forms spontaneously and instantly when fresh metal surfaces are exposed to air, water, seawater, or brines, even when fully deaerated. Requiring mere traces of moisture or oxygen, a mechanically damaged oxide film can reheal/repair itself instantaneously in air, hydrocarbon fluids, and seawater.

Like wrought base metal, the same oxide-filmed weldments, heat-affected zones, and castings of titanium alloys exhibit full passivity and near-nil corrosion rates in seawater up to at least 250^{0}C. This thin, but hard, abrasion-resistant, and rehealable oxide surface film also accounts for the superior resistance of titanium alloys to erosion-corrosion and cavitation in flowing, turbulent seawater and brines[3].

Localized Corrosion Resistance. Stemming from their exceptionally high anodic pitting and repassivation potentials in aqueous chlorides, there is no concern for chloride pitting attack on titanium alloys. Although titanium alloys also resist crevice corrosion at low and near-ambient seawater temperatures, chloride crevice attack may be possible in higher temperature seawater and brines if severe crevices (i.e., flange-to-gasket or under-salt deposit crevices) exist. The threshold crevice temperature for titanium alloys in aerated seawater lies in the range of 75 to 85^{0}C[2,3]. When component metal surfaces in seawater exceed temperatures of ~80^{o}C, selection of more crevice-resistant titanium alloy grades is recommended. These resistant alloys include Ru-enhanced (0.08% Ru min.) or Pd-enhanced (0.04% Pd min.) titanium alloys such as Ti Grades 18, 24, 28, and 29 (see Table 1) and/or any alloys containing ≥3.5 wt.% molybdenum[3]. The benefits of Ru or Pd alloy additions are well documented[6,7,8], significantly raising crevice threshold temperatures of base and weld metal to at least 250^{0}C even in acidic chloride brines as shown in Fig. 3.

Fracture Resistance. The alpha-beta titanium alloys, such as the Ti-6A1-4V-based alloys listed in Table 1, are fully resistant to chloride stress corrosion (SCC) in smooth and notched component configurations[5]. However, these higher strength alloys may exhibit some degree of SCC susceptibility in seawater when cracks exist under high tensile stress (i.e., high stress intensity factors). This manifests itself as a reduction in seawater fracture toughness (i.e., K_{1scc} compared to air values (i.e., K_{1c},), and slightly increased crack growth rates. The degree of susceptibility depends on numerous factors[5], which primarily include alloy composition, microstructure, and crystallographic texture.

As indicated previously in Fig. 2, air and seawater fracture toughness (i.e., K_{1scc}) can be maximized by; 1) limiting alloy interstitial (O, N, C) and aluminum content to utilize ELI alloy grades; and 2) process alpha-beta alloy products to achieve fully beta-transformed microstructures, and not conventional equiaxed alpha-beta structures. Fortunately, Ti-6Al-4V alloy weldment microstructures are also inherently beta-transformed, even after typical stress relief anneal treatments, and, therefore, weld metal fracture toughness equals or exceeds that of wrought base metal.

Fatigue Resistance. Titanium alloys exhibit smooth S-N fatigue endurance limits, which generally fall in the range of 50-60% of alloy ultimate tensile strength. Unlike many other engineering alloys which suffer serious corrosion fatigue, air endurance limits for Ti-6Al-4V and most titanium alloys show very little (below 12%) reduction in seawater and other chloride media[3,9,10] (see Fig. 4). S-N fatigue strength tends to follow its relationship with tensile strength as temperature increases based on limited data on Ti-6Al-4V to date. Current testing is focused on further defining S-N fatigue behavior of Ti-6Al-4V-Ru alloy welded pipe joints in seawater up to 150°C. Since welded joints may be the "weakest" link in a catenary riser with respect to fatigue design life, it is paramount that weldments be produced with minimal defects and acceptable quality, exhibit no severe surface stress risers, be well stress-relief annealed, and be rigorously inspected.

Fatigue crack growth (FCG) rate in the Ti-6Al-4V-based alloys have been extensively studied in air and saltwater at ambient temperature[3,11,12,13]. As with fracture toughness, FCG resistance in Ti-6Al-4V is significantly enhanced in the ELI grade, particularly in the fully beta-transformed condition (such as in weldments). Highest threshold ΔK (ΔK_{TH}) values, and lowest Stage 1 and 2 FCG rates are obtained in air and seawater in this alloy condition. Below ΔK values of ~10 MPa √m, near-threshold cracking behavior appears to be rather insensitive to environmental effects even at low frequencies, and is similar to that of carbon steel. ΔK_{TH} values for Ti-6Al-4V decrease with R-ratio and are also very comparable to those of carbon steel[3]. Closure-corrected ΔK_{TH} values generally fall into the range of 2.0-3.6 MPa √m in ambient seawater. Although Stage 2 cracking rates (i.e., ΔK above ~12-15 MPa √m) may be somewhat higher than those of steel in seawater[3], crack growth does not appear to be detrimentally affected by impressed cathodic potentials as negative as -1.1 volts (vs. Ag/AgCl ref.). Current testing is aimed at defining Stage 1 and 2 FCG behavior of Ti-6Al-4V-Ru alloy welded pipe joints in aerated seawater as high as 150°C.

Resistance to Hydrogen. The oxide film on titanium alloy surfaces serves as a highly effective barrier to both molecular and atomic hydrogen that contacts metal surfaces. As a result, no significant hydrogen absorption occurs in titanium alloys normally exposed to seawater, even at higher temperatures. However, significant, continued hydrogen absorption may be possible when titanium components are cathodically charged for extended periods at potentials negative to -0.8 volts (vs. Ag/AgCl ref.) in ambient seawater[3]. The subsequent penetration and accumulation of absorbed hydrogen could eventually form Ti hydride phase and embrittle the component, depending on alloy type and condition. As beta phase volume fracture increases, the solubility and tolerance for hydrogen dramatically increase in the alloy. Therefore, tolerance to absorbed hydrogen damage in titanium alloy types increases as follows: beta > alpha-beta > alpha.

Titanium alloy risers will normally be in direct electrical contact with steel platform hulls and/or subsea wellheads in seawater, which are cathodically-protected via attached activated Al/Zn anodes providing a sustained cathodic potential of around -1.05 volts. Computer modeling of the cathodic potential field along a typical deep-water titanium alloy riser[14] suggests that steady-state potentials remain negative to -900 mV (vs. Ag/AgCl ref.) over the full riser length. Therefore, lacking relevant long-term cathodic charging exposure data for Ti riser alloys in seawater, a highly conservative and safe approach at this time is to assume that long-term hydrogen embrittlement of these alloys will occur, and that preventative measures must be incorporated into titanium riser design.

Depending on the specific riser component and application, long-term hydrogen damage to titanium alloy components can be practically and effectively prevented by one of two basic design strategies:

1) Electrically isolate the titanium alloy component from cathodic steel structures via insulating terminal flanges or couplings. Electrical isolation in flanges is achievable using commercially available

insulating flange gaskets and flange bolt sleeve/washer kits. Monoblock- or (monolithic-) type titanium-to-steel transition insulating flanges are also commercially available.

or 2) Apply insulating OD surface coatings or bonded sheathing of proven, seawater-resistant polymers.

Resistance to Produced Fluids

As indicated in Table 5, titanium alloys are also extremely resistant to all constituents in produced well fluids including all hydrocarbons, acidic gases (CO_2 and H_2S), elemental sulfur, organic acids, and sweet and sour chloride brines to temperatures as high as 260°C. Owing to the surface oxide film, near-nil corrosion rates and total pitting resistance can be expected even under fully-deaerated, highly-sour well environments at elevated temperatures and gas pressures. These alloys are all fully resistant to sulfide stress corrosion cracking even at elevated H_2S pressures, and the Ti-6A1-4V-Ru alloy is pending approval in the NACE MR-01-75 Standard for sour service use. However, three aspects of alloy corrosion performance should be considered when metal surface temperatures exceed ~75°C: crevice and stress corrosion cracking (SCC) resistance, and galvanic hydrogen absorption.

Avoidance of possible chloride crevice corrosion in sweet or sour brines is simply achieved by selecting any of the Ru-or Pd-enhanced titanium alloys (Ti Grades 18, 24, 28, and 29) as indicated in Table 5, and/or an alloy containing at least 3.5 wt.% molybdenum. These Ru- or Pd- additions to the Ti-6A1-4V alloy also enhance SCC resistance in hot brines. Extensive slow-strain-rate and C-ring SCC testing in low-pH, sour chloride-rich brines[6,7,8] has demonstrated that the Grade 24 and 29 titanium alloys resist SCC as high as 250°C, as shown in Fig. 3.

Galvanic hydrogen absorption and embrittlement of titanium alloys are possible when the (noble) titanium component is galvanically-coupled to an active metal (i.e., carbon steel or active stainless steel) in a hot, sour aqueous electrolyte (i.e., sour brine). This concern is readily addressed by electrically-isolating Ti alloys from active metals, or interfacing titanium components with more resistant and galvanically-compatible alloys, such as Ni-Cr-Mo or other Ti alloys. Galvanic hydrogen is not a concern in a hot sour hydrocarbon stream when little or no aqueous phase (no continuous electrolyte) is present.

Resistance to Workover Fluids

Titanium alloy riser components may also be periodically exposed to various well workover fluids. As indicated in Table 6, exposure of titanium alloys to hydrofluoric acid mixtures should be avoided in all cases due to rapid metal dissolution. Alternative acidizing solutions include 10-12 wt.% HCl solutions inhibited with appropriate oxidizing species (e.g. , 1% sodium molybdate), or uninhibited organic acids (e.g., 10% acetic or formic acids).

Methanol injected downhole to dissolve hydrates must contain at least 2.5-3.0 wt.% water to prevent stress corrosion cracking of titanium alloy components. Anhydrous methanol grades must be avoided, or water (or seawater) should be mixed in prior to injection. Commercially available, grades of methanol which contain 3-30 wt.% water are recommended as effective, more fire-safe solvents for hydrate dissolution which are compatible with titanium components.

MANUFACTURE OF TITANIUM ALLOY RISER COMPONENTS

Titanium alloy tubulars can be manufactured to ASTM B337, B861, or B862 Specifications via three basic processes: 1) break-form and seam-weld, 2) hot extrusion, and 3) hot pipe rolling (i.e., rotary-piercing or press-piercing). Selection of the most appropriate process will depend on required tubular dimensions (OD, wall, and/or length), alloy type, required properties, cost, size of job, and/or production rate/schedule. The break-form and seam-weld process is limited to only the cold-formable, lower-strength alpha or alpha-beta alloys, or certain beta alloys when formed in the solution-annealed condition. Pipe length and wall thickness (<25 mm) are limited by press size/capacity. Lower and higher strength titanium alloys can be hot extruded in sizes up to 92 cm OD and 51 mm wall, in lengths up to 12 m length. This lower yielding process is favored for heavier walled components, and smaller quantity orders.

A quantum leap toward increasing tubular production rate and reducing unit cost has been achieved for large quantity orders (such as riser strings) using hot rolling processes. These high production rate, high yield (near-net shape) rotary-pierce and press-pierce processes typically used for steel can successfully produce Ti-3A1-2.5V- and Ti-6A1-4V-based alloy tubulars in sizes up to 66 cm OD, 25 mm wall, and 12 m lengths.

Flanges, taper stress joints, and other heavier-section components are readily hot forged in air by conventional means, annealed, and surface conditioned.

DESIGN CONSIDERATIONS

Obviously the vast majority of the length of a riser is simply pipe, sized to retain the pressure of the contents and resist buckling from bending and external pressure. The demanding part of riser design lies in configuring the overall system to withstand dynamic loading, and detail design of components (such as connections) to ensure a safe and economic design.

System Configuration

Titanium risers can be designed in the same configurations previously used for flexible risers (Steep 'S', Lazy 'S' etc). There are various attributes of titanium of which the designer/analyst should be aware in order to get the most advantageous configuration.

- Various configurations in use for flexible hose can be achieved in titanium by the application of weight and buoyancy over discrete lengths of the riser. As titanium risers are very light compared with both steel and flexible pipe, there is a greater freedom in choosing how to distribute the weight.

  A recent case studied by RMI and Seanor a.s. (Norway) is illustrated in Fig. 5. It is interesting to note that when the production was shut-in and the riser and pipeline depressurized, gas separated from the oil and migrated to the riser. Sections of the 286 mm ID x 13 mm wall riser, in spite of the added weight, became buoyant and the configuration changed radically as shown in Fig. 6. It should be noted that in this case analysis showed that the riser performed perfectly adequately despite this dramatic change of configuration.
- Titanium alloy riser pipe can be pre-bent using induction-bending techniques to give configurations, which improve the compliance of the system. A good example of this is the early configurations proposed for Norsk Hydro's Visund Field, as illustrated in Fig. 7, where the platform is located over the wells enabling them to be drilled and completed from the platform. This gave rise to a requirement to allow the platform to be moved off station in the case of a blowout whilst remaining connected to the riser system. Originally the risers were sized at 178 mm bore and the large horizontal excursion could only be accommodated by prebending sections of the riser to a 25 meter radius. In fact, the riser bore was subsequently reduced to 152 mm for titanium (this was possible due to the low friction of the smooth bore and titanium's resistance to flow erosion) which obviated the requirement for pre-bending.
- Platform end connections have a much greater influence on the global behavior of a titanium riser than an equivalent flexible hose and it is, therefore, necessary to account for the stiffness of such connections early in the configuration.
- Titanium risers frequently require coatings on the outside for reasons discussed below. Such coatings can substantially increase the drag diameter and therefore must be defined before undertaking a dynamic analysis.

Subsea Termination

For most riser configurations the subsea riser termination is fairly straightforward in that it can be located at some location along the flowline away from the bending loads in the sag-bend section of the riser. As there are no fatigue loads in this section, current pipeline connection technology can be used without the need for extensive proof of fitness for purpose.

It might also be required that electrical isolation is provided where dissimilar metals are joined (galvanic couples) or for protection of the riser against the effects of a cathodic protection system. The riser can be joined to the flowline by an isolating flange such as that illustrated in Fig. 8. The isolating gasket can be a Pikotek®-brand Flowlock-VCS gasket, comprised of a sandwich of a titanium metal core and glass fiber-reinforced polymer layers with a spring-energized PTFE seal[15]. Selection of the appropriate glass-filled polymer permits application as high as 150°C and 1030 bar. Bolt sleeve and washer kits in these glass-filled polymers are also available to complete flange isolation. These gaskets and bolt isolation kits were developed for petrochemical use, principally on ANSI flanges. Some points to note when using them with titanium alloy flanges include:

- Titanium alloy bolts might be used so that their superior strength enables a more compact and, therefore, cheaper flange which places a greater bearing stress on the washers than in normal use. This raises concern for creep deformation of insulating polymeric washers, and resulting loss of preload in flange bolts. This can be overcome by using noncompressible, insulating washers (e.g., ceramics).
- The gaskets have spring-activated fluoropolymer seals and have been used up to 150°C. However, at temperatures higher than this, or with high CO_2 concentrations, there is a question over the suitability of such material.

Alternatively, various commercial monolithic (or "monoblock") isolation joints for connecting carbon steel to duplex stainless steels are available and can be used with titanium alloys. If the riser is configured in a steep "S" as shown in Fig. 9 then there is a considerable bending load at the subsea termination and a taper joint would be required where the loads are transmitted into the riser base.

Platform Termination

The platform termination is usually an area of high loading due to wave action. If the riser is rigidly fixed to the platform this can result in high bending stresses in the riser and high bending moments on the platform support structure.

The cheapest form of termination is a simple titanium taper joint, which can be flanged to the platform or fixed in a tapered seat as shown in Fig. 10. Coatings can be used to isolate the joint if required. The termination can be designed to limit the temperature of the coatings.

A simple taper has the advantage of producing a fixed point relative to the platform thereby easing the design of the jumper (fluid offtake) system. Due to the short length of pipe required to make a taper joint, even if there are many risers to be installed of the same size, the basic joint is produced by extrusion. As this is an expensive and slow way to produce titanium pipes as discussed in Section 6, it is worth making an effort in the design to minimize the length of the taper.

The main disadvantage of a taper joint is that bending loads transmitted to the platform and/or the required wall thickness of the taper may be excessive. This can be overcome by an arrangement as shown in Fig. 11 where the taper joint is mounted on an external elastomeric flex-joint. This reduces the bending moment on the platform and minimizes the taper. Placing the flex-joint external to the pipe enables the temperature of the elastomer to be limited, whilst the exclusion of exposure to well fluid increases the choice of elastomer type giving the designer greater freedom in meeting stiffness and life requirements. The greater bending moment that can be transmitted to the platform, the less the top of the risers rotates. Therefore, the flex-joint will have to meet a minimum as well as a maximum stiffness requirement. Flex-joints like this can be designed with stiffnesses in the range 10 to 100 kN-m/^{0} giving the designer great freedom in achieving a satisfactory compromise.

The jumpers require some form of flexible pipe work. Traditional flexible piping can be used, though their durability might be questionable in some well applications. They are, however, in a readily accessible position where they can be monitored and changed out if necessary. Alternatively, titanium alloy jumpers could be designed depending on the amount of motion to be accommodated and the space available. If this is the case the stiffness of the jumper piping must be accounted for when carrying out a global analysis of the riser.

A further method of achieving a satisfactory compromise between rotation and bending moments is to have a stop on the flex-joint. This permits bending to be transferred to the titanium alloy taper if it exceeds a given angle.

A simpler solution to limiting the bending moment is to fit a conventional flex-joint as used for drilling risers. These have the disadvantage that the elastomer is exposed to the well fluid, but the manufacturers are developing new concepts with a thermally insulating layer between the titanium and flex-element to protect the working elastomer enabling the flex-joints to work at temperatures as high as 150^{0}C. These joints are, however, quite expensive.

A variation on the platform interface occurs in the case of a ship shape system where the risers are terminated in the mooring turret. In this case, the risers pass up through tubes in the turret, which are generally well able to cope with the riser loads. A system currently being worked on is shown in Fig. 12. It comprises a back to back taper joint with an elastomer bearing round the outside, which bears on the wall of the tube. The bearing itself has some rotational flexibility and some of the bending is therefore taken out in the riser pipe above the bearing.

It can be seen that the platform termination can be a challenging interface area in some circumstances, requiring coordination between the platform design team, topsides piping and the riser design team if the best solution is to be achieved.

COATINGS

Titanium riser components may require external coatings for four possible reasons: protection against handling damage during installation, protection against long-term hydriding, thermal insulation, and/or weight addition. Protection against installation damage can be handled by thin epoxy-amide and/or polyurethane marine paint coatings. Electrical isolation of risers can be achieved with thicker (5-10 mm) flexible polymer coatings including fusion-bonded-epoxy polyethylene or polypropylene, polyurethane, or the higher cost but more robust seawater-resistant rubbers (i.e., polychloroprene, chlorobutyl rubber, or EPDM rubber). Thermal insulation of risers may require much thicker coatings, such as polyurethane foam with an outer protective sheath or syntactic foam to withstand hydrostatic pressure. Some "weight" coatings consist of elastomers blended with iron or lead powder, which tend to be expensive. A cheaper, promising coating for both weight addition and thermal insulation is a form of "flexible concrete" consisting of cement and aggregates in a polymer matrix. This can be cast onto pipe surfaces in a continuous or batch fashion in the fab yard or on the lay vessel.

JOINING METHODS

Riser joints require assembling into risers by welding or mechanical couplings. With current technology, a welded riser would probably entail an offshore tow to install since reeling or high-speed welding processes are still under development.

Welding

Titanium alloys are readily weldable by a variety, of methods including: GTA (TIG), GMA (MIG), plasma, electron-beam, flash-butt, and friction welding. The first three fusion methods require total ID/OD side inert-gas shielding (typically argon) on the weld joint, and will require orbital welding techniques for riser assembly. Currently, hot-or cold-wire TIG welding is most developed for large titanium alloy tubulars. Disadvantages of TIG butt-welding are the slower speed and the needs to stress-relief anneal weldments, further slowing riser assembly. After stress-relieving, welded joint ID and OD surfaces may be ground or machined flush with pipe surfaces to avoid fatigue stress concentrators.

Efforts to achieve much higher welding rates are currently focused on orbital plasma-welding, which is not yet proven, and friction welding. Radial friction welding, described elsewhere [16], offers a very fast and low-cost method of joining pipes even on lay vessels, and has been used for steel pipelines. This technique works well with titanium alloys which readily diffusion-bond under high contact pressure and heat. Due to the lack of metal fusion in this process, inert gas shielding is not required and even a final stress relief anneal may be optional. Qualifying radial friction equipment with the capacity to join up to 30 cm titanium alloy pipe is currently under way, and could represent a major breakthrough in riser assembly and deployment offshore.

Couplings

An advantage of mechanical coupling over welding is the speed of make-up on site. Titanium alloy riser joints can be assembled by threaded couplings or flanges. Threaded couplings are used for downhole tubulars as pictured in Fig.13. These comprise a male thread machined in the wall of the pipe and a separate threaded female coupling to complete joint connection. One half of the coupling is a right-hand thread and the other a left-hand thread so that rotating the female coupling pulls the two pipes together without rotating the pipes. The couplings have double metal to metal seals and are being developed for use on titanium risers. Anti-seizing/galling surface treatments have been developed for titanium alloy threads that permit many connection make-breaks if required. However, machining the thread in the pipe wall means that joint efficiency is reduced to approximately 80%, and makes it difficult to achieve a good fatigue life.

If pipe wall thickness is increased at the ends, for example, by welding on a short, thicker wall section, then the strength and fatigue life of the pipe can be matched or exceeded in the coupling. Alternatively, it is often possible to take advantage of the localized nature of fatigue on a riser and locate couplings where fatigue loading is insignificant.

Titanium alloy flanges have been successfully used for pressure tight couplings subject to high bending moments, for example on the Heidrun drilling riser and Neptune taper stress joints. These are compact, bevel faced flanges complete with titanium alloy bolts. Such designs could readily be used for compliant risers, particularly for couplings on taper joints at the platform connection where bending moments are often highest.

CONCLUSIONS

1. Titanium alloys possess a unique combination of physical, mechanical, and corrosion properties that make them highly attractive for design and constructing highly reliable compliant risers.
2. All of the technology and components needed to produce a complete, viable titanium alloy compliant riser system, including pipe, termination designs, joining methods, and coatings are available.
3. Guidelines for riser design and termination are proposed that offer electrical isolation to avoid long-term hydrogen damage and galvanic effects with steel components, while successfully handling required anticipated bending stresses in various deep-water riser designs. OD surface coatings offer a means of providing thermal insulation, added weight in some cases, and/or a barrier to cathodically charged hydrogen.
4. Logical base-case titanium alloys for dynamic riser application are the Ti-Al-4V-based (alpha-beta) alloys. The ELI alloy grade with a beta-transformed structure offers components maximum damage tolerance and fracture resistance under static and cyclic loads.

5. The Ti-6A1-4V-based or other candidate Ti riser alloys can be enhanced with minor ruthenium or palladium additions to elevate crevice and stress corrosion temperature thresholds as high as 260^{0}C in seawater and produced fluid environments.
6. Titanium alloy riser tubulars can be cost-effectively produced at high rates, comparable to those of steel pipe, by hot rolling processes.
7. Titanium alloy riser assembly is currently feasible using orbital-GTA welding. Other tubular butt-welding methods under current development such as orbital plasma welding or, especially, radial friction welding offer the promise of far higher rates of riser assembly and deployment offshore. Alternatively, risers can be assembled by mechanical means.

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Table 1. Higher Strength Commercial Titanium Alloys Considered for Offshore Riser Application

Alloy Type	Nominal Composition	ASTM Grade	Min. Yield Strength Mpa (ksi)
Alpha (Near-alpha)	Ti-3Al-2.5V	9	483 (70)
	Ti-3Al-2.5V-0.05Pd	18	483 (70)
	Ti-3A1-2.5V-0.lRu*	28	483 (70)
Alpha-Beta	Ti-6Al-4V (ELI Grade)	23	759 (110)
	Ti-6AI-4V-0.1Ru* (ELI Grade)	29	759 (110)
	Ti-6Al-4V (Std. Grade)	5	827 (120)
	Ti-6Al-4V-0.05Pd (Std. Grade)	24	827 (120)
	Ti-6A1-2Sn-4Zr-6Mo*	--	896-1103 (130-160)**
	Ti-6A1-2Sn-2Zr-2Cr-2Mo-0.12Si	--	931-1089 (135-158)**
Beta (Near-beta and metastable beta)	Ti-10V-2Fe-3Al	--	965-1138 (140-165)**
	Ti-l5Mo-2.7Nb-3Al-0.15Si	21	793-1172 (115-170)**
	Ti-3Al-8V-6Cr-4Zr-4Mo*	19	793-1241 (115-180)**

*Represents Ti alloys currently approved under the NACE MR-01-75 Spec. for sour service.

**Typical range depending on product and metallurgical condition.

Table 2. Comparison of Titanium Alloy Types

	Alpha	Alpha-Beta	Beta
Density	M	L/M	H
Modulus	M/H	M	L
Cost	L/M	L/M	H
Corrosion resistance	H	H	H
Strength	L/M	M/H	H
Fatigue strength	L/M	H	H
Toughness	L/M	H	M
H_2 tolerance	L	M	H
Machinability	M/H	M/H	L
Producibility	M/H	H	L/M
Weldability	H	H	L/M
Micro/property control	L	H	L

L = low M = medium H = high

Table 3. Room Temperature Properties of ELI Ti-6Al-4V and Ti-6Al-4V-Ru Alloy Products

0.2% YS (min.)	758 MPa (110 ksi)
UTS (min.)	827 MPa (120 ksi)
Elongation	6-15%
Elastic Modulus	115 x 10^3 Mpa
K_{Ic} (air)	77 - 104 MPa √m
CVN (impact)	27 - 50 Joules
Density	4.43 g/cm^3
Coef. Thermal Expansion	9 x 10^{-6}/°C
Thermal Conductivity	7 W/m - °C
Electrical Resistivity	171 x 10^{-6} ohm - cm
Hardness	HRC 32

Table 4. Corrosion Resistance in Seawater

	Ti-6-4 ELI	TI-64-RuIPd
General corrosion	R	R
Pitting attack	R	R
Crevice corrosion	S*	R
MIC (Bio-corrosion)	R	R
Corrosion fatigue	R	R
Stress corrosion	R/S	R
Erosion Corrosion	R	R
Galvanic attack	R	R
Weld/HAZ attack	R	R

R = Resistant as high as 250^0C, S = Susceptible to attack
*May be susceptible to attack above 75^0C

Table 5. Resistance to Produced Well Fluids

Well Fluid Component	Ti-6-4	Ti-6-4-Ru/Pd
Hydrocarbons	R	R
NaCl Brines	R/S*	R
Organic Acids	R	R
$C0_2$	R	R
H_2S	R	R
Elemental Sulfur	R	R
Liquid Mercury	R	R

R = Resistant as high as 250^0C, S = Susceptible to attack
*May be susceptible to crevice corrosion above 75^0C, with some reduction in K_{Ic} (i,e., K_{Iscc}).

Table 6. Resistance to Well Workover Fluids

Well Workover Fluid	Ti-6-4	Ti-6-4-Ru/Pd
12% HCI/3% HF Acid	S*	S*
15% HCl Acid	S*	S*
10-12% HCI Acid (inhibited with N_2MoO_4)	R	R
10% Acetic Acid	R	R
10% Formic Acid	S	R
Methanol (<2% H_20)	S	S
Methanol (≥3% H_20)	R	R

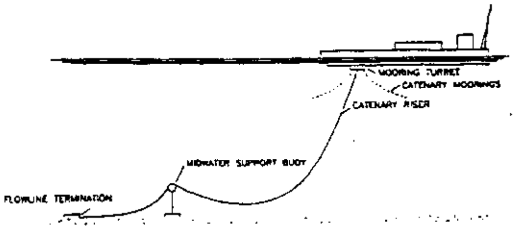

Fig. 1. Example of a typical compliant riser.

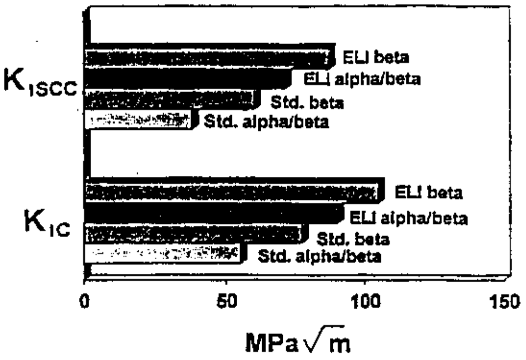

Fig. 2. Typical air and saltwater fracture toughness values for the Ti-6Al-4V alloy.

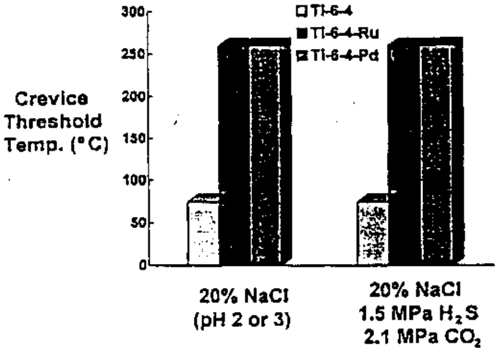

Fig. 3. Beneficial effect of Ru and Pd additions on crevice corrosion resistance of Ti-6Al-4V in acidic brines.

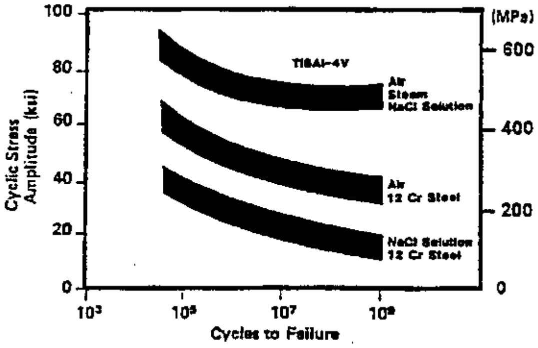

Fig. 4. Air/saltwater fatigue curves for Ti-6Al-4V compared to steel[9].

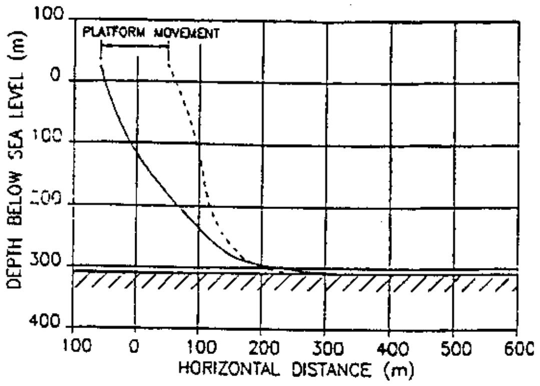

Fig. 5. Oil-filled TLP titanium alloy riser shape.

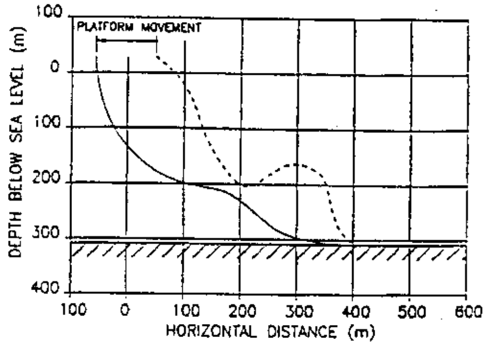

Fig. 6. Gas-filled TLP titanium alloy riser shape.

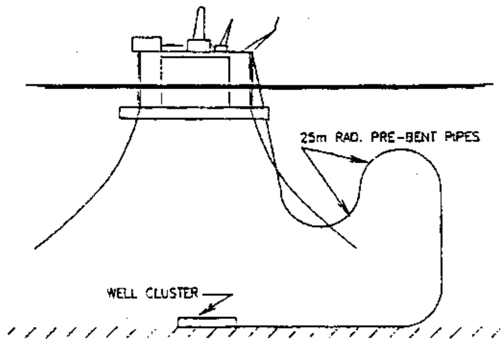

Fig. 7. Titanium alloy riser configuration using pre-bent pipes.

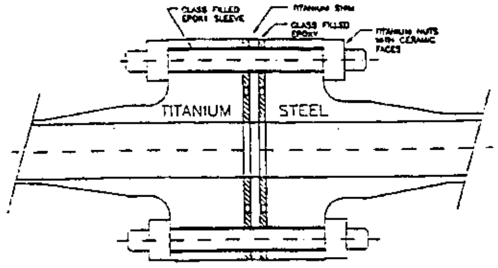

Fig. 8. Electrically-isolated flange assembly.

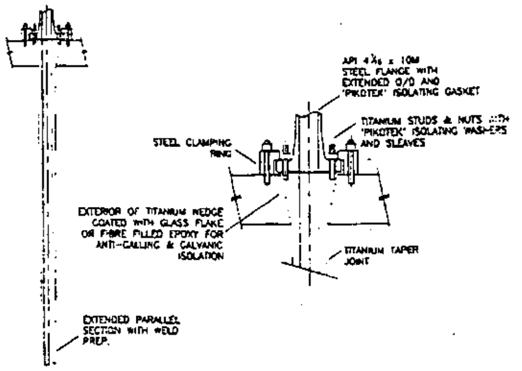

Fig. 10. Platform termination using a titanium alloy taper joint.

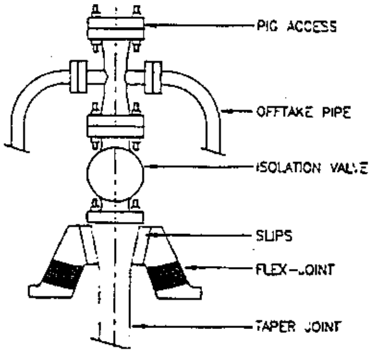

Fig. 11. Platform termination using an external elastomeric flex-joint.

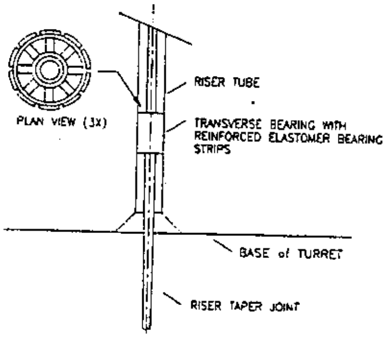

Fig. 12. Platform/riser interface using a mooring turret.

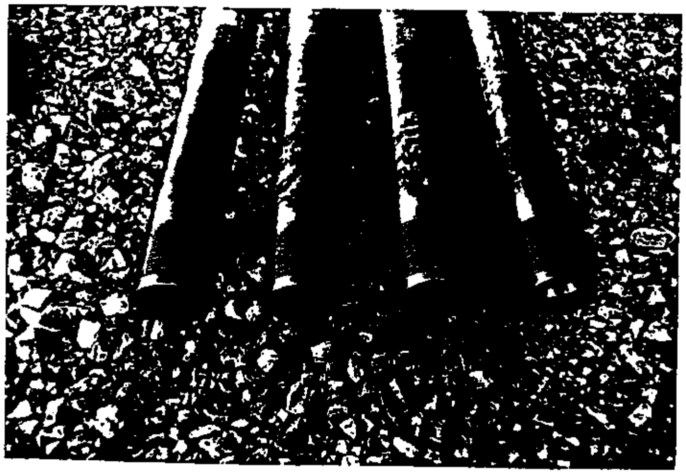

Fig. 13. Threaded male connections on titanium alloy tubulars.

BASICS AND BENEFITS OF TITANIUM FOR SEA SERVICE

A REVIEW

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INTRODUCTION

Titanium is used throughout the world in providing corrosion free tubing and pipe for cooling water and service water applications, including utility steam condensers, de-salination, salt production, refineries, and air conditioning among others. Its use is expanding due to its virtual immunity to corrosion and MIC in all natural and harsh waters -- seawater, brackish, fresh, polluted, chlorine laden, etc., while providing a substantial reduction in maintenance (zero where corrosion is an issue) and eliminating corrosion concerns related to mechanical cleaning, stagnant, and/or no-flow conditions.

Titanium's lower density at half that of copper-nickel alloys and 55% that of stainless steels, combined with its high resistance to erosion/corrosion, which allows both wall reductions and O.D. size reductions, provides significant weight reductions to upwards of 75% or more.

The intent of this paper is to present the basics as to properties, heat transfer and corrosion immunities of Commercially Pure (CP) Grade 2 titanium, while highlighting the benefits of reduced or eliminated maintenance, weight reductions, applications, and life of ship service.

This presentation is meant to provide information to those unfamiliar with titanium while providing a review and update for those familiar (or somewhat familiar) with the metal. While proceeding through these topics, the benefits of titanium's use for sea service are clearly established and serve to indicate why titanium should be and is both being considered and used in providing uncompromised service.

CHEMISTRY

Grade 2 is by far the most widely used of all the CP titanium grades. It is an unalloyed grade of medium strength (40 ksi min. yield / 50 ksi min. tensile) with good cold formability. Typical average titanium content is 99.6%. (See Fig. 1.)

This grade is the most readily available and least expensive form of C.P. titanium. This grade would be used for heat exchangers (plate and frame and shell and tube), chillers, and piping systems throughout the ship.

CHEMISTRY

MAX. WEIGHT % PER ASTM B338								
	O_2	Fe	H_2	C	N_2	Other, Each	Other, Total	Ti
Grade 2	0.25	0.30	0.015	0.08	0.03	0.1	0.4	Balance

MECHANICAL PROPERTIES

PROPERTY	Titanium Grade 2		90-10 Cu-Ni		70-30 Cu-Ni		316 Stainless	
	KSI	MPa	KSI	MPa	KSI	MPa	KSI	MPa
Tensile Strength (min.)	50	345	40	275	52	360	75	515
Yield Strength (min.)	40	275	15	105	18	125	35	240
Yield Strength (max.)	65	450						
Elongation (min.)	20%		30%		15%		30%	
Elastic Modulus 10^6 psi	16		18		22		28	
Thermal Expansion* Coefficient Micro in/in°F	4.8		9.5		9.0		8.9	
Thermal Conductivity BTU/hr-ft^2°F/in	150		348		204		95	
Density (lbs./in^3)	.163		.323		.323		.286	

* Thermal Expansion Coefficient for HY80 Steel = approx. 6.0.

In Fig. 2 comparisons of the Mechanical Properties of Cu-Ni alloys and 316 Stainless are shown. A brief synopsis comparing titanium with these other materials is indicated below:

Yield Strength

If we eliminate 316 S.S. from consideration (as tubing and piping in most all cases are compared only against the copper-nickel alloys), Grade 2 titanium has the benefit of significantly higher yield strength minimums.

Elongation

Higher than that of 70-30 Cu-Ni yet lower than 90-10 Cu-Ni, Grade 2 at 20% minimum (25% or more being typical) has more than sufficient ductility for any tube or piping application.

Elastic Modulus

A measure of the "flex" or rigidity (stiffness). Although close to that of 90-10 Cu-Ni, due to the much lighter walls in titanium, the distances between supports will generally be shorter. In heat exchangers this equates to shorter distances between support plates.

Thermal Expansion Coefficient

Closer to that of carbon steel this relatively low value equates to lower stress on the material from thermal fluctuations.

Thermal Conductivity

Having undergone state of the art testing in late 1991 under the sponsorship of the Electric Power Research Institute (EPRI) and the Empire State Electric Energy Research Corp. (ESEERCO) titanium was proven to have a 32% greater thermal conductivity rating than was used in the past.[1] This favorably impacts heat exchanger design for better economy. Although much lower than either 70-30 Cu-Ni or 90-10 Cu-Ni, with thinner walls (due to its having a zero corrosion allowance), the heat transfer differences between titanium and the copper nickel alloys can be minimal and in several cases can be identical to or even slightly better in conventional shell and tube heat exchangers.

Density

At 0.163 lbs/in^3 titanium is half that of the Cu-Ni alloys (.323 lbs/in^3) and 55% to 57% that of stainless steels (.286 to .292 lbs/in^3). Even without considering the use of thinner walls, density alone accounts for a 50% weight reduction in service water piping throughout the ship with additional weight savings in the internals of heat exchangers and chillers.

TIMET

SEAWATER CORROSION RESISTANCE

	CU-NI ALLOYS	316 SS	GRADE 2 TITANIUM
GENERAL CORROSION	RESISTANT / SUSCEPTIBLE	RESISTANT	IMMUNE
PITTING ATTACK	SUSCEPTIBLE	SUSCEPTIBLE	IMMUNE
CREVICE CORROSION	SUSCEPTIBLE	SUSCEPTIBLE	IMMUNE (<180°F)
STRESS CORROSION CRACKING	RESISTANT	SUSCEPTIBLE (>140°F)	IMMUNE
EROSION/CORROSION	SUSCEPTIBLE	RESISTANT	RESISTANT
GALVANIC ATTACK	SUSCEPTIBLE	RESISTANT	IMMUNE
MICROBIAL CORROSION	SUSCEPTIBLE	SUSCEPTIBLE	IMMUNE
WELD/HAZ CORROSION	SUSCEPTIBLE	SUSCEPTIBLE	IMMUNE

J.A.MOUNTFORD,JR. 6/06/96

Crevice Corrosion

For sea service conditions with temperatures under approximately 180°F (82°C), titanium is not subject to crevice corrosion. (Grades are available to extend this range to 500°F (260°C) and higher where needed.)

Stress Corrosion Cracking (SCC)

Grade 2 titanium is immune under all sea service conditions and SCC should not be a consideration for any on-board ship applications. (Only chemical process environments such as absolute methanol, red fuming nitric acid, nitrogen tetroxide, and cadmium induce SCC in titanium.)[6-8]

Erosion/Corrosion

Titanium's hard ceramic-like protective oxide film (TiO_2) allows seawater velocities of over 90 ft/sec (27 m/sec) to 120 ft/sec (36 m/sec) in the absence of suspended solids. Under sand laden seawater conditions, flow rates can be as high as 15 ft/sec (4.6 m/sec) without any erosion effect. (This is in sharp contrast to other materials generally limited to from 7 to under 12 ft/sec (3 to 3.7 m/sec) under reasonably good conditions (not sand laden) before erosion and metal carryover can occur.)[9]

It is common in tube I.D.'s to have shells/sand/debris/organisms, etc., imbedded within the tube walls. With a severe decrease in area within these localized tube sections, water velocities can be extreme and cause erosion/corrosion and through wall penetration in softer metals. Titanium protects units from leaks caused by these conditions -- a result of its high resistance to both high water velocity and erosion concerns.

Galvanic Corrosion

Titanium is the noble metal in chloride environments necessitating protection of <u>other</u> metals for proper design considerations. Plastic sleeves (for bolts) and gaskets, etc., are readily available to afford the protection required for sea-service applications. Short "sacrificial" sections connecting two different materials can also be used (i.e., Ti to Cu-Ni to Cu-Ni valves) as can transition joints of a material between titanium and Cu-Ni on the galvanic chart also be considered.

Hydriding

There has been a great deal of misrepresentation with respect to titanium and the hydriding issue. Basically, hydriding occurs at temperatures above about 170°F (77°C) - higher than service water or heat exchanger cooling water temperatures. Hydrogen freed by any galvanic action below this temperature remains on the tube surface with no "driving force" to enter the titanium or change any of its properties.

If cathodic protection systems are being used, impressed potentials of -0.7 to -0.8 volts are standard recommended limits (versus either Ag/AgCl or Standard Calomel Electrode [SCE]). Even at potentials at a level of -1.0 volt it would take 20 to 30 years to have hydriding of any significance occur.

One reported incidence where hydriding affected condenser tubing was shown to have had an out of control cathodic protection system voltage at approximately -2.0 volts for several years. Even under this severe situation, with a corrected cathodic protection system, the affected tubes have continued in service for over 9 years and remain so today.)

Microbiologically Influenced Corrosion (MIC)

Titanium has never exhibited any incidence of MIC. It has been shown to be totally resistant to either aerobic or anaerobic bacteria.[10-11]

Other

Titanium is resistant to any corrosive effects of oxidizing biocidal agents, such as hydrogen peroxide, sodium hypochlorite, and to non-oxidizing organic treatments, as well as to shock chlorination.

WEIGHT COMPARISONS

For firemain systems in titanium for new LPD-17 shipsets, SCH 10 piping is being specified for the ability to withstand fire hazards -- as determined by having undergone and survived fire tests --1832°F (1000°C) for 10 minutes then pressurized to approximately 10 bar (145 psi) with flowing water for 2 hours (Lloyd's of London) and 1700°F (927°C) for 17 minutes @200psi static pressure under no flow performed by the Auxiliary Engineering Group (AEG) at Naval Sea Systems Command (Arlington).[12] (The titanium had a gradual failure mode while Cu-Ni lasting slightly longer failed in an explosive mode.)

In other non-critical applications, wall thickness can be reduced significantly and diameters can also be reduced for added weight savings.

Weight comparisons between titanium and Cu-Ni alloys are shown in Figs. 4, 5, 6.

Opportunities will exist where a current nominal O.D. size can be reduced for titanium pipe (as replacement for the next higher schedule size in Cu-Ni) due to the ability to withstand higher velocities with no erosion effects and the overall zero corrosion allowance. This greatly increases the weight savings as is exemplified in Fig. 7.

PIPE WALL THICKNESS (INCHES)

TITANIUM VERSUS CLASS 200 CU-NI

PIPE DIAMETER NOMINAL (Inches)	PIPE DIAMETER ACTUAL (Inches)	WALL CLASS 200 CU-NI (Inches)	WALL GRADE 2 TI (PER ASME CODE)*	WALL GRADE 2 TI SCH 5
2	2.375	0.083	0.019	0.065
3	3.500	0.095	0.028	0.083
6	6.625	0.135	0.053	0.109
12	12.750	0.250	0.101	0.156

* Allowable

Figure 4

WEIGHT SAVINGS FOR TI PIPING VERSUS CLASS 200 CU-NI PIPING

PIPE DIAMETER NOMINAL (Inches)	PIPE DIAMETER ACTUAL (Inches)	WEIGHT CU-NI PIPE (Lbs/100 Ft)	WEIGHT GRADE 2 TI (Lbs/100 Ft)	WEIGHT SAVINGS SCH 5 TI %
2	2.375	232	92	60
3	3.500	394	174	56
6	6.625	1060	436	59
12	12.750	3805	1207	69

Figure 5

WEIGHT COMPARISONS
TITANIUM VERSUS CU-NI SCH 10 PIPE

O.D. Nominal (Inches)	O.D. Actual (Inches)	WALL Nominal (Inches)	WEIGHT Cu-Ni (Lbs/100 Ft)	WEIGHT Grade 2 Ti (Lbs/100 Ft)	WEIGHT SAVED (Lbs/100 Ft) @49.5%
2	2.375	0.109	301	152	149
3	3.500	0.120	493	249	244
4	4.500	0.120	640	323	317
5	5.563	0.134	886	447	439
6	6.625	0.134	1,058	534	524
8	8.625	0.148	1,527	771	757
10	10.750	0.165	2,126	1,073	1,053
12	12.750	0.180	2,754	1,390	1,364

Figure 6

WEIGHT SAVINGS

CU-NI		TITANIUM			
PIPE SIZE	WEIGHT (Lbs/100 ft)	PIPE SIZE	WEIGHT (Lbs/100 ft)	WEIGHT SAVINGS Lbs.	%
6" SCH 10	1,058	5" SCH 10	447	611	58
4" SCH 10	640	3" SCH 10	249	391	61
10" SCH 10	2,126	8" SCH 10	771	1,355	64

Figure 7

In addition to the above material weight savings, consideration must also be given to the reduction in the volume of water inside the piping (directly related to the area difference between titanium and Cu-Ni pipe sizes and their varying pipe I.D.'s). In the above example (Fig. 7), the water volumes are reduced by 31%, 41%, and 36% respectively (assuming full flow conditions), thus increasing further the overall weight savings by using titanium pipe.

For condenser re-tubings, a Cu-Ni tube of 1" O.D. X .049" wall [18 BWG] (0.2864 lbs/ft) would typically be replaced by titanium at 1" O.D. X .028" wall [22 BWG] (0.1672 lbs/ft) for a weight savings of 42%. What may appear at first as being insignificant in terms of lbs/ft in reality is not as tubing in these applications are in the many thousands of feet.

BENEFITS

- Seawater/Polluted Water Corrosion Immunity
- Seawater High Erosion Resistance/Immunity
- Good Mechanical Properties (High Strength/Weight)
- Reduced Maintenance
- Significant Topside and Overall Weight Reductions
- Life of the Ship Service (No Replacements)
- Highly Favorable Life Cycle Costs
- Reusable

MAINTENANCE CONSIDERATIONS

Reduced overall inspections for corrosion effects in piping systems and heat exchanger tubing due to titanium's absence of corrosion.

Ability to use mechanical cleaning (scrapers) with no corrosion effects. Titanium's highly stable hard surface oxide corrosion resistant layer instantly reheals itself when mechanically removed. It is, therefore, always passive. This is unlike copper or most stainless steels where galvanic and pitting initiation sites can be set up and where additives may need to be used to re-passivate these systems.

Elimination of any corrosion concerns with regard to stagnant, low flow, or poor drainage during lay-up results in cost and time reductions for flushing, draining, and drying requirements, as well as much of the cost for chemical additives/additions associated with corrosion abatement, as with other metals. [Operations for eliminating "mechanical" debris, etc., would remain (if required), but those for corrosion concerns can be eliminated.]

Anticipated increases in procurement costs of 10-20% for titanium over that of a 90-10 Cu-Ni system still show the net life cycle costs for titanium approximate a 50% savings due to reduced maintenance. This equates to a return on investment approximating 800%, or 25% per annum over a ship's life.[12]

Once installed, titanium sections/parts of systems will remain unaffected throughout the life of the ship and beyond. This eliminates maintenance required for re-installation and replacements of metal, as is currently the case. The feasibility is real for titanium piping systems to be disassembled, cleaned, and re-used in other areas after ship's completion of service.

DESIGN CONSIDERATIONS

Fabrication

Titanium is readily fabricated (having been done for over 40 years), generally on the same equipment as that used for stainless steels or nickel base alloys. Over the past several years, there has been a marked increase in shop fabrication from small to large as the industrial customer base has expanded. Guidelines for cutting, machining, drilling, and forming are available from several references.[13-18]

Welding

Titanium can only be welded to titanium (or other reactive metals - Zr, Nb, Ta). Techniques used include Gas Tungsten Arc (GTA), Gas Metal Arc (GMA), plasma, resistance, friction, electron beam, laser, and pressure welding using the same equipment as that used for welding other high performance materials. Cleanliness is obviously important as is inert gas shielding which includes a trailing shield to protect completed welds from contamination (absorbing oxygen) from the atmosphere until it has cooled below 800°F. Finished welds are very fluid and segregation is not a problem due to the fact that Grade 2 (and the other CP grades) is essentially a pure metal. This also accounts for the fact that both the welds and Heat Affected Zones (HAZ) have the same corrosion resistance/immunity as the base metal. Weld training, literature, seminars, and videos are available.[13,18-22]

APPLICATIONS

Many areas currently exist for the use of titanium shipboard for heat exchanger tubing. A list of several of these applications along with several applications on offshore (oil) platforms which may have relevance to additional potentials for on-board sea service is shown in Fig. 8.

TITANIUM HEAT EXCHANGER APPLICATIONS
ON NAVY SHIPS AND OFFSHORE PLATFORMS

SHIPBOARD	OFFSHORE
Ship service turbine generator condenser (S/T)	Lube oil cooler (S/T)
	Engine jacket cooler (P/F)
Racer steam condenser (S/T)	Compressor cooler (P/F)
	Central exchanger (P/F)
Radar electronic cooler (S/T and P/F)	Direct low pressure crude oil service cooler (P/F)
De-Salination Units (S/T)	
Other electronic coolers (P/F)	Discharge cooler (S/T)
Air conditioning freon condenser (S/T)	Quench water cooler (S/T)
Distillation unit brine heater and preheater (P/F and S/T)	Propane condenser (S/T)
	Gas Dehydrator cooler (S/T)
Lube oil and engine jacket coolers for TAO oilers (P/F)	Natural gas cooler (S/T)
Low pressure air compressor cooler (S/T)	Glycol cooler (S/T)
	Flash gas compressor
	Intercooler (S/T)
	Interstage oil cooler (S/T)

P/F = Plate/Frame Exchanger
S/T = Shell/Tube Exchanger

Figure 8

Areas that are being considered or would be ideal candidates for titanium pipe for shipboard sea service are indicated in Fig. 9.

TITANIUM APPLICATIONS FOR SHIPBOARD PIPING

- Firemain Systems
- Seawater Ballast Systems
- Aegis Radar Cooling Water Systems
- Oily Waste Systems
- Deck Draining Systems
- Magazine Sprinkling Systems
- HVAC (Ducting)
- Seawater Service System
- Feedwater to Distilling Plants
- Seawater Compensated Fuel Oil Systems
- Bilges
- Countermeasure Washdown Piping
- Missile Deluge Systems
- Stanchions

Figure 9

In addition to pipe and tubing of C.P. Grade 2, there are other titanium alloys being used or considered for many other shipboard applications; i.e., Grade 9--3Al-2.5Va strip for uptakes in DDG-51 destroyers, while other alloys are being tested and proven for other uses; i.e., Near-Alpha Alloy for fastener stock.[24,25] Also, other forms of C.P. Grade 2, etc., such as bar, plate, and sheet are available for numerous other potentials.

CONCLUSION

In terms of corrosion resistance/immunities, titanium is unsurpassed in seawater service. Because of its low density, high strength/weight ratio, and erosion resistance, titanium offers unexcelled performance in eliminating corrosion and reducing or eliminating maintenance while providing very significant weight savings. It is the material that provides the necessary and desired solutions to the problems that have plagued the many shipboard applications and, as in industry where harsh water environments are prevalent, will be the material of choice for sea service.

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Titanium for Secondary Marine Structures

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Overview:

Materials of construction for secondary marine structures must exhibit an optimum combination of saltwater corrosion resistance, mechanical reliability, high strength-to-weight ratio, reliable fabricability and maintainability, and low life cycle cost. To minimize life cycle costs, design and materials selection must include engineering for reduced maintenance.

Titanium provides a unique combination of these features. Titanium exhibits:

Excellent corrosion resistance in all sea water environments

Non-toxicity to people, aquatic life , or the surrounding environment

Strength-to-weight ratio unmatched by any other common engineering metal

Structural stiffness comparable to the best other common engineering metals

Non-magnetic in all alloys and forms

Simple and reliable forming, fabrication, and welding processes

Reliable near net shape casting and forging processes

Reliable commercial availability in sheet, plate, tube, pipe, and bar form

Established industry standards worldwide

The greatest impediment to the increased use of titanium in marine structures is a lingering, age-old misconception that titanium is an expensive, exotic, difficult to process metal. Undeniably titanium is more expensive than most steel and aluminum alloys. It is cost comparable to many copper alloys and is lower cost than many of the nickel alloys. The key to cost effective use of titanium is to utilize its unique properties and characteristics in the design rather than to simply substitute it for another metal.

The broad range of titanium alloys available to the design engineer are listed in Table 1. Virtually all of the common titanium alloys, in plate and sheet form, are covered in the ASTM Specification B265. Marine structures are commonly constructed from one of the higher strength unalloyed grades, such as Grades 2 or 3. Where crevice corrosion may be an issue, such as gasketed sealing surfaces, the palladium alloy, Grade 7, is a common choice. Where higher strength is mandatory, Grades 9 or 12 are used.

Features of Titanium for Seawater Applications:

Corrosion Resistance:

Titanium is fully resistant to natural seawater regardless of chemistry variations and pollution effects (Ref 1). Corrosion rates of well below 0.01mpy have been measured in extended programs (exceeding 20 years) in subsea, splash, and tidal zones. The excellent corrosion performance is attributable to a very thin, tenacious and highly protective surface oxide film. If scratched or damaged, this surface oxide will immediately reheal and restore itself in the presence of air or seawater. Weldments, and castings of the common titanium marine grades exhibit corrosion resistance comparable to wrought materials, eliminating a concern over heat affected zones or a need to upgrade alloying in weld metal or castings.

The fatigue properties and toughness of common marine grade titanium alloys are unaffected by seawater exposure. The alloys are immune to seawater stress corrosion cracking. Unalloyed titanium is susceptible to crevice corrosion pitting in some severe seawater environments, such as at gasketed mechanical joints. The problem can be completely eliminated by upgrading to Grade 7 or similar alloys in these locations.

The resistance to seawater environmental corrosion eliminates the need for elaborate corrosion resistant coating systems and the inherent high cost of maintenance. Painting of titanium components becomes simply a cosmetic issue.

Erosion Resistance:

In seawater environments, titanium alloys are immune to all forms of localized erosion corrosion. The titanium alloys will withstand seawater impingement at flow velocities in excess of 100 ft/sec. Abrasion and cavitation resistance is outstanding. Table 2 presents a comparison of alloy erosion corrosion resistance at various seawater test locations. The erosion and caviation resistance make titanium an ideal alloy for seawater piping, pumps, and heat exchangers. (Ref 2)

Heat Transfer Efficiency:

Under "in service" conditions, the heat transfer properties of titanium approximate those of admiratly brass and copper-nickel. Although titanium has a lower coefficient of thermal conductivity, the reasons for the good heat transfer are:

>Titanium's higher strength permits the use of thinner walled equipment

>The relative absence of corrosion in seawater leaves the surface bright and smooth for improved surface heat transfer

>The superior erosion-corrosion resistance permits significantly higher operating velocities.

Superior Strength to Weight Ratio:

The density of titanium and its common marine grade alloys is in the 0.163 lb/cu-in range while the yield strength is above 40,000 psi. The strength is equivalent to that of commonly used shipboard steels while being 43% lower weight for an equivalent section. The reduced weight is typically very beneficial. The overall weight and related space demand is lowered, reducing initial costs and ongoing transport costs.

Manufacturability:

The common marine titanium grades are readily manufacturable. Manufacturing techniques were initially developed for the aerospace industry. Over time the processes have been refined and cost optimized to a broad range of commercial products;

>Titanium piping, fitting, valves, and pumps have been produced for the chemical process and utility industries for over 40 years

>Titanium heat exchangers, both "shell and tube" and plate exchangers, are extensively used in these same industries. Titanium exchangers are the preferred choice for reliability and safety in the nuclear power industry.

>Reliable, low cost manufacture has helped titanium products to gain an exceptional position in many markets; for example, the highly competitive sports equipment industry and the medical equipment and implant industries. Factors driving success in these fields also apply to the marine industries.

Fabrication processes are reliable and well developed. Titanium components can be produced by near net shape processes such as forging and casting. The titanium alloys can be readily and reliably joined by welding. Like most non-ferrous alloys, welding of titanium requires special care (Ref 3). As with all metals, titanium must be clean for reliable welding. The weld metal must be protected from oxidation by inert gas shielding while above approximately 1000F. Production of high quality weldments in titanium is generally easier than with many of the marine grade aluminum, copper, and nickel alloys. Experienced welders claim that titanium welding is easier than stainless steel welding.

Toxicity:

Unlike many of the commonly used metals, titanium is truly non-toxic to people, marine creatures, and the environment. It can be used without concern for the health and safety of the fabricator or the end user. For example, this feature of titanium has made it a preferred material for medical and dental implants, pacemaker cases, heart valves, etc.

Availability:

The titanium grades that are commonly required for marine uses are readily available in sheet, plate, tube, pipe and rod form. There is a broad base of both mill and warehouse supply for these products. This availability results from the extensive range of uses for these versatile alloys. Designers and users are often misled regarding availability by the less common availability of the more complex aerospace alloys.

Industry Standards:

Titanium alloy standards are well established. The aerospace, chemical, and power industries have lead in assuring broad acceptance of industry standards worldwide. Established ASTM Standards cover plate, sheet, tube, pipe, rod, bar, etc. Since titanium is a relatively newer metal, industry standards are more universally equivalent worldwide than for many of the older metal families.

Current Applications of Titanium and its Alloys in Secondary Marine Structures:

Piping: Titanium has become an accepted metal for piping in Naval Ships (Ref 4, 5). The features of titanium provide cost reduction and enhanced reliability:

>Due to the superior corrosion and erosion resistance, combined with high strength, piping can be thinner wall.

>The erosion resistance permits higher water velocities. This in turn permits use of smaller diameter pipes to achieve the same volume transfer.

>The weight is significantly reduced due to the lighter wall, smaller diameter piping and reduced weight of the water contained within the pipes.

>The reduced diameter and tighter bend radii greatly reduce the space requirement, providing greater design flexibility.

Table 3 presents a list of applications of titanium piping in naval ships.

Heat Exchangers: The features that have made titanium a material of choice in piping have also driven its use in heat exchangers (Ref 5, 6). Titanium exchangers are now used extensively in commercial fishing and transport vessels, navy ships, and offshore platforms. Table 4 presents a list of current applications of titanium heat exchangers in secondary marine applications.

Exposed Hardware and Electrical Components: Corrosion of hardware and electrical components exposed to seawater conditions is a major maintenance concern. Unlike most other metal, titanium components can resist the severe corrosion conditions without periodic painting. In fact, the absence of a need for perpetual cleaning, painting, stripping, cleaning, painting, etc makes titanium a low cost choice of much of this equipment. Titanium is being used for ladders, electrical boxes, lighting fixtures, stanchions, hatches, covers, antennas, and a myriad of other topside components on naval ships (Ref 7). These relatively small, but very critical items, can be a very heavy demand upon the maintenance support team when constructed of less suitable metals.

Exposed Structures: Corrosion of exterior structures presents a high maintenance demand with most metal choices. This is not the case with titanium. Due to the excellent corrosion resistance, elaborate coating systems and the continuing maintenance demand is unnecessary. Titanium is being used for exterior bulkheads, roofing, and splash guards. For many of these applications, titanium clad steel is the low cost option; a thin titanium exterior layer is supported by an inexpensive steel base metal on the non exposed side (Ref 9).

Design and Fabrication Concerns:

The primary longterm concerns of using titanium in secondary structures relates to inter-relationships with other metals.

Proper repair, maintenance, and modification of any metal component requires an understanding of what the material of construction is and which procedures are suitable for that specific metal type. It is critical that maintenance personnel understand the differences in the various materials of construction. For example, welding of a steel attachment to a titanium component will only result in the damage of both components. (In this regard, titanium is no different than aluminum or most of the copper and nickel alloys.) Maintenance procedures which include material type identification prior to cutting, welding, etc are critical for any application where various metal and non-metal components are used together.

Corrosion of joints between components of differing metal types can also be a significant concern. The superior corrosion performance of titanium can result in accelerated galvanic corrosion of adjacent components of a less noble metal, such as steel, stainless steel, or aluminum. The extent of galvanic corrosion will depend on many factors such as anode to cathode ratio, seawater velocity and seawater chemistry. The most successful strategies eliminate this galvanic couple through material selection and design. By moving the dissimilar metal interface to a location that is corrosion protected, serious galvanic attack can be avoided. However, in many instances this cannot be achieved. In these cases it is best to electrically insulate the titanium components from adjacent lesser noble metals. A wide range of dielectric joint designs have been developed for this purpose. Some installations, such a naval combatant topside equipment, require universal grounding or bonding, in these cases insulation is not an option.

Galvanic corrosion is significantly frustrated if a crevice is present between the dissimilar metals, such as in a mechanical connection. Corrosion conditions can be significantly enhanced in the presence of a dissimilar metal crevice. Further, crevices at mechanical attachments are virtually impossible to protect with paint. Since titanium cannot be welded to steel using conventional fusion welding processes, a crevice-free joint is not readily achievable by direct welding. Titanium can be welded to most other metals using one of several cold welding processes, such as explosion welding, friction welding, and diffusion bonding. However, these technologies do no lend themselves to conventional marine fabrication environments.

Dissimilar metal transition joints provide a corrosion control mechanism where dissimilar metal joints cannot be avoided or are cost preferable to their elimination (Ref 9).

Figure 1 shows the transition joint concept. The transition joint is produced by a non-conventional welding method, which produces a crevice free, mechanically strong, metallurgical bond between the dissimilar metals. For example, when joining titanium to steel, a titanium-steel transition joint would be procured from an explosion welding company. The titanium would then be welded to the titanium face using conventional titanium processes and the steel to the steel face likewise.

The transition joint provides a mechanically reliable, electrically conductive, crevice free joint between the dissimilar metals. However, it does not eliminate the galvanic corrosion potential. The elimination of the mechanical joint and the related crevice now makes painting a viable protection method.

Transition joints have been used since the late 1960's for corrosion control at aluminum-to-steel connections (Ref 10). Most of the naval ships constructed over the past 25 years have used welding transition joints for joining aluminum superstructures and deck houses to steel decks and hulls. Similar transition joints are readily available for joining titanium to steel, stainless steel, aluminum, and copper alloys.

Total Cost Overview:

When initial component cost is considered, titanium is rarely the low cost metal. The comparative cost of titanium and other metals is presented in Table 5. (The ratios are based upon 1996 metals costs, which may change significantly in the future. However, it is notable that these ratios have not changed appreciably in the prior two decades.) As displayed here, titanium is more than 10 times as expensive as carbon steel when compared on a volumetric basis. In a simple cost per unit weight comparison, it is more than 20 times as expensive as steel.

The cost benefits of titanium result from it lower weight and reduced maintenance costs. Corrosion prevention programs are not needed for titanium equipment. The costs of frequent inspections, cleaning, painting, and repeating in a few months to a few years is fully avoided. Naval estimates place the cost of re-painting for corrosion protection to exceed $40./square foot (Ref 11). For comparison, this is greater than the cost differential between a 0.188" thick sheet of titanium (Grade 2) and an equivalent piece of steel or aluminum.

In addition to the elimination of a regular corrosion maintenance program, the cost of maintenance of the maintenance team can be avoided. In shipboard and platform conditions, the cost of the related space for housing, feeding, recreation, etc. can be very significant. The savings are potentially exponential.

In comparison to aluminum, titanium structures offer improved fatigue performance; particularly where welds are involved. This reduces the need for regular inspections to assure component mechanical integrity. It further reduces the need for mechanical repairs as equipment becomes older and fatigue becomes a real cost issue.

In summary, for many secondary marine structure uses, titanium is the material of choice. Reductions in life cycle costs have been proven to be particularly significant in piping, heat exchangers and topside corrosion environments.

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Table 1

SELECTED TITANIUM ALLOYS AND PERFORMANCE FEATURES

Gr# (*)	Basic Alloy Components	Cost (**)	Features/Motivation for Alloy (***)
1	Ti (Chem. Pure)	1.1	Low Cost, Low Strength, Excellent formability
2	Ti (less pure)	1.0	Low Cost , Moderate Strength
3	Ti (less pure)	1.0	Low Cost, Higher Strength
5	Ti+6AL+4V	1.2	High Strength and Erosion Resistance
7	Ti Gr2+0.15Pd	1.9	Crevice Corrosion Resistance
9	Ti-3Al-2.5V	1.3	High Strength and Erosion Resistance
11	Ti Gr1+ 0.15Pd	1.9	Crevice Corrosion Resistance
12	Ti+.3Mo+.8Ni	1.2	High Strength and Erosion Resistance
16	Ti Gr2 + .05Pd	1.4	Crevice Corrosion Resistance, Lower Cost
17	Ti Gr1 + .05Pd	1.4	Crevice Corrosion Resistance, Lower Cost
18	Ti Gr 9 + .05Pd	1.6	Crevice Corrosion Resistance
24	Ti Gr5 + .05Pd	1.6	Crevice Corrosion Resistance
26	Ti Gr1 + 0.1Ru	1.2	Crevice Corrosion Resistance, Lower Cost
27	Ti Gr2 + 0.1Ru	1.2	Crevice Corrosion Resistnace, Lower Cost

Legend:

* ASTM B265 Grade Designation

** Cost Ratio to Lowest Cost Alloy, Current Metal Prices at time of Presentation

*** When Comp. shows "Gr.# + addition", alloy <u>also</u> exhibits features of the base Gr.

Table 2

Comparison of Alloy Erosion-Corrosion Resistance at Various Seawater Test Locations (Ref 1)

Location	**Flow Rate (m/sec)**	**Duration (months)**	**Corrosion Rate (mm/y)**		
			Titanium	**Cu-Ni (70-30)**	**Aluminum**
Brixham Sea	9.8	12	<0.0025	0.3	1.0
Kure Beach	1.0	54	7.5 x 10 (-7)	-	-
	8.5	2	1.2 x 10 (-4)	0.05	-
	9.0	2	2.8 x 10 (-4)	2.1	-
	7.2	1	5.0 x 10 (-4)	0.12	-
Wrightsville Beach	0.6-1.3	6	1.0 x 10 (-4)	0.02	-
	9.1	2	1.8 x 10 (-4)	-	-

Table 3

Titanium Applications in Shipboard Piping Systems (Ref 5)

Firemain Systema
Seawater Ballast Systems
Aegis Radar Cooling Water Systems
Oily Waste Systems
Deck Draining Systems
Magazine Sprinkling Systems
HVAC (Ducting)
Seawater Service System
Feedwater to Distilling Plants
Seawater Compensated Fuel Oil Systems
Bilges
Countermeasure Washdown Piping
Missile Deluge Systems
Stanchions

Table 4

Titanium Heat Exchanger Applications on Navy Ships and Offshore Platforms (Ref 5)

Shipboard	**Offshore**
Ship service turbine generator condenser	Lube oil cooler
Racer Steam Condenser	Engine jacket cooler
Radar and other electronic coolers	Compressor cooler
De-Salination units	Central exchanger
Air conditioning freon condenser	Direct low pressure crude cooler
Distillation brine heater and preheater	Discharge cooler
Lube oil and engine jacket coolers (TAO oilers)	Quench water cooler
Low pressure air compressor cooler	Propane condenser
	Gas dehydrator cooler
	Natural gas cooler
	Glycol cooler
	Flash gas compressor
	Intercooler
	Interstage oil cooler

Table 5

Comparative Cost of Titanium with Other Marine Structural Materials

Comparison Costs of Plate Products in Late 1996
Basis is Carbon Steel at Ration of 1.0

Alloy	Cost Ratio
Carbon Steel	1.0
Aluminum 5456	1.8
Stainless Steel, 316L	4.3
Cu-Ni (90-10)	9.4
Cu-Ni (70-30)	11.8
Alloy 825	12.2
Titanium, Grade 2	12.8
Alloy 400	14.2
Titanium, Grade 16	16.3
Titanium, Grade 7	21.0
Nickel Alloy 600	23.1
Nickel Alloy 625	26.0

This Comparison is on a Volumetric Basis Only. It does not take into consideration strength and modulus factors.

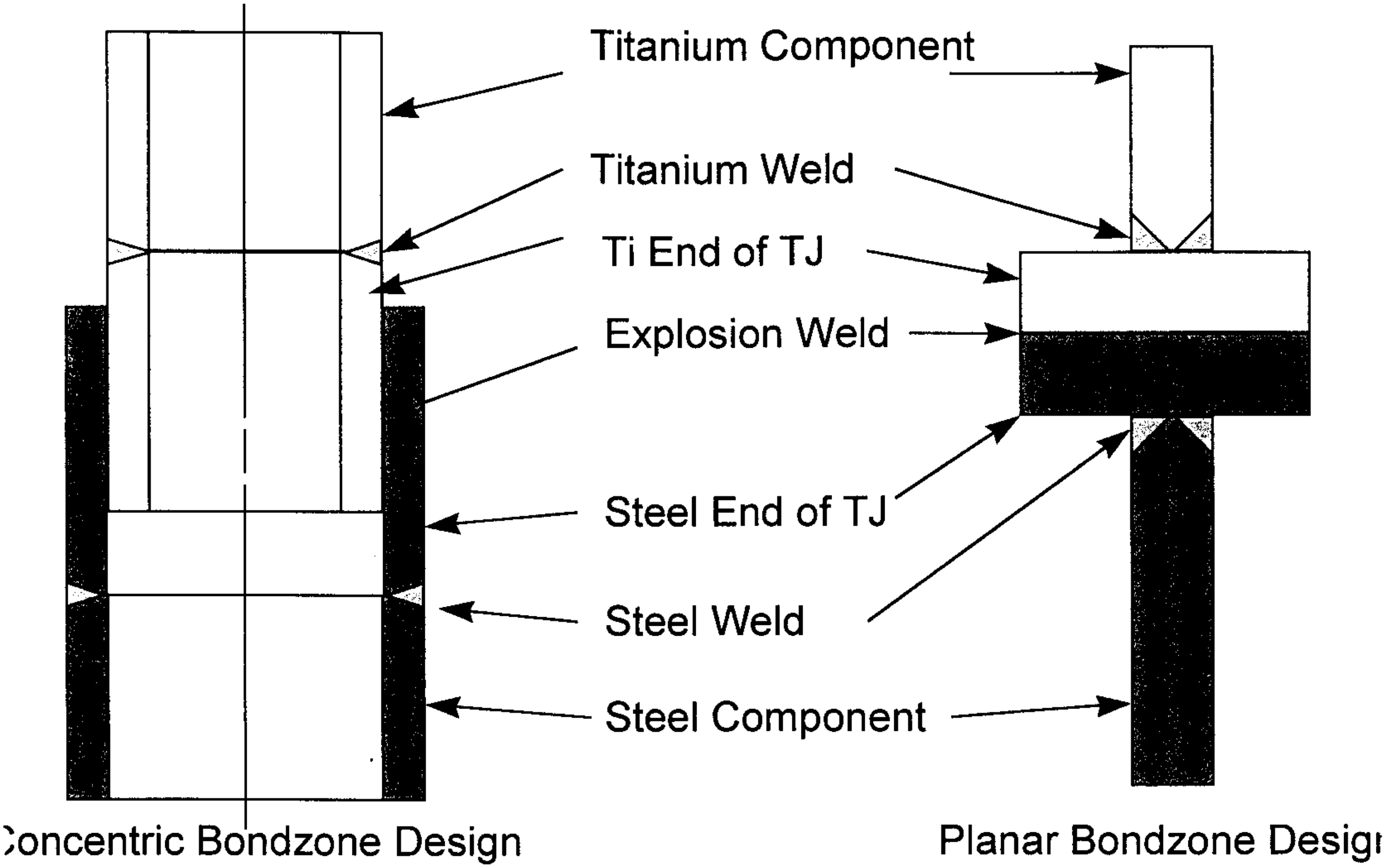

Figure 1

Titanium-Steel welding transition joints permit welded, crevice free joints between titanium and steel. The planar concept is most commonly used in ship construction. In piping, the concentric option may be modified to a tapered bond configuration eliminating the internal step.

SHIPYARD FABRICATION OF TITANIUM PIPING SYSTEMS

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Until recently, most shipboard piping systems were fabricated using materials such as steel, copper, copper nickel, aluminum, monel, bronze, brass, and sometimes more exotic materials such as Inconel 625. For years, the United States Navy has employed 90/10 and 70/30 copper nickel for seawater systems because these materials are more resistant to corrosion than the various steels used for seawater in the merchant marine or for oil systems aboard combatant ships. In addition, copper nickel was favored because it exudes an oily film which is inimical to marine growth. However, this film does not last long at today's piping systems' design flows, especially if the water contains suspended solids, such as silt or other dirty harbor water contaminants.

In addition, it has recently been observed that copper nickel is too soft for long term use aboard ships. The Navy has experienced leaking pipes, due to corrosion and erosion, requiring replacement about every 5 years. Since their ships are designed to last 35 to 40 years, this results in excessive life cycle maintenance costs, system downtime, and intensive man-hour investment.

Titanium's greater strength, resistance to corrosion and erosion, and lighter weight had made it a much preferred alternative. However, for years titanium was on the restricted availability list because of its use for airplane's hydraulic tubing by the U.S. Air Force. Around 1980, it was dropped from this list and the price came down accordingly. Therefore, the industrial and Naval community reevaluated its potential for shipboard seawater piping systems. Concerns addressed included:

1. Availability
2. Acquisition Cost
3. Fabricability in a shipyard environment
4. Necessity for prevention of marine growth
5. Incorporation into ship design, including galvanic effects when connected to other materials.

Each of these topics are addressed in the following sections.

I. AVAILABILITY

Titanium's availability is sufficient to provide all the pipe and plate the ships of the world would ever need. This is due to a number of factors.

1. Dropped from the Restricted Availability List.

2. Ninth most abundant earth's element.

3. Supplies now available from Russia and other former Iron Curtain countries, as well as mines in North America, Australia, Africa, and Southern Asia. Sea mining of titanium ore nodules on the ocean beds may someday be more practical and increase supplies even more.

II. ACQUISITION COST

A cost analysis was conducted for 90/10 and 70/30 copper nickel pipe versus Grade 2 titanium. Generally, titanium's price was found to be about 50 percent higher than 90/10; and to be equal to or less than 70/30. More detailed results can be found in Table I. Since the Navy's standard practice for repairing leaking 90/10 pipe has been to replace the affected sections with 70/30, it can be seen than installation of titanium pipe would pay for itself if 90/10 had to be replaced even once during a ship's life. If a ship has a 40 year life, and replacement of 90/10 pipe is necessary about every 5 years, that makes 8 replacements necessary. Therefore, use of Grade 2 titanium pipe would save at least 700 percent on material cost alone. To this can be added the savings due to elimination of the costly man-hours required for ripout and reinstallation.

III. FABRICABILITY IN A SHIPYARD ENVIRONMENT

A Titanium Applications Seminar was held at Ingalls Shipbuilding in January 1991. The meeting was well attended by representatives of the Titanium Development Association (TDA); Naval Surface Warfare Center (NSWC), White Oak; Naval Ship Weapon Systems Engineering Station (NSWSES), Port Hueneme; Supervisor of Shipbuilding, Conversion and Repair (SUPSHIP), Pascagoula; and various concerned shipyard departments. It was concluded that the shipyard had adequate equipment and personnel to successfully fabricate and install titanium piping systems aboard ships. This was concluded because the shipyard had the equipment and experience necessary for welding stainless steel, which has similar requirements for welding titanium. In addition, the pipe bending machines in use for other materials were deemed satisfactory for titanium processing.

Later that year, one TDA member company provided some titanium plate and pipe samples. The plates were delivered to the Welding Laboratory, where they were successfully cut, bent, drilled, and welded by shipyard personnel. A report on this activity follows:

Commercially Pure Titanium.

Bending: A 1/8 inch thick piece was bent to a radius of 1/4 inch and 3/4 inch. Both bends were successful with no indication of cracking.

Drilling: A 1/4 inch diameter hole was drilled with no difficulty.

Thermal Cutting: A 1/4 inch thick piece was cut with both oxy-acetylene and plasma processes. Both processes made acceptable cuts. Because of the speed of cutting, it was difficult to perform manually. The cut edges were heavily oxidized.

Welding: A butt weld was made in an 1/8 inch thick plate. Gas tungsten arc welding using Ti-1 wire was utilized. There was no apparent problem with this welding.

Alloy Titanium (6AL-4V). Bending: A 1/8 inch plate was bent to a 3/4 inch radius with no cracking but with a large amount of springback. A 1/8 inch plate was used to attempt to make a 1/4 inch radius bend but the material failed brittlely.

Drilling: A 1/4 inch diameter hole was drilled with no difficulty.

Thermal Cutting: A 1/4 inch plate was cut using oxy-acetylene and plasma processes. As with the CP titanium, both processes will cut the material but the required speeds make manual cutting difficult. Again, the edges were heavily oxidized.

Welding: A butt weld was made in a 1/8 inch plate using gas tungsten arc and 6AL-4V wire. A crack developed in the weld. This was attributed to welding over remnant oxides on the cut edges. Because of material availability, a 1/16 inch plate was welded and this was successful.

Lessons Learned. Both types of titanium alloys can be processed using shipyard processes. The commercially pure titanium is easier to use and would be the recommended choice if titanium was to be incorporated into ship design.

It was therefore determined that the Welding Laboratory had all the capability necessary to fabricate grade 2 titanium plates and shapes. This is the "commercially pure" grade installed at the Navy's titanium pipe test facility and the grade that would normally be recommended for shipboard seawater piping systems. Shipboard seawater coolers would require a different grade of titanium alloy, such as the 6AL-4V, which has better heat transfer characteristics.

The 1 inch diameter pipe segments were delivered to the shipyard's Pipe Shop. After bending several segments, Pipe Shop personnel observed that the thin wall titanium pipe had more springback than the copper nickel or corrosion-resistant (stainless) steel (CRES) they normally dealt with. For instance, using one straight section of titanium pipe, they attempted to form a 5 inch radius 90 degree bend. Even though the pipe was initially bent by the bending machine to 114 degrees, when released from restraint, it sprang back to less than 90 degrees. It was determined that the pipe had to be bent to 132 degrees before it would spring back to produce a 90 degree bend with that radius. The Pipe Shop believed this would present no future fabrication problem. As long as the springback property was known, the bending machine could be set to compensate for it. Thus, it was proved that the shipbuilder could perform hot and cold work on titanium plate and pipe in a shipyard environment.

Test Site Supply Main

The Navy operates a titanium pipe test facility in Dania, Florida. Seawater is pumped from a Ft. Lauderdale ship channel, through the piping system, and then discharged back into the channel. The test site's 4-inch supply main, from the feed pump to the seawater duplex strainer, was composed of polyvinyl chloride (PVC). It was desired to change the material to titanium, so that the system would be uniform and to stop leaks. The shipyard volunteered to purchase the materials, fabricate the pipe segment, and ship it to the test site. This would serve the dual purpose of proving that a shipyard has the capability to fabricate titanium piping systems in a shipyard environment and providing the test site with a desired product. Refer to Figure 5 for a drawing of this pipe configuration.

Welding. A proper titanium weld is indicated by the finished weld exhibiting a silver color on the surface. In decreasing order of acceptability, the following chart applies.

Silver - most acceptable
Light or dark straw (gold) - acceptable
Light blue - marginal
Dark blue - reject
White or gray - completely unacceptable

This is one advantage unique to welding titanium. The very color of the finished weld gives an indication of the quality of the weld. The other normal shipyard materials - such as copper, nickel, bronze, carbon steel, mild steel, stainless steel, HY-80 steel, and aluminum - do not exhibit such telltale indications.

It took about two weeks to train a shipyard welder in the proper methods for working with titanium. Some difficulties were experienced with his first attempts at qualification, when he butt welded two pieces of 4 inch pipe together. He was welding scrap pieces of the subschedule 5, grade 2 pipe which would be used to fabricate the supply main.

The welder's first attempts produced welds with a blue color and some that were powdery white, both being unacceptable. Further welds produced a more acceptable color, but x-rays showed impurities in the weld. Several factors contributed to these results:

1. The welding was performed on the open floor of the rather large Pipe Shop, which was open to the atmosphere at both ends of the building. Thus, the weld area was susceptible to stray wind currents.

2. Two sizes of welding rods had been ordered and received: 1/16 inch and 3/32 inch diameter. The 3/32 inch rods had been used to produce the unacceptable welds. These took longer to heat up and cool down than the smaller diameter rods. Therefore, the inert gas welding rod shield had already moved on before the weld had cooled enough to prevent oxidation.

3. The weld must be performed with inert gas both inside and outside the pipe. The inert gas must blanket the weld and keep oxygen away until the titanium cools below about 600 degrees F. The shipyard normally uses argon with a similar welding procedure for stainless steel. The titanium industry also recommends argon or helium for use with titanium alloys. The welder had used the same size shield around the tip of his welding rod that is normally used when welding stainless steel.

The following measures were therefore put into effect:

1. A small enclosed booth was put together on the shop floor, consisting of sheets of clear plastic. The pipe to be welded was inserted through a break in the plastic curtain, and when finished, pushed out the other side of the booth. Series production would require something more efficient and permanent, such as a separate trailer or small room. The most important attribute of such an enclosure being to prevent stray currents of air blowing across a hot weld.

2. The smaller 1/16 inch diameter weld rods were used. They heated up and cooled faster, allowing less chance of oxygen getting to the hot weld before the argon shield moved on.

3. The welding rod shield was made wider and longer, again to prevent oxygen getting to the weld before the titanium could cool below 600 degrees F.

All these measures taken resulted in a silvery weld surface, which also exhibited no impurities when x-rayed. The welder was therefore qualified and subsequently certified by SUPSHIP, Pascagoula.

Bending. The supply main piping system was to be fabricated from three 4-inch segments which were each 20 feet long. The finished product would be about 50 feet long, with an S-bend near one end. To form the S-bend, the pipe was fed into an electrohydraulic bending machine, after insertion of a mandrel with 3 balls, widely spaced. Unfortunately, the pipe formed surface ripples along the inside of the bend. There were ripples for about 4 inches, followed by about 4 inches of smooth pipe surface, followed by about 4 inches of ripples, etc. Each ripple was about 1/8 to 1/4 inch deep.

A tool manufacturer recommended that the mandrel be replaced with one having more balls, more closely spaced. This would give more support to the inside surface of the pipe, to help prevent buckling. To support the outside surface, it was recommended that a wiper dye be used. This is a convex surfaced tool that is placed on the machine just before the pipe feeds into the big pulley wheel, prior to bending. See Figures 6 and 7 for more details on mandrels and wiper dyes.

A new section of pipe was put onto the machine; a mandrel having 5 more closely spaced balls was inserted into the pipe; and a wiper dye installed just before the pulley. These measures resulted in a smooth S-bend, with no deformities.

Fabrication. The test facility preferred sliding flanges, in order to allow more flexibility in system alignment. Therefore, titanium flared end fittings were purchased to weld to each end of the five pipe sections. Stainless steel flanges were installed. There should be no galvanic action with the seawater inside the pipe, because the flanges are on the outside. The qualified welder slipped the flanges onto each section and successfully welded the flared end fittings in place.

Hydro Testing. The finished pipe sections were bolted together with gaskets between the flanges. The complete assembly was then hydrostatically tested to 225 pounds per square inch (psi) for 30 minutes, twice as long as the normal Navy requirement. The pressure was taken as 1.5 times the maximum seawater system operating pressure aboard TICONDEROGA Class cruisers: the firemain pressure of 150 psi. No leaks were detected, except for a few drops at one of the gasketed connections. This was probably due to those bolts not being tightened quite enough.

Installation. The main was disassembled, shipped to Ft. Lauderdale, and retrofit at the test facility where the system has been operating successfully for three years.

IV. PREVENTION OF MARINE GROWTH

Overview of Various Fouling Control Methods

Since titanium is more prone to the formation of a surface layer of marine growth than the copper nickel piping systems it might replace, various available water treatment methods were reviewed.

Chlorine. The Navy is familiar with chlorine, having previously used it to purify shipboard potable water systems. In addition, the Navy has conducted extensive study of the use of chlorine for seawater purification. Electrolytic chlorinators are installed on various U.S. Navy piers. U.S. submarines, which have some titanium seawater system components, hook up to the chlorinators to clean out their systems between patrols. Chlorine is a relatively strong halogen that has a harmful effect upon the local marine environment when pumped overboard. The Naval Surface Warfare Center (NSWC) has reported that zero chlorine effluent may soon become required for U.S. waters.

Chlorine Dioxide. This chemical has an advantage over chlorine in treatment of one type of bacteria; but chlorine has the advantage in another area. However, it is still basically chlorine, relatively strong, and harmful to the marine environment. It would also be affected by the zero chlorine effluent requirement if that becomes the law.

Electron Beam Radiation. This involves subjecting the incoming seawater to nuclear radiation. There are some factories in this country that use this method to purify their drinking water. Because of potential shipboard safety impacts and relative cost, this method was dropped from further consideration.

Bromine. The Navy is quite familiar with this water treatment method. It is used throughout the fleet for potable water purification. Being weaker than chlorine, it might not be strong enough to effectively keep seawater piping systems clean. Conversely, although a weaker halogen than chlorine, it would still be harmful to the marine environment.

Ultraviolet Light. Ultraviolet (UV) light treatment is used throughout the merchant fleets of the world, including the U.S., to purify potable water. It is allowed by the U.S. Coast Guard and the American Bureau of Shipping as an alternate to bromination. Many American municipalities use UV light treatment, sometimes together with ozonation, to purify drinking water and/or sewage. UV light is environmentally friendly. It is a method not yet used aboard U.S. Navy ships.

Ozone. As mentioned above, bubbling ozone (O_3) into drinking and/or sewage water is a purification method used all over the United States. It was suspected of being an intermediate by-product which might have contributed to the successful seawater purification testing that Ingalls conducted about four years ago. This involved the electro capacitance discharge technology discussed in Reference [1]. Ozonation is also environmentally friendly. It is another method not yet used aboard U.S. Navy ships.

Based upon this review, UV light treatment and ozonation were selected for test evaluation and determination of effectiveness for shipboard seawater system purification.

Test System

Titanium Pipe Test Facility. A piping system design was prepared and various vendors agreed to supply components thereof. It was decided to install the proposed test equipment on one leg of a titanium pipe test facility already established in Ft. Lauderdale, Florida.

The original test loop was constructed in 1990. Seawater is pumped directly from the Port Everglades shipping channel, passed through a coarse duplex strainer (3/16 inch hole diameter) to filter out large shells and is then pumped (300 gpm at 120 psi) through the test loop and discharged back into the channel. The loop was designed to test a variety of parameters including the effects of different flow rates on biofouling. Piping legs of varying diameters were incorporated into the titanium test loop to achieve flow velocities of 3, 8, and > 10 ft/sec. A blank-off and stagnant leg, with a cruciform piping configuration to allow for observation of undisturbed stagnant seawater, were also installed. A test and evaluation plan was drawn up and formalized via a Cooperative Research and Development Agreement (CRADA).

Equipment Supply. Several organizations participated in this test effort by supplying various equipment. A list of those participants and equipment is contained in Table I.

TABLE I. PROJECT PARTICIPANTS.

ORGANIZATION	EQUIPMENT
ALFA-LAVAL MARINE & POWER	TITANIUM PLATE HEAT EXCHANGER
DOBSON'S USA, INC./AQUAFINE CORP.	ULTRAVIOLET PURIFIER
DRESSER INDUSTRIES	COMPOSITE VALVES
EMERY TRAILIGAZ	OZONE GENERATOR
NAVAL SURFACE WARFARE CENTER CARDEROCK DIV., ANNAPOLIS DETACHMENT	TITANIUM SHELL & TUBE HEAT EXCHANGER
OREGON METALLURGICAL CORPORATION	TITANIUM PLATE & PIPE SAMPLES
SPECIALTY PLASTICS, INC.	FIBERGLASS PIPE & FITTINGS
TITANIUM METALS CORP. (TIMET)	TITANIUM PIPE

It was originally planned to fabricate a copper nickel and bronze piping system which would be a mirror image of the already installed titanium piping system. The copper nickel system would be connected to the titanium system and, with seawater flowing through both, comparative analysis of marine fouling rates could be made and the effectiveness of alternative water treatment methods could be determined. Due to revised priorities, this plan was put on hold. An existing copper nickel system at the shipyard was disassembled and shipped to the test site as a substitute. It had previously been used for some flowing seawater tests. Although not a mirror image of the titanium system, it was believed that the system would still be useful for comparative analysis.

It was decided to install some fiberglass reinforced plastic (FRP) in the titanium portion of the system to evaluate its performance. Therefore, FRP fittings, provided by Specialty Plastics, were retained for all the required elbows, tees, and reducing fittings. Composite valves for all the check, isolation, and sampling valves were included in the system design. Figure 1 depicts the final system design configuration.

It was originally planned to provide titanium flanges with stub ends to weld to the titanium pipe. However, sliding, rotatable flanges would allow more flexibility in system fabrication. Therefore, since the flanges would not see any of the seawater flowing inside the titanium pipe, the use of stainless steel sliding flanges was adopted as the most cost effective alternative.

System Fabrication. Receipt of all the system components at the test site was completed in December 1992. During January 1993, the coolers and seawater treatment equipment were connected to the supply main via the fiberglass valves and fittings. Since the total connected length of FRP valves and fittings formed a subsystem sufficient for evaluation, no straight sections of FRP pipe were installed. It was therefore decided to utilize the FRP pipe already received for future piping system evaluation at the test site.

The requisite lengths of titanium pipe necessary for completion of the system were determined. Astro Metallurgical became another participant by offering to cut the titanium pipe to the proper lengths, slide on the stainless steel flanges, and flare the pipe. The pipe and flanges were shipped to their fabrication facility in Wooster, Ohio, fabricated, and returned to Ft. Lauderdale. The finished pipe was connected into the test loops, completing system fabrication in early April 1993. Figures 2 through 4 show the completed installation. Please refer to the Acknowledgments for a complete list of project participants.

Water Testing & Analysis

System Testing. Successful system lightoff was accomplished on 14 April, with the assistance of representatives from the various equipment suppliers. Some operational problems were experienced: (1) Backup of water into the ozone generator occurred, but this was resolved by installing a small check valve in the ozone supply tubing. (2) The ambient humidity in the area was so high that the single tower, nonregenerative air dryer became saturated within 24 hours, causing ingestion of excess moisture by the ozone generator. This problem was resolved by replacing the dryer with a two tower regenerative unit. (3) The site was hit by lightning, knocking out both the ozone generator and the UV purifier, in addition to other nonrelated equipment at the facility. The damaged equipment was repaired and put back on line. (4) The system supply pump failed several times and was eventually replaced. (5) Replacement of a nearby navigational aid required that the system be shut down because of the aid's proximity to the system's supply inlet. Operation of the system during installation would have posed a safety hazard to the divers installing the aid and would also have caused an abnormal ingestion of debris into the system. (6) Excessive barnacle incrustation of the system's sea suction basket severely reduced flow performance until the basket was cleaned. (7) Installation of other buildings and support services nearby at the facility caused further disruption and temporary curtailment of operations.

Water Analysis. When the equipment problems were resolved, the water analysis test plan was accomplished as follows:

1. Ten days running treated, with daily water samples taken for analysis.

2. Open and inspect for marine growth, corrosion, and erosion.

3. Ten days running untreated, with daily water samples taken for analysis.

4. Open and inspect for marine growth, corrosion, and erosion.

5. During both treated and untreated tests, take water samples, let remain stagnant up to ten days, and analyze.

Local personnel at the test site took the water samples, performed the initial analyses required (such as oxygen and ozone content, turbidity, and temperature); packed the samples in dry ice; and shipped them to marine laboratories for more in-depth analysis. Marine and/or micro biologist conducted the detailed water analyses required. The results of the analysis showed that UV purification and ozonation significantly reduced marine fouling in titanium and fiberglass seawater piping systems. Detailed results are contained in the "NSWC/WO and Ingalls Shipbuilding CRADA Final Report"[2] which can be made available on request.

Open and Inspect Examinations of the Titanium Test Loop. Light biofouling (a matrix of microbial growth and a few macrofouling organisms) and what appeared to be a layer of sand/sediment on the "Y" area was observed during the open and inspect examination. The mineralogical deposits with microbial biofilm could be wiped off easily by hand and the titanium pipe surface showed no discoloration or under-deposit pitting. The titanium plate heat exchanger was also opened and inspected. No macrofouling was observed after 10 days of untreated seawater running through the titanium plate heat exchanger.

UV and O_3 Lessons Learned. The UV purifier apparatus operated more reliably than the ozone generator, with much less maintenance downtime. Another drawback associated with the operation of the ozone generator involved the requirement for more support services. Both the UV and the ozone units required an electrical power source; however, the ozone unit also required fresh water cooling and a supply of clean, dry air. The manufacturer advised that either compressed oxygen cylinders or an air compressor with dryer would suffice. A compressor and a deliquescent dryer were therefore connected to the air supply. Due to the extremely humid ambient conditions in the area, the deliquescent medium became saturated too frequently, requiring replacement. Therefore, the dryer was replaced with a self regenerative, dual tower desiccant unit. That type of dryer operates by using one tower for drying the air supply, while the second tower is being dried via a small portion of the dry air from the first tower. The functions of the two towers are automatically switched via a timing mechanism.

Ozone generators produce ozone via high voltage (33,000 volts) discharge across glass or synthetic crystal tubes, which have a dielectric constant compatible with the process. UV purifiers kill microorganisms by shining ultraviolet rays across similar glass or crystal tubes through which water is flowing. Either of these apparatuses would probably be acceptable for pierside use. However, the ozone generator manufacturer requested that his unit be protected from the elements. Therefore, a plywood box was used at the test site to house the apparatus, as shown in Figure 2. The UV apparatus, including the purifier and its control panel, also shown in Figure 2, did not require any special protection from the elements.

For shipboard shock survivability, it is believed that the stronger, less brittle crystal tubes would be preferable to glass. Also, the tubes should be soft mounted, rather than their present land-based hard mounted configuration. This might be accomplished via employment of synthetic rubber mounts at the ends of each tube.

In regards to size and weight, the UV purifier was much lighter in weight and occupied much less space. In regards to shipboard operating personnel safety, the ozone generator produces much higher voltage than the UV purifier. Note the warning label plate on the ozone unit shown in Figure 4.

Because of the superior reliability demonstrated by the UV purifier unit and the other considerations discussed above, at the conclusion of the project testing, the UV purifier was kept on line but the ozone generator was sent back to the manufacturer. A visit was made to the El Diablo nuclear power generating plant in California. This plant successfully employs large capacity UV light treatment equipment for purification of its seawater cooling systems. Thus, similar equipment may be useful in preventing marine fouling of shipboard seawater piping systems. Further comparative testing of UV purification is planned at another test facility in King's Bay, Georgia, and the UV equipment manufacturer has agreed to provide a unit for that testing. Chlorination is currently being tested at that facility. However, it is reported that the Environmental Protection Agency (EPA) may soon forbid discharge of any chlorine into U.S. harbors; so UV purification is seen as a possible alternate and environmentally friendly water treatment method.

Composite Components Performance. The composite valves and fittings tested exhibited no indications of corrosion. No conclusions can be drawn, however, regarding erosion resistance because of the relatively short period of testing. The composite valves were installed without any protective coating. As a result, the yellow valve surfaces were bleached to a much lighter color within a few months. Discussion with the manufacturer verified that this might be attributed to ultraviolet light from the sun and be indicative of an embrittlement of the surface layers of the valve. This could be prevented by application of a protective coating (paint) or by impregnating the composite material with other substances. For instance, the fiberglass tees and elbows installed in the system were impregnated with carbon black to absorb ultraviolet rays. The carbon black distributes the absorbed energy throughout the material. This prevents an excessive rise in the pipe's surface temperature which would cause vaporization of the resin that holds the glass together. Therefore, protective coatings or impregnation would be required for weather deck applications of composite, specifically fiberglass, piping components installed aboard ships.

At a Navy/Industry meeting, a submarine community spokesman verified that pierside chlorinators were installed at various submarine bases for cleaning seawater systems between patrols. Also, that the Seawolf Class submarines have electrolytic chlorinators installed aboard ship. Some submarines currently in service have titanium coolers, but the interconnecting piping systems are Inconel 625, which is more expensive than titanium. A titanium industry representative present stated that Inconel 625 is subject to stress corrosion cracking under these conditions, whereas titanium is not.

A microbiologist at that meeting stated that marine organisms in seawater attach themselves to the walls of copper nickel pipe via excretion of an acidic solution. This solution reacts with the metal to create a small pit in which the organisms reside. This also sets up a galvanic couple between the surface beneath the organisms and the still intact protective film on the metal surface just outside the colony. This causes further corrosion of the metal surface beneath the colony, deepening the pit. Thus originates the term microbiologically influenced corrosion (MIC). This phenomenon was studied in research projects described in References 3 through 9.

However, the microbiologist further went on to explain that, since titanium is resistant to almost all acidic attack, marine organisms can only attach themselves to a surface layer of green slime, if one has formed. However, when water flow through the pipe is started or increased, these organisms are frequently washed away. Therefore, it would be logical to assume that titanium seawater systems will remain cleaner than copper nickel systems, especially at higher allowable flows.

V. SHIPBOARD SYSTEM DESIGN, GALVANIC EFFECTS & COST ANALYSIS

Navy Request

The Navy AEGIS Program Manager for cruisers and destroyers visited the test site on 16 April 1993. After a briefing on the project's aims and achievements, he requested that a prototype titanium seawater piping system or subsystem be designed that, pending approval, would be installed aboard an AEGIS cruiser or destroyer. After review of the available 3M failure data (contained in Appendix 1) for all AEGIS cruisers commissioned since 1983, the forward AEGIS cooling water system, being small and relatively independent, was selected for titanium retrofit. Accordingly, a proposal was prepared and submitted for installing this system aboard, the Ingalls-built USS PORT ROYAL (CG 73), the last AEGIS cruiser to be built. This proposal was eventually rejected because the cruiser construction program was nearing completion.

Destroyer Design

The Navy Program Manager for AEGIS destroyers later visited the test site and was also briefed on the project. Subsequently, an AEGIS destroyer proposal was prepared for a titanium seawater piping system. Since the AEGIS cooling water system aboard the destroyers is not an independent system, and since an Engineering Change Proposal (ECP) already existed to install titanium tubes in the AEGIS coolers, an alternate system was selected. Review of the 3M failure data aboard the AEGIS cruisers revealed that the gas turbine generator (GTG) seawater cooling systems were also prone to failure. Since those systems aboard the destroyer remained independent, they were selected to be the candidates for replacing copper nickel components with titanium.

Piping and flow were redesigned to make optimum use of the advantages inherent in the use of titanium, including:

1. The common fix currently employed to remedy leaking 90/10 seawater piping systems involves replacing with 70/30. The 70/30 is a little stronger than 90/10, but is still relatively soft compared with titanium. The shipyard conducted a comparative analysis of pipe acquisition costs: grade 2 titanium versus 90/10 and 70/30 copper nickel. Table II indicates that titanium is about 50 percent more expensive than 90/10 and was equal to or less than 70/30. Titanium once installed should last the projected 40 year life of each ship. As indicated in Appendix 1, copper nickel seawater piping system failures are not rare. If copper nickel has to be replaced even once, the titanium pays for itself. Therefore, titanium seawater piping systems would be more life cycle cost effective.

2. The seawater system design velocity could be increased over the destroyer's currently specified upper limit for copper nickel, 12 feet per second (fps), because of titanium's superior abrasion resistance. The AEGIS cruiser's seawater systems were designed with a 15 fps upper limit. Therefore, the destroyer's allowable velocity was raised from 12 to 15 fps. The Navy personnel associated with ship noise signatures indicated that the resultant increase in noise generated would be within acceptable limits. One advantage to be gained from increased velocity is decreased proliferation of marine growth on the pipe walls. This may mitigate the necessity for water treatment.

3. This increase in velocity allowed decreasing the pipe size from 2-1/2 inches to 2 inches, making the titanium system more cost effective.

4. Retention of bronze valves also improved cost effectiveness. Titanium ball valves made in the United States cost about 10 times the price of bronze valves. During a recent trip to Norway, it was determined that titanium valves there were about 3 times more expensive vice 10.

A gas turbine propelled patrol boat, the HIDDENSEE, was built in Russia in 1985 for the East German Navy. When East and West Germany united, the boat was given to the U.S. Navy. Titanium seawater piping systems were part of the design, with bronze valves. To prevent galvanic corrosion of the bronze by the titanium pipe, the Russians had inserted composite gaskets, bolt sleeves, and washers at the appropriate interfaces. Examination of the valves determined that, if the valves were those originally installed, they had weathered nine years of operation without deterioration.

Retention of bronze valves would decrease system acquisition cost without seriously degrading long term system operation. Bronze valves last much longer than copper nickel pipe. It was therefore decided to use composite gaskets in the AEGIS destroyer's GTG titanium cooling water system design. This would include any interface with a dissimilar metal: cross connect with the firemain, bronze valves, sea chest, overboard discharge, etc. The Navy will use these gaskets in titanium systems which they plan to install aboard other ship classes, as discussed in the next section.

5. Again to improve system cost effectiveness, it was decided to retain the bronze and copper nickel system components within the GTG module. The GTG manufacturer was apprised of these intentions, and if they decide to do so, may change their part of the system to titanium at some later date. Their subsystem includes three copper nickel and bronze shell and tube type coolers. If they eventually opt for titanium, it is hoped they will change to plate and frame units which are less maintenance intensive (easier to clean and to determine when clean) and are usually smaller and lighter in weight. They are also comparable in cost to the older type of shell and tube coolers.

6. The piping wall thickness was decreased due to titanium's superior strength. This will decrease system weight and increase ease of installation.

7. Pump characteristics were revised as necessary to accommodate the change in flow. Titanium pumps would be used, if available, for compatibility and decreased weight. If titanium units were not available, composite gaskets would be added.

A rough order of magnitude (ROM) price was estimated for the proposal, based upon material and labor impacts associated with new construction, for a Flight IIA AEGIS destroyer. The shipyard planned to submit this proposal to PMS 400D as an Affordability Cost Candidate (ACC) for long term savings.

Subsequent Developments

The shipyard met with the Navy and some titanium manufacturers to help determine whether it was practical to retrofit some titanium seawater piping systems aboard the Ingalls-built LHA Class during overhaul, and aboard the new LPD 17 Class during construction. It was decided that both plans were practical and cost effective and are now proceeding accordingly. USS SAIPAN (LHA 2) was retrofit with titanium piping systems. Titanium piping systems were also included in the shipbuilding specifications for SAN ANTONIO (LPD 17).

At one of these meetings, the Navy stated that rules and regulations would be formulated for titanium fabrication; that any shipyard wishing to fabricate titanium systems or structure for a Navy contract would be visited; and the acceptability of the shipyard's facilities, training, safety, and operational procedures would be determined.

IV. CONCLUSIONS

1. Copper nickel seawater piping systems exhibit failures due to erosion and corrosion mechanisms in time frames as small as one year, depending on service.

2. Cost analysis indicates the following.

   a) Titanium pipe prices are about 50 percent greater than 90/10 copper nickel and equal to or less than 70/30 copper nickel.

   b) Titanium valves currently cost from 3 to 10 times more than bronze valves.

   c) Based upon the copper nickel seawater piping system failure rates reported, utilization of titanium pipe and fittings, with retention of bronze valves, should provide a more cost effective system over the projected 40 year ship life. This assumes a cost effective method to prevent galvanic action between the titanium and nontitanium system components. (See No. 4 below.)

3. Based upon titanium's properties and its use aboard offshore oil rigs; in heat exchangers aboard merchant ships, and aboard foreign combatants, it is predicted that titanium seawater piping systems would last the 40 year projected life of U.S. Navy ships.

4. Use of composite gaskets, bolt sleeves, and washers may be an effective isolation method to prevent galvanic corrosion of nontitanium components of titanium seawater piping systems.

5. Titanium seawater piping systems can be successfully fabricated in a normal shipyard environment, provided the welding is performed in a draft-free area by a qualified welder.

6. Ultraviolet radiation and ozone generation are effective, environmentally friendly methods for reducing marine fouling of seawater piping systems.

7. Based upon the equipment tested and the time period involved, ultraviolet radiation equipment appears to be more reliable, safer, lighter weight, smaller, and require fewer support services than ozone generation. Additional evaluation would be warranted, for both water treatment techniques, to determine associated shipboard and/or pierside impacts; these would include both material and labor impacts associated with installation, operation, maintenance, and spare parts inventory.

8. Nonmetallic composite pipe, valves, and fittings resist corrosion.

9. Nonmetallic composite materials installed on ships' weather decks would require a protective coating and/or impregnation to prevent deterioration due to ultraviolet radiation from the sun.

10. The Navy and private industry can successfully cooperate in testing programs geared to the improvement of ship design, construction, operation, and maintenance.

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COPPER NICKEL VS. TITANIUM

COMPARATIVE PIPE PRICES

($/FT:BASED UPON A 1000 FT ORDER)

PIPE SIZE	CLASS 200: 90/10 COPPER/NICKEL			CLASS 200: 70/30 COPPER/NICKEL			SCHED 5 GR 2 TITANIUM	
(IN.)	A	B	C	A	B	C	D	E
1.5	5.71	5.50	-	7.25	8.51	10.14	12.39	7.75
2.0	8.28	6.64	-	10.78	15.02	14.69	14.91	13.35
3.0	14.65	14.32	-	18.90	28.49	24.77	29.37	25.35
4.0	21.65	20.83	-	27.94	36.74	33.40	34.23	31.85
5.0	34.93	37.40	32.52	43.98	53.21	48.37	-	50.90
6.0	45.37	45.37	42.35	56.70	68.76	59.79	60.90	57.65
8.0	56.00	68.28	65.66	73.10	96.56	83.96	92.15	82.50

A	ALASKAN COPPER AND BRASS, WASHINGTON (07-25-95)
B	PRODUCTION SUPPLY CO., LOUISIANA (07-26-95)
C	ANSONIA COPPER AND BRASS, CONNECTICUT (07-21-95)
D	RMI TITANIUM COMPANY, OHIO (08-08-95)
E	TITANIUM METALS CORPORATION, OHIO (07-21-95)

Table II.

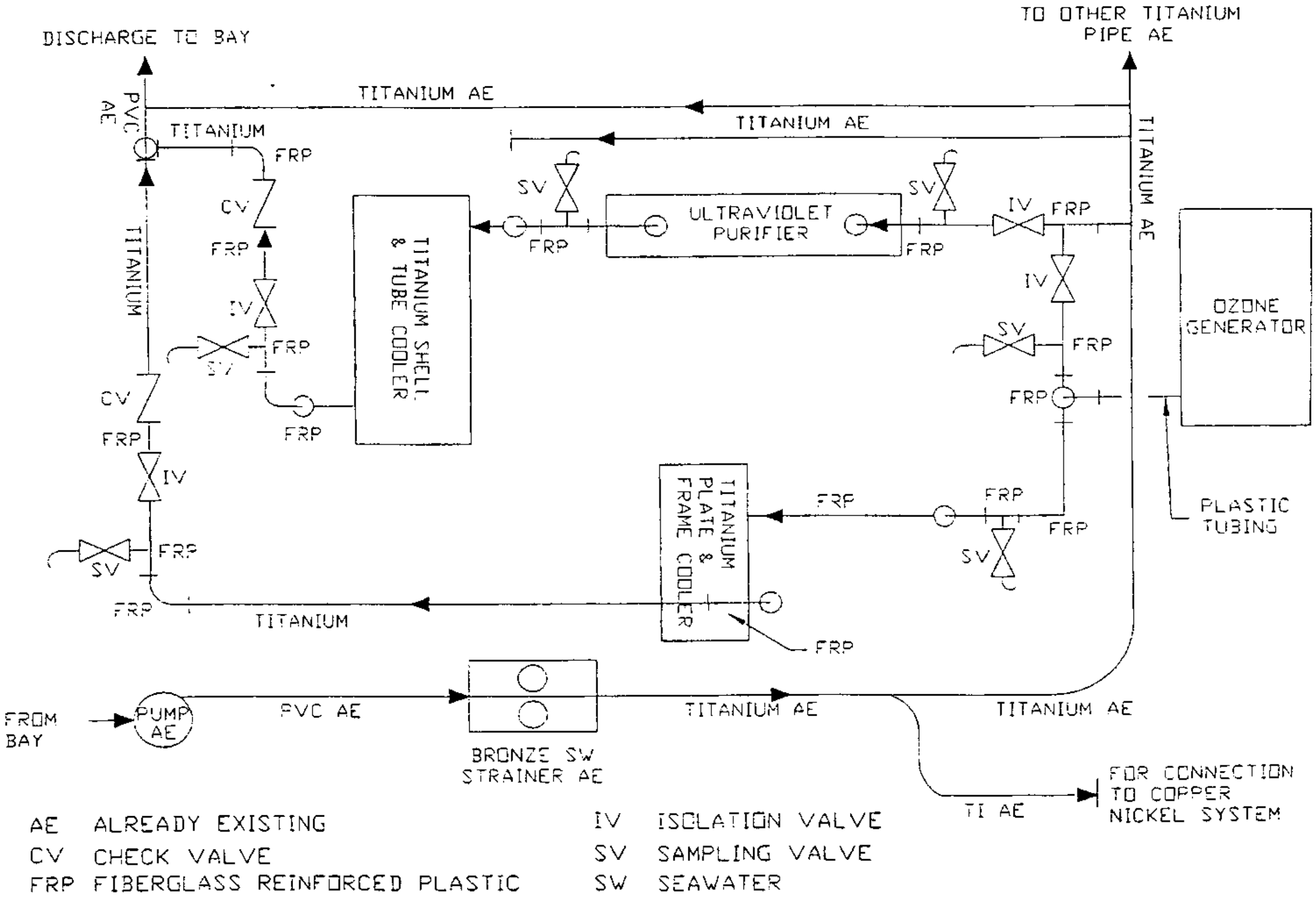
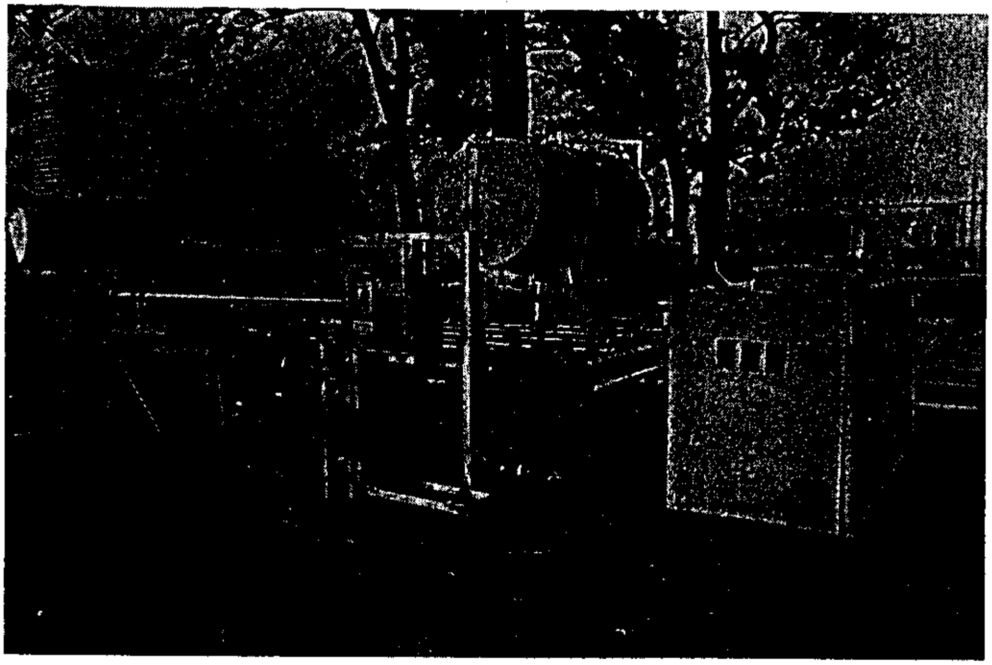


Figure 1. Test Equipment Arrangement Sketch

TOP: Ozone generator in white box on right. UV purifier control panel in center.

BOTTOM: Duplex strainer in SW supply main on left. Titanium plate & frame cooler to right of strainer. UV purifier just to the right of heat exchanger. Titanium shell and tube cooler behind plate & frame unit.



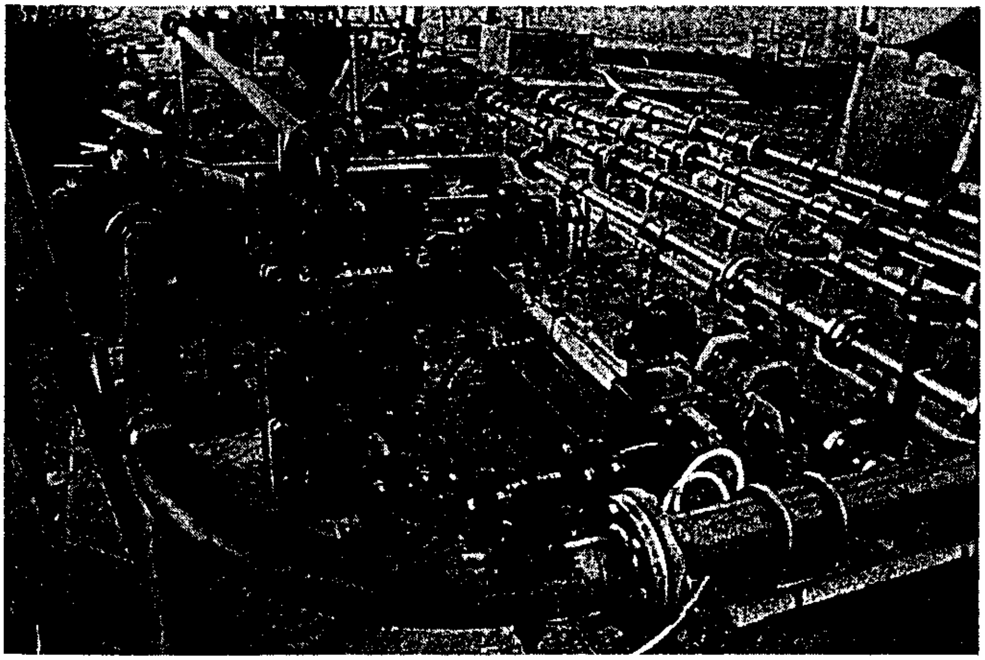


Figure 2. Completed System Installation.

LEFT: Alfa-Laval titanium plate & frame cooler.

RIGHT: NSWC titanium shell & tube cooler.

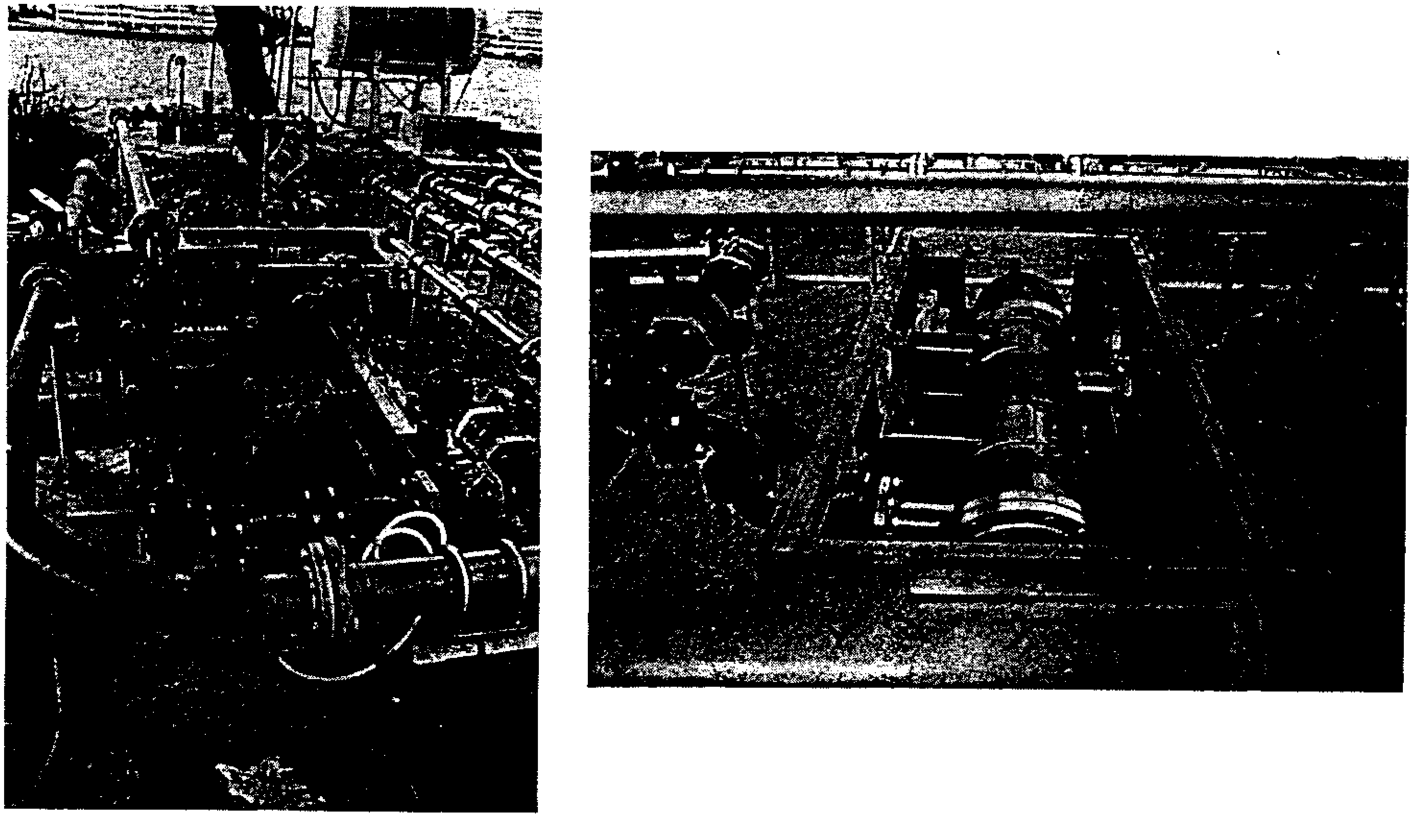


Figure 3. Titanium Heat Exchangers.

TOP: Emery Trailigaz Ozone Generator

BOTTOM: Aquafine Ultraviolet Purifier

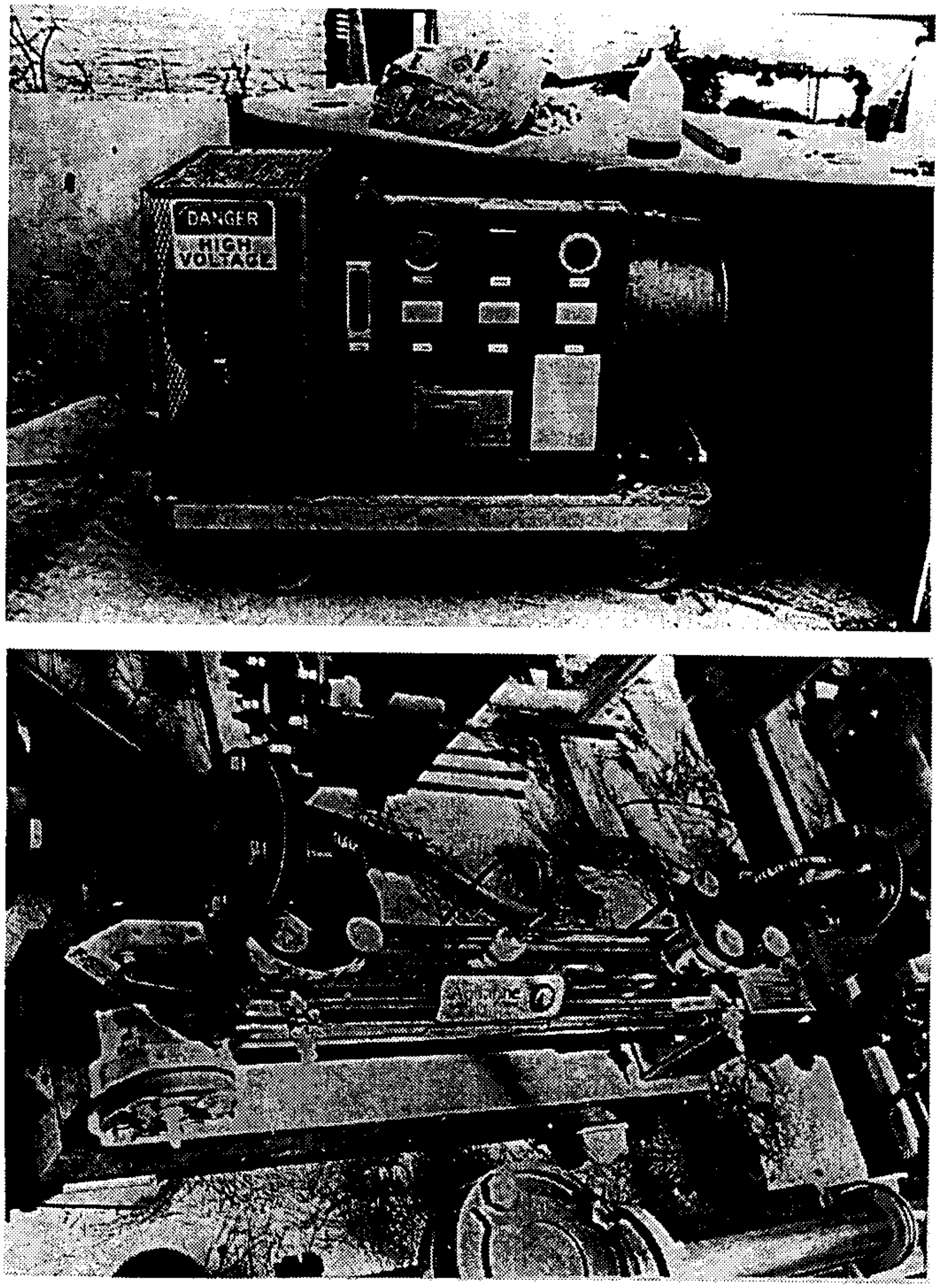
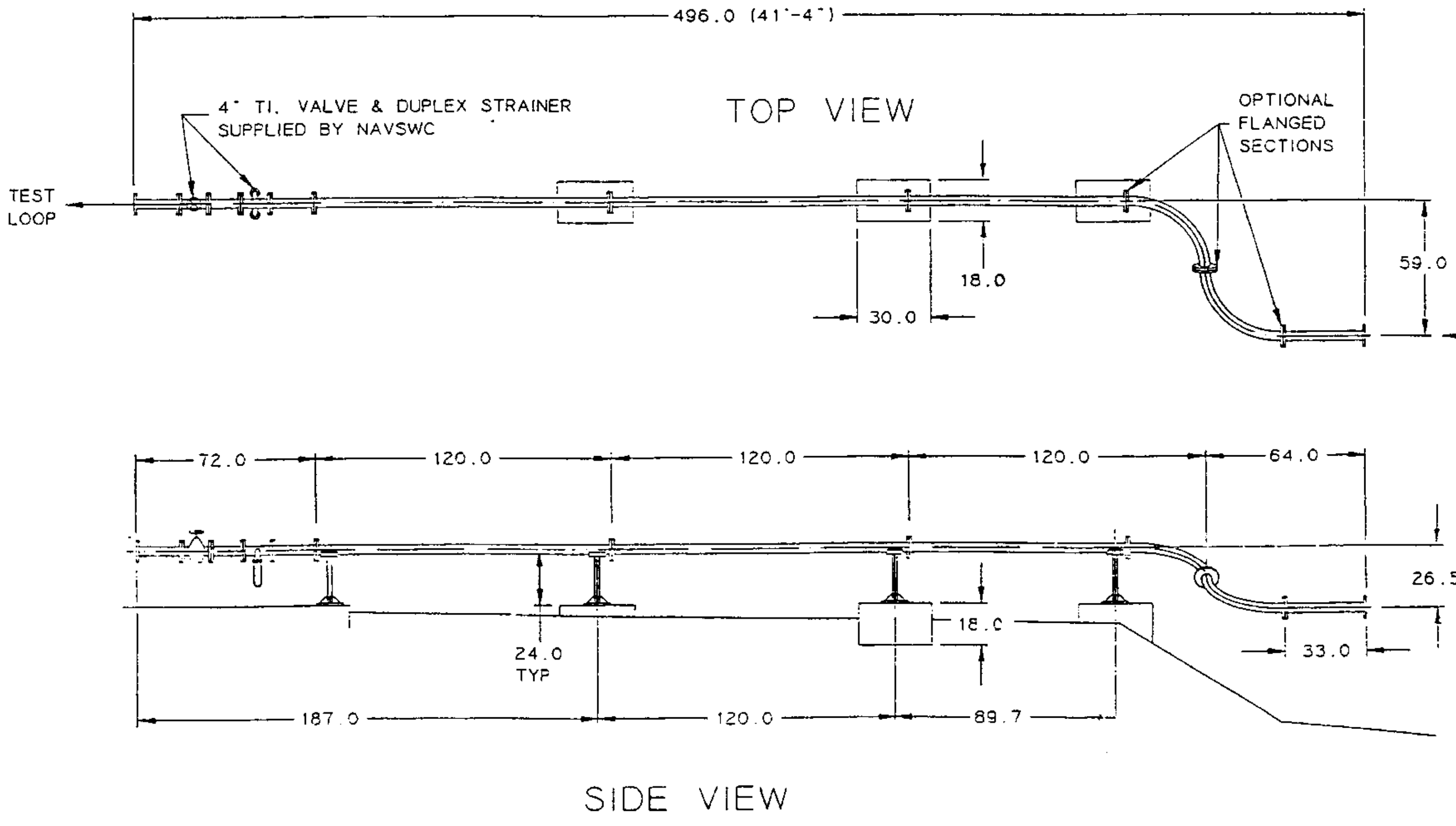


Figure 4. Water Treatment Equipment



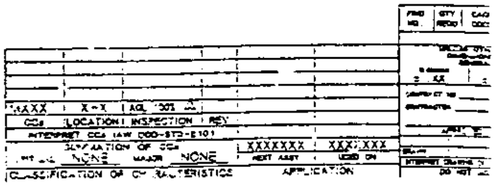
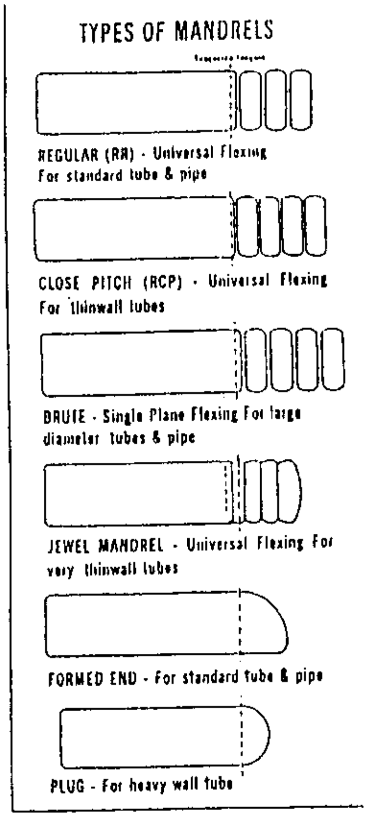
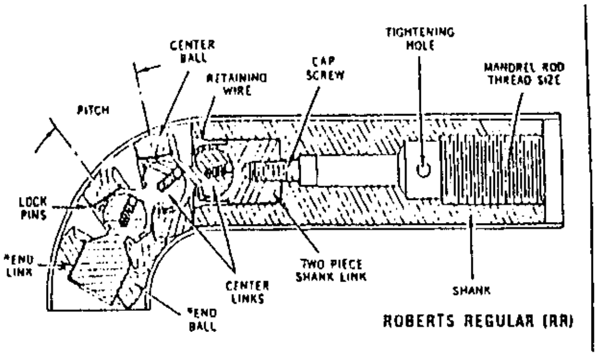


Figure 5. NSWC Supply Main

NOTE: Dimensions are in inches.





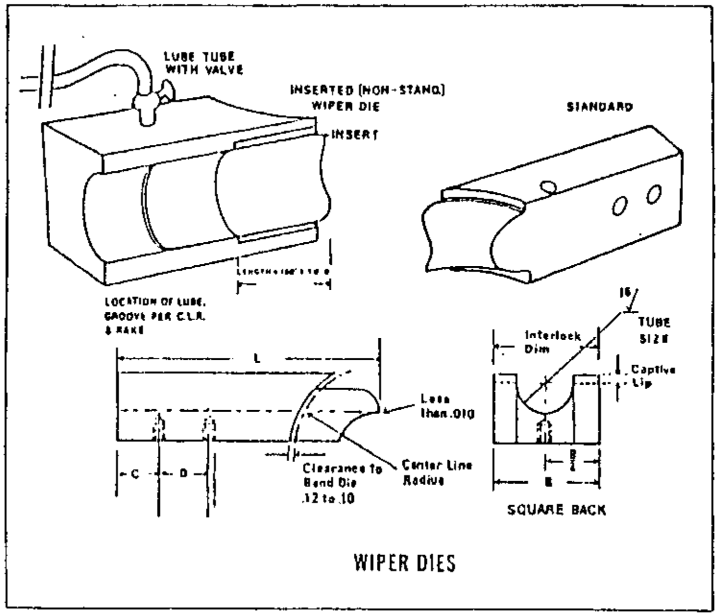
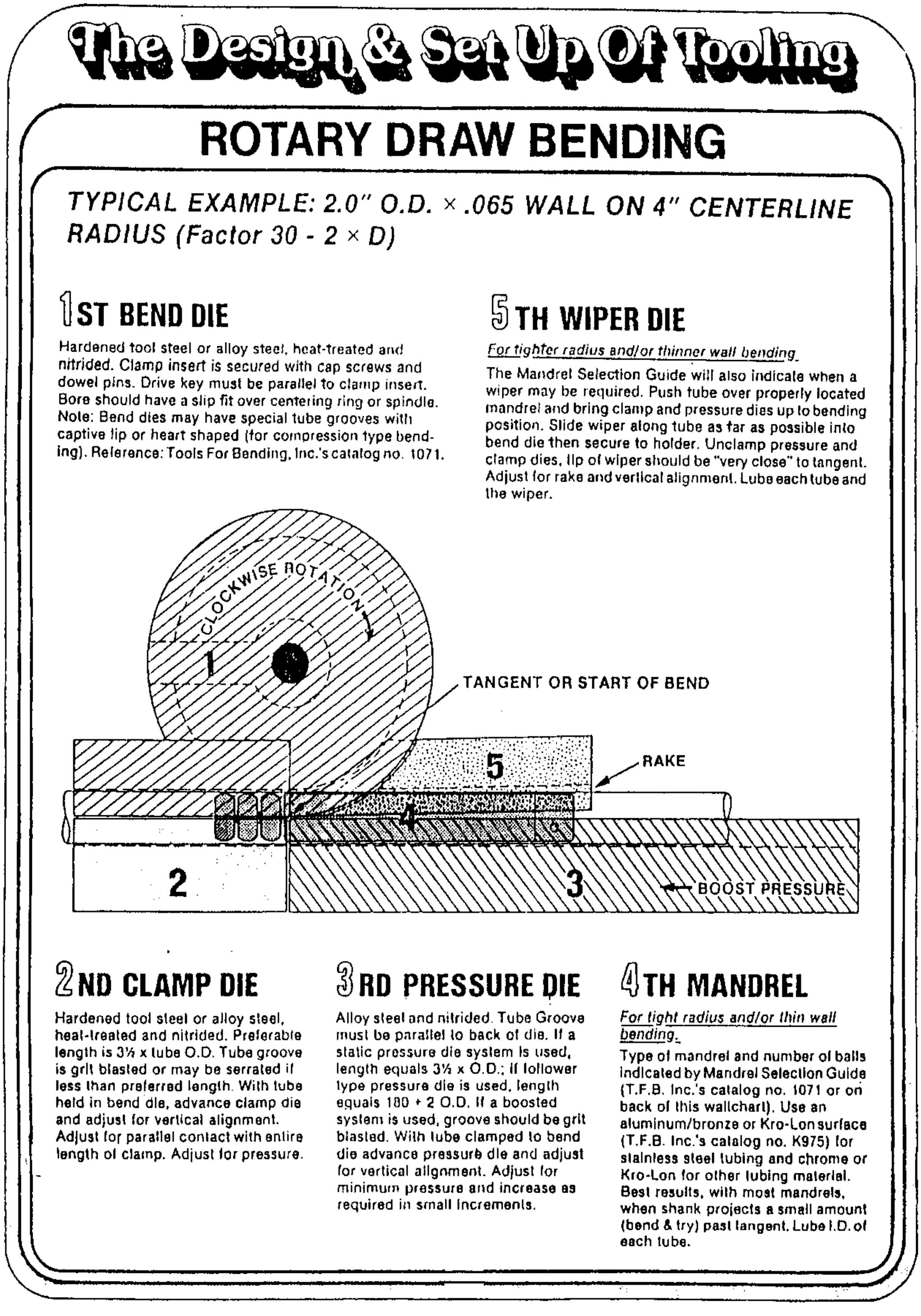


Figure 6. Mandrels and Wiper Dies.

Figure 7. Pipe Bending Machine.



The Design & Set Up Of Tooling

ROTARY DRAW BENDING

TYPICAL EXAMPLE: 2.0" O.D. × .065 WALL ON 4" CENTERLINE RADIUS (Factor 30 - 2 × D)

1ST BEND DIE

Hardened tool steel or alloy steel, heat-treated and nitrided. Clamp insert is secured with cap screws and dowel pins. Drive key must be parallel to clamp insert. Bore should have a slip fit over centering ring or spindle. Note: Bend dies may have special tube grooves with captive lip or heart shaped (for compression type bending). Reference: Tools For Bending, Inc.'s catalog no. 1071.

5TH WIPER DIE

For tighter radius and/or thinner wall bending

The Mandrel Selection Guide will also indicate when a wiper may be required. Push tube over properly located mandrel and bring clamp and pressure dies up to bending position. Slide wiper along tube as far as possible into bend die then secure to holder. Unclamp pressure and clamp dies, tip of wiper should be "very close" to tangent. Adjust for rake and vertical alignment. Lube each tube and the wiper.

2ND CLAMP DIE

Hardened tool steel or alloy steel, heat-treated and nitrided. Preferable length is 3½ x tube O.D. Tube groove is grit blasted or may be serrated if less than preferred length. With tube held in bend die, advance clamp die and adjust for vertical alignment. Adjust for parallel contact with entire length of clamp. Adjust for pressure.

3RD PRESSURE DIE

Alloy steel and nitrided. Tube Groove must be parallel to back of die. If a static pressure die system is used, length equals 3½ x O.D.; if follower type pressure die is used, length equals 180 + 2 O.D. If a boosted system is used, groove should be grit blasted. With tube clamped to bend die advance pressure die and adjust for vertical alignment. Adjust for minimum pressure and increase as required in small increments.

4TH MANDREL

For tight radius and/or thin wall bending.

Type of mandrel and number of balls indicated by Mandrel Selection Guide (T.F.B. Inc.'s catalog no. 1071 or on back of this wallchart). Use an aluminum/bronze or Kro-Lon surface (T.F.B. Inc.'s catalog no. K975) for stainless steel tubing and chrome or Kro-Lon for other tubing material. Best results, with most mandrels, when shank projects a small amount (bend & try) past tangent. Lube I.D. of each tube.

APPENDIX I

SUMMARY 3M FAILURE DATA

CG 47 CLASS 1983 THROUGH 1993

MINIMUM REPORTED FAILURES

SYSTEM	FAILURES	MTBRME**
FIREMAIN:		
PIPING	311	3,486.8
PUMP IMPELLER	4*	363,279.3
SEAWATER SERVICE:		
PIPING	100	10,844.1
PUMP IMPELLER	4	317,191.6
AEGIS COOLING WATER:		
PIPING	33	63,093.2
GAS TURBINE GENERATOR:		
STRAINER & PIPING	97	11,403.1

* THESE FAILURES WERE FROM THE CuNi ALLOY IMPELLERS ABOARD CG 47-65. FOR THE TITANIUM FIREPUMPS ABOARD CG 66 & FOLLOW, THERE WERE NO REPORTED FAILURES.

** MEAN TIME BETWEEN RELEVANT MAINTENANCE EVENTS.

APPENDIX I
AEGIS CRLTISER SW SYSTEM
3M DATA

CG 47 CLASSSHIP

MINIMUM REPORTED AEGIS SW PIPING FAILURES - SPY
1983 - 1993

DATE	HULL	LOCATION	REMARKS
09/91	47	5-260-0-E	PIPING FROM AEGIS PUMP #2 LEAKS
12/84	48	2-260-0-Q	AEGIS SW PUMP VENT PIPING IS LEAKING
01/92	49	5-138-0-E	AEGIS SW PUMP VENT LINE IS LEAKING
02/89	49	3-382-2-Q	PIPE FOR AFT COOLING SKID IS CORRODED
08/90	49	3-382-2-Q	PIPE IS LEAKING
09/90	49	5-220-0-E	PIPE IS LEAKING
02/92	49	5-138-0-E	RECIRC LINE IS LEAKING
09/90	49	5-220-0-E	PIPE FOR FWD SKID IS LEAKING
09/92	50	3-383-2-Q	INLET SW PIPE IS WORN AND NEEDS REPLACEMENT
06/91	52	5-138-0-E	PIPE FROM SEA CHEST TO PUMP DETERIORATED
06/91	52	4-276-1	PIPE IS DETERIORATED
12/86	52	5-138-0-E	DISCHARGE PIPING FOR PUMP LEAKS
11/87	54	03-188-0-Q	DISCHARGE PIPING FROM SKID IS RUPTURED
07/89	56	5-138-0-E	SW SUPPLY LINE TO MECH. SEAL IS LEAKING
06/89	57	5-138-0-E	DISCHARGE PIPING IS CORRODED
01/90	57	5-260-0-E	SW PIPING ON OUTPUT OF PUMP IS LEAKING
03/89	57	VARIOUS	90-10 COPPER-NICKEL PIPING IS CORRODED
06/92	58	5-138-0-E	INLET PIPING FROM PUMP LEAKS
02/92	60	3-382-2-Q	SW PIPING FOR SKID IS LEAKING
07/92	60	3-382-2-Q	SW PIPING FOR SKID IS LEAKING
05/91	61	5-260-0-E	VENT PIPE FOR PUMP BROKE
05/90	62	3-382-2-Q	PIPE FOR SKID IS LEAKING
03/92	62	5-260-0-E	VENT LINE FOR PUMP LEAKS
07/92	62	5-260-0-E	VENT LINE FOR PUMP LEAKS
03/93	62	5-260-0-E	FWD AEGIS PUMP HAS ERODED 90-10 CU/NI PIPING
05/93	62	5-260-0-E	AFT AEGIS PUMP HAS ERODED 90-10 CU/NI PIPING
03/93	64	3-382-2-Q	COOLING PIPING IS CORRODED
03/92	65	5-260-0-E	SW PIPING ERODED BEYOND REPAIR
07/93	67	5-220-0-E	SW COOLING LOOP HAS DEVELOPED A LEAK
09/93	67	-	PINHOLE LEAK IN SW INLET PIPING
06/93	67	3-382-2-Q	LEAK IN SW LINE FOR SKID
08/92	68	VARIOUS	RECIRC PIPE FOR PUMP IS LEAKING
08/93	68	3-382-2-Q	PIPING IS CORRODED

AN/SPY-1 COOLING SKID HEAT EXCHANGERS

DATE	HULL	LOCATION	REMARKS
12/90	47	03-282-0-Q	HEX CLOGGED - REPLACED
04/88	47	03-138-2-Q	HEX CLOGGED - CLEAN AND FLUSH
11/88	47	03-138-2-Q	HEX CLOGGED - CLEAN AND FLUSH
11/88	47	03-282-0-Q	HEX CLOGGED - CLEAN AND FLUSH
05/89	47	03-138-2-Q	TUBE BUNDLE LEAK - REPLACE HEX
04/90	47	03-282-0-Q	TUBE BUNDLE LEAK - REPLACED
08/90	47	03-282-0-Q	TUBE BUNDLE LEAK - PLUGGED
12/90	47	03-282-0-Q	HEX CLOGGED - CLEANED
05/89	48	03-282-0-Q	REPLACE HEX TUBE BUNDLES
05/89	48	03-138-2-Q	REPLACE HEX TUBE BUNDLES
05/92	48	03-282-0-Q	REPLACE HEX TUBE BUNDLES
08/86	48	03-138-2-Q	HEX CLOGGED WITH DEBRIS
10/90	48	03-282-0-Q	HEX LEAKING - PLUG TUBE
08/91	49	3-382-2-Q	REPLACE HEX TUBE BUNDLES
01/92	49	3-382-2-Q	HEX FOULING - ROD OUT AND HYDRO
01/92	49	3-220-2-Q	SUSPECT HEX 1 LEAK - PLUG/REPAIR
01/92	49	3-220-2-Q	HEX 2 CLOGGED - CLEAN AND HYDRO
09/85	49	3-382-2-Q	HEX LEAKS - CLEAN AND REPAIR
04/92	50	3-220-2-Q	REPLACE HEX TUBE BUNDLES
04/92	50	3-220-2-Q	REPLACE HEX TUBE BUNDLES
04/92	50	3-382-2-Q	REPLACE HEX TUBE BUNDLES
04/92	50	3-382-2-Q	REPLACE HEX TUBE BUNDLES
03/91	50	3-220-2-Q	HEX CLOGGED - CLEANED
01/87	52	3-382-2-Q	HEX FOULED - FLUSH AND CLEAN
01/87	52	3-220-2-Q	HEX FOULED - FLUSH AND CLEAN
01/90	52	3-220-2-Q	HEX CLOGGED - CLEANED
09/92	53	5-220-0-E	HIGH DIFF. PRESSURE - CLEANED HEX
09/92	53	3-382-2-Q	HIGH DIFF. PRESSURE - CLEANED HEX
02/91	55	5-220-0-E	HEX WEARING OUT - OVERHAUL
02/91	55	5-220-0-E	HEX SEAWATER EROSION - OVERHAUL/REPLACE
07/91	57	3-382-2-Q	HEX CLOGGED BY ASH
03/91	61	5-220-0-E	HEX DISCHARGE LEAK - REPLACED GASKET

AEGIS SW PIPING FAILURES - SPS-49

DATE	HULL	LOCATION	REMARK
04/86	47	03-199-1-Q	SUPPLY PIPING HAS NUMEROUS LEAKS]
08/90	47	03-199-1-Q	PIPING LEAKS
09/91	47	03-199-1-Q	PIPING LEAKS
08/90	47	03-199-1-Q	SUPPLY PIPING CRACKED
09/90	47	03-199-1-Q	PIPING LEAKS AT THE ELBOWS
01/91	48	03-199-1-Q	SW PIPING ON SKID IS CORRODED
07/91	48	03-199-1-Q	SW DISCHARGE PIPING IS DEFECTIVE
10/86	49	03-199-1-Q	PIPE FOR SKID IS RUPTURED
08/87	49	03-199-1-Q	SUPPLY PIPING LEAKS
05-88	49	03-199-1-Q	DISCHARGE PIPING LEAKS
11/91	49	03-199-1-Q	SKID DISCHARGE PIPE LEAKS
08/92	49	03-199-1-Q	SUPPLY PIPING CLOGGED
07/87	50	03-199-1-Q	PIPING LEAKS
04/89	50	03-199-1-Q	EXCESSIVE EROSION ON 90-10 PIPING
03/88	51	03-199-1-Q	SW RETURN LINE LEAKING
01/88	52	03-199-1-Q	INLET PIPING IS LEAKING
09/89	55	03-199-1-Q	SUPPLY PIPING IS LEAKING
02/91	55	03-199-1-Q	PIPING IS DETERIORATED
02/91	56	03-199-1-Q	PIPE IS LEAKING
07/89	57	03-199-1-Q	PIPING RUPTURED
07/89	59	03-199-1-Q	DISCHARGE PIPING IS LEAKING

COPPER ALLOYS FOR MARINE CONSTRUCTION

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INTRODUCTION

Copper and its alloys have been used traditionally in marine engineering where high resistance to sea water corrosion is required. The alloys can be broadly grouped into copper-zincs (brasses), copper-tins (bronzes), copper-aluminum (aluminum bronzes) and copper-nickels. These alloys are central in the galvanic series and are more noble than steels and aluminum but less noble than stainless steels and titanium.

There are important differences in properties between the groups of alloys and variations in properties within each group. However, for the purposes of this workshop, this paper will focus on copper alloys used for sea water piping, condensers and heat exchangers, pumps and valves, ship propellers, boat hulls and sheathing of offshore structures. In so doing, the copper-nickel and the aluminum-bronze groups of alloys are examined as they provide high reliability in marine conditions.

Use of the copper-nickel alloys to take advantage of their inherent resistance to sea water corrosion and biofouling have provided a number of novel applications. Three applications are reviewed. Copper-nickel has found use as a reliable ship hull material on numerous smaller craft and offers promise as a hull sheath on large ships. Copper-nickel sheathing of offshore platform structural members and risers is a proven application as is its use as trash or diversion screens for power plant water intake systems.

PROPERTIES OF COPPER ALLOYS

COPPER-NICKEL ALLOYS

Composition and Physical Properties

The main two copper-nickel alloys considered for sea water service contain 10 and 30% nickel. These have the UNS designations C70600 and C71500 and will be called 90-10 and 70-30 alloys respectively. Both have small but important additions of manganese and iron (Table I).

TABLE I
Typical Compositions

Description	Cu	Ni	Fe	Mn	Al	Si	Nearest Equivalent Designations
Copper-Nickels							
90-10	Rem	10	1.6	0.7			UNS C70600 BS CN102, ISO CuNi10Fe1Mn CEN CW 352H*
70-30	Rem	30	0.6	0.8			UNS C71500 BS CN 107 ISO CuNi30Mn1Fe CEN CW354H*
Aluminum Bronzes **a. Wrought**							
	Rem				7		ISO CuAl7 BS CA102
	Rem		2.5	1	7		ISO CuAl8Fe3 BS CA106. CW303G* UNS C61400
	Rem	5	4.5		10		ISO CuAl10Ni5Fe4 BS CA104 CW307G* CEN UNS C63000
	Rem				7	2	UNS C64200 BS CAl07 ISO CuAl6Si2
b. Cast							
	Rem	5	5	1	10		IS0 G-CuAl10Fe5Ni5 BS 1400:AB2 CS533G* UNS:C95500
	Rem	4.5	4	1	9		UNS C95800
	Rem		0.6		6.2	2.2	ISO G- CuAl6Si2Fe BS 1400 AB3
	Rem				7.0	2	UNS C95600

* proposed Euronorm Designations

These levels were chosen to optimize the resistance of these alloys to sea water velocity effects and localized corrosion.

The physical properties of copper-nickels are given in Table II. Of particular interest for heat exchangers and condensers are the thermal conductivity and expansion characteristics. Although conductivity values for both are good, the 90-10 alloy has the higher value. In addition, the 70-30 alloy is essentially non-magnetic and has a magnetic permeability very close to unity. The 90-10 alloy with the higher iron content is non magnetic if the iron can be retained in solid solution during processing. For 90-10 tubing used in mine sweepers, air cooling after the final anneal suppresses precipitation sufficiently to provide low permeability.

TABLE II

Physical Properties of Copper-Nickel Alloys and Nickel Aluminum Bronze

Property	90-10	70-30	Nickel Aluminum Bronze
Specific Gravity	8.9	8.95	7.6
Thermal Conductivity W/m°C	50	29	42
Coefficient of Linear Expansion $10^{-6}/°C$	17	16	17
Modulus of Elasticity GN/m^2	135	152	120

Other copper-nickel alloys used for condenser and heat exchanger applications worthy of mention are C72200, developed in the US, which has 15%Ni and a 1.6%Cr addition, and C71640 which contains 30%Ni, 2%Mn and 2%Fe which was developed in Europe for the power industry and is now used in more demanding areas of desalination plants. Both were developed to withstand higher sea water velocities and erosive conditions.

Copper-nickels are predominantly wrought alloys although castings are made often of the 30% nickel alloy with additions of niobium or chromium. In recent years, the UK Navy have developed a carefully controlled version of the chromium-alloyed material as Naval Engineering Standards NES 824.

Formability and Fabricability

Typical annealed properties for the 90-10 and 70-30 copper-nickel alloys are shown in Table III. Both alloys have good mechanical strength although the higher nickel alloy does possess better inherent strength. Copper-nickels are ductile and have excellent resistance to fracture under impact loading. Both alloys are single phase solid solution alloys which cannot be hardened by heat treatment although the strengths can be increased by work hardening. The alloys are readily fabricated and welded. A 70-30 copper-nickel consumable is preferred for the 90-10 alloy providing a weld which is galvanically more noble than the base metal. For dissimilar welding to steel, 65% nickel 30% copper alloy consumables are preferred [1].

TABLE III

Typical Mechanical Properties of Copper-Nickels and Aluminum Bronzes

Alloy Designation					
UNS	**ISO**	**0.2% Proof Stress (MPa)**	**Tensile Strength (MPa)**	**Elongation %**	**Hardness (HV)**
Wrought					
C70600	CuNi10Fe1Mn	90 min.	280-350	30-6	90-120
C71500	CuNi30Mn1Fe	120 min.	310-420	35-10	80-110
C61400*	CuAl 7	140-160	420-720	55-10	100-230
C63000	CuAl 10Ni5Fe4	320-500	650-820	25-10	200-240
C62400	CuAl8Fe3	230-450	500-600	40-20	140-190
C64200	CuAl6Si2	280-400	550-650	45-30	160-210
Cast					
C95220	G-CuAl 10Fe3	170-270	500-650	40-18	90-160
C95500	G-CuAl 10Fe5Ni5	250-360	640-740	20-13	140-180
C95600*	G-CuAl6Si2Fe	180-190	460-500	30-20	--

*Closest UNS Alloy

Corrosion Resistance

The good corrosion resistance to sea water offered by copper-nickel alloys results from the formation of a thin, adherent, protective surface film which forms naturally and quickly on exposure to sea water. The film is complex but when formed in clean sea water is predominantly cuprous oxide with the protective value enhanced by the presence of nickel and iron.

The rate of film formation was elegantly portrayed by Tuthill [2], from measurements of the copper content in condenser sea water effluent over a three-month period after start up, Figure 1. The copper content was found to decrease by 90 percent in 10 minutes and 99 percent in an hour. After three months the copper content in the effluent was virtually the same level as in the intake water.

If exposed to polluted water, any sulfides present can interfere with film formation, producing a black film containing cuprous oxide and sulfide. This is not so protective as films formed in unpolluted water and can undergo higher general corrosion rates and pitting. The sulfide film can be gradually replaced by an oxide film if subsequently exposed to aerated conditions [2] although high corrosion rates can be expected in the interim. However, if an established cuprous oxide film is already present, then periodic exposure to polluted water can be tolerated without damage to the film.

Once the surface film forms the corrosion rate will continue to decrease over a period years. It is for this reason that it has always been difficult to predict the life of copper-nickel alloys based on short term data. Figure 2 shows 14-year exposures of 90-10 copper-nickel to sea water in quiet, flowing (0.6 m/sec) and tidal conditions [3]. The corrosion rate is shown to continue to decrease for some years depending on the exposure conditions before stabilizing at about 1.3 μm/year. The results were similar for both the 90-10 and 70-30 alloys.

Copper-nickel alloys have very good resistance to localized corrosion. Crevice corrosion seldom occurs and when encountered it tends to be a metal concentration cell corrosion type which

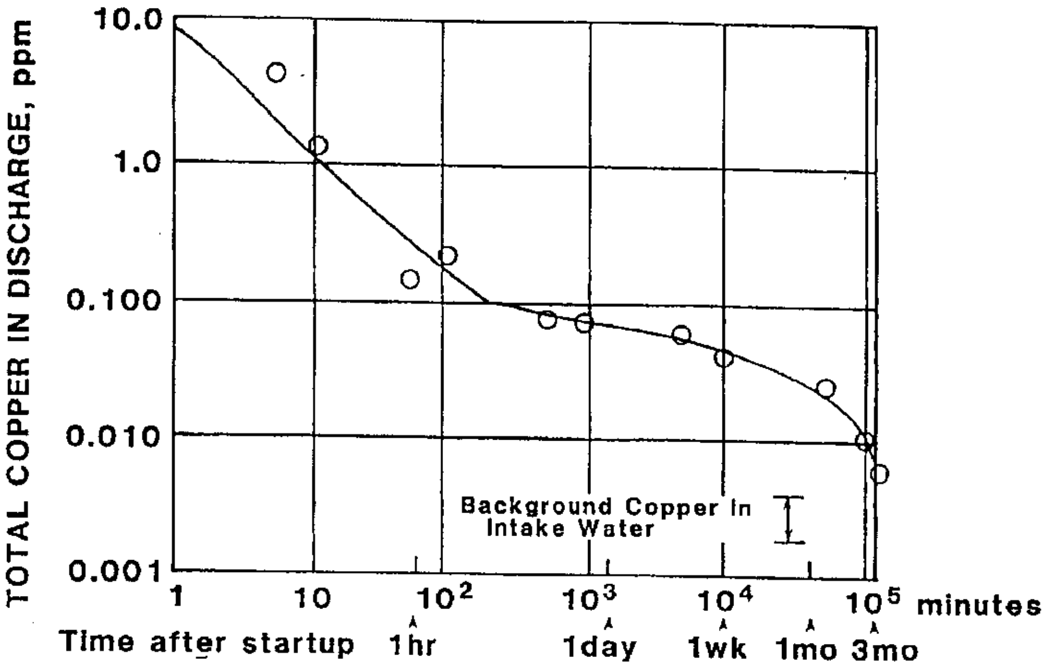


Figure 1 - Formation rate of corrosion product film on 90-10 copper-nickel in sea water.

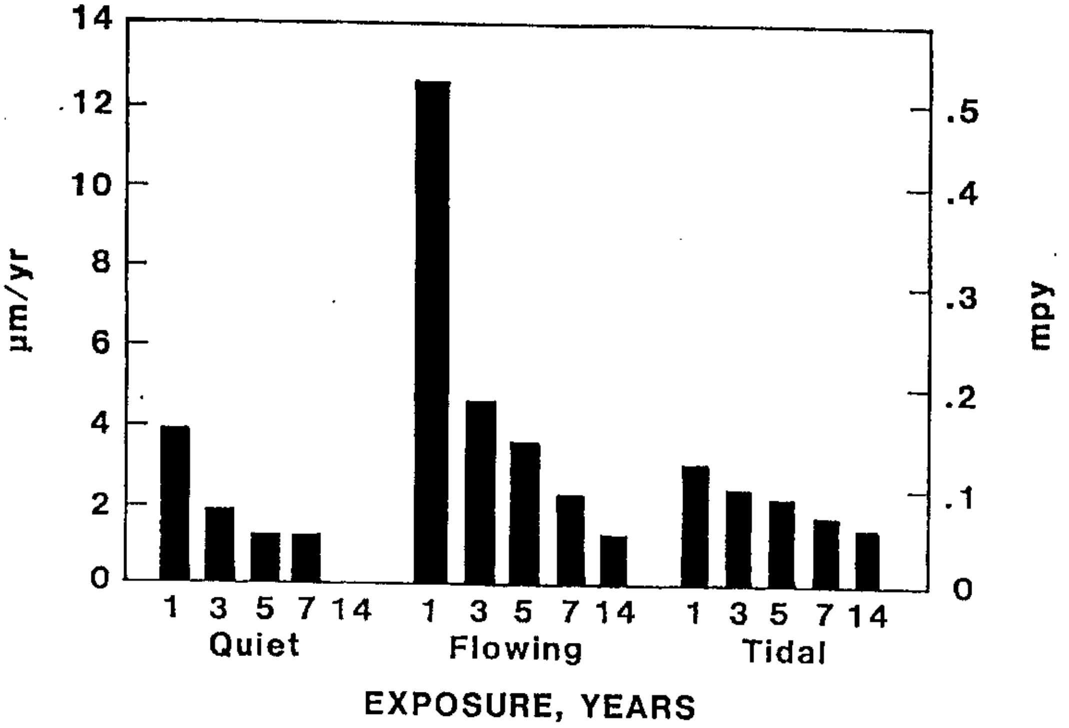


Figure 2 - The change in corrosion rate with time for 90-10 copper-nickel in quiet, flowing and tidal zone sea water.

means that metal ions accumulate in the crevice area and the crevice becomes noble. Dissolution occurs adjacent to the crevice on surfaces exposed to oxygenated bulk sea water and penetration rates are mild. The alloys also have a good resistance to pitting. Pits when they do occur tend to be broad and shallow in nature rather than undercut. The alloys are resistant to chloride and sulfide stress corrosion cracking and no evidence has been identified of stress corrosion cracking due to ammonia in sea water.

Dealloying can occur in copper alloys but it is not a common occurrence in copper-nickel alloys. Denickelification has been encountered occasionally in the 70-30 copper-nickel alloy in refinery overhead condenser service, where hydrocarbon streams condense at temperatures above 150 C. This appears to be due to thermogalvanic effects resulting from the occurrence of local hot spots. The solution has been to remove deposits which lead to the hot spots either by more frequent cleaning or by increasing flow rates.

Sea Water Velocity Effects and Sand Abrasion

With increasing sea water flow rate, corrosion rates remain low due to the resilience of the protective surface film. Once, however, the velocity for a given geometry is such that the shear stress action of the sea water on the film is sufficient to damage it, impingement attack can occur. General experience has shown that 90-10 copper-nickel can successfully be used in condensers and heat exchangers with velocities up to 2.5 m/s. For pipeline systems higher sea water velocities can safely be used in larger diameter pipes as indicated by BS MA18, "Salt water Piping Systems in Ships" which suggested a maximum design velocity of 3.5 m/s in pipes of 100 mm and larger for 90-10 copper-nickel and 4 m/s for the 70-30 alloy. Although these values are now considered to be conservative, such guidelines have worked well because they take into account normal velocity raisers within pipework systems such as bends which can cause areas of high local flow rate. Nevertheless, extreme turbulence has to be avoided. Instances where this may occur include tight radius bends, partial blockages and areas downstream of partially throttled valves. However, under intermittent flow condition typical of fire water systems on offshore platforms, short term exposure to higher velocities than normally acceptable in continuous flow systems can readily be accommodated by copper-nickel as the average weight loss over the longer term is still low.

The hydrodynamics of ship hulls are somewhat different to pipework systems. Experience to date [4] has shown minimal corrosion after 14 months at 24 knots (12 m/s) for the 90-10 alloy whereas the highest recorded velocity is 38 knots (19 m/s) for a patrol boat which showed no measurable thickness loss after 200 hours at maximum operating speed. The upper service velocity for hulls is still to be established.

The effect of sand abrasion in sea water has been investigated but is difficult to quantify. Sand loadings of less than 200 ppm rarely damage good protective films on copper-nickel alloys. Very fine sand (<0.05 mm) loadings are tolerable up to about 1000 ppm. Larger diameter sand particles tend to be increasingly abrasive to the film in the 200-1000 ppm range. The 70-30 alloys have somewhat greater tolerance for sand and aluminum brass, C68700 somewhat less. For sand loadings of 1000ppm and for larger particles of sands in the 200-1000ppm range, the 2% manganese and 2% iron alloy, C71640, has proven very resistant in the shallow water estuaries and in shallow water intakes of desalination plants along the Arabian Gulf.

Resistance to Biofouling

The 90-10 copper-nickel alloy has a very similar antifouling response to copper itself. In order to maintain its good antifouling properties, copper-nickel must be allowed to freely corrode albeit at very low corrosion rates. Cathodic protection or galvanic coupling to less noble metals is therefore excluded for optimum biofouling resistance (3a and 3b).

Experience has shown that under the exposed conditions of offshore platforms and operating conditions of boats, the slime layers which form on the copper-nickel surface do not thicken sufficiently to allow macrofouling. Under quieter conditions, some macrofouling can eventually occur [5,6] but will slough away at intervals.

Although cathodic protection will significantly reduce the biofouling protection, it does not completely do so; sheathing after 12-year exposure as splash zone protection on cathodically protected legs in the Morecambe Bay Gas field , UK, and also 10-year trials on pilings at the LaQue Center for Corrosion Technology, North Carolina [7], have both shown significantly reduced levels of fouling on the copper-nickel (Table IV).

TABLE IV

Biofouling Mass on Copper-Nickel Sheathed Steel Test Pilings after Ten-Year Exposure (ICA Project No. 358)

Piling	kg/sq.m	% Coverage
Bare Steel (control) - not sheathed		
5 year removal	18	100
10 year removal	12	100
Concrete Insulated		
5 year removal	0.36	1.9
10 year removal	0.14	1.2
Directly Welded		
5 year removal	7.95	44.3
10 year removal	4.43	36.8
Rubber Insulated		
5 year removal	0.26	1.4
10 year removal	0.51	4.2

The general assumption has been that 70-30 copper-nickel has less resistance to biofouling than the 90-10 alloy. However, there are discrepancies; five-year trials by Efird [5] at the LaQue Center for Corrosion Technology showed their response to biofouling to be almost identical. Certainly, long term experience with the 70-30 copper-nickel hull of the *Asperida*, a 16 m sailing ship built in 1968 in Holland, gave no necessity for any beaching to remove fouling in 20 years. In other work, 70-30 welds have been noted to foul earlier than the 90-10 copper-nickel they join but this could be that 70-30 has sufficient galvanic protection from the 90-10 to prevent full biofouling resistance. Any difference that does exist, it would seem, is of little practical significance for boat hulls.

The final, yet important observation has been that even when some biofouling has accumulated under long term quiet conditions on copper-nickel alloys or when cathodic protection has been applied,

Figure 3a -
Mounted raft panels. Left to right: steel with anode, Cu-Ni sheathed steel with anode, Cu-Ni panel with anode, Cu-Ni panel without anode.

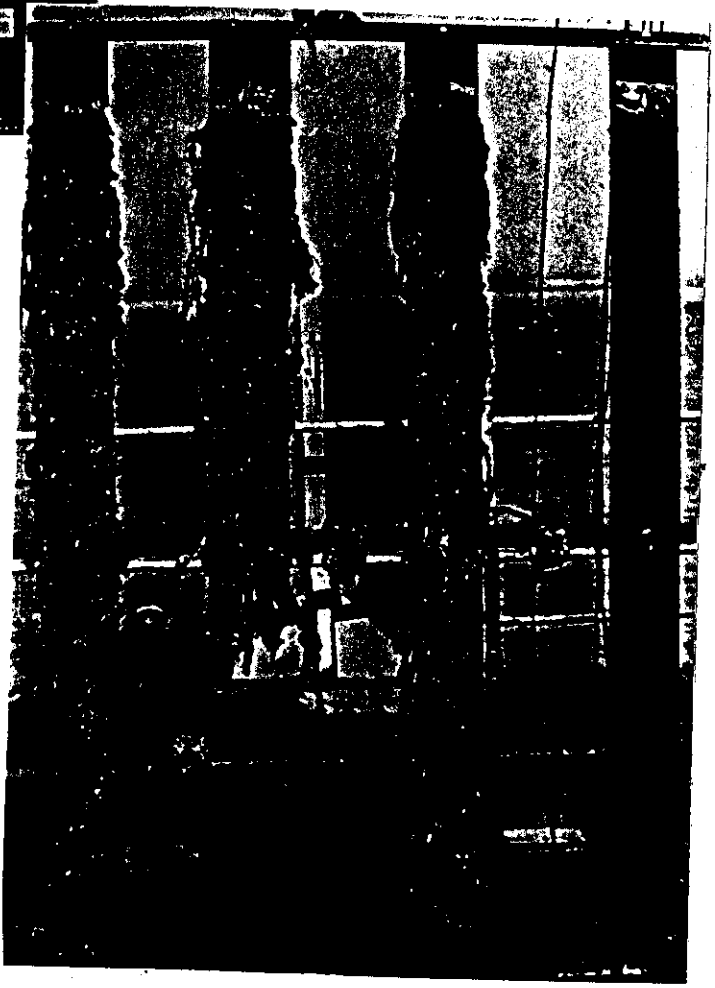


Figure 3b -
As 3a after 55 week exposure. Cu-Ni panel with no cathodic protection gives excellent biofouling resistance.

the biofouling has readily been removed by a wipe or light scraping operation which would not be the case on other surfaces [6]. Also, it has been observed that accumulations have been effectively removed on boat hulls at velocities of 3-8 knots such that a self cleaning property is exhibited [8].

ALUMINUM BRONZE ALLOYS

Composition and Structure

Commercial aluminum bronzes contain between 5 and 11% aluminum often having additions of iron, nickel, manganese and silicon. The range of alloys provides suitable grades for both cast and wrought alloy forms. Above about 8% aluminum, the alloys have complex microstructures and it is by strict control of composition and thermal treatment that maximum corrosion resistance is achieved [9,10].

Aluminum bronzes containing up to about 8% aluminum have a ductile single (alpha) phase structure and are suited for more intensively cold worked products. Typically these include ISO CuAl7 and CuAl8Fe3 and UNS C61400. A UNS alloy, C61300, with a 0.35% Sn addition for improved resistance to intergranular stress corrosion cracking in superheated steam, is also available in the United States. Higher aluminum products are strengthened by a second phase, beta, which is stronger and harder than alpha. Alloys with 9-10% aluminum are noted for their high strength and are the more suited for cast and hot worked products. On slow cooling, the beta phase becomes unstable at temperatures below 565C and decomposes to alpha and a less noble gamma 2 phase. Thin sections generally cool sufficiently quickly to avoid this but thick sections require a rapid cool from 600-650C. Alternatively, to allow slower cooling to a more acceptable structure, nickel and iron, or manganese, can be added to the composition. With nickel and iron, the beta will mainly become an alpha and kappa phase during cooling whereas manganese will stabilize the beta. Nickel aluminum bronze developed for more severe marine environments contains nominally 5%Ni, 5%Fe and 10%Al and is available in both cast and wrought forms. ISO CuAl10Ni5Fe4 and UNS C63000 are typical of wrought nickel aluminum bronze; in the cast form it is covered by G-CuAl10Fe5Ni5 and UNS C95500. British Naval Engineering Standards are NES 833 and NES 747 for wrought and cast alloys respectively. The US Navy standard for sand cast nickel aluminum bronze C95800 is MIL B24480. The wrought nickel aluminum bronze alloys have no U.S. military specification at present. They are covered by ASTM B171.

The high manganese, aluminum bronze alloys are really propeller alloys and have now been largely replaced by the nickel aluminum bronze alloys. However, it is worth mentioning that a range of aluminum silicon bronze alloys exists for marine applications requiring low magnetic permeability; e.g. G-CuAl6Si2Fe, NES 834, C95600.

The more commonly used aluminum bronze alloys are listed in Table I with physical and mechanical properties in Tables II and III. The wear resistance of nickel aluminum bronze is excellent and the alloy is frequently used as a bearing material.

Corrosion Resistance

Aluminum bronzes are protected by a passive surface oxide film in the same manner as the copper-nickels but, for these alloys, the film is predominantly aluminum oxide with some cuprous oxide. The nature of the film offers a degree of biofouling resistance but is not as effective as for the copper-nickels.

The resistance of aluminum bronze to general corrosion is good and chloride pitting does not cause a problem in this type of alloy. Any crevice corrosion tends to take the form of minor selective phase de-alloying where the aluminum is removed and copper redeposited. Normally this results in little reduction in strength or impairment to surface finish. In addition, aluminum bronzes and particularly the nickel aluminum bronze alloys have excellent resistance to corrosion fatigue.

Aluminum bronze alloys have a fairly high resistance to ammoniacal stress corrosion although a stress relief heat treatment may be advisable in more severe environments. When welded with matching filler metal, some aluminum bronzes can become susceptible to stress corrosion in marine and desalination environments. Microfissuring of both the weld metal and heat affected zones leaves these areas prone to selective phase attack/dealuminification and stress corrosion. The answer is to weld with a higher aluminum content (10%) duplex filler metal. The final pass should be made with nickel aluminum bronze to minimize the possibility of galvanic corrosion with the higher aluminum filler metal. Nickel aluminum bronze propellers are routinely welded successfully with nickel aluminum bronze filler metal without increasing the susceptibility to stress corrosion in service.

The aluminum bronzes are generally considered to have excellent resistance to flowing sea water due to the rapid self repair of the protective oxide film. Nickel aluminum bronze is among the most resistant of all the copper alloys and is usually used at design velocities up to 4.3 m/s. Considerable experience with impellers and propellers in marine engineering has also proved their excellent resistance to cavitation damage.

As with copper-nickels, aluminum bronze corrodes at an increased rate in sulfide contaminated sea water due to the change in the structure of the passivating layer by incorporation of less protective copper sulfide. This leads to what is normally a general or pitting type corrosion. Where copper alloy castings are required for sour environments, it is common to specify tin bronze for impellers and leaded red brasses (gun metals) for pump casings.

Combating Selective Phase Attack [9]

The complex nature of the multiphase alloys can mean that different phases exhibit different potentials in sea water. This can introduce the possibility of selective phase attack. This takes the form of dealloying called dealuminification of the more susceptible phase and has largely been prevented under most conditions by ensuring that alloys are free from the gamma 2 phase. Nevertheless cast nickel aluminum bronzes have exhibited dealuminification which is normally associated with crevices, galvanic corrosion, electrical leakage and welding effects. Often this is slight but for severe conditions and where components are critical, further precautions are required to counteract this. Whereas in the alpha-beta alloys slight preferential corrosion can occur in the beta phase, in nickel aluminum bronze such attack can also occur on residual amounts of beta but is more likely to affect a narrow band of alpha phase immediately adjoining any lamella kappa and from there spread into the kappa phase. Over the years much development work has been carried out particularly by navies to optimize composition and heat treatment of nickel aluminum bronze castings. This work has shown that tighter controls on composition and heat treatment are beneficial. The latter takes the form of a six-hour heat treatment at 675C ± 15C followed by cooling in still air. This converts any beta to alpha plus kappa, modifies lamella kappa and greatly reduces the possibility of selective attack on the adjacent alpha phase. The US Navy standard, MIL B 24480, for C95800 pump and valve components and UK Naval Engineering Standard 747 have both addressed these aspects. The US propeller alloy C95500 and Navy Specification MIL B 21230 however have remained unchanged and weld repairs are permitted and routinely made on the propeller alloy without sensitizing the alloy to dealuminification in later service.

APPLICATIONS

The excellent combination of sea water corrosion resistance and antifouling properties exhibited by copper alloys makes these materials particularly useful in a number of marine applications [11]. Copper-nickel alloys are extensively used in the tubing and tube sheet of power plant condensers and other marine heat exchangers as well as for shipboard sea water piping systems and for cooling and fire protection systems of large offshore structures. The aluminum bronze alloys are formed as tube sheet in condensers having copper alloy as well as titanium and stainless steel tubing. Pumps, valves, water boxes, diffusers and other hardware to handle sea water are frequently fabricated from cast or wrought aluminum bronze alloys. Copper-nickel alloys are extensively used in the multi-stage flash distillation desalination process for heat exchanger tubing, tube sheet, water boxes, piping and evaporator shells.

Three of the more recent and interesting applications of copper-nickel alloys in marine construction are reviewed here; copper-nickel ship hulls, sheathing for steel support structures of both offshore and shoreline facilities, and power plant trash racks and diversion screens.

SHIP HULLS

Copper has a long history dating back to Alexander the Great and later by the British Admiralty with the frigate *Alarm* in 1761 to protect wooden ships protect against wood boring worms and fouling by marine organisms. With the advent of steel hulls, copper sheathing gave way to copper antifouling paints. The modern approach to achieving a maintenance free hull using the copper-nickel alloys dates to 1941 with the construction of Miss Revere, a 13.7 m yacht with a 2 mm thick copper-nickel hull. Since then, about two dozen boats to length of 22 m have been built with solid 90-10 or 70-30 copper-nickel alloy hulls, or with steel clad by hot roll bonding with the 90-10 alloy [4,11]. More recently, wooden, steel and fiberglass hulls have been covered with an adhesive-backed 90-10 alloy foil.

Prohibition of the very effective organotin-containing antifoulant systems in many parts of the world together with regulations on the collection and disposal of contaminated grit from dry dock refurbishment practices have put pressure on the shipping industry. Use of copper-nickel alloy for corrosion and antifouling protection is an alternative that should be explored further based on the successful applications to date. Copper-nickel sheathing will last the lifetime of the ship thus avoiding repainting at three to five year intervals.

Copper Mariner

The advantage of copper-nickel hulls was first demonstrated by *Copper Mariner*, a 20.4 m commercial fishing trawler built in Mexico in 1971 as a joint project of the Copper Development Association Inc. and the International Nickel Company [8]. The objective was to determine whether the inherent corrosion and biofouling resistance of 90-10 hull would generate sufficient fuel and maintenance savings to justify the cost premium for the copper-nickel hull. This trawler has a 6 mm thick 90-10 alloy hull welded to steel framing which is protected from galvanic corrosion by a heavy paint system. *Copper Mariner* demonstrated a return on investment in the range of 12.9 to 16.7 percent after taxes for shrimping operations off the coast of Nicaragua. These figures are based on measured fuel and maintenance savings and estimates of the increased earnings potential of this boat due to additional days of availability compared to that of the sister steel hulled boats. Hull plate thickness measurements after 52 months of service showed that the corrosion rate of the 90-10 alloy was less than 0.00125 mm/yr.

The copper-nickel hull of *Copper Mariner* is very resistant to fouling; comparison with the steel hull of a sister ship just prior to its third cleaning after only 18 months service, is striking (Figures 4a and 4b). *Copper Mariner* was still in service in 1991 and as reported then by the Minister of the National Fishing Industry in Nicaragua, the copper-nickel hull has never required maintenance. Contact with officials was lost during the civil war in Nicaragua.

Solid copper-nickel hulls and foil sheathing are techniques with practicality and appeal for small pleasure craft, fishing or work boats. New initiatives with these techniques are underway. The Copper-Nickel Boat Co. of Deale Island, Maryland, is just beginning construction of a series of 14.6 m yachts after a popular design by Bruce Roberts. These craft will be weld fabricated with a 4 mm thick 90-10 alloy plate and framing.

The adhesive-backed copper-nickel foil product was developed by Fred Mitchell in the UK. Mr. Mitchell applied this system to numbers of wood, steel and fiberglass hulls with considerable success on about 40 craft. The system, known as Mariner 706, was subsequently licensed in 1993 to a New Zealand company, Gulf Ferries, Ltd., part of the Fullers Group, for application initially on their own ferries used for commuter traffic in and around Auckland harbor. Three fiberglass hull vessels have been sheathed. The material is applied by hand and is therefore labor intensive although it appears that the process could be mechanized over large flat areas of the hull. Foil thickness is selected depending on the size of the craft and severity of intended operation but is 0.15 mm or greater. Currently panels are about 200 x 500 mm and are applied with a 15 mm overlap between individual panels which is positioned in the direction of water flow past the hull. Panels are easily cut and positioned even other difficult contours. The method is versatile and clearly lends itself to both pleasure craft and commercial vessels.

Copper-Nickel Sheathing of Large Ships

For large ships, solid copper-nickel hulls are obviously impractical. Practical means of facing the steel with copper-nickel include both cladding and sheathing. Cladding refers to a composite plate system with a metallurgical bond between the steel and the copper-nickel alloy by hot roll bonding or explosive bonding. Sheathing refers to the attachment of relatively light gauge copper-nickel alloy to the steel hull by welding (or by adhesive, although this method is not considered here). Sheathing is therefore applicable to retrofitting existing ships as well as to new construction. Sheathing is the focus here because this technique is believed to be simpler and considerably less expensive.

As noted above, sheathing of ship hulls is an old concept. Experiences with many smaller craft have verified the excellent performance of the copper-nickel alloys as ship hull materials. But the material has not yet been applied for corrosion and biofouling protection of large ocean-going vessels, apparently because a variety of technical and economic issues remain unresolved in the minds of engineering staff of the ship building community and because the up front capital expense is a deterrent.

The copper industry together with the U.S. Maritime Administration examined these issues in some detail in the mid 1980's. Erosion corrosion of the copper-nickel and galvanic corrosion of the steel structure in the vicinity of the copper-nickel are to issues that were examined. Experiments on large ships were performed to assess the velocity and erosion corrosion effects. A rudder was sheathed and installed on the *Great Land*, a 24-knot roll-on/roll-off vessel [12]. The rudder is a region of complex and turbulent flow. The test showed that the 90-10 alloy and the Cu-Ni-Cr alloy (C72200) are durable even in conditions where ice and abrasive silt are encountered. A couple of panels of the 74m^2 rudder were lost in regions of high turbulence showing that the weld attachment methods needed improvement. Sheathing thickness was measured at intervals over a period of 14 months of operation.

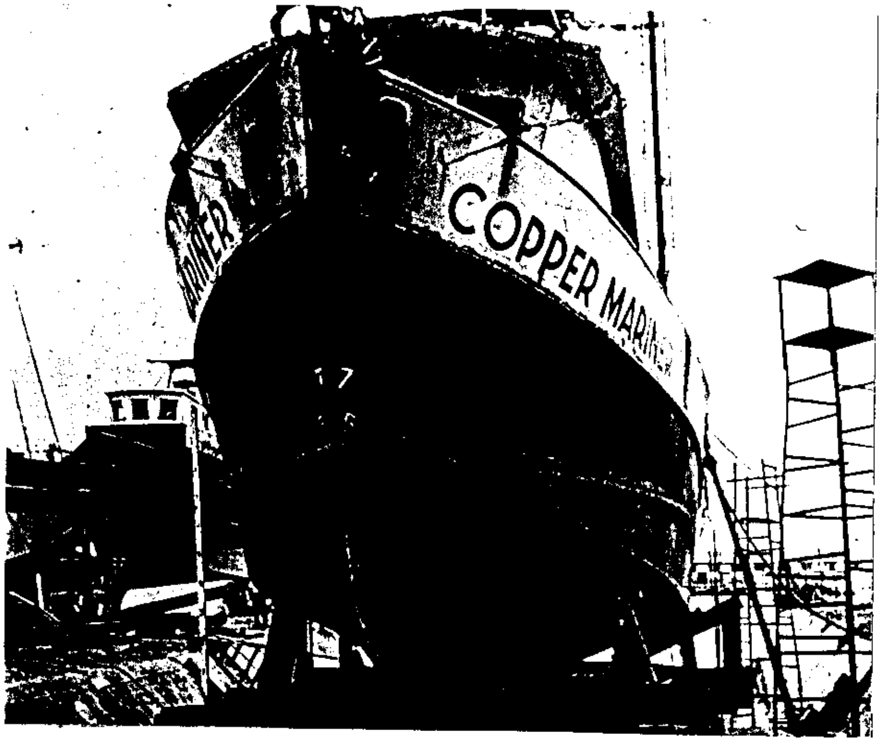


Figure 4a - The *Copper Mariner* hull is free of fouling.

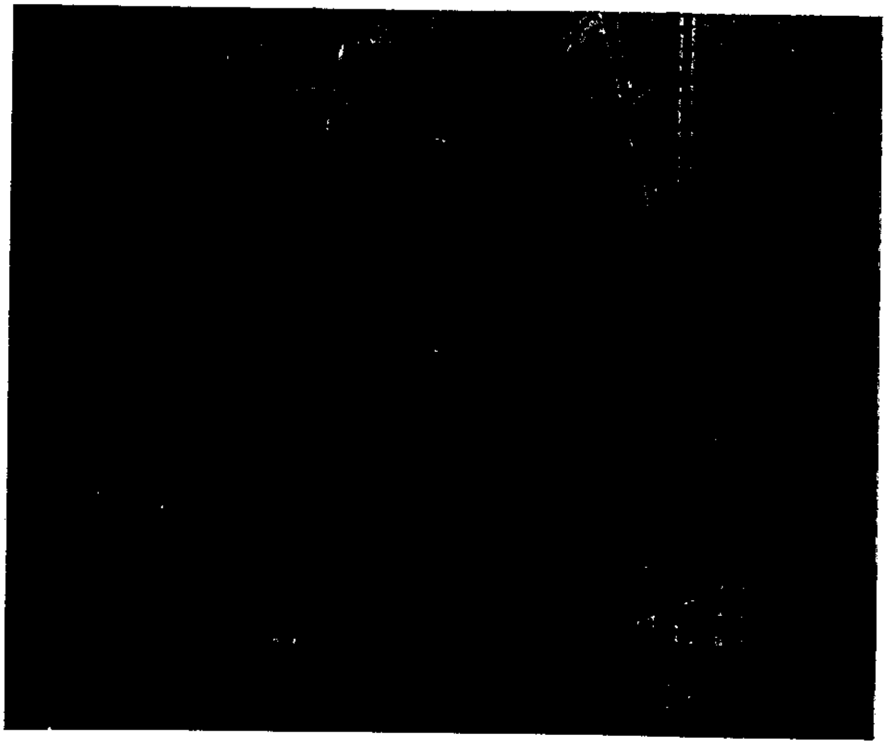


Figure 4b - Marine fouling on the steel hull boat, *Jinotega*, prior to its third cleaning after 18 months of total service.

Maximum thickness loss never exceeded 0.1 mm and, importantly, the mean loss rate decreased with time to less than 0.025 mm/yr at the 14-month point showing that a stable corrosion film was forming even under these high velocity conditions. Later, in the early 1980's copper-nickel panels were attached during construction at the Newport News Shipbuilding, Inc. to the hull of the *Arco Texas*, a crude oil tanker [13]. After two years in service in a wide spectrum of sea service conditions including warm gulf waters and a number of trips through the Panama Canal, and West Coast waters from Southern California to Alaska, the panels were intact with all but undetectable corrosion loss (<0.0125 mm/yr). No evidence of biofouling was seen indicating that the panels were freely corroding, albeit at a very low rate, and not cathodically protected by the surrounding painted steel hull. These experiments demonstrated that erosion corrosion rates at velocities of 25 knots (12.5 m/s) were low and stable even though this velocity is more than three times the maximum velocity recommended for 100 mm and large pipe (3.5 m/s). The ship hull apparently acts as a pipe of infinite diameter allowing considerably higher velocity without shear failure of the corrosion film.

Galvanic Corrosion

The question of rapid and potentially disastrous corrosion of the steel hull plate in the event of damage to the copper-nickel sheathing had been raised at the outset of discussions of sheathing steel structures. Work in Germany using machined "defects" on copper-nickel clad steel plate showed that the steel corrosion is self-limiting and provides more than adequate time for repairs to the copper-nickel cladding to be made [14].

The corresponding situation involving defects in a sheathed hull is somewhat different, as indicated in an experiment on the corrosion of steel in the vicinity of a defect in the sheathing of a steel piling [15]. A small defect in the copper-nickel sheathing will allow a thin layer of water to enter the narrow space between the sheathing and the steel hull bounded by the peripheral sheathing welds to the steel. The cathode/anode area ration will be much smaller than the apparent geometric ratio. Corrosion of the steel will proceed rapidly for a very short period until the oxygen is consumed because the entrapped film of water has very poor contact with the outside sea water. It would appear that this situation is less threatening to the integrity of the hull and will allow more than ample time to make a repair to the sheathing.

Hull Roughness

A most important reason for using copper-nickel on the hull of a ship is for fuel economy by virtue of the reduce hull roughness achieved with copper-nickel. The hull roughness is directly related to the shaft horsepower required to overcome simple hull friction; the rest of the power is expended in wave making. It has been estimated that a ship owner pays a penalty equivalent to a one percent increase in power requirement for an increase of 10 μm in hull roughness (in the range 0-230 μm) and 0.5 percent for every 10 μm beyond that [16,17]. Based on a British study of 400 ships, the average roughness of a new hull is 125 μm, the best attainable roughness is 75 μm, and the average yearly increase in roughness ranges from 50 to 70 μm. A conventional hull, therefore, begins to lose efficiency from the day it is launched while a copper-nickel hull, if there is any change, contributes to increased efficiency with time. In fact, measurements have shown that copper-nickel panels on the *Arco Texas* became slightly smoother after the sea trials.

Roughness data enable calculation of probable ship performance if the entire wetted surface of the *Arco Texas* had been sheathed with copper-nickel. At the end of the test period, the mean roughness of the painted steel hull was 250 μm. The correspondence roughness of the copper-nickel was only 53μm. Based on these measurements and the above reasoning, full-wetted surface sheathing of the *Arco Texas* would result in a 19.7% improvement in fuel efficiency.

Sheathing Methods and Cost Analyses

To obtain a sound analysis of the cost of sheathing a large ship, a project was undertaken by the Newport News Shipbuilding Co. under contract from the U.S. Maritime Administration (MARAD) [12]. This analysis was done in great detail and can only be summarized here. Initially, weld attachment of 90-10 copper-nickel sheets (122 cmx 366 cmx 2.5 mm) to a T-AO 187 class, T-AO 191 series fleet oiler with 7,115 m^2 of hull area from a line above the maximum load water line. About 193 tonnes of alloy sheet would be required. An array of 25 mm x 9.5 mm slots would provide weld attachment points to the steel hull to prevent panting of the plates in addition to about 17,000 linear meters of peripheral welds. Twelve steps in the construction sequence from docking the vessel, erecting staging, blasting, grinding flush steel welds and sheathing welds, through to undocking the vessel were considered in the cost analysis. The cost in 1986 U.S. dollars was found to be \$608.59/m^2.

A second analysis invoking some innovative technology to reduce costs was then done. Applying the copper-nickel sheathing from rolled sheet, reducing the weld grinding and steel hull preparation and adopting a semi-automated MIG Beam welding technique resulted in a sheathing cost of \$379.61/m^2. When the slot welds were replaced in the analysis with a series 4.8 mm diameter spot weld, the cost was reduced again to \$357.02/m^2. Another scenario worth noting is for sheathing during initial construction where certain costs, including dry-docking charged to sheathing installation are eliminated. In this case, the unit cost of sheathing was calculated to be \$273.30/m^2.

Life Cycle Performance Economics

Studies have been conducted to generate a comparison of the life cycle costs of providing corrosion and antifouling protection for a ship via: 1. Conventional copper-bearing antifouling paint with primer and CP system; 2. Organo-tin copolymer antifoulant (OCA) system; and 3. Copper-nickel sheathing. In this study, an analysis by the Webb Institute for a different ship, a C-4 cargo vessel for which a large body of operating data was available, was updated. The cost of fuel was taken to be \$18 per barrel. In the analysis of sheathing during new construction, life cycle economics were based on a comparison of such factors as; engine cost (specific engine-propeller combinations were chosen on the basis of expected coating performance), the cost of the coatings, fuel consumption, normal dry-dock costs during the 20-year service life and salvage revenue (copper-nickel). Cargo revenue was held constant to all coating systems, a consequence of sizing the engine-propeller system to give the same speed in all cases. The coating's effectiveness is reflected in the size of the engine (a capital cost factor) and the resulting fuel consumption rate.

The results of the discounted cash flow analysis are shown in Table V.

Copper-nickel sheathing of this ship would be expected to yield a savings of as much as \$6,481,000 over the 20-year service life using the most advanced sheathing technology. The smaller engine requires results in a \$1,841,000 savings up front; this partially offsets the higher coating cost of copper-nickel sheathing compared to the paint systems. But the greatest part of the total savings is in substantially reduced fuel costs.

Ship hull sheathing remains a promising technology awaiting application by a shipping company with a long-term perspective.

TABLE V
Economic Comparison of Hull Protection Methods for Installation During Construction

(All costs in thousands of 1986 dollars)

Case	Engine Cost	Coating Cost	Fuel Cost	Normal D.D. Cost	Salvage Value	Total Savings
Base (Conv.)	9,200	102	20,263	715	-	-
OCA	8,237	163	17,438	961	-	3,481
Cu-Ni @ $56.54	7,359	2,622	14,841	440	19	5,037
Cu-Ni @ $35.28	7,359	1,636	14,841	440	19	6,014
Cu-Ni @ $25.40	7,359	1,178	14,841	440	19	6,481

SHEATHING OF OFFSHORE STRUCTURES

Whereas sheathing of ship hulls for corrosion and biofouling protection is a concept awaiting a definitive demonstration, sheathing of offshore structures is a proven application for copper-nickel alloys and the nickel-copper alloy Monel 400. The spray/splash zone of a steel piling or other structure is the difficult region to protect. Coating systems are very vulnerable and cathodic protection cannot be effective because this region is not fully immersed. Sheathing has proved to be effective in the spray/splash region with the sheath extending a few meters above the high tide line and a short distance below the tidal zone. Fouling is also a problem in that attachment and growth of marine organisms adds considerable weight to a structure. More importantly, the increase in side loads due to currents, wind and waves on the enlarged projected area is a major design consideration.

Corrosion of Steel Structures in Sea water

The intensity of corrosion of an unprotected steel structure in sea water varies markedly with position as shown in Figure 5. The spray and splash zone above the mean high tide level is the most severely attacked region due to continuous contact with highly aerated sea water and the erosive effect of spray and tidal action. Corrosion rates as high as 0.9 mm/y at Cook Inlet, Alaska, and 1.4 mm/y in the Gulf of Mexico have been reported. Corrosion rates are often very high at a position just be low mean low tide in a region that is very anodic relative to the tidal zone due to powerful differential aeration cells.

Monel alloy 400 was applied to this task as early as 1949 on an offshore platform in the Gulf of Mexico off the Louisiana coast [19,20]. The LaQue Center at Wrightsville Beach, North Carolina, USA, conducted extensive trials of sheathing using the steel piling supporting the sea water corrosion test wharfs at the laboratory as test specimens. Sheathing or protective materials tested included Monel, AISI 304 stainless steel, 70-30 copper-nickel, and nickel-clad and Monel-clad steel. All of these were reported to be performing very well after 36 years of exposure [18]. A large number of proprietary coatings, including galvanized and sprayed zinc aluminum, were also tested; all proved to have finite effective lifetimes extending up to 13 years [21].

The 90-10 copper-nickel alloy was not included in these early sheathing trials because its composition with regard to iron and manganese was not yet established.

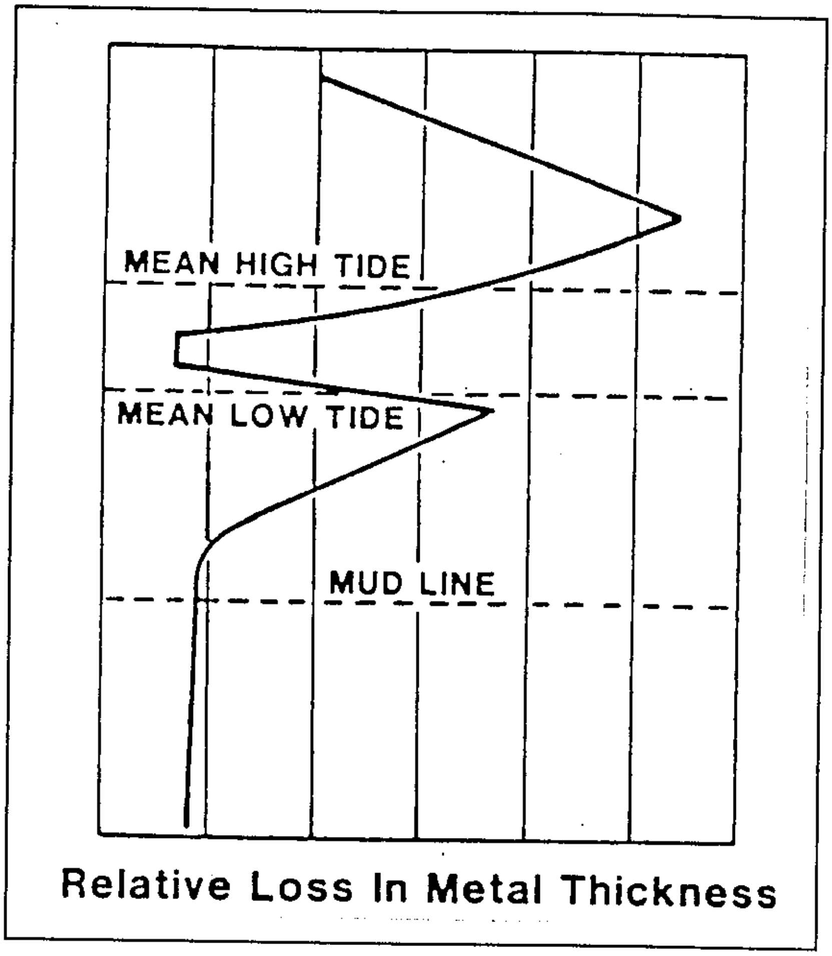


Figure 5 - Profile of the Thickness Loss Resulting From Corrosion of an Unprotected Steel Structure in Sea Water

In the early trials, the Monel and the 70-30 copper-nickel alloy sheaths were welded directly to the steel. One might assume that corrosion of the anodic steel below mean low tide would be accelerated because it is in direct contact with the much more noble sheathing material. A number of experiments were conducted at the LaQue Center to investigate this [22]. It turns out, that in the tidal zone, steel is by far, the most cathodic material, and the more noble sheathing alloys result in lower currents and corrosion of submerged steel than no sheathing at all.

This conclusion is illustrated nicely in the results of galvanic corrosion tests conducted to determine the effects on submerged steel coupled to other alloys in the tidal zone as shown in Figure 7. Plates of the alloys placed in the tidal zone are coupled to submerged steel plates, and the total current per tide was measured periodically over the 14-months of exposure. Current decreased with time, but the results demonstrated clearly that the most severe galvanic couple is steel to steel. This is because even though the potential difference developed in the noble alloy-to-steel couples is significantly greater than between two steel panels, the more rapid and more nearly complete polarization of the noble metals results in a great reduction in galvanic current.

Fouling Protection

As discussed in an earlier section of this paper, the 90-10 copper-nickel alloy provides the best combination of corrosion resistance and biofouling protection. Attachment of this sheathing material to the steel structure by welding or mechanical fasteners will result in cathodic polarization of the sheath material and a reduction in the antifouling capability of the 90-10 copper-nickel alloy. Therefore it is necessary to electrically insulate the sheath from the steel jacket members to get full advantage of the properties of the alloy. Insulation can be achieved by pumping cement or an epoxy into the annular space between the component and the sheath or, more simply, by use of an elastomer or rubber-base insulator. The copper-nickel can be in the form of sheet, wire grid, particles [23] or flame-spray. Bonding of the steel-elastomer-copper-nickel interfaces can be by vulcanizing, by the use of epoxy adhesives, by mechanical means or a combination of methods. Estimated costs in 1986 ranged from \$194 to \$322/m^2 [24].

Long term sheathed piling exposures to assess the effectiveness of corrosion and biofouling protection and measure the cathodic protection current required for several situations have been sponsored by the International Copper Association and the Copper Development Association Inc. at the LaQue Center for Corrosion Technology, Wrightsville Beach, North Carolina [7]. Over 50 ASTM Type A-36 piling 17-cm in diameter were sheathed with 4.6 mm thick x 3 m long 90-10 copper nickel. Some sheaths were directly welded to the steel, others were insulated from the steel with concrete or with 6 mm of a butyl rubber compound. Some piling were cathodically protected with Galvalum III anodes while others remained unprotected. Piling were removed after two, five and ten years of exposure for study of corrosion of the steel and the fouling.

After the two-year exposure, the extent of biofouling accumulation on the directly-welded sheathing was greater than that on the concrete-insulated sheathing and comparable to that on the bare steel. But after five and ten years, the biofouling accumulation on the bare steel had dramatically exceeded that on the directly-welded sheathing. The results of biofouling accumulation on these pilings after ten years of exposure were discussed above and presented as Table IV. On a weight per unit area basis, the amount of biofouling on the bare steel after ten years was almost three times that on the directly-welded copper-nickel sheathing and more than 80 times that on the concrete-insulated sheathing. Inspection of these pilings showed that the 90-10 copper-nickel alloy sheathing, when electrically insulated from the steel, was highly resistant to attachment of marine macro-organisms; although some barnacles were present, their population was very significantly less on the insulated sheathing compared to bare steel. Again, as noted above, the biofouling on the copper-nickel was easily dislodged by wiping.

It was also observed that even in the directly welded sheathing technique where piling were exposed without cathodic protection for ten years, there was no grossly accelerated attack of the steel immediately above or below the sheath. The average corrosion rates in the steel adjacent to the sheathing below the mean low tide point did not exceed 0.25 mm/y, no higher than the rate in the freely corroding, unsheathed steel control pilings. Of course, exposure of any steel piling without cathodic protection is not recommended.

A proprietary system called "Bio-Shield" developed by the Shell Development Company, has met with considerable success on offshore installations off the coast of California [25]. Biofouling can be quite severe along the Southern California coastline. Bioshield consists of 1-1/2 mm thick 90-10 copper-nickel and a high density elastomer with the trade name Splashtron made by the Mark Tool Company of Lafayette, Louisiana. After a laboratory test program, this system was applied to the design of the 214-m water depth Eureka platform with 60 well conductors (0.6 m OD). A total of 152 tonnes of structural steel, otherwise required to handle the loading from the marine growth, was eliminated. The platform was installed in July 1984. After several years, the copper-nickel surface of the Bioshield was free of fouling while the unprotected areas were covered with an 8-13 cm thick layer of barnacle and mussel growth. Platform responses were reduced: wave forces,-6%; base shear -10%; overturning moment, -10%; deck deflection, -10%; and pile load, -7%. The reduced platform response values are the reasons that prevention of marine growth can clearly reduce platform costs. Money was saved in reduced steel for corrosion allowance and improved fatigue characteristics in the major platform joints. Estimated savings realized from installing the sheathing system on the 60 conductors from +1.5 m mean low water line to -4.9 m for the 214 m structure were as follows in (1983-84):

Conductors - 55 tons x $1,000/ton	=	$ 55,000
Paint - 10,600 ft^2 x $3/ft^2	=	$ 32,000
Anodes - $1,250 each x 4	=	$ 5,000
Structural Nodes -114 tons x $2,500/ton	=	285,000
Total	=	$377,000

Estimated savings of $50,000 to $100,000 per cleaning was also to be realized. Installed costs for this system on the Eureka platform were reported to be $250,000 or about $340/m^2. Clearly, this installation of a copper-nickel sheath system in this example was very cost effective.

British Gas Experience, Morecambe Bay, UK

The structures deployed in Phase One of the Morecambe Bay gas field project were sheathed with 90-10 copper-nickel alloy by welding 4 mm thick plate directly to the steel legs over the tidal and splash zones from 2 m below low tide level to 13 m above. A production platform, an accommodation platform, three drill platforms and a flare stack have been so treated. The main purpose of the sheathing was to provide corrosion protection in the splash zone. The submerged portion of the structure is protected by anodes attached directly to the steel. An economic assessment [26] indicated that the 90-10 copper-nickel alloy sheathing was more cost effective than either the Monel 400 alloy sheathing or conventional systems using non-metallic coatings with increased steel thickness previously used on British Gas structures.

The certifying authorities required sacrificial steel (12 mm thickness) in this highly corrosive area when a paint system or neoprene wrap is specified. Sacrificial steel is not required with a copper-nickel (or Monel) metal wrap system. The economic justification was based on a platform life of 15 years. All maintenance costs were discounted to net present value at 10%. Costs were summarized as follows:

System Costs, Million Pounds Sterling

	Protective Coating/Sheathing			
	Paint	**Neoprene**	**Monel**	**90-10 Cu-Ni**
Initial Cost - Extra Steel	2.3	2.3	-	-
Protective Material & Labor	0.1	0.3	2.2	0.95
Maintenance Cost	2.4[(a)]	unknown[(b)]	0.15[(c)]	0.15[(c)]
Extra Weight (Tonnes)	660	660	180	180

(a) Repainting eight years after installation and every five years thereafter

(b) No long-time experience; no large scale repairs assumed in less than 18 years

(c) Minimum maintenance, confined mainly to accident repair

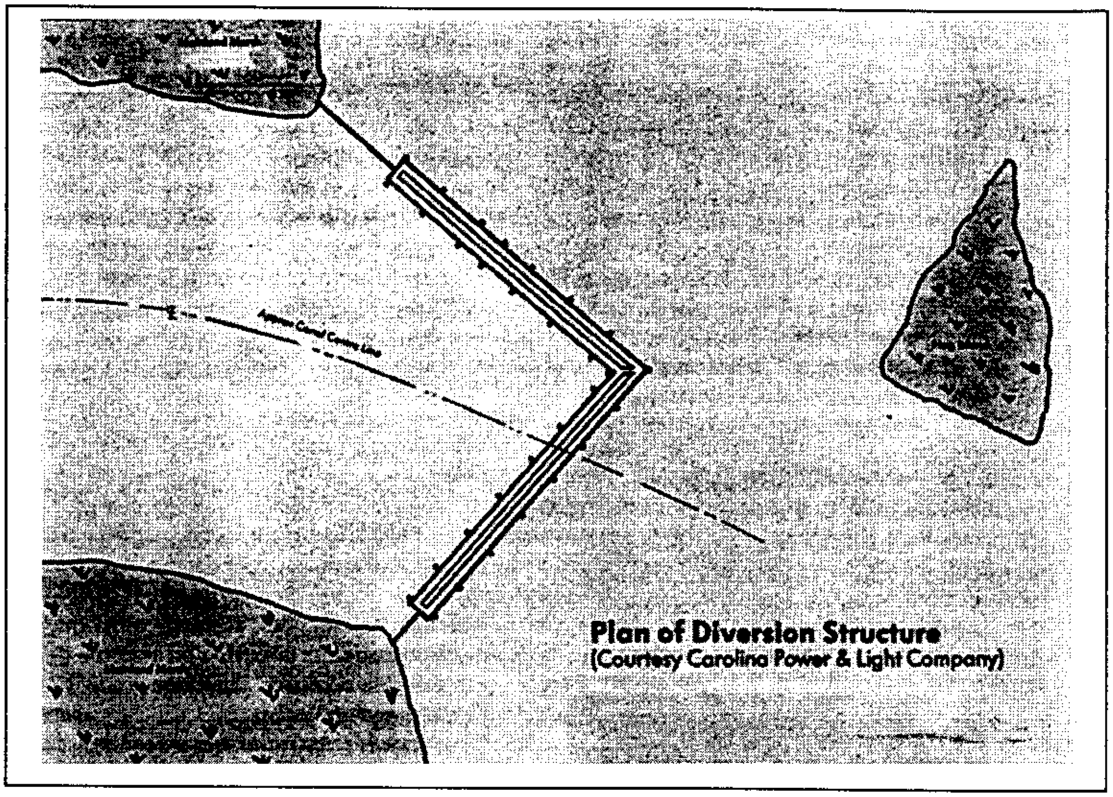
Numbers of inspections by underwater video have been made of the sheathed steel members. The most recent was in 1995, about 12 years after construction. The sheathing appears, as expected, to be free of corrosion and although welded directly to the steel, there is considerably less fouling than on adjacent bare steel members.

Test programs on sheathing of offshore piling have shown the steel underlying the sheathing is virtually completely protected. Biofouling of insulated 90-10 copper-nickel sheathing greatly reduces the potential for structure loading due to increased weight and cross sectional area in turbulent waters. An appreciable decrease in the initial cathodic protection current required by the sheathed piling as compared to the bare steel piling has been observed.

Sheathing of support members and conductors of large offshore platforms has been commercially applied. A number of large installations have performed as expected with documented cost savings compared to the unsheathed design.

A POWER STATION DIVERSION AND TRASH SCREEN

A simple but high maintenance structure that has benefited from the use of copper-nickel alloys is the diversion screen required at the entrance to power plant cooling canals to prevent fish and other large objects from entering. Galvanized steel screening has been used extensively, but short life due to corrosion and the requirement for frequent cleaning to remove marine fouling result in high costs. In the early 1980's, Carolina Power & Light Company conducted tests on a 90-10 copper-nickel mesh made by slitting and expanding sheet. This test resulted in installation of a 144-m diversion screen system employing 45 tonnes of sheet, solid frames and guides in a double row design. The parallel arrangement of screens allows one screen segment to be raised to remove debris while the back screen remains in place to provide a continuous barrier. A schematic plan view of the diversion screen across the inlet is shown in Figure 6. The use of 90-10 copper-nickel frames and guides prevented galvanic corrosion and assured that the copper-nickel mesh would not be cathodically protected for maximum antifouling resistance. This screen has given trouble-free service for 15 years and has substantially reduced maintenance costs.



Plan of Diversion Structure
(Courtesy Carolina Power & Light Company)

Figure 6 - Schematic plan view of the Carolina Power & Light Company diversion structure across the inlet.

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Theme Paper

STAINLESS STEELS AND NICKEL ALLOYS FOR MARINE CONSTRUCTION

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Introduction

Stainless steels and nickel alloys have many characteristics that make them excellent materials for use in marine construction. Resistance of many stainless steels and nickel alloys to corrosion in the marine environment makes them excellent candidates for many applications in marine construction. Depending on alloy composition and other metallurgical factors, stainless steels and nickel alloys have varying levels of resistance to corrosion in the marine environment. While some alloys are essentially immune to corrosion in natural marine environments, others are subject to various forms of corrosion such as pitting, crevice corrosion and stress corrosion cracking. As in the case of any material, the required corrosion resistance must be established for each specific application and the alloy for that application must be selected to have the appropriate level of corrosion resistance in the specific environment to which it will be exposed. Environmental characteristics such as complete immersion versus atmospheric exposure, the temperature and oxygen content of the seawater and the level of marine growth in immersion conditions affect the performance of not only stainless steels and nickel alloys, but of most other materials for marine construction as well.

In most marine applications, complete immunity to corrosion is not required and certain types and levels of corrosion can be tolerated without a significant effect on the performance of the system. In addition to resistance to corrosion by the marine environment, resistance to other environments is also required in many applications. For example, piping and tankage handling corrosive chemicals may require resistance to corrosion by the specific chemical being handled as well as resistance to corrosion by the marine environment. Many stainless steels and nickel alloys are widely used in the chemical process industries for their resistance to specific chemicals. The combination of resistance to corrosion by the combined marine and chemical environments offered by the stainless steels and nickel alloys make them uniquely suited to many of these specialized marine applications.

Corrosion resistance is not the only factor that is important in the selection of materials for marine applications. Strength is an important factor in most marine applications. Stainless steels and nickel containing materials have a wide range of yield strength varying from about 200 MPa (30 ksi) to over 1000 MPa (150 ksi). Ductility and toughness are also important material characteristics for most marine applications. Many of the stainless steels and nickel alloys have excellent ductility and toughness, even at very low temperatures. Some of the stainless steels and nickel alloys have good ductility and toughness at cryogenic temperatures.

Ease of fabrication is also a very important material characteristic. Stainless steels and nickel alloys can be formed and fabricated using conventional fabrication equipment. In most cases, specific procedures must be used that are different from the fabrication of ordinary carbon or alloy steel, but when these procedures are used, the final product will retain the required combination of strength and corrosion resistance. Machining and welding are examples of processes that require different procedures during the manufacture of stainless steel and nickel alloy components. Welding procedures in particular must be specifically matched to the alloys being fabricated. However, these procedures have already been developed for a wide range of applications and materials and are available from alloy producers and other sources. Stainless steels and nickel alloys are also available in a wide range of product types such as plate, sheet, strip, bar, pipe, tubing, and forgings. In addition, many of the stainless steels and nickel alloys can be cast, or are available as alloy variations developed specifically for casting.

These characteristics make many of the stainless steels and nickel alloys excellent materials for use in marine construction. The best material for a specific application is the most cost effective material for that application. In order to select the most cost effective material for a specific application, many factors must be assessed. Initial cost is, of course, an important factor, but other factors must be included in evaluating the actual life cycle cost of various material alternatives for a specific application. Even initial cost must be carefully determined.

Using the cost of the raw material as cost per unit weight is often very misleading. Actual fabricated cost of a component must be determined in order to obtain a realistic value for initial cost. Cost of fabrication often greatly exceeds the cost of the raw materials used. In some cases, a component fabricated from material with a high cost per unit weight will have a lower overall cost due to its low cost of fabrication. In many cases, parts fabricated from materials with high levels of corrosion resistance can be made lighter and thinner than when the same part is made using a less corrosion resistant material where extra material must be added to allow for corrosion. Similarly, using a material with high strength can often reduce the amount of material required for a specific component to a degree that offsets the higher cost of the high strength material. The best way of evaluating the initial costs of alternative materials is to use actual fabricated component costs.

In addition to initial cost, there are other costs that vary significantly when alternative materials are being considered. The increased life that can be obtained from a component through higher resistance to corrosion can reduce the effective annual cost by increasing the number of years of service that can be obtained. Increased life can also reduce costs through the reduction in the need for spares and in the labor costs associated with component replacement. More corrosion resistant materials can also reduce the need for frequent and costly maintenance and repair associated with materials with lower corrosion resistance. This is particularly true when the materials with lower corrosion resistance require protective coatings or other forms of corrosion control in order to provide acceptable levels of corrosion resistance.

In addition to affecting operating costs associated with maintenance and repair, other operating costs can also be affected by selection of materials. Roughening of surfaces by corrosion can increase resistance to fluid flow. In piping systems this can result in increased pumping requirements. Corrosion of pumps can reduce their efficiency requiring the use of larger pumps or longer pump operating times. Loss of product due to leakage can not only increase operating costs directly but can also result in large costs associated with environmental damage.

The downtime of systems due to corrosion is also frequently considered as an operating cost. Some nickel - containing materials, such as the cupro-nickels have inherent resistance to biofouling. This can be used to advantage to reduce operating costs in many marine applications as will be described later in this paper.

Increased reliability offered by corrosion resistant materials can also reduce cost. Reduction in the need for redundancy in critical systems can reduce overall system cost. Increased reliability can often reduce insurance costs, particularly when failure could result in accidents or environmental damage.

Corrosion resistant materials can improve the environmental compatibility of marine systems in many ways. The amount of corrosion products introduced into the environment can be reduced through the use of more corrosion resistant materials. Reduction in leakage can also reduce environmental impact. Elimination of the need for protective coatings can also reduce environmental impact (and costs) associated with surface preparation and coating application. Even the improved appearance of systems fabricated from corrosion resistant materials can be considered to be an improvement in environmental compatibility.

Many of the costs used to determine the most cost effective material for a specific application vary with time. The materials that were once the most cost effective for a given application may no longer be the most cost effective. Other factors such as interest rates, taxes and labor rates can affect the selection of the most cost effective material for a given application. The thorough economic analysis required to select the most cost effective material for a specific application requires considerable effort, but the cost savings associated with the selection of the most appropriate materials can have a large effect on profitability.

State of the Art Stainless Steels for Marine Construction

Stainless steels for marine applications can be grouped into five families of alloys. These families are the austenitic stainless steels, the super austenitic stainless steels, the duplex stainless steels, the ferritic and martensitic stainless steels and the precipitation hardening stainless steels.

The austenitic stainless steels contain chromium and nickel as their primary alloying elements. Many austenitic alloys also contain other alloying elements such as molybdenum and nitrogen. Austenitic stainless steels are used in marine applications primarily because of their resistance to corrosion. The austenitic stainless steels are readily fabricated, welded and cast

The strength of the austenitic stainless steels cannot be increased by heat treatment but can be increased through cold work. The annealed strength of the most commonly used austenitic stainless steels such as UNS S30400 [1] and UNS S31600 is approximately 200 MPa (30 ksi). These alloys can be cold worked to increase their yield strength to 515 MPa (75 ksi) or more. The strength of alloys in this family can also be increased by additions of nitrogen which increases both strength and corrosion resistance. For example, the low carbon grade alloy UNS S30403 has a yield strength of 170 MPa (25 ksi). Through the addition of nitrogen to the basic UNS 30403 composition, UNS 30453 alloy is formed. This alloy has a yield strength of 205 MPa (30 ksi).

[1] Alloy designations using the Unified Number System (UNS) will be used throughout this paper. Nominal compositions of the alloys described in this paper are given in Table 1.

The austenitic stainless steels have varying levels of corrosion resistance in marine environments. Crevice corrosion, pitting and stress corrosion cracking are the forms of corrosion that are most commonly considered when selecting austenitic stainless steels. Resistance to these forms of corrosion varies with alloy content and metallurgical condition. Many of the more highly alloyed austenitic stainless steels, particularly those containing molybdenum and nitrogen have excellent resistance to pitting and crevice corrosion in many marine applications, including atmospheric and immersion exposures. Stress corrosion cracking can occur on austenitic stainless steels in marine applications. The likelihood of stress corrosion cracking of austenitic stainless steels increases as the stress level on the component and the temperature of exposure increases. Stress corrosion cracking failures of annealed austenitic stainless steels at temperatures below 50 ^{O} C (125 ^{O} F) have occurred, but are rare.

In some austenitic stainless steels, manganese is substituted for some of the nickel in the more common austenitic stainless steels. By addition of nitrogen to these alloys, such as UNS S20910 and UNS S24100 materials with good marine corrosion resistance and high strength are formed. For example, alloy UNS S20910 has a annealed yield strength of 380 MPa (55 ksi) while maintaining useful corrosion resistance in marine environments.

The super-austenitic stainless steels are closely related to the austenitic stainless steels but have significantly higher contents of alloying materials such as chromium, nickel and molybdenum and significantly superior resistance to corrosion than their less highly alloyed relatives. The molybdenum content of the super austenitic stainless steels usually exceeds 6% and they contain substantial amounts of nitrogen (0.20% or more). In fact, some of the super-austenitic stainless steels have sufficient content of alloying elements that their iron content is less than 50%, thus some of the super-austenitic stainless steels are not true steels, but are included in this alloy family due to their similarity with other alloys in the family that contain iron in excess of 50%. Super-austenitic stainless steels such as UNS S31254 and UNS N08367 (strictly speaking a nickel alloy, thus the "N" letter designation in the UNS number) are essentially immune to pitting and crevice corrosion in all but the most severe marine environments. However, they remain susceptible to stress corrosion cracking in marine environments at high stress levels and elevated temperatures. The super-austenitic steels austenitic stainless steels are readily fabricated and welded and many can be cast.

The duplex stainless steels also utilize chromium and nickel as their primary alloying elements. They may also contain molybdenum, nitrogen, copper, tungsten and other alloying elements. Duplex stainless steels have a microstructure that contains a mixture of austenite and ferrite. A mixture of about 50% ferrite and 50% austenite is usually preferred. This family of alloys is not new, but many new alloys have been added to the family in the past ten years. The strength of duplex stainless steels is roughly twice the strength of comparable austenitic stainless steels. For example, UNS S31803, a common duplex stainless steel has a yield strength of 450 MPa (65 ksi) compared with the 205 MPa (30 ksi) yield strength of UNS S30400. The corrosion resistance of the duplex stainless steels is roughly equivalent to the austenitic alloys that contain equivalent amounts of chromium, nickel molybdenum and nitrogen. Duplex stainless steels having a continuous ferrite matrix (the preferred microstructure for most alloy compositions) are highly resistant to stress corrosion cracking in marine environments. The pitting resistance of the duplex stainless steels is frequently evaluated using a pitting resistance equivalent (PRE) number that is based on the composition of the alloy. The PRE number is a good indication of the relative resistance of duplex stainless steels to pitting corrosion in marine applications. Duplex alloys having a PRE number greater than 40 are often called "super-duplex" stainless steels. Duplex stainless steels can be readily fabricated. Welding processes must be closely controlled to maintain the proper amounts and distribution of the ferrite and austenite phases in the alloy. There are several duplex stainless steels that can be cast.

The ferritic and martensitic stainless steels contain chromium as their primary alloying element. Martensitic stainless steels usually have higher carbon contents than ferritic stainless steels and can be hardened by heat treatment. Ferritic stainless steels, like austenitic stainless steels, cannot be hardened by heat treatment. While the ferritic and martensitic stainless steels do not possess the high levels of corrosion resistance of the austenitic, super-austenitic and duplex stainless steels in marine environments, most of the martensitic and ferritic stainless steels have significantly better resistance to atmospheric marine corrosion than the carbon steels and low alloy steels. The ferritic grades, particularly those alloys that contain high levels of chromium and other alloying elements such as nickel and molybdenum, show good resistance to corrosion in both marine atmospheric and marine immersion service. These super-ferritic grades such as UNS S44627, UNS S44635 and UNS S44660 have good resistance to pitting, crevice corrosion and stress corrosion cracking in many marine environments.

The precipitation hardening stainless steels contain chromium and nickel at their primary alloying elements. They also contain elements such as aluminum, copper, columbium (niobium) and molybdenum. Precipitation hardening alloys may either be martensitic, semi-austenitic or austenitic. The primary characteristic of the precipitation hardening stainless steels that makes them useful in marine applications is their high strength. This high strength is achieved by a precipitation hardening heat treatment that is performed at relatively low temperatures (480 to 620 ^{O} C (900 to 1150 ^{O} F)) and does not require quenching to achieve high strengths. Avoiding the need for quenching reduces the distortion and cracking that can occur during quenching. Because of their susceptibility to stress corrosion cracking and hydrogen embrittlement in marine environments when heat treated to their highest strength levels, the precipitation hardening stainless steels are seldom used in marine applications at these high strength levels. The strength levels that can be achieved using heat treatments that give good resistance to stress corrosion cracking and hydrogen embrittlement in marine environments are relatively high when compared to many other materials. Alloy UNS S17400, for example, has a yield strength of 800 MPa (125 ksi) when heat treated to the H1075 condition that gives the alloy good resistance to stress corrosion cracking. Under immersion conditions where sulfides are present and hydrogen embrittlement is more severe, lower strength levels are required to give resistance to hydrogen embrittlement. For example, the highest strength level that can be used for alloy UNS S17400 in seawater with sulfide present is 690 MPa (100 ksi). Special heat treatments have been developed for some precipitation hardening stainless steels that allow higher strength levels to be achieved while retaining the required level of resistance to stress corrosion cracking and hydrogen embrittlement. While the resistance to pitting and crevice corrosion of the precipitation hardening stainless steels is not as good as the better austenitic, duplex and ferritic grades, their resistance to pitting and crevice corrosion is appreciable and the levels of pitting and crevice corrosion resistance achieved makes the precipitation hardening stainless steels useful in many marine applications where high strength is coupled with moderate resistance to corrosion is required.

State of the Art Nickel Alloys for Marine Construction

Many nickel containing alloys other than stainless steels have characteristics that make them excellent candidates for marine applications. These characteristics include resistance to corrosion by both the marine environment and many chemical environments, high strength, good strength at both low (cryogenic) and high temperatures, resistance to biofouling, low coefficients of thermal expansion, and shape-memory effect.

Many nickel-chromium alloys and nickel-chromium-iron alloys have characteristics that make them excellent candidates for many marine applications. Alloys in this group such as UNS N06600, UNS N07214, and UNS N08825 are primarily used where a combination of corrosion resistance and resistance to elevated temperatures is required. Alloys in this group containing higher amounts of molybdenum such as UNS N06625, and UNS N10276 have greatly improved marine corrosion resistance when compared to alloys in the group with lower amounts of molybdenum such as UNS N06600. Alloys with very high molybdenum contents such as UNS N06625 and UNS N10276 are essentially immune to pitting corrosion in marine environments and are resistant to crevice corrosion under all but the most extreme conditions. Other alloys in this group such as UNS N08020 have corrosion resistance intermediate between the austenitic stainless steels and the highly resistant - high molybdenum content alloys.

The nickel-copper alloys have a long record of excellent service in the marine environments, primarily due to their corrosion resistance. Alloy UNS N04400, containing roughly 2/3 nickel and 1/3 copper, has been used for over 50 years for its resistance to marine corrosion. However, alloy UNS N04400 is surprisingly susceptible to pitting corrosion under seawater immersion exposure. However, in many cases, alloy UNS N04400 is exposed to immersion such that it is electrically connected to more active materials and receives sufficient cathodic protection from this electrical coupling to mitigate pitting. While alloy UNS N04400 does not have high strength (170 MPa - 25 ksi yield strength), addition of aluminum and titanium to the basic alloy UNS N04400 composition produces an alloy (UNS N05500) that is precipitation hardenable. This alloy can be heat treated to very high strength - 900 MPa (130 ksi) yield strength.

The copper-nickel alloys are widely used in marine applications. Addition of nickel to copper increases the resistance of the copper to corrosion under quiescent immersion conditions and also increases the resistance of these alloys to attack by seawater under velocity conditions. Alloys in this group with high copper contents such as alloy UNS C70600 (10% nickel) corrode at a rate that releases sufficient copper at the metal surface to give the alloy resistance to biofouling under immersion conditions. This resistance to biofouling reduces the adverse effects of biofouling on heat transfer and clogging of marine heat exchangers. It can also reduce drag and fuel consumption when the alloys are used for ship hulls. The biofouling resistance of these alloys is also useful in many other marine applications. Copper-nickel alloys with higher nickel contents such as alloy UNS C71500 (30% nickel) have improved resistance to velocity attack under immersion conditions but have reduced resistance to biofouling when compared to the higher copper content copper-nickel alloys.

The nickel based superalloys are precipitation hardening alloys that have high strength capabilities. Many of the alloys in this group also have good resistance to corrosion in marine environments, such as UNS N07718, that has a yield strength of up to 1190 MPa (172 ksi). These alloys find use in marine structures in applications such as fasteners where a combination of high strength and good corrosion resistance is required.

Nickel alloy steels, containing about 36% nickel, have very low coefficients of thermal expansion. For example, alloy UNS K93600 has a coefficient of thermal expansion of less than 1 µm/m · K as compared with ordinary carbon steel that has a coefficient of thermal expansion of about 12 µm/m · K. These alloys are primarily used in the marine industry for storage and handling of materials such as liquefied natural gas at cryogenic temperatures. Alloys with nickel contents other than the lowest expansion composition have coefficients of thermal expansion between that of the minimum expansion alloys and ordinary steels.

Nickel-titanium alloys having nickel contents of approximately 50% have a unique property called the shape memory effect. When properly treated, they can be deformed, then, when heated to a relatively low temperature will return to their original shape., This property has been used to advantage in specialized marine applications such as mechanical couplings for pipe and tubing where the couplings are stretched to fit the tubing, then heated so that they shrink back to their original size thus providing a tight mechanical joint.

Current and Future Applications of Stainless Steels and Nickel Alloys for Offshore Structures

Stainless steels and nickel - containing alloys have both current and potential future applications for marine moorings and risers. Mooring components such as fasteners and connectors (shackles) are frequently fabricated from corrosion resistant materials such as stainless steel. The corrosion resistance of these components both increases the life and reliability of these critical components of mooring systems, but also allows for easy disassembly and re-assembly during maintenance and repair. Stainless steel has been used for chain and wire rope with mixed results. The more commonly used grades of stainless steel such as UNS S30400 and UNS S31600 are subject to crevice corrosion and have relatively low strength. Chain and wire rope have numerous crevice sites and, thus, crevice corrosion limits the useful life of mooring systems from these alloys. Wire rope and chain fabricated from more corrosion resistant grades of stainless steel and nickel alloys such as UNS S31803, UNS S31254 , UNS N08367 and UNS N10276 have potential applications where superior corrosion resistance is required. When these more corrosion resistant alloys are used, more corrosion resistant hardware and connectors fabricated from similar materials may also be required.

Platforms are traditionally fabricated from low alloy steel and this material will likely be used in the future for major underwater structural components of platforms. Traditionally, the underwater sections of platforms have been protected from corrosion by cathodic protection, sometimes augmented by protective coatings. This trend is likely to continue. The above-water sections of platforms have been traditionally protected from corrosion through the use of protective coatings. These coatings, however, require periodic repair or replacement. Coating repair or replacement at sea is extremely expensive and, due to contamination of the surfaces with sea salts, frequently results in a coating system with poor performance. This situation is even worse in the intertidal and splash and spray zones of the platforms where corrosion is commonly the most severe. The intertidal zone is particularly difficult to recoat in place. The use of materials with inherent corrosion resistance superior to ordinary alloy steels may be more cost effective as they can be exposed without the need for protective coatings and subsequent coating repair. Metallic cladding of platform components in the intertidal zone and the lower portions of the splash and spray zones of platforms have been used previously with success.

Materials such as UNS N04400, UNS C70600 and UNS C71500 are commonly used for cladding of steel The anti-fouling properties of alloys such as UNS C70600 also provide the added advantage of reducing the weight and hydrodynamic drag that are associated with the attachment of fouling organisms in the intertidal zone. The claddings are commonly attached by welding, mechanical fasteners, adhesives and clamps. The use of clad metal (where a relatively thin layer of corrosion resistant material is metallurgically bonded to a carbon or alloy steel substrate) may also prove to be useful for cladding of platforms in the intertidal and splash and spray zone. The steel substrate provides the structural strength required and the corrosion resistant material serves as an extremely effective and durable form of protective coating. One concern in the use of corrosion resistant materials as cladding is the potential for the acceleration of corrosion of the structural steel directly beneath the cladding and the structure immediately below the clad zone due to galvanic corrosion between the steel and the cladding material. The corrosion of steel directly beneath the cladding has proven to be minimal even when there was no attempt to exclude seawater from this joint through the use of sealants. This has been attributed to the rapid filling of the space between the steel and the cladding with corrosion products that reduce circulation of seawater between the cladding and the steel and reduce corrosion in this area to low values. The use of steel with a metallurgically bonded cladding will eliminate corrosion in this area completely. Corrosion of the steel platform elements at an elevation immediately beneath the clad zone will be mitigated by the cathodic protection system on the platform. If alloys such as UNS C70600 are used as cladding for anti-fouling purposes, they should be electrically isolated from the steel platform in order to provide their full anti-fouling properties. If electrically coupled to the steel platform, the release of copper at the surface of the cladding will be reduced to levels that may not provide the highest level of fouling resistance. To provide the best anti-fouling properties, these materials should electrically isolated from the steel by the interposition of an insulating material or an insulating sealant between the steel and the cladding.

Floating offshore structures may also benefit from the use of corrosion resistant and anti-fouling alloys in a manner similar to platforms. The reduction in weight that can be obtained through the use of high strength corrosion resistant materials may be more useful for floating structures than for platforms. Additionally, the use of higher strength materials is obvious. However, the use of corrosion resistant materials can also reduce weight by reducing or eliminating the necessity of adding extra material as a corrosion allowance. Corrosion resistant materials also reduce maintenance costs through the elimination of the need for coating maintenance. Where coating maintenance requires dry-docking, even greater economic benefits may be obtained. Downtime is also reduced by reducing the frequency of corrosion - related failures and reducing dry-docking time. Reduction of weight gain of the floating structure due to the accumulation of fouling organisms can also be reduced or eliminated through the use of inherently anti-fouling materials such as UNS C70600 on the submerged portions of the structure.

Deckhouses on both platforms and floating offshore structures are exposed to highly aggressive marine environments. Traditionally, these deckhouses have been fabricated from steel and require almost continuous coating maintenance. The use of corrosion resistant materials for deckhouses can eliminate the need for frequent coating maintenance. Weight reduction of deckhouses is also important and the use of corrosion resistant materials can reduce weight by eliminating the need for additional material as corrosion allowance. The use of higher strength corrosion resistant materials can further reduce the weight of deckhouses.

Pipelines and flowlines have been traditionally fabricated from carbon and alloy steel. Where ambient temperature product is being carried by these lines, traditional coatings and cathodic protection have been successful in controlling external corrosion of the submerged portions of these components in many instances. However, when high temperature product is being carried, traditional coatings and cathodic protection have proven to be difficult. In these cases, the use of materials with improved inherent corrosion resistance may be appropriate. The duplex stainless steels such as UNS S31803, with their resistance to stress corrosion cracking at elevated temperatures may be considered for these applications. Where higher resistance to corrosion is required, alloys such as UNS N10276, UNS N06625, UNS S31254, or UNS N08367 may be required. Interior corrosion of pipelines and flowlines may also be a consideration in some cases. In these cases, the use of a material with better corrosion resistance than carbon steel or alloy steel may be required. The more corrosion resistant material may be used for the fabrication of the entire pipelines or flowlines or as an internal lining for a carbon steel line.

Burners or flares require a combination of corrosion resistance and resistance to elevated temperatures that is met by many of the high nickel alloys. Alloys such as UNS N06002, UNS N08800, UNS N08810, UNS N08811, UNS N08825 and UNS R30556 are excellent candidates for this critical application.

Process equipment such as seawater piping, pumps and heat exchangers require corrosion resistant materials. In many cases, alloys such as UNS S31600 have given good service in seawater piping systems when the systems are properly designed and fabricated. This is particularly true when the systems operate continuously at relatively high velocities. When stagnant conditions are anticipated, the system should be designed so that it can be flushed with fresh water and drained, or more corrosion resistant materials will be required. When greater corrosion resistance is required than is provided by the use of alloys such as UNS S31600, austenitic alloys such as UNS S31254 and UNS N08367, or duplex alloys such as UNS S31803 or UNS S39255 may be considered for use as piping handling seawater. Alloys with higher corrosion resistance may be required if the seawater is chlorinated for control of biofouling or is at an elevated temperature. Nearly complete immunity to seawater corrosion can be obtained through the use of high nickel alloy piping such as UNS N06625 or UNS N10276 in critical piping applications.. Copper-nickel alloys such as UNS C70600 and UNS C71500 have also provided excellent service as seawater piping materials. Both alloys have limited resistance to velocity attack with the UNS C71500 alloy having a higher velocity limit than alloy UNS C70600. The inherent resistance to biofouling of the UNS 70600 alloy is also useful for seawater piping system using raw seawater.

Cast equivalents of many of the alloys used for seawater piping can be used for seawater pumps. Alloy UNS J92800 is the cast equivalent of alloy UNS S31600 and has given very good service as an impeller material in pumps with cast iron cases. The cast iron provides cathodic protection to the stainless steel shaft and impeller, which is responsible for the good performance of this alloy in this service. Nickel containing cast irons such as those described in ASTM specification A439 perform well as casings for seawater pumps using more corrosion resistant impellers and shafts. Alloys such as UNS S31254 or UNS S39255 may be required for pumps that use corrosion resistant alloys for the case as well as for the impeller and shaft. Navy fire fighting pumps fabricated from alloy UNS N08020 have provided excellent service.

Both tube - type and plate - type heat exchangers have been used seawater application. The tube type heat exchangers commonly use corrosion resistant materials such as UNS S31254, UNS N08367, UNS N10276 or UNS N06625 where high performance is required. These alloys can also be used as tubesheet materials. While these materials do not have inherent resistance to the attachment of biofouling, they are remarkably resistant to biofouling if the velocities in the tubes are kept high. High velocities can be used with these materials as they have excellent resistance to velocity attack. The smoothness of tubing made from these materials and the retention of this smoothness during operation probably contributes significantly to the in-service biofouling resistance of these alloys. Alloys with inherent resistance to biofouling such as UNS C70600 are also widely used for tubes in heat exchangers where their resistance to biofouling and their high heat transfer coefficients result in very efficient heat transfer. However, the velocity of flow and turbulence in the tubes must be carefully controlled in order to obtain optimum corrosion resistance from alloys such as UNS C70600 or UNC C71500.

Plate - type heat exchangers require very high resistance to crevice corrosion as their design results in numerous tight crevices. Alloys such as UNS S31254, UNS N08367, UNS N10276 or UNS N06625 that have very good resistance to crevice corrosion are probably required for use in plate - type heat exchangers handling either raw or chlorinated seawater.

Current and Future Applications of Stainless Steels and Nickel Alloys for Waterfront Structures and Equipment

Nickel containing materials have many current and potential applications for waterfront structures such as piers and wharves and their associated utility systems.

Steel piling exposed to the intertidal and splash and spray zones of piers and wharves suffers from corrosion in these areas similar to that encountered on offshore platforms. Wood piling also suffers from attack by marine organisms in the submerged portions of the piling. In many cases, the submerged portions of steel piling are protected from corrosion by the use of coatings and / or cathodic protection. The above-water sections of steel piling are usually protected from corrosion by protective coatings. As in the case of platforms, the intertidal zone of the piling often suffers from the most severe and difficult to control attack. Metallic cladding of piling in the intertidal zone and the lower portions of the splash and spray zones of steel pilings has been used previously with success. Materials such as UNS N04400, UNS C70600 and UNS C71500 are the most frequent candidates for this cladding. The anti-fouling properties of alloys such as UNS C70600 also provide a benefit for waterfront structures, primarily because of the reduction of the weight accumulation due to fouling. As in the case of platforms, galvanic interaction between the cladding and the submerged steel may be important, particularly if the submerged portions of the piling are not protected by cathodic protection. In these cases, it may be advantageous to electrically isolate the cladding from the piling. Wood piling can also be protected from deterioration by marine organisms by covering the surface of the piling with a cladding that provides a barrier to the oxygen required for the proliferation of the organisms. Because of the less mechanically aggressive environment encountered in many waterfront structures as compared to open ocean platforms, the cladding thickness for protection of either wood or steel piling can be substantially less than that required for offshore platforms. Systems have been developed for attachment of cladding to steel pilings by welding, mechanical fasteners and adhesive bonding, and is not limited to round piling. Sheet piling and H-beams as well as most other structural shapes can be effectively clad. Wooden pilings are usually wrapped with thin sheet material that is either nailed to the piling or are retained by external clamps.

Carbon steel is the most commonly used material for reinforcement and prestressing of concrete structures. However, carbon steel is subject to corrosion in marine concrete structures. Due to the higher probability of cracking of the concrete, reinforced concrete marine structures are more prone to corrosion of the reinforcement than are prestressed structures, but both types of structures are vulnerable. Corrosion of embedded steel can be minimized by good design (primarily the depth of concrete cover over the steel) and by the use of concrete mixes that maximize the protective properties of the concrete (such as generous amounts of cement, low water/cement ratios and the use of admixtures) but corrosion of embedded steel will eventually occur due to penetration of chlorides from the marine environment. Austenitic stainless steels such as UNS S30400 and UNS S31600 have been used as reinforcement for marine structures with good success. Prestressing strand made from alloys such as UNS S24000 have been used in concrete piers where the primary requirement was for non-magnetic prestressing materials. However, the superior corrosion resistance of the UNS S24000 in concrete when compared to carbon steel will also result in a structure with significantly improved life. Other alloys such as UNS S20910 and UNS S39209 are also being considered as prestressing strands where corrosion resistance in marine environments is a primary requirement.

Nickel - containing alloys also find many applications in waterfront structures as fasteners and hardware. In the splash, spray and atmospheric zones, alloys such as UNS S30400 and UNS S31600 have sufficient resistance to corrosion to provide excellent service in many of these applications. Where improved performance is required, or under conditions of complete immersion in seawater, alloys such as UNS S31254, UNS N08367, UNS N06625 or UNS N01276 may be required. Where high strength is required alloys such as UNS N07718 or UNS N05500 may be required. Where maximum strength and corrosion resistance are required in a fastener, alloy UNS R30035 may be considered as it is essentially immune to marine corrosion and can have yield strengths of up to 1585 MPa (230 ksi).

Utility systems for waterfront structures include items such as seawater pumps and piping systems, waste collection and treatment systems, housings for electrical and mechanical equipment, fasteners and hardware. Corrosion resistance is an important factor in the selection of all of these components for waterfront structures if economical and reliable service is to be obtained. Materials for seawater pumps and piping systems should be selected using the same general criteria as described above for offshore structures. Seawater pumps such as those used for fire fighting water supplies are often used intermittently and have long idle periods where they are filled with stagnant seawater. This is an important factor in selection of materials for these pumps and more corrosion resistant materials such as UNS N08367, UNS N10276 or UNS N06625 are often required for these applications where reliability and resistance to stagnant seawater are very important.

Equipment housings for waterfront structures have been traditionally fabricated from carbon steel and protected from corrosion by protective coatings. This frequently results in housings that have a short useful life and require nearly continuous maintenance painting. In many cases, deterioration of the housings leads to deterioration of the equipment contained within the housings. The use of moderately corrosion resistant alloys such as UNS S30400 and UNS S31600 for these housings can result in considerable life cycle cost savings over the initially less expensive coated steel. Likewise, the use of moderately corrosion resistant materials such as UNS S30400 and UNS S31600 for fasteners and hardware can both increase the reliability and life of the systems using these alloys as fasteners. In addition, fasteners fabricated from corrosion resistant materials are easier to disassemble and reassemble than ordinary carbon steel or alloy steel fasteners. This can result in significant savings when disassembly and reassembly is required for maintenance, modification or repair of the systems. Waste collection and treatment systems are subject to both the marine environment and the wastewater environment. The wastewater environment can be particularly aggressive when seawater is used as an input as in the case for most ship wastewater systems. Alloys such as UNS S31803, UNS N08367, UNS N06625 or UNS N10276 may be required for these aggressive environments.

Current and Future Applications of Stainless Steels and Nickel Alloys for Ships and Small Craft

Covering the hulls of ships with copper alloys to prevent biofouling attachment has been practiced for nearly 300 years. The use of more modern copper-nickel alloys as a hull material or as cladding over steel hulls has been proven to be successful for over 50 years. Both alloy UNS C70600 and UNS C71500 have shown good resistance to biofouling and corrosion. While the UNS C70600 alloy is normally considered to have better resistance to biofouling attachment, alloy UNS C71500 is also resistant to biofouling and has higher strength. Alloy UNS C71500 has most frequently been used as an integral hull plating whereas alloy UNS C70600 has been used both as an integral hull plating and as a cladding material over steel. The UNS C70600 cladding has also been applied as a thin foil attached by adhesives. The use of these fouling and corrosion resistant materials has many advantages including increased speed and reduced fuel consumption, the reduced need for dry-docking or hauling-out to remove fouling and the elimination the need for coating of the hull. To date, successful applications of these materials has been limited to craft of less than 25 meters in length, but the cladding of larger hulls is feasible. The primary consideration in the use of these materials for hulls is the economic balance between the additional cost of using these alloys and the economic benefits. Both of these factors vary with time and the economic viability of clad hulls will also vary. Increased cost of fuel is perhaps the most important factor in determining the economic viability of clad hulls.

The selection of materials for seawater pumps for ships and small craft has considerations similar to that for platforms and waterfront structures. However, for smaller pumps, the cost of materials is less significant than for larger pumps and more costly but highly corrosion resistant materials may be justified. As in the case of all pumps, stagnant conditions must be considered when selecting pump materials. Alloys UNS C70600 and UNS C71500 have been widely and successfully used for seawater piping systems on ships for many years. However, where very high velocity flows or turbulence are encountered, the use of alloys with greater resistance to velocity attack coupled with excellent resistance to crevice corrosion such as UNS S31245, UNS S32750, and UNS N08367 may be necessary.

Shipboard waste collection and treatment systems create an extremely corrosive environment. As described above for waterfront utility systems, alloys such as UNS31803, UNS N08367, UNS N06625 or UNS N10276 may be required for these aggressive environments. This is particularly true where chemical treatments such as chlorination are used to treat the wastewater for discharge.

Copper alloys have been traditionally used for propellers for ships and small craft for many years. Alloys such as UNS C95800 have been used for both large and small ships propellers. Stainless steels such as UNS J92500, UNS J92900 and UNS J92800 have also been used for many years as material for propellers of up to about 1.5 meters in diameter for small craft. These propellers provide excellent seawater service. The materials for and electrical connections between the hull, propeller, shaft and stern tube must be proper in order to obtain optimum corrosion performance. Alloy UNS J91540 has also been successfully used for larger icebreaker propellers where its higher strength is an advantage. An additional benefit of the use of these stainless steel propellers is their repairability. They can be repeatedly straightened and weld repaired when damaged. This is not the case for copper alloy propellers that can only be straightened a few times and are difficult to repair by welding. Stainless steels such as UNS S30400, UNS S31600 and the higher strength alloys such as UNS N20910 have also been widely used as a shaft material for small craft with great success, particularly when through electrical connection to the steel hull of the vessel.

Chemical tanks and piping systems on ships are commonly fabricated from corrosion resistant alloys in order to provide resistant to the materials being contained and handled. Stainless steels such as UNS S30400, UNS S31600 and UNS S31803 frequently have adequate resistant to the chemical environments and, if the systems are carefully designed to eliminate external crevices and features that trap and hold seawater, have adequate resistance to the marine environment. In other cases, more corrosion resistant alloys are required for chemical compatibility and the compatibility of these alloys with the marine environment must be evaluated separately.

Cryogenic storage tanks such as those used for the storage of liquefied natural gas are commonly constructed using alloys with very low coefficients of thermal expansion such as UNS K93600.

Inert gas generation systems on petroleum tankers are used to produce gas that is low in oxygen from the vessels exhaust. This gas is used for filling void spaces that are carrying or have carried flammable liquids to reduce the risk of fire or explosion. The high temperature environment in portions of these systems, frequently heavily contaminated with chlorides, sulfur compounds, nitrogen oxides and soot is very aggressive and materials such as UNS N06625 or UNS N10276 may be required.

As for waterfront structures, fasteners and hardware fabricated from relatively inexpensive stainless steels such as UNS S30400 or UNS S31600 frequently have sufficient corrosion resistance to give excellent performance as materials for deck equipment and hardware. Fasteners fabricated from these alloys are particularly suited to deck application, particularly where ease of disassembly and reassembly is an important factor. In service where elevated ambient temperatures may cause stress - corrosion cracking of alloys such as UNS S30400 or UNS S31600, or where additional corrosion resistance is required alloys such as UNS N06625, UNS N10276, UNS N31803, UNS S32750, or UNS S31254 may be considered.

Summary

Nickel - containing alloys are widely used for marine construction due to their combination of corrosion resistance and other desirable physical and mechanical properties. There are also many additional applications where the superior properties of nickel - containing alloys can result in improved reliability and lower life cycle costs for marine structures. Each of these applications requires a thorough evaluation of alloys to determine which one is best suited to that specific application. There are a wide variety of nickel - containing materials currently available and more are being developed on a continuing basis. In some cases, the choice of materials is fairly obvious, in other cases, the services of a materials expert are necessary to select the best alloy for a specific application. In some cases, alloys will be developed to meet the requirements of a specific application or range of applications.

A wide variety of literature and technical assistance for the use of nickel - containing materials in marine applications is available from the Nickel Development Institute in Toronto, Ontario, Canada.

Table 1. Nominal Composition of Nickel Containing Alloys

UNS Number	Nominal Composition (%)
C70600	Cu - 88.5, Ni - 10, Fe - 1.5
C71500	Cu - 69, Ni - 30, Fe - 1
C95800	Cu - 79, Al - 9, Fe - 4, Ni - 4, Mn - 1
J91540	Fe - 79, Cr - 13, Ni - 7, Si - 1
J92500	Fe - 70, Cr - 19, Ni - 9, Si - 2
J92800	Fe - 66.5, Cr - 20, Ni - 9, Mo - 2.5, Si - 2
J92900	Fe 66.5, Cr - 19, Ni - 10, Mo - 2.5, Si - 2
K93600	Fe - 64, Ni - 36
N04400	Ni - 66, Cu - 31.5, Fe - 1.5, Mn - 1
N05500	Ni - 66, Cu - 28.5, Al - 2.5, Fe - 1, Mn - 1, Ti - 0.5
N06002	Ni - 49, Cr - 22, Fe - 18, Mo - 9, Co - 1.5, W - 0.5
N06600	Ni - 75, Cr - 16, Fe - 8, Mn - 1
N06625	Ni - 62, Cr 22, Mo - 9, Fe - 4, Cb - 3.5
N07214	Ni - 76.5, Cr - 16, Al - 4.5, Fe - 3
N07718	Ni - 52.5, Cr - 20, Fe - 19, Cb - 5, Mo - 3, Al - 0.5
N08020	Fe - 39, Ni - 34, Cr - 20, Cu - 3.5, Mo - 2.5, Cb - 1
N08367	Fe - 47.5, Ni - 24, Cr - 21, Mo - 6.5, Mn - 1, N - 0.2
N08800	Fe - 44.5, Ni - 32.5, Cr - 21, Mn - 1, Al - 0.5, Ti - 0.5
N08810	Fe - 44.5, Ni - 32.5, Cr - 21, Mn - 1, Al - 0.5, Ti - 0.5
N08811	Fe - 44.5, Ni - 32.5, Cr - 21, Mn - 1, Al - 0.5, Ti - 0.5
N08825	Ni - 42, Fe - 33, Cr - 20, Mo - 3, Cu - 2
N10276	Ni - 59, Mo - 16, Cr - 15, Fe - 5, W - 3.5, Co - 1.5
R30035	Ni - 35, Co - 35, 20 - Cr, Mo - 10
R30556	Ni - 37, Fe - 33, Cr - 25, Co - 3, Mo - 2, W - 2
S17400	Fe - 73, Cr - 17, Ni - 4, Cu - 4, Mn - 1, Si - 1, Nb - 0.25, C- 0.07
S20910	Fe - 58, Cr - 22, Ni - 12, Mn - 5, Mo - 2, Si - 1, N - 0.3, C - 0.06
S24000	Fe - 65, Cr - 18, Mn - 13, Ni - 3, Si - 1, N - 0.3, C - 0.08
S24100	Fe - 65.5, Cr - 18, Mn - 12.5, Ni - 2, Si - 1, N - 0.3, C - 0.15
S30400	Fe - 68.5, Cr - 19, Ni - 9.5, Mn - 2, Si - 1, C - 0.08
S30403	Fe - 68.5, Cr - 19, Ni - 9.5, Mn - 2, Si - 1, C - 0.03
S30453	Fe - 68.5, Cr - 19, Ni - 9.5, Mn - 2, Si - 1, C - 0.03, N - 0.15
S31254	Fe - 53, Cr - 20, Ni - 18, Mo - 6, Cu - 1, Mn - 1, Si - 1, N - 0.2
S31600	Fe - 65.5, Cr - 17, Ni - 12, Mo - 2.5, Mn - 2, Si - 1, C - 0.08
S31803	Fe - 66.5, Cr - 22, Ni - 5.5, Mo - 3, Mn - 2, Si - 1, N - 0.15, C - 0.03
S32750	Fe - 62, Cr - 25, Ni - 7, Mo - 4, Mn - 1.2, Si - 0.8, N - 0.28, C - 0.03
S39255	Fe - 62.5, Cr - 24.5, Ni - 5.5, Mo - 3, Cu - 2, Mn - 1.5, Si - 1, N - 0.3
S44627	Fe - 68.5, Cr - 26, Mo - 4, Si - 1, Ni - 0.5, N - 0.02
S44635	Fe - 66, Cr - 25, Ni - 4, Mo - 4, Si - 1, N - 0.03
S44660	Fe - 67, Cr - 26, Ni - 3, Mo - 3, Si - 1, N - 0.03

Stainless Steels and Nickel Alloys for Marine Construction

James F. Jenkins, Consultant

Nickel Development Institute

Nickel Development Institute

Market development and applications-research arm of the primary nickel industry

- Headquarters, Toronto, Ontario, Canada
- Offices in England, Australia, South America, India, Japan & South Korea
- Represents 16 of the major worldwide producers of primary nickel
- Over 80 consultants worldwide

Stainless Steels and Nickel Alloys

Wide Range of Characteristics

- Corrosion resistance
- Strength
- Ductility and toughness
- Ease of fabrication
- Physical properties

Selecting the Best Material

- Suitable characteristics
  - Reliable service
- Lowest cost
  - Actual fabricated cost
  - Cost of operation, maintenance and repair
  - Environmental damage
  - Costs vary with time

Stainless Steel Types

- Austenitic
- Super-austenitic
- Duplex
- Ferritic & martensitic
- Precipitation hardening

Austenitic Stainless Steels

- Iron + chromium & nickel
- Molybdenum & nitrogen additions
- Relatively low strength
- Varying levels of corrosion resistance
  - Crevice corrosion
  - Pitting corrosion
  - Stress corrosion cracking

Austenitic Stainless Steels

Common Austenitic Stainless Steels

- UNS S30400
- UNS S30403
- UNS S30453
- UNS S31600
- UNS S20910
- UNS S24100

Super-Austenitic Stainless Steels

- Higher alloy contents
  - Chromium
  - Nickel
  - Molybdenum
  - Nitrogen
- Superior corrosion resistance

Super-Austenitic Stainless Steels

Common Super-Austenitic Stainless Steels

- UNS S31254
- UNS N08367

Duplex Stainless Steels

- Iron + chromium & nickel
- Other alloying elements
- Mixture of austenite & ferrite
- Many new alloys
- Higher strength
- Resistant to stress corrosion cracking
- “Super duplex” alloys - pitting resistant

Duplex Stainless Steels

Common Duplex Stainless Steels

- UNS S31803
- UNS S39255

Ferritic & Martensitic Stainless Steels

- Iron + chromium
- Other alloy additions
- Martensitic can be hardened by heat treatment
- Moderate corrosion resistance
- High chromium "super ferritics" have better resistance

Ferritic and Martensitic Stainless Steels

Common Ferritic & Martensitic Stainless Steels

- UNS S43000 (Ferritic)
- UNS S41000 (Martensitic)
- UNS S44627 (Super Ferritic)
- UNS S44635 (Super Ferritic)
- UNS S44660 (Super Ferritic)

Precipitation Hardening Stainless Steels

- Iron + chromium
- Other alloy additions
- High strength by precipitation hardening
- Moderate corrosion resistance
- Hydrogen embrittlement
- Stress corrosion cracking

Precipitation Hardening Stainless Steels

Common Precipitation Hardening Stainless Steels

- UNS S17400
- UNS S13800
- UNS S66286

Nickel Alloys and Nickel Containing Alloys

- Nickel - chromium alloys
- Nickel - chromium - iron alloys
- Nickel - copper alloys
- Copper - nickel alloys
- Nickel based superalloys
- Nickel alloy steels
- Nickel - titanium alloys

Nickel - Chromium and Nickel - Chromium - Iron Alloys

- Combination of corrosion resistance and resistance to high temperatures
- High molybdenum alloys have excellent marine corrosion resistance

Nickel - Chromium and Nickel - Chromium - Iron Alloys

Common Nickel - Chromium and Nickel - Chromium - Iron Alloys

- UNS N06600
- UNS N07214
- UNS N08825
- UNS N06625
- UNS N10276
- UNS N08020

Nickel - Copper Alloys

- Long record of excellent service
- Susceptible to pitting
- Protected by coupling with more active materials
- High strength alloy available

Nickel - Copper Alloys

Common Nickel - Copper Alloys

- UNS N04400
- UNS N05500

Copper - Nickel Alloys

- Nickel improves corrosion resistance
  - Quiescent conditions
  - Velocity conditions
- Anti - fouling properties - 10% nickel alloy
- Higher nickel content improves velocity resistance - 30% nickel alloy

Copper - Nickel Alloys

Common Copper - Nickel Alloys

- UNS C70600
- UNS C71500

Nickel Based Superalloys

- Precipitation hardening - high strength
- Good resistance to marine corrosion

Common Nickel Based Superalloys

- UNS N07718

Nickel Alloy Steels

- Steels with about 36% nickel have low coefficient of thermal expansion
- Cryogenic applications

Common Low Expansion Nickel Alloy Steels

- UNS K93600

Nickel - Titanium Alloys

- 50% nickel - 50% titanium
- Shape memory effect
  - Deform annealed alloy
  - Returns to original shape on heating to intermediate temperature

Applications for Offshore Structures

- Risers & moorings
  - Wire rope & chain
  - Fasteners & fittings
- Platforms
  - Cladding in intertidal zone
    - Corrosion & fouling resistance
  - Cladding in splash & spray zone
    - Corrosion resistance

Applications for Offshore Structures

- Floating Structures
  - High strength alloys reduce weight
  - Corrosion resistant alloys reduce weight
    - Corrosion allowance reduced / eliminated
    - Need for coatings eliminated
  - Anti- fouling alloys reduce weight gain
- Deckhouses
  - Higher strength alloys reduce weight
  - Need for coating eliminated

Applications for Offshore Structures

- Pipelines & flowlines
  - High temperature product
  - Interior corrosion
- Burners & flares
  - Corrosion & high temperature resistance

Applications for Offshore Structures

- Process equipment
  - – Piping
    - Velocity resistance
    - Stagnant conditions
    - Resistance to chlorinated seawater
  - – Pumps
    - Casting alloys
    - Stagnant conditions
    - Protection of internals by lower alloy casings

Applications for Offshore Structures

- Process equipment
  - Heat exchangers
    - Tube type
      - Corrosion resistance
      - Velocity resistance
      - Resistance to stagnant conditions
      - Fouling resistance
    - Plate type
      - Crevice corrosion resistance
      - Resistance to chlorinated seawater

Applications for Waterfront Structures

- Cladding of piling
  - Fouling resistance
  - Corrosion resistance
  - Eliminates need for coatings
  - Cladding of wood pilings
- Reinforced & prestressed concrete
  - Excellent service experience

Applications for Waterfront Structures

- Fasteners & hardware
  - Long life
  - Ease of disassembly
  - High strength
- Utility systems
  - Seawater pumps & piping
  - Water & wastewater systems
  - Equipment housings

Applications for Ships and Small Craft

- Anti-fouling hulls
  - Long history
  - Copper-nickel (10% Ni) alloy
  - Copper nickel (30% Ni) alloy
  - Base hull material
  - Alloy clad steel
  - Adhesive attached foil

Applications for Ships and Small Craft

- Seawater pumps and piping systems
  - Velocity & stagnant conditions
- Wastewater collection & treatment systems
- Propellers
  - Copper alloys traditional
  - Stainless steels
    - Corrosion resistance
    - Repairability

Applications for Ships and Small Craft

- Chemical tanks and piping systems
- Cryogenic storage
- Inert gas generation
- Fasteners, hardware & housings

Summary

- Nickel containing alloys have many current and potential future applications
- Nickel containing alloys have a wide variety of useful characteristics
- Corrosion resistance is frequently the most valuable characteristic

Summary

- Reliability and life cycle costs can frequently be maximized through the application of nickel containing materials
- The Nickel Development Institute can provide information and technical assistance for the application of nickel containing materials

ALUMINUM FOR MARINE CONSTRUCTION

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ABSTRACT

Aluminum alloys are well established as engineering materials for a wide range of marine applications because they offer a combination of low weight-to-strength ratio, high strength, good corrosion resistance, formability and weldability. This paper discusses the historical development and current status of aluminum applications in marine construction. Current aluminum alloys for marine applications will be reviewed and metallurgical considerations of merits and shortcomings of these alloys will be discussed. The emphasis of this paper is given to the new development in advanced aluminum alloys and new development in manufacturing technology which could utilize the advanced aluminum alloys in marine structural applications.

INTRODUCTION

Good weldability and good corrosion resistance are required for marine grade aluminum alloys. These requirements favor solid solution strengthened aluminum alloys such as 3XXX and 5XXX alloys or very lean age hardenable alloys such as Cu free 6XXX alloys. Naturally, strength capabilities of these alloys are limited. Most of the past attempts to increase strength of these alloys lead to poor corrosion resistance. As a result, there has been no new major alloys developed for marine applications for past several decades. Since there are more incentives for high performance alloys in aircraft industry, most of new alloy development efforts in aluminum industry have been focused on high performance and, fatigue and corrosion resistant age hardenable alloys for aircraft applications. Recently, there have been increasing demands for high speed light crafts for passenger and vehicular ferries, cargo container vessels, and commercial, military, and patrol applications around world. For such high performance ships, there are more incentives to utilize high performance materials. Some of the new weldable, corrosion resistant alloys for aircraft application could provide potential candidate materials for high performance ship structures. This paper reviews the historical background and current status of aluminum alloy utilization in alloy development point of view and, introduce some new high performance aluminum alloys for future potential marine applications.

HISTORICAL PERSPECTIVE

Aluminum was first used for hull construction in the 1890's shortly after the first inexpensive commercial quantity of aluminum was produced in 1886. The material was chosen because it was light and corrosion resistant. However, it was not satisfactory initially because pure aluminum did not have adequate structural mechanical properties and the corrosion aspects of aluminum fabrication were not understood. It was not until 1929 when the aluminum magnesium alloys were developed that the use of aluminum alloys was truly established for marine structures. The chronology of technological progress of aluminum alloys as marine structural applications are discussed below by six major events.

Al-Mg alloys and the first all aluminum boat with riveted hull structure

In 1931, Diana II (55 feet all aluminum motor cruiser) was built in England. The hull and superstructure were built almost entirely with aluminum magnesium alloys. It was of riveted construction using rivets in aluminum magnesium alloy because suitable welding procedures were not available at that time. Galvanic corrosion due to lack of insulation such as between bronze seacocks and aluminum plating has been the only source of deterioration in over forty years. Obviously, aluminum magnesium rivets were the state of the art of the time, because earlier aluminum boats built with brass rivets or brass hulls with aluminum rivet construction were big disappointments. Having served during World War II, Diana II was still in good shape. After an inspection in 1958 dissimilar metals were replaced with aluminum and cathodic protection was added.. After five decades of service, she was reported as being in good shape[1][2].

Development of TIG and MIG welding techniques

The development of Tungsten-Inert Gas Shielded Arc welding(TIG) and Metal-Inert Gas Shielded Arc(MIG) welding processes opened a new era for marine aluminum alloy applications.. The first all welded aluminum hull was built in 1953. The Morag Mhor was a 73 feet-3 inch twin screw auxiliary motor ketch. Plate and sheet were aluminum-4% magnesium alloy and extrusions were aluminum -5 % magnesium - 0.5% manganese alloy. Welding filler wire alloy was the same as extrusion alloy. Inspection in 1980 indicated that both painted and unpainted areas of the hull and deckhousing were in good condition justifying the alloy selections. Even by today's standards these alloy selections were excellent choices. Unprotected aluminum surfaces had suffered no more than general corrosion..

Development of Al-Mg-Si (6XXX) alloys

An additional boost to aluminum alloy construction for marine application came from the development of aluminum magnesium silicon alloys, such as 6061, 6063 and 6082. Compared to aluminum magnesium alloys, these alloys were easier to extrude in complicated shapes, and easier to fabricate in theT4 temper. T4 temper can be aged to T6 temper after fabrication to higher strength for structural applications. These alloys are weldable, more economical and provide good corrosion resistance. Progress in the corrosion science of aluminum alloys also played an important role in the successful build up of the aluminum marine industry.

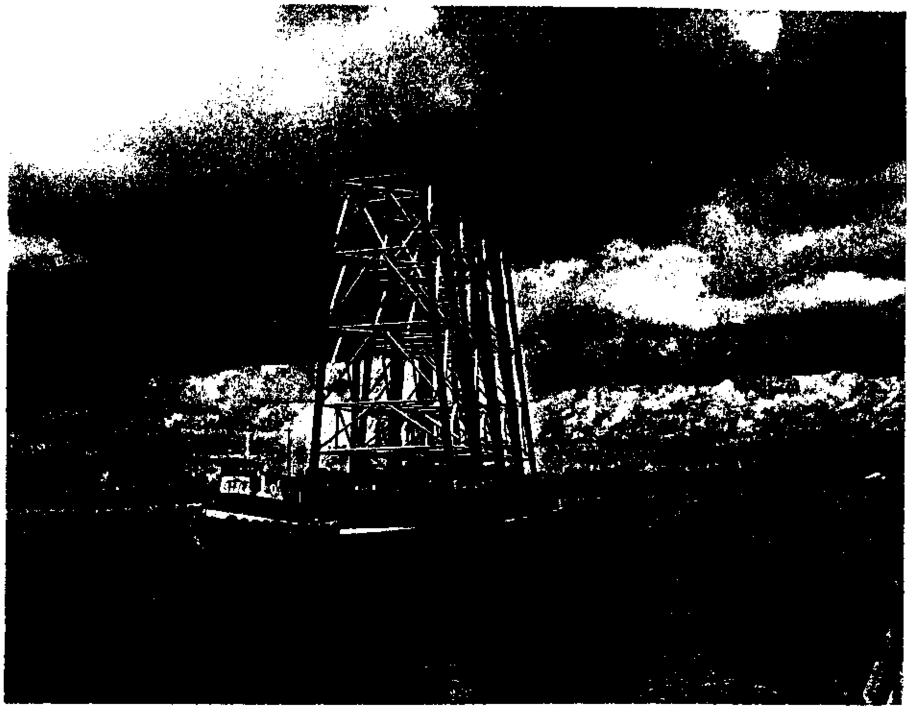

Figure 1. Aluminum platforms for oil pipelines at Lake Maracaibo, Venezuela (6061-T6 extrusion structures)

One of the successful early marine application of 6061-T6 extrusions were the 90 off shore structures built in Lake Maracaibo, Venezuela in the late 50's (Figure 1)[4]. This was a very challenging project. Steel structures were not practical and concrete would take too long to construct. Aluminum structures were prefabricated and installed rapidly.. Aluminum platforms, surge tanks and pipelines were in service in this location for fifteen years with little or no maintenance. The water in this lake is laden with suspended solids and has a salinity which varies from several hundred to several thousand parts per million.. The only corrosion reported on external surfaces has been scattered pitting with less than 0.010 inch penetration. This pitting has no significance in terms of structural integrity. Steel in this brackish water would require periodic painting and continuous cathodic protection, both of which are costly maintenance problems.

There are many interesting cases worth discussing, however, the history of boat and ship building would best illustrate the evolution and selection of aluminum alloys and their fabrication technology development.

Immediately after World War Two, the pleasure boat market boomed due to the sharp increase in recreational activities by consumers in North America. To meet the demand, the pleasure boat builders produced boats with the most abundant source of aluminum sheet - a huge surplus of 2xxx series (aluminum copper based alloys) aluminum sheet which were originally produced for aircraft applications. These high copper containing alloys are not suitable for marine applications due to their poor corrosion performance. These early mis-application of aluminum alloys set the industry backward , not to recover until the early to mid 50's when aggressive marketing efforts of 6061 alloy sheet were put into small boat applications market. The "Reynolds Lifetime boat" was built from AA6061 sheet hulls measuring 22" deep, 55" wide by 12 feet long. [5]

In North America, the commercial field was spearheaded by aluminum crew boat market. These vessels, usually under 100 feet in length were built by numerous shipyards in Louisiana. As commercial aluminum ship building grew, the "Society of Naval Architects and Marine Engineers (SNAME)" established the S-11 panel of the Hull Structural Committee to develop alloy standardization for production and distribution. AA6061 was recommended for ship structures requiring a moderate strength alloy having comparatively good corrosion resistance and suitable for either riveted or welded construction. The non-heat treatable alloys suggested were 5086 as a medium strength weldable alloy and AA5456 as a higher strength weldable alloy. However, the high magnesium content of AA5456 required a special temper to avoid exfoliation and stress corrosion cracking problems..

Development of H116 temper for high Mg containing alloys for improved exfoliation corrosion resistance

During the Vietnam war, the U.S. Navy reported severe corrosion problems in the bilge areas of PCF boats. These crafts were extensively used in river patrol. The material used for the hull was 5456-H321, one of the high magnesium, high strength alloys. Both exfoliation and severe pitting were observed on hull plate samples taken from the bilge. This problem is unique to high magnesium containing alloys(higher than 5%). The reputation of aluminum and future application of these alloys to marine service was seriously threatened. The problems arose due to the continuous grain boundary precipitates, $MgAl_3$, that is anodic to the matrix solid solution. Development of new tempers -H116 and -H117 eliminated the problem by modifying the grain boundary precipitate morphology.[6] Eventually, -H117 temper has been dropped and -H116 temper has been a standard practice as of today for these alloy product for marine applications.

Thermal Properties of Aluminum alloys

During Falkland war, the H.M.S.Sheffield was totally destroyed by fire. This was incorrectly blamed for her aluminum superstructure by media at the time. This raised safety issues regarding the fire hazard of aluminum structures. However, this ship was entirely built of steel and contained no structural aluminum.

Aluminum as powder will burn as used in rocket fuels. However, aluminum structural members do not burn. Thermal softening of aluminum occurs at about 800°F. With high reflectivity and high thermal conductivity, aluminum structures are more efficient dissipating heat and more difficult to raise its temperature. Therefore, a greater heat input is necessary to bring aluminum up to a given temperature than that required to heat steel to the same temperature. Flammability and thermal softening of aluminum at elevated temperatures had been addressed in marine structural applications.[7] After the Falkland war, there were more regulations put in place specifically relating to fire prevention and insulation in marine structures.[8]

In case of fire hazards with extremely high heat environments, such as war ships carrying heavy loads of ammunitions or off-shore oil platforms with extensive hydrocarbon flammables aboard, aluminum alloys as structural material are in somewhat limited use such as helicopter landing platforms on ships and oil rigs.[8][9]

High Speed Light Crafts

In recent years, aluminum alloys re-emerge as primary structural materials for ship building as the needs for marine transport market changes with introduction of fast surface effect ships with speeds of 60 to 80 knots or more and high speed ferries with multi-hulled catamaran-type ships with speeds of 30 to 50 knots. These fast ships require extremely weight efficient structures and extensively utilize aluminum alloys. The most common alloys currently used for high speed aluminum intensive ships include 5083 or recently optimized 5383 for hull structure. Extruded structures in these ships have largely included 6082-T5 or T6, and 6005A-T5. To lesser extent, 6060-T4, 6063-T5 or T6, and 6061-T6 extrusions have been employed in these ships, including superstructures and many other uses.[10][11]

MATERIAL CHARACTERISTICS REQUIRED FOR MARINE APPLICATIONS

For marine structural applications, materials are chosen largely for combination of suitable mechanical properties, good corrosion resistance and weldability for the applications concerned. High strength, high fracture toughness aluminum alloys commonly used for aircraft applications are usually not suitable either due to the limited corrosion resistance in sea water or hot cracking tendency during welding.

Corrosion Resistance

In considering the corrosion behavior of aluminum alloys in marine environment, it is important to distinguish pitting corrosion, intergranular/exfoliation corrosion and Stress Corrosion Cracking(SCC) behavior. Ranking aluminum alloys for corrosion resistance would differ depending on the type of corrosion behavior. In addition, proper design and maintenance of aluminum alloy structures would be required to avoid two kind of corrosion behavior: galvanic corrosion between dissimilar metals and crevice corrosion. These two forms of corrosion would occur if necessary design and operational precautions are not properly followed, regardless of how good corrosion resistance of the specific aluminum alloys involved. [10][16] The recent developments in understanding the corrosion behavior of aluminum alloys are discussed by Kemal Nesancioglu in detail[12].

Pitting Corrosion

Aluminum and its alloys are corrosion resistant due to the continuous, impermeable very thin oxide layers formed on the surface. These highly protective oxide layers are very stable in neutral pH conditions, but unstable in acid and alkaline environment. Therefore, uniform corrosion occurs in aqueous solutions at extreme pH level. In neutral pH media, the presence of cathodic intermetallics in the metal surface cause flaws in the protective film and enhance microgalvanic corrosion process, which lead to localized dissolution of matrix (pitting). Copper bearing alloys and alloys with higher impurities are more prone to pitting attack, compared to commercial marine grade alloys such as 5083 and 6061. Although shallow pitting corrosion is not considered as structurally damaging, excessive deep pits could provide stress risers and lead to fatigue crack nucleation. [13]

Intergranular corrosion

A prerequisite for intergranular corrosion is an electrochemically active path in the grain boundary region. The degree of susceptibility to IG can vary widely with different alloys, tempers and environment. Usually active path is the solid solution. But for high Mg containing 5xxx alloys, the path may be closely spaced anodic precipitate particles within the grain boundary and, a work hardened and partially annealed temper (-H116) would be necessary to avoid intergranular corrosion attack. The identities of the specific active paths giving rise to the electrochemical attack of the grain boundaries are discussed by Sprowls et al. [14]

Exfoliation

Exfoliation occurs in wrought mill products having an elongated grain structure where IG corrosion produces voluminous insoluble corrosion products which form wedges in the grain boundary regions. The gradual extension of the wedges mechanically accelerates corrosion along the elongated grain boundaries. Susceptability to exfoliation can be limited and usually eliminated in all alloy systems by appropriate regulation of thermal treatments during processing of the mill products, but usually with some sacrifice in strength or ductility. Special exfoliation tempers, such as -H116 temper for Al-Mg alloys, -T7XX tempers for Al-Zn-Mg-Cu alloys and T8511 temper for 2024 alloys have been developed. [14]

Stress Corrosion Cracking(SCC)

Aluminum alloys that are susceptable to SCC generally are characterized by microstructure wherein there has been a localized decomposition of solid solution at the grain boundaries. SCC typically occurs in electrochemically active preexistent paths, usually along or in the grain boundaries.[15] SCC is regarded as a catastrophic failure because it often occurs at nominal stress levels far below the yield strength of the product. In wrought aluminum alloy product, SCC is essentially intergranular fracture behavior therefore, short transverse direction is the most susceptable to SCC failures. During the last 30 years, SCC resistant alloys, tempers and improvements in processing have been developed for various aluminum alloys. The marine alloys are generally considered resistant to SCC.

Welding

The two main welding processes used for aluminum alloys are MIG(metal arc inert gas) and TIG(tungsten arc inert gas) processes which include pulsed and plasma arc welding processes. MIG is more common for general manual and machine welding as the process has the higher production rates than TIG. Quality welding is one of the keys to competitive aluminum utilization in marine applications. Recommendations for joint design, proper machine settings, and weld techniques can be found elsewhere. [17]

Weldability

For an aluminum alloy to be utilized in welded structures, both good weldability and good post weld properties are required. Weldability is frequently defined as low susceptibility to hot cracking during fusion welding. However, recent development in various types of fusion welding techniques and development of many new aluminum alloys, it is not always easy to either quantify or rank aluminum alloys per weldability. Among the structural wrought aluminum alloys, 5XXX, 6XXX alloys and 2XXX alloys with low Mg contents and 7XXX alloys with low Cu content are easy to weld by traditional fusion welding techniques.[15]

Post Weld Properties

The post weld properties of interest include strength, elongation and corrosion resistance of weldment and heat affected zone(HAZ). 5XXX alloys, solid solution strengthened alloys, lose less strength after welding and maintain much better corrosion resistance in sea water compared to other age hardened alloys. Corrosion behavior of most weldable high strength aluminum alloys are temper sensitive and, various thermal history of weld and HAZ of the welded joints cause difficulty of utilizing the best temper conditions in marine environment. Long term exposure of welded joints to sea water confirmed the applicability of 6XXX alloys in marine environment and that 6063 and 6061 alloys perform better than 6082.[18] 5XXX alloys with Mg content less than 5%, are still the best suitable aluminum alloys to date for welded hull structures in bare surface.[19]

ALUMINUM ALLOY SELECTION FOR MARINE APPLICATIONS

For Aluminum alloys to be suitable for marine applications, it requires not only a suitable combination of mechanical properties but good weldability and good post-weld corrosion resistance in marine environment. This is why many high strength high fracture toughness aircraft alloys are not suitable for marine use. Among the wrought aluminum alloys, the most suitable alloys for marine structural applications are Al-Mg-(Mn) based alloys(5XXX alloys) and Al-Mg-Si-(Mn)based alloys(6XXX alloys). The most commonly used structural aluminum alloys are reviewed in light of their potential for marine structural applications.

7XXX alloys:

Al-Zn-Mg-Cu alloys: These alloys give high strength and high fracture toughness and good SCC resistance in proper temper conditions such as 7050-T7 type temper. However, they are generally susceptable to hot cracking during welding. Therefore, these alloys are generally not suitable for marine structural applications.

Al-Zn-Mg alloys:

Al-Zn-Mg alloys with either no or very lean on Cu, such as AA7017, AA7020, AA7030 and AA7079 are weldable and could provide higher strength than 5XXX alloys or 6XXX alloys. However, corrosion resistance of these alloys are not as good as 5XXX alloys or 6XXX alloys.[20] Therefore, these alloys are generally not in use for marine applications unless appropriate protection can be provided during service in limited applications.

2XXX alloys:

Al-Cu-Mg alloys: The high strength Mg containing Al-Cu based alloys such as 2024-T6 or -T8 temper product are generally susceptable to hot cracking during welding and not suitable for marine applications.

Al-Cu alloys: Al-Cu alloys with either no Mg or very lean Mg content, are readily weldable especially for high Cu containing alloys such as 2219 (Al-6.3 weight % Cu). However, high Cu content leads to poor pitting corrosion behavior in marine environment.

3XXX alloys:

Al-Mn alloys such as 3004 have good corrosion resistance in marine environment, however, the strengths of these alloys are low and only adequate for secondary structural applications.

5XXX alloys:

Al-Mg-(Mn) based alloys are strengthened by solid solution strengthening and have excellent work hardening capabilities. These alloys exhibit initial surface oxidation at a rate faster than pure aluminum or 3xxx series alloys, showing dull appearance. Appearances can be deceptive. Al-Mg alloys are less prone to pitting and will give better overall service life in marine environments in spite of their weathered appearance, compared to 3XXX and 6XXX alloys. Al-Mg alloys exhibit excellent corrosion resistance in any temper conditions for the alloys containing less than 4% Mg content. For higher Mg containing alloys , such as AA5456(nominally Mg content of 5.2%) , a work hardened and partially annealed temper condition (-H116 temper) would be necessary to avoid exfoliation corrosion. For some alloys, small amount of Mn are added to increase strengths(usually a small increase) without impairing corrosion behavior of the alloy. Comparing to another marine grade alloy system, 6XXX alloys, Al-Mg alloys are generally more difficult to fabricate and extrude, hence higher in cost than 6XXX alloys. However, corrosion resistance and post-weld properties of 5XXX alloys, particularly toughness and high impact resistance, are superior to 6XXX alloys, which makes Al-Mg alloys most adequate for plate and sheet product for welded hull structures. Mechanical properties including fatigue performance on 5083, 5086 and 5456 alloy sheet and plate are well documented by aluminum industry both in work hardened and/or annealed temper and on as-welded plate. A recommended aluminum welding filler alloys for various Al-Mg alloys can be found elsewhere[10]. Typical mechanical properties of the 5XXX series alloys are listed in TABLE I including post-weld ultimate strengths.

TABLE I: Typical mechanical properties of sheet and plate marine grade 5XXX alloys and tempers[10][19]

Alloy and temper	Yield strength (MPa)	UTS (MPa)	Elongation (%)	Welded UTS (MPa)
5005-H34	103	137	8	103
5052-H34	179	234	10	172
5251-H34	179	231	7	170
5083-H116	213	303	16	268
5086-H116	193	276	10	241
5086-H34	234	303	10	241
5454-H34	199	268	10	213

6XXX alloys:

Al-Mg-Si-(Mn)-(Cu) alloys(6XXX alloys) are age hardenable by Mg_2Si precipitates. Therefore, at peak aged temper these alloys could reach high strength as wrought product but post-weld properties in as-welded conditions are low compared to that of solid solution strengthened alloys(5XXX alloys). However, its low solute content compared to 5XXX alloys make them much easier to fabricate in hot deformation processes such as extrusion. After extrusion, these alloys can be solution heat treated to T4 temper where the alloy is very soft and readily formable with ease. After final fabrication or forming steps, the alloy can be age hardened to T6 temper condition to utilize the maximum strength capability. A typical application of this type is the aluminum canoe, which is stretch formed in the T4 condition and then aged to T6 for maximum strength. Comparing to 5XXX alloys, these alloys are slightly less corrosion resistant and lower in cost. The most common usage for 6XXX alloys in marine application are in extruded products. 6061-T5 and -T6 extrusions are most commonly used in North America, while 6082-T5 and T6 extrusions are most commonly used in Europe and Australian marine industry. Typical mechanical properties of the 6XXX series alloys are listed in TABLE II including post-weld ultimate strengths.

TABLE II: Typical mechanical properties from extruded shape marine grade 6XXX alloys and tempers[10]

Alloy and temper	Yield strength (MPa)	UTS(MPa)	Elongation (%)	Welded UTS (MPa)
6063-T5	110	151	8	117
6063-T83	248	275	--	117
6060-T5	110	151	8	117
6106-T6	210	230	8	117
6061-T6	241	289	8	165
6351-T5	241	262	8	165
6351-T6	255	293	8	165

NEW DEVELOPMENT IN ALUMINUM ALLOYS

In the past two decades, there has been an accelerating demand for higher speed ships for passenger and vehicular ferries, cargo container vessels, and commercial, military and patrol applications around the world. Aluminum alloys are playing an increasing role for many of these applications, partly because of its combination of favorable properties, including its light weight and excellent corrosion and fatigue resistance, as well as relative ease of fabrication. Until recently, shipyards around the world have used aluminum products, such as 5086 and 5083 for plates and 6061 and 6082 alloys for extrusions for building high performance ships. In pursuit of light weight, high speed, multi-hulled ships and hovercrafts, the demand for high performance material is ever increasing. In light of meeting such demands new development in aluminum alloys will be reviewed in three areas: 1)Alloy improvement by optimization, 2)New alloy development and 3) Friction stir welding (a Solid state welding) of aluminum alloys

Alloy Improvement by Optimization

The commonly used aluminum alloys for marine applications were not originally developed and optimized for today's use. It is the customary for aluminum industry that the registered alloy composition limits are very broad compared to the actual acceptable processing limits within capability of today's aluminum industry. Since design properties are dependent upon the statistical minimum values with a specified confidence level, further optimization of alloy/product can be achieved within the existing alloy composition limits and temper practices by tightening operating composition range and raising the design minimum properties. As a result from such efforts, a new set of aluminum alloys were introduced by Pechiney Rhenalu [21]

Optimized AA6005A: An alternative to 6082

AA6005 was registered in 1972, mainly for transportation market. When the international standards were published, the alloy was not optimized and its mechanical properties were lower for AA6005A than that for 6082. Pechiney Rhenalu optimized the composition of 6005A for improved minimum values for 6005A extrusions. TABLE III listed the chemistry ranges for AA6005A and 6082, a current marine grade extrusion alloy. Figure 2 shows the registered composition limits of Mg and Si contents for the four marine grade aluminum alloys including 6005A for comparison.. Comparing to 6082, 6005A alloy was optimized by 1) Excess Si and Mg contents were reduced, 2)Fe, Mn and Cr limits were reduced to be a cleaner alloy and 3) a slightly higher Cu limit was allowed to increase the strength without impairing corrosion resistance. It was claimed by Pechiney Rhenalu that the following property improvements were achieved:

- Transverse mechanical properties are higher for 6005A-T5 than for 6082-T5 before and after welding.
- In longitudinal direction, Tensile strengths of 6005A are about 10 MPa higher for 6005A than 6082. Yield stresses are about the same.

TABLE III: Registered composition limits of AA6082 and AA6005A

	Si	Fe	Cu	Mn	Mg	Cr
AA6082	0.7-1.3	0-0.5	0-0.1	0.4-1.0	0.6-1.2	0-0.25
AA6005A	0.5-0.9	0-0.35	0-0.3	0-0.50	0.4-0.7	0-0.30

AA5383: An optimized AA5083

A new alloy was derived from AA5083 by Pechiney Rhenalu and registered as AA5383. The chemical compositions for both 5083 and 5383 are listed in TABLE IV. The registered composition limits of Mg and Mn contents for six marine grade aluminum alloys including 5383 are plotted in Figure 3 for comparison. To increase the post weld properties, AA5383 is characterized by 1)low Si ,Fe and Cr content to reduce impurity levels, 2)high Mn content for higher post weld strength, and 3)higher Cu, Mg, Zn and Zr maximum allowable content to increase strength.

TABLE IV: Registered composition limits of AA6082 and AA6005A

	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Zr**
5083	0-0.4	0.1-0.4	0-0.1	0.4-1.0	4.0-4.9	0.05-0.25	0-0.25	0-0.05
5383	0-0.25	0-0.25	0-0.20	0.7-1.0	4.0-5.2	0-0.25	0-0.4	0-0.2

Material performance comparisons between 5383 and 5083 are made in TABLE V which shows post-weld mechanical properties, corrosion in weight loss and ASSET test, Fatigue strength after 10 million cycles. The result clearly shows improvement of AA5383 over AA5083. The typical yield stress and ultimate strength of 8 mm and 16 mm thick butt welded 5383-H116 plate shows consistent 20-30 MPa improvement than those of 5083-H116 plates.

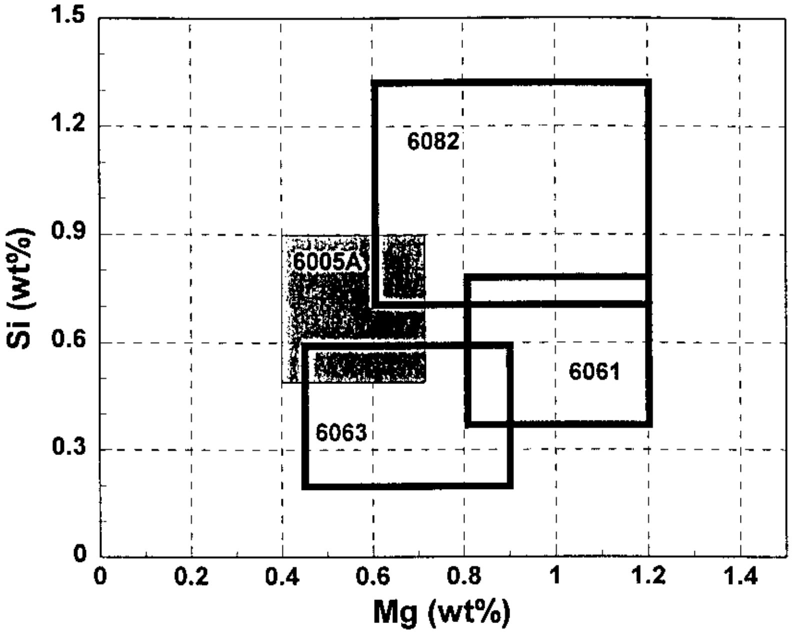

Figure 2. Registered chemistry range of Mg and Si for 6005A, 6061, 6063 and 6082 alloys.

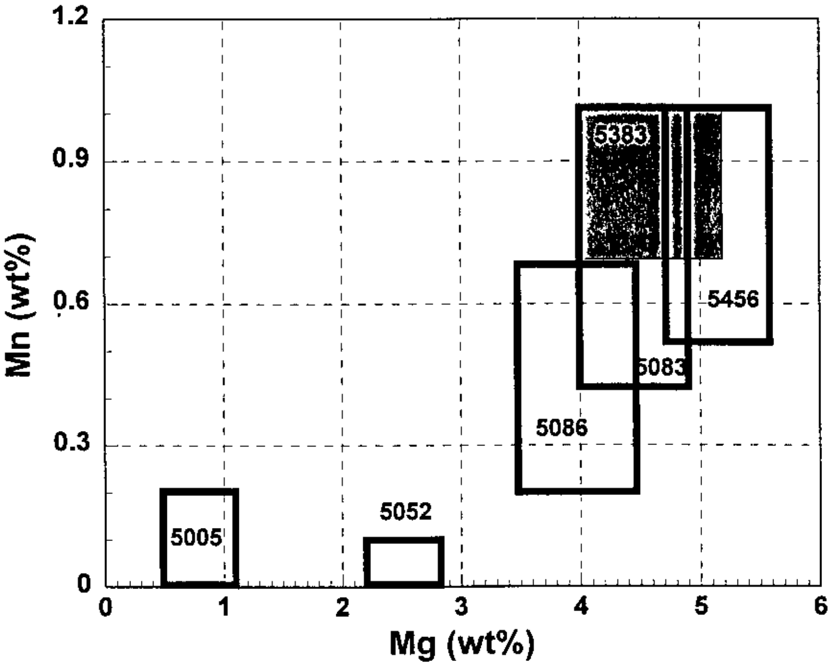

Figure 3. Registered chemistry range of Mg and Mn for 5005, 5052, 5086, 5083, 5456 and 5383 alloys.

TABLE V: Mechanical property comparison of 5083-H116 and 5383-H116

	5083-H116	5383-H116
Postweld TYS (MPA/ksi)	125/18	145/21
Corrosion; weight loss (g/cm^2)	2.6	0.7 (25 days)
ASSET	PC/EA	N/PB (25 days)
Fatigue strength at n=10^7	210/30	230/33

New Alloy Development

For the past three decades in aluminum industry, new high strength aluminum alloy development efforts have been primarily targeted for aircraft applications due to their ever increasing property requirement and their willingness to pay premiums for low density, high performance materials. Among these alloys, some alloys are weldable and with good corrosion resistance which would be suitable for superstructures where 6061 and 6082 alloys are commonly used. Due to the higher cost of these alloys, however, none of these alloys have ever been considered for marine structural applications. However, for limited applications with high performance requirement, some of these new weldable, corrosion resistant alloys could be candidate materials for high speed light craft structural applications.

Al-Mg-Sc alloys:

Al-Mg based alloys provide excellent combination of weldability and corrosion resistance for marine applications. However, their strengths are somewhat limited compared to other age hardenable alloys. There have been various attempts to increase strengths by adding Cu, Zn or even higher Mg content. Any of these approaches resulted in serious corrosion problems. Adding small amount of Mn to Al-Mg binary alloys and forming finely dispersed intermetallic particles helps increase strengths by dispersoid strengthening without impairing its corrosion resistance. However, only limited increase in strength can be achieved with Mn addition as can be seen in 5086, 5083, 5383 and 5456. More effective dispersoid strengthening in aluminum alloys without compromising corrosion resistance can be achieved by adding a small amount of Scandium(Sc). Scandium forms coherent and spherical Al_3Sc particles in aluminum alloys and very effective in preventing recrystallization. Therefore, strength increase in Al-Mg-Sc alloys are attributed to particle strengthening, coherency strengthening and dislocation substructure strengthening mechanisms in addition to solid solution strengthening by Mg. Unfortunately, Sc is one of the very rare elements and quite expensive in the Western hemisphere. With increasing availability from Russia and China, there has been new interest in Sc containing aluminum alloys. By adding .25% Sc to Al-5%Mg-.3% Mn alloy (TABLE VI) shows increase in tensile yield stress of 110 MPa and a significant improvement in fatigue strength, TABLE VII. Even higher strength was achieved by a Russian alloy 01570, with higher Mg and Sc contents as shown in TABLE VI and TABLE VII. Possible drawbacks of these alloys, besides high cost, could be their somewhat limited fabricability, availability, repairability, and directional strength anisotropy due to their unrecrystallized grain structure. These alloys are still in developmental stage for aircraft application and may need further optimization with additional data including long term corrosion tests in marine environment. [22][23]

TABLE VI: Typical compositions of two experimental Al-Mg-Sc alloys

	Mg	Sc	Mn	Zr
Al-5%Mg	5.10	--	.32	.06
Al-5%Mg-.25Sc	5.18	.25	.32	.06
01570	6.0	.4	.3	.1

TABLE VII: Typical mechanical properties of three experimental alloys

	5%Mg	5% Mg-0.25Sc	01570
TYS (MPa/ksi)	130/19	240/35	280/41
UTS (MPa/ksi)	280/41	370/54	380/55
Fatigue strength (MPa/ksi)	90/13	150/22	n.a.

Al-Mg-Li alloys:

Addition of Li, up to 2.5%, to Al-Mg alloys would increase mechanical properties without deleterious effects on corrosion resistance. The benefits of Li addition include lowering density and increase elastic modulus and improve fatigue strength and fatigue crack growth resistance. However, Li is very reactive element in molten state and Li containing alloys are more expensive to cast than more conventional aluminum alloys due to its high cost casting procedure in inert gas environment. For the same reason, welding Li-containing aluminum alloys would require back side shielding to minimize contamination during welding operation (a similar procedure to Titanium alloy welding).

Al-Li-Mg alloys are strengthened by solid solution strengthening as well as age hardening. Advantage of Al-Mg-Li alloys is that these alloys would retain high post-weld strength in as-welded condition compared to that of other age hardened alloys. Russian alloys, 01420 and 01421 alloys having 5% or higher Mg contents are found to be not adequate to meet corrosion resistance requirement. Experimental alloys under alloy family name of Weldalite-050 were studied as candidate alloys for U.S.Navy's torpedo hull applications[24]. Among the various compositions, one alloy variant (3.8% Mg-2.2%Li-.40%Ag-.14%Zr) showed more attractive combination of properties. Selected properties in transverse direction are listed in TABLE VIII in comparison with 5456-T6 and 6061-T6. Clearly, WL050 alloy shows significantly higher strength with higher elastic modulus and lower density.

With renewed interest on Al-Mg-Li alloys from aircraft industry as the potential candidate alloys for future welded aircraft structural applications, the efforts to optimize weldability, corrosion and fracture toughness properties have been renewed. For more corrosion resistant and damage tolerant application, Frydlander et al. proposed lower Mg containing Al-Mg-Li alloy variants compared to the two older alloys, 01420 and 01421 [25]. The typical mechanical properties including post weld properties are listed in TABLE IX. Both experimental alloys clearly show the property advantage in wrought product and in post weld conditions.

TABLE VIII: Typical properties of WL050 in comparison with 5456 and 6061[24]

	WL050-T6	5456-H116	6061-T6
TYS (MPa/ksi)	336/48	228/33	242/35
UTS (MPa/ksi)	499/71	317/46	290/42
Density (g/cm^3/lb/in^3)	2.51/0.09	2.66/0.096	2.70/0.098
E (Gpa/Msi)	79/11.4	71/10.3	69/10

TABLE IX: Typical properties of two experimental Al-Mg-Li alloys in comparison with 5083 and 6061[25]

Alloy/ Temper	TensileYield (MPa)	UltimateStr. (MPa)	Elongation (%)	WeldedUTS (MPa)
3.5Mg-2.0Li*	360	455	7.5	345
3.5Mg-1.75Li*	325	430	10.0	325
5083-H116	213	303	16	268
6061-T6	241	289	8	165

note: * : two experimental alloys from [25]

Al-Cu-Li-Mg-Ag alloys(Weldalite 049 type alloys):

Historically, Cu bearing aluminum alloys are known as unsuitable for marine application due to their poor corrosion performance. These include Al-Cu, Al-Cu-Mg, Al-Cu-Li and Al-Cu-Li-Mg based alloys such as AA2219, AA2024, AA2090 and AA2091, respectively. However, adding a small amount of Ag to Al-Cu-Li-Mg alloys, a great improvement in corrosion performance can be achieved[26]. Improvement in SCC resistance in broad temper conditions is most spectacular that Al-Cu-Li-Mg-Ag alloys (also known as Weldalite 049 type alloys[27]) such as AA2195 and AAX2096 are the best SCC resistant aluminum alloys ever developed. AA2195-T8 plate, for example, shows no failure in short transverse direction at 414 MPa(60 ksi) after 30 days of alternate immersion tests in 3.5% NaCl solution(ASTM G47 and G44). Intergranular attack/exfoliation corrosion resistance of these alloys are also excellent[28]. However, pitting corrosion characteristics of these alloys are not as good as that of 5XXX and 6XXX alloys, even though better than that of other 2XXX and 7XXX alloys. Therefore, if properly painted or protected, these alloys could be utilized for high performance applications especially for superstructures. The registered chemistry ranges and typical mechanical properties of AA2195 and AAX2096 are listed in TABLE X and TABLE XI, respectively.

TABLE X: Registered composition limits of Al-Cu-Li-Mg-Ag-Zr alloys (Weldalite 049 type alloys)

	2195	X2096
Cu	3.7-4.3	2.3-3.0
Li	0.8-1.2	1.3-1.9
Mg	.25-.80	.25-.80
Ag	.25-.60	.25-.60
Zr	.08-.16	.08-.18

TABLE XI: Typical mechanical properties of AA2195 and AAX2096 plate in Long transverse direction.

	2195-T8	X2096-T8
TYS(MPa/ksi)	587/85	504/73
UTS(MPa/ksi)	614/89	538/78
Elongation(%)	10	10
Density(g/cm^3/lb./in^3)	2.72/.098	2.63/.095
E(Gpa/Msi)	75.9/11.0	77.3/11.2
SCC in ST dir.(MPa/ksi)*	414/60	345/50
FatigueStrength (MPa/ksi)	331/48	290/42

note:* Alternate Immersion test for 30 days in 3.5% NaCl solution

Friction Stir Welding (a Solid State Welding)

Friction stir welding is a relatively new technique developed by The Welding Institute(TWI) for joining of aluminum alloys[29]. The process uses the friction from a rotating pin to generate sufficient heat and forging forces to weld adjoining material together as shown in Figure 4. A macroscopic view and a microscopic view of a friction stir welded joint is shown in Figure 5[30]. Because the process is completely solid state, problems associated with the liquid-solid phase transformation are eliminated. The resulting benefits on post-weld properties include increased weld strengths, improved ductility and better fracture toughness. Since there is no melting involved, structural designers are no longer restricted in alloy selection by weldability. For example, 7075-T6 plate was successfully welded with excellent post weld properties by FSW, even though , AA7075 is generally considered as not weldable alloy[30].

Post-Friction Stir Welding (FSW) properties of aluminum alloys:

Unlike steel or titanium alloys, the mechanical property of fusion welded joint in age hardened aluminum alloys are generally lower significantly than that of parent product. Therefore, improvement on post-weld properties by FSW, compared to that by traditional fusion welding is of great interest to design engineers, although limited to components, more likely, rather than entire ship structures. This has been demonstrated on 6082[31], Al-SiC MMC[32], 2014[33] and 2195[34]. Figure 6 shows the result of a comparative study on AA2195-T8 plate at various gauges which demonstrated up to 50% increase in post weld ultimate strength by FSW compared to that by fusion welding. Another important advantage of FSW is that fewer number of process variables are involved in FSW than in fusion welding and, variability of post weld properties can be reduced dramatically. This would increase the statistical minimum value of design allowables[32]. Recently, the feasibility of the process as a full scale industrial operation was examined by Christner and Silva[33] by conducting an extensive process variability study[33]. Their results showed that the FSW tolerance limits for mismatch, gap, thickness, and tool plunge depth variations are not overly critical and within current design and shop floor practices and capabilities.

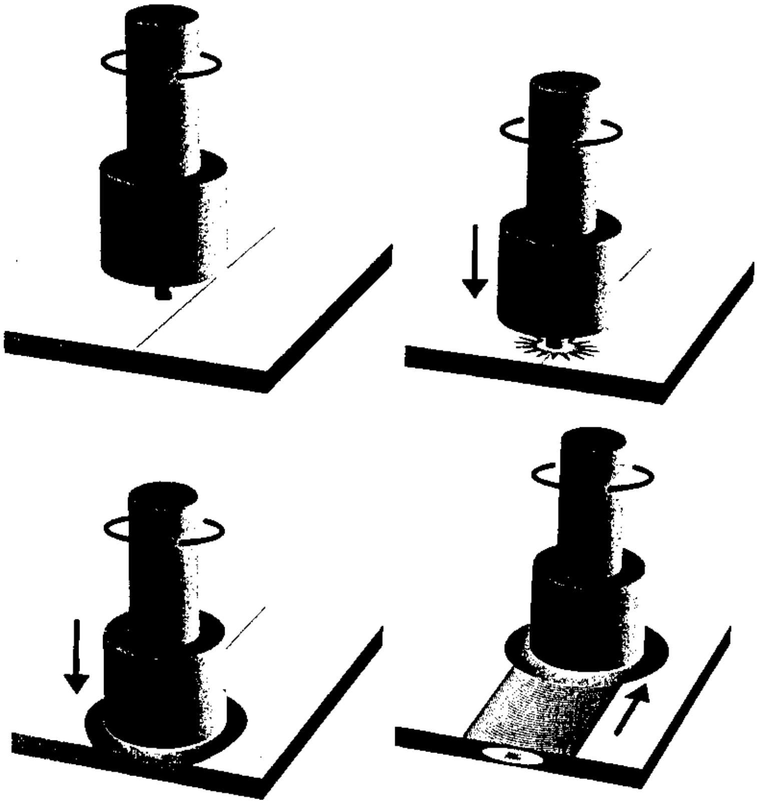

Figure 4. Schematic illustration of Friction Stir Welding process

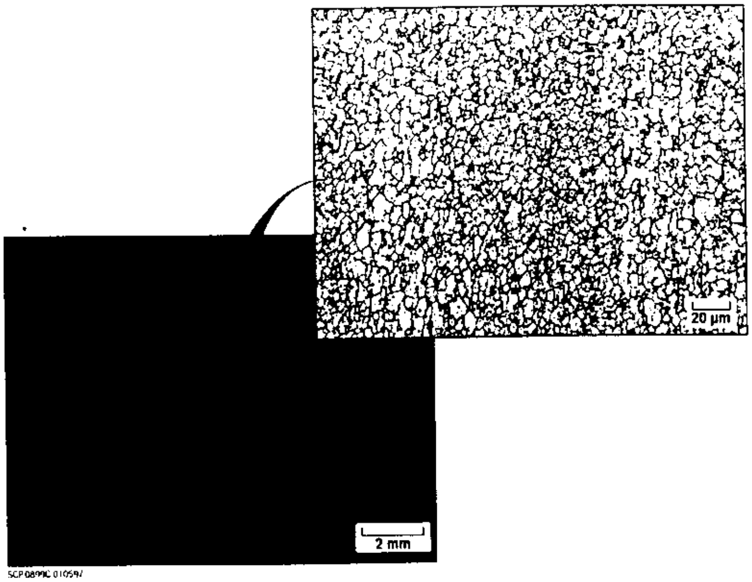

Figure 5 A macroscopic view and a microscopic view of cross section of a friction stir weld in AA 7075 plate (Courtesy of M.Mahoney)

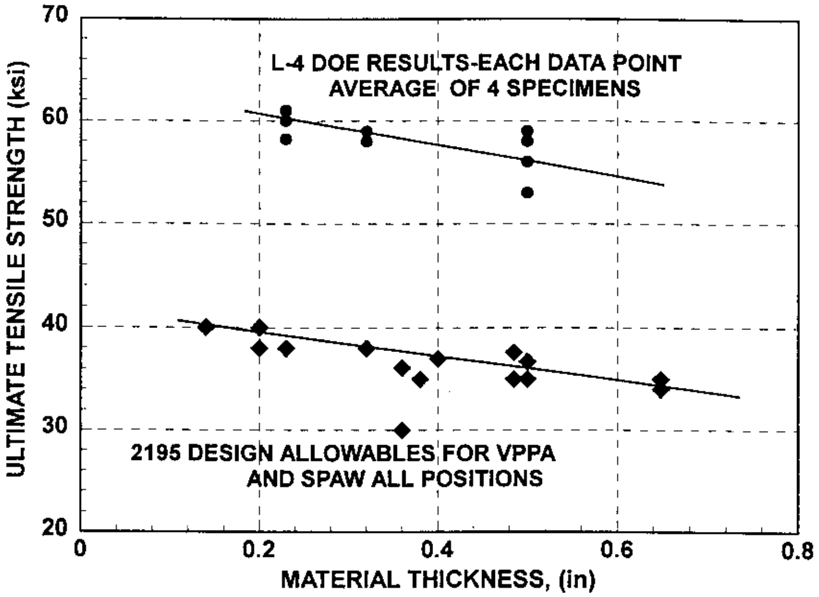

Figure 6 Mechanical property comparison of 2195-T8 friction stir weld and VPPA weld (unshaved sample). Data courtesy of P.J. Hartley at Lockheed Martin Manned Space Systems, New Orleans, LA

SUMMARY AND CONCLUSION

1. History and current usage of marine grade aluminum alloys are reviewed in alloy developer's point of view.
2. Two new optimized alloys; 5383 and 6005A are compared to the commonly used aluminum alloys, 5083 and 6082. The two new alloys appeared to be good alternatives with better post weld properties.
3. New weldable aluminum alloys with good corrosion resistance, which originally developed for aircraft application, are reviewed as potential candidate material for future marine applications.
4. Recent ·progress in Friction Stir welding of aluminum alloys are reviewed. Improvement of post weld properties and reduction of process variability are discussed.

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POLYMERS FOR MARINE CONSTRUCTION

by

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SUMMARY

This paper discusses the role of polymers in marine constructions that are sufficiently critical in nature for quantitative life prediction to be important. The applications referred to are drawn from offshore engineering for oil and gas production and exploration, but the methods and properties are applicable to other marine applications. A considerable amount of research in this area has been stimulated by the novel and critical demands of the offshore oil and gas industry during the past 15 years. A barrier to the cost effective use of polymers still lies in the lack of knowledge about their lifetime in specific service applications.

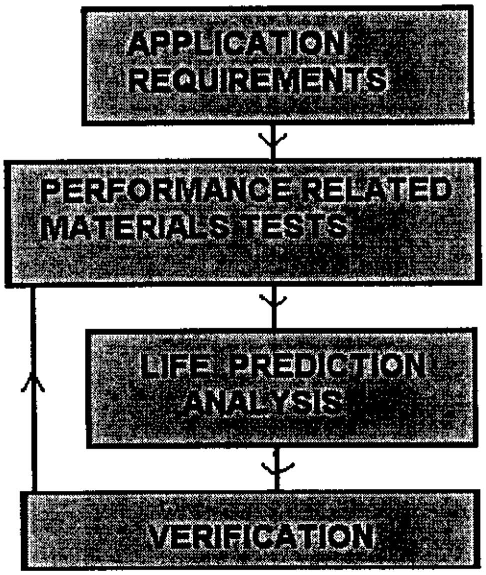
The first structural application of polymers in offshore engineering was the use of elastomeric flex elements for deep water compliant structures. Polymers have now also been used in other critical applications, such as thermoplastic pressure sheath walls of flexible pipe constructions. Composites have been used for piping and are now under consideration for structural mooring and topside applications. In all these applications failure of the material could lead to major consequences beyond failure of the component. This raises the need to quantify the life of the material in service.

This paper will consider the current state of the art, illustrating life prediction methods by reference to some specific applications. These methods are not yet fully developed, although research is underway. A lack of confidence limits usage of polymers in areas where they may offer significant cost or performance advantages. As the input information of the service loading history is generally only known after at least some period of actual service a further step is required so that maintenance and replacement schedules can, if necessary be determined efficiently. Residual Life Engineering , a new approach, can then build on verified life prediction methods to determine the remaining life of polymeric components already in service. This is of direct operational value as well as giving confidence at the design stage.

GENERAL APPROACH TO LIFE PREDICTION

The general approach to life prediction of polymeric components consists of first defining application requirements, next designing and performing performance related materials tests, then using the data from such tests to perform life prediction analysis of the components and finally designing verification tests the results of which may be used to provide further data to calibrate the whole process. The general scheme is illustrated in Figure 1

Figure 1



The **application requirements** need to be defined in terms that relate the functional performance of the structure to the behaviour of the materials. This usually consists of reviewing the application to identify the performance requirements and then defining quantitative failure criteria. The critical material properties can then be defined. Standard tests, such as tensile tests, frequently do not provide adequate information on material properties for these purposes. **Performance related materials tests** therefore need to be defined. Typical performance related tests are fracture toughness, fatigue crack initiation and propagation, non-linear elasticity behaviour, permeation/solubility in fluids , stress-chemical interactions, stress relaxation and creep. The geometry of loading in the application needs to be considered so that the correct mode of loading is reproduced in the testpiece. This is particularly important for fatigue and fracture tests, where unrealistic results may be obtained if the mode of loading is unrealistic. Performance related tests need to be performed at the service temperature and also in the service fluids - if fluid exposure occurs. A sequence of tests needs to be performed if the rate of change of the property is to be quantified either with time or with cycle number. Appropriate data analysis needs to be carried out in order to determine the correct materials models for changes to material properties. **Life prediction analysis** can only be built on the basis of sound performance related material properties and reliable mathematical models for the rate of change of these properties with time. There are then several methods that may be used to assess component service life. Mechanical fatigue is considered using fracture mechanics methods, which enable calculations to be made of the resistance to fracture and the rate of crack propagation on the basis of the appropriate materials models and the geometry of the component loading. Materials characterisation needs to be on a sufficiently fundamental basis to obtain intrinsic properties that can be related to component performance in service. If the changes are chemical in nature then an Arrhenius approach may apply to determine the appropriate activation energy. All polymeric materials have some sensitivity to environmental conditions at temperatures below 300°C and there is frequently acceleration of chemical processes below this - provided that melting points or other transitions determine the rate of change at at least 5 different temperatures in the range of interest and to determine the rate using at least 10 testpieces exposed at different times. If the mechanical fatigue and the chemical ageing aspects can be integrated then a unified life prediction assessment can be made. A particular problem in many materials is the difficulty of defining stress/chemistry interactions. **Verification** of the life prediction analysis is essential for each new category of application for which this method is developed. This should preferably include full scale (or at least scale model) components with a realistic combination of loading and service fluid /temperature exposures. Such a verification test will inevitable be an accelerated snapshot of the component behaviour - but appropriately designed, the verification test programme will provide a means both of calibrating the analysis and of checking its accuracy at certain key points.

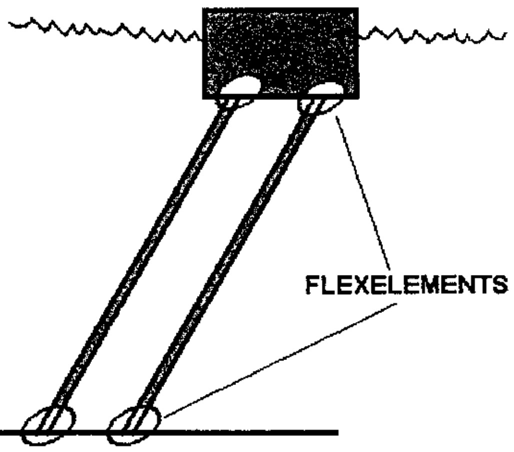
ELASTOMERS IN STRUCTURAL BEARINGS FOR DEEP WATER PLATFORMS

Applications Review

Elastomeric components were introduced into the structural design of deep water oil and gas production platforms to provide flexible articulation of the structure and minimise the fatigue loading on tubular steel members. The concept is illustrated in Figure 2. The tension leg platform works essentially as an inverted pendulum with buoyancy providing a positive tensile force on the tether legs. The action of wind and current introduces lateral forces and motions of the platform. The introduction of flexelements into the upper and lower ends of the tethers allows rotation of the tethers through an angle of up to 15° while transferring only minimal bending force into the tether legs themselves.

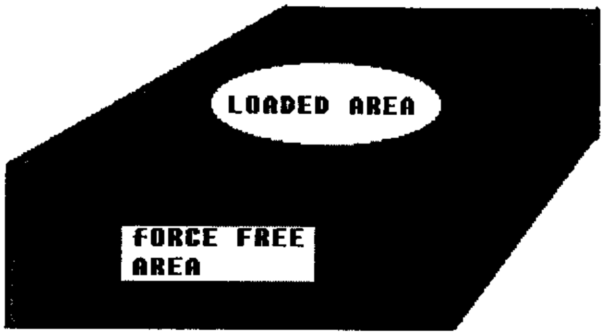
Figure 2

Tension Leg Platform Concept



Flexelements consist of a number of layers of alternating steel and elastomer spherical shells which are terminated at boundary angles with the radius of each successive shell increasing through the stack. If the rubber layers are designed to have a high shape factor (see Figure 3), then they will have a high load capacity in the compressive direction. The shape factor concept for elastomers is based on the near incompressibility of this type of material. The Youngs modulus, or shear modulus of an elastomer is usually about 2000x smaller than the bulk modulus of rigidity of the material. This is because the former is determined by the sliding action of long chain polymer molecules whereas the latter is determined by molecular chain extensions or contractions. Thus if rubber is deformed in such a way that it is free to bulge into an open space with molecular chain rotation then the effective modulus will be less than if it is constrained so that only molecular chain extensions or contractions are possible. The shape factor is defined as the ratio of the loaded area (where it is fully constrained) to the force free area of a rubber block. Thus the smaller the shape factor the more the rubber is free to with a stiffness dominated by the shear modulus. At higher shape factors it is more constrained and eventually becomes dominated by the bulk modulus. The compression modulus of elastomeric components is proportional to the square of the shape factor. Thus the load capacity of rubber layers can be greatly increased by design, by increasing the shape factor. It has been shown (*Reference 1*) that high shape factor laminates can be analysed using fracture mechanics techniques.

Figure 3
Shape factor Concept for Elastomers



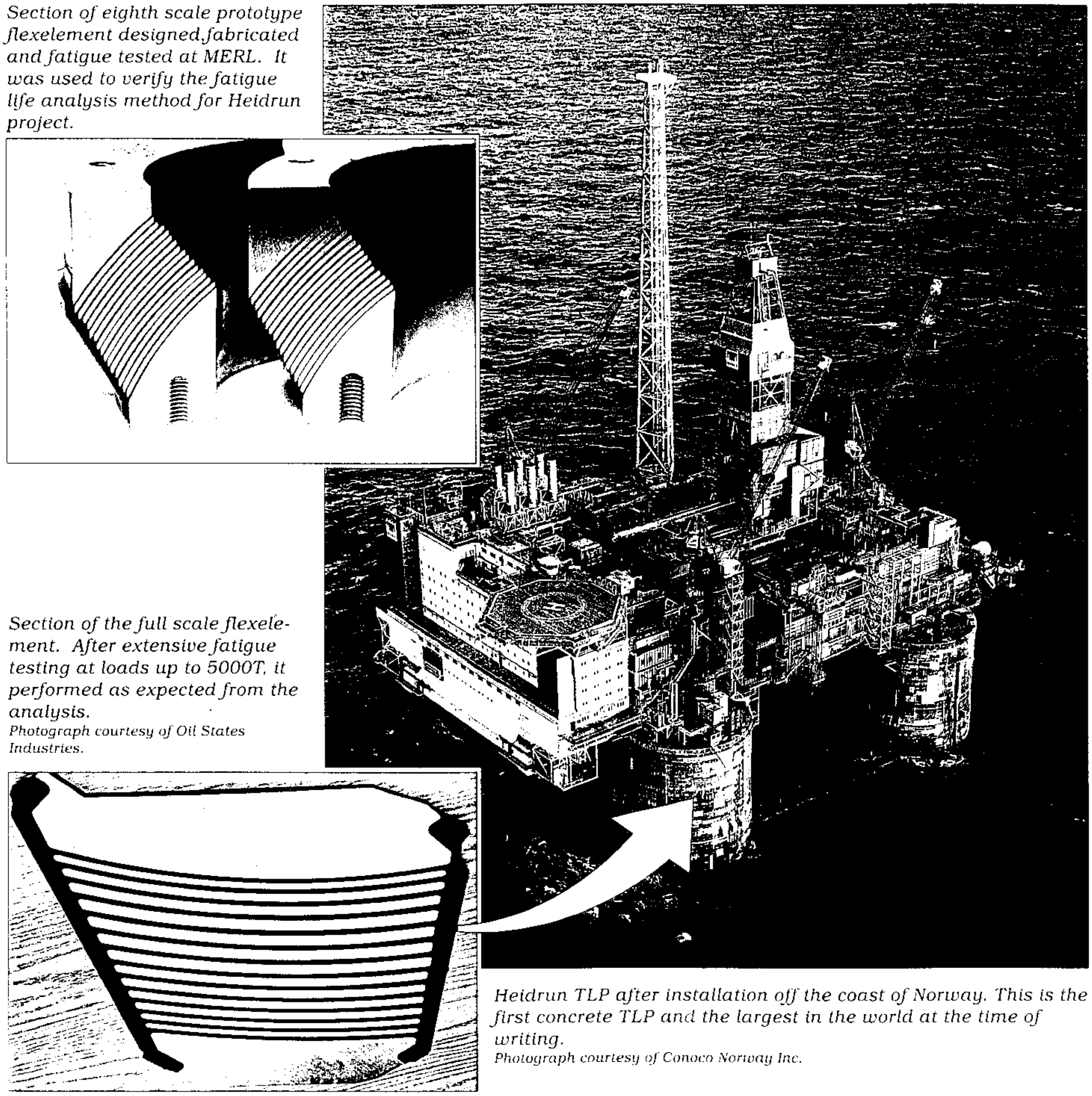
SHAPE FACTOR = LOADED AREA÷FORCE FREE AREA

A flex element is manufactured using a large compression mould. Each rubber layer is carefully laid up by hand and the unit is moulded so that a strong rubber/metal bond is formed during vulcanisation of the rubber in a compression mould. There are two key requirements; (a) that the position of each spherical sections steel layer should be accurately retained during cure and (b) that the rubber/metal bond should be high integrity and durability. To some extent these are conflicting requirements. However manufacturing techniques have been developed which achieve this. These are generally large units, up to 2m in diameter. The rubber cure process may take more than 24 hours. Every unit is tested for rotational stiffness and carefully inspected for defects.

The first elastomeric articulation was designed for the Deep Water Wavity Tower in the mid 1970's (*Reference 2*). Although extensive tests were performed during the early 1980's this structure was never built. The first tension leg platform was built during the period 1982-1984 and was successfully installed by CONOCO in the North Sea in 1984. Since then, there have been several other tension leg platforms both in the N Sea and in the Gulf of Mexico each using elastomeric flexelements as primary load bearing components supporting the tether system structure.

Figure 4 shows a photograph of the Heidrun tension leg platform built by Conoco for the Norwegian sector of the N Sea. This was the first concrete TLP and also the largest in terms of the load requirements for the flexelements, which were fatigue tested at loads up to 5000T with angular rotations up to 10° to a fatigue test programme designed to simulate 30 years life

Figure 4



Section of eighth scale prototype flexelement designed,fabricated and fatigue tested at MERL. It was used to verify the fatigue life analysis method for Heidrun project.

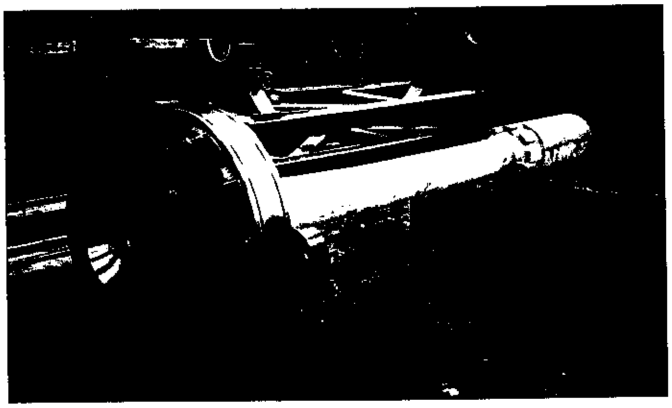
Section of the full scale flexelement. After extensive fatigue testing at loads up to 5000T, it performed as expected from the analysis.
Photograph courtesy of Oil States Industries.

Heidrun TLP after installation off the coast of Norway. This is the first concrete TLP and the largest in the world at the time of writing.
Photograph courtesy of Conoco Norway Inc.

A different application of structural elastomeric bearings has been made in the Troll Gas platform. Here the bearing are located at intervals around a plinth. There is a system of upper and lower bearings used to provide articulation at the deck level. This structure is the tallest concrete structure in the world, with a height of 368m. The maximum operational topside weight is 25,600Tonnes and the platform has been designed to have an operational life of 50 years - with appropriate safety factors.

After 7 years service several flex elements were removed from the Hutton tension leg platform installed in 1984 and were subjected to detailed inspection by the author - following removal to an on shore yard. It was found that given the actual environmental conditions experienced, the condition was as expected from the fatigue life analysis carried out at design stage. Figure 5 shows a photograph of one of these units. The units were considered suitable for further service and had sustained no visible fatigue damage. However, it was found that after 7 years there had been some hardening of the nitrile rubber compound used (*Reference 3*). However the rubber was in generally good condition and there was no crack growth. The conditions experienced by the flex elements was monitored by a system of load cells and the conditions actually experienced turned out to be less severe then had been originally expected and allowed for by the analysis and testing at design stage. These flexelements have now been in service for 12 years and, so far, have functioned according to design. Further analysis may establish residual life.

Figure 5



TLP flexjoint inspected by MERL after 7 years service in the Hutton Field in the North Sea. Observations were in accord with expectations from fracture mechanics fatigue life estimates made by MERL staff

Fracture mechanics theoretical basis for elastomers

Fracture mechanics was used as a basis for the fatigue life calculations in each of the examples considered above. According to this method, the tearing energy is calculated for each layer of the flexelement under the specified conditions of loading.

Energy Criterion for Fracture. Considering crack propagation as a thermodynamic process, as a crack extends, the decrease in mechanical strain energy is balanced by an increase in surface free energy. This has been called the Energy Balance Concept. According to this criterion, the elastic energy released or work of the applied forces during crack propagation provides the additional surface energy of increasing crack area required for crack growth. If this condition were not satisfied, propagation of the crack, with its associated increase of surface free energy would violate the first or second law of thermodynamics. In general, however, this criterion is a necessary but not a sufficient condition and energy losses in materials must also be considered. It sets a lower bound for mechanically-activated fatigue mechanisms. Higher levels of energy (eg by two orders of magnitude) are usually required to fracture polymers.

- The Energy Criterion for Fracture states that crack growth will occur when the system composed of the cracked body and the external forces is capable of delivering the energy required to form an additional crack of area dA. Thus:

$$\frac{d}{dA}(F-U)=\frac{dW}{dA} \qquad \text{..................(1)}$$

where: U is the elastic energy contained in the body
F is the work performed by the external forces
W is the energy consumed by crack propagation

By definition:

$$T=\frac{d}{dA}(F-U) \qquad \text{....................................(2)}$$

is the Tearing Energy, or Elastic Energy Release Rate

Under linear elastic conditions, unstable crack propagation is associated with a critical value, T_c, of the energy release rate at which fracture occurs. This quantity has also been referred to as "Tearing Energy". Under fixed displacement conditions, external forces can do no work and the release of elastic energy is the driving force for crack growth. For rubbers, Rivlin Thomas[10] expressed the Griffith Energy Criterion in the following form:

$$T=-\left[\frac{\partial U}{\partial A}\right]_{\ell} \qquad \text{......................................(3)}$$

where: U is the stored elastic energy;
A is the area of new crack growth
l denotes that the partial differentiation is at constant deformation

There is no fundamental reason why constant deformation has to be chosen and it is straightforward to express the criterion in more general terms to include the work done by applied forces. However, the mathematical analysis is simplified in most cases by use of constant deformation, when applied forces do no work.

Rivlin & Thomas (*Reference 5*) first validated this approach for rubbers in 1953 using experiments with strips cut from thin unfilled rubber sheets with cuts of different lengths. Force deflection curves were obtained until tearing just occurred. Stored energy vs Crack Length slopes then give experimental values for tearing energy. Theoretical relations were derived for two different geometries, namely a short, wide strip with a long central cut (pure shear) and a strip pulled in a trousers configuration. Good agreement was found between the experimental and theoretical values and between the different geometries.

<u>Trouser testpiece</u>

$$T=2F\lambda/t-wW \text{ ....(4)}$$

where F is the force applied to each leg
t is the testpiece thickness
w is the testpiece width
λ is the extension ratio in the legs
W is the strain energy density i
Pure shear testpiece $T = W \cdot l_o$ ....(5).........
where l_0 is the unstrained height

Simple extension testpiece $T = 2kWc$ ....(6)
where k is a geometrical function, slowly varying between approx π and $\pi/2$ as λ increases from 1 to 10. c is the crack length

These testpiece geometries provide a convenient way of measuring the relationship between crack growth rate and tearing energy. Materials fatigue characterisations can readily be obtained in either pure shear or simple extension.
Most engineering components involve plain strain and so this is an important category for the application of tearing energy concepts to calculations of component fatigue life.

Shear of thick blocks. - Lindley et al (1979) (*Reference 6*) investigated the case of simple shear of a thick bonded block of rubber, fatigued at various strain levels.. At high strains, this configuration becomes similar to that of tension and may cease to be plane strain. For long initial cracks experimental work confirmed the tearing energy approach for simple shear.

For simple shear:

$T = 0.4\ t$ short cracks
$T = 0.8\ W\ t$ long cracks

where W is the uniform stored energy density in the rubber layer.
t is the rubber layer thickness

Compression of thick blocks. The first systematic application of fracture mechanics concepts to rubber in compression was made by Lindley & Stevenson (1981) (*Reference 7*) who studied unbonded rubber blocks of various shape factors, surface friction conditions and edge profiles. Compression is a complicated mode of deformation comprising a central core under hydrostatic compression and a distribution of shear stresses from the core to the outer surface which may also possess tensile elements. Modulus is shape and strain dependent in a way not the case for the other modes (tension and shear). A theoretical fracture mechanics solution was provided by Stevenson (*Reference 8)* for bonded blocks in compression, based on energy balance considerations and a mathematical model of the 3-Dimensional locus of crack growth as a parabaloid section. The equation for tearing energy in its complete form was given as follows:

$$T = \frac{3(r-k)W}{\frac{6d}{2(r-k)} \sin^{-1} \frac{2(r-k)}{d} \pm \frac{6(r-k)}{d} \sqrt{\left[l + d^2 / 4(r-k)2\right]}}$$

where : r is outer radius
k is core radius
d is height

W is stored energy density.

Rates of crack growth measured for bonded blocks of unfilled rubber were found to be in close agreement with values calculated using the equation for T and reference to the intrinsic dc/dN vs T relation for the rubber of the materials used in the experiments. Material characterisation data were obtained from simple extension tests (plane stress). Experiments in compression with a wide range of edge lengths (10mm-250mm), rubber layer thicknesses (0.5mm-50mm), shape factors (0.25-50) and rubber hardnesses (30-80 IRHD) all confirmed a unique materials relation between Tearing Energy and Crack Growth Rate - identical for plane strain and plane stress configurations. A simplified version of the above equation derived for T in uniaxial compression is:

$$T = 0.5\ W\ t$$

where W is the uniform stored energy density in the rubber layer.

t is the rubber layer thickness.

In shear and in compression, the tearing energy is not a direct function of crack length. This means that the growth of a fatigue crack will not accelerate, as it will in simple extension - where the direct dependence on c causes T to increase as the crack grows. This is the reason why rubber is not normally used in tension, but only in compression or shear.

The possibility of obtaining the same materials relation in plane strain and plane stress means that fracture mechanics analysis of more complex geometries is likely to be successful without the need to consider any extraneous factors or plastic zones.

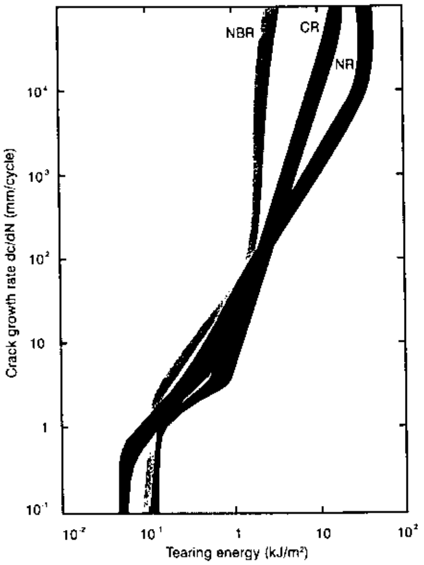
Application of Tearing Energy Concept to Dynamic Fatigue The tearing energy concept was first successfully applied to cyclic, or dynamic, fatigue crack growth in rubber in the early 1960's (see for example Lake & Lindley 1964) (*Reference 9*) It was shown that if the amount of crack growth per cycle (dc/dN) was plotted against the maximum tearing energy attained per cycle, then the results were independent of the sample geometry for different geometries. At high enough values of tearing energy, T, failure will occur from a single cycle, and dc/dN increases asymptotically towards T_c the static critical tearing energy, or catastrophic tearing energy. At moderate to high tearing energies the behaviour was described by a power law relation of the form:

$$dc/dN = BT^{\alpha}$$

where B and α are constants characteristic of the material At lower tearing energies the power law relationships were reported to break down and for NR a linear region was reported with an intercept on the T axis. This represents the minimum energy, T_o, required for the initiation of crack growth. At very low tearing energies, below T_o only chemical failure mechanisms occur. These proceed at an extremely low rate (0.1mm/year) and are attributed to the effects of ozone. The minimum value for T below which no mechanical fatigue crack growth can occur is referred to as the threshold value, T_o. The value of this varies for different elastomers between 0.05 and 0.1kJ/m^2 and may be understood in terms of the molecular structure of the rubber.

Different elastomers have different forms of the T vs de/cN relation and the curves may even cross. Figure 6 shows, as an example, typical results for Natural Rubber (NR), Polychloroprene (CR) and Acrylonitrile-butadiene rubber (NBR). Which material provides the longest fatigue life depends which portion of the dc/dN curve predominates for the life of the component. for very large numbers of very low amplitude cycles CR will show less crack growth than NBR and NBR less than NR. Above T_O there is a central region where the fatigue resistance of all three rubbers is similar.

Figure 6



Tearing energy plots for three engineering elastomers showing crossovers.

At high tearing energies, the situation is reversed, with NR sustaining only moderate crack growth rates, when NBR in particular would be expected to fail catastrophically, CR being an intermediate case. The excellent strength properties of NR at high energies or strains is attributed to its ability to strain crystallise at the crack tip, a property not generally available in oil resistant elastomers.

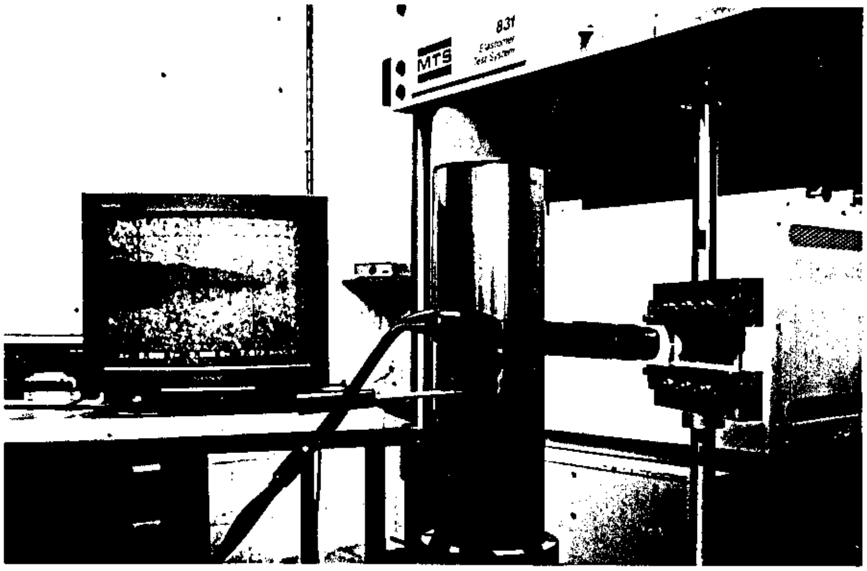
Consideration of the shape of the T vs dc/dN curve immediately suggests the basis for good fatigue resistant design - namely to ensure that the maximum tearing energies of a component in service are in a stable region well away from the asymptote to T_C - where even approximate predictions of crack growth rate become very difficult.

Non-Relaxing Conditions. - Under relaxing conditions, each deformation cycle includes zero strain and there is a unique relation between the amount of crack growth per cycle and the maximum tearing energy per cycle. Under non-relaxing conditions the strain does not relax to zero each cycle but only to a minimum value. Unless the amount of crack growth is strongly influenced by time dependent effects, it will only depend on the minimum and maximum tearing energies of the cycle and not on how the tearing energy varies with time between these limits. This may be characterised by means of the ratio:

$$R = T_{\min} / T_{\max}$$

Fo sufficiently large values of the ratio "R", crack growth rates can be a factor of 1000 or more lower ..

Figure 7
Experimental Arrangement for Materials Fatigue Tests on Elastomers



The test approach has been further developed with the help of accurate servohydraulic test equipment. The advantage of improved precision and the ability to monitor hysteresis during fatigue cycling is felt most strongly for time-dependent materials.. As temperature increases at each tearing energy crack growth rates can increase by a factor of 1000 or more. The nature of these relationships are not generally understood and many elastomers used at high temperatures have not yet been characterised in this way. The large scale of some temperature effects is much greater than would be expected from conventional ageing tests on standard tensile testpieces.

Application to fatigue life calculations of flexelements

A flexelement consists of alternating bonded layers of steel and rubber of spherical section. The design is defined by the bounding angles , θ , the inner and outer radii , r_i and r_o , and the thicknesses of the rubber and steel layers. The rubber modulus may be intentionally varied through the stack of layers and so may the rubber layer thickness.

The deformations of each rubber layer may be considered separately compression and torsional contributions. Tearing energies are calculated separately with the aid of a specially developed computer program, FLEXFM, taking into account the curvature of the layers. Tearing energies may then be combined on a worst case basis, for example, using the following equation:

$$T = [\sqrt{}T_c + \sqrt{}T_s + \sqrt{}T_t]$$

where T_c refers to the tearing energy in compression

T_s refers to the tearing energy in shear

T_t refers to the tearing energy from the additional compression caused by interleaf plate tilting.

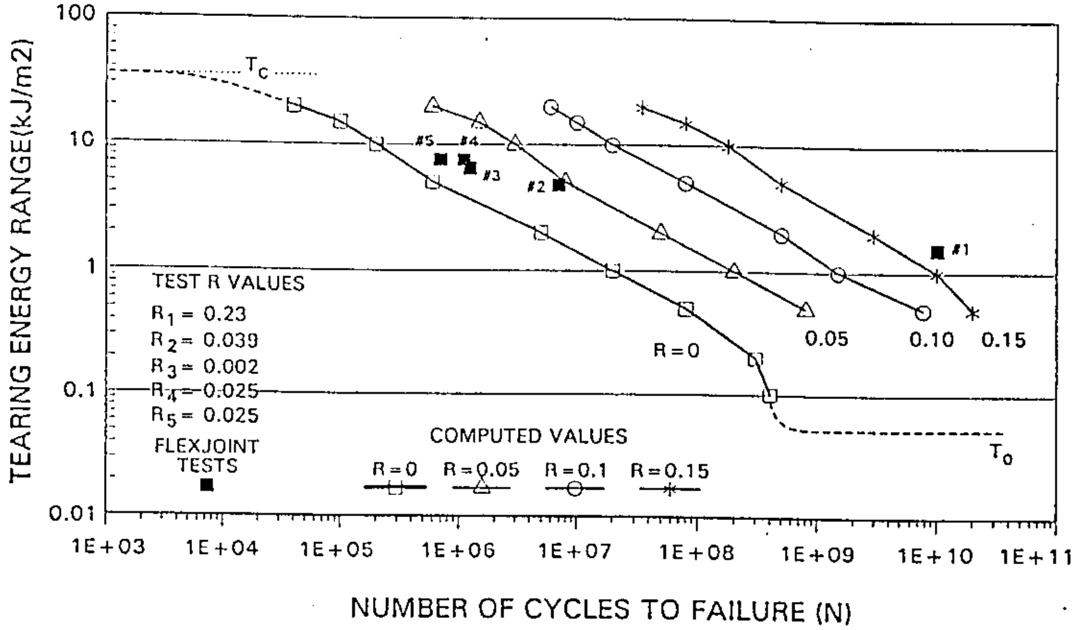
Once the tearing energy is calculated, the crack area can be computed from the crack growth rates determined from materials fatigue tests. The tearing energy range and the ratio of the minimum to maximum tearing energy must both be considered. Figure 8 shows the results of an extensive series of materials fatigue tests to characterise material behaviour using pure shear testpieces (*Reference 4*). A conservative approach for design would be to use R=0 data in all cases but this would lead to substantial overdesign in some important applications. Also shown on Figure 8 are the results of flexelement fatigue tests..

An extensive flexelement test programme formed part of the Esso Deepwater Integrated production System research programme initiated in 1987. The results of this programme are described in more detail elsewhere (*reference 4*). Six flexelements were manufactured using black filled natural rubber and subjected to different fatigue test conditions, each comprising a combination (in phase) of rotation and axial compression. The maximum rotation was 10.5^o and the maximum axial compression was 3MN. The individual test durations ranged from 14Mc to 520 kc. This provided tests with a range of different tearing energy range values between 1.2 and 7.4 kJ/m^2. The tests were in most cases continued until there was a measured reduction in torque at maximum rotation of more than 10%. The longest test showed less reduction than this and was terminated after 12 months due to time limitations. After an initial non-linear reduction in torque due to stress softening in the rubber there was a linear reduction associated with a stable region of crack growth. It is in this region that the analytical assumptions made are expected to be applicable. Finally there is a region where there is a much faster reduction in torque as the crack growth accelerated. In this region there is likely to be significant interaction between the different layers of the flexelement and the analytical assumptions cease to apply.

After each test was terminated the flexelement was cut into 8 segments and a detailed map was made of the crack areas. The maximum area in each layer of each flexelement was then compared with the analytical prediction. All of the measured cracks were within the rubber layers and not at the bond surface. Since the rotational moment was applied about one fixed axis, the cracks were mainly concentrated over two 90^o arcs, 180^o apart. Crack areas were converted to an equivalent crack length by taking the square root. The resulting measured values were in fairly good agreement with calculated values. The definition of a crack length in a 3 dimensional space is of course problematic since it would be more natural to allow all definitions to rest in terms of area. However this conversion facilitated comparisons in a more conventional manner.

Figure 8 shows a calculated flexelement fatigue life chart , constructed from the results of the fracture mechanics analysis and the materials fatigue data, using as a failure criterion the growth of sufficient crack area to cover one half of one layer of the flexelement. The contours refer to the effect of non-zero minimum conditions in reducing crack growth rates. Also shown on this Figure as solid squares are data from the flexelement tests. When the appropriate value of the R-ration R_1 to R is taken into account each of these data points occurred where it was predicted to by the analysis, within experimental error *(reference 4)*. The limitations of the approach concern cases when crack growth in one layer would be significant enough to affect the stored energy in other layers. For such cases specialised finite element code, FLEXPAC, is under development to carry out the fracture mechanics analysis as a part of the finite element process. This requires extensive experimental validation before it can be proposed as a reliable engineering tool.

Figure 8 Flexelement Fatigue Life Chart



This case study shows that fracture mechanics techniques can be successfully applied to the calculation of expected fatigue life for elastomeric flexelements. This provides an important tool to allow engineers to make more use of elastomers in critical applications.

Conclusions and future research directions

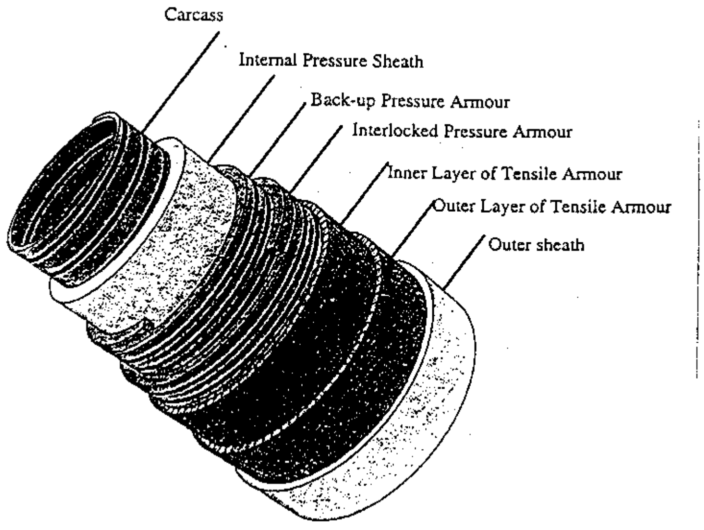
The development of fracture mechanics techniques for elastomers is now well established and their application to those geometrical cases for which there are verified solutions has generally proven successful. This has played an important part in developing engineers confidence in the use of these materials in critical applications. For the future, the challenge is to automate the approach so that the fatigue life calculations can become an integral part of the initial design process - with design and material selection being optimised for fatigue resistance. Safety factors are currently used that will probably be seen as unrealistically conservative when a more quantitative approach is widely available.

For the future it also will be necessary to develop ageing models for the elastomer materials so that the chemical effect of the service environment can be determined and the ageing model integrated with the mechanical fatigue life calculations shown here. It is a weakness of the current approach that fatigue is generally determined based on materials tests on new unaged material whereas in reality fatigue would occur after some years service.

THERMOPLASTICS IN FLEXIBLE PIPE CONSTRUCTION

Application requirements

Figure 9 Flexible pipe construction



Thermoplastics are used in critical components as flexible pipes to retain high fluid pressures. Flexible pipeline constructions usually consist of several layers each serving different functions and are used to carry oil and gas at pressures up to 5000psi and temperatures up to 120C. there are currently moves to develop a new generation of flexible pipe constructions for higher temperatures, up to 200C. Flexible pipe constructions consist of an inner carcass consisting of interlocking steel windings to provide resistance to collapse of the pressure sheath under large internal pressure reductions and external water pressure. The next layer is the pressure sheath, which is a high performance thermoplastic tube extruded onto the carcass. This is the most critical layer for containment of the high pressure fluid transported by the pipeline. The pressure sheath is supported by an outer steel interlocking layer which provides the mechanical support for the fluid pressure. There are then outer layers that provide additional support and also external protection from sea water ingress and mechanical damage. The general concept of a flexible pipe construction is shown in Figure 9 *(from reference 10)*.

If the lifetime and performance in service of the pressure sheath is to be determined then there is a need to know performance related material properties that are not provided by standard tests. Standard tensile tests do provide a coarse and approximate idea of the general behaviour of materials in a fluid environment, but do not provide the quantitative information needed for engineering design.

A new Joint Industry Research Project, the CAPP project has developed new tests for high pressure gas permeation, fatigue resistance, fracture toughness, flexural modulus and compressive stress relaxation as well as employing tensile modulus, tensile strength and elongation at break to aid fluid exposure evaluations. Central to the programme has been the attempt to characterise the rate of change of each of these properties due to exposure to service fluids at a range of different temperatures. This includes changes due to deplasticisation effects as well as due to chemical ageing. The exposure conditions of the testpieces have included the imposition of strains designed to represent those that may be experienced in a flexible pipe (*Reference 11*).

In a flexible pipe, operating at high pressures, thermoplastic materials may be subjected to a combination of bending, tensile and compressive strains that may be static or dynamic in nature at different times during the life of the pipe. The material will generally experience a range of temperatures during its service life typically from 4 to 120°C. The first requirement is therefore to know the effect of temperature on the flexural and tensile moduli. For most engineering thermoplastics this effect is large, even well below the melting point of the material. The type of thermoplastic in use is partially crystalline usually with between 50 and 60% crystallinity. In the programme reported here the two materials studied in greatest depth have been PVDF and ETFE (polyvinylidene fluoride and ethylene tetrafluoroethylene copolymer respectively).

The unaged yield characteristics of the material needs to be determined The current API guidelines limit allowable strains to 7% but full yielding will not generally occur until above 20% and departure from linearity may commonly occur above 3%. There is thus a region where design calculations of stress under specified pipe deformations could be in error, unless the non-linearity of the material behaviour within the allowable strains is taken into account.

If there is a constant applied pressure or any other constant stress then the thermoplastic will be likely to creep. The creep rate therefore needs to be characterised in a realistic mode of deformation and over a long enough time period to establish the validity of any extrapolation. If instead of constant stress there is a constant strain, such as may be required in an end fitting region to maintain sealing or for some other reason, then there will be a relaxation of stress and the stress relaxation rate should be measured, again using a realistic mode of deformation.

Most applications will experience some dynamic motion and some flexible pipe are designed as dynamic systems. In that case the fatigue behaviour of the material should be characterised. This is best done on a geometry free basis. For example if the crack growth rate is measured as a function of the energy available to cause crack growth (G or J) then a materials relation is available against which the performance of the material can be assessed.

Flexible pipes are required to transport fluids at high temperatures and pressures. Hence another requirement is that the permeation of gas and liquid through the material should be within acceptable limits. At high pressures and temperatures some thermoplastics can have high gas permeation coefficients. Some thermoplastics may contain substantial quantities of plasticiser that may be removed during service, leading to shrinkage of the material and affecting permeation rate. The shrinkage rate needs to be quantified and this information taken into account in pipe design.

In addition to the initial properties meeting the design requirements, it is also necessary that the performance properties remain within acceptable limits for the specified life of the pipe during contact with the service fluids. This is much more difficult to quantify, and requires the development of new methods to provide assurance of long term durability.

An important part of the approach proposed here is to correlate changes in performance properties caused by fluid exposure with changes in chemical and/or physical structure.

Performance related materials properties for thermoplastics

Performance properties have been discussed in *reference 13*

Tensile properties These tests are relatively straightforward and may be performed on tensile dumbbells prepared to ASTM 638. The material thickness should be the same as the wall thickness of the pipe. Table 1 summarises some tensile properties at different test temperatures for PVDF, the thermoplastic used for critical flexible pipe applications with elevated temperatures. There is a substantial effect of temperature with lower modulus and higher creep rates at higher temperatures.

TABLE 1 INITIAL TENSILE PROPERTIES

	Young's Modulus MPa		Yield Stress MPa		Yield Strain %		Ultimate Strength MPa		Ultimate Strain %	
	22°C	110°C	22°C	110°C	22°C	110°C	22°C	110°C	22°C	110°C
PVDF	785	190	36	11	22	28	23	25	63	420

Fracture toughness Fracture toughness may be conveniently measured using the compact tension testpiece, illustrated in Figure 10. There is a draft ESIS protocol for such tests on plastics dated May 1994 and on ASTM standard test D5045.. The compact tension testpiece is small enough to be machined from the wall of a 6mm diameter wall thickness pipe. Care needs to be taken to machine the shape of the notch correctly with a specially shaped fly cutter. The testpiece is pulled to a defined amount of crack opening on a universal test machine and the amount of crack growth measured. A plot of fracture resistance against crack depth then provides the intrinsic fracture toughness of the material, by extrapolating to zero crack growth or to a small initial flaw size such as 0.2mm (usually referred to as $J_{0.2}$).

Figure 10
Fatigue test arrangement for compact tension testpieces.

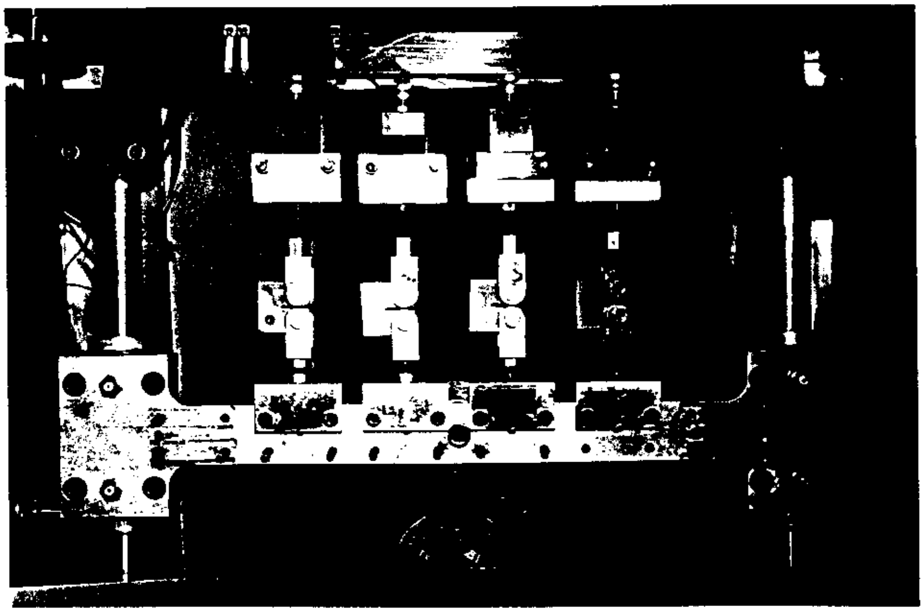


TABLE 2 FRACTURE TOUGHNESS

	$J_{0.2}$(kJ/m^2)	
	22°C	70°C
PVDF	9.0	2.7

Fatigue resistance This also uses the compact tension testpiece. However instead of deforming the testpiece to the extent that there is significant crack growth on one loading cycle, in fatigue the material is continually cycled at a low amplitude and the amount of crack growth measured using a video microscope system after thousands or millions of cycles. A fatigue resistance curve is then constructed as a chart of the rate of crack growth vs. fatigue energy, or J. Figure 10 shows the experimental arrangement at MERL for multiple fatigue tests and Figure 11 illustrates typical fatigue data. The sharpened crack tip quickly blunts to a natural shape during this test, which is then a material characteristic.

Figure 11 Typical fatigue resistance data for PVDF

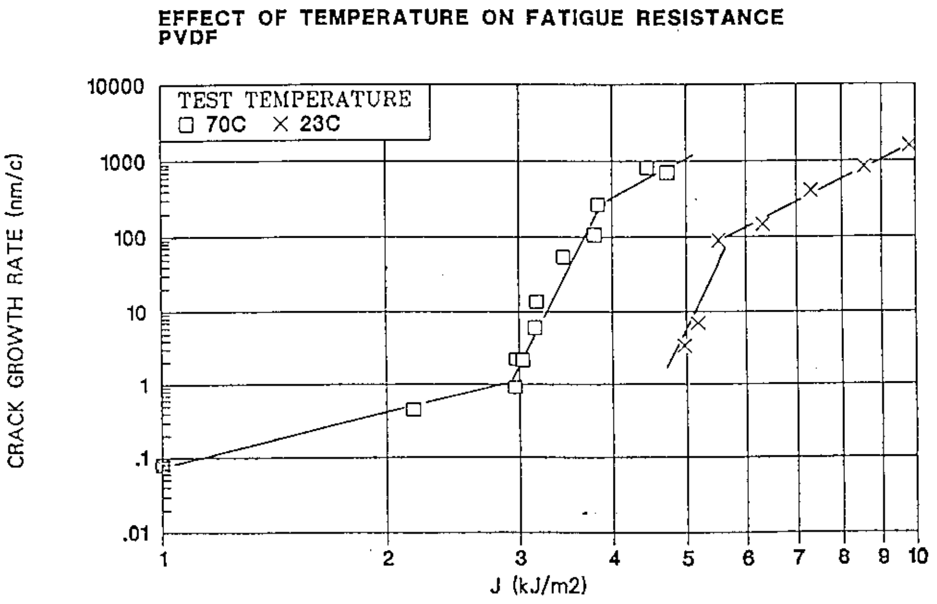


Figure 11 shows typical fatigue resistance data for PVDF. The tests were performed on compact tension testpieces at RT and at 70°C over a range of fatigue energies. There was a sensitivity to temperature and higher fatigue crack growth rates were obtained at 70°C. However all of the values for PVDF showed lower crack growth rates (i.e. higher fatigue resistance) than for ETFE. There is however a convergence at higher energies indicating the need to measure crack growth rates over a range of energies.

High pressure gas permeation. This test uses a specially designed test cell which includes a segment cut from an extruded bar or pipe wall to be sealed into a special holder. Appropriate sealing is employed to withstand the high pressure: the cell is described elsewhere (*Reference 12*) The permeation of gas is measured continuously. Arrhenius-type plots for methane which vary somewhat with applied gas pressure have been developed after a series of long-term permeation tests through PVDF. The Arrhenius behaviour follows established behaviour for permeation at 'normal' pressures. The changes brought about by high pressures have been discussed and show the need for high duty applications at severe conditions for gas permeation testing to be performed at service temperatures and pressures. When required diffusion and solubility coefficients, plus gas concentration, can also be obtained by this technique (*Reference 12*).

Flexural Tests Flexural properties can be characterised using 3 point or 4 point bend tests, as illustrated in Figure 3. The advantage of 4 point bending over 3 point bending is that the centre portion experiences a uniform state of stress and the contact points are not at the position along the testpiece length of the maximum stress, as in 3 point bending. Four point bend tests may also be used to characterise creep and stress relaxation properties.

The maximum strain in the outer "fibres" of the material in the four point bend test occurs when the load span is half of the support span and is given by

$r = 4.36\ D.d./L^2$ where: r is the maximum strain, D is the maximum deflection at the centre of the beam , d is the depth of the beam
L is the support span

Table 3 shows how temperature can affect flexural modulus significantly, and increase associated creep properties excessively.

TABLE 3 FLEXURAL PROPERTIES

1% Flexural modulus MPa			Creep rate (% per decade)	
22°C	80°C	110°C	22°C	110°C
1000	340	120	7.2	121

Creep and stress relaxation Creep tests provide a measure of the rate of increase in deformation during a constant state of stress. Stress relaxation provides a measure of the rate of decrease in stress during a constant state of strain. In either case it is desirable to provide a means of continuous measurement and collect data over 3 or more decades of time. The tests may be performed either in tension, in flexure, or in compression. ASTM D2290 or D2291 give some guidance on these test methods. The material is then characterised by the slope of a plot of creep, or stress against the logarithm of time from an initial time which should be long compared with the time taken to load the testpiece.

Liquid absorption Liquid mass uptake measurements performed on simple test plaques can lead to the equilibrium mass uptake and volume swell for a polymer/liquid system, and provide diffusion and permeation information data (which are independent of pressure for liquids, unlike the case for gases).

For chemical ageing/life prediction usage, diffusion aspects are preferably minimised. If simple test plaques of orientated crystalline thermoplastics are being tested, this is indeed the case as can be demonstrated using liquid uptake measurements.

Life prediction of flexible pipe materials

The most common method of accelerating ageing is to raise the temperature. However, it needs to be established that there is a single activation energy over the range of interest so that the natural logarithm of the rate of change (or time to failure) is linear when plotted against the reciprocal of absolute temperature giving a so-called Arrhenius plot. To do this properly requires the rate of change to be measured in the detail described above for five or more different temperatures in the range of interest. This requires a large amount of testing and is usually a costly exercise. The temperature may not be raised above the value at which the Arrhenius plot ceases to be linear. Temperature is clearly a method of acceleration but not the only one - increased concentration of an aggressive chemical species (e.g. H_2S or amine) may also be used to accelerate ageing.

Chemical ageing resistance Testpieces of each of the above types may be exposed to a simulated service fluid at elevated pressure and temperature in suitable pressure vessels. Special fixtures have been designed which permit these exposures to be performed while maintaining a static state of strain on the samples.

The changes in chemical or physical structure that accompany ageing in severe service environments need to be identified. Appropriate chemical analytical techniques are thus applied to determine changes in crystalline levels, elemental content, functional groups etc, so that a rationale can be developed to relate property changes to structure changes. In this way life prediction techniques are being developed.

The effect of chemical ageing resistance needs data on the effect of chemical ageing on the performance properties such as fatigue discussed previously. The effect of strain encountered in service on such changes also needs to be understood. For this reason specially designed test fixtures have been developed to strain compact tension testpieces while being exposed to the test fluid in a pressure vessel (e.g. at 5000psi) for various periods of time. The fatigue and fracture toughness values can then be determined after ageing. A range of test fluids has been formulated for use in this work designed to represent different service conditions for flexible pipes and umbilicals.

A 100% methane
B 97% methane gas, 3% carbon dioxide with saturated water vapour
C 97% methane gas, 3% carbon dioxide, dry
D 94% methane gas, 5% carbon dioxide, 1% hydrogen sulphide gas
E 94% methane gas, 5% carbon dioxide, 1% hydrogen sulphide gas with saturated water vapour
F Fluid E with 1% ethylene diamene
G Fluid A with 1% ethylene diamene
H Fluid B with 1% ethylene diamene

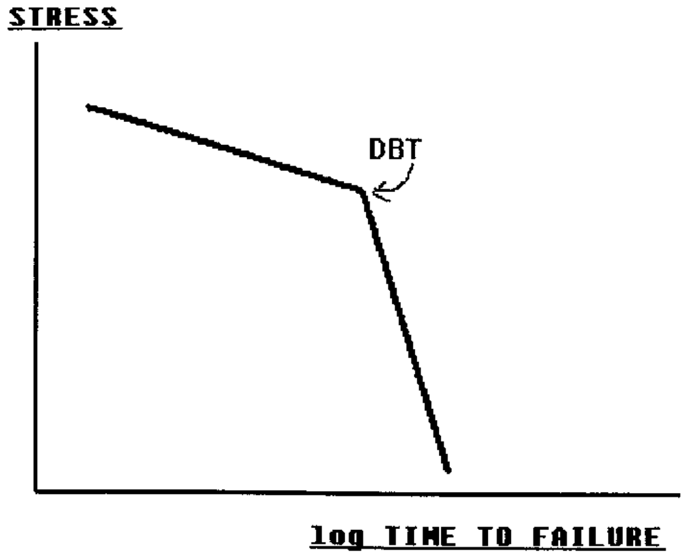
After chemical ageing in the test fluid the performance properties are measured and a rate of change at the test temperature is obtained. Analytical analyses are performed to obtain structural changes and search for correlation and mechanisms of chemical change.

Tests are performed for a series of temperatures up to 140°C in each fluid to establish the rates of change in the properties discussed in the previous section. The results of the chemical ageing resistance tests are not available for release at this time.

Ductile/brittle transitions

A specific problem area that is currently under investigation is the phenomenon of ductile/brittle transitions. According to this phenomenon a relatively low level of stress may lead to an unexpected failure after a long time. Figure 12 illustrates the phenomenon. This has led to unexpected failures of polyethylene pipes and happens at earlier times at higher temperatures. When failure occurs at the lower stress levels it is associated with less deformation of the material in bulk and so is referred to as brittle. A third stage has also been proposed as due to chemical degradation effects (*reference 14*).

Figure 12 DBT Transition for thermoplastics giving rise to unexpected failures after long service times



COMPOSITE MATERIALS IN OFFSHORE CONSTRUCTION

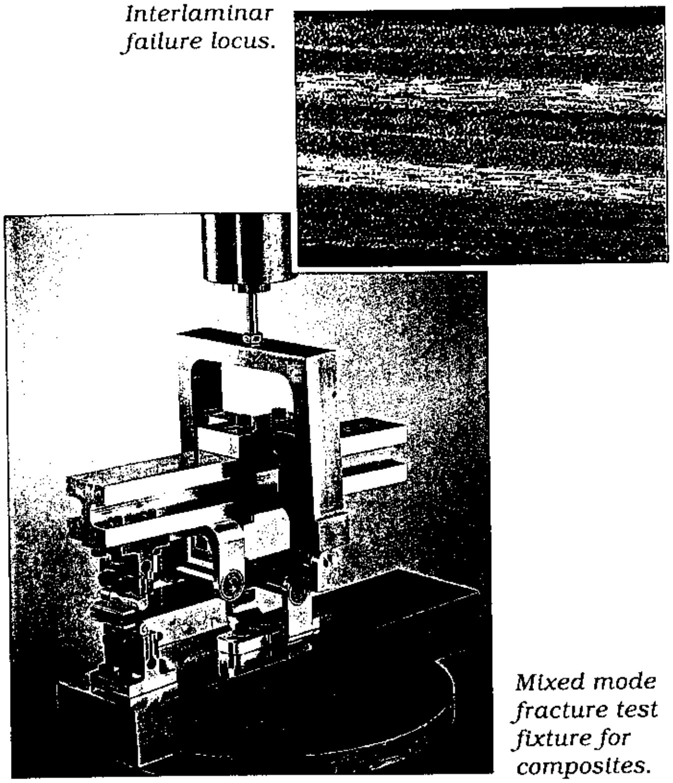
Applications and design procedures

Fibre reinforced plastics materials (FRP's) offer the marine construction and offshore engineering industries new ways of cutting costs and improving the durability of constructions especially those in contact with sea water (*Reference 15*). They are already used for marine vessels, piping and some secondary structures such as gratings, ladders, cable trays and blast panels. Other applications have included piping for cooling, well injection, firewater and drainage, downhole tubing, caissons and subsea protection. The advantages of FRP's are primarily their good corrosion low maintenance and high strength to weight properties. To increase the usage of FRP's in offshore structures will require a higher level of confidence in their safety and durability. There is currently no general design procedure that will ensure long life but there a number of methods that if correctly applied can meet the needs of the composite material designer to determine durability and strength of the composite materials and structures.

Design guidance is needed for offshore structural engineers who wish to use composites in structures. Standard process specifications and tooling methods are required. Designing the structure requires documented design methods, standardised test methods, verified failure criteria and a database of material properties. After the offshore structure is manufactured it must pass through quality control procedures to inspect for defects. Inspection criteria need to be standardised. Many of these standards and procedures have been developed for the military aerospace industry. These methods must now be modified and developed for the offshore marine construction sector. In this sector there will be less concern with very small tolerances and more concern with low cost and large volume.

Failure criteria and performance related tests

Figure 13 Mixed Mode Fracture Test for Composites



Interlaminar failure locus.

Mixed mode fracture test fixture for composites.

Design guidance should include suitable failure criteria, a data base of composite material properties and test methods to obtain these properties. Composite materials fail in a progressive manner. Generally the first damage mode is a crack in the matrix of a ply caused by a fibre matrix debond or failure of the polymer. These cracks then begin to accumulate to saturation. Matrix cracking can be a benign failure mode but generally is the precursor to a more dominant damage mode such as delamination. Delamination is the separation of individual plies of the laminate due to peel and shear stresses. When designing composite structure, in plane stresses and strains need to be kept well below the static strength or fatigue endurance limit to ensure a safe life. However out of plane stress may also arise that may cause delamination, due to structural or material disnontinuities such as free edges, an impact event, a hole or a terminated ply within the material that effects a change in thickness. Once a delamination has begun, it will continue to grow until another damage mode initiates elsewhere or until final failure such as load bearing fibre failure or global buckling occurs (*Reference 15*).

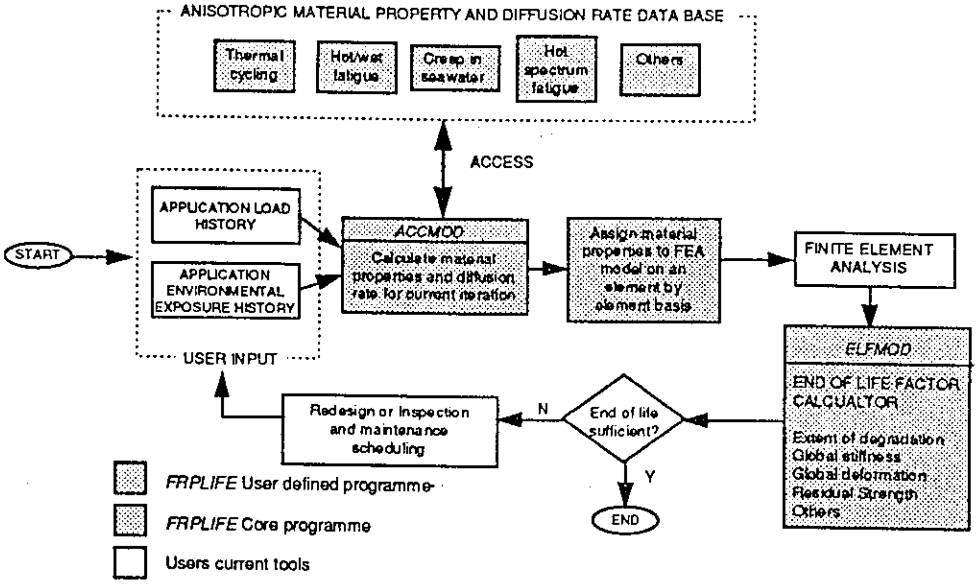
Designers must define what part of the above damage progression is acceptable to their application in order to define the durability and damage tolerance levels. These levels will be established by the mechanical and environmental loads of the application. The global design process consists of evaluating the in-plane stresses and using in-plane failure criteria to meet the durability requirements defined. Once this is established, a detailed analysis is conducted of the local stresses, the structural and material discontinuities and the effect of defects. The inputs for all this modelling include tension, shear and compression strength as well as the modulus of the fibres, the matrix and the composite. The input data is generated from standardised tests. Some specific tests are:

Double cantilever beam (Mode I interlaminar fracture)
End notched flexure specimen (Mode II interlaminar fracture)
Mixed mode bending specimen (mixed mode fracture)
Short Beam method for interlaminar shear strength
Curved beam method for interlaminar tension strength.

Figure 13 shows the mixed mode fracture test for composites.

Life prediction methods

Figure 14
Life Prediction Scheme for Fibre Reinforced Composites



In order to predict the service life of a load bearing composite component it is necessary to know both the mechanical fatigue crack growth rate and the rate of any chemical ageing in the service environment. At present the latter is usually done by means of knock down factors applied to mechanical properties of new materials, which is a relatively crude approach. In the future it may be possible to model the rates of both the environmental ageing and the mechanical crack growth on an interactive iterative basis. This would also provide a means to perform residual life calculations at any stage of the components history.

Future Research Directions

Although the test methods have been developed and a significant amount of data has been obtained there is a lack of a coherent methodology for life prediction of composite structures. For the future it will be necessary to integrate fatigue and fracture mechanics analysis with chemical ageing analysis and the diffusion effects of fluids to provide an integrated life prediction modelling tool for designers.

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Theme Paper

COMPOSITES FOR MARINE CONSTRUCTION

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ABSTRACT

Composites offer many potential advantages for marine construction based on their low density, corrosion resistance, and excellent fatigue performance. In addition, the use of composites allows for greater design flexibility for tailoring the properties to meet specific design requirements, thus promoting better system oriented, cost-effective solutions. On a one-on-one replacement basis, composite components are often more expensive than their steel counterpart. However, on a performance equated basis, the economic incentive to use composite components can often be demonstrated based on their capability to reduce system and life cycle costs. This paper presents information on composite materials that are candidates for use in the offshore industry. This information includes discussion of material properties, fabrication methods, design philosophy, safety requirements and regulation issues. The paper reviews current applications of composites in related industries such as marine, surface transportation and infrastructure and discusses opportunities to use composites in deep water oil and gas developments. The paper also presents a discussion of financial incentives to develop composite applications, identifies the main challenges facing the introduction of composites into service and discusses steps currently being taken to address these issues.

INTRODUCTION

As part of the oil industry's effort to reduce the life cycle cost of deep water developments and to improve reliability, serious effort is being devoted to the evaluation and application of innovative and cost competitive alternative materials. Advanced polymeric composite materials offer the potential to make improvements because of their attractive properties such as lighter weight, corrosion resistance and excellent fatigue performance compared to metals. In addition, composites offer the unique advantage of providing design flexibility to tailor the materials properties to optimally meet specific design requirements. One new innovation being developed is to embed fiber optics and electrical conductors into the composite part to monitor quality during manufacturing, structural integrity and loads during service and to obtain operational conditions from remote locations. In addition, composites are considered environmentally friendly materials because they require less energy to process and manufacture than metals.

In this paper, the definition of composite materials is limited to fiber-reinforced polymer (FRP) materials. Metal matrix composites and particulate composites are not addressed. FRP materials consist of small diameter fibers of high strength and modulus embedded in a matrix with bonded interfaces which permit the fibers and matrix to form a new material which captures the desirable characteristics of each. The fibers are the main load-carrying member while the matrix maintains the fibers in the preferred orientation, acts to transfer load into the fibers and protects the fibers from the surrounding environment. The most common fibers are glass, carbon and aramid. Other fibers such as silicon carbide, boron and aluminum oxide may have superior properties, but, are normally not used because of higher cost.

Polymeric matrix materials can be thermoset or thermoplastic. The most common polymeric matrix materials are polyester, vinyl ester, phenolic, acrylics and epoxy. Fibers are incorporated in the matrix in long continuous lengths or are sometimes utilized as short discontinuous fibers. Composite components are formed by stacking several lamina (single plies) to build up a composite structural laminate. The definition of common terms used in the composites industry are presented in Appendix 1 [High Performance Composites, Nov/Dec. 1996].

The successful commercialization of advanced composite components requires that development programs incorporate input from all participants in the development including material supplier, manufacturer, engineering contractor, user, and regulatory agency. Advanced composite applications can often draw on the knowledge and extensive data base developed by defense and aerospace companies. Any successful development must include extensive economic analysis to ensure that the results are aligned with the needs of the oil industry, particularly deep water development. This paper presents key information on composite materials that are considered candidates for use in the offshore industry. The paper reviews current applications of composites in related industries such as marine, surface transportation and infrastructure and identifies opportunities associated with deep water oil industry developments. The paper also identifies the main challenges facing the application of composites and discusses the steps that are currently being taken to address them.

PROPERTIES OF COMPOSITE MATERIALS

The properties of a composite material depend on the properties of the two main constituents: the fibers and matrix. A summary of characteristic fiber and matrix properties is presented below.

Fibers

A large number of fibers with different physical and chemical properties are commercially available. They can be obtained in several different physical forms including tow, ribbon, continuous woven mats and chopped strand mats. Fiber tow is the most common form used for high performance reinforcement. The fibers most likely to be used in the offshore industry are E and S glass, carbon and aramid (Kevlar®). Table 1 provides a quantitative comparison of these fibers and Table 2 summarizes some of the physical properties. Other fibers such as nylon, polyester and polyethylene are being used in pure fiber form (without matrix) for mooring ropes, but they are not expected to be competitive in composite form due to their significantly lower modulus.

Table 1. Qualitative Comparisons Between the Different Classes of Fibers.

Fiber	Advantages	Concerns
E-glass	Low cost	Environmental degradation
Carbon	High specific strength/stiffness Good fatigue and creep resistance	High cost Low damage tolerance
Aramid	High specific tensile strength/stiffness Good damage tolerance	Low compressive properties High moisture absorption Difficult to machine

Table 2. Properties Of the Most Common Fibers.

Fiber	Fiber Dia., micron	Tensile Strength ksi (MPa)	Tensile Modulus, msi (GPa)	Failure Strain, %	Spec. Gravity	Coeff. Thermal Expan., (10^{-6} in/in/°F)	Cost $/lb
E-Glass	10	500 (3450)	10.5 (72.4)	2.4	2.54	2.8	0.8
S- Glass	10	625 (4300)	12.6 (87)	2.9	2.49	3.1	4
High Strength Graphite (Pan)	8.5	520 (3585)	34 (234)	1.6	1.74	-0.04	13
High Modulus Graphite (Pitch)	10	460 (3200)	55 (380)	0.8	2.0		30
Kevlar® 29	12	520 (2900)	10 (70)	3.6	1.44	-1.1	10
Kevlar® 49	12	520 (2900)	19 (130)	2.5	1.44	-1.1	15
High Mol.Wt. Polyethylene	38	375 (2586)	28 (193)	1.7	0.97		15

RESIN

Resin selection requires consideration of properties (chemical resistance, toughness, abrasion resistance, stiffness, and strength), processing (lay-down rates, process temperature, and processability), and cost (materials and processing). The main two classifications of resin systems are thermoset and thermoplastic. Thermoset resins are more commonly used to make composites than thermoplastic material. Table 3 provides a list of commonly used thermoset resins along with a list of assets and limitations.

Thermoplastic resins are linear polymer arrays with amorphous, semi-crystalline, or mixed morphology. A wide variety of commercial thermoplastics are available. These include polyamide (nylon), polyamide-imide, polyimide (PI), polyarylate, polyarylsulfone (PAS), ployether sulfone (PES), polyphenylene sulfide (PPS), high density polyethylene (HDPE), polyethylene terephthalate (PET), polyetheretherketone (PEEK) and polyetherketoneketone(PEKK). Thermoplastic resins are attractive because they offer good mechanical properties, exhibit excellent toughness and damage tolerance, display process repeatability, and simplify repair. Since thermoplastics have limited cross-link density, they have lower chemical and creep resistance. Chemical resistance, however, can be improved by the development of crystalline morphology or by achieving active polymer linkages. Thermoplastic resins are usually more expensive than thermoset resins. Table 4 provides a brief comparison of thermoplastic resins being considered for offshore applications.

Table 3. Thermoset Resins.

Resin	Advantages	Concern
Epoxy	Broad experience Good damage tolerance Good chemical resistance Flexible formulation Low Cost	Smoke
Phenolic	Good chemical resistance High temperature resistance	Brittle Volatiles produced during Cure High void content in laminate.
Vinyl ester	Good chemical resistance High temperature resistance Good mechanical properties	Special ventilation equipment for processing and cure
Polyester	Easy to tailor for desired mechanical and chemical properties Low temperature cure	Limited pot life Special ventilation equipment for processing and cure
Bismaleimide	Epoxy-like processing High temperature resistance	High cure temperature Expensive
Polyimide	High temperature resistance	Difficult to process Special ventilation equipment for processing and cure Expensive

Table 4. Comparison Between Thermoplastic Resins.

Material	Advantages	Disadvantages
PET ($2.2/lb)	High toughness Low moisture absorption Low melt viscosity	Sensitive to oil and solvents above 140°F Brittle at high fiber volume Only filled products available
PA	Similar to PET Good oil /grease resistance	High mold shrinkage Hygroscopic (10%)
PES ($5.4/lb)	High creep resistance Low moisture absorb.	Marginal solvent resistance
PAS	Similar to PES	Marginal solvent resistance
PPS ($5.7/lb)	Good chemical resistance Low moisture absorb.	Low interfacial adhesion Low toughness
PEKK ($20/lb)	Good chemical resistance Good temp. resistance	High process temperature High cost
PI ($100/lb)	Excellent high temperature properties	Difficult to process Very expensive

MANUFACTURING

Composites can be manufactured using several different processes including filament winding, pultrusion, resin infusion molding, resin transfer molding, braiding, spraying and hand layup. The critical parameters for all processes are fiber wetting, fiber orientation, resin flow/consolidation and solidification. Table 5 compares the production rates of several different processes. For offshore applications, the processes that are most likely to be used are filament winding, pultrusion, and resin infusion or resin transfer molding.

Table 5. Composite Production Rates

Process	Production Rate, lb/hr
Filament Winding	5 - 500
Pultrusion	25 - 100
Resin Infusion Molding	5 - 50
Resin Transfer Molding	10 - 100
Braiding	2 - 10
Spraying	100 - 500
Hand layup	2 - 5

DESIGN

Unlike other commonly used offshore material such as steel that are homogeneous and isotropic continua, fiber reinforced composites are microscopically inhomogeneous and orthotropic. As a result, predictions of stresses, strains and deformations in composites are more complex than conventional materials. Fortunately, the advances that occurred in design and analysis of composites during the last few decades resulted in development of many software packages that are capable of conducting analysis of very complex composite geometries. The two common approaches to analysis of composites are the micromechanics approach and the macromechanics approach. The micromechanics approach is based on consideration of the elastic and thermal characteristics of individual lamina based on consideration of the interaction between the various constituents. The macromechanics approach, on the other hand, uses equations of orthotropic elasticity to calculate stresses, strains and deflection and assumes that composites have homogenous properties.

APPLICATIONS

Glass fibers were commercially introduced in 1938 and were used initially for insulation and acoustic isolation applications. One of the first structural applications for composites was in the automotive industry where fiberglass was introduced in the 1950's for sports car bodies. Fiberglass pipe and tanks have been used in the onshore oil industry for almost 45 years [Oswald, 1988]. Advanced composites were developed initially for military and aircraft applications where high stiffness and strength properties have a significant impact on performance. Interest in the use of composites to improve performance in offshore oil industry applications began in the early 1980's primarily driven by interest in eliminating corrosion and reducing weight on offshore platforms. For most applications, the high cost of composites characteristic of the aerospace industry is not cost-effective in the oil industry. Wide spread applications of advanced composites in the oil industry will occur only if the costs of products can be made affordable using low cost manufacturing processes and low cost fibers. Much of the cost of aerospace components is introduced by the pedigree record required to ensure high performance and reliability. The trade-off to reduce cost for oil applications is to increase the safety factors to account for material variability and accept lower material design allowables which translates into lower weight savings. This compromise, however, is normally acceptable since the weight comparison for the oil industry is relative to steel rather than aluminum, the material of choice for most aerospace applications. Weight savings of 50 percent or more are possible when composites replace steel components. Weight savings for aerospace applications based on replacing aluminum commonly range from 25 to 30 percent. Figure 1 illustrates that the cost of most oil industry applications will be somewhere between the cost of typical aerospace components and the cost of commodity products such as bathtubs.

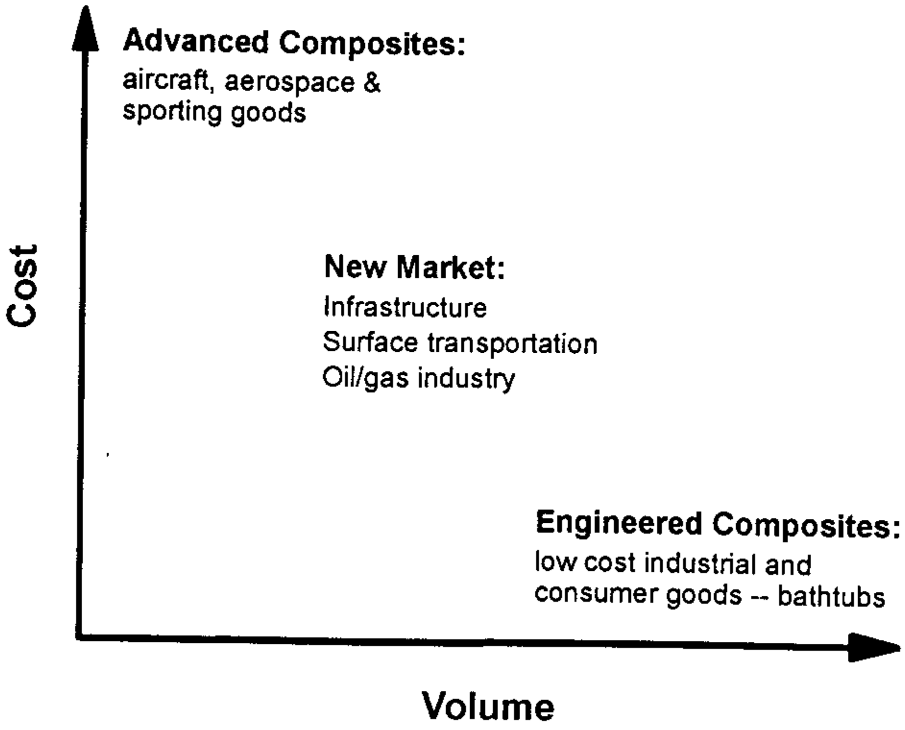

Figure 1. - Key Market Thrusts for Composites.

Marine Applications

Fiber reinforced composites have been used in many marine applications including canoes, speedboats, coastal and ocean going yachts, work boats, life boats, naval vessels, high performance crafts, and underwater vehicles (Dow and Bird, 1994). The reason composites are popular in marine applications include large pressure-hull weight reductions, increased diving depth, flexibility in sculpturing structural geometries, acoustic signature reduction, reduction in magnetic and electrical signatures, and reduced maintenance. Materials selection for speciality ships is governed by three parameters: yield strength, buckling strength and fatigue strength (Schnitler and Moe, 1997). Buckling strength is governed by geometry and the elastic modulus of the material.

The most significant application of composites in the marine industry has been the construction of mine countermeasure vessels (MCMV). The world first GRP minesweeper was launched by the British Navy in 1972. The reasons for using GRP were their low magnetic signature, lower cost, improved durability and better shock resistance than laminated wood. Currently, GRP minesweepers are being used by the navy of at least 15 nations around the world. The hull of many of these vessels is sandwich construction incorporating a rigid PVC foam core and E-glass/ isophthalic polyester GRP skins including woven and chopped strand reinforcement. GRP has also been used for building high performance commercial and military hovercraft and fast patrol craft. Filament wound S-glass or hybrids of glass/carbon composites are being seriously considered for high performance submersibles for naval and deep water exploration. Composites offer ease of construction of complex geometries including spherical shapes, conveniently allow variations in thickness and permit local changes in fiber orientation to provide a more optimum design.

Surface Transportation projects

There are currently two major efforts underway to develop and demonstrate cost competitive composite products for the surface transportation industry. DuPont-Hardcore in partnership with Burlington Northern Railroad and Trinity Industries are engaged in the design, manufacture and qualification of insulated composite railroad box cars. Composite were selected because they offer reduced weight, damage tolerance, excellent insulation and improved safety. The safety improvement is achieved by the lower load and inertia associated with opening and closing the doors and the simplicity of cleaning the insides of the box car. The second effort is a project led by Northrop Grumman to develop a composite bus for the Los Angeles county Metro Transportation Authority. The composite bus offers lighter weight, fewer parts and longer service life.

Civil Infrastructure Projects

Composite materials are being studied for numerous civil infrastructure applications. Their light weight and high durability make them attractive for both new structures and for retrofit and repair of existing structures, particularly, in earth quake sensitive regions. There are currently numerous projects underway to evaluate the applications of composites to repair and strengthen aging bridges, and for developing construction methods for new bridges. One of these program sponsored by the United States government Technology Reinvestment Program is being conducted by a consortium composed of DuPont advanced material systems and Hardcore Composites, as well as a number of corporate and academic partners. The project is to construct a new long span (400 ft) bridge in southern California. The fabrication of the bridge will be done using Hardcore's vacuum infusion molding technology, a vacuum assisted resin transfer molding process.

Current Offshore Applications

Fiber glass composites have been used by the offshore oil industry in a variety of applications including storage tanks, vessels, low pressure pipes, torque shafts, structural elements, seals, gratings, fire and blast walls, cable trays, etc. [Williams, 1987,1991]. The motivation to use composites offshore includes lower weight, reduced maintenance and lower installation and life cycle costs. Recent vintage TLP's starting with Mars have used GRP pipe for the firewater ring main and glass/phenolic resin for the gratings. Each successive new TLP designed for installation in deep water Gulf of Mexico has increased the utilization of composites for low pressure water transport and other applications.

Future Offshore Applications

So far, the main emphasis on potential applications of advanced composites for the offshore industry has focused on high pressure tubulars (above 1000 psi pressure) which are either discrete (20 to 80 feet long)for use as drilling and production risers, choke and kill lines, tubing, casing, and pipe or continuous (many thousands of feet long) for use as coiled tubing (Quigley, Nolet, Williams, and Sas-Jaworsky, 1997) and flowlines (Hansen, Asdal, and Williams, 1997). Continuous pipes are of relatively small diameters (< 5 inch) and are designed to be spooled. Spoolable composite pipes have been proposed for use as coiled tubing, velocity strings, capillary tubes, subsea pipeline clean out lines, subsea flow lines and subsea control lines. High pressure composite coiled tubing is attracting major attention because it provides enabling capabilities to work over, log and complete highly deviated wells as well as provide operational improvements for a wide variety of other oil field applications.

There also are other applications under consideration for composites which do not fall under the high pressure tubular classification such as TLP tendons. One proposed tendon concept uses a strand assembled of many continuous small diameter carbon fiber rods or a belt laminate constructed using carbon fiber rods. The tether, like coiled tubing, would be designed to be spoolable to improve the economics of installation.

Flexible pipe manufacturers are evaluating the use of composites to replace steel as the structural reinforcements for deep water applications. In the composite design, the hoop stress is carried by circumferentially wound flat strips of thermoplastic fiberglass composites while both axial and hoop loads are carried by helically wound composite wires. A composite reinforced flexible flowline has been installed by Coflexip in deep water Brazil [Salama, 1997]. The lighter weight flexible pipe allows smaller less expensive vessels to be used for installation.

FINANCIAL INCENTIVES TO USE COMPOSITES ON OFFSHORE PLATFORMS

The primary purpose of a floating offshore platform structure such as a Tension Leg Platform (TLP) is to support the topside payload which includes the weight of the accommodation module, helideck, production and process facilities and drilling equipment. In addition, the hull must support the deck structure and react the tension loads associated with the production and drilling risers as well as carry the pretension and weight of the mooring system. A reduction in topside weight will reduce the size, weight and cost of the supporting structure with the savings premium dependent on the type and size of the TLP and design parameters including environmental loads [Botros, Williams, and Coyle, 1997]. There is a significant economic incentive to reduce the topside weight through the use of composites. The premium for achieving this reduction is estimated to be on the order of 4 to 7 $/lb for TLP's [Salama, 1997]. Other benefits derived from composites such as system simplification, lower maintenance and better reliability will contribute additional financial incentive. Composites can also reduce the production downtime associated with hot-work modifications and repair which can provide significant financial payback.

BARRIERS TO THE APPLICATION OF ADVANCED COMPOSITES

The expanded application of composites in the oil industry continues to face technical, financial and emotional barriers that must be overcome to allow the full potential of composites to be realized in critical offshore applications. Solutions to these barriers involve developing a more comprehensive design and manufacturing data base to allow competent risk assessment, establishment of reliable cost structure for both components and systems, and educating offshore contractors and suppliers to provide them with sufficient confidence to design and use these new materials. The cost to make these advancements is not insignificant and for a primary component could total several million dollars. To gain acceptance, there is a need to share financial risk and experiences through alliances and consortia. It is also vitally important that the end user (including oil and service companies) precisely define the requirements to insure that products developed are practical and affordable. One way the United States government has helped provide a stimulus is through the Advanced Technology Program (ATP)administered by the National Institute of Standards and Technology. Table 6 provides a summary of ATP projects directed toward developing composite products for the oil and gas industry.

Table 6. Summary of ATP Composite Projects

Program	Goal	Industry Sponsors	Cost (MM$)
Production Riser	Design, manufacture and qualify 10 3/4", 6000 psi production riser	Lincoln Composites, Hercules, Amoco, Shell, Conoco, Stress Engineering, Brown and Root, Hydril, CEAC	7.168
Drilling Riser	Design, manufacture and qualify 18", 3000 psi drilling riser	Nothrop Grumman, Hercules, Deepstar, Vetco, Reading & Bates, OTRC	4.814
Drill Pipe	Design, manufacture and qualify drill pipe	Spyrotech, Phillips, Amoco, CEAC	2.77
Spoolable Pipe	Design, manufacture and qualify spoolable pipes for coiled tubing and flowline applications	Hydril, Amoco, Shell, Phillips, Mobil, Elf Atochem, Dow chemicals, CEAC	5.015
Joining/ Fitting for Pipes	Develop and qualify fittings for offshore GRP pipes.	Specialty Plastics, NASA	2.867
Intelligent Flexible Pipe	Develop and qualify flexible composite pipe with built in performance monitoring for use in oil and gas production	Wellstream	5,760

CONCLUDING REMARKS

Selected advanced applications of composites offer potential performance and economic advantages compared to steel. The introduction of primary structure products into service, however, will be slow in developing or even denied unless the manufacturer is provided support in defining the requirements and evaluating the performance of new products including making facilities available for field testing. The key to the successful development of composite components for the offshore oil industry is project implementation within a value chain partnership including owner, designer, material supplier, fabricator, regulator, and system integrator. This partnership is illustrated in Figure 2.

Regulatory agencies are receptive to new technology and there is not foreseen any regulatory requirements that will prohibit the use of composites for offshore applications. Composites must, similar to other materials, be "fit for purpose" which includes satisfying economic metrics and complying with safety and environmental requirements.

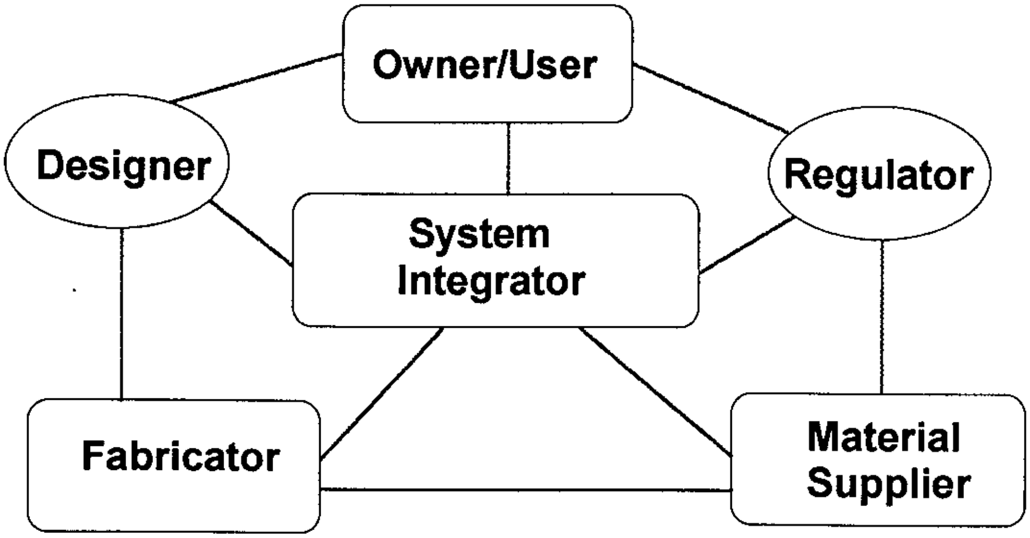

Figure 2. Partnership for Successful Commercialization.

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APPENDIX 1

Selected Glossary of Composite Terms

(Ref: High Performance Composites. Nov./Dec. 1996. Vol. 3, No. 6, Ray Publishing)

A-Stage - An early stage of polymerization of thermosetting resins in which the material is still soluble in certain liquids and is fusible.

Ablative - Material that absorbs heat through a decomposition process called pyrolysis at or near the exposed surface.

Accelerator - Chemical additive that hastens cure or chemical reaction.

Amorphous - Polymers with no crystalline component.

Anisotropic - Fiber directionality wherein different properties respond to stresses applied along axes in different directions.

Aramid - Aromatic polyamide fibers, commonly DuPont's Kevlar.

Aspect Ratio - The ratio of length to diameter of a fiber.

Axial Winding - Filament winding wherein the filaments are parallel to the axis.

B-Stage - Intermediate stage in the polymerization reaction of thermosets, following which material will soften with heat and is plastic and fusible. The resin of an uncured prepreg or premix is usually B-stage.

Balanced Laminate - all lamina except those at 0/90° are placed in plus/minus pairs (not necessarily adjacent) symmetrically about the layup centerline.

Basket weave - Woven reinforcement where two or more warp threads go over and under two or more filling threads in a repeat pattern. This weave is less stable than the plain weave but produces a flatter, stronger, more pliable fabric.

Bias fabric - A fabric in which warp and fill fibers are at an angle to the length.

Biaxial winding - Filament winding wherein helical bands are laid in sequence, side by side, with no fiber crossover.

Bismaleimide (BMI) - A type of polyimide that cures by an addition reaction to avoid formation of volatiles, and exhibits temperature capabilities between those of epoxy and polyimide.

Bleeder Cloth - A layer of woven or nonwoven material, not a part of the composite, that allows excess gas and resin to escape during cure.

Braiding - Weaving fibers into tubular shape.

C-Stage - Final step in the cure of a thermoset resin, resulting in irreversible hardening and insolubility.

Carbon Fiber - Reinforcing fiber that is produced by pyrolysis of an organic precursor fiber in an inert atmosphere at temperature above 1800 F. The material can also be graphitized by heat treating at 3000F.

Circumferencial Winding - Filament winding wherein the filaments are perpendicular to the axis.

Cohesion--tendency of a single substance to adhere to itself, force holding a single substance together.

Commingled Yarn--A hybrid yarn made with two types of materials intermingled in a single yard; for example, thermoplastic filaments intermingled with carbon filaments to form a single yarn.

Composite--A material that combines fiber and a binding matrix to maximize specific performance properties; neither element merges completely with the other. Advanced composites utilize only continuous, oriented fibers in polymer, metal, and ceramic matrices.

Consolidation--A processing step that compresses fiber and matrix to reduce voids and achieve a particular density.

Continuous Filament--An individual, small-diameter reinforcement that is flexible and indefinite in length.

Continuous Roving--Parallel Filaments coated with sizing, gathered together into single or multiple strands, and wound into a cylindrical package. It may be used to provide continuous reinforcement in woven roving, filament winding, pultrusion, prepregs, or high-strength molding compounds, or it may be used chopped.

Cowoven Fabric--A reinforcement fabric woven with two different types of fibers in individual yarns; for example, thermoplastic fibers woven side-by-side with carbon fibers.

Crazing--Region of ultrafine cracks that may develop a network on or under a resin surface.

Crimp--A fiber's waviness, which determines its capacity to cohere.

Critical Length--the minimum length of a fiber necessary for matrix shear loading to develop fiber ultimate strength y a matrix

Cross- Laminated--Material laminated so that some of the layers are oriented at various angles to the other layers with respect to the laminate grain. A cross-ply laminate usually has plies oriented only at 0/90.

Cure--To change the physical properties of a material irreversibly by chemical reaction via heat and catalysts, alone or in combination, with or without pressure.

Cure temperature--The temperature at which a material attains final cure.

Damage Tolerance--A measure of the ability of structures to retain load carrying capability after exposure to sudden loads (for example, ballistic impact).

Delaminate--The separation of ply layers due to adhesive failure. This also includes the separation of the layers of fabric to core structure. A delamination may be associated with bridging, drilling, and trimming.

Denier--A numbering system for yarn and filament in which yarn number is equal to weight in grams of 9000 meters of yarn.

Design Allowable--A limiting value for a material property that can be used to design a structural or mechanical system to a specified level of success with 96% statistical confidence.

Doubler--Extra layers of reinforcement for added stiffness or strength with fasteners or other abrupt-load transfers

Draft Angle--A mandrel's taper or angle for ease of part removal.

Drape--the ability of prepreg to conform to the shape of a contoured surface.

Dry Winding--A filament winding operation in which resin is not used.

E-glass--Stands for "electrical glass" and refers to borosilicate glass fibers most often used in conventional polymer matrix composites.

Fabric-Nonwoven--A material formed from fibers or yarns without interlacing

Fabric-Woven--A material constructed of interlaced yarns, fibers, or filaments.

Fabrication--The process of making a composite part or tool.

Fiber content--Amount of fiber in a composite expressed as a ratio to the matrix. the most desirable fiber content is a 60:40 ratio, or 60% fiber and 40% matrix resin.

Fiber Orientation--direction of fiber alignment in a nonwoven or mat laminate wherein most of the fibers are placed in the same direction to afford higher strength in that direction.

Fiber Placement--A continuous process for fabricating composite shapes with complex contours and/or cutouts by means of a device that lays preimpregnated fibers (in tow form) onto a nonuniform mandrel or tool. It differs from filament winding in several ways: there is no limit on fiber angles; compaction takes place online via heat, pressure, or both; and fibers can be added and dropped as necessary. The process produces more complex shapes and permits a faster putdown rate than filament winding.

Fiber Reinforced Plastics (FRP)--term used to designate mid-range,reinforced composites.

Filament Winding--A process for fabricating composites in which continuous reinforcing fibers, either preimpregnated with resin or drawn through a resin bath, are wound around a rotating, removable mandrel.

Filaments--Individual fibers of indefinite length used in tows, yarns, or roving.

Filler--Material added to the mixed resin to increase viscosity, improve appearance, and lower the density and cost.

Film Adhesive--An adhesive in the form of a thin, dry resin film with or without a carrier; commonly used for adhesion between laminate layers.

Finish--Material applied to fibers--after sizing is removed--to improve matrix-to-fiber coupling.

Gel Time--Period of time from initial mixing of liquid reactants to the point when gelation occurs as defined by a specific test method.

Glass Transition--Reversible change in an amorphous polymer between a viscous condition and a hard, relatively brittle one.

Glass Transition Temperature (Tg)--Approximate temperature at which increased molecular mobility results in significant changes in properties of a cured resin. The measured value of Tg can vary, depending on the test method.

Graphitization--The process of pyrolization at very high temperatures (up to 5400F) that converts carbon to its crystalline allotropic form.

Hardener--Substance used to promote or control curing action by taking part in it, as opposed to catalyst.

Heat-Distortion Temperature (HDT)--Temperature at which a test bar deflects a certain amount under specified temperature and stated load.

Helical--Ply laid onto a mandrel at an angle, often a 45 angle.

Honeycomb--Resin-impregnated material most commonly manufactured in a hexagonal cells that serves as a core in sandwich structure. May also be metallic or polymer in rigid, open-cell structure.

Hoop--Ply laid onto a mandrel at a 90 angle.

Hybrid Composite--A composite with two or more types of reinforcing fibers.

Integral Heating--A system in which heating elements are built into a tool, forming part of the tool and usually eliminating the need for an oven or autoclave as a heat source.

Interface--Surface between two materials: in glass fibers, for instance, the area at which the glass and sizing met; in a laminate, the area at which the reinforcement and laminating resin meet.

Interlaminar--Existing or occurring between two or more adjacent laminae.

Interlaminar shear--Shearing force that produces displacement between two laminae along the plane of their interface.

Isotropic--Fiber directionality with uniform properties in all directions, independent of the direction of applied load.

Kevlar--Strong, lightweight aramid fiber trademarked by DuPont, used as a reinforcement fiber.

Laminate Ply--One fabric/resin or fiber/resin layer that is bonded to adjacent layers in the curing process.

Layup--Placement of layers of reinforcement in a mold.

Liquid-Crystal Polymers (LCP)--High-performance melt-processible thermoplastic with improved tensile strength and high-temperature capability.

Mandrel - Elongated mold around which resin-impregnated fiber, tape, or filaments are wound to form structural shapes or tubes.

Mat - A fibrous reinforcing material composed of chopped filaments (for chopped-strand mat) or swirled filaments (for continuous-strand mat) with a binder applied to maintain form; available in blankets of various widths, weights, thicknesses, and lengths.

Matrix - Material in which reinforcing fiber of a composite is imbedded; polymer, metal, ceramic.

Metal-Matrix Composites (MMC) - continuous carbon, silicon carbide, or ceramic fibers embedded in a metallic matrix material.

Multifilament - A yarn consisting of many continuous filaments.

Nomex - Nylon paper treated material trademarked by DuPont that is made into honeycomb core.

Nonwoven Roving - A reinforcement composed of continuous rovings loosely gathered together.

Phenolic Resin - Thermosetting resin produced by condensation of an aromatic alcohol with an aldehyde, particularly phenol with formaldehyde.

Pitch - Residual petroleum product used in the manufacture of certain carbon fibers.

Ply - One of the layers that makes up a stack or laminate; also, the number of single yarns twisted together to form a plied yarn.

Polyacrylonitrile (PAN) - Base material in the manufacture of some carbon fibers.

Postcure - An additional elevated-temperature exposure often performed without tooling or pressure to improve mechanical properties.

Pot Life - Length of time in which a catalyzed thermosetting resin retains sufficiently low viscosity for processing.

Precure - Full or partial setting of a resin or adhesive before the clamping operation is complete or before pressure is applied.

Precursor - For carbon fibers, the rayon, PAN, or pitch fibers from which carbon fibers are made.

Preform - A fibrous reinforcement preshaped on a mandrel or mock-up to approximate contour and thickness desired in the finished part.

Prepreg - Resin-impregnated cloth, mat, or filaments in flat form that can be stored for later use. The resin is often partially cured to a tack-free state called B-staging. Additives such as catalysts, inhibitors, flame retardants, and others can be added to obtain specific end-use properties and improve processing, storage, and handling characteristics.

Pultrusion - A continuous process for manufacturing composites in rods, tubes, and structural shapes having constant cross sections. After the reinforcement is passed through the resin-impregnation bath, it is drawn through a shaping die to form the desired cross section; curing takes place before the laminate can depart from that cross section.

Quasi-isotropic - Approximating isotropy by orienting plies in several directions.

Reinforcement - Key element added to matrix to provide the required properties (primarily strength); ranges from short fibers through complex textile forms.

Release Agents - Used to prevent cured matrix material from bonding to tooling; usually sprayed or painted on mold.

Release Film - An impermeable film layer that does not bond to the composite during cure.

Resin - Polymer with indefinite and often high molecular weight and a softening or melting range that exhibits a tendency to flow when subjected to stress. As composite matrices, resins bind together reinforcement fibers.

Resin Rich - Localized area filled with excess resin as compared to consistent resin/fiber ratio.

Resin Starved - Localized areas lacking sufficient resin for fiber wetout.

Resin Transfer Molding (RTM) - A molding process in which catalyzed resin is pumped into a two-sided, matched mold in which a fibrous reinforcement has been placed. The mold and/or resin may or may not be heated. RTM offers the ability to consolidate structural parts. Its major drawback is the high cost of the initial, two-sided mold.

Resin Viscosity - Viscous property of a resin system or solid to liquid transition resistance to flow, which can be altered by temperature and pressure as necessary to achieve desired flow characteristics.

Roving - A collection of bundles of continuous filaments either as untwisted strands or as twisted yarn.

S-glass - Stands for "structural glass," and refers to magnesia/alumina/silicate glass reinforcement designed to provide very high tensile strength. Commonly used in advanced composites.

Sandwich Structure - Composite composed of lightweight core material (usually honeycomb or foam) to which two relatively thin, dense, high-strength, functional, or decorative skins are adhered.

Sealant - Applied to a joint in paste or liquid form that hardens in place to form a seal.

Sizing - Compound that binds together and stiffens warp yarn, providing resistance to abrasion during weaving; normally removed and replaced with finish before matrix application.

Solvent - A liquid used for dissolving and cleaning materials.

Structural Adhesive - An adhesive used for transferring loads between adherents.

Structural Bond - A bond joining load-bearing components of an assembly.

Tape - Thin unidirectional prepreg in widths up to 12 inches for carbon fiber.

Thermal Stress Cracking - Crazing and cracking of some thermoplastic resins from overexposure to elevated temperatures.

Thermoplastic - Composite matrix in advanced composites formed by heat and cooling. Can be reshaped more than once.

Thermoset - Composite matrix cured by heat and pressure or with a catalyst into an infusible and insoluble material. Once cured, a thermoset cannot be returned to the uncured state.

Thixotropic - Materials that are gel-like at rest, but fluid when agitated. Having high static shear strength and low dynamic shear strength at the same time. Losing viscosity under stress.

Tool - The mold - either one- or two-sided and either open or closed - in or upon which composite material is placed in order to make a part.

Tow - An untwisted bundle of continuous filaments, usually designated by a number followed by K, indicating multiplication by 1000 (for example, 12K tow has 12,000 filaments).

Unidirectional - Refers to fibers that are oriented in the same direction, such as unidirectional fabric, tape, or laminate; often called UD.

Voids - Pockets of entrapped gas that have been cured into a laminate.

Volatiles - Materials in a sizing or resin that can be vaporized at room or slightly elevated temperature.

Weave - Pattern by which a fabric is formed from interlacing yarns. In plain weave, warp and fill fibers alternate to make both fabric faces identical; in satin weave, pattern produces a satin appearance with the warp tow over several fill tows and under the next one (for example, eight-harness satin would have warp tow over seven fill tows and under the eighth).

Weft - Yarns running perpendicular to the warp in a woven fabric; also called "woof."

Wet Layup - Application of a resin to a dry reinforcement in the mold; a manual creation of a form of prepreg.

Wet Winding - Filament winding wherein fiber strands are impregnated with resin immediately before they contact the mandrel.

Wetting Agent - A surface-active agent that promotes wetting by decreasing the cohesion within a liquid.

Winding Pattern - Regularly recurring pattern of the filament path in a filament winding after a certain number of mandrel revolutions.

Wire Mesh - Fine wire screen used to dissipate the electrical charge from lightning.

Woven Roving - Heavy, coarse fabric produced by weaving continuous roving bundles.

Wrinkle - Imperfection in the surface of a laminate that looks like a crease in one of the outer layers; occurs in vacuum-bag molding when the bag is improperly placed.

X-Axis - The axis in the plane of the laminate used as 0° reference; the Y-axis is the axis in the plane of the laminate perpendicular to the X-axis; the Z-axis is the reference axis normal to the laminate plane in composite laminates.

Yarn - Continuously twisted fibers or strands suitable for weaving into fabrics.

Zero Bleed - Laminate fabrication procedure that does not allow loss of resin during cure.

Concrete for Marine Construction

by Ben C. Gerwick, Jr.[*]

Concrete has a very long history of service in the marine environment, extending from Roman use in port construction to the advanced high performance concretes of today. Recent research, rapidly transferred into practice by the demands posed by coastal and offshore developments, has revolutionized concrete's material properties, making it technically and economically the material of choice for many marine applications.

Let's look at a few of the outstanding structures which have been constructed of reinforced and prestressed concrete.

Oosterschelde Storm Surge Barrier, The Netherlands.
Statfjord A, B, C Oil Production Platforms, Norwegian North Sea.
Troll Offshore Oil Production Platform, in 305 m waterdepth.
CIDS Arctic Drilling Platform, Beaufort Sea, Alaska.
N'Kossa barge Floating Production Facility, Congo.
Wharves for Container and Petroleum Vessels, Ports of Los Angeles, and Oakland, California.

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[*] **Chairman, Ben C. Gerwick, Inc., Consulting Engineers, San Francisco, California.**

Hay Point Terminal, Queensland, Australia

Shuwaikh Wharves, Kuwait

The key properties of modern high performance concrete, properly reinforced and prestressed, are:

- High compressive and tensile strength
- Durability in the marine environment
- Ductility under earthquake and accidental impact
- Fatigue endurance under cyclic loads
- Abrasion resistance
- Moldability - that is, easily formed into complex shapes
- Shell action under out-of-plane loads plus good membrane shear strength under in-plane loads. These are of especial benefit in deep water.

- High punching shear strength

- Stable properties at low temperatures, down to -165°C, (LNG) and fire resistant at elevated temperatures.

- Creep, that is, plastic deformation under high stress, when limited by proper concrete design, can actually be of benefit in marine structural applications, because it redistributes and relieves local stress concentrations.

- Economy - lowest cost to strength ratio for most marine applications.

What are the disadvantages of concrete, the barriers to more widespread use?

- High weight to strength ratio. This can be partially offset by the use of light weight and modified density concretes.

- Cracking, with its implications for lowered fatigue resistance, leakage of oil, and corrosion of reinforcement. These problems are controlled in modern advanced structures by proper design and construction.

It is belatedly becoming apparent that the standards developed about 1990 for offshore, that is ocean structures went to unnecessary and counter-productive extremes in their over-concern about cracking. The resultant increase in required reinforcing steel created severe problems in constructing, as well as significant additional cost. More thorough analysis has shown that more efficient solutions to the potential problems of cracking can be achieved.

Corrosion of reinforcement below sea water is essentially a non-problem due to the low oxygen content, and can be completely eliminated at low cost by the use of sacrificial anodes.

For the splash zone, adequate concrete cover, plus coatings or the use of cathodic protection can give a durability up to 100 years.

Leakage of oil through concrete can be prevented by prestressing, by well-distributed reinforcement and by the use of flexible polyurethane coatings.

To resist fatigue under high cycle fully-reversing loads, such as waves, prestressing can be effectively used. Prestressing, by keeping the concrete always in the uncracked range, effectively resists degradation due to cyclic loading.

The effectiveness of these measures is substantiated by the successful performance of concrete structures in the marine environment for over 50 years.

This conference is heavily oriented towards the use of advanced steel construction. Thus, it seems an appropriate forum to present what I think is an optimum material for ocean structures, such as offshore platforms, both fixed and floating - that is to combine steel and concrete in composite action. This concept is proving itself in bridge construction in Europe and Asia, and has even greater potential benefit to marine applications. By joining the two materials, we combine the benefits of the impermeable membrane of steel plate with the shell action and structural capacity of concrete. The plate action of the steel, if properly connected to the concrete, reinforces it in the two in-plane directions while the connectors ensure composite action and provide out-of-plane reinforcement. The concrete prevents buckling of the steel plate under compression. Corrosion of the steel plate is countered by coating or cathodic protection or sacrificial thickness.

Composite design enables the reduction of reinforcing steel by 30 to 40%, and can serve as a partial or full support and form for the concrete.

Studies of typical sections under high out-of-plane and in-plane loads show that the net cost of comparable structural sections in steel, concrete and composite steel-concrete are often lowest for the composite design.

This composite construction merges two construction disciplines and hence, requires an open attitude on the part of designers and constructors, since the fabrication of the two materials has to be integrated.

There are secondary benefits that may be of major economic performance, such using the steel shell as a floating shell upon which to place the concrete, and hence, eliminating the need for a graving dock or construction basin.

This concept is not new. The composite steel concrete concept has been applied for 40 years to underwater tunnels (tubes) where it has been developed to a high degree of reliability and efficiency. It is strange that it has not been more widely utilized in the offshore field. The answer appears to be in the artificial separation of engineering disciplines - those of us who are offshore designers need to be more aware of developments in the inland waterways while inland marine designers have to be more conversant with offshore developments. The Corps of Engineers is now recognizing this latter in their concept development for their new lock and dam structures, including the New Orleans Ship Canal Lock, for which they are developing a float-in concept.

In present day tube design, the external shell is of steel, joined by welded studs to reinforced concrete. Durability is provided by cathodic protection: the design lifetime of these tubes is usually 100 years or more. Among the many advantages, the steel shell's ductility and water tightness under accidental loads has proven invaluable.

This concept of composite steel-concrete construction can be especially useful for application to floating structures, such as semi-submersibles and TLP's, also to subsea oil storage and to LNG carriers, joining the best characteristics of both materials in synergistic interaction.

Working Group Reports

Mamdouh M. Salama (Conoco, Inc.)
Richard B. D'Souza (Aker Omega)
Advanced Materials for Mooring Systems

F. Joseph Fisher (Shell E&P Technology Company)
King Him Lo (Shell Oil Products Company)
Su-Su Wang (The University of Houston)
Material Requirement for Risers

Havard Gulbrandsen
Rolf Kvamsdal
Christian Winthermark
John Reiersen (Kvaerner Oil and Gas, Norway)
Materials Requirements for Floaters

Jeff Price (Chevron Research and Technology Company)
Materials Requirements for Fixed Structures

Martin Eskijian (California State Lands Commission)
Ronald Heffron (Han-Padron Associates)
Thomas Spencer (Blaylock Engineering Group)
Michael Garlich (Collins Engineers, Inc.)
Don Brunner (U.S. Navy, NFESC)
Materials Requirements for Harbors

S. Ibarra (Amoco Worldwide Engineering and Construction)
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Material Requirements for Offshore Processing Equipment

Olaf Anderson (Statoil)
J. Kirk Brownlee (Mobil Oil Company)
Bruce D. Craig (Metallurgical Consultants, Inc.)
Materials Requirements for Offshore Pipelines/Floatlines

Brian Blanchette (Ingalls Shipbuilding - Litton Industries)
Garland Borowski (Ingalls Shipbuilding - Litton Industries)
J. Walter Whitehead (Ingalls Shipbuilding - Litton Industries)
Material Requirements for Secondary Ship Structures

Jeffrey Beach (Naval Surface Warfare Center)
Brian Blanchette (Ingalls Shipbuilding - Litton Industries)
Garland Borowski (Ingalls Shipbuilding - Litton Industries)
Stephen Sharpe (Ship Structures Committee)
Material Requirements for Ship Hulls

Lt. Kathy Moore (United States Coast Guard)
Challenges in Using Advanced Materials in Marine Structures

Working Paper # 1

ADVANCED MATERIALS FOR MOORING SYSTEMS

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SUMMARY

Conventional mooring systems become increasingly inefficient and costly as oil and gas exploration and production move toward greater water depths. As water depth increases, station keeping efficiency, mooring line weight, fabrication and installation costs, system reliability, and condition monitoring represent major challenges that demand development and application of new technologies. This paper presents a discussion on the important considerations in the selection of a suitable mooring system, and a review of the important material parameters for the different mooring lines. The paper identifies gaps and opportunities driven by the need for developing cost effective deepwater mooring systems. Key technology issues and challenges related to materials performance, conditions monitoring and certification are emphasized for novel mooring system concepts such as synthetic ropes and composite strands.

INTRODUCTION

As the oil industry continues its effort to meet the challenge of expanding oil and gas exploration and development in deeper waters, increasing attention is being focused on floating platform concepts. These concepts include Floating Production Storage and Offloading systems (FPSO's), Floating Production Systems (FPS's), Spars and Tension Leg Platforms (TLPs). The mooring system of these concepts is a critical aspect of their design, performance and reliability. Fundamental to the design of a mooring system is its capability to constrain, with acceptable reliability, the vessel offset to within the integrity of the risers.

The design of mooring systems is generally governed by several objectives that include functioning predictably and reliably in the hostile corrosive environment of the sea for at least their design lives, resisting the severe fatigue loading conditions, provision for corrosion protection, inspection, and replacement, and redundancy such that the failure of one line in an extreme storm will not be lead to catastrophic system failure. In addition, the mooring lines size and weight must be minimized and the their components fabricated from available materials at reasonable cost.

The mooring lines must also meet specific strength and stiffness requirements. In increasing water depths, the challenge for a designer is to minimize several things, including the reduction of stiffness and restoring efficiency, the increase of the relative mass of the mooring lines to the platform mass, and the complication of mooring system installation. Permanent mooring lines to date have employed some combination of chain and wire to compensate for the increase of the in-water weight in deepwater. Major efforts are currently underway to develop innovative light weight solutions to improve platform performance and reduce cost without compromising safety and reliability.

Depending on the type of mooring system, its primary function will be to either restrain vessel movement in the horizontal plane, or to restrain movement in both horizontal and vertical planes. Figure 1 shows the three primary classification as catenary, taut, and tension mooring systems.

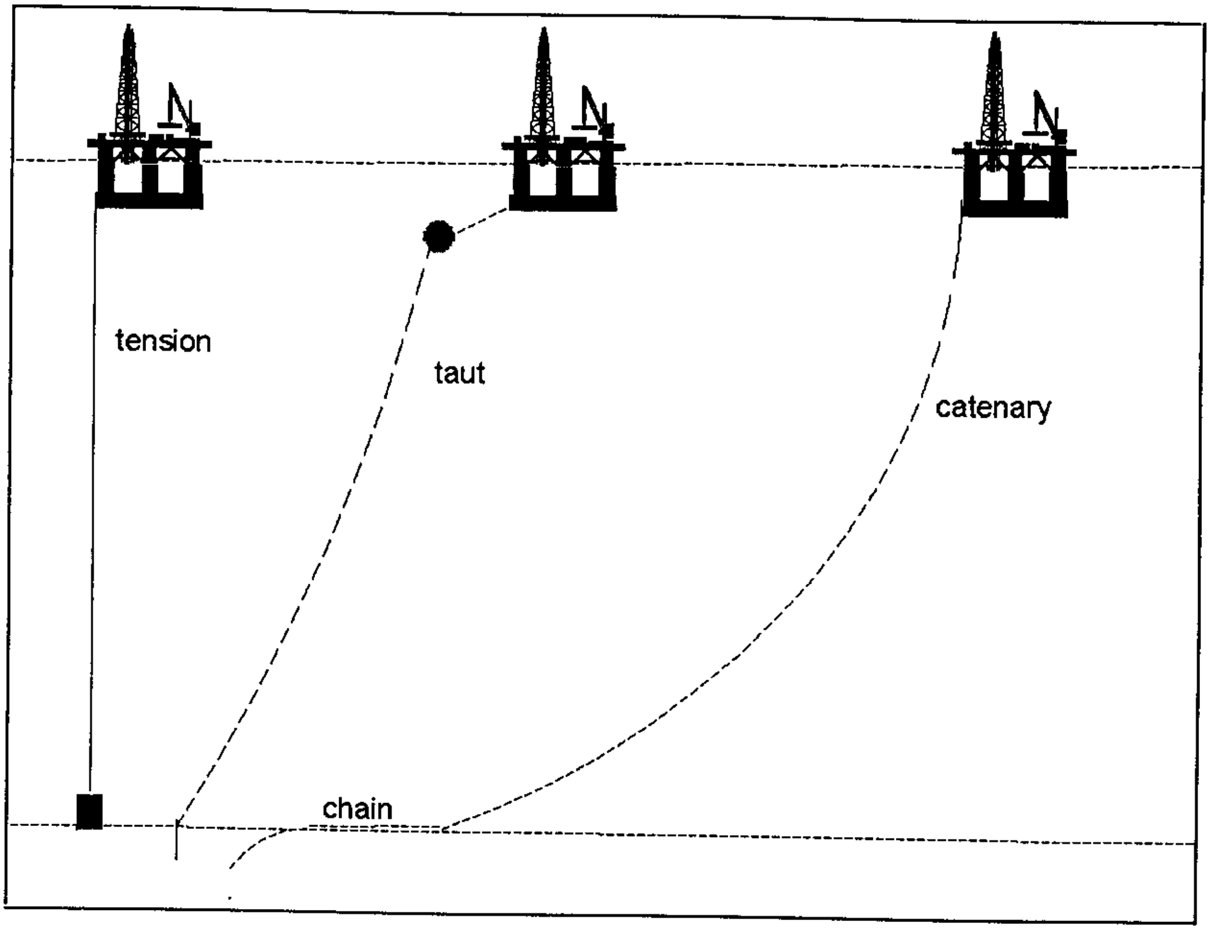


Figure 1. Types of Mooring System

The catenary system is composed of a number of free-hanging mooring lines and is used to moor floating vessels such as semi-submersibles and tankers. A typical mooring line is composed of single lengths of chain, rope, or a combination of both chain and rope. The taut leg mooring system is also used for mooring floating vessels and is characterized with short scope mooring ropes and vertically loaded anchors. The tension mooring system is made of either tubulars or parallel strand ropes and is used to restrain the motion of TLPs. While the catenary and the taut mooring systems are used for station keeping only, the tension mooring system is used for both station keeping and stability. A distinction between the catenary and the taut mooring systems is that the catenary system provides restoring force through mooring line weight while the taut mooring system utilizes the axial elasticity of the mooring line. Typically, the catenary system does not impose any vertical force at the mudline anchor while the taut system imposes a vertical force on the mud line anchor.

Mooring systems can also be classified by their main components which include chains, steel ropes, synthetic ropes, tubulars and composite strands. Chain and steel ropes are commonly used for a catenary mooring system, but could also include mooring line segments consisting of fibre ropes for deep water applications. The main line segment of a taut mooring systems will typically consist of a synthetic fibre rope, with either steel wire rope or chain at the upper and lower ends. Tubulars and composite strands are used for tension mooring systems. This paper reviews design requirement for the different mooring systems and discusses the important considerations in the selection of a suitable mooring system. It presents important material parameters for chains, steel ropes, synthetic ropes, tubulars and composite strands. Gaps and opportunities driven by the need for developing cost effective deepwater mooring systems are identified. Key technology issues and challenges related to materials performance, conditions monitoring and certification are emphasized for mooring systems comprised from synthetic ropes and composite strands.

DESIGN REQUIREMENTS

Catenary/Taut Mooring System

Mooring systems develop horizontal restoring forces at the attachment point to structure in response to lateral platform displacement. The primary function of a mooring system is to restrict the lateral excursion of a floating structure, subject to catenary or taut constraints of maximum tension loads and anchor uplift.

API RP2SK provides guidelines for the design of vertically compliant, permanently moored floating production systems. Key design criteria are summarized in Table 1. Classification societies (DnV, ABS, Lloyds) and bodies (USCG, NMD, DOE) also provide guidance or minimum requirements that may differ from these guidelines.

In a catenary system, mean offset is controlled by line weight and pretension. Lines composed of materials with lighter weights and larger pretensions produce smaller offsets. Steel catenary systems in deepwater require buoys to reduce pretension and vertical load on the platform and improve restoring efficiency. Catenary systems accommodate wave induced fairlead motions by adjusting catenary shape. The movement creates drag and inertia forces that act normal to the catenary axis, generating additional tensile loads in the line.

TABLE 1. API RP2SK DESIGN GUIDELINES

Design Environment	100 yr.return period storm
Safety Factor Most Loaded Line, Intact Mooring	2 quasi-static; 1.67 dynamics
Safety Factor Most Loaded Line, One Line Damage	1.43 quasi-static; 1.25 dynamics
Safety Factor Anchor holding; Intact Mooring	1.8 quasi-static; 1.5 dynamic
Safety Factor Anchor holding; One Line Damage	1.2 quasi-static; 1.0 dynamic
Max. Line Angle on Bottom Drag Anchor, Intact	5 degrees
Max. Line Angle on Bottom Drag Anchor, Damage	10 degrees
Max. Offsets	8-12% water depth

In a taut system, the entire line is always suspended and the mooring line runs mostly straight from the vessel to the anchor point. The line resists lateral platform offsets in response to applied environmental loads by the incremental tensile loads generated in the line primarily due to elastic stretch. The greater the elastic stiffness of the line, the smaller the offset. The two key parameters available to the designer to control these tensions are material elastic modulus and line scope. Lines with low elastic modulus i.e. (polyester rope) and large line scope will have higher offsets but lower tensions. Buoys or clump weights can be introduced into steel taut moorings to improve system efficiency. Light weight synthetics generally do not require buoys or clumps.

In deepwater, dynamic positioning may be considered as an alternative to moorings, subject to satisfaction regarding the integrity of performance. For lesser depths a thruster assist may well be utilized to control peak loads and to facilitate alignment of a vessel orientation to the incident environment. For benign environments, active management of a spread mooring system for a monohull, combined with ballast control and sparing capability to quickly replace a broken line makes it potentially possible to utilize steel risers and surface wellheads.

Tension Mooring System

The primary advantage of a TLP over a semisubmersible is the TLP's limits on the vertical motions to permit the use of rigid risers and installation of the wellheads on the platform. The function of a TLP mooring system is to restrain both the lateral and vertical motions of a TLP hull. While the lateral stiffness of a mooring system represents its station keeping performance, axial stiffness is also critical for TLP mooring lines to ensure that the heave, roll and pitch natural periods are maintained below about 4 seconds to minimize TLP ringing. This limit of the natural period may be questioned, especially in relatively benign environments. The need for the high axial stiffness makes the use of steel tubulars and high stiffness composite strands are the most viable options. As water depth increases, the external hydrostatic pressure on the TLP tendons increase which necessitates the need to reduce the diameter to thickness ratio. The increase of tendon weight results in a reduction in its restoring force due to its sag as the hull moves laterally.

Although the riser system of a TLP contributes to both the loading and resistance of the mooring system, to date this capability has not been used in tendon design. System design may, under certain circumstances, allow the riser to effectively perform the mooring function.

CHAINS

Chains are still one of the most widely used mooring lines and are routinely used in conjunction with rope systems for the high abrasion zones at the fairleads and touchdown on the seabed. Chains are quite large and heavy in comparison to other mooring lines of similar break strength. In cases where it is necessary to minimize the weight in order to achieve a proper buoyancy, as is the case for deepwater applications, the high weight of the chain system becomes a distinct disadvantage. Therefore, for deepwater a chain/wire rope combination is used. Chains are still used because they posses several desirable characteristics such as tolerance to corrosion and external abrasion, ease of storage, transportation, handling and attachment, and ease of repair by using a special connecting link. When chains are used in short lengths, they are quite inelastic and can be used to maintain the desired position of the vessel. The large weight of chains provides an increased holding power of the anchor system if part of the chain is allowed to lie on the ocean bottom.

Chains can be obtained in several grades depending on their break strength. Oil Rig Quality (ORQ) chains are the most often used and in general are used as a reference for other grades. As an example a ORQ + 20% means that the break of strength of the chain is 20% higher than the ORQ grade. The 4 (K4) grade chains have the highest strength and their break strength is about 130% of the equivalent ORQ chain.

Although the operating loads on chains are less than one third, and typically one fourth to one fifth, of the minimum breaking strength, failures have occurred at a relatively high rate. In a fleet of 45 semis that det norske Veritas classifies, a total of 99 chain cable failure occurred between 1982 and May 1989 (Bush, et al., 1992). Of the 99 failures, 59% involved ORQ grade chain and 41% K4 grade chain. The causes of failures were attributed to design, materials selection, manufacture, service condition and maintenance, with the largest number of failures attributed to materials imperfections. Also, a review of 30 station-keeping incidents from the Health and Safety Executive (HSE) record for the period of November 1981 to August 1990 showed that 27 incidents were due mooring line breakage (Bush, et al., 1992). Of theses incidents, 26 were due to failure of the chain cable. Using these data and others, it was estimated that the average annual probability of chain failure is 0.4, or once on average every 2 1/2 year rig years. This level of probability will, undoubtfully, be lower for chains that are manufactured according to an acceptable standards such as DNV classification note CN 2.6 that was issued on July 1985 (Petterson, 1992).

Unstable brittle failure and fatigue are the two critical failure mechanisms (Salama, 1988). Fatigue strength of chains is an important parameter for the design of permanently moored floating production systems. Experience with the mooring of ships has shown that the failure frequency of the chain connecting links is, in general, significantly higher than the failure frequency of common links. Failures due to abrasion and wear have also been reported but to a lesser extent. Brittle fracture occurs in chain links when defects exist and the material has low notch toughness. Defects are, generally, either welding or casting flaws. Low toughness can be attributed to either improper chemistry or heat treatment. Most specifications for chains do not specify fracture toughness requirement, however, they may specify heat treatment requirement such as annealing. Verifying that such a heat treatment is properly performed requires either microstructure examination to ensure fine grain size or some mechanical test to assess the toughness of the materials. For critical applications charpy V-notch (CVN) or crack tip opening displacement (CTOD) criteria are specified.

A recent JIP program (Stiff, et al., 1996) on fatigue of chains, included seven fatigue tests in air and nine in seawater. These tests produced 49 fatigue failures. The program included tests on 3" chains having 9 links and 4" chains having 7 links. When a link failed, it was replaced by a kenter link and the test continued. The vast majority of failures occurred as would be expected at the area of the highest stress concentration, at the half crown position, with the fatigue cracks initiating at the intrados and propagating outward. Links that had not been failed were inspected using magnetic particle and large number of fatigue cracks were found on all inspected links suggesting that a large portion of fatigue life is spent on crack propagation. These results is contradicting the traditional concept that chains will fail in fatigue without excessive cracking, suggesting that the majority of fatigue life is spent on crack initiation.

The results fatigue tests in seawater on 4" K4 chains showed lower fatigue lives than the lives for the lower breaking strength ORQ chain (Stiff, et al., 1996). The data also showed that whereas K4 fatigue tests in air demonstrated the conservatism in the API fatigue curve (API RP 2FPI, 1993), the fatigue tests in seawater suggested that the API curve may be un-conservative. This suggests that the use of high strength steel chains provides no fatigue advantage which is contradictory to the API RP 2FPI recommendation that gives the following relationship between the number of cycles to failure and the breaking strength:

$$\textit{Number of Cycles} = 370\left(\frac{\textit{Breaking Strength}}{\textit{Cyclic Tension Range}}\right)^{3.36}$$

However, the recent API RP 2SK resolved this issue by recommending that for higher strength chains, the breaking strength of ORQ chains should be used as an upper limit. Although this change in the API recommended practice eliminates the fatigue benefits of using the higher strength the K4 grade chains, these chains may still be used if the ORQ chain is unable to meet the code required tension safety factors. In this regard, one must be careful because higher grade steels may be subject to more uncertainties due to sensitivities to heat treatment. A study by Luo and Ahilan (1992) showed that the K4 chain may not be superior to the ORQ chain (to the extent of its greater mean strength) if the uniformity of its link strength is not maintained to the same degree as for the ORQ chain. The reliability improvement due to the increase in K4 strength will be cancelled if the coefficient of variation of its link strength reaches 10% (double the ORQ chain link).

The results of the JIP project (Stiff, et al, 1996) also showed that the mean stress has a pronounced influence on the fatigue life in air but has a minimal influence on the fatigue life in seawater. This may attributed to the observation that fatigue lives in air are dominated by crack initiation which is greatly influenced by material's strength and mean stress while seawater fatigue lives are dominated by crack growth which is not influenced by these factors.

Most chains are currently provided with studs. But in recent years, studless chains became available (Canada, et al., 1996) and since their introduction in 1989, they have been used in nine offshore projects. In comparison to studlik chains, studless chains offers about 10 to 20% lower elastic stiffness, about 10% less weight, more versatility regarding connections with shackles and accessories, better performance in windlasses and fairleads, better inspection conditions, and a similar fatigue strength. The similarity in fatigue strength should be expected because data by Stiff, et al. (1996) showed that the presence of the stud, whether welded or pressed, had no impact on the fatigue life of any chain sample.

STEEL ROPES

Although there is bout a half million rope types with different combinations of materials and construction, only few are appropriate for deepwater mooring application. Wire ropes are generally made from high strength steel and for some seawater application, corrosion resistance alloys such as stainless steel and copper alloys have been used. For steel wires, corrosion resistance can be provided by either galvanizing (using zinc coating) or aluminizing (using aluminum coating). Other approaches that are used to improve corrosion resistance of steel ropes include blocking, sheathing, and cathodic protection (Lucht and Donecker, 1977).

Ropes are constructed from either individual wires or strand. The strand is fabricated by weaving individual wires into a small cord; these cords (or strands) are then wound into ropes. Spiral strand construction offers a significant size and weight advantage when compared to chain but it provides very little stretch and exhibits poor performance in bending. Spiral strands are not recommended for any application where large number of bending cycles over sheaves or saddles are required.

A wire rope construction refers to stranded ropes and is described by the number of strands and the number of wires in each strand, i.e., 6 x 37 rope has 6 strands and each strand contains 37 wires. Wires do not have to be of the same size, e.g., for cases where wear is important the strand will have larger outer wires to provide a larger surface wear. For cases where flexibility is important the strands are made using small size wires. The nomenclature for stranded ropes also describes the center core, the direction of winding, and whether the strands have small non-load-bearing filler wires to minimize movement between adjacent load-bearing wires. Wire ropes can be fabricated with the individual wires in the strand are either laid in the opposite direction to the lay of the strands (regular lay) or laid in the same direction as the lay of the strands (lang lay). Lang lay ropes have more resistance to abrasion and bending fatigue than regular lay ropes, but they have less resistance to deformation and kink. Also, lang lay ropes rotate easily when one end of the line is not fixed, because the rope tends to develop a very high torque value resulting in spinning and untwisting. These properties are not compatible with mooring lines and, therefore, lang lay ropes are not used (Salama, 1988).

Ropes are designed to meet a broad spectrum of service requirements that include water depth, sea states, tensile strength, stiffness, and useful service life. Failure of ropes can be generally characterized as tensile overloading, fatigue, or a combination of both. Factors such as wear, corrosion, loss of lubrication, and deformation can result in premature failures by dramatically reducing both tensile and fatigue strengths. Therefore, it is prudent to establish the appropriate tensile strength and to assess the effect of various operating conditions on fatigue performance of wire ropes. The strength of a rope is not only affected by its material and construction, but it is also greatly influenced by the type and workmanship of its termination. There are various methods for terminating ropes, however, the most common are eye spliced, and zinc potted terminations. Zinc potted terminations are the most common.

Mechanical damage, corrosion, and wear can occur in ropes due to careless handling of the rope and the use of improper handling and installation equipment. Damage of the rope protective sheath, for example, can lead to accelerated corrosion, resulting in deterioration of strength. Degradation of the rope strength due to abrasion and wear occurs when the rope is dragged over rough surfaces and runs over improper or damaged pulleys, rollers, and fairleads.

Kinking can occur in wire ropes due to unwinding. Due the geometric relationship of the load carrying wires and of the strands to the axis of the applied load, the rope will, in most cases, unwind in a direction opposite to its lay when a load is applied while one end of the rope is free to rotate. If the applied load is suddenly reduced the rope will wind back, to its unloaded state, too fast causing the rope to twist up on itself. This results in the formation of tight loops, which will be pulled, forming kinks when the load is reapplied. These kinks can reduce the rope strength by as much as 90% (Lucht and Donecker, 1977). This problem can be avoided by protecting the rope during deployment from the application of load until both ends are fixed or by using torque balanced constructions. Unfortunately, torque balanced ropes are not available in all sizes.

Fatigue strength of ropes represents a very important parameter in the design of mooring systems for both deepwater and permanent installations. Unfortunately, only limited amount of fatigue testing on ropes has been conducted under marine conditions. Also, most of the available data were developed using small ropes of less than 50 mm (~2 inch) diameter. Most of the data are obtained by bending tests, and few are obtained under direct tension. Since a rope with a good bending fatigue strength does not necessarily has a good tensile fatigue strength and vice versa, it is important to determine whether the long-term fatigue life of a mooring line is limited by the tensile or the bending fatigue characteristics. In general, the design of mooring lines that are wrapped around a saddle or a sheave will be governed by tensile fatigue if the wrap angle does not vary under normal operating conditions. If, however, the arc of contact between the mooring line and the saddle or sheave continues to change with more than one half the lay length, the service life of the rope will be governed by its bending fatigue strength (Gibson, 1983).

In the past, available fatigue data were adequate because most applications, e.g, masts and bridges, required ropes with diameters between 30 mm (11/4 inch) to 70 mm (23/4 inch). However, current offshore mooring applications require larger diameter ropes, typically between 70 and 170 mm (23/4 to 63/4 inch). The validity of extrapolating small rope fatigue data for use in the design of the large diameter ropes is questionable, because the internal compressive stresses and the relative motions that are developed within the rope increase rapidly with increasing diameter. Therefore, for cases where the failure mechanism is influenced by either the internal stresses or the relative motions, such as in bending fatigue, a change of the scale can affect the fatigue performance. API RP 2FP1 (1993) recommends the use of the following equation to calculate fatigue lives for mooring ropes:

$$Number\ of\ Cycles = 731\left(\frac{Breaking\ Strength}{Cyclic\ Tension\ Range}\right)^{4.09}$$

This equation was developed based on tests conducted in air for six strand ropes. For galvanized ropes with high quality compound and proper jaketing the above equation can be used for seawater applications. API RP 2FP1 recommends that the calculated component fatigue life should be three times the service life. For rope segments that are not replaceable, it is recommended that the ratio between calculated life and design life is to be at least 10 (Lohne, 1996).

SYNTHETIC ROPES

Mooring system weight is an important design parameter for deepwater platforms. In order to reduce the weight, the use of synthetic fibers for rope construction is currently expanding. Synthetic fibers include nylon, polyester, polypropylene, high molecular weight polyethylene (HMPE), and aramid. Table 2 illustrates the economic advantage of using synthetic ropes by comparing the installed cost of steel and synthetic mooring systems for two developments scenarios in 5000 ft of water in the Gulf of Mexico. Table 3 gives a weight comparison between several mooring lines with similar breaking strength (Gibson, 1983). The selection of which fiber is the best for a specific mooring rope depends on many factors such as strength, stiffness, creep, fatigue and abrasion. Table 4 presents basic properties for some of these fibers.

Table 2. A Comparison Between Installed Cost for Mooring Systems in 6000 ft (GOM) (mooring cost = 7-10% of capital cost , ex. drilling)

	Semisubmersible	SPAR
Catenary steel	1.0	1.0
Taut steel	0.9	0.8
Taut synthetic	0.6	0.65

TABLE 3. COMPARISON OF SIZES AND WEIGHTS OF SEVERAL MOORING LINES WITH SIMILAR BREAKING STRENGTH

Description	Nom. Diam. inch	Strength lbs	Weight in air lb/ft	Weight in water lb/ft
Mooring Chain	1-7/8[a]	432,000	34.9	30.5
Galvanized Spiral Strand	1-7/8	432,000	7.42	6.48
Galvanized 6x37 IWRC Wire Rope	2-1/4	444,600	9.36	8.18
Stranded Kevlar® Rope	2-1/2	450,000	1.92	0.54
Nylon Double Braid Rope	4	436,000	4.23	0.52
Polyester Double Braid Rope	4-1/4	451,000	5.92	1.63

(a) Bar Stock Size

TABLE 4. PROPERTIES OF DIFFERENT FIBERS

Property	Aramid	HMPE	Polyester	Nylon	Steel
Density, gm/cc	1.44	0.98	1.38	1.14	7.86
Tensile Strength, N/mm^2	2760	2700	1150	2620	2400
Initial Modulus, GPa	70	89	14	4.5	200
% Elongation	2.1	3.5	13	13	1.1
Internal abrasion	Poor	Good	Good	Poor	Good
Creep	Excellent	Poor	Good	Fair	Excellent
Fatigue	Excellent	Fair	Good	Fair	Fair
Est. Fiber Cost ($/lb)	10	15	1.5	1.5	1.0

Nylon was the original high strength synthetic fiber for rope applications. Nylon ropes have exceptionally high elongation characteristics that can be utilized to accommodate large amplitude motions. However, the great elasticity of nylon ropes can be a serious disadvantage because of the large stored energy which can be released explosively when a mooring line fails. Nylon has a good strength and good abrasion resistance when dry, but it absorbs water, which causes swelling resulting in a 10% to 20% loss in strength and adversely affecting its abrasion resistance (McKenna, 1983).

Polyester is as strong as nylon and does not loose its strength when wet. Special coatings can be applied to the basic polyester filaments to improve its wet abrasion resistance by a factor of eight over uncoated polyester and by a factor of 20 over wet nylon (McKenna, 1983). Polyester has about one half the elongation of nylon.

High molecular weight polyethylene (HMPE) ropes, such as Dyneema and Spectra ropes, have been used in the tugging and salvage of ships where strength and weight are important. The strength and elastic modulus of HDPE fibers are high, but one must be careful because these values are very sensitive to strain rate and temperature. These ropes are not seriously considered for mooring applications because of their high cost, poor creep resistance and sensitivity to temperature. Figure 2 presents a comparison between the creep rate of HMPE fiber and the rate for polyester and aramid fibers, illustrating the poor creep resistance of the HMPE fibers.

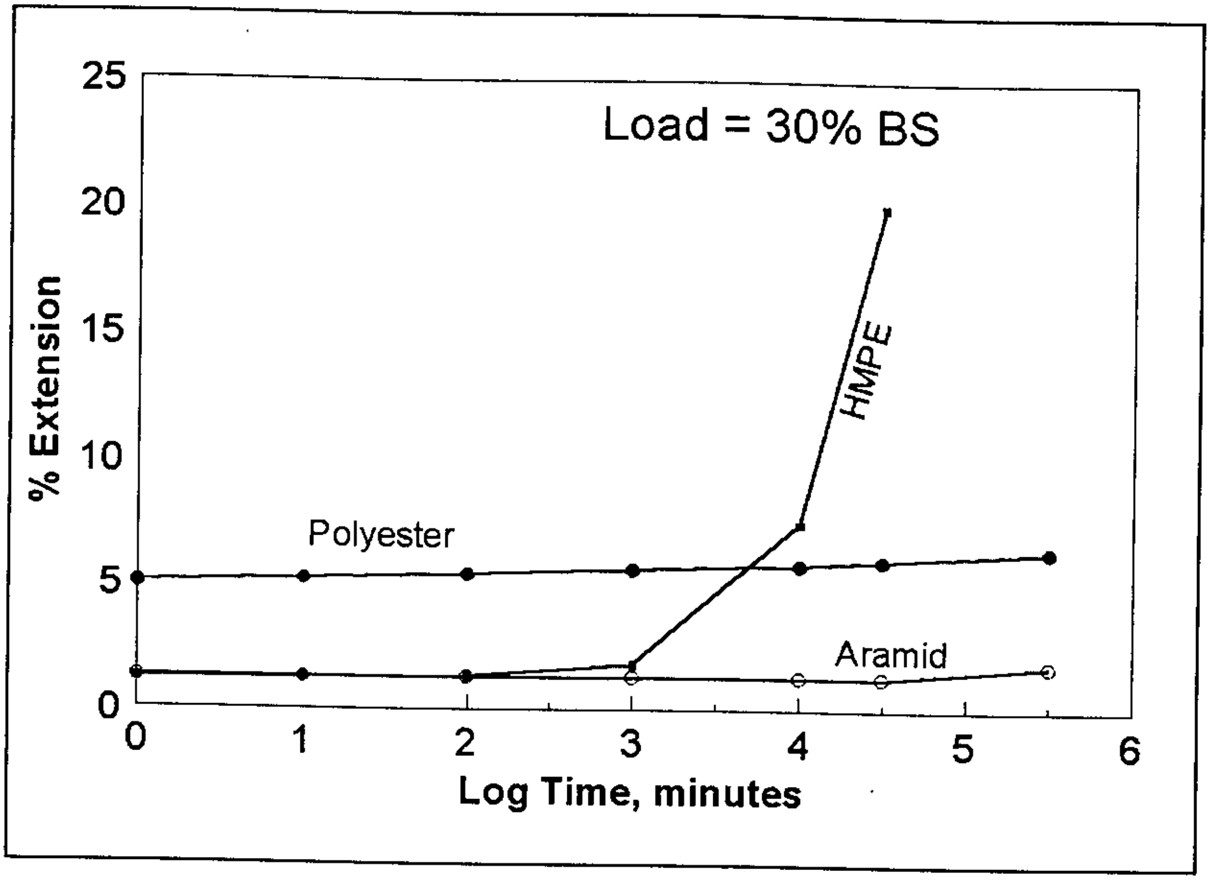


Figure 2. Creep Strain of Different Fibers Under Load Equals 30% of Their Break Strength

Aramid (Kevlar® 29) ropes provide mooring lines with exceptionally high strength-to-weight ratios. The elongation of Kevlar® is typically at least twice that of a steel wire rope. While Kevlar® ropes are light, easy to handle, and unaffected by conventional corrosion in the ocean, they, similar to other synthetic ropes, are quite easily damaged unless special protection is provided. Protection by jacketing the entire lengths of rope with polyurethene, nylon, or other plastics has proven successful in greatly improving abrasion and cutting resistance while retaining flexibility. However, the jacket design must consider the known fact that aramid fibers have modest compressive properties. If a Kevlar® rope is allowed to unwind, excess length is created which makes the strands want to bulge. The bulge can be prevented with a tight jacket causing the strands to go into compression if the tension on the rope is not high enough. Kink bands can form when strands are subjected to compressive strains greater than 0.5%. If care to avoid the application of compressive strains is not exercised in the design and application of Kevlar® ropes, premature failures can result. Reiwald (1986) reported on a field failure that was caused by this mechanism. Reiwald showed that the tensile strength of a rope can be reduced to less than 50% of its original value when subjected to a million compressive strain cycles of

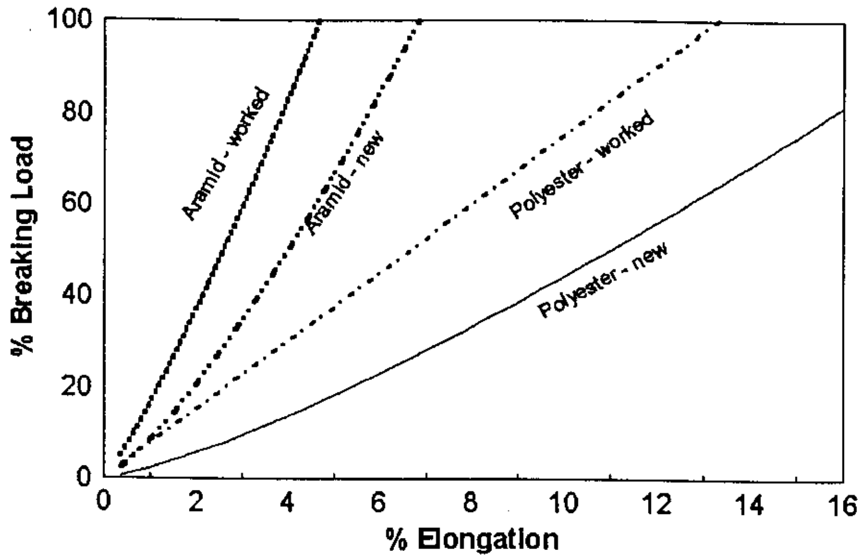
0.8% strain.

Similar to steel ropes, synthetic ropes can be produced with stranded, braided, or parallel strand constructions. Stranded construction is similar to that of wire ropes. Braided construction has the advantage that the rope is non-rotating. Ropes with parallel strands or fibers are very efficient and provide the highest stiffness. For mooring lines, stranded and parallel lay ropes are the most attractive for catenary and tension systems, respectively. The three most favorable rope constructions are spiral strand, n-strand (where n is the number of strands which is typically 6), and parallel strand (this includes bridge strand and parallel yarn construction). Similar to steel ropes, the strength of synthetic ropes is not only affected by its material and construction, but it is also greatly influenced by the type and workmanship of its termination. The most common terminations for synthetic ropes are eye spliced, resin potted, and spike-in-socket terminations. The spike-in-socket termination is mainly used for parallel lay ropes.

Currently, the two synthetic ropes that are being seriously considered by the offshore industry for deepwater mooring are polyester and Kevlar•. Table provides a comparison between size, weight and stiffness of similar strength polyester and Kevlar• ropes. When comparing rope stiffnesses, it is important to note that the stiffness value depends on both the load value, frequency and history, in addition to rope construction. Figure 3 presents a comparison between the load-extension curves of both polyester and aramid superline ropes (manufactured by Marlow®) showing the stiffness non-linearity and illustrating the effect of load history.

Table 5. Polyester and Aramid Rope Properties

BS, kips	D, inch	Wt (air), (lb/ft)	Wt (water), (lb/ft)	Stiffness (EA), (kips)
Polyester Rope				
1500	6.30	11.77	3.03	23,100
2000	7.35	16.05	4.12	30,800
2500	8.29	20.40	5.25	38,500
3000	9.15	24.83	6.38	46,200
Kevlar				
1500	3.90	5.29	1.38	46,700
2000	4.69	7.06	1.98	66,000
2500	5.30	8.82	2.47	82,083
3000	5.91	10.59	2.96	98,167



new: first loading to break;
worked: loaded to 50% breaking strength, rested for 24 hrs, then loaded to break.

Figure 3. Load-Elongation Curves of Polyester and Aramid Superline Ropes.

The first large scale application for synthetic taut leg mooring ropes involves the use of 700 ton of polyester ropes, costing about £4 million, for Petrobras' floating production system to be installed in 770 m in the Marlim Field. The primary reason for using polyester taut leg moorings is to reduce the anchor footprint by about 60% to meet the operational logistics and interference requirements. However, in using large load capacity (1500 T) synthetic ropes, issues such as heat build under cyclic loading, radial pressure under tension, creep, recovery after high load excursion, and proper scaling of terminations must be addressed. Heat build up in a rope depends on its size, mean applied load, cyclic load amplitude, and cyclic frequency. Recent laboratory testing of polyester and Kevlar ropes of up to 1500 tonne break strength showed a possible temperature rise in the order of 50°C when the rope is subjected to a high frequency strain amplitude that exceeds 0.5%. It is expected that Kevlar* ropes will have better damage and creep resistance, and higher fatigue lives than polyester ropes as shown in Figure 4. The installation of deepwater polyester moorings brings the problem of handling large volume of easily damaged lines, making the development of innovative options such as floating reels necessary.

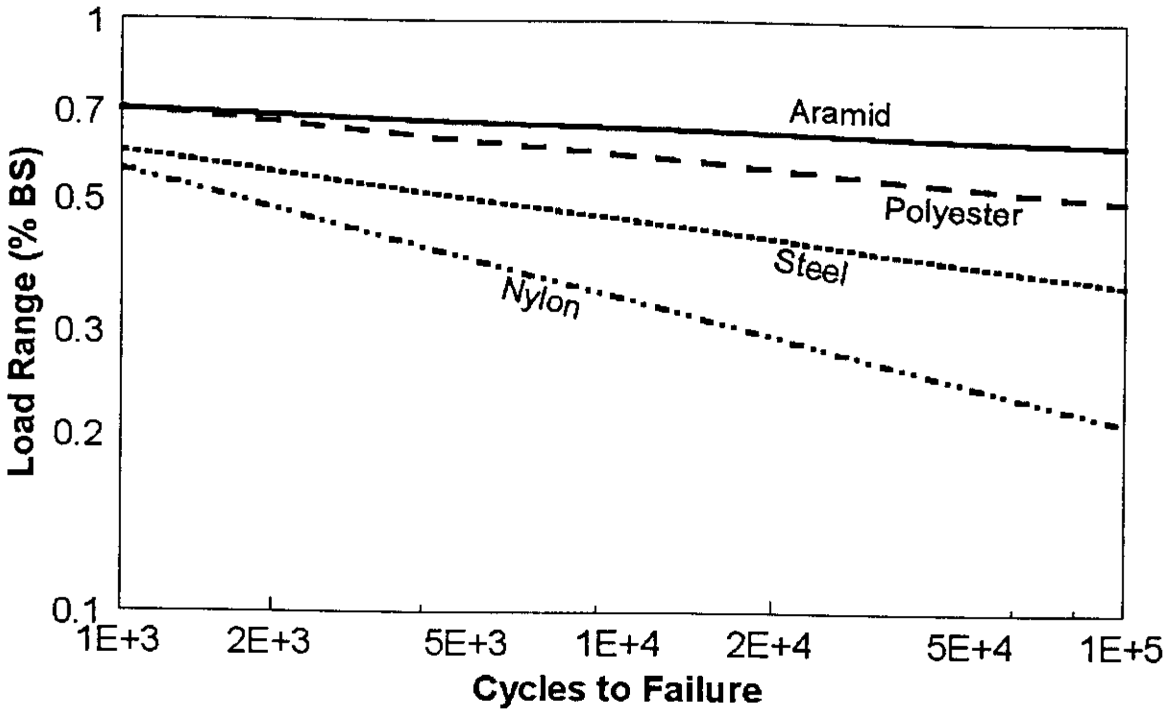


Figure 4. Tensile Fatigue of Ropes

ECONOMICS OF SYNTHETIC ROPES

A comparison of alternative mooring lines is terms of their cost equated materials performance can be misleading. Only, comparisons of full system cost to a common performance specifications can provide a true economic picture. In a study by Chaplin and Del Vecchio (1992), a cost comparison between three mooring systems for Aker H3.2 floating production system in 1000 m in the West of Shetland, North sea was developed. The three mooring systems are parallel strand polyester rope, parallel strand aramid rope, and six strand wire rope. In all systems the ropes are attached to an ORQ ground chain and drag embedment anchor. An 8 line 45° symmetric mooring pattern was assumed. A performance and cost comparison between these systems is given in Table 6. The results of this study concluded that the aramid rope/chain combination resulted in the highest cost. This cost and performance comparison can be disputed based on another study by Wilde, et al. (1996) that was undertaken to provide a comparison between the performance and installed cost of two taut mooring systems fabricated from 36 strand aramid rope and "Superline" parallel strand polyester rope.

TABLE 6. DESIGN, PERFORMANCE AND COST OF DIFFERENT MOORING SYSTEMS IN 1000 m WATER DEPTH IN THE NORTH SEA

Property	**Polyester**	**Aramid**	**Steel**
Design			
Chain diam./length (mm/m)	84/600	92/780	107/600
Rope diam./length (mm/m)	125/2500	94/1500	122/1500
Chain MBL, kN	5550	6550	8560
Rope MPL, kN	5460	6625	8970
Performance			
Max. offset, m	68.8	97.4	98.0
Max. Tension, kN	3110	3878	5073
Total vertical force, kN	3688	3415	9916
Cost			
Capital cost for 8 lines, MM$	3.0	5.5	3.6

The mooring systems were designed for Aker P45 Semisubmersible Drilling and Production Platform whose displacement is 49,600 tons and for operation in 3000 feet in the Gulf of Mexico. The two mooring systems were designed to meet the safety factors given by API RP 2SK. For the polyester design two rope sizes are considered. The first is a rope with a break strength equal to that of Kevlar® but its size is currently beyond the manufacturer stated capability. The second corresponds to the maximum diameter rope can be produced; using this size required increasing the scope of the mooring legs by 460 ft to compensate for the reduced rope diameter. A summary of the design, performance and cost parameters of both the aramid and polyester mooring systems is presented in Table 7. Although the cost of the aramid mooring lines is 35% higher than the same strength polyester rope, the total installed cost is only 6% than a comparable polyester system. This slight increase in system cost may be offsetted by the benefits of the aramid's smaller diameter and better creep performance and higher resistance to damage and thermal degradation. In the above study the aramid fiber that was considered was DuPont's Kevlar® 119 fiber which has lower modulus and higher elongation and fatigue strength than the traditional Kevlar® 29 fiber.

TABLE 7. DESIGN, PERFORMANCE AND COST OF THE DIFFERENT SYSTEMS (49,600 ton Vessel displacement, 3000 ft of water, GOM)

Property	Aramid (BS 2300 kips)	Polyester (BS 2300 kips)	Polyester (BS 2100 kips)
Design			
No. of lines	12	12	12
Platform K4 chain length, ft	328	328	328
Rope length, ft	4200	4200	4660
Anchor K4 chain length, ft	328	328	328
Intact Mooring			
Min. factor of safety	2.08	2.01	1.98
Max. Tension, kips	1,108	1,147	1,063
Max. Offset, % WD	3.8	4.0	4.0
One Line Damaged			
Min. factor of safety	1.56	1.53	1.50
Max. Tension, kips	1,470	1,505	1,398
Max. Offset, % WD	5.1	5.3	5.6
Rope Properties			
diameter, inch	5.05	7.93	7.55
Air weight, lb/ft	7.76	19.53	16.91
Wet weight, lb/ft	2.17	5.02	4.35
EA, msi	36.2	36.96	32.34
Schedule			
Rope manufacturing, month	10	24	16
Installation, day	35.5	37.5	37.5
Cost			
Component Cost, MM$	13.837	12.169	11.839
Installation Cost, MM$	6.723	7.226	7.226
Total Cost, MM$	*20.560*	*19.395*	*19.065*

TUBULARS

Tubulars are used primarily for the mooring of Tension Leg Platforms (TLP). Both thin wall (about 1 in thick) and thick wall tubulars are being considered. Only Hutton TLP utilizes forged high strength thick wall steel tubulars with 92.5 mm (3.64 inch) wall thickness (Salama and Tetlow, 1984). Deepwater TLPs such as Jolliet and Hedriun utilize thin wall neutrally buoyant tubulars with a diameter to thickness ratio of 30. Tendons for Augur and Mars are also thin wall tubulars, but not neutrally buoyant, to minimize their weight in water. The use of pressurized tendons is being considered to avoid the weight penalty associated with the need for thick wall pipes to resist the hydrostatic pressure. This concept will, however, require serious consideration of manufacturing quality control, installations techniques, and in-service monitoring to achieve an acceptable reliability.

Thin wall tubulars are a well known commodity in the oil industry, hence they have attractions for use as mooring lines. Facilities for the production of high quality steel tubulars with yield strength of 80 ksi (552 MPa) or less in various diameters and wall thickness, which would be suitable for this application, exist throughout the world providing the tendon diameter is maintained below the capacity of the UOE pipe forming process. The junction of the tubular lengths will be made either by welding tubular lengths together or by screwed connections. If welding is used, the mooring line will be either field welded offshore or the welding will be done onshore and the welded mooring line will be towed to location in one piece. For screwed connections it is most likely that two forged connectors, forming the pin and the box ends, will be butt welded to a steel pipe rather than being machined directly on forged ends. Materials proposed for this type of mooring lines include API 5LU X-80 (1Ni-0.5Cr-0.4Mo) and HY-80 for the pipe and ASTM A541 cl.6 (2¼ Cr-1Mo), A508 cl.2a (1.5Ni-0.5Cr-0.4Mo) or A372 cl.6 (3.0Ni-1Cr)for the connector (Akahide, et al., 1985; Hauser and Crooker, 1986). These steels have a yield strength around 600 MPa (87 ksi) and a CVN toughness value that exceeds 200 J at -20°C.

Since TLP mooring lines are pretensioned to a high tensile load and are subjected to high cyclic tension load in sea water, corrosion fatigue and stress corrosion cracking (SCC) are important design and materials selection factors. For tubulars with welded connectors, the fatigue life is controlled by both the threaded and the welded joint, and, therefore, fatigue information is needed for both. Fatigue design of the welded joint can be based on the ASME Section VIII S-N curve. Although this curve is intended to be used for components subjected to air environment, it can be used for properly protected components in seawater.

The use of high strength steels as mooring lines raises questions concerning the possibility of SCC. The SCC is a type of spontaneous cracking which can develop under the combined action of sustained tensile load and the exposure to a corrosive environment such as seawater. Detailed evaluation of candidate steels for TLP mooring lines showed that SCC under purely static loading is not likely to be a significant factor in their structural application (Hauser and Crooker, 1986). As an example, fatigue precracked specimens from Hutton steel did not show any indication of crack growth after 4500 hours of loading at a K_I level of 120 ksi-in$^{1/2}$. However, results by Hauser and Crooker of NRL have shown that when a ripple- loading of 3% ($\delta K=3.8$ ksi-in$^{1/2}$) at 0.1 Hz was added, while maintaining the above K value, the specimens failed after 3000 hours (@ 1,000,000 cycles).

ADVANCED COMPOSITE STRANDS

The tension legs of TLP's are stiffness critical structural elements. It is the current TLP design practice to limit the platform heave, roll and pitch natural periods to less than 4 seconds to avoid resonance which is known to increase fatigue loading and may also increase the extreme load. While steel has been used to date, several other materials can be used in the construction of tethers providing their designs incorporate the amount of material required to obtain the necessary stiffness to satisfy the natural period limits. Carbon fiber (PAN or pitch) reinforced plastics in a long-laid parallel wire construction and large diameter strands can provide adequate stiffness with sufficient strength. Strands of up to 5 1/8 inch (131 mm) diameter and 3.8 million pounds breaking strength have been produced for suspension bridges. Larger sizes up to 10 inches (254mm) may be required for TLP applications. This increase in strand sizes have a major drawback of increasing unit weight and the associated handling and transportation problems. To address these problems a new concept utilizing pultruded 5 mm diameter carbon fiber or Kevlar® 49 composite rods instead of the high strength steel wires is proposed (Walton and Yeung, 1987; Kim, et al, 1988).

Walton and Young (1987) conducted fatigue tests on 300,000 pounds breaking strength strands and showed that the fatigue life of carbon-vinyl ester composite strands are ten times longer than steel strands. These composite strands were constructed from 61 wires (rods) laid up in a close packed hexagonal formations. The strands have an overall diameter of 1 3/4 in (45 mm) and a nominal strand pitch of 11 ft (3.3 m) which corresponds to a lay to diameter ratio of 75 to 1. The 61-wire strands were formed using a track based manufacturing system. The wire rods are supplied in the form of 6 ft diameter coils. The helical bundle is formed together without inducing any torsional stresses into the rods. Intermittent tape wrappings were applied to assure strand integrity during coiling and handling. To protect the strand and improve handling a thermoplastic jacket is fitted to the strand.

The tether body can be formed by a number of parallel strands with each strand is approximately 2 inches in diameter. The strands can be terminated, similar to a steel bridge strand, using potted terminations. Although carbon fiber composite tendon possesses superior fatigue resistance suggesting that natural period limits may be relaxed, this is not desirable because the increased load will affect both the foundation and the connections to the hull. In order to achieve the 4 second design criterion for a Heidrun type concrete TLP in 4400 feet in the North Sea, the required tendon stiffness per corner is about 300 MN/m. If the mooring systems is made of steel, the mass of the tendons will exceed 80,000 mT and the tendon pipe design will be very complicated to achieve a reasonable weight in water and number of tendons. If the tendon system is fabricated of P-55 (55 x 10^6 psi modulus) carbon fiber composites, the mass will be about 14,000 mT (@ 30 x 10^6 lb) and under these condition the maximum stresses in the tendon will be about 20% of its ultimate strength. This number demonstrates that there is sufficient business incentive for both fiber and composite manufacturers to support the development of TLP composite tendons. The possibility and effects of relaxing the natural heave period limitation when using carbon tethers should be considered particularly in this context. If found to be feasible it would mean a significant reduction in the required amount of carbon fibre and , thus, increase its competitiveness with steel.

Although previous economic studies showed that the composite material and processing costs are too high, the current efforts of developing low cost discontinuous high stiffness (50 to 75 msi) pitch carbon fiber and the recent introduction of a low cost ($6-8/lb) intermediate stiffness (30 to 35 msi) carbon fiber by Zoltek change the economic picture. An economic comparison between TLP steel tendons and tendons manufactured using composites made using the discontinuous carbon fiber showed a cost saving between $30 to 300 MM, depending on the TLP size, in favor of composites as shown in Table 7. This economic advantage motivated several studies to develop and qualify carbon fiber composite tendons.

Table 7. A Comparison Between Installed Cost for TLWP Mooring Systems in 5000 ft (North Sea)

	Steel	**Composite Strand**
Cost	1.0	0.73
Dimension, inch	34 OD x 1.0-1.5 t	10.8 OD
weight in air, tonne	11,180	1,135
Weight in water, tonne	1205	136

INSPECTION

Because the reliability of mooring lines is critical to offshore operations, in-service assessment of the rope condition is of paramount importance. Mooring lines are subject to both short-term and long-term degradations during their service life. Short-term degradation can result from accidents, mishandling, and operational problems. Long-term degradation can result from wear, corrosion, fatigue, and any combination of these mechanisms. Mooring safety can greatly increase by using more dependable inspection methods, combined with a better understanding of degradation mechanisms and discard criteria (Weischedel and Chaplin, 1992). The type and frequency of inspection of mooring lines are influenced by statutory requirements, manufacturer's recommendations, criticality of application, severity of loadings, service life, reliability of the inspection method and results of previous inspections.

The Norwegian Maritime Directorate regulation requires thorough inspection of chain or steel wire rope mooring lines at least once every two years. After four years the recommended inspection includes removing and mechanical testing of sample length every two years for chains and every one year for wire ropes. The API RP 2I specifies a maximum inspection interval that depends on the service life of the mooring system as shown in Table 7. However, API inspection is limited to visual inspection with periodic tailing and re-termination.

Table 7. API RP 2I Recommended Inspection Interval

Service Life, years	Inspection Interval, months
≤ 2	18
3 to 5	12
> 5	9

For ropes, the discovery of short-term damage can be relatively easy because it takes highly visible forms such as kinks, bends, bird cages, crushing, cork screwing, and broken strands. The long term damage is the one that causes the greatest problem for inspection. The most frequently used inspection approaches are electromagnetic, radiographic, ultrasonic, acoustic emission, and infrared techniques.

Visual inspection of wire ropes is specified by several standards such as API RP 2I, BS 6570 and ISO 4309. The procedure to detect damage visually is done mainly by an inspector standing beside a slowly moving rope with cotton waste or rags wrapped around the rope which get snagged in broken or damaged wired. This type of inspection is ineffective for heavily greased ropes, ropes with sealing plastic material, or ropes with internal broken wires. For internal examination, clamps are used to twist and open-up the rope. This process is cumbersome, time consuming, ineffective if rope is covered by grease, and can cause damage to certain rope constructions such as multi-strand ropes. Visual inspection of mooring ropes by divers or ROV's is both expensive and unreliable. The API RP 2I recommends washing the rope with a high pressure water jet prior to inspection. This is both time consuming and can remove valuable lubricant/blocking compound which, if not replaced, will impair the subsequent life of the rope.

The application of NDT techniques to detect damage and degradation or to monitor the deterioration of ropes in services could increase the useful life of mooring ropes by increasing confidence in the effectiveness of rope examination, and avoiding unnecessary and potentially damaging mooring line removal and cleaning operations. The NDT techniques are used for damage detection by giving an indication or measure of damage or flaws in rope construction such as broken, damaged, or missing wires and loss in metallic area due to corrosion or abrasion. These techniques include visual, galvanic, radiographic, and electromagnetic. The reliability of the electromagnetic (EM) technique is universally accepted for the inspection of wire ropes for mining and ski lift applications. The EM inspection of rope is based on correlating changes in the magnetic field of magnetized section with damage in rope. The combination of the EM inspection with visual examinations provides an effective and comprehensive inspection program (Weischedel and Chaplin, 1992).

Radiographic techniques pass a beam of high-energy, subatomic particles through the rope and onto a film that shows the variations in metallic density. Ultrasonic techniques introduce high-frequency sound waves that reflect from discontinuities. Acoustic emission approaches listen for the noises made by the microscopic and macroscopic changes occurring during the degradation process. Electromagnetic, ultrasonic, and acoustic emission techniques are by far the most widely used (Egan, 1977). For TLP tubular steel tendons, in-service inspection can be achieved by acoustic emission, ultrasonic, acoustic holography, or eddy current. An ultrasonic system is being used for the inspection of Hutton lines (Hein, et al., 1984). Acoustic holography appears to be more attractive, particularly if testing can demonstrate its capability for external inspection of tubulars without the need to remove marine growth.

CERTIFICATION

Certification requirements for materials, design, manufacture and testing of mooring lines are required to ensure consistent reliability. The DNV certification notes 2.5 (1995) provides such requirements for offshore large diameter (>100 mm) steel wire ropes. The specifications address topics such as approval of suppliers, certifications of quality system, materials, design, manufacturing and testing. There is a need to develop similar specification for synthetic ropes and composite strands. There is also a need to develop a specification for terminations. These specification should set a criterion for the frequency of full scale production tests on terminated ropes and strands.

RECOMMENDATIONS

1. Design standards need to be updated and unified to accommodate taut mooring systems. There is also a need to develop engineering guidelines for synthetic ropes and composite strands. Developing a system design methodology that includes the coupling with risers is essential to exploiting the full potential of advanced materials for mooring systems.

2. Design optimization of mooring systems requires the development of reliability based safety factors and a coupled hull-mooring dynamic analysis methods. There is also a need to develop a strategy to apply CFD analysis to predict coupled platform-mooring-riser response in lieu of model testing which is becoming scale limited as the water depth increases.

3. Very sparse cyclic and static fatigue data exist on synthetic ropes; there is a need to develop time-temperature-load degradation data base and prediction model. for both ropes and their terminations. The degradation model should account for issues such creep, stiffness under different load frequencies, and potential damage during installation and service.

4. Because of the criticality of mooring systems, field calibration of synthetic mooring concepts is essential to verify mooring system response, validate degradation model, develop installation procedures, assess potential damage mechanisms, and build-up confidence.

5. A reliable quality assurance program for synthetic ropes and composite strands is an area where developments need to be pursued. Such a program should include manufacturing & quality control specifications, in-service inspection methods, on-line integrity

monitoring techniques, and discard/retirement criteria.

6. The three most common terminations are eye spliced, zinc or resin potted, and spike in socket. Although potted and spike in socket terminations have performed well for small diameter ropes, their application for large diameter ropes is far from satisfactory and need to be developed. Eye splices for large ropes (up to 1500 tonne NBL) have been found to function properly but the details of the eye to pin area has been found to greatly influence the long term integrity of the rope.

7. Preliminary results on developed carbon fiber ropes have demonstrated attractive properties, such as light weight, high axial stiffness and excellent fatigue properties, for potential use as TLP tendons. Assessment of damage resistance and fabrication characteristics, and verification of properties using large scale testing would be required before actual use.

8. Fatigue strength of steel ropes is an important parameter for deepwater installations. Limited data is available today; most obtained by testing small size ropes under bending. The use of these data for the design of large diameter ropes is questionable.

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Material Requirements for Risers

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Abstract

This paper discusses risers in the context of their applications, functional requirements, performance specifications and present-day realizations including materials of construction. Although steel is the predominant material for riser construction, other materials including titanium and polymeric composites are being introduced into riser technology. The several reasons contributing to this material transition or evolution are cost-savings, improved performance and technical enablement. These reasons will intensify with the continued movement into greater offshore waterdepths.

Numerous riser-development activities involving composite and hybrid steel-composite construction are in progress with the common goal of producing commercially viable products within the next several years. These programs are discussed along with associated barriers.

Introduction

First of all, what is a riser and why all the concern about its material of construction? Simply stated, a riser is a fluid conduit that extends through the offshore water column connecting a seafloor well or pipeline to a floating structure at the sea surface. The conduit may consist of one or more parallel (side-by-side or concentric) tubulars and its trajectory through the water column ranges from near vertical to variations on the catenary theme. A few of these configurations are shown in Figure 1.

To emphasize the importance of risers to the development of deepwater offshore reserves, risers serve to facilitate the drilling of offshore exploration and development wells (drilling risers), the production of reservoir fluids from subsea wells (production or import risers) and the transfer of produced and, often, treated fluids to seafloor pipelines (export risers) . Without these capabilities, an offshore platform, e.g., a TLP, would be quite useless. So much for motivation.

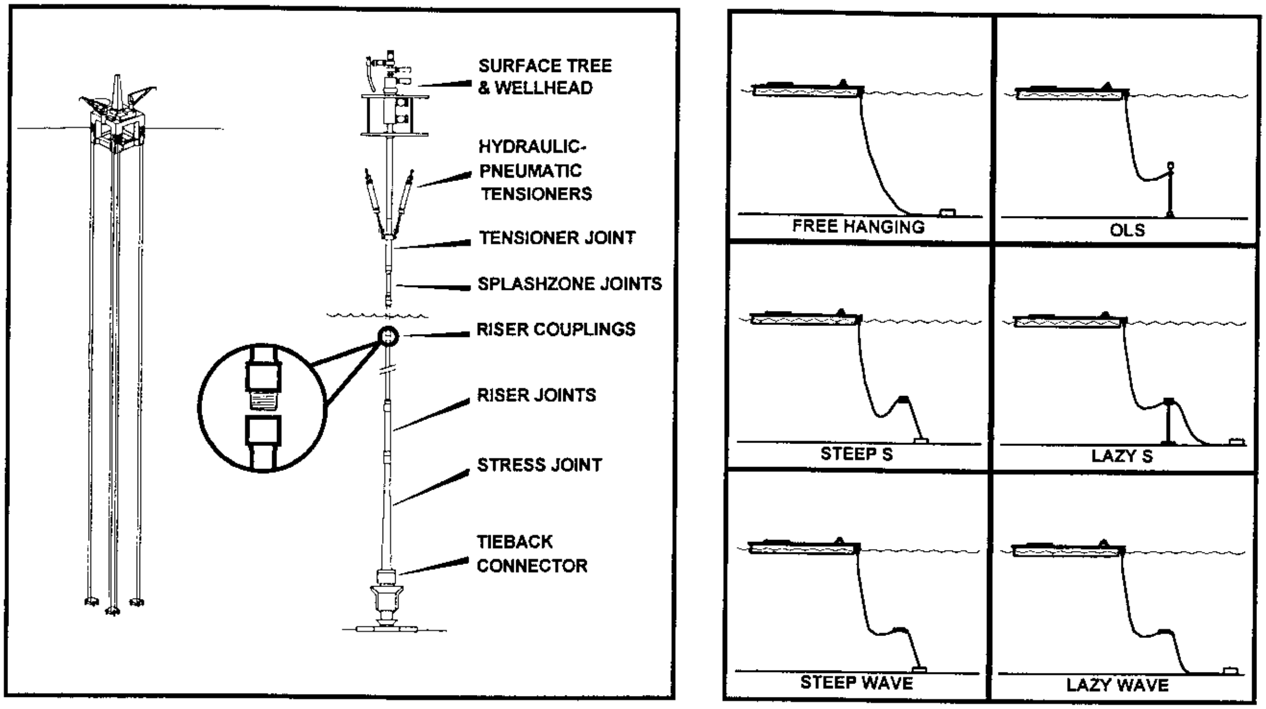


Figure 1 - Near-vertical and catenary-type risers.

Representative functional requirements, or "purposes," for risers are indicated in Table I. These describe "what" a riser is to do.

Table I - Riser Functional Requirements

- Provide structural self-support (strength) under submerged weight and environmental loading,
- Provide pressure and fluid containment under normal operating, e.g., flowing, and accidental, e.g., well-control, conditions,
- Provide a means for guiding drilling, workover and other well-intervention tools and tubulars into and out of the well,
- Support auxiliary lines for well control,
- Serve as, or be incorporated into, floater mooring system, and
- Other specialized functions such as wellbore-annulus access for monitoring or fluids injection.

For subsea wells which require intervention from a host floater, near-vertical risers are preferable, if not essential. This is certainly the situation when drilling and completing a well, as it is for recompletion and workover operations. Such drilling and production risers consist of multiple finite-length joints of hard-pipe, or rigid, tubulars connected by bolted flanges or threaded connections (Figure 1). The successful application of such vertical risers depends upon sufficiently small motions of the host floater and, usually, a compliant riser-to-floater interface system, e.g., a tensioner. Special hardware at the built-in seafloor wellhead and sometimes at the floater keel, e.g., a stress joint, is also required to accommodate large riser bending moments that can develop. These important "interface" components are also indicated in Figure 1.

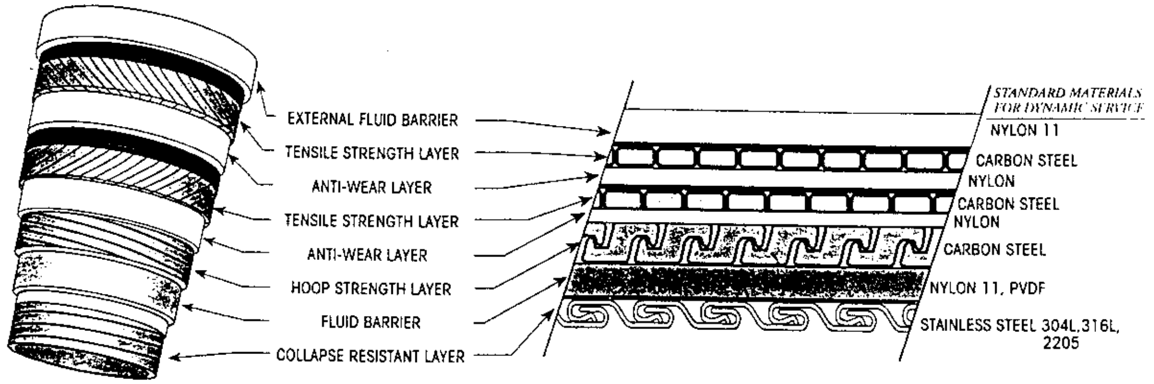
In this configuration, the riser must withstand a multitude of loads. First of all, there are steady axial tensions associated with the submerged self-weight and overpull (typically 20-40%) of the riser system. Then there are the operating and accidental internal (burst) pressures and thermal loads associated with internal fluids, and external (collapse) pressures associated with the column of seawater. Finally, there are extreme and fatigue loads that arise from direct current and wave environmental excitation and from indirect environmental excitation, including wind, as a result of floater motions.

Riser performance specifications are indicated in Table II. These describe the conditions under which the riser must perform and how well it must perform. Several of these "specifications," e.g., operating and extreme tensions, are not known a priori but instead are functions of the riser design including its material of construction.

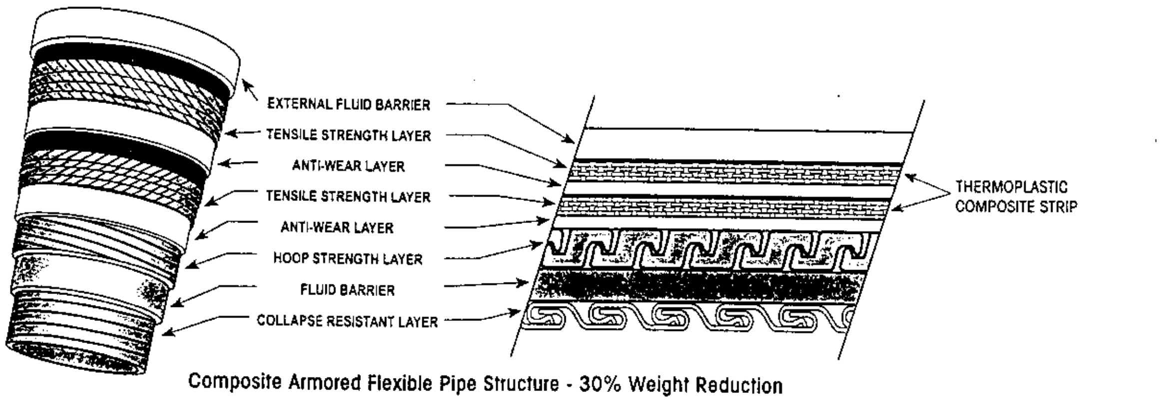
Table II - Riser Performance Specifications

• Waterdepth	2,000 - 10,000 ft
• Anticipated environment	location dependent
• Floater responses	floater and location dependent
• Service life	10-30 yrs
• Chemistry of internal fluids	hydrocarbons, CO_2, H_2S,...
• Thermal loads	100 - 250°F
• Operating and extreme internal pressures	1,000 - 10,000 psi
• Operating and extreme tensions	200 - 1,000 kips (steel)
• Operating and extreme rotations at floater attachments	5° - 35° amplitude
• Fatigue loads	floater and location dependent

For production situations where well intervention from the host floater is not required and in virtually all export situations, nearly vertical risers are not required. This is indeed fortunate, since vertical risers are not compatible with several economically attractive floating production systems, e.g., tankers and semisubmersibles, by virtue of these floaters' long-term motion behavior. In such situations, steel catenary risers (SCR), and buoyed variations thereof, and unbonded flexible risers produced, for example, by Coflexip and Wellstream are commonly employed. Representative construction for flexible risers is shown in Figure 2. This construction can be referred to as hybrid steel-polymeric construction wherein the hoop and helical-axial elements contend with radial and axial loads, respectively, and the polymeric liners provide barriers to fluid ingress and egress. In an attempt to reduce the submerged weight of flexible risers, the above-mentioned manufacturers have investigated, or are investigating, substitution of polymeric composites for the steel helical-axial tensile-strength layers [1]. Another very important feature of steel catenary and flexible risers is that their installation can be greatly facilitated by virtue of their continuous, reelable (spoolable) form. Wherever this method of installation is permissible, it has definite advantages over the piece-by-piece installation of finite-length riser elements.



Non-Bonded Flexible Pipe Structure



Composite Armored Flexible Pipe Structure - 30% Weight Reduction

Figure 2 - Schematic of flexible-pipe construction.

Riser self-weight and associated top tension become increasing design challenges as waterdepth increases. It is for this reason that materials having increased strength-to-weight ratios, e.g., titanium and polymeric composites, have become attractive alternatives to the conventional material for riser construction, i.e., steel. The strength-to-weight ratio, or specific strength, of titanium is 2.5 - 3.3 times that of steel. Increasing riser compliance, or flexibility, without sacrificing strength is very important in reducing static and dynamic loads within the riser itself and at critical riser terminations, e.g., stress joints and flex-elements. Resistance to seawater corrosion and chemical attack from internal riser fluids is also a very attractive attribute for candidate riser materials. For any such considerations, the riser engineer and material scientist must be guided by the need for cost-effectiveness (minimization), enhanced performance and maintenance of a sufficient level of reliability. In the opinion of many, cost-effective riser technology is the key to deepwater petroleum development.

For alternative riser materials to be "cost-effective," it is not imperative that the composite, titanium or other riser itself be less expensive than the steel riser that it replaces, but instead that its introduction result in an overall systems' savings. This may be accomplished by observing that reduced floater payloads (riser top-tensions) resulting from lighter risers are "rewarded" at the rate of \$3-5/lb and more for TLPs and similar floaters. These savings result from structural simplifications, e.g., less steel, and reduced buoyancy requirements.

It has been estimated [2] that the titanium drilling riser employed on Conoco's Heidrun TLP resulted in a "systems" savings of \$14.5 MM (\$22.0 MM vs \$36.5 MM) although the titanium material costs of \$7.69 MM were three times those of estimated steel forgings. The tensioner savings alone were estimated to be \$12.75 MM. During 1998 drilling operations, a composite drilling-riser joint will be inserted at several different locations within the Heidrun titanium drilling riser as part of a development-qualification program.

Technical enablement is also a very important issue driving the consideration of alternative riser materials. Equipment currently available for installing catenary risers by the J-lay or S-lay method is limited to top tensions of around 300 kips. This limitation represents one of the biggest obstacles to the development of ultra-deepwater prospects in 4,000 - 10,000 ft waterdepth.

The Workshop on Marine Riser Mechanics held at The University of Michigan in the fall of 1992 points toward the direction of using advanced materials and particularly composites for construction of future marine risers. In the area of advanced materials, the workshop report also proposes that titanium, high strength steel structures and hybrid structures be considered. Fatigue performance of such alloys must be investigated since their performance is not as high as that of mild steel. In composite materials, the following research problems were identified:

- Define design criteria for risers, e.g., fatigue, buckling, stress loads, installation loads, static and dynamic performance
- Define special operations and conditions
- Determine set of design environments for deepwater riser extreme stress estimation
- Define sources of uncertainty in order to establish a basis for reliability-based design
- Define design verification process

A survey of 50 oil companies conducted by the UK Marine Technology Directorate and the HSE lists four factors for the increasing use of titanium metal offshore: (1) more deepwater discoveries, (2) high-temperature, high-pressure wells, (3) the decline and stabilization of titanium prices, and (4) the souring of wells with age. Titanium catenary risers are now being considered by half of the companies responding, and some are considering the metal for subsea manifold pipes, flowlines, umbilicals, and chemical injection lines. Other possible uses include rigid production and export risers, and Christmas tree and flowline jumpers.

Several reasons for replacing steel, in part or in total, by other materials for riser construction have been given or implied. These reasons are: (1) cost-savings, (2) enhanced performance, and (3) technical enablement. It should be emphasized that total, installed system costs for material substitution and not just component cost should be examined when computing "cost savings." For example, whereas composite production-riser tubulars may cost 3-4 times that of steel tubulars, system savings are anticipated due to floater-deck, -hull and -mooring simplifications associated with reduced riser top tensions [3].

Enhanced riser performance and, ultimately, technical enablement can readily justify alternative riser materials and/or construction even at material-cost premiums. However, prerequisites for any new riser material-construction are that:

- The new riser must have reliability which is comparable to the existing steel riser,
- The new riser must be "easy" to design, fabricate and qualify,
- The new riser can be stored, transported, inspected and installed (handled) without undue complication, and
- Total project profitability must meet specific corporate criteria.

Current Applications and Development Activities

As mentioned earlier, materials with high strength-to-weight ratios, such as titanium and fiber-reinforced polymeric composites, are attractive alternatives for riser construction. Unfortunately, the base costs of these alternative materials are usually higher than that of steel. Hence, risers made of these materials will be more costly than steel risers and will be difficult to justify on the basis of material cost (material substitution) alone even though such risers can be made to provide desirable performance characteristics. Current interest in using these materials for risers stems mainly from potential "system" cost-savings, including installation, that can be derived with the use of these materials and, hence, from the potential to provide more cost-effective solutions for deepwater exploration and production operations. In general, the oil and gas industry is more familiar with titanium than it is with polymeric composites and therefore more receptive to using this material for demanding applications. Furthermore, extensive development and qualification programs are required to justify the use of high-performance polymeric composites for the construction of marine risers. In this section, some current riser development and application activities using titanium and polymeric composites are discussed.

Near Vertical Risers

A 22-inch inside-diameter titanium-alloy (Ti-6Al-4V ELI) high-pressure drilling riser has been designed by Hunting and fabricated by RMI Titanium for Conoco's Heidrun TLP in 1132 feet of water [2]. Due to its light weight, the titanium drilling riser helps to overcome potential riser interference and crossover problems with the surrounding production risers in severe weather conditions. At the same time, it provides the additional benefit of reducing the cost of the drilling riser system including the riser support deck structure and the associated riser handling equipment.

The Heidrun drilling riser consists of a tapered stress joint at its lower end, 24 standard riser joints, a lower centralizer joint and bearing assembly, and a pup joint. Each riser joint is 48-ft long and was fabricated by girth welding two 3.25-ft flange pipes to the ends of a 42-ft long straight pipe. All riser joints have a 7/8-inch minimum wall thickness. The maximum flange diameter is 37 inches. The flanges are configured to support and align the 3-inch inside-diameter booster-line stabs and are coupled with 24 M48 Ti-6A1-4V ELI titanium-alloy through bolts. The working pressure of the riser is 4000 psi. However, in the factory acceptance test, the riser was pressurized to 6200 psi. Inconel 625 alloy overlays were applied to the ferrous surfaces at the interface points to isolate the titanium alloy from the less noble material used. Titanium is susceptible to sliding metal wear and galling when in contact with the rotating steel drill string. For the Heidrun drilling riser, the wear problem was resolved by manually applying two layers of 0.12-inch thick (hydrogen) peroxide-treated (neoprene) HNB rubber to the riser inner surface. Bonding of the rubber to the riser pipe wall was achieved by using a steam curing process.

The titanium drilling riser system on the Heidrun TLP costs about $22 million, or about 60% of a comparable-size and pressure-rated steel drilling-riser system. The cost of titanium was higher than that of steel, but the forging, machining and inspection costs were about the same. Overall cost-savings came from elimination of buoyancy modules and flex-joints, and the lower handling, tensioning and support-structure costs. Since titanium has a lower elastic modulus than steel, the axial dynamics of a partially buoyed titanium riser string will be different from that of a fully buoyed steel riser string. Riser designers will need to consider the lower stiffness of titanium in the design of the titanium drilling riser string.

In addition to the Heidrun TLP drilling riser, titanium alloys have also been used for tapered stress joints. For example, the Ti-6A1-4V ELI alloy was used to fabricate the tapered stress joints for the Conoco Heidrun drilling riser and the Oryx Energy Neptune Spar production risers. Such applications of titanium alloy provide the "controlled" riser flexibility needed to accommodate large platform horizontal offsets.

Polymeric composites are even lighter than titanium and are potential candidates for drilling-riser construction. Currently Northrop Grumman Marine Systems (formerly Westinghouse Marine) is leading a joint-industry research and development venture to develop technology to commercialize light-weight advanced composite tubulars for deepwater oil and gas exploration and production. The venture is also funded jointly by the National Institute of Standards and Technology (NIST) Advanced Technology Program (ATP). The first target application of the technology is a composite drilling riser system with the riser body (20-inch diameter) and the high pressure (15,000 psi) choke and kill lines made of advanced composites. The venture is currently half way through a 3-year, $4.8 million project. The objective of the project is to demonstrate successful deployment of a light-weight advanced composite drilling riser pup joint prototype in a deepwater drilling program. The project plan includes material characterization, design, fabrication and land test of riser prototypes in addition to fabrication and testing of an in-the-water prototype. Preliminary design and fabrication of two 25-ft long drilling riser main body prototypes as well as the high-pressure choke and kill line prototypes have been completed. Land tests of these prototypes will commence in the near future. As in the case of the titanium drilling riser, the light-weight composite drilling riser is expected to lower the total cost of the drilling riser system. A similar composite drilling riser development effort, led by Conoco and Statoil, is also currently underway. Composite drilling riser joints will be inserted at several locations within the Heidrun titanium drilling riser string as part of a development-qualification program.

Polymeric composites have also been considered for production riser construction. The first study on composite production risers [4] was initiated more than a decade ago. The drop in the price of advanced composites in recent years and the current accelerated activities in deepwater exploration and production have prompted renewed interest in using composites for production risers. A joint-industry project on composite production risers, jointly funded by NIST/ATP, is currently underway. The goals of the project are to design, develop, manufacture, test and qualify a production riser made with fiber-reinforced polymeric composites. Lincoln Composites is leading the effort in engineering design and fabrication of the composite riser. A concentrated effort was conducted in the first part of the project to design a low-cost, light-weight composite production riser suitable for deep water (3000-5000 feet). The functional requirements and performance specifications of the riser were determined by oil-company participants and were based on the results of an iterative analysis of the response of a representative composite production riser to typical platform motions and direct environmental loads.

The composite production riser is a hybrid structure design with carbon and glass fibers embedded in an epoxy matrix. The composite-to-metal interface design relies on a special configuration which has been used before in some aerospace structures. A premium light-weight threaded connection is used for the metal connector. The external geometry of the metal connector has been chosen to accommodate standard riser handling equipment. Hence, no special tooling will be required to handle and install the composite production riser. Internal and external liners will be incorporated into the production riser to provide fluid-tight pressure barriers and protection from damage due to accidental impact and wear. Full-scale and subscale riser spool pieces are being fabricated and will be tested to validate the design assumptions and riser performance characteristics. Qualification of the composite production-riser joint for field service has been planned and will be carried out upon completion of fabrication of the full-scale (diameter) riser joints. Other elements of the project include a detailed reliability and safety study to ensure the serviceability of the composite production riser, and development of advanced design/analysis methods to enable direct translation of the results of the project to other production-riser designs.

Catenary-Type Risers

Non-bonded flexible risers are critical elements in floating systems for deepwater offshore oil and gas production [1]. Current applications in increasingly demanding environments, with a design temperature up to 265° F, a design pressure in excess of 5000 psi, sour production fluids, waterdepth exceeding 1000 meters, severe wave and current conditions, and larger diameters (more than 10-inch inside diameter), are challenging conventional flexible pipe design and construction. A non-bonded flexible pipe is designed as a multi-layer conduit consisting of thermoplastic layers for sealing the conveyed fluid from the external environment and metallic layers of carbon steel to provide axial and hoop structural reinforcements. In deeper water where longer-length flexible pipes will be used, the weight of the carbon steel reinforcements becomes a critical factor in the design of a flexible pipe. The large tension load induced by the pipe weight could lead to unacceptable stress levels in the pipe structure and excessively large deck and installation loads. As the pipe stress level increases, larger cross-sectional areas of the steel members are required, further increasing the weight of the pipe. To reduce the pipe unit weight, while retaining the required strength level, polymeric composites have been proposed and used as armor wires to replace the steel axial reinforcement.

The first application of composites in a non-bonded flexible pipe was carried out by Coflexip Stena Offshore using armor wires made of glass-fiber reinforced epoxy. The shapes of the composite wires are flat and rectangular similar to those used for steel armor wires. To minimize residual stresses after laying, the composite wires are initially preformed to a given lay diameter and armoring angle. Coflexip Stena Offshore has manufactured and installed flexible risers with glass-fiber composite armors for Petrobras in Brazil.

Currently, Wellstream is leading a project, jointly funded by NIST/ATP, to investigate the use of fiber-reinforced thermoplastic composite strips/wires to replace the carbon steel tension armor layers in non-bonded flexible pipe for deepwater sour service [1]. This material substitution reduces the weight of the flexible pipe by about 30%. Work is also underway to evaluate the performance of the composite armor flexible pipe; to develop sensors for life monitoring of the thermoplastic composite armor; and to develop a service life model of the armor. The cost of the composite-armor flexible pipe is expected to be higher than that of a steel-armor pipe but the total system cost-savings associated with the lighter weight flexible pipe are expected to be sufficient to offset the higher cost of the composite flexible pipe.

Light-weight, spoolable, all-composite tubulars are beginning to attract attention as alternatives to the heavier non-bonded steel and steel-composite flexible pipe. With the recent advancement in manufacturing processes, spoolable composite tubulars can now be produced in long continuous lengths. A typical spoolable composite tubular usually consists of load-bearing layers of carbon, glass, and/or kevlar fibers in a polymeric matrix. The fluid-pressure barrier is provided by means of a chemically resistant thermoset or thermoplastic inner liner. If needed, an outer thermoplastic protective layer can be added to the composite structural layers. Interest in the use of composite spoolable tubulars can be seen from the various current development efforts described below.

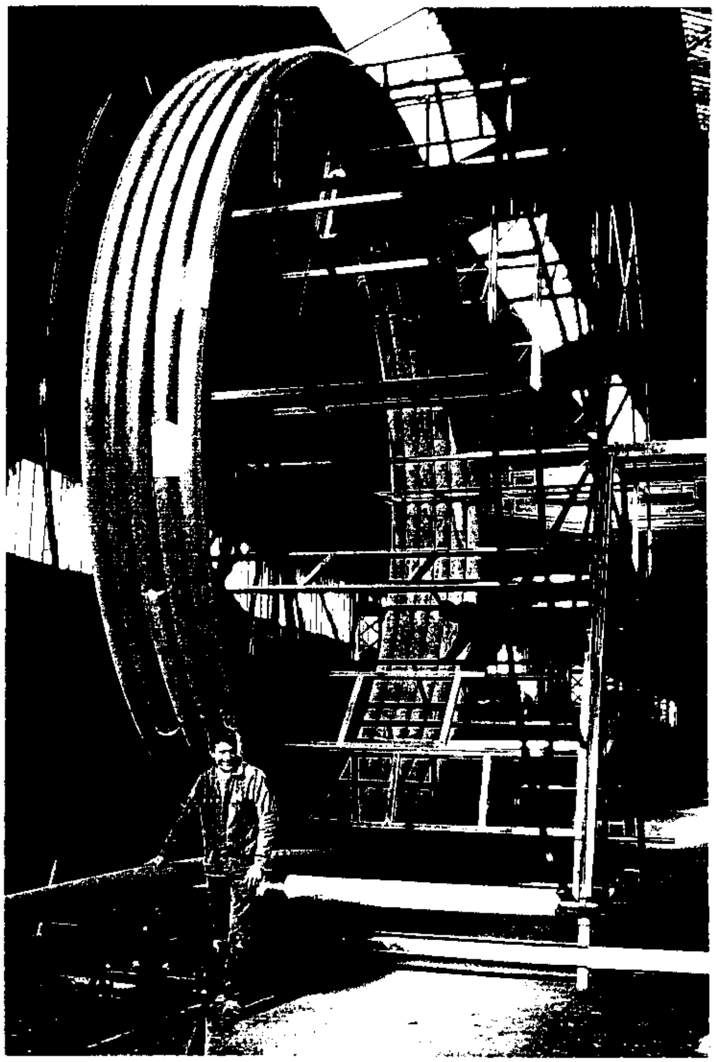


Figure 3 - Reel of Tubes d'Aquitaine Reinforced Thermoplastic Pipe.

COMPIPE has recently completed the first phase of a composite flowline joint-industry project [5]. The objectives of the project are to develop and qualify a spoolable composite flowline. The diameter of the flowline studied in the project was in the 100 mm to 250 mm range and the pressure rating was in the 100 bar to 350 bar range. Cost comparisons of composite flowline with coated carbon steel, conventional flexible flowline, duplex steel, and 13% Cr steel flowline show that a continuous polymeric composite flowline is economically viable. The total cost-savings in pipe material and fabrication range from 17% to 48% when compared with a duplex steel flowline. The cost of installing a composite flowline is similar to that of a reeled steel line.

Fiberspar has developed manufacturing technology for long continuous spoolable composite tubulars and is proposing a joint-industry project to qualify non-metallic bonded spoolable tubulars for offshore applications. Fiberspar estimates that the cost of a spoolable composite tubular will be competitive with the acquisition cost of a similar API 17J flexible pipe on a per-foot basis. However, the life cycle cost is expected to be reduced because the spoolable composite tubular is corrosion resistant, lighter and easier to deploy, has longer fatigue life, and has the potential to reduce overall riser system complexities and costs.

A similar joint-industry project is currently underway, led by Hydril and jointly funded by NIST/ATP, to develop an advanced manufacturing method for long continuous spoolable composite tubulars in the 1-inch to 6-inch diameter range for deepwater applications in the Gulf of Mexico. The current project is based on the results of an earlier joint-industry project on composite coiled tubing which demonstrated that superior performance can be realized with a properly designed and fabricated spoolable composite tubular.

The above discussion on spoolable composite tubulars was concentrated mainly on pipes made with thermoset resins. It should be pointed out here that a new class of spoolable composite tubulars made with fiber-reinforced thermoplastics [6] is beginning to emerge in the oil and gas industry. For the manufacture of this reinforced thermoplastic pipe, pre-formed fiber-reinforced tapes having a compatible thermoplastic matrix are utilized. Initially, layers of these tapes are helically wound around a thermoplastic tubular. Preferably, tape widths are such that for a given pipe outer diameter and a given wind-angle, the pipe outer surface is completely covered by each tape layer. Usually, pairs of tape layers are applied having opposite wind-angles for each layer to ensure torque balance of the fabricated pipe. Following application of one or more pairs of tape layers, an outer layer of thermoplastic pipe is co-extruded on top of the tape-wrapped inner pipe.

The several layers of this sandwich-type construction are usually bonded together by thermal or other means either as the layering proceeds or following the co-extrusion step. Wavin of the Netherlands has demonstrated the continuous manufacture of such pipe by producing 200 feet of 4-inch pipe having two tape layers. Tubes d'Aquitaine of France are currently manufacturing both the reinforced tapes necessary for this manufacture as-well-as finite-length pipes having various diameters and tape layers. Tubes d'Aquitaine have also designed and qualified a cost-effective, easy-to-install threaded connector. Their ultimate goal is continuous fabrication of this spoolable pipe. A reel of pipe having intermediate connectors every 12 m is shown in Figure 3. (Photo courtesy of Tubes d'Aquitaine). The potential of this class of spoolable tubulars for riser applications should be investigated.

Barriers To The Use of Alternative Materials For Risers

Despite the current development efforts on titanium [7] and polymeric-composite risers, it is important to point out that many challenging barriers remain to be resolved for these risers to be fully accepted for oil and gas exploration and production. Some of these challenges are described below. Since titanium has been studied previously and considered for demanding applications, the barriers discussed here are more relevant to composites. Hence, the following discussion should be treated as mainly focused on composite risers with only occasional reference to their titanium counterparts.

- Cost - The base costs of polymeric composites are higher than that of steel. Even though composite risers will be lighter than steel risers, they will be more costly than steel risers and will be difficult to justify on the basis of material cost or material substitution alone. For deepwater offshore applications, unless the weight-savings from a composite riser can be readily translated to potential cost-savings (in platform structures, top tension, related equipment, and/or installation), support for using a composite riser or developing a new riser application will be difficult to obtain.

While safety improvement, low maintenance cost, and low life cycle cost are often cited as important factors/benefits in choosing composites over steel, they are not the driving force behind the current development activities in composite risers. Developing a new composite riser purely on the merit of providing potential enabling technology is difficult to justify in the current economic climate. In view of the high base costs of polymeric composites, improvement/reduction in composite riser fabrication cost, including the metallic connectors, may be needed to help improve the economic attractiveness of composite risers.

- Material and Performance Data Base - Polymeric composites are relatively new to the offshore industry. Hence, their performance in an offshore oil and gas exploration and production environment is always of concern to offshore operators. One major issue is the long-term performance of composites. Data on these materials are usually not readily available. Besides, manufacturers of composite products often regard the data as proprietary information. Further, the large possible combinations of composite material and lamination variables that can be considered in design and fabrication of risers complicate the long-term performance issue. Another important issue is the lack of proper translation of laboratory-generated material-performance data to the actual behavior of the material in prototype structures. The lack of information on materials and performance often leads to discussions of the long-term reliability issue, a critical concern for riser applications. To expedite the acceptance of composite risers and to accelerate current and future riser development efforts, an industry-wide standard and acceptable data base on composites for offshore operations should be established to enable uniform designs to be developed for riser applications.

- Liners - Thermoplastic and elastomeric liners are often used to provide fluid-tight pressure barriers for risers. In some applications, these liners also serve as abrasion-resistant layers. Liner materials are required to maintain sufficient dimensional stability, strength, and ductility over the entire service life of the risers. Hence, the mechanical performance and chemical/physical compatibility of liners in drilling and/or production fluids will need to be evaluated. Service-life models based on aging tests will have to be developed to substantiate the suitability of a material as a riser liner. The use of a bonded or unbonded liner is also an important design, manufacturing, and performance issue which can impact the cost of a riser. The resistance of a liner to damage due to rapid decompression must be investigated to account for shutting down of risers for maintenance. Riser liners must also be able to withstand the mechanical and thermal loads during riser fabrication. For some future applications, liners with high-temperature capability will be needed. Although liners having melting temperatures above 450° F are available, efforts to develop and qualify cost-effective liners for high-temperature applications will be essential to extending the temperature capability of bonded and non-bonded flexible risers from the current limit of around 230° F [8].

- Design Methods - No standard design methods are currently available to assist in the selection of an optimum combination of composite materials and lamination variables for the riser body. It is quite obvious that different composite product manufacturers rely on different methods to derive their final riser designs. Standard design methods are needed to facilitate <u>preliminary</u> riser designs, especially at the early stage of a design project, for cost, size, and weight estimates and to provide representative information to assess riser responses to platform motions and environmental loads. An important feature of a composite riser (and a titanium riser) that needs to be recognized is that the axial stiffness of a composite riser will be lower than its steel counterpart. Lower axial stiffness might lead to unacceptable riser dynamics (axial resonance) which might require the use of a less optimum riser design. This could have a negative impact on the riser economics. On the other hand, the increase in flexibility of a riser might help to reduce or eliminate the need for heavy, expensive tensioning equipment and/or support structures. The resulting cost-savings must be taken into account in the preliminary economic assessment of a riser system since they might influence the final choice of a riser. An easy-to-use standard design method will help to provide timely results to enable composite risers to be considered for specific applications.

- Joint Design - Composite riser designs rely heavily on metallic connectors for load transfer from one riser joint to another or from a riser joint to its supporting metal structure. A critical challenge for composite risers is the design of the load transfer mechanisms and fabrication details at the interface between the composite riser body and the metallic connector. Since an inner liner is often used to provide a fluid-tight pressure barrier for the composite riser body, a reliable seal design for the liner will need to be provided at the composite-metal connection. Various composite-metal interface designs have been proposed. However, their relative merits have not been fully understood and evaluated. Since the cost of metallic connectors and complexities of composite-metal interface construction will have a major impact on the weight, cost, and performance of a composite riser, more attention should be given to the design and fabrication of the metallic connector and the composite-metal interface. Hence, there is a need to:

a. develop clear understanding of various advanced design concepts for load transfer at the composite-metal interface,

b. identify and evaluate the characteristic performance of various available liner seal and composite-metal interface designs,

c. develop industry-wide acceptable standard designs for the composite-metal interface, and

d. develop advanced analysis/design methods to enable scaling of subscale test results to predict the performance of full-scale composite-metal joints.

For titanium-alloy risers, opportunities to reduce costs and fabrication/assembly times are directly related to the tubular joining method. The conventional, multi-pass GTA (TIG) orbital welding method, though qualified for butt-welding of titanium riser joints, is a rather slow process and requires post-weld stress relief heat treatment. Development and qualification of faster butt-welding methods for titanium-alloy tubulars (such as orbital plasma welding and radial friction welding) will need to be pursued. Development and qualification of fatigue-resistant and high-pressure threaded connectors for titanium-alloy tubulars will also help to reduce riser fabrication/assembly time.

- Manufacturing Process Control - The mechanical behavior of an advanced composite structure is, to some extent, dependent on the manufacturing process. Adequate control of the processing variables will have a significant influence on the quality and uniformity of the final product. This is particularly true for large-diameter riser joints and long continuous spoolable products. A computer-controlled manufacturing process with on-line monitoring of the fabricated product will ensure product quality and uniformity.

- Inspection - Titanium risers can be inspected by well established inspection methods which have been used for steel structures. Although NDT methods are available for inspecting composite risers, such methods are still somewhat controversial, costly, and too difficult to be conducted in the field. More work is definitely needed in this area.

Recommendations

To overcome the barriers identified above, the following recommendations are made. Some of these recommendations have already been discussed; they are summarized here for completeness.

1. To facilitate and expedite increased use of advanced materials for riser applications, collaborative development and qualification efforts involving end-users, manufacturers, material suppliers, academia, regulatory agencies, etc., must be encouraged and cultivated. Such collaborative efforts will help to pull together resources to overcome the high initial development cost of such risers, and to ensure that commercially viable products meeting the needs of the offshore industry will be developed.

2. System cost-savings must be investigated and emphasized when advanced materials are considered for new riser applications. Cost-savings based on direct material substitution alone, though present for some special applications, might not provide sufficient incentive for using advanced materials for risers.

3. A JIP should be conducted to develop an industry-accepted database for the design of risers using composites. Emphasis should be placed on long-term material performance of composites in marine environments.

4. Standardized simple design methods should be developed to facilitate preliminary riser designs for cost, size and weight estimates. Standardized advanced design methods should also be developed and utilized for all final designs of risers.

5. Innovative riser designs should be promoted to reduce material, manufacturing, fabrication, installation and other costs.

6. Promote and standardize composite-to-metal joint designs to reduce the cost and need for qualifying and re-qualifying products of different designs.

7. Develop cost-effective butt-welding methods and fatigue-resistant threaded connectors for titanium-alloy tubulars.

8. Develop appropriate NDE/NDT methods to aid composite-product acceptance/rejection.

9. Minimize the need for extensive inspection of composite risers by developing computer-

controlled manufacturing processes with on-line monitoring of the fabricated product to ensure product quality and uniformity.

10. Accelerate the development of continuous, reelable composite tubulars. Such reelable tubulars will minimize the need for "costly" metallic connectors, will facilitate riser installation and will facilitate the installation of integral sensors for monitoring the integrity of the risers through their service life.

Summary

Steel risers have served the offshore industry well in "routine" and very demanding applications. In all likelihood, steel will continue to be the material of choice for riser construction for some time to come. However, alternative materials such as titanium alloys and polymeric composites are becoming increasingly attractive as offshore development proceeds into greater waterdepths. This is largely a consequence of increased riser self-weight as the riser traverses thousands of feet of the water column. Justifications for using alternative materials include (system) cost-savings, improved performance and, ultimately, technical enablement. Current riser-development programs attest to the existence of these justifications. In order to gain acceptance by the offshore community, these emerging products must be cost-effective and must not compromise the integrity of the overall system of which they are a part.

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White paper: #3

Material Requirements for Floaters

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1. INTRODUCTION

This paper presents the floating production concepts today, with focus on the governing global design requirements. On this basis the fitness of different materials in different floater designs are discussed. The discussion of the different materials is made in an overall manner, since it is expected that other papers will present in detail the different developments and status for various materials. At last a table of different materials superiority with respect to different design aspects are presented. The table represent the subjective opinion of the author, and is only meant for discussion purposes during the workshop.

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2. SUMMARY

The traditional floater concepts; Semi, TLP and FPSO, as well as the new concept Spar buoy is discussed with respect to major design aspects and criteria. A few new and non-proven floater concepts is also discussed briefly. A separate section is discussing, in very general terms, the different structural materials steel, concrete and composites with the focus on their potential use as construction materials in the main structural body of the different floaters relevant for the future. The materials aluminium and titanium are also briefly discussed.

3. CONCLUSIONS

From the evaluation of the different materials used in different kind of floaters, it is concluded that the dominant material for the future will still be *steel*. Further, the trend is that the use of steel materials with high strengths will increase. The main reason for this is; the very good access to steel materials "everywhere", low price, that steel is easy to fabricate/weld, good fabrication efficiency is developed, sufficient safety against total damage is in general obtained. In addition the steel material is well accepted in all parts of the industry, and well established design rules are available. All the aspects mentioned will also be important factors in the future.

In some few special applications other materials might be selected, such as:

- concrete in deep draft floaters (DDF's, Spar Buoys)
- concrete in ice infested waters
- concrete in regions with limited infrastructure, deep water/sheltered areas and low manpower costs
- composites in very deep water TLP hulls, say in 2000 meter water depths and beyond
- composites in deck structures for semi's and deep water TLP's

The use of light weight materials, like composites, aluminium (and titanium) will be used in more extent in topside applications in the years to come. This will influence the costs also for the substructure due to a reduced weight to carry for the floater. However, the use of alternative materials in topsides applications should not be part of this paper, and further discussions is therefore left to another occasion.

4. RECOMMENDED DEVELOPMENTS

4.1. Steel

The recommended development of steel is within:

- Materials with higher tensile capacity combined with good fracture toughness.
- Develop efficient methods to protect steel against corrosion
- Continued improvements of other material properties, weldability, fabrication, quality control, corrosion resistance etc.

Additionally, it is seen as a potential to better utilise the materials by development of better design tools to improve the designs with respect to fatigue.

4.2. Concrete

The recommended development of concrete is within:

- More efficient construction methods, using less manning
- More efficient quality control methods
- Light weight concrete, also efficient to fabricate

4.3. Composites

The recommended development of composites is within:

- Cost efficient fibres, resins and fabrication methods
- General qualification of composites as construction material
- General qualification of composites in fire and toxicity safety perspectives

4.4. Other materials

The recommended development of *aluminium* is within:

- Alloys with higher structural capacities (ultimate strength, fatigue, crack propagation)
- More efficient welding methods providing good properties also after welding

The recommended development of *titanium* is within:

- Alloys better with respect to crack propagation
- More cost efficient materials in general

5. FLOATER DESCRIPTIONS

5.1. FPSO

Characteristics

The FPSO, or the Production Ship, consist of a ship hull with different tanks; mainly for storage of crude oil, condensate and ballast water. The hull deck carries the process packages, utility systems, the living quarters, cranes, the off-loading systems etc. The ship hull is typically arranged with a moon-pool for the turret, as illustrated in **Fig. 1.**

The ship hull has typically a length of 200 to 250, a breadth of 35 to 50 m and a depth of 20 to 30 meters. The storage volume for crude oil varies typically from 50 000 m^3 to 250 000 m^3. The ship hull will be designed to withstand a 100 year storm condition, survival in a 10000 year storm condition and when damaged in a 10 year storm condition. Additionally, sufficient structural capacity to fatigue loading for the service life, typically 10 to 30 years, is required.

The stability is provided by a GM of minimum 1 meter in intact condition, and minimum 0.3 m in a damaged condition in combination with sufficient freeboard. The tank arrangement in the hull is arranged in such a way that a minimum draft change during off-loading is provided, and so that the stability is sufficient even with a number of tanks half filled (considering free surface corrections to the GM).

The hull is further designed in such a way that dynamic motions are acceptable for the process. The turret is traditionally positioned forward of mid-ship, hence giving natural weather vaning capability of the hull. In this way the static environmental loading on the hull is kept to a minimum, resulting in a minimum size of the mooring system, and reduced loading on the risers, turret etc. Additionally, the motions become small which is advantageous for the operation of the process and the comfort for the personnel onboard.

The turret is a turntable moored to the seabed. Additionally, the turret supports the flexible risers which provide the transportation of the unprocessed hydrocarbon fluid from the reservoir to the process topside, via a swivel or a drag chain system.

The critical functional requirement for the design of the hull size is the storage volume and the topside area requirements. A storage volume of typically 4-8 days production is common, mainly given shuttle tanker available. The depth of the hull is primarily governed by fatigue requirements. The freeboard must be satisfactory to avoid water on the process deck. In most cases stability concerns are not critical.

Lately the development of FPSO's with drilling facilities, see **Fig. 2.** (For large FPSO's, say with lengths above 200 meters, the motion characteristics of the drilling area become superior). In the future FPSO's with dynamic positioning will probably also be used. The design considerations will in principal be the same for these vessels as for traditional FPSO's. However, for an FPSO with drilling both stability and deck space requirements could become critical due to more weight and equipment needed on the topsides. Hence a wider ship hull might be needed.

Material requirements

Fatigue loading from the longitudinal dynamic wave bending moments, see **Fig. 3** will normally be the critical design loading for the hull. The use of normal ship steel qualities are traditionally used in most parts of the hull. Efforts are made to make designs details which avoid high stress levels causing fatigue damage.

Normally, the floating production units are built in accordance with the Rules of recognised classification societies like DNV, Lloyds Register of Shipping etc. The design rules, material selection/requirements and fabrication/quality control requirements are specified in detail. In Norway all semi's and production vessels are designed to DNV Rules (Njord, Visund, Norne Troll C). In recent years the Norwegian Offshore Industry has developed their own standards for offshore production platforms; NORSOK standards, where experience from previous projects are implemented to material and fabrication standards. These refer to established international standards like EN standards. Materials with strengths from 230 to 500 MPa are specified.

For primary and special structural elements highly weldable steel grades are specified; low carbon equivalent steels with low level of impurities are required. This means that fabricators have more freedom to select welding parameters. As a consequence it is then possible to weld these steels to lower costs. However, still the main requirements are, "as always", that the structure shall be free from crack-like defects in fatigue sensitive areas. Modern designs take into account fracture mechanical analyses to ensure that defects not become critical during the design life. Brittle fracture developed from fatigue is rather rare today with use of modern steel and good quality control measures. But with the introduction of high strength steels, the risk for brittle fracture may increase as the general stress level increase and therefore the fracture toughness acceptance level may increase if defect tolerances are kept constant.

From one specific project, Kværner selected to use normal strength (NVNS) steel in all parts of the hull except for the double bottom where high strength (NVHS or NVE36) steel was chosen due to buckling criteria. In the turret area increased plate thickness was chosen to compensate for the higher stress levels. High tensile steel was not selected due to fatigue considerations. Where low temperature design is needed, steel grades with impact toughness is required at a specified temperature. Fracture toughness testing of hull steel is normally not required by the Classification Societies (only Charpy V- impact testing required).

The use of light weight materials (like composites or aluminium) have normally given limited benefits due to normally good floating stability for production ships, and that there is no need for forward speed (an issue which often is important for merchant ships). If the FPSO's stability become critical due to high topside weights, the natural design change is to increase the breadth of the hull. The use of light weight materials in the topsides will generally have limited effect to a high cost.

In West Africa the worlds first concrete barge is installed at the N'Kossa field. This ship is not turret moored since no weather vaning capability is required due to small environmental loads and the very dominant wind and wave direction. Additionally the wave heights are moderate, hence the global bending moments and fatigue loading is very small. The selection of concrete as the construction material reduces however the load bearing capacity. A separate ship moored adjacent to the barge is therefore used as a storage vessel. Corrosion issues were also important in the selection of construction material for this barge.

For oil and gas floating production units in steel, the use of standard efficient shipyard construction techniques make it possible to fabricate large volume of ship hulls to low costs. This is a major factor why FPSO's are very cost efficient. Additionally, the topside process become less expensive than modules, on fixed offshore platforms, due to the larger area available, which make it possible to arrange the different process and utility systems in packages, hence a large proportion of the topsides may be subcontracted. This also give an excellent flexibility for the hook-up and commissioning phase, due to the possibilities of doing parallel work. Possible delays in one system package give limited impact on other systems.

Normal and high tensile steel will probably be used in FPSO's in favour of composites and concrete for many decades to come. However, the use of higher strength steels will probably increase as more reliable acceptance criteria are worked out. The use of concrete hulls could however be selected in some very special cases. Use of aluminium or titanium are unrealistic due to cost concerns. For fatigue critical structures, like FPSO's, use of aluminium and titanium have limited potentials.

5.2. FPS's

Characteristics

The FPS, Floating Production Semi, or only the Semi, is characterised with a number of vertical columns arranged between the deck structure and the submerged pontoons, see **Fig 4**. The columns are typically arranged in the corners of the deck. Optionally, also columns between the corner columns might be arranged. (For new builds the lower hull consist typically of either a ring pontoon or two pontoons connected together by use of horizontal trusses (catamaran semi's).

A number of drilling semi's are also converted to production units after some years in drilling operation. The most used semi's for this purpose are the Aker H-3 and the Sedco Forex 600 and 700 series, see **fig. 5 and 6.** These semi's have typically 6 to 8 columns and a set of diagonal and vertical trusses to support the deck structure. Typically 2 pontoons are arranged.

The motion behaviour of a semi is excellent. Therefore the semi is often used for drilling of exploration and production wells. A good motion behaviour is obtained by *i)* a small water plane area in combination with submerged buoyancy columns give very small hydrodynamic excitation forces from the waves, *ii)* carefully selecting design parameters like distance between columns, depth of pontoons, width of pontoons etc. giving cancellation of vertical excitation forces, high hydrodynamic damping etc.

A semi is often the preferred concept where inclusion of drilling facilities is desired by the operator. Inclusion of drilling facilities on the production unit is often desired because *i)* the reservoir is complex and need for work over operations in the wells are frequent, *ii)* higher drainage is made possible by utilising new technology made available throughout the life of the field. Many operators prefer to have access to their own drilling facilities since this enable them to get more oil out of the reservoir. Additionally the rates of mobile drilling units have lately increased significantly, mainly due to lack of available rigs. This issue is very important for deep water operations.

The semi is kept into position by means of catenary mooring lines arranged from the corner columns typically. Dynamic Positioning (DP) is used for some few drilling semi's but is not yet used as the only mean to keep position for permanent production platforms.

The semi is quite weight sensitive in the way that the stability of the semi often is the governing design parameter. Sufficient stability is provided by a combination of *i)* sufficient water plane inertia moment, *ii)* small enough compartments to limit inclination in case of water filling. A low vertical centre of gravity (VCG) is desired from a stability point of view. For this reason typically 10 000 to 20 000 tonnes of ballast waters in the pontoons are arranged during operation. This ballast water also act as a mean to control the horizontal centre of gravity, and could be used to minimise global static loading if so desired.

A typical draft for a steel semi is 20 to 30 meters, see **Fig 4, 5 and 6**. A concrete semi will typically be deeper, like the Troll B semi with a draft at 40 meters, see **Fig. 7**.

Structural-wise, the idea with a steel semi is often that about the same global stiffness is provided in the deck structure as in the pontoon structure. In this way extreme loading is avoided, hence reducing the criticality for fatigue. For the Troll B concrete semi, the pontoon to column connection is so stiff that minimum moments were transferred between the column top and the deck structure. In this way the structural loading in the deck structure become relatively small. However, this requires a very stiff substructure which probably is best obtained by using concrete in the substructure.

Material requirements

With reference to the characteristics of the semi as described above, it is for stability reasons, important to keep the weight of the topside low, while it is no meaning to reduce the weight in the pontoons, since weight reductions in this part of the structure must be compensated by ballast water in order to keep a low VCG. For the columns a low weight have limited but some positive effect. Further, the hydrostatic pressure become an important design parameter for columns and pontoons for increasing drafts. Considering the issues mentioned, the use of concrete in the pontoons is in principal a good idea. Similarly, for stability reasons, the use of composites in the lower hull seem not to be a good solution. The use of steel in the lower hull is also logic, and suitable for hulls with limited drafts.

Use of light weight materials like composites and aluminium will however make sense in the topsides from a stability and corrosion point of view. A topside structure is however very complicated with a lot of penetrations, heavy point loads and exposure to fire and impact loads. Use of both composites and aluminium in the topside deck structure is expected to be unrealistic in a short time perspective. However, in the future these materials might be used provided improvement of materials fabrication processes (cost related issues) and successful qualification/testing of such materials hydrocarbon environment.

The use of light weight materials in topside applications, in non-structural parts like living quarter, helideck, fire walls etc., make sense from a stability point of view. However, non structural applications is not meant to be covered in this paper and is therefore not further discussed.

Steel will probably be the dominant material for the main structural parts in semi hulls and topside decks for many years to come. For deeper and large semi's, there is however potentials for concrete. Obviously, the use of hybrid structures, i.e. concrete in the lower part (pontoons and lower part of columns) and steel in the upper part of columns and deck is theoretically a logic combination of materials.

5.3. TLP's

Characteristics

The TLP is a floating structure consisting of columns and submerged pontoons similar to the semi. The positioning of the unit is however made by use of vertical tensioned pipes (tethers) arranged vertically between the pontoons and the foundations arranged on the seabed directly below the TLP, see **Fig. 8**. In this way the TLP is allowed to move horizontally but not vertically. The pretension in the tethers is sufficient to avoid slack tethers in the extreme wave conditions. The natural frequencies for the TLP in heave, pitch and roll is in the high frequency domain of the wave spectrum in order to avoid fatigue damage in the tethers. This is different for all other floating concepts which typically have all natural frequencies in the low frequency domain of the wave spectrum, see **Fig 9**. The formula for the eigen period in heave is expressed as $T_{heave} \approx 2\,\pi * (M+A_{33}/\,k)^{1/2}$, where $k = E*A/L$, M = platform mass, A_{33} = added mass in heave, E = Young's modulus for the tethers, A = tether cross sectional area, L = tether length. Considering this expression, it is seen that the eigen period in heave increases with increased mass and with increased water depth. This means that it become increasingly important to keep the mass low when the water depth increases. For large water depths the eigen period in pitch (and roll) become increasingly important since the stiffness in pitch (and roll) is mainly given by the arm (a_t) between the tethers (read column distances) and the water depth. The formula for the eigen period in pitch is $T_{pitch} \approx 2\,\pi * (M_r+A_{55}/\,k)^{1/2}$, where $k = E*A*a_t/L$, M_r = rotational platform mass, A_{55}= added mass in pitch. For moderate water depths, say 300 - 800 meters, the eigen periods in roll and pitch are not critical. However, for TLP's in deeper waters, say from 1000 to 2000 meters, these eigen periods could influence the design by requiring a larger distance between the tethers unless the weight can not be reduced. In this perspective a triangular shaped TLP will have some advantages, see **Fig. 10.** However, for a triangular TLP the increased span between the columns give increased steel weights in the topsides. In addition, the available deck area for risers for a triangular shaped structure is more limited than a squared shaped. An alternative to the triangular shaped TLP will be to have a squared TLP with inclined columns, see **Fig 11,** hence giving enough distance between the tethers to provide sufficient stiffness in pitch/roll as well as giving a squared deck arrangement providing many wells, and reducing the deck span.

Material requirements

All TLP's world wide up to date, except for Heidrun, are made of steel. The materials guidelines used for the design of TLP's has traditionally been the specifications for fixed offshore platforms. Important material requirements are generally high robustness against brittle fracture and high fracture toughness. Fracture mechanical analyses have commonly been used for critical areas. Strict requirements to weldability and minimum allowable cracks in welds have usually been specified. Requirements to material qualification is often used for critical structural elements. The reason for all these strict requirements are the harsh environments for the structures, low temperatures, cyclic loading, large plate structures, normally large in-built tension, difficult access for repair and maintenance and potentially enormous consequences in case of damage to the structure. Additionally, the design life is often 20-50 years without possibilities for docking. Therefore, any repair operation will be expensive. For all these reasons all steel qualities used must have very good weldability and strict requirements towards brittle fracture. The welds must be free from cracks which could lead to brittle fracture through fatigue damage. This of special importance in critical structures with high level of tension. Generally in may be stated that the acceptable crack sizes in welds decrease with increased yield strength (level of tension) in the material.

Use of high strength steels have been introduced where weight saving are desired. In Snorre and Heidrun topsides, high strength steel with strict requirements to fracture toughness and defect acceptance level were used.

The TLP is the most weight sensitive structure of all floaters. The use of light weight materials like composites and aluminium (titanium) in TLP's and in particular deep water TLP's is therefore of large interest. For TLP's in deep waters the effect from the pretension in the risers is of large significance. The use of light weight risers, and in particular composites have shown to be the single most important measure to reduce the topside loading.

For the Heidrun TLP, the use of concrete in the hull was selected. The philosophy was that the very large buoyancy volume needed was most efficiently obtained by making the columns deep. The high hydrostatic pressures will require a quite thick wall and the weight increases. However, for very deep draft TLP's, relative small vertical dynamic loading from the waves are introduced. Hence a relative moderate size of tethers is required, seen in the perspective of the large displacement of the TLP.

As stated above, both philosophies (composites for small deep water TLP's and concrete in large and deep draft TLP's at moderate water depths) make sense. These alternatives must however compete with traditional steel designs which today look as the most cost effective solution. In some cases, alternative materials could however be selected (composites in very deep waters and concrete in very large structures or in icy waters).

Kværner is participating in a European research work in order to establish safe acceptance criteria for use of X-tra high strength steels (500 MPa) to ensure that brittle fracture does not occur.

5.4. Spar Buoy

Characteristics

The Spar Buoy is in principal a large cylinder which is floating vertically in the sea, see **Fig 12 and 13**. The excitation in the vertical direction (heave) is mainly governed by the draft. The formula for the eigen period in heave is $T_{heave} \approx 2\ \pi * (M+A_{33}/\ k)^{1/2}$, where $k = A_w*\rho*g$, M = platform mass, A_{33} = added mass in heave, A_w = water plane area, ρ = specific density of water and g = gravity of acceleration. The idea with the Spar Buoy is that the deep draft introduce small vertical forces and hence the motions also become small. In this way pre-tensioned risers and drilling facilities may be included. In Gulf of Mexico with mild environmental conditions, the Spar Buoy seem well suited. For Norwegian waters, where the seas are very rough, the required draft should be in the range of 150-220 meters to avoid excitation of the eigen period by swell. (25 sec. giving 150 m, 30 sec giving 220 m typically). Such deep drafts represent challenges with respect to overall costs, deck mating and towing (draft limitations). Since the Spar Buoy yet is an non-proven concept the hydrodynamic behaviour is somewhat uncertain. Consequently the availability for drilling operation is therefore also somewhat uncertain.

For the Spar Buoy crude oil storage may be provided in the lower part of the structure. Providing tanks open to the sea, the differential pressure between the inside and the outside of the shell will be limited. In the case that storage is not required, the lower part of the structure should be non-buoyant. This will in both cases provide a relatively low differential pressure between the inside and the outside of the shell, hence steel may be used. Buckling will however in many cases govern the design, especially for large diameter spars. This means that concrete could be a good alternative to steel.

At the lower elevations the substructure is primarily in tension, and in this perspective the use of steel is logic. Using concrete means that the concrete must be very highly pre-tensioned.

At higher elevations where the structure is more in compression, the use of concrete make sense from a structural point of view. Concrete at high elevations will however give stability penalties.

In the deck area the use of steel is logic since the Spar Buoy is relatively robust for high topside weights. For the same reasons, the use of light weight materials in the topsides give limited benefits. Further, the use of light weight materials in the lower hull is not the way to go, since this will increase the VCG and compensation by use of heavy ballast will be needed. This will represent a non-cost-efficient structure.

Material requirements

Summarising the discussions above the most cost efficient material to be used in the Spar Buoy will probably be steel. This applies most clearly to smaller Spar Buoys. For larger Spar Buoys with storage, concrete might be preferred, but steel is still an alternative.

For the topside deck structure steel is the obvious selection. Using light weight materials such as composites or aluminium in the topsides from stability issues alone will not pay off for a Spar Buoy.

5.5. Other Concepts

Mini-floater

The mini-floater is a vertical tensioned spar buoy, see **Fig. 14.** The design issues for a mini-floater is a combination of the issues relevant for the spar and the TLP.

In fact, the structure looks like a spar buoy, but is in principal a TLP. The hull is more in tension than a traditional spar buoy due to the tether tension, and some more buoyancy will be needed for a mini-floater than for a spar comparing same topsides. Consequently a deeper draft or a larger diameter is required. The principal idea with a mini-floater is however that it shall be a minimum solution. Therefore the substructure of a mini-floater will in most cases be small, and hence the use of steel as construction material is the most probable selection.

DDF

The DDF is a semi with very deep draft, see **Fig 15,** and uses the same design principals as a spar; a deep draft means small excitation forces from waves. The DDF will therefore move more or less like a spar both in heave, pitch and roll. However, the 4 column typically of a DDF offers excellent conditions for traditional deck mating. Additionally, the arrangement of many risers is possible without using a guide frame for the risers. An additional benefit compared to a spar buoy is that a possible gas leakage in one production riser can be naturally ventilated and the chances for explosions are reduced.

The DDF is also fit for crude oil storage.

All this indicate that concrete as construction material is logic. However, steel is also an alternative since the storage tanks will be open to sea and buckling problems may therefore be limited.

The DDF is relatively robust against high deck loads and the use of light weight materials will therefore have limited effect. Steel is therefore recommended for the topside main structure.

KRiS

KRiS is the Kværner Rigid Riser Semi and is in fact two concept assembled into one, however able to move relative each other, see **Fig. 16**. The inner structure is a mini-minimum TLP; in fact only carrying the riser tension and the well-heads with riser tensioning systems. The main structure is a deep semi, something in between a regular semi and a DDF. This semi may move with the waves and will carry all the main loads, such as drilling systems, drilling loads, process, living quarters, utilities, storage etc. As known, since the TLP is a very weight sensitive concept the cost penalty for the tether system is high unless the weights may be reduced. However, the TLP offers dry well-heads (in fact the only proven floating concept today with dry well-heads). On the other hand, for a TLP the load bearing capacity is expensive. Therefore the KRiS concept; take the best from both the TLP and the semi / DDF and mix them. The two bodies may slide in relation to each other by using a sliding bearings consisting of a synthetic material towards steel.

For the central minimum TLP type structure, steel should be used, alternatively could be considered. The outer semi structure should be in both steel and concrete (as for traditional semi's and DDF's).

6. OPTIONAL MATERIALS - A BRIEF DISCUSSION

6.1. General

This section presents a brief discussion of some material aspects of importance for the designers when doing a global structural design of a floater.

A more detailed discussion of specific materials is expected to be covered by other authors at the conference.

In general terms it may be said that extensive mechanical qualification programmes are needed prior to use of non-traditional materials in order to establish an acceptable level of safety. This is necessary in order to obtain Authority approvals. Lack of design rules, experience, limited availability etc. are factors which retard the development of application of new materials. The oil and gas industry is considered conservative when new materials are proposed used.

Kværner was one of the first companies to design platforms with the new high tensile TMCP steel already in mid 1985. Since then Kværner has been the leading company with introduction of new steel materials. Kværner also designed the worlds first drilling riser in Titanium (Heidrun) and did the qualification of the proposed Titanium production and export risers for the Visund field for Norsk Hydro in 1995. Kværner has also lately, together with DuPont and Conoco developed conceptual designs for the use of composites in TLP main structures. Kværner is also one of the worlds most advanced user of Aluminium, ref. the spherical LNG tanks in the ships designed by Kværner Maritime and built by Kværner Masa Yards and other yards. Kværner has their own fabrication site for concrete structures (Hanøytangen), and delivered the world first concrete semi, i.e. the Troll B semi to Norsk Hydro in 1995.

All these experiences make Kværner feel very well competent to discuss the issues of the use of materials in floaters.

6.2. Steel

6.2.1 General

Within the oil and gas offshore business, the following categorisation of steel apply:

- Normal steel with yield strength up to 240 MPa
- High tensile steel with yield strength from 265 to 390 MPa
- Extra high tensile steel with yield strength from 420 to 690 MPa

Within the shipbuilding industry the use of so-called mild steel with yield strength between 240 MPa (NV 24) is the most common materials, but high tensile steel up to 360 MPa (NV 36) is also used in some extent. Within the oil and gas industry the use of steel with tensile strength of 420 to 490 MPa is very common. In special applications like mooring systems and steel tethers for TLP's the use of steel with yield strength up to 690 MPa is used (Heidrun and Snorre).

6.2.2 Market Acceptance

Carbon steel material are the far most common materials used in main structural elements in the offshore oil and gas business. The reason for this is many, of which the most important probably are:

- long tradition with use of steel as construction material generally (merchant ships, marine ships, submarines etc.). Construction techniques are well known by numerous personnel. Recognition and acceptance has been achieved in all industries and by authorities and classification societies
- efficient repair techniques are developed, also for welding under water.
- a variety of materials have been developed over the years, generally with increasingly good properties like weldability, structural capacity, fatigue resistance, fracture toughness toughness and easy to protect adequately against corrosion
- the cost for procured steel has been reduced over the years
- the cost of steel fabrication has over the years been reduced due to modern construction techniques like automatic welding, shipyard construction principals, pre-assemblies etc.,
- large investments have been made in construction facilities, systems for transportation and installation. The size of structures have increased with successful results generally.
- the oil and gas industry has up to now primarily been involved in field developments in relatively shallow water (less than 300 meters) where fixed platforms can be used. The need for light weight structures in these water depths are quite moderate due to the fixed platforms relatively high capacities for carrying topside loads.
- the steel industry has been subsidised in many countries for decades due to the high priority from politicians to increase local employment

6.2.3 Material Developments

The latest developments of steel materials is mainly within improved steel melting and refinement practices and advanced rolling techniques, which have resulted in:

- higher tensile strengths and ductility
- better weldability, less need for expensive heating and post weld heat treatment, larger heat input during welding can be tolerated without ruining the material properties
- better brittle fracture resistance and improved fracture toughness
- better fatigue resistance

In addition, the designers continuously improve the designs against fatigue damage, and develop better surface protection systems which protects the steel against corrosion.

The most important development the last years is probably the development of steel with high capacity and good waldability. In this respect the development of high strength, ultra clean, low carbon steel and low carbon equivalent (CE, PCM), like so-called TMCP (thermo-mechanical controlled process) steels have gained a large market share in recent years. To day these steels may offer very good weldability where optional chemical composition, rolling, heat treatment techniques are combined. Heavy plate structures can be welded with minimum pr-heating and high heat input welding methods may be used.

Also modern quench and tempered steel offer good weldability properties when high strength steels are selected (above 450 MPa). Normalised steel which were the main materials 5-10 years ago are still perhaps the most common material in the 300-400 MPa range.

The main problem the recent years has been to develop weld metal properties with same good properties as for the plate material.

Better properties in the weld metal has been a general requirement in order to prevent global deformation takes place in the weld. Whether this approach is correct for high strength steel is questioned especially if it is low fracture toughness adjacent to the weld metal.

6.2.4 New steel applications

The use of floating production platforms have increased over the latest years. Both semi's, TLP's, production ships and spar buoys are selected as concepts for development of hydrocarbon reservoir world-wide. Even if we have seen a few concrete floaters, the dominant material used is steel. This trend is expected to continue.

6.2.5 Costs

The procurement cost for some steel alloys in large quantities are typically:

normal steel bought in Europe:	4 NOK / kg
high tensile steel bought in Europe:	5 NOK / kg
high tensile steel bought in Asia	4 NOK / kg

The fabrication cost depend a lot of the fabrication complexity, tolerance requirements, need for machining or surface treatment etc. The geographical area of construction is also of importance, however less nowadays than only few years ago. The far East seem to be the less expensive, while the cost rates in Europe are less varying than before. Typical cost for fabricated steel in Europe today (floater hull with engineering, procurement, fabrication and surface treatment) is typically in the range of 30-50 NOK / kg.

6.2.5 Future Research & developments

The development of steel materials in the future will probably focus on increased

- use of higher tensile strength steel, especially same level of safety as for normal strength material
- Establish acceptance criteria, develop reliable fracture mechanical test data and design analyses
- improve fatigue resistance, and fatigue resistant design

- improve corrosion protection methods
- improve weldability for HS steels, hence more efficient fabrication methods can be used
- improve impact toughness/fracture toughness for HS steels and weldments
- connection to other materials like aluminium and composites etc.
- more efficient welding techniques without ruining mechanical properties

It is also seen as a great potential to lower the costs for steel structures by utilising more the capacity in the materials by; developing the design tools and improve the co-operations between designers, fabricators and material experts.

6.3. Concrete

6.3.1 General

Concrete has its major advantage by a high capacity in compression. The notation of different concrete qualities is therefore denoted C60, C70 where the figure (60, 70) represent the compression strength in MPa. Typical qualities for offshore applications are C60 to C120, but qualities up to C150 exist as standard product in the market.

In addition to this notation the concrete is denoted according to its density, such as

- NDC (Normal Density Concrete) with typical densities in the range of 2,4 - 2,8
- LDA (Low density Aggregate) with densities 2-2,3
- ULD (Ultra-low Density Aggregate) with densities below 2,1.

6.3.2 Market Acceptance

Concrete as construction material has been used with success for a couple of thousand years, many of the oldest structures are still existing and quite a few of them even still in use. Also in marine environments concrete has often been a preferred construction material due to its strength and durability and its minimum requirement for maintenance. In periods concrete also was a frequent construction material for ships, but does of course have a handicap due to its low dead-weight/displacement ratio with regard to self propelled vessels carrying cargo on long journeys. For this reason concrete has in connection with marine structures during the last few decades mainly been chosen for gravity based or anchored structures, like quay structures, bridge foundations and offshore platforms for the oil and gas industry.

Since the start of the oil and gas era in the North Sea in the early seventies, 26 large concrete structures have been installed in the North Sea for water depths ranging from 70 to 350 m.

Most of them have been of the gravity base structure (GBS) type. These platforms have been installed virtually completed, carrying with them topsides loads of up to 65,000 tonnes from the inshore construction site to the field location. The two last ones, however, have been floating structures, the Heidrun TLP (tension leg platform) carrying 65,000 tonnes topsides and the Troll B catenary anchored, semisubmersible platform carrying 32,500 tonnes topsides.

Five further concrete platforms are presently being completed. These are the GBS for the Hibernia field in Canada, a concrete barge for the N'Kossa field outside West Africa, the two GBS's for West Tuna and Bream B for Bass Strait, Australia and a GBS for the Wandoo field outside Western Australia.

Major oil and gas platforms have been built in Norway, Great Britain, Sweden, the Netherlands, France, Germany, Canada, USA and Australia, but smaller structures for the same purpose have been built all over the world for a series of oil companies.

The start of using concrete in fixed platforms in the Norwegian part of the North Sea was primarily driven by cost consideration. Some other factors were also important, such as:

- their was a need for very large fixed platforms for developing some large fields discovered. Their was a need for storage since limited pipeline infrastructure was present
- their was a limited number of available steel construction yards in Norway and the need for increasing local employment required new-thinking for establishing competitive solutions to steel structures. The invention of the GBS (Gravity Base Structure) by Selmer Furuholmer came timely.
- Norway had long experience with construction of concrete structures, also exposed to sea-water environments etc. (bridges, foundations, quays etc.)
- Deep Norwegian fjords made it possible to do inshore deck mating successfully, with subsequent tow out to the field with a fully commissioned deck
- Cost of manpower in Norway in the 1970's was low

Concrete gravity structures had it's main cost advantage by the possibility of doing complete hook up and commissioning inshore.

For two floating structures; Heidrun TLP by Aker and Troll B semi by Kværner, both were successful with respect to design and project schedule. However, severe cost overruns were envisaged in both cases due to i) natural prototype additional costs and ii) additional work introduced to secure that no repeat of sinking during submergence testing should happen (ref. the sinking of the Sleipner A substructure during submergence test in 1991). Since these overruns mainly were covered by the two referred contractors, their willingness today to offer such platforms again on EPCI-basis is very low. Therefore, the use of concrete as a construction material in floating platforms, in the North Sea at least, does not look encouraging in a short time perspective.

However, concrete have some attractive features which make concrete still a candidate for field developments in deep waters and icy conditions.

6.3.3 Material developments

The development of light weight concrete has showed large improvements over the last years. The developments of high capacity concrete has also progressed, as well as more corrosion resistant concrete materials and concrete absorbing less water. This trend is foreseen to continue.

LWA Concrete
In fixed offshore construction normal density concrete (NDC) has normally been used. For floaters it is crucial to minimise the weight. For this reason the preferred concrete in the future will most probably be light weight concrete (LWA typically). Some key design considerations using LWA are presented below.

In Norway the development of a new kind of LWA has taken place the latest years. A modified normal density (MND) concrete was developed for the Troll GBS. It has also been used on the Troll Olje floater. The MND concrete has the same design parameters as a normal density concrete except for the density which is reduced to 2,250 kg/m^3 (non-reinforced).

The following parameters are significant when considering LWA concrete:

- Concrete strength
- Bending Moment versus axial forces
- Concrete stiffness
- Shear capacity
- Detailing
- Tightness

Concrete Strength
The concrete strength over density ratio is approximately the same for a LWA concrete as for a ND concrete. This means that the capacity to carry membrane forces are almost unchanged for the LWA concrete.

Bending moment versus Axial force capacity.
The axial forces is approximately the same for the LWA and ND concrete in walls /slabs with different thickness but with the same concrete weight. But the bending moment capacity

increase significantly for the LWA and gives weight saving potentials especially for the concrete floaters. This gives cost savings because the floaters are sensitive to weight.

Concrete stiffness
The concrete rigidity decreases significantly with the density even if the weight is taken in account.

Shear Capacity
The concrete shear capacity is considerable less for LWA concrete even if the slab/wall thickness is increased to account for the weight.

Detailing
The reduced compressive and tensile strength call for cautious detailing. In general the weaker aggregate of LWA concrete has reduced capability to stop or divert crack propagation and call for more correct detailing.

Tightness
The tightness of LWA concrete has shown to be better than for ND concrete.

Construction
The LWA concrete is somewhat different materials than ND concrete it is important to use skilled and experienced personnel in the construction work.

As reinforcement material in the concrete steel is generally used today. The development within steel qualities apply also for such reinforcement materials. New materials like carbon fibre could also be used if the cost of carbon fibres come down. Research in this area is performed.

6.3.4 Fabrication

Construction of concrete is traditionally a highly manual process, and is to a limited extent suited for automatic processes. However, if concrete shall be able to compete with steel in the future, it is seen necessary that more efficient fabrication processes should be developed.

An other issue is the aspect of flexibility. It is an impression in the Norwegian market that the flexibility of a concrete platform is much less than for a steel floater. One issue is that it is harder to increase the stability for a concrete semi than for a steel semi. Additionally it is hard to make adjustments to facilities to be arranged onto the hull such as riser guide frames etc. since such possibilities are limited to the available embedment plates built into the structure during the initial construction phase.

Repair procedures for concrete can be made by traditional techniques like grouting (as used for piles and similar applications)

6.3.5 New concrete applications

Lately, as previously mentioned the use of concrete in floating structures has showed technical feasibility in the three different floating concepts TLP (Heidrun), semi (Troll B) and Production ship (N'Kossa).

In the near future the use of concrete in floaters probably has largest potentials for

- ice infested waters
- in the hull for deep drafts; the DDF (deep draft floater) and the Spar buoy concept having their biggest potentials in deep waters
- floaters not exposed to severe loading and where corrosion issues could be dimensioning (West Africa etc.)

6.3.6 Costs

The main cost elements for a concrete structure are:

1. material (sand cement, steel reinforcement bars / cables)
2. manpower, construction work
3. form-work, yard
4. marine operations
5. capital, insurance etc.

Compared to the similar costs elements for steel, the steel costs referred to item 1, 2 & 3 above, all have been reduced significantly over the last years. For concrete the same trend is not envisaged.

Considering the general increase in man-hour rates for personnel in the developed countries, the cost efficiency of concrete structures in the near future is doubtful, unless significant automatic methods are developed. However, considering the nature of the concrete structure, it is hard to see how construction costs can come down significantly (extensive quality control will always require a lot of personnel, etc.).

Yard costs and marine operations (out of dock operations) could however come down provided additional investments at the yards, such as dry docks with removable and reusable dock ports.

Conclusively, it is hard to see how the cost for concrete construction will come down to a level low enough to compete with steel in the near future.

6.3.6 Research & developments

The main effort in research and development for concrete should come in areas of:

- more efficient construction techniques using lower manning
- more efficient quality control methods
- lighter materials which also are efficient to fabricate

6.4. Composites

6.4.1 General

Composites as a material is constructed from fibres with high axial strength and stiffness bonded with a matrix material (resin) giving shear strength and keeping the shape of the fibres. There exist a variety of fibre qualities and resin materials with a wide range of properties. The composite properties may also be tailored by varying the fibre amount and direction within a section.

Up to present day, composites have only to a limited extent been used in floaters, except for high speed vessels and small craft boats. In offshore business, composites have mainly been used in tanks and low pressure pipes, grating and hand-railing. These are products that can be machine-manufactured in small sections which are easily be installed/assembled on the floater.

The advantages of composite materials may be summarised as high strength/weight ratio, good formability thus allowing complex shapes, and high fatigue and corrosion resistance, leading to low life-cycle costs.

The main disadvantages of composites are lack of design rules and qualification of material, design and fabrication methods. There is little in-service experience from composites in offshore constructions. Composites have low impact and post-impact strength.

6.4.2 Latest Progress in material developments

Chemical and fiber companies currently devote a great deal of effort to the development of advanced fibers and resins and significant improvements have come available in recent years. Prices are falling as volume and competition increases.

The most extreme fibers give laminate modulus comparable to that of steel, with a density of 20% that of steel. Remarkable improvements in the stiffness of carbon fiber have been achieved while retaining their high strength and strain to failure. A unidirectional laminate with a modulus matching the modulus of steel, yet weighing approximately one-fifth as much is obtainable.

6.4.3 Applications

Composites have not been used as construction material within floaters up to date.

The conceptual work performed by DuPont, Conoco and Kværner under the Composites Alliance Agreement show that composites structures are technically feasible both for pontoon, columns and deck structures for TLP's, as was studied. (The same will apply to similar structural components for semi's). However, no total cost gains for the overall (TLP) structure was observed when comparing to a similar structure in steel. This, combined with the fact that composites must go through significant testing due to lack of reference projects and common concerns about safety fire and toxicity issues, indicate that the use of composites as main structural elements in offshore platforms will be far into the future.

One exception to this might be for ultra deep water TLP's (say 2000 meter water depths and beyond), where weight reductions will be very important. In such cases the use of composites may pay off also in main structural elements.

The use of composites in riser and topside application make sense and will pay off in many cases in a total concept cost perspective. However, this topic is not part of this paper.

Detailed results from the research mentioned will be presented at the OTC conference 1997.

6.4.4 Construction

Generally, there are many more variables (material, angle, form, thickness, etc.) available to the designer of composite components and therefore many more possible solutions compared to construction using concrete or metals. It becomes however increasingly important to precisely specify the functional requirements (loads, dimensional limitations, stiffness, etc.) at the start of the design process. Experience teaches that the more complex the design requirements are, the more impact seemingly insignificant changes have on design optimizations. Prototype testing is an efficient way to confirm both the design adequacy and the integrity of the manufacturing process. It is much more important in composite design to consider the manufacturing process during design, not only to avoid designs which are impractical to make, but also to minimize the component cost, e.g. by repetition of simple forms. It is also important to efficiently plan and exercise the design process and qualification test program so as not to put undue economic burden on the price of new products.

Once a composite structure is designed, the challenge is to construct the material as it was designed; to keep the fibres located and oriented as specified until the resin has hardened, and to secure correct amount of resin smoothly through the material without creating voids. Ideally, the structure should be constructed in one piece to avoid joining of sub-assemblies. All joining are potentially weak points, and often require much material and intensive labour to meet strength requirements.

To make composite parts, the fiber and resin must be combined, configured into the desired shape and orientation, and heat and pressure applied to either cure or consolidate the part. Heat can come from an oven, autoclave, heated press platen, heated tool, or the exothermic reaction of two chemicals mixed together. One atmosphere can be applied to a part by encapsulating it in a vacuum bag. If more than one atmosphere of pressure is required, the part is processed in an autoclave or press. Composite sections that can be manufactured by machines are generally much cheaper than sections that require labour.

Generally, the following principal composite processing methods are available:

- Bulk hand lay up
- Spray Up
- Vacuum Bag/ Autoclave
- Filament Winding
- Pultrusion
- Resin Infusion Molding (SCRIMP©)
- Helical Braiding

For a floater the main structural elements showed to be most efficiently produced by the methods: Filament Winding, Pultrusion and SCRIMP. These methods are briefly described below.

Filament Winding
Numerous fiber ends are impregnated, and wound under tension at room temperature on a rotating mandrel. The part is then cured either at room temperature, in an oven, or autoclave depending of the resin system used. The mandrel is then pulled from the part, cleaned, and recycled back to the winding area for reuse. The wound part is then subsequently finished (machined, painted, joined to other components) as required. Thermo-set filament winding can be carried out wet or with dry pre-impregnated tow that has been previously "B-staged" or dried.

The chief advantages to filament winding are that it is highly repeatable and production rates of up to 500 lbs per hour can be obtained. Details of the part geometry will drive the set up time and the number of tows that can practically be wound simultaneously. The technology is very mature, with 5 and 6 axis control machines capable of manufacturing complex geodesic shapes fairly common within the industry. The practices for winding closed ends are well developed, as is the practice of winding in situ metal joints.

Filament winding should be considered as a potential process for pipes, shells, trusses, and large structural boxes, and may be used in combination with other processes such as pultrusion.

Pultrusion
Pultrusion is an automated process for manufacturing composite materials into continuous, constant cross section profiles. The pultrusion process consists of the following six process steps:

1) Fibers and/or fabric pulled from creels.
2) Fibers and/or fabric impregnated in resin bath.
3) Impregnated feedstock physically oriented in shape of final product.
4) Feedstock passes through precisely machined die that provides the heat and pressure required to cure (or consolidate) the part.
5) The profile is cooled in ambient or forced air, and continuously pulled by a mechanism that simultaneously clamps and pulls.
6) Product is cut to length by a flying (automatic) cut off saw.

A wide variety of sections (including hollow) and sizes have been successfully pultruded. The grating used on the Mars platform is fabricated using pultrusion of glass fibers and phenolic resin. The chief limitation of pultrusion is that the cross section must be constant or near constant. A wide variety of part sizes have been made using pultrusion. Parts up to 8 inches high and 60 inches wide have been demonstrated, but most of the industry experience is with parts in an envelope of 8 inches high and 24 inches wide. As parts get substantially larger the dies become very expensive and the required pulling power gets very large.

Pultrusion is also a very mature process, and most of the industries experience has been with polyester, vinylester, epoxy, and phenolic resins. Thermoplastic pultrusion technology is also reaching maturity.

Pultrusion is a good processing candidate for making beams, pipes, and trusses, and for supplying sub-elements to be used in combination with SCRIMP or filament winding.

SCRIMP

The Seemans Composite Resin Infusion Molding Process(SCRIMP) is a patented vacuum assisted resin transfer molding. In a typical process, a dry fabric pre-form is laid up on a female tool. The pre-form is then covered in turn with a peel ply, distribution medium, and vacuum bag. Resin and vacuum lines are attached to appropriate ports. A vacuum is first applied , and then the ports are opened to allow the resin to flow into the pre-form. The key to this process is that the distribution media allows the resin to first spread out over the entire part and then infiltrate the pre-form only through the part thickness, rather than over the full length of the part as in conventional resin transfer molding. This allows for very rapid resin infiltration and low voids. Core materials such as structural foams, and pre-cured composite or metallic inserts can be encapsulated directly in the SCRIMP process.

Scrimp is ideally suited for large but relatively uncomplicated structural configurations. The chief advantages are their relatively low cost and the ability to both infiltrate and cure at room temperature. A variety or coatings and additives are being investigated to enhance both the flammability and smoke properties of these composite parts.

The low temperature and pressure associated with the SCRIMP process allows the use of relatively low cost tooling. The use of glass fabric that is pre-plied and stitched to the required orientation and thickness greatly simplifies the part lay up task.

SCRIMP is one of the most promising processing candidates for off shore applications. Structural configurations that should be considered for fabrication via SCRIMP include beams, plates, shells and large structural boxes.

Joining Techniques

Composite elements can be joined by bonding, bolting, or by co-curing the elements as a single component. Different structural configurations require different joining techniques. For example, a tube may be joined to another tube by a metal coupling which is integrated into the tube ends during fabrication of the tube. Threaded or bell and spigot joints are commonly used to join fiberglass pipe. It is important in designing joints that bond line interfaces or co-cured interfaces are not subjected to high shear and transverse tension stresses as this is a weakness associated with pure loading of the matrix. The theory of composite bonded joints and bolted joints is well established and analysis codes are available to help complete a design.

Repair

It must be assumed that damage to an offshore structure could occur at some time during a service life. Some structures will need to be repaired in place and procedures must be available. Lightly-loaded structure repair is essentially state-of-the-art. Procedures for offshore repair must be established and personnel trained to ensure that quality repairs are made. Damage to heavily loaded components will be more difficult to repair and would probably require replacement with a backup component. Any local discontinuities as a result of repair may cause stress concentrations that may significantly reduce the fatigue life of the structure.

Reparations below water is also difficult. A habitat may be required at the location of the damage.

6.4.4 Costs

Capacity and production limitations need to be taken into account when designing products in composites, but these are not regarded as major obstacles for the extension of composites in offshore applications. Topics to be considered in assigning the rating for fabrication costs for different applications should include:

- Costs of projected raw materials.
- Rate of production for selected process.
- Potential for repeat or series production.
- Material scrap rates.
- Process yield rates.

Material supply should be considered for short term developments of new applications, e.g. carbon tethers, however on longer term it is expected that capacity will be brought on line accordingly.

Investment Costs

Fibre costs for commonly used fibres are in the range of 0,8 to 15 $/lb, but aerospace qualities may cost up to 30$/lb. Fabric costs are in the range 1,50 to 35 $/L

Life Cycle Costs

By introduction of composites in an application where competing materials are commonly used, further evaluation of life cycle cost for the actual product must be highlighted. Due to the composites excellent corrosion performance and the ability to build in properties which are required for the product lifetime, the composite application has a high potential to win over its competitors related to life cycle costs. The benefits with respect to reduced downtime of a production facility caused by reduced maintenance, no hot work and thereby reduced ignition sources can be quantified and evaluated against surface protection (coating), grinding, machining and welding on metallic materials.

Life cycle cost benefits can include:

- direct replacement costs if the structure must be replaced during its lifetime.
- labour and materials associated with maintaining the structure, such as scraping and painting.
- the costs associated with down time to repair or replace worn out structures.

6.5. Other materials

Aluminium

The most common materials for marine structures are the 5000 series for plates and the 6000 series for extruded profiles. The maximum allowable stresses for the most commonly used plate material AA 5083 is 145 MPa and for AA6082 for extrusions is 115 MPa. New materials are normally compared to these existing materials as for the recently introduce AA7108 for extrusions. Maximum allowable stresses is set to 145 MPa although the material have proved yield strength in the welded zone of 180 MPa. Other high strength aluminium alloys are also available as the Russian AlMg1561 with a yield strength in the heat affected zone of 200 MPa.

Development work is now ongoing to improve the allowable stresses for new high strength Aluminium alloys. Kværner, Norsk Hydro Aluminium and Det Norske Veritas have actually joined forces in this respect, and launched a project called "Aluminium in Ships". This project focuses on both the material side and the design/fabrication side of marine structures in Alumnium.

E modulus of Aluminium is about 1/3 of steel. This means that special attention should be paid to buckling.

Aluminium looses its structural capacity at about 600 °C, compared to about 1300 °C for steel.

This means that aluminium can not compete with steel on an isolated application. The possible benefits from the total system must be taken into consideration such as better stability for the vessel, smaller tethers for a TLP etc.

Fatigue is also an area which has to be carefully looked into. Aluminium alloys have normally no lower fatigue limit as the steel materials. this means that fatigue capacity in the weld zones must always be checked no matter how low the stress level in the structure is. Deformation during welding has also been a challenge. New welding techniques as the Friction Stir Welding method reduces these problems.

Galvanic corrosion between aluminium and steel must be avoided when joining aluminium and steel structures. This is solved by using either bolted connections with neoprene gaskets or special bi-metallic flat bars. These solutions have been used for many years in the shipbuilding industry when joining aluminium superstructure to a steel hull and aluminium spherical LNG tanks to the steel support.

Titanium

Titanium is a very interesting material in a long term perspective, because of it's excellent material qualities like structural strength versus weight (facto of 3 compared to steel), flexibility given by a lower E-modulus (factor of 1/2 compared to steel.) It is also a very robust material towards corrosion and fatigue, at least some alloys are. However, crack propagation seem to be a general problem with the major number of alloys available today.

The main problem with titanium is the very high cost of the material. Compared to steel the procurement costs are about 30 to 40 times dependant on alloys compared. At this very high figure the utilisation of titanium as a construction material for main structures will not be considered at all. The use of titanium could however come in special areas like dynamic riser applications etc., in areas where it is worth paying for the flexibility (where the alternative is not steel but more sophisticated solutions like Coflexip type of flexible risers etc.)

The Russians have however used titanium in their submarines for some decades. The reason for this that the costs for the carrying capacity for a submarine is very high and that the material costs for titanium is affordable. An other question is how the costs for such applications were calculated in the former Soviet Union. The Russians titanium suppliers have large production capacity. The entrance of these suppliers into the western market was expected to cause a drastic fall in the price for titanium. However, this is not the case; it seem as if the Russians suppliers have increased the prices lately. In this perspective it seem as if titanium in the short term perspective will be too expensive to be used as construction material in offshore structures.

A major qualification programme of the use of titanium alloys in risers has been carried out lately by Kværner for Norsk Hydro. This program proved that titanium is a candidate material, however expensive, for both production and export risers. However, this topic is not meant to be part of this paper.

7. DISCUSSION

Below is presented a comparison of different materials fitness as construction material in view of different design requirements, see table 7.1

Further is presented the different design criteria's criticality in the design for the different floater types FPSO (table 7.2), FPS (Table 7.3) and TLP (Table 7.4).

The figures presented represent the subjective judgement by the author only, and is meant to be basis for discussion only.

Table 7.1 Evaluation of different material's superiority for various design aspects.

No.	Design Aspect	Steel	Aluminium	Titan	Composites	Prestressed Concrete
1	Strength vs. weight	5	5	8	10	2
2	Tensile strength	5	5	8	10	-
3	Capacity in compression	4	4	4	2	10
4	Fatigue resistance	5	2	8 1)	10 1)	6
5	Reparability	10	5	3	4	4
6	Constructability	10	6	4	5	7
7	Structural capacity in fire	8	4	5	6	10
8	Impact resistance (toughness)	10	8	6	4	9
9	Corrosion resistance	4	6	9	10	7
10	Creep	10	8	10	6	2
11	Price vs. weight	10	6	1	5	8

Note 1): defect free material

Table 7.2. Criticality of some design aspects for various parts of an FPSO

No.	Design Aspect	Bottom hull	Hull sides	Top deck
1	Strength vs. weight	1	3	6
2	Tensile strength	8	4	8
3	Capacity in compression	8	5	3
4	Fatigue resistance	10	10	10
5	Reparability	7	6	5
6	Constructability	8	8	8
7	Structural capacity in fire	0	4	8
8	Impact resistance	1	4	8
9	Corrosion resistance	9	9	9
10	Creep	5	5	5

Table 7.3 Criticality of some design aspects for various parts of an FPS

No.	Design Aspect	Pontoons	Columns	Trusses	Deck
1	Strength vs. weight	5	5	5	10
2	Tensile strength	1	3	8	7
3	Capacity in compression	10	6	4	6
4	Fatigue resistance	3	7	10	8
5	Reparability	4	4	6	4
6	Constructability	6	6	6	6
7	Structural capacity in fire	0	4	0	10
8	Impact resistance	4	6	2	8
9	Corrosion resistance	6	6	6	6
10	Creep	4	4	4	6

Table 7.4 Criticality of different design aspects for various parts of a TLP 300 m / 2000 m water depth

No.	Design Aspect	Pontoons	Columns	Deck
1	Strength vs. weight	2 / 8	4 / 9	5 / 10
2	Tensile strength	5	6	7
3	Capacity in compression	10	6	6
4	Fatigue resistance	5	7	8
5	Reparability	6	5	4
6	Constructability	6	6	6

7	Structural capacity in fire	0	4	10
8	Impact resistance	5	7	8
9	Corrosion resistance	6	6	6
10	Creep	4	4	6

8. REFERENCES

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9. FIGURES

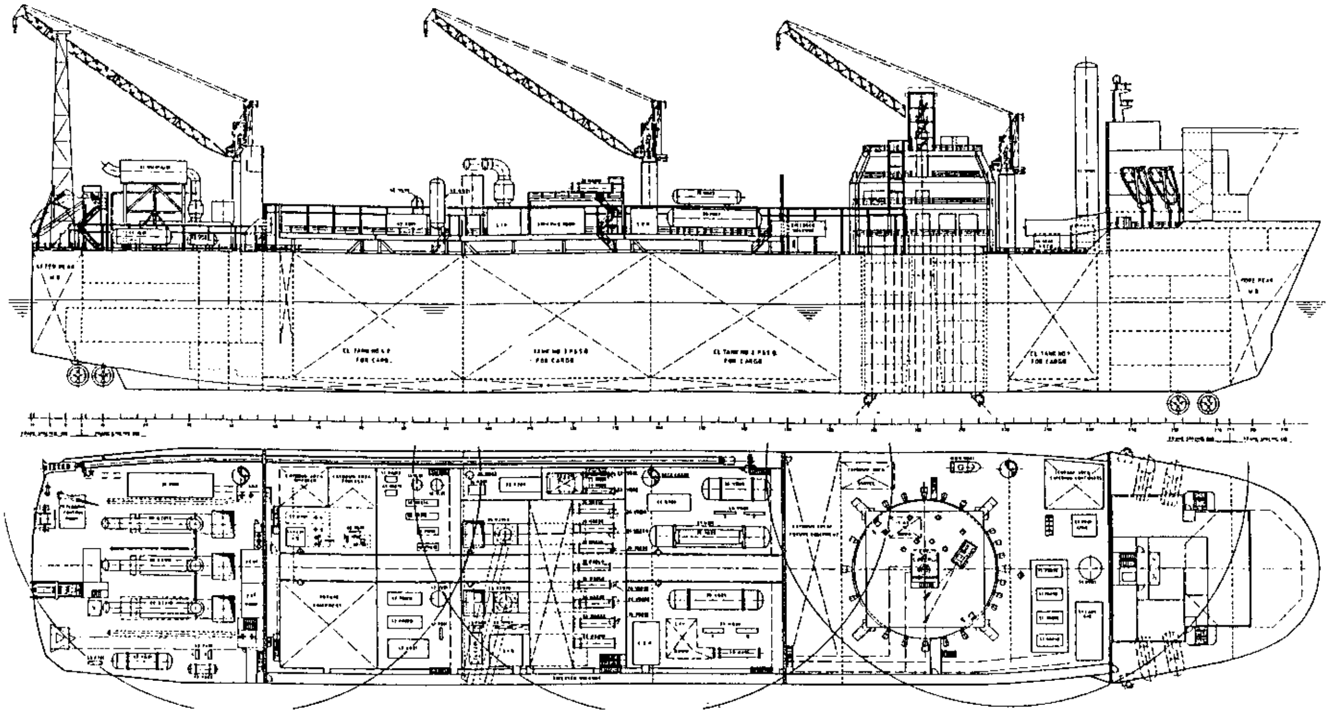


Fig. 1 Kværner's FPSO: PS 100

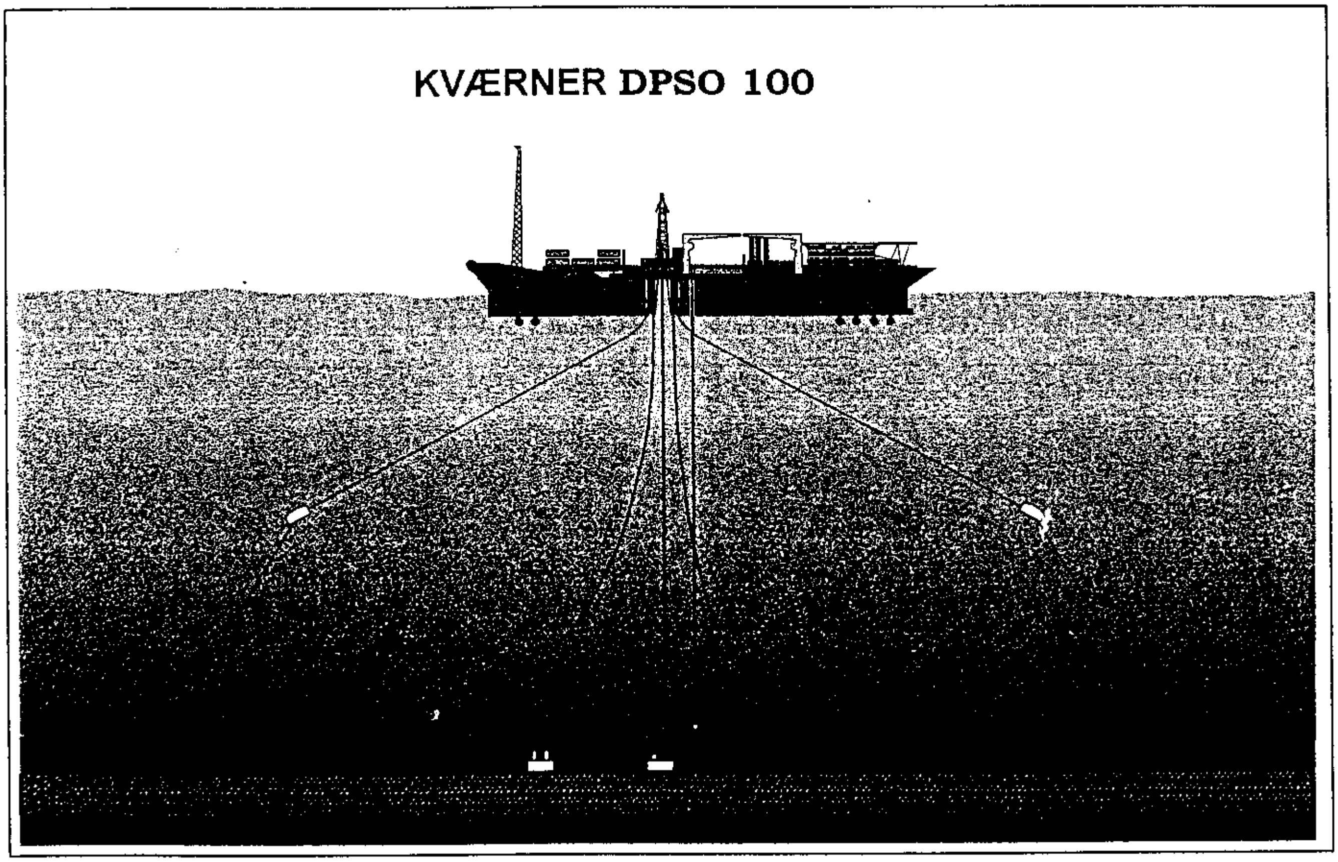


Fig. 2 Kværner's FPSO with drilling: DPSO 100

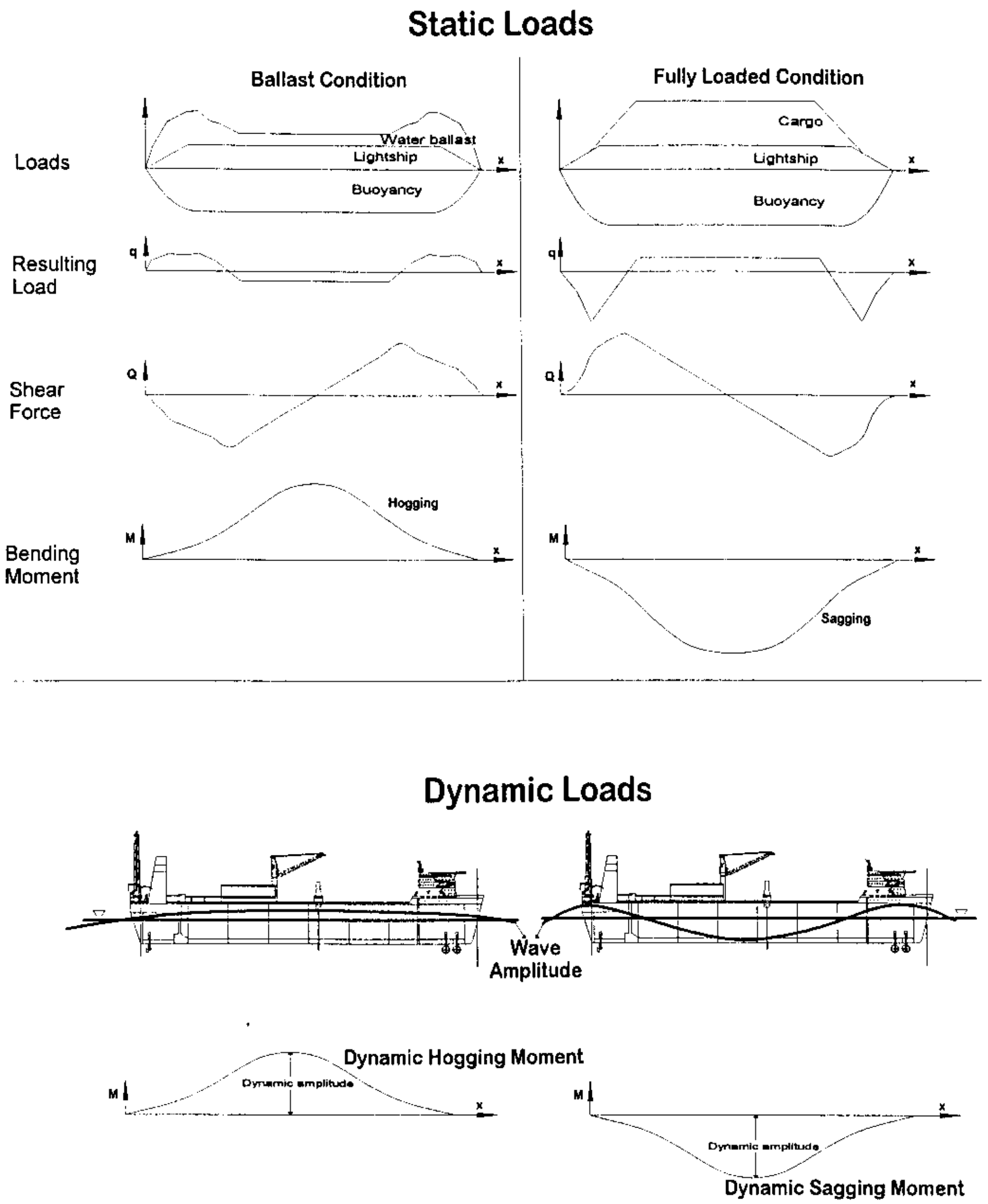


Figure 3. Typical Static and Dynamic Loads for an FPSO

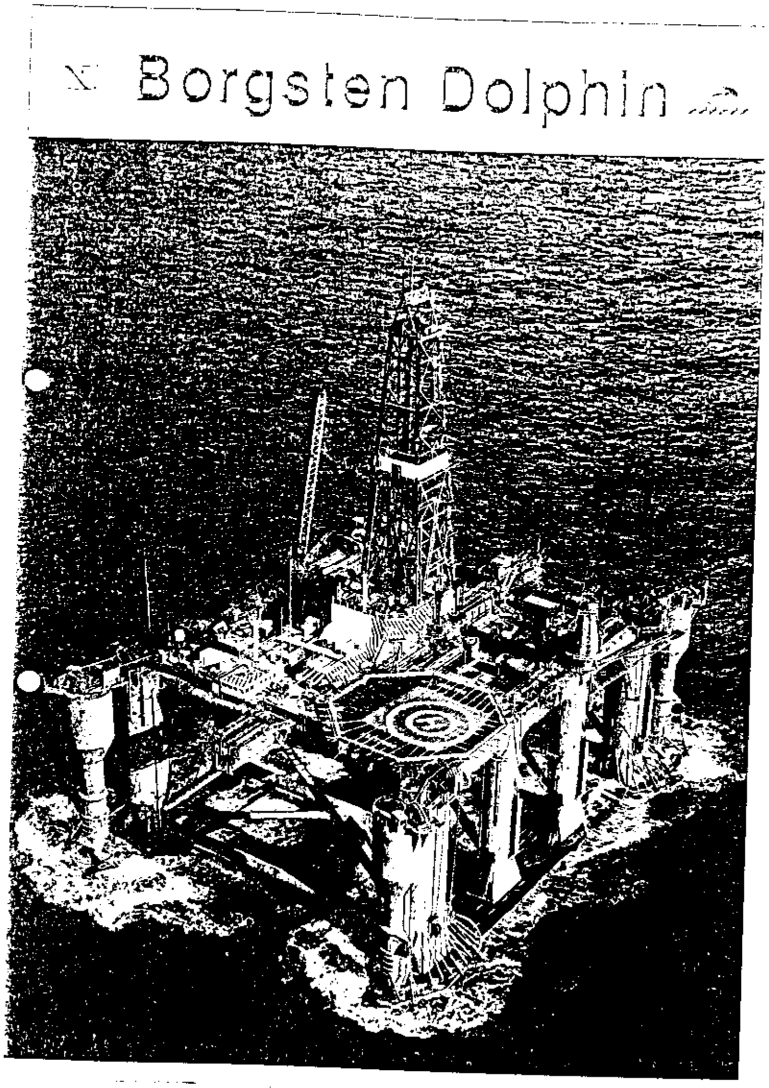


Fig. 5 Aker H-3

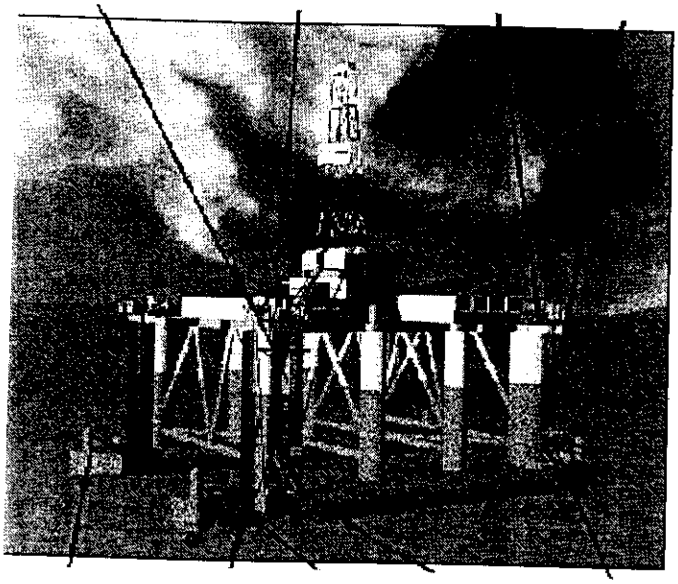


Fig. 6 Sedco Forex semi

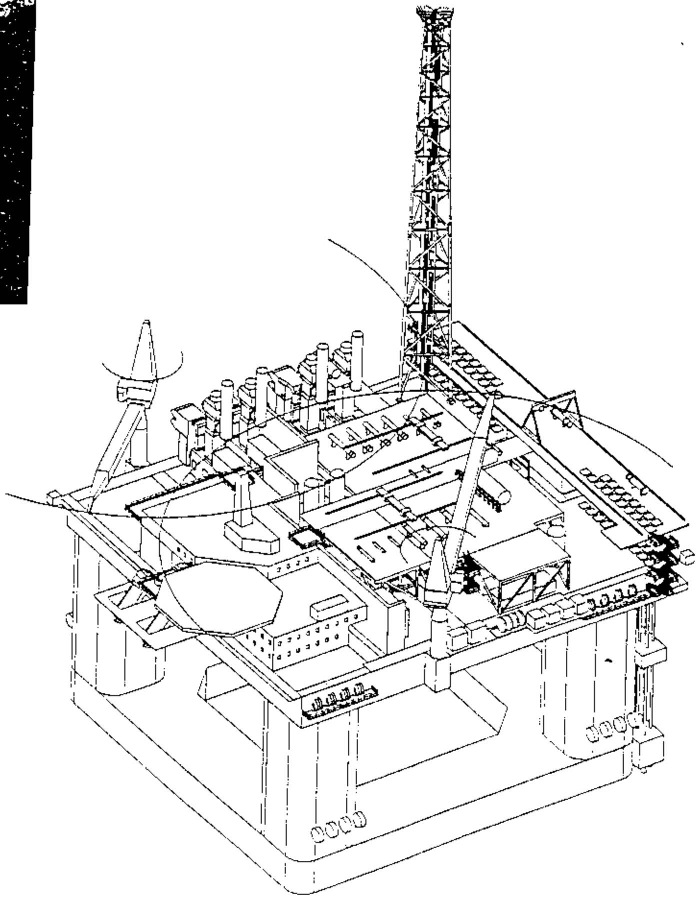


Fig. 4 Typical FPS with ring pontoon

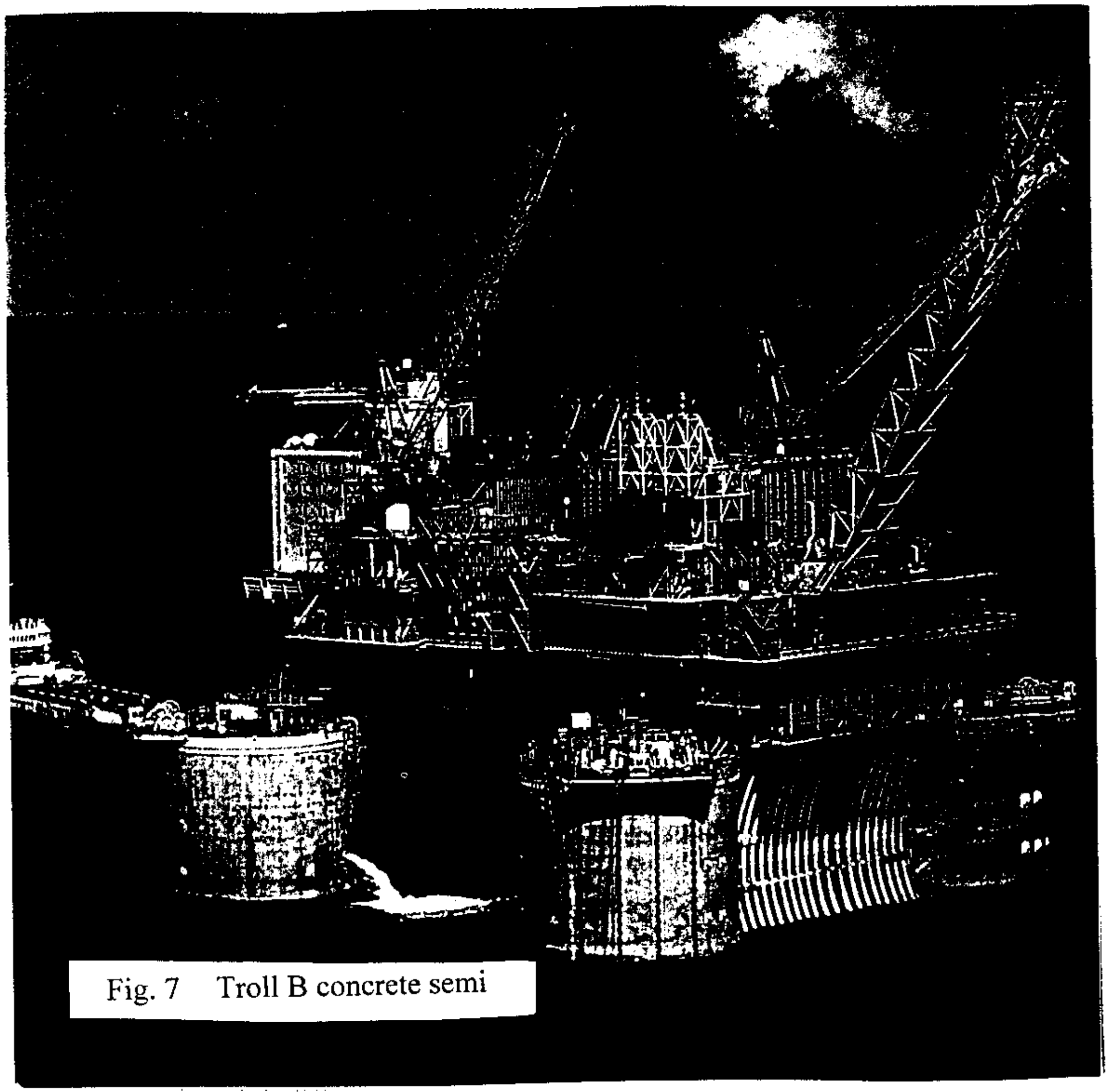


Fig. 7 Troll B concrete semi

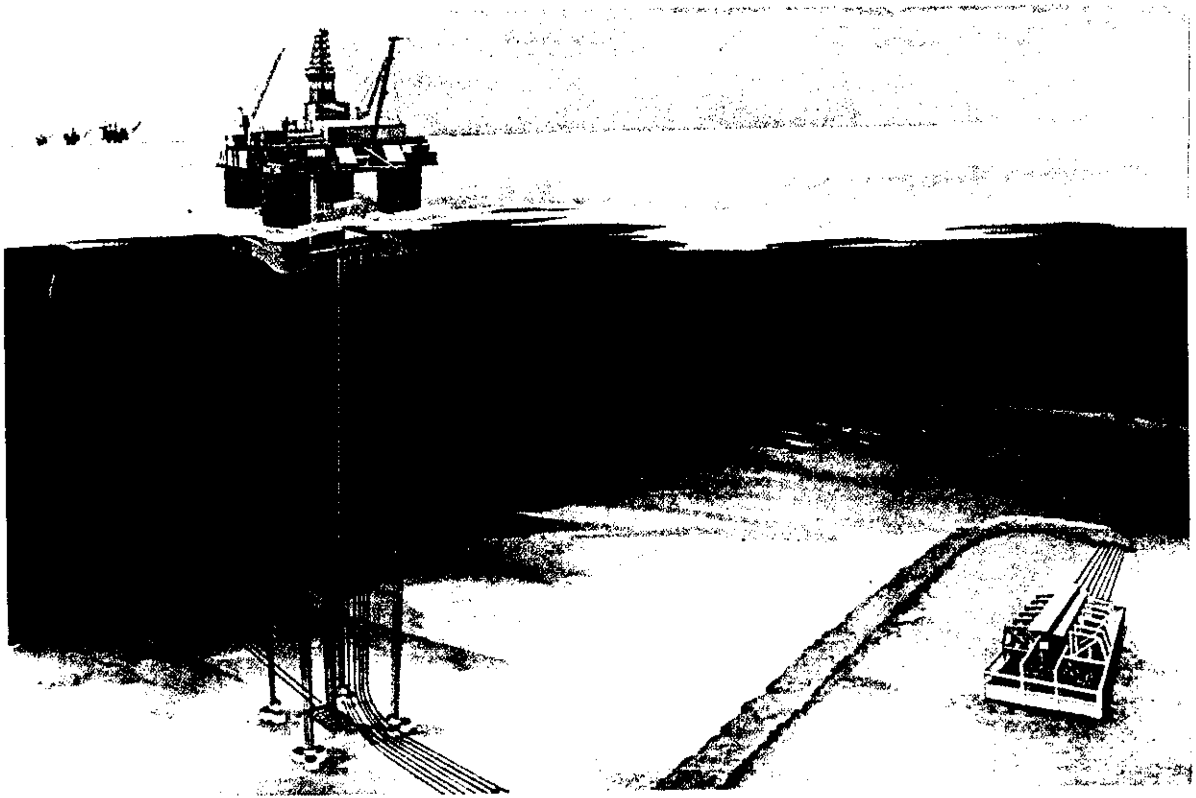


Fig. 8 Snorre TLP with tether system

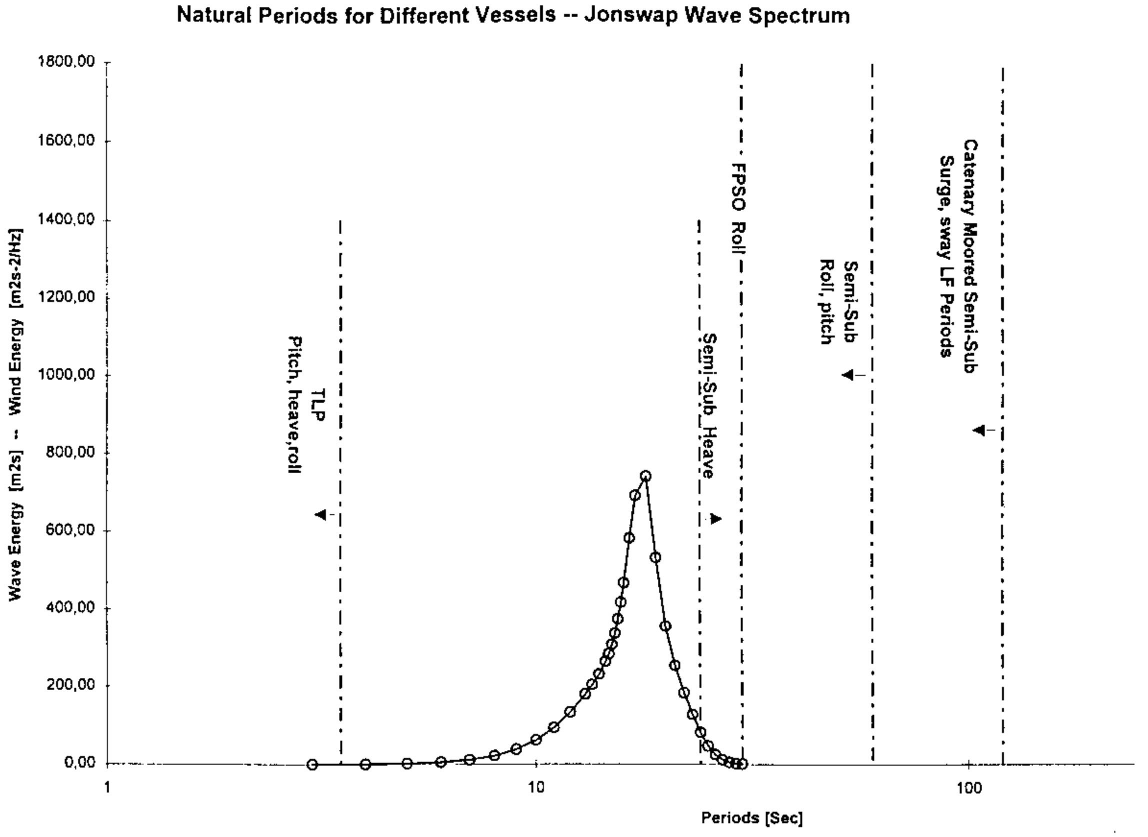
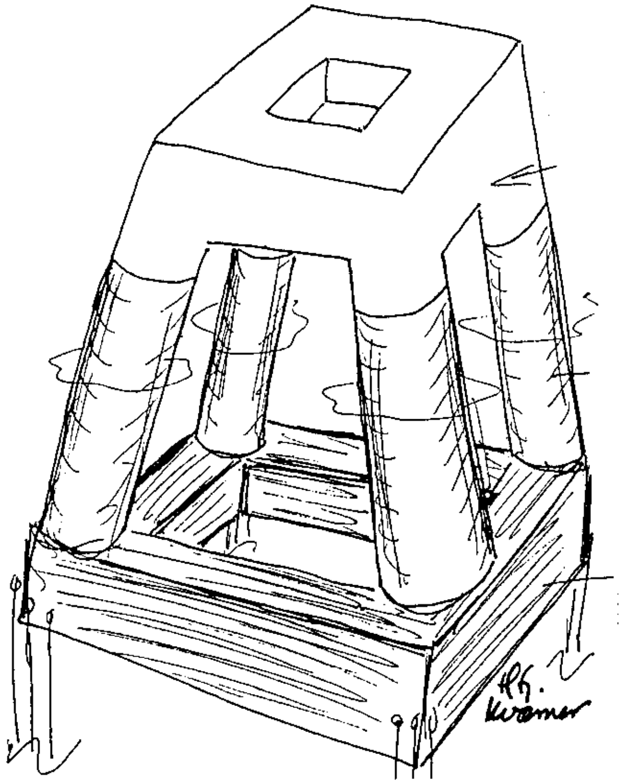


Fig. 9 Eigen periods for different type of floaters in the wave spectrum



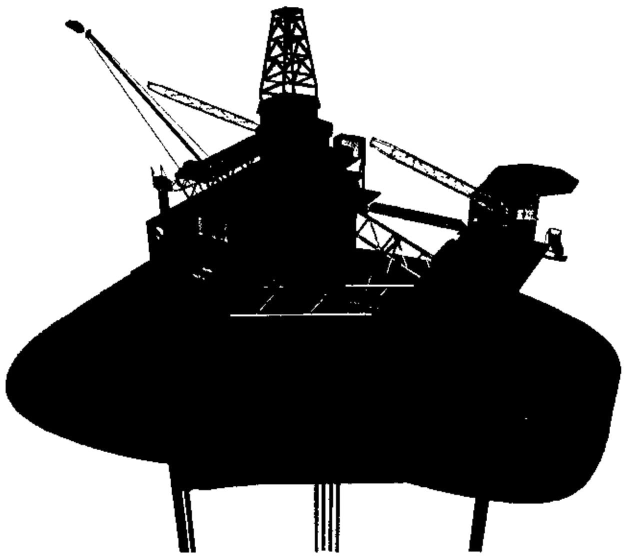


Fig. 10 A typical triangular TLP (Saga/Aker)

Fig. 11 Principals of a TLP with inclined columns

Title
Material requirements for floaters

Date:
February 5.-7. 1997

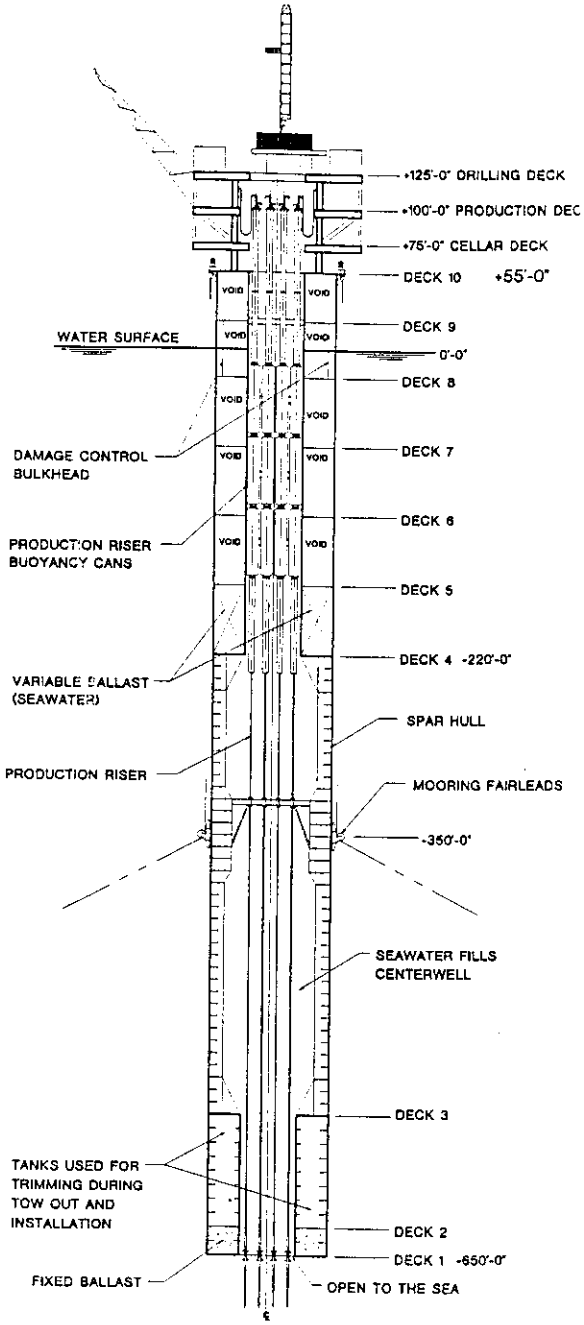


Fig. 12 A steel Spar Buoy (Aker)

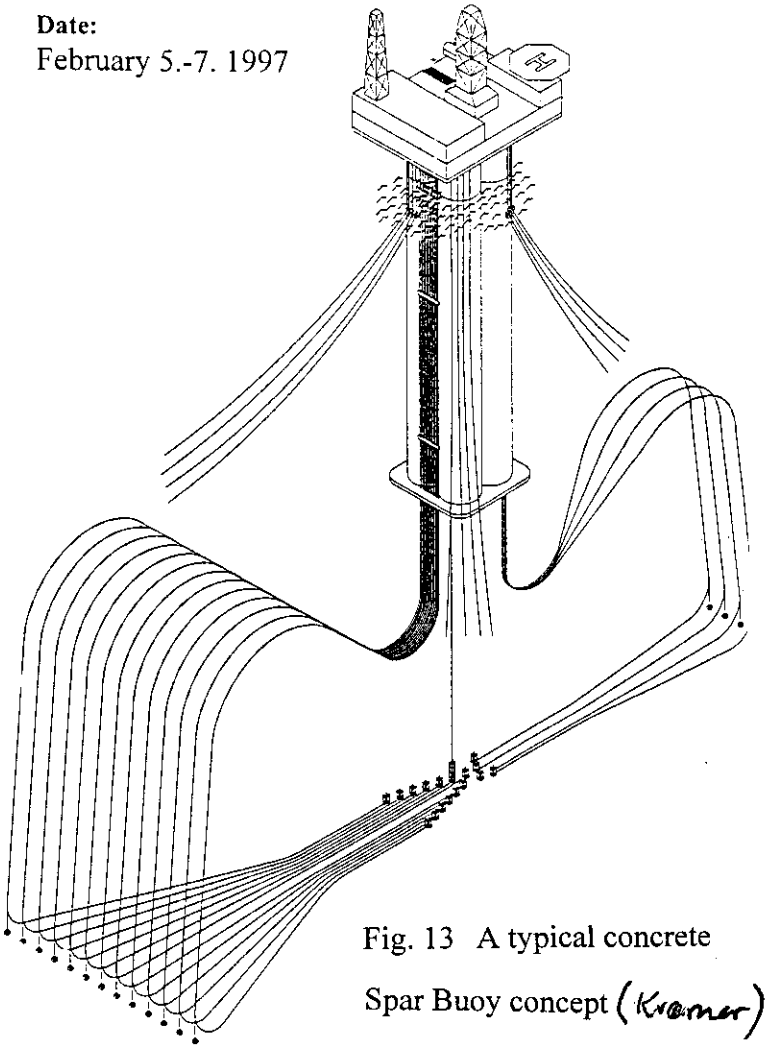


Fig. 13 A typical concrete Spar Buoy concept (Kværner)

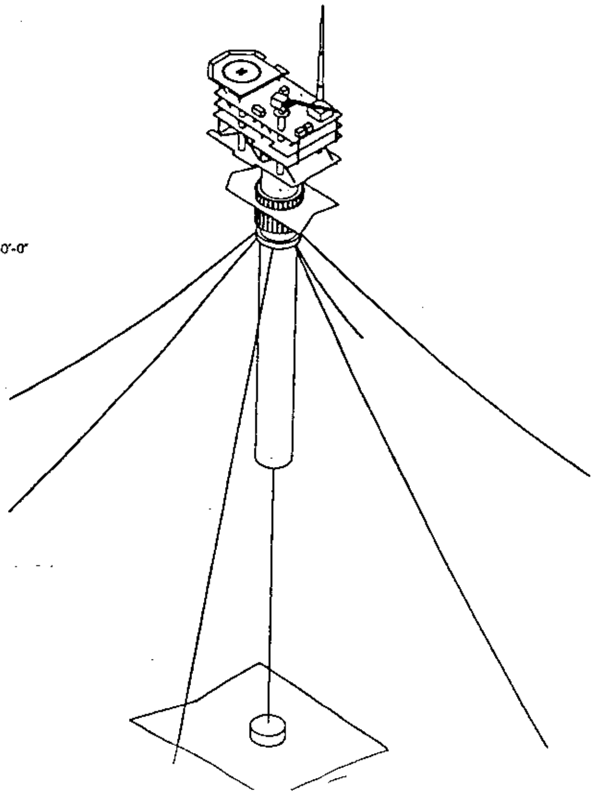


Fig. 14 The mini-floater concept

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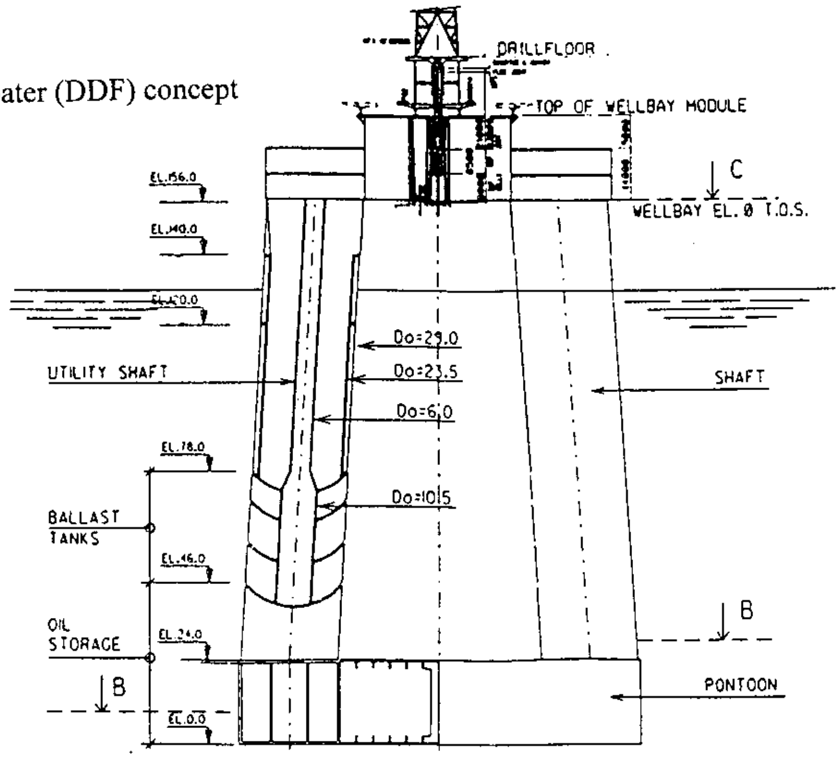

Fig. 15 The Deep Draft Floater (DDF) concept

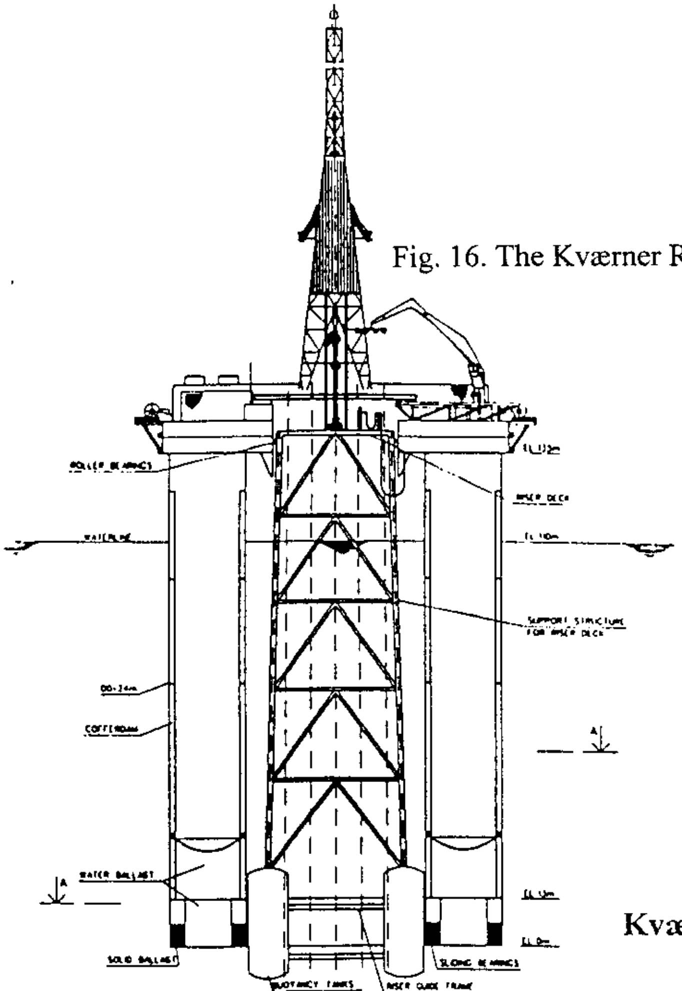

Fig. 16. The Kværner Rigid Riser (KRiS) concept

Advanced Materials for Marine Construction

Working Group #4

MATERIAL REQUIREMENTS FOR FIXED STRUCTURES

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INTRODUCTION

To date, most fixed offshore structures have been constructed primarily of steel and concrete. Significant advances have been made with respect to the use of higher strength steels with high fracture toughness and good weldability, to reduce weight without sacrificing structural integrity. Lighter weight materials such as FRP and aluminum have been used to some extent for primary topsides structures, including living quarters and helidecks, and to a greater extent for secondary structures such as grating, but steel still accounts for the majority of the tonnage in the structure.

DEVELOPMENT OF OFFSHORE STRUCTURAL STEELS

Ordinary strength structural steels. such as ASTM A36, have been used successfully for offshore structure fabrication for many years. However, as both the overall size of offshore structures and the size of individual members and joint cans has increased, the demand for higher strength steels with improved fracture toughness and weldability has also increased. The chemical composition, rolling practice, and heat treatment of modern offshore structural steels are specifically designed to produce steels with low carbon equivalents for good weldability (low risk of hydrogen cracking) and excellent Charpy and CTOD toughness in both the base plate and weld heat affected zone.

Normalized 50-ksi yield strength steels, such as API 2H Grade 50, have become standard for joint cans on almost all offshore structures. These steels have a reduced carbon content to improve weldability, with the increased strength obtained by adding microalloying elements (Nb, V, or Ti), and are heat treated to improve Charpy impact toughness. The standard impact testing temperature for API 2H Grade 50 is 40°C, which provides a margin of at least 30°C between the typical lowest anticipated service temperature for the structure and the nil ductility temperature of the steel. This margin insures that failure by brittle fracture is unlikely to occur, even if relatively large fabrication defects or fatigue cracks are present in the structure. Supplementary requirements which call for low sulfur and through-thickness tensile testing are usually invoked for joint can steels to insure resistance to lamellar tearing during fabrication.

The most recent step-change in increased strength, weldability, and toughness for offshore structural steels came with the introduction of steels produced using thermo-mechanically controlled processing (TMCP) or quenched-and-tempered heat treatments (Q&T), such as API 2W and 2Y respectively. These steels have even leaner chemistries (lower carbon content and less alloying elements) than normalized steels which is made possible by the use of advanced rolling practices (TMCP) or more expensive heat treatment (Q&T). These steels are available with specified minimum yield strengths of at least 60 ksi (some manufacturers offer 65 ksi grades which have not yet been included in API standards) with excellent weldability and toughness.

API 2W and 2Y steels can be purchased with a supplementary requirement that invokes API RP 2Z pre-production qualification testing of both heat affected zone fracture toughness and weldability. The testing required by API RP 2Z is carried out by the steel manufacturer, avoiding the need to repeat costly and time consuming CTOD tests for each project. However, the prequalification is only valid as long as the manufacturer continues to supply the same grade of steel produced using the same chemistry and processing route, which includes both melting and rolling practices. Some manufacturers have had to repeat the qualification testing several times, due to changes in their mill practices which invalidated the previous test results.

STRUCTURAL STEEL SELECTION

Steel selection for an offshore structure attempts to optimize strength and toughness requirements for each element of the structure as part of an overall fracture control strategy.

Inter-related factors which must be considered in establishing this overall strategy include the design of both the overall structure and the individual joints, the steel selection, and the welding, fabrication, and inspection requirements. Steel used for critical elements such as joint cans is typically upgraded first, while ordinary structural steels may continue to be used for elements which are less critical, redundant, or less heavily loaded. For larger structures, the need to reduce weight typically drives increased usage of higher strength (50 and 60 ksi) steels, which in turn drives the need for more conservative fracture control requirements.

One approach to standardization of structural steel selection, which has been developed jointly by two API task groups working on revisions to API RP 2A, uses multiple levels of inter-related requirements for materials, welding, fabrication, and inspection that would be appropriate for different types of structures. The different levels (referred to as PSL's) are described as follows:

PSL-l defines a set of minimum requirements appropriate for smaller structures in shallow water, typically unmanned, with relatively low consequences of failure. Good examples would be a satellite well platform or a small gathering station with minimal topsides processing equipment. Steel selection includes API 2H joint cans, with ordinary structural steels used for most other parts of the structure. Welding and inspection requirements generally follow AWS Dl.1 and the current API RP 2A. These requirements are consistent with past practices for structurally redundant, unmanned platforms in areas such as the Gulf of Mexico and the west coast of Africa.

PSL-2 defines a set of somewhat more conservative requirements appropriate for larger structures in moderate water depths. Examples would include larger platforms with significant consequences of failure, which are typically manned and have significant topsides processing capability. Steel selection makes greater use of higher strength (particularly 50 ksi) grades, although ordinary structural steels may still be used for primary members of the structure including legs and bracing. Welding and inspection requirements are upgraded to some extent, although fracture toughness requirements are still based on Charpy impact testing. These requirements are consistent with current practices for large platforms in the Gulf of Mexico, California, and other areas.

PSL-3 defines the most stringent set of requirements, appropriate for critical structures which are a step-out from the current experience base. Examples would be very large structures in deep water, where the consequences of failure justify a very high level of assurance with regard to structural integrity. Steel selection is primarily higher strength steels with improved fracture toughness, and CTOD testing is mandatory for critical elements (primarily joint cans). Welding and Inspection requirements are upgraded to be consistent with this higher level of criticality. These requirements are consistent with current practice for deep water structures in the Gulf of Mexico.

As an illustration of the PSL approach to steel selection, several tables developed by the API task group are included below. Table I defines generic performance requirements for structural steels according to strength group and toughness class For example, the common ASTM or API steel specifications which would match several of the generic categories are:

36-C	ASTM A36
50-A	API 2H Grade 50
50-AZ	API ZH Grade 50 with through thickness supplementary requirements
50-AZX	API 2W or 2Y with API RP 2Z prequalification (CTOD testing)

Tables II and III give recommended steel selections for various elements of tubular jackets and topsides. These recommendations are similar to the general guidance in the current API RP 2A for selection of steel toughness class (A, B, or C) but are more prescriptive in terms of outlining the recommended steel selection according to both the global PSL designation for the structure and the specific structural element.

WELD METAL AND HAZ TOUGHNESS REQUIREMENTS

The fracture toughness of weld metal and the weld heat affected zone are equally or perhaps even more critical to the overall fracture control plan than the toughness of the base metal, since fabrication defects and fatigue cracks occur most frequently at welds. Overmatching of the weld metal with respect to the base metal on both strength and toughness has typically not been difficult to achieve for ordinary structural steels such as ASJM A36, with the exception of cases where higher strength grades such as ASTM A572 are used interchangeably with lower strength grades. However, development of welding consumables and procedures which can achieve weld metal and HAZ Charpy impact toughness and CTOD values matching that of API 2H, 2W or 2Y plate has been a significant challenge.

Weld metal and HAZ toughness requirements proposed by the API task group for the different PSL's defined above are given in Table IV. The requirements are keyed to the steel group and toughness class, and generally follow the base metal requirements except that an allowance is made for deterioration in the heat affected zone by raising the Charpy impact testing temperature. This relaxation is unique to API RP 2A, where most other design codes worldwide have the same test temperature and absorbed energy requirements for base metal, weld metal, and HAZ.

Specification of the minimum required CTOD value for the weld and HAZ is purposely left to the designer, based on the requirements for the specific structural design. The requirements for HAZ prequalification testing in API RP 2Z, which are sometimes also applied to weld metal, are quite high relative to actual CTOD values needed for a safe design with reasonable assumed flaw sizes. CTOD requirements developed for specific projects arc frequently less stringent.

In order to insure that the required Charpy impact toughness and/or CTOD values are consistently achieved during production welding, additional limits on essential welding variables are needed. The essential variables given in AWS D1.1 were intended primarily to address strength and weld metal soundness, with some consideration to Charpy impact toughness through mandatory testing of filler metals on standardized test coupons. Limitations appropriate for welds with low temperature Charpy impact requirements. CTOD testing requirements, and more restrictive limits on maximum hardness are not adequately addressed. The API task group has developed the list of additional essential variables shown below, for which any change outside the specified range requires requalification of the welding procedure:

For welding procedures qualified with Charpy impact toughness testing:

- an increase of more than 0.03% in the carbon equivalent or 0.02% in the Pcm value of the base metal versus the material used for the procedure qualification test
- an increase of more than 50°F over the maximum interpass temperature attained during the procedure qualification test
- a change greater than +/- 25% in the heat input from the average value calculated for the procedure qualification test (fill passes and cap passes are grouped separately)
- a change in the electrode or electrode/flux brand name or place of manufacture when the Charpy impact test temperature is lower than 0°F
- a decrease in heat input and preheat below that used on the procedure qualification test for cap passes adjacent to the base metal, unless bead-on-plate tests are performed at the lower preheat and heat input to demonstrate that the maximum hardness is acceptable
- a deletion of the temper head or modification of the bead sequence or bead placement when using a procedure qualified with a temper bead technique.

For welding procedures qualified with CTOD testing, the following limitations apply in addition to those stated above for Charpy impact toughness testing:

- any increase in the maximum interpass temperature over that qualified in the high heat input CTOD procedure qualification test
- any increase in joint thickness greater than that used for the CTOD procedure qualification test
- any decrease in heat input from the average heat input qualified for fill passes during the low heat input CTOD procedure qualification test
- any increase in heat input from the average heat input qualified for fill passes during the high heat input CTOD procedure qualification test
- any change in electrode or electrode/flux brand name or place of manufacture
- any reduction in the depth or width of backgouging as measured during the CTOD procedure qualification test

The above limitations are consistent with current specifications from a number of major operating companies, which include similar limitations beyond those in AWS D1.1.

SPLASH ZONE PROTECTION

In offshore structures a certain zone, the splash zone, deserves particular attention. High corrosion rates are experienced by steel in the splash zone due to the combination of highly aerated water and erosion. Cathodic protection is not effective in this area and so applied protection is necessary. A nickel-copper alloy, UNS 04400, has been successfully used for many years in this application. Also, UNS C70600, a 90-10 copper nickel alloy, has given excellent service for 12 years to date welded onto legs in stage one of Maracaibo Field (British Gas). In addition, divers inspection have also revealed reduced fowling on the 90-10 alloy sheathing. (For more reference, please refer to "Copper alloys for marine Construction" Theme Paper.)

DISCUSSION QUESTIONS ON STEEL STRUCTURES

The following questions must be answered in order to further expand the utilization of steels in marine applications:

1. What are the barriers to increasing usage of currently available 60 ksi yield strength steels?
2. What are the key design criteria for 60 ksi materials?
3. Is there a need for development of higher strength structural steels? In what applications?
4. Are requirements for CTOD testing of welds becoming too onerous? Are they worth the cost? (For example, experience base says that low CTOD's in the HAZ are not significant. What is the value of doing this testing?)
5. Would light weight structures designed and built from high strength steels (e.g. 60ksi strength) be more economical to build and install? (This question targets on improved economics of marginal fields in terms of weight savings and cost savings.)
6. Since deep water platforms may need greater thickness, what maximum thickness is available (versus needed) for high strength steels? (Current availability is: up to 4 in. for 50 ksi material and up to 3 in. for 60 ksi steel plates).

COMPOSITE STRUCTURES

Composite structures could offer significant advantages in terms of lighter weight and increased corrosion resistance compared to steel. Current applications of composites include repair and strengthening of primary structures, and addition of new primary structures. Composite materials, primarily glass or carbon fiber reinforced plastics (polyester, vinylester, phenolic, or epoxy), are already becoming fairly common in some secondary structural applications such as grating, stairways, handrails, cable trays, and blast resistant walls/enclosures. Fiberglass piping systems are also being used more widely, particularly for seawater Systems (both utility water and fire water), and drain systems. However, use of composite materials for primary structural applications presents a greater challenge. Some of the technical barriers to the use of composite materials include:

- the lack of design standards and data for composite structures in offshore applications
- unfamiliarity in the offshore industry with composite fabrication technology
- the lack of reliable and well-understood nondestructive testing methods for composites
- concerns about the long term durability of composites, particularly with respect to fatigue and impact loads
- concerns about the fire resistance of composites

In contrast to the many technical barriers, composite materials also exhibit strong potentials for increased application in marine structures. For example, the low weight/high mechanical properties of these materials can be exploited to produce lightweight structures. The high stiffness of carbon fiber composites can be exploited in strengthening and repair applications, to create new load paths in selected areas and thereby allowing for more efficient use of traditional materials. Such hybrid solutions are likely to lead to both cost and weight savings.

Over the past few years, North Sea operators (primarily in the UK and Norway) have funded significant JIP research efforts directed towards increasing the use of composite materials in the offshore industry. At least one program, managed by Marinetech Research and British Gas, has placed particular emphasis on the use of composite materials for structural applications. Additional efforts are now underway in the USA using leveraged funding from the NIST

Advanced Technology Program, with specific programs aimed at developing composite drilling risers, production risers, drill pipe, and spoolable composite tubing. Several of these programs, along with other projects related to piping applications, have been launched through the University of Houston's Composites Engineering and Applications Center. At least

DISCUSSION QUESTIONS ON COMPOSITE STRUCTURES

The following questions must be answered in order to further expand the utilization of composite materials in marine structures:

1. How much interest is there in the use of composites for primary structural applications on fixed structures? Is the potential weight savings worth the cost of developing this technology?
2. Should we continue to focus most of our efforts on composites for secondary structural and process piping applications?
3. How can we pool effort and knowledge from previous JIP's and applications to produce an industry wide design manual?
4. How can we develop educational programs on structural fabrication utilizing composite materials such that these materials can be more easily incorporated into new structures?
5. What additional barriers exist to increasing the use of composite materials?

CONCRETE STRUCTURES

Concrete structures are more heavily used in North Sea because of the very large topsides in which the weight tends to favor concrete base. Construction technology is also available in Europe, ahead of steel fabrication technology. Concrete structures in offshore applications are actually composite structures of concrete, reinforcing steel and prestressing steel. A more widespread usage of concrete in marine environment will depend on resolving several technical barriers (perceived and real). These are: corrosion of reinforcing steel, high weight-to-strength ratio and cracking.

Corrosion of reinforcing steel is adequately answered today through the use of mineral admixtures (finely ground silica and limestone) and chemical admixtures (high range water reducing admixtures) so that a very impermeable concrete - 10^{-12} to 10^{-13} m/s is achieved. The weight-to-strength problem can be approached in two ways - internally and as a system. Internally, concrete of proper properties can be made with light weight coarse aggregates, replacing all or part of the normal weight aggregates. As a system, the high strength concrete with proper reinforcement and prestressing results in thinner sections, hence less weight. This reduction is limited by considerations of span-to-depth ratios, etc. Cracking of concrete has significant implications for oil and water leakage, fatigue and corrosion. This problem can be countered by proper arrangement of reinforcing (closely-spaced small bars) and by prestressing.

Current Norwegian codes require excessive reinforcement in order to limit calculated crack width. These codes are based on linear elastic analysis, whereas concrete is a material that exhibits non-linear behavior. UK codes require much less reinforcement, yet their structures have behaved properly in the North Sea. Early Norwegian structures, built to the codes of that time, also behaved well. This is a major area to be addressed, i.e. a rational approach that considers the specific environment and performance criteria.

The utilization of concrete in offshore concrete structures requires special attention to the development of ductile response under overload and of high shear resistance under concentrated loads (sea ice, icebergs, barge impact, etc.) Both of these requirements can be satisfied by the provision of steels with through-thickness toughness, in the form of stirrups. However, there are severe limitations and cost and schedule impacts when using the conventional bent reinforcing bars. Further, they lose efficiency under high load, about 70% of yield. The new headed reinforcing bars, often called T-headed bars, develop full anchorage, 100% efficiency, and ductile response when stressed beyond yield. Typically only one-sixth as many bars are required. Installation labor is greatly reduced, concrete placement is facilitated and overall cost savings are significant. Some 2,000,000 T-headed bars have been used on Hibernia and 1,500,000 on Troll. Extensive testing has been performed, primarily at SINTEF in Trondheim and at the University of California at Berkeley.

DISCUSSION QUESTIONS ON CONCRETE STRUCTURES

The following questions must be answered in order to further develop the usage of concrete in marine applications.

1. How can a designer be sure of the reliability of joints in concrete structures?
    a) There have recently been a great many tests (generally half-scale) in the U.S. of the behavior of typical joints under strong earthquake - low cycle, high amplitude loading beyond the ultimate strength.
    b) The experience from actual behavior in earthquakes has shown the need for adequate confining reinforcing.
    c) Finite element analysis (3-D linear and 2-D non-linear) of specific joints, along with physical model testing.
    d) Instrumentation on offshore platforms.

Further development of composite steel-concrete, using the steel as an impermeable barrier, either inside or outside, joined in composite behavior to the steel plate by welded shear studs.

ALUMINUM STRUCTURES

Aluminum structural alloys are available with high strength and good weldability, and have the advantages of lower weight and better corrosion resistance than steel. Aluminum alloys have been used successfully for primary structural applications on helidecks and living quarters buildings, in addition to secondary applications such as HVAC ducting.

In the late 1950s, approximately 100 offshore platforms were installed in Lake Maracaibo, Venezuela with jackets fabricated from 6061-T6 aluminum. The lake's low salt and high dissolved oxygen content created a corrosive environment that precluded the use of conventional steel jackets since cathodic protection was not effective. Although they were more expensive, the prefabricated aluminum jackets could be installed substantially faster than the concrete platforms in use at that time. These platforms required the development of an entire new technology to design, fabricate and install. As an example, an extruded joint reinforcement was developed to replace the strength of the aluminum that was lost due to welding.

These were four pile structures for use with a drilling tender. Only the jackets were fabricated of aluminum. Steel piling, which were separated from the aluminum jacket legs by insulators, were driven through the jacket legs. The piles were then grouted to the legs as a structural connection. Prior to installation, it was necessary to coat the inside of the jacket legs with a coal tar material since wet cement grout in contact with aluminum generate hydrogen causing a potential hazard and damaging the bond connection. As a note of interest, even with the jacket legs flooded, the jacket bracing had sufficient buoyancy that the jacket would not sit on bottom. Temporary weights were used to hold the jacket in place until the grout had set.

These structures performed satisfactorily until they were removed when the field was depleted. Aluminum jackets were developed and used to satisfy a particular need at that period of development in the offshore industry. It is an example of how aluminum can be effectively utilized for special marine applications in an usual environment.

DISCUSSION QUESTIONS ON ALUMINUM STRUCTURES

The following questions must be answered in order to further expand the utilization of aluminum alloys in marine structures:

1. What are the technical barriers to increased use of aluminum structural alloys?
2. Is high cost the primary reason why these alloys have been used only in certain applications?
3. Do design codes exist for aluminum structures in offshore applications? (AWS may address primarily welding/fabrication requirements, but not design.)
4. Are the yards equipped for structural fabrication using aluminum alloys and composite materials?

Summary Presentation on Fixed Structures (Sheldon Fortenberry - Chevron)

1. Steel has been the primary material for fixed platforms, and will continue to be.
   a) Advances to increase strength toughness and weldability
2. Concrete is appropriate in some applications, such as heavy topsides in North Sea platforms, also many shallow water platforms in the Gulf of Mexico.
3. Light weight materials such as composites and aluminum alloys have some applications in

offshore structures, especially in decks.

4. Need to address design codes, fabrication technology, in-situ repair of damages, fire and blast loadings, etc.

Acknowledgment

Frazer Barnes of DML, Griff Lee of McDermott, Andrew Stevenson of MERL, and Ben Gerwick of UC Berkeley contributed to portions of this document.

TABLE I Performance Requirements for Structural Steels

Steel Group	SMYS*	Toughness Class	Max CE	Fine Grain Practice	Max Sulfur	Charpy V-Notch Toughness Testing	Through Thickness Testing	CTOD Testing
I	36	C	0.45	Yes (1)	–	–	–	–
I	36	B	0.45	Yes	–	15 ft-lbs @ LAST	–	–
I	36	A	0.45	Yes	0.015	15 ft-lbs @ LAST -54°F	–	–
II	50	C	0.45	Yes (1)	–	–	–	–
II	50	B	0.43	Yes	0.015	25ft-lbs @ LAST	–	–
II	50	A	0.43	Yes	0.015	25 ft-lbs @ LAST -54°F	–	–
II	50	AZ	0.43	Yes	0.006	25 ft-lbs @ LAST -54°F	Yes	–
II	50	AZX	0.43	Yes	0.006	25 ft-lbs @ LAST -54°F	Yes	Yes (2)
III	60	A	0.43	Yes	0.015	35 ft-lbs @ LAST -54°F	–	–
III	60	AZ	0.43	Yes	0.006	35 ft-lbs @ LAST -54°F	Yes	–
III	60	AZX	0.043	Yes	0.006	35 ft-lbs @ LAST -54°F	Yes	Yes (2)

Notes: (1) Fine grain practice if greater than 1/2 inch thick

(2) CTOD prequalification per API RP 2Z if greater than 2" thick

* SMYS = Specified Minimum Yield Strength

SMYS 36 includes 34 up to 42 ksi

SMYS 50 includes >42 up to 50 ksi

SMYS 60 includes >52 up to 65 ksi

– indicates not specified, follow standard specification

TABLE II MATERIAL SELECTION FOR TUBULAR JACKETS

		SMYS	TOUGHNESS CLASS		
		Group	PSL-1	PSL-2	PSL-3
Joint Cans (6) up to 2" thick		50	A (1)	AZ	AZ
	greater than 2" thick	50	A (1)	AZ (2)	AZX (3)
Bracing	primary	36	C	C	C
		50	–	B	A or B
		60	–	–	A
	secondary	36	C	C	C
	brace end stubs @ nodes	36	–	–	A
		50	–	–	A
Legs	launch legs	36	C	–	–
		50	–	A or B	A
		60	–	–	A
	launch cradle	36	C	–	–
		50	–	B	A
		60	–	–	A
	legs elsewhere	36	C	B or C	B
		50	–	B	A or B
		60	–	–	A
Stiffeners	at nodes	50	A	A	A
	elsewhere	36	C	C	C
		50	–	B	A or B
Piling	heavy wall at mudline	50	B	A or B	A
	piling elsewhere	36	C	C	C
		50	–	C	B
	compliant tower piling	60	n/a	n/a	A
Miscellaneous	conductor panels	36	C	C	C
	boat landings, walkways	36	C	C	C

Notes:
(1) Specify low sulfur content per API 2H S-5
(2) For PSL-2 nodes greater than 3" thick, consider AZX
(3) For PSL-3, AZX includes mandatory CTOD testing if greater than 2" thick
(4) Where two toughness classes are given, the higher class is recommended for tension members greater than 1" thick
(5) For thicker primary bracing, especially in areas subject to collisions a higher toughness class is recommended
(6) Includes joint cans in legs and in primary bracing

TABLE III MATERIAL SELECTION FOR SUPERSTRUCTURE

		SMYS	TOUGHNESS CLASS		
		Group	PSL-1	PSL-2	PSL-3
Deck Legs	nodes up to 2" thick	50	A (1)	AZ	AZ
	nodes greater than 2" thick	50	A (1)	AZ (2)	AZX (3)
	elsewhere	36	C	B or C	A
		50	B	B	A
Deck Truss	chords	36	C	C	–
		50	B	A or B	A
		60	–	–	A
	diagonals	36	C	B or C	A or B
		50	B or C	B	A or B
Girders	flange @ nodes & panel points	50	A (1)	AZ	AZX (3)
		60	–	AZ	AZX (3)
	other flange, web, stiffeners	36	C	B or C	A
		50	B	B	A
		60	–	A	A
Secondary bracing & floor beams (redundant)		36	C	C	C
		50	C	C	B
Crane Pedestal		50	A (1)	AZ	AZX (3)
Lifting Points	padeye main plates & attachment points	50	A (1)	AZ	AZX (3)

Notes:

(1) Specify low sulfur content per API 2H S-5

(2) For PSL-2 nodes greater than 3" thick, consider AZX

(3) For PSL-3, AZX includes mandatory CTOD testing if greater than 2" thick

(4) Where two toughness classes are given, the higher class is recommended for tension members greater than 1" thick

TABLE IV		Weldmetal and HAZ Toughness Requirements			
Steel		Toughness		Weldmetal	
Group	SMYS	Class	PSL - 1	PSL-2	PSL-3
I	36	C	20 ft-lbs @ LAST (1)	20 ft-lbs @ LAST (1)	20 ft-lbs @ LAST (1)
I	36	B	n/a	20 ft-lbs @ LAST	20 ft-lbs @ LAST
I	36	A	n/a	n/a	20 ft-lbs @ LAST -36°F
II	50	C	20 ft-lbs @ LAST (1)	20 ft-lbs @ LAST (1)	n/a
II	50	C	20 ft-lbs @ LAST	20 ft-lbs @ LAST -36°F	20 ft-lbs @ LAST -36°F
II	50	A	20 ft-lbs @ LAST -36°F	25 ft-lbs @ LAST -54°F	25 ft-lbs @ LAST -54°F
II	50	AZ	20 ft-lbs @ LAST -36°F	25 ft-lbs @ LAST -54°F	25 ft-lbs @ LAST -54°F
II	50	AZX	n/a	25 ft-lbs @ LAST -54°F	25 ft-lbs @ LAST -54°F (2)
III	60	A	n/a	30 ft-lbs @ LAST -54°F	30 ft-lbs @ LAST -54°F
III	60	AZ	n/a	30 ft-lbs @ LAST -54°F	30 ft-lbs @ LAST -54°F
III	60	AZX	n/a	30 ft-lbs @ LAST -54°F	30 ft-lbs @ LAST -54°F (2)
	Notes:	(1) Weld metal toughness by filler metal specification only			
		(2) CTOD testing required if greater than 2" thick			
Steel		Toughness		Heat-affected Zone	
Group	SMYS	Class	PSL-1	PSL-2	PSL-3
I	36	C	–	–	–
I	36	B	n/a	15 ft-lbs @ LAST	15 ft-lbs @ LAST
I	36	A	n/a	n/a	15 ft-lbs @ LAST -18°F
II	50	C	–	–	–
II	50	B	15 ft-lbs @ LAST	25 ft-lbs @ LAST	25 ft-lbs @ LAST
II	50	A	25 ft-lbs @ LAST	25 ft-lbs @ LAST -18°F	25 ft-lbs @ LAST -18°F
II	50	AZ	25 ft-lbs @ LAST	25 ft-lbs @ LAST -18°F	25 ft-lbs @ LAST -18°F
II	50	AZX	n/a	25 ft-lbs @ LAST -36°F	25 ft-lbs @ LAST -36°F (3)
III	60	A	n/a	35 ft-lbs @ LAST -18°F	35 ft-lbs @ LAST -18°F
III	60	AZ	n/a	35 ft-lbs @ LAST -18°F	35 ft-lbs @ LAST -18°F
III	60	AZX	n/a	35 ft-lbs @ LAST -36°F	35 ft-lbs @ LAST -36°F (3)
	Notes:	(3) HAZ CTOD testing is covered by API RP2Z prequalification, unless heat input is outside prequalified range			
		– indicates testing is not required			

Working Paper

Material Requirements for Harbors

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SUMMARY

This paper presents the structural problems and degradation associated with materials used for piers, wharves and secondary structures of ports and harbors. The United States port and harbor infrastructure is deteriorating; much is still in use after 70 years. Deterioration of these structures, as a result of the marine environment, pests, vessel impact and seismic damage is discussed. Structures addressed include steel, timber and concrete piers and wharves, and their associated fender systems. Recently, various synthetic materials have come into use as secondary structural members and accessories. This paper discusses the causes of deterioration in traditional materials, identifies uses of advanced materials, and discusses some of the roadblocks, research and development needs to further facilitate the use of these materials.

INTRODUCTION

With the US port and harbor infrastructure aging, repair and rehabilitation of damaged wharves, piers, docks, breakwaters, sea walls and secondary structures has become critical to the continuing operation of our port facilities. Much of this aging infrastructure has not been structurally inspected in 20 to 30 years, or in some cases since construction more than 70 years ago. In addition to the problems of reassessment, frequency and type of structural inspection, one of the most critical issues is how to repair damage and what design criteria should be used. This paper will focus on damage assessment and successful repair methodologies.

The intertidal zone, including the splash zone is especially aggressive in its effects on common structural materials, though submerged elements are also subject to deterioration. The rate and extent of material deterioration depend upon a variety of factors such as salinity, temperature, marine growth, tidal changes, pollution and the presence of marine organisms. Other factors that cause deterioration include vessel impact, abrasion, ice, debris, poor maintenance and misuse (such as overstressing members).

For any damage assessment in marine construction, the following questions should be answered:

1. What is the cause of the damage?
2. What is the structural significance?
3. How should the damage be repaired?
4. How can further damage be prevented?

TYPES OF PORT AND HARBOR STRUCTURES ADDRESSED

There are many types of coastal, port and harbor structures. The following types of structures are considered:

A. Primary Structures - Piers and Wharves

Piers are structures that project out from shore into the water, that are either perpendicular to the shore, or at an angle. Most piers are pile-supported structures, shore-connected at one end, although mole piers, constructed of fill materials, can also be found.

A wharf is a structure usually oriented parallel to shore; wharf types include marginal, T-type, island and others. A marginal wharf is connected to the shore, along its full length, with a retaining structure to contain upland material. "T" type wharves commonly berth large vessels along the outside wharf, with smaller vessels or barges on the inside face (underside of the 'T'). An island wharf consists of a loading platform (commonly used for oil terminals), dolphins, and has no direct connection to shore; submerged pipelines carry product to shore (Refs. 1, 2). Personnel access is by vessel.

Other miscellaneous structures include quaywalls, breakwaters, dolphins (either breasting or berthing), floating-type breakwaters and other unique structures. A dolphin is usually a small independent structure used for berthing or mooring loads. These structures are normally connected to the main wharf with catwalks.

B. Secondary Structures

Secondary structures or substructures include camels, fendering systems, mooring fittings, deadmen, etc. Because of the unique construction of these components designed for specific types of vertical and horizontal loading, as well as the extensive use of synthetic materials, they are treated separately in this discussion.

MAJOR STRUCTURAL MATERIALS AND MARINE DETERIORATION

A. Concrete

Concrete is one of the primary materials used for the construction of harbor and port facilities. Components constructed of concrete include piles, pile caps, decks, beams, retaining walls, sheet piles and other miscellaneous types of structural elements. These components may be precast or cast-in-place and are typically reinforced with steel bar or prestressing strands. The type of construction can have a significant role in the manner and rate of deterioration in the marine environment. Current design and construction practice focuses on ensuring greater durability by providing highly impermeable concrete to protect the embedded steel. Concrete is composed of cement, aggregates, water and other admixtures. Performance of the concrete is highly dependent upon mix design. Concrete is weak in tension; therefore reinforcing steel is added to carry tensile loads. Because this reinforcement is susceptible to corrosion, particularly in a marine environment, concrete is also expected to provide protection and "cover" for the reinforcing steel. Corrosion of reinforcing steel is probably the primary cause of deterioration of concrete structures in a marine environment. Active and passive cathodic protection systems are being increasingly applied to concrete structures for both above and below water corrosion control. Also, corrosion-resistant metallic materials such as stainless steels, galvanized steels and non-metallics, such as glass and carbon fibers are now being tested by the US Navy (Office of Naval Research, PE0603725N and PE0602234N) for use as reinforcing materials.

A description of concrete deterioration and possible mitigation strategies are as follows:

1. Overstressing cracks

An overstressing crack, also referred to as a stress crack, results from external loads that induce high internal stresses, exceeding the strength of the concrete member. Photo 1 shows an overstressing crack on a concrete pile. This type of defect may be found on any marine structure wherein the strength of the member has been exceeded; however, it is most commonly found in areas of high seismic activity. In addition, these cracks are often the result of pile mishandling, driving stresses during installation and wave forces on uncapped piles. Cracks may be more common on older prestressed piles because these were typically constructed with a smaller percentage of spiral reinforcing than is now used. Excessive or dense spiral reinforcement can result in fabrication and constructability problems, such as spalling during pile driving.

Concrete members subject to overload typically exhibit cracking that is perpendicular or inclined with respect to the main reinforcing steel, or areas of broken off concrete. In addition to a possible reduction in load-carrying capacity, depending upon the severity of damage and the yielding of reinforcing steel, the resulting cracking may increase the rate of deterioration due to corrosion.

2. General cracks

A general crack is a small crack that can result from a number of causes which, under normal circumstances, are not distinguished during the inspection of marine concrete components. Various causes of general cracks may include plastic shrinkage caused by rapid moisture loss in fresh concrete, poor consolidation, drying shrinkage caused by long-term moisture loss, thermal shrinkage, cycles of freeze-thaw, wetting-drying, heating-cooling, and chemical reactions. Photo 2 shows a general crack on a concrete slab.

3. Corrosion Cracks and Spalls

A corrosion crack is a split in a concrete component caused by the expansion of chemical products generated by corrosion of the steel reinforcement. Corrosion cracks are found in both prestressed and non-prestressed components. Photo 3 shows a corrosion crack on a prestressed concrete pile; Photo 4 shows a corrosion crack on a non-prestressed concrete pile. The structural significance of a corrosion crack on a prestressed component is much more severe than for a non-prestressed component because by the time a corrosion crack is observable, the prestressing strand is usually almost 100 percent corroded.

Corrosion of the reinforcing steel, whether steel bars or prestressing strands is a result of the ingress of chloride ions present in sea water or deicing chemicals. The passivating layer at the surface of the reinforcing bar is reduced and the chlorides produce an electrolyte for the corrosion of the reinforcing steel. Chloride concentrations are often greatest just above the splash zone, where evaporation contributes to their buildup.

Deterioration due to reinforcing corrosion is typically first seen as corner cracking parallel to the reinforcement. In advanced states, all concrete outside the reinforcing can be lost, significantly reducing structural capacity. Reinforcing corrosion also reduces bond and anchorage capacities of the reinforcing bars. Deterioration is most rapid in concrete with high water-cement ratios, low cement content, poor consolidation, insufficient cover over the reinforcing steel and areas of high chloride concentration. If concrete diffusion rates for chlorides are known, one can estimate the time until onset of corrosion. For concrete components constructed of high quality concrete, including admixtures and pozzolans, along with concrete cover of three or more inches, the reinforcing bars may remain protected from corrosion for fifty or more years.

The use of reinforcing steel coated with epoxy or zinc, or constructed of stainless steel or polymer materials is a further effort to reduce corrosion of reinforcement. While some experience has been unsatisfactory, the use of epoxy coated bars or galvanized bars is wide spread in the United States. Poor performance of such materials appears to be most often due to poor specifications, the lack of quality control or the bending of bars after being coated. Stainless steel reinforcement has been widely used in marine and other aggressive chloride containing environments in Europe, and to a lesser extent in North America. It has been used by the US Navy both for prestressing strands and also reinforcement in specialized (non-magnetic) piers, with 10 years of service without significant corrosion.

A closed corrosion spall exhibits incomplete separation of a fragment of concrete cover, resulting from corrosion of the reinforcing steel. Photo 5 shows a typical closed corrosion spall on a concrete pile. A closed corrosion spall usually becomes an open corrosion spall within a short time.

An open corrosion spall is a recess in the concrete surface resulting from complete separation of a fragment of concrete cover due to corrosion of the reinforcing steel. Photo 6 shows a typical open corrosion spall on a pile cap beam. Photo 7 shows a close-up of an open corrosion spall.

4. Erosion

Erosion, sometimes referred to as scaling, is the general reduction of a component's cross-sectional area due to deterioration of the outer concrete layer. The deterioration can be the result of wave action , current action, freeze-thaw, wetting-drying, chemical deterioration, mechanical abrasion from floating debris or sediment transport, or bio-degradation by marine organisms. Photo 8 shows a typical erosion area of a non-prestressed concrete pile. Photo 9 shows a typical erosion area of a prestressed concrete pile. Erosion may be found in all areas of the United States, but may be more prevalent in northern climates where freeze-thaw action is more common, particularly in older concrete that was not air-entrained. This type of freeze-thaw deterioration is most severe in the splash zone, and over time can extend many inches into the member. Erosion or scaling reduces the available concrete "cover" over the steel reinforcement and promotes the onset of corrosion.

5. Built-up Cracks on Piles

A built-up crack refers to a crack appearing at the interface between the precast pile and the cast-in-place concrete section built on top of the pile. This situation is common where concrete piles are driven below the design cut-off elevation and must therefore be extended upward by building-up the pile to the proper final elevation. Cracks quite often occur at the interface due to a weak bond at this location, as well as stresses introduced through temperature and the difference in elastic properties of the cast-in-place versus precast sections. These cracks, once formed, provide an opening for corrosion deterioration to occur. Photo 10 shows a typical built-up crack on a concrete pile.

6. Chemical Reactions and Concrete Failure

Concrete in sea water is attacked by sulfates and magnesium found in sea water. Sulfate attack is usually detected as a softening of the surface of the concrete. With further deterioration, the surface is easily chipped away and the exposed surface exhibits whitish deposits from the sulfate reaction with the cement. Advanced deterioration includes swelling and cracking of the concrete. Sulfate attack may show up gradually and primarily in older structures constructed of Type I cements, that are high in tricalcium aluminate.

Where certain types of volcanic rock were used for aggregates, concrete may exhibit alkali-aggregate deterioration. This deterioration results from a reaction between the alkalis present in the cement paste and/or salt water and reactive forms of silica contained in the aggregate. Water is required to develop this reaction and is readily available in the marine environment. This reaction causes expansive forces which crack the concrete.

Deterioration, such as freeze-thaw damage, sulfate attack and alkali-silica reactivity is most often found in older structures, built before these problems and corresponding preventative measures were well understood. The choice of proper mix materials and admixtures should minimize such attack mechanisms in new construction.

7. Underwater Cracking of Concrete Piles

Very little information is available regarding the problem of underwater cracks on prestressed concrete piles. These cracks are oriented longitudinally to the pile, and may be either continuous or intermittent. Investigations of the cracks suggests that a primary cause may be alkali-aggregate reaction within the concrete (Ref. 3). Photo 11 shows an underwater crack of a prestressed pile.

For longitudinal cracks in concrete piles (prestressed and non-prestressed), a program is in progress to monitor and evaluate these cracks that have occurred below the water line. The Port of Los Angeles, Han-Padron Associates and Blaylock Engineering Group have formed a joint industry project to evaluate these cracks, perform core sampling, petrographic studies, and research on aggregate and chemical reactions in the concrete. In addition, it is not clear what the structural implications of this damage are, and whether or not the damage is critical to the continued fitness-for-purpose of the piles.

8. Concrete Design Considerations for Durability

The long term durability of concrete structures is dependent on using appropriate design considerations. Recommendations for durable concrete can be found in American Concrete Institute publications (ACI 201.ZR, "Guide to Durable Concrete"; ACI 357R, "Guide for the Design and Construction of Fixed Offshore Concrete Structures"). Typically these concrete mixes should contain Type II, low tricalcium-aluminate, cements as well as fly ash and/or silica fume to maximize their resistance to chemical attack by sea water. In general, the following mix design parameters should be considered when designing concrete for the marine environment:

a. Fly ash or silica fume increase density of the concrete, making it less porous, resulting in improved durability. Fly ash and silica fume raise the silica content to a level that prevents sulphate attack and increases the resistance to alkali-silica reactivity.

b. Air entrainment improves freeze-thaw resistance of the concrete and aids in durability, by providing an entrained volume for by-products from corrosion and chemical reactions

c. Corrosion inhibitors, such as calcium nitrite can be effective. Their long-term effectiveness is still under study.

d. Water reducers are commonly used to reduce water/cement ratios, and also increase the workability of the concrete. A lower water/cement ratio reduces permeability.

e. Anti-washout admixtures are used for underwater construction to minimize segregation of the components.

The use of multiple admixtures should be used with caution, as reactions may occur between various ingredients. In addition, increasing concrete cover can be an effective means to delay the onset of corrosion. Epoxy-coated reinforcing bars have been used for corrosion resistance. However, the past performance of these bars have been a problem in some cases. A new standard A934/A934M (Ref. 4) has recently been developed; note that longer bond lengths are required. The use of epoxy coated rebar may preclude the cost effective use of cathodic protection, since epoxy restricts the necessary continuity.

9. Concrete Rehabilitation Considerations

Areas of concrete deterioration should be removed by chipping, cleaning and then repaired. The cleaning and repair will not arrest further corrosion in adjacent unrepaired areas; therefore active and passive cathodic protection systems are being studied as methods to limit further corrosion of the reinforcing bars. One study, under the direction of the University of California at Berkeley, uses a zinc wire wound around the ends of rebar exposed while repairing the concrete (Ref. 5). The zinc acts as a sacrificial anode and is effective in moist environments. If the concrete remains dry, the system is not effective. If it remains wet, the zinc anode is activated; a three year study has indicated that further corrosion has not taken place. For any cathodic protection system to be effective, electrical continuity needs to be achieved.

10. Concrete Research Needs

Research needs to be performed on the effects of aggregate and admixtures to prevent or minimize chemical deterioration of the concrete and corrosion of reinforcing steel in the marine environment. Manufacturing of corrosion-resistant reinforcing bars must be accomplished at a comparable price to ordinary steel reinforcing bars, or have benefits which justify the higher cost. One new type of reinforcing bar, DFM (Dual-phase Ferrite Martensite) steel has been developed by Professor Gareth Thomas and his team at the University of California at Berkeley. This new type of bar has tested superior to conventional steel rebar, both in terms of corrosion resistance and dynamic loading.

Another area that needs further study is effective surface preparation methods for repairs (i.e. abrasive versus water-jetting). These methods should consider the environmental impact of use in a sensitive, coastal marine area.

A documented database of performance of novel cathodic protection techniques, such as imbedded zinc anodes, spray applied zinc/titanium, titanium rods and ribbons in the splash zone needs to be established.

B. Steel

Steel is frequently used for harbor and port structures. Components constructed of steel are most often limited to bearing, batter and sheet piles, but may include cross-bracing and other framing components. A description of typical deterioration of steel components and remediation strategies are as follows:

1. Corrosion

The primary cause of steel damage in the marine environment is corrosion. Corrosion of unprotected piles is most prevalent in the vicinity of the tidal zone, but is also present in submerged components. Photo 12 shows corrosion in a steel H-section pile; Photo 13 shows corrosion in a steel sheet piling and Photo 14 shows severe corrosion in a steel tubular pile. Corrosion rates are highest in salt or brackish water; these rates are influenced by the presence of oxygen, moisture, pollution and chemicals, marine growth, water currents and stray electrical currents. The highest corrosion rates occur at high and low tide elevations.

Corrosion is the conversion of the metallic ion, through electrochemical reactions, into a compound form (rust). In the electrochemical process, there must be a current flow. This current flow can be caused by differences in potential between various areas of a single member, between differing metals used in the same structure, or the presence of external currents. External currents can be generated by various port activities such as electrical work on the wharf. Both overall general corrosion and localized pitting corrosion are usually present.

Salt water, or other waters that contain significant amounts of sulfur or chlorides are more acidic and make better electrolytes, so that the corrosion rate is much faster than in fresh water. In the splash zone and in areas of high velocity currents, the corrosion rate is most rapid. The moving water provides more wet-dry cycles, carries more oxygen to the metal and tends to remove the initial film of corrosion, which would normally retard further deterioration. Warm water also tends to accelerate corrosion rates.

2. Abrasion

Abrasion of steel components is the reduction in cross-sectional area resulting from continuous rubbing, typically by sediment being transported in waves or current.

3. Overload

Overloading of steel components is manifest as a distortion in the shape of the component, due to external loads exceeding the member's elastic capacity. Typical examples may include a sheet pile wall bulging outward due to pressure behind the wall or members displaced towards the shore, as a result of vessel impact. Photo 15 shows overloading of a sheet pile bulkhead; Photo 16 shows general overloading of a tubular steel pile. This type of defect is found in all regions of the United States, but may be more common to high seismic areas, where seismic lateral soil loads may cause overloading.

4. Steel Rehabilitation Considerations

Various coatings can be applied to reduce corrosion. Some of these include petroleum pastes and wraps, epoxies, urethanes, glass flakes and concrete encasements. The life expectancy of these coatings varies with type, exposure conditions and quality of application. Coatings are subject to deterioration and damage; these areas may become locations for accelerated corrosion due to the large adjacent protected areas. Coating maintenance must be an ongoing activity for marine facilities. Both passive and active cathodic protection systems may also be used to reduce the deterioration of steel structures.

The effects of corrosion can be reduced by using high alloy steel and other metal alloys for specific applications. However, except for high nickel structural steel, such as the U.S. Steel Mariner product, these materials are primarily found in secondary members. In addition, metallic sheathing using alloys such as UNS C 70600 (90% Cu and 10% Ni), UNS C 71500 (70%Ni and 30% Cu) and UNS 04400 (Monel Alloy 400) have been used for corrosion protection of steel in the intertidal and splash/spray zones of waterfront structures.

5. Steel Research Needs

Research on novel methods of applying cathodic protection in areas above the water line are being investigated by various researchers. The specifications for steel coatings in the marine environment, specifically in the splash zone/intertidal area needs further research.

Investigation of newer splash-zone coatings and a comparison of these to standard methods in use today should be initiated (epoxy or epoxy/urethane, coal tar epoxy, etc.). Also thermal spray coatings should be investigated. Specifications should be improved for the use of steel coatings and their application to the marine environment, especially in the splash zone/intertidal area.

C. Timber

Timber is commonly used in the construction of port/harbor facilities. Timber components include piles, pile caps, stringers, retaining structures, cross-bracing and decking. Historically, the timber has been treated with preservatives. A description of typical deterioration of timber components and mitigation strategies follows:

1. Marine Borer and Insect Attack

Marine borer infestation is the most common form of deterioration in submerged timber components such as piles and cross-bracing. Damage is manifested in the form of a reduction in cross-sectional area of the component. The two primary groups of marine invertebrates causing the deterioration are Teredo (shipworms) and Limnoria (Gribbles). Teredo bore into the interior of the timber component as they grow, while Limnoria attack the timber from the exterior. The Teredo leave a trail of openings to obtain nourishment from the water. The series of tubes created by these borers run vertically in a pile and can substantially reduce the cross-sectional area of the member. Damage can occur anywhere between the mudline and the water line. The Limnoria is a surface boring crustacean, that is about 1/8 inch long and bores only a short distance into the wood. As water action breaks down the thin layer of wood protecting it, the crustacean bores deeper. Eventually it produces a hourglass-shaped deterioration pattern in wood piles. Photo 17 shows typical marine borer attack on a timber pile; Photo 18 shows a close-up of a marine borer attack. As the harbors of the United States have gotten cleaner over the last several years as a result of the Clean Water Act, marine borer damage has become more prevalent.

Above the water line, termites are often the cause of timber component deterioration, resulting in a weakening of the component through a reduction in cross-sectional area. Termite infestation of marine timber components may be found throughout the southern United States and Pacific islands.

2. Fungi and Rot Damage

Fungi and rot damage occur above the water line and is characterized by discoloration and softening. In advanced stages, destruction of the wood cells occurs and fruiting bodies such as mushrooms may be evident. Photo 19 shows fungi and rot damage on timber beams.

Fungi thrive on the organic matter in wood cells. Ideal conditions for growth including moisture, oxygen and warmth are found in many port facilities. These microorganisms can easily penetrate untreated timber, or older timber where the preservatives have become ineffective. In early stages, decaying members appear slightly discolored. In advanced states of rot, the wood becomes spongy, stringy, crumbly and splintered. Internal decay is harder to detect, but results in hollow members. This type of deterioration may be found in marine environments anywhere in the United States.

3. Shrinkage damage

Shrinkage of timber components leads to splits and checks in the wood. While some splitting and checking is normal, excessive shrinkage can reduce the structural integrity and provide an opening for marine borers and insect ingress. This type of deterioration is most common in dry climates.

4. Overloading

Overloading of timber components may be manifest in bulging of the timber fibers, breakage of the component or ripping of connections. Photos 20 and 21 show typical timber beams subjected to overload.

5. Abrasion

Abrasion of timber components may be characterized as a reduction in cross-sectional area resulting from suspended sediments or ice. Timber fender components are also susceptible to abrasion damage from vessels rubbing against them. Photo 22 shows abrasion damage on a timber pile, subjected to rubbing by a timber camel. This type of deterioration can be found in any port or harbor area, given the proper environmental or operational conditions.

6. Ice Heaving

Ice heaving is caused by the adherence of ice to a pile which may cause the pile to shift as the tide raises. This type of damage can cause entire structures to shift or displace, and can seriously affect bracing connections.

7. Timber Reconstruction Considerations

In order to protect timber from biological deterioration, preservative treatments have been used. Creosote preservatives have proven effective against Teredo attack and arsenate preservatives have been effective against Limnoria. Marine timber may receive a dual treatment incorporating both preservatives. Due to environmental concerns, creosote is now restricted in some areas, and it is probable that increasing constraints will be placed on the other preservatives as well.

Other methods of protection include polymer coatings and wrapping materials applied prior to or as a retrofit after construction. (Wrap installation following significant deterioration, i.e. more than 5 percent may not be successful, due to the looseness of the wrap). The use of wood species, which are believed to be resistant to marine organisms has also increased. However, their performance is often unsatisfactory and availability may be limited.

SECONDARY STRUCTURAL MEMBERS AND MARINE DETERIORATION

A. Fender Systems

Typical materials used for fendering at marine structures are timber, steel, concrete, plastic and rubber. Each material is used for specific applications, depending on the fender system selected. These materials are used both for specific mechanical properties such as elasticity and energy absorption, as well as their resistance to material deterioration such as rot, corrosion or borer attack. Most of the synthetic materials have a short history of use and hence much still remains to be learned about their long term performance.

In many cases, these materials are polymers, subjected to cross-linking due to ultraviolet radiation and hence are normally black (or a similar dark color) to limit light penetration. Prolonged aging can cause changes in mechanical properties as well as surface crazing and cracking. Mechanical properties may also be temperature dependent. In cold climates, some materials may experience fractures and breakage, particularly under accidental impacts or overload. More common deterioration of these components is due to tears and gouges from misuse or local overload around fasteners.

1. Timber

Historically, fendering systems were comprised of timber piles, blocks, chocks and wales. These systems absorb energy through bending of the timber piles and wale, and compression of the chocks and blocks. In the 1960's, hollow cylindrical rubber fenders were introduced in place of the blocks. The addition of the rubber fenders increased the system's total energy capacity. These fender systems have typically used a dual preservative treatment of coal tar creosote and copper arsenate in the timber elements. The timber elements have been susceptible to different types of deterioration depending on their placement relative to the water line. Underwater deterioration has been due to marine borers, principally Limnoria and Teredos. Additionally, the fender piles experience impact damage from berthing loads and abrasion. The combination of marine borer damage and berthing and mooring loads, will in time cause the timber elements to fail. A secondary problem, associated with replacing the broken piles, is the misalignment of the timber piles. In most cases, replacement piles are placed in the same location as the broken pile. Because of the difficulty of removing the pile stubs, the pile stubs are typically left in place. This causes the tip of the replacement pile to be placed adjacent to the broken pile stub, thereby in many cases, causing a misalignment of the piles. This misalignment causes the berthing and mooring loads to be distributed to fewer piles than anticipated in the original design, thereby increasing the loads on the individual piles.

As a result of environmental concerns relative to the fabrication, storage, use and disposal of timber treated with wood preservatives have become an issue. Because of this and the minimal life expectancy of untreated timber piles, other materials are being used in marine fender systems.

Timber fender system damage above water is generally due to fungal decay and/or termites. Typically, this occurs at the saw cuts, bolt holes, or checks and splits in the timber material. These locations create avenues for fungal decay and termites to penetrate beyond the treated material into the untreated heartwood.

2. Concrete

There are currently two different methods used in the design of fender systems utilizing concrete piles. The first method uses the pile as a flexural element, which absorbs the berthing energy by deflection. To accomplish this, prestressed concrete piles are designed with a low effective prestress. The prestress is low enough to allow the pile to deflect under load and when the load is released the pile moves back to its initial position. Concrete cracks will form if lateral loads exceed about 30 percent of the pile capacity, but will typically close back upon unloading due to the partial prestressing. This system has been used by the U.S. Navy since 1986, and has served as an effective fender system. There are some concerns relative to the migration of chlorides to the prestressing strands through the cracks caused by bending of the piles; however, these cracks are typically open for only a very short time and are small.

The second method uses the concrete piles as rigid elements behind foam-filled fenders or hydro-pneumatic fenders. In these systems, the concrete piles transfer the load from the fender to the foundation soils and structure. This system has been used successfully for ten years or more.

Abrasion of the fender on the concrete piles has been observed on systems which use floating fender elements. This problem is exacerbated because the piles tend to drift and rotate when driven, resulting in protruding pile edge surfaces. This surface minimizes the wear areas on the fenders. As long as the foam-filled fenders are floating and subject to tidal action and wave induced motion, abrasion will be a problem.

A problem associated with the use of timber or plastic camels in conjunction with concrete piles is that the camels will deteriorate quickly due to abrasion on the concrete piles from wave action. These problems can be alleviated somewhat with the use of polyethylene rubbing strips, placed on the surface of the concrete piles.

3. Steel

Steel fender systems have been used successfully as both fender piles supporting camels or separators and as a backing system for foam-filled fenders. In either system, the typical deterioration is corrosion of the steel and delamination of the protective coating. Typically, these systems have protective coatings and cathodic protection systems to counteract the corrosion. Both active and passive cathodic protection systems have been used on fenders systems. Maintenance of active cathodic protection systems is essential to the systems operation, and in many instances the necessary maintenance is neglected.

4. Plastic

The use of plastic in the design of fender systems is a relatively new application. There are principally two types of plastic piles in use, a fiberglass reinforced plastic pile and a steel pipe reinforced plastic pile. The fiberglass reinforced plastic pile has fiberglass reinforcing bars arranged near the perimeter of the pile. The piles are very flexible and are effective as a fender system for smaller vessels. Steel pipe reinforced plastic piles are composed of steel pipe encased with approximately three inches of plastic. These piles are much stiffer than the fiberglass reinforced piles because the pipe is the principal energy absorbing element. The energy dissipated by the pipe is limited by the small deflections necessary to cause the steel to yield, thereby limiting the effectiveness of the fender. If properly designed, these piles can be used in conjunction with rubber fender elements to form an effective fender system.

Plastic piles are a newer technology and manufacturers are grappling with problems associated with cracking of the plastic. Most of the plastic is comprised of recycled materials. The quality of the material is of concern, therefore quality assurance of the finished material is a concern. There has been limited testing of the fiberglass reinforced plastic piles to document that cracking of the piles only minimally reduces the flexural and energy capacities of the pile. There is also some concern about the fiberglass reinforcing migrating towards the tension face of the pile under load. Cracking is a potential problem for both types of plastic piles because the cracks can allow corrosion of the steel pipe in one case and deterioration of the fiberglass rebar in the other.

One major problem to further use of plastic piles is that the stiffness of the conventional steel, timber or concrete piles should be matched, so that deflections are uniform, and one type of pile doesn't fail with the other type remaining intact. The US Navy is investigating a strategy for secondary members, and matching the stiffness of these new composite piles. Generally, the fender elements should all be of the same stiffness and type.

5. Rubber Fenders

Rubber fenders are manufactured in numerous shapes and sizes for use as fender elements. The most efficient fender element currently manufactured is a buckling column. Buckling column type fender systems are comprised of rectangular rubber buckling column elements and a face panel mounted on a vertical surface. The typical deterioration observed with these systems is due to tearing of the rubber buckling element during overload and loss of face panels due to ship induced shear loads. The manufacturers have been relatively successful in providing ozone resistance of the rubber and corrosion protection of the mounting hardware.

Rubber fender shapes can be hollow cylinders, “D” shaped, or numerous other rubber elements which have been used as rubbing strips and fenders. Problems associated with these elements have been tearing and cracking. In many cases these problems have been exacerbated from punctures of the rubber by the mounting bolts. Typically, this has been because the bolts extend a significant length beyond the nuts, allowing punctures to occur during compression of the fender.

6. Foam-filled Fenders

Foam-filled fenders can be used as the energy absorbing element of a concrete, steel or timber system. These fenders require a backing panel of closely spaced fender piles or a flat vertical face to provide sufficient contact area. Problems associated with these elements are due to the fact that many of them float, and as such move up and down with each wave against the backing surface. This movement causes abrasion of the foam-filled fenders. Additionally, marine growth builds up on the bottom of the fenders, causing the fenders to remain in one position which contributes to fixing the location of the abrasion.

Another problem observed with these fenders is associated with the swivel mounted in the end of the fender. In some cases, the swivel binds under load causing the mounting chain to roll up on itself as the foam-filled fender moves up with the tide, when the fender is loaded.

7. Hydro-pneumatic Fenders

Hydro-pneumatic fenders are used as the energy absorbing element of a concrete or steel pile system. These fenders require a backing panel or closely spaced fender piles to provide sufficient contact area. Hydro-pneumatic fenders, ballasted with water and concrete weights to float vertically, are currently being used for deep draft fendering of submarines.

B. Mooring Fittings

Mooring fittings at marine facilities are usually comprised of bollards, double bitts, cleats or pelican hooks. Typical materials used are cast steel. There have been relatively few problems observed associated with the use of bollards and double bitts. However, partial embedment of the mooring fittings into the concrete superstructure of a wharf or pier has contributed to the deterioration of the concrete. This occurs when corrosion occurs at the base of the steel mooring fitting, causing expansion of the steel and thereby spalling and cracking the concrete mooring foundation. This allows water to further penetrate to the steel reinforcement and cause corrosion. Deterioration of cleat mooring foundations with similar detailing has also been observed. Additionally, breakage of the horns on cleats has been observed. At many facilities, bollards and cleats are used interchangeably, while the original design load capacities were very different. At Naval facilities the design load capacity is typically 25 tons for a cleat and 100 tons for a bollard or double bitt. This is probably the reason for the broken cleat horns observed at some of the sites.

Pelican hooks are used at many marine oil terminals and other locations where large ships are moored or where environmental loads are extreme. They are used because of their ability to be released under load. Some concern associated with their use is in determining the load on the hook and the mooring lines. In some cases, this problem has been addressed by incorporating load cells in the hooks to warn personnel of high mooring loads.

C. Fasteners

Mechanical fasteners are used to connect structural members together, to attach supporting members, and to hang utilities and fittings, among other things (Ref. 6). The proper choice of fasteners is important to the performance of these components, as their deterioration through corrosion can sometimes have serious consequences. Some non-metallics, stainless steel and nickel alloys have potential use for fasteners and hardware for waterfront structures. If properly matched to the service environment, these fasteners provide longer life, improved reliability and ease of disassembly.

SUMMARY AND CONCLUSIONS

Concrete, steel and timber have been discussed as effective materials in a marine environment. Deterioration and its causes have been discussed, along with various repair/replacement and mitigation strategies. Various research requirements have been discussed. In general, there is a need for a comprehensive database of failures and repair methodologies, in order to evaluate success, in terms of long-term durability.

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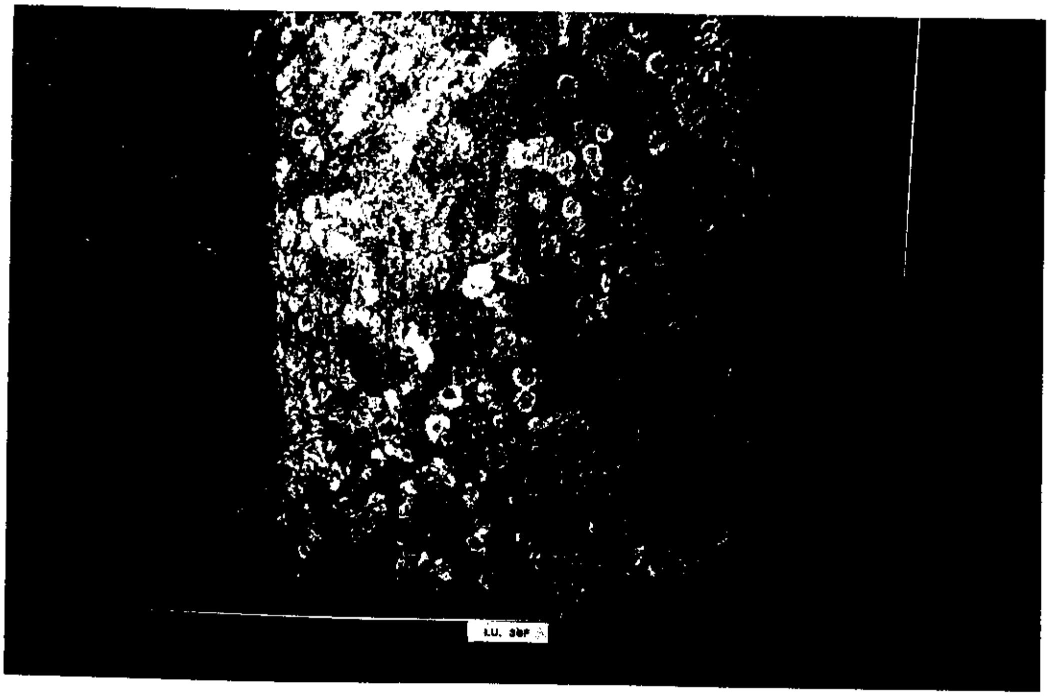
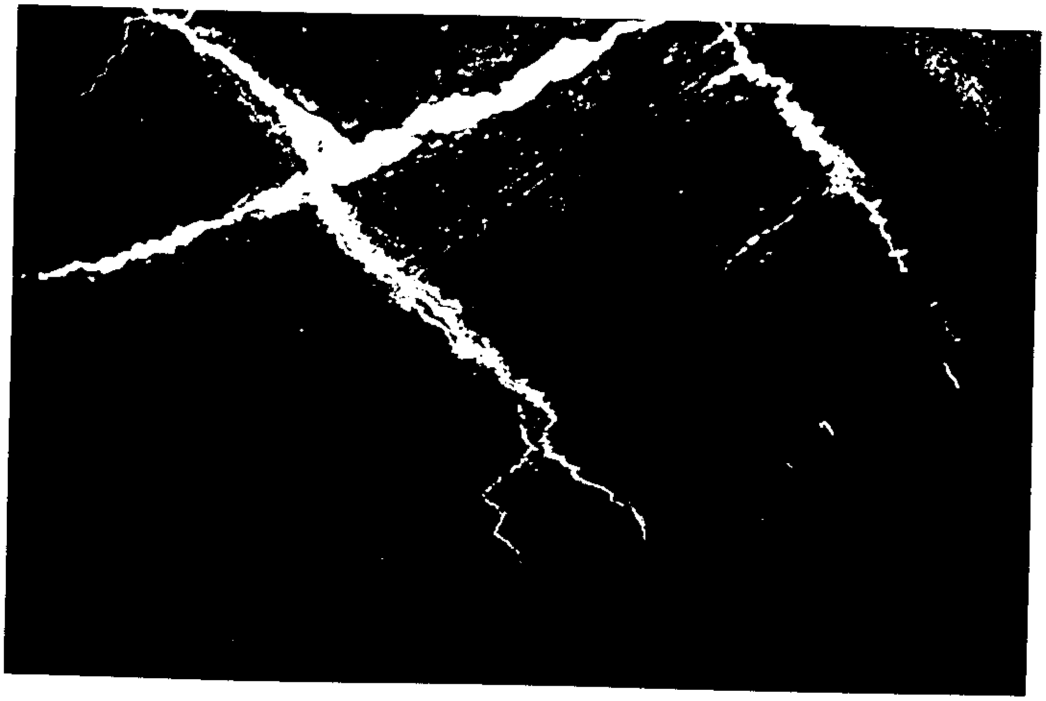


PHOTO 1. A typical overstressing crack in a concrete pile

PHOTO 2. A general crack on a concrete slab



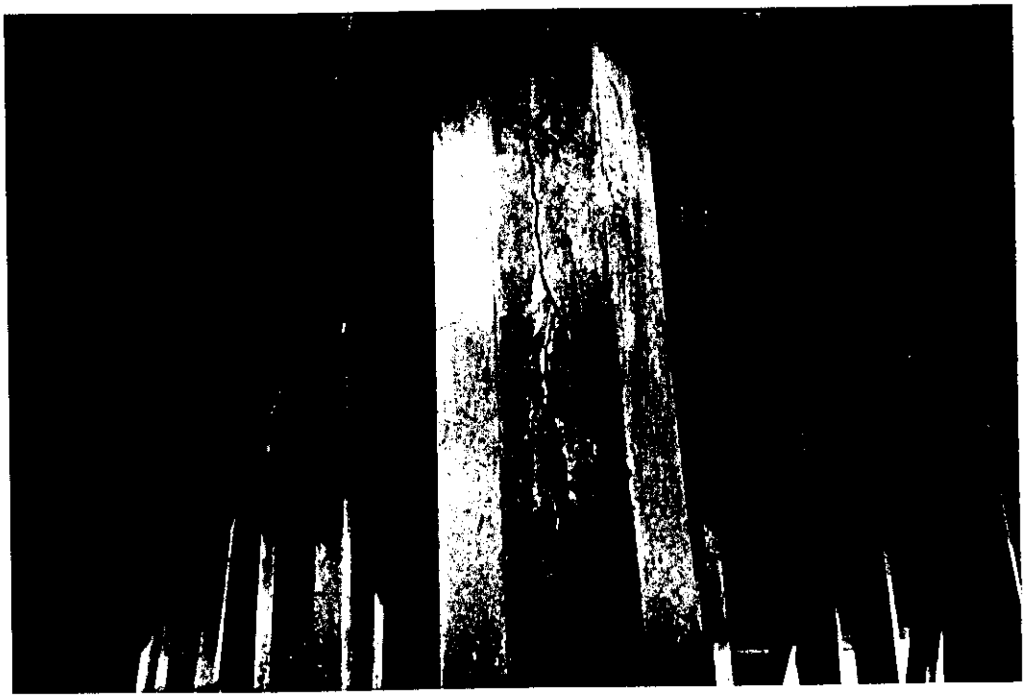


PHOTO 3. Corrosion crack in a prestressed concrete pile

PHOTO 4. Corrosion crack in a non-prestressed concrete pile

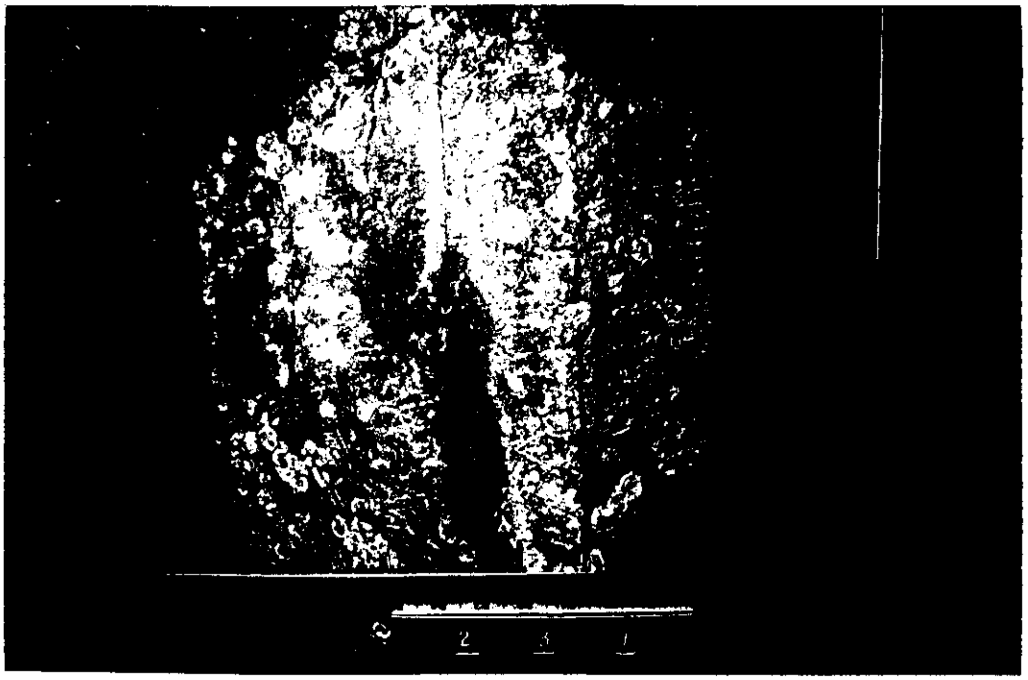
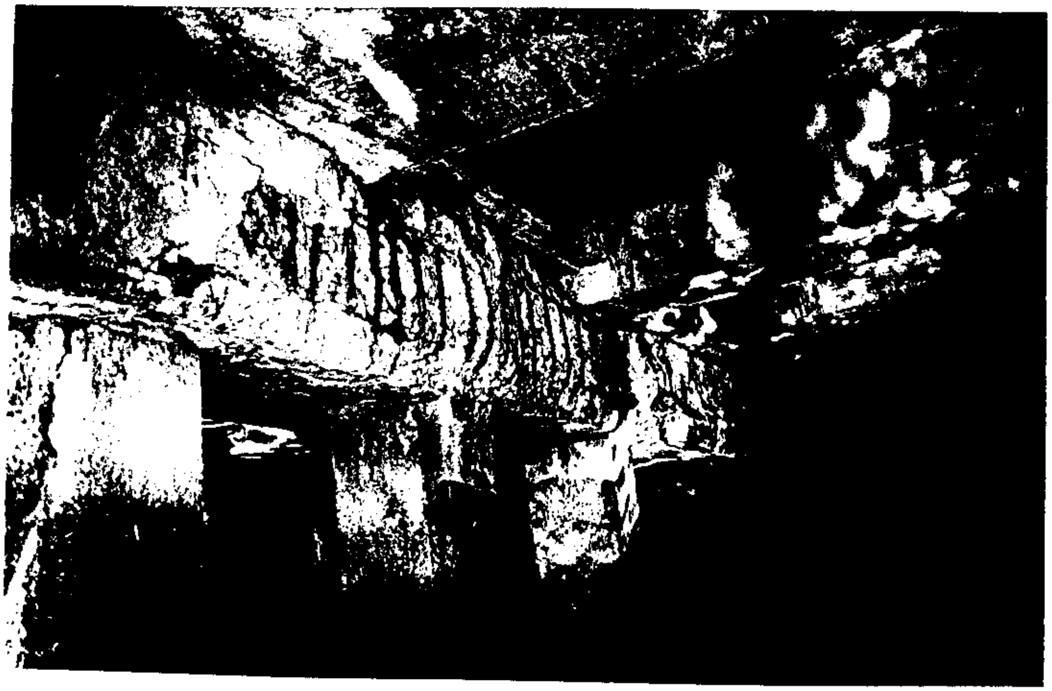


PHOTO 5. A closed corrosion spall in a concrete pile

PHOTO 6. An open corrosion spall in a concrete pile



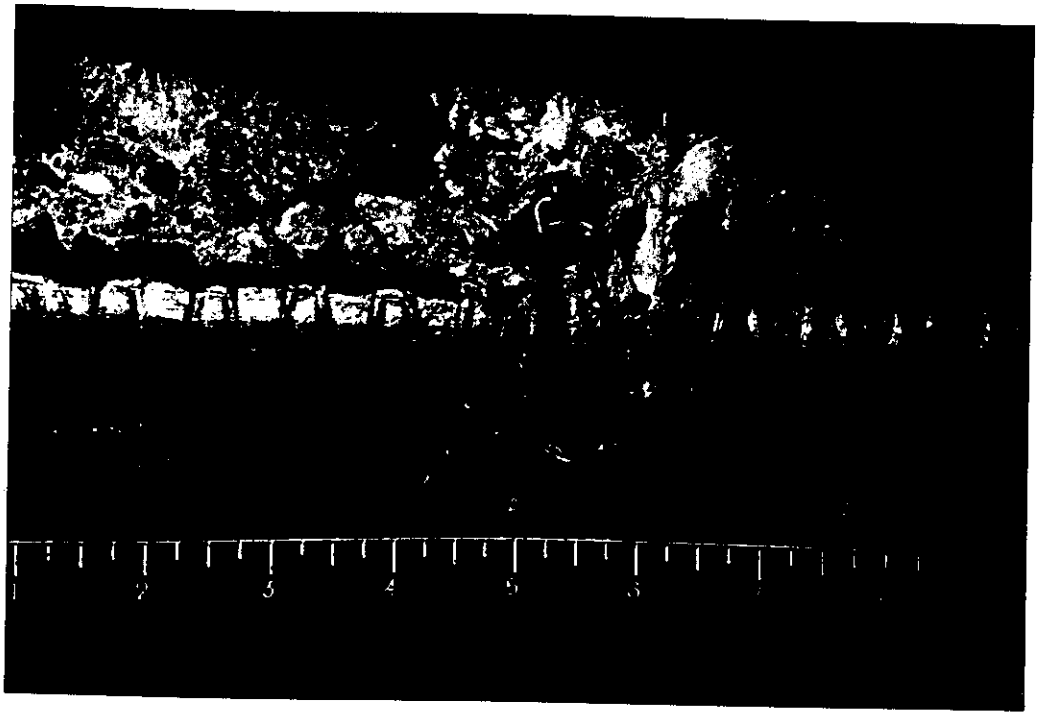
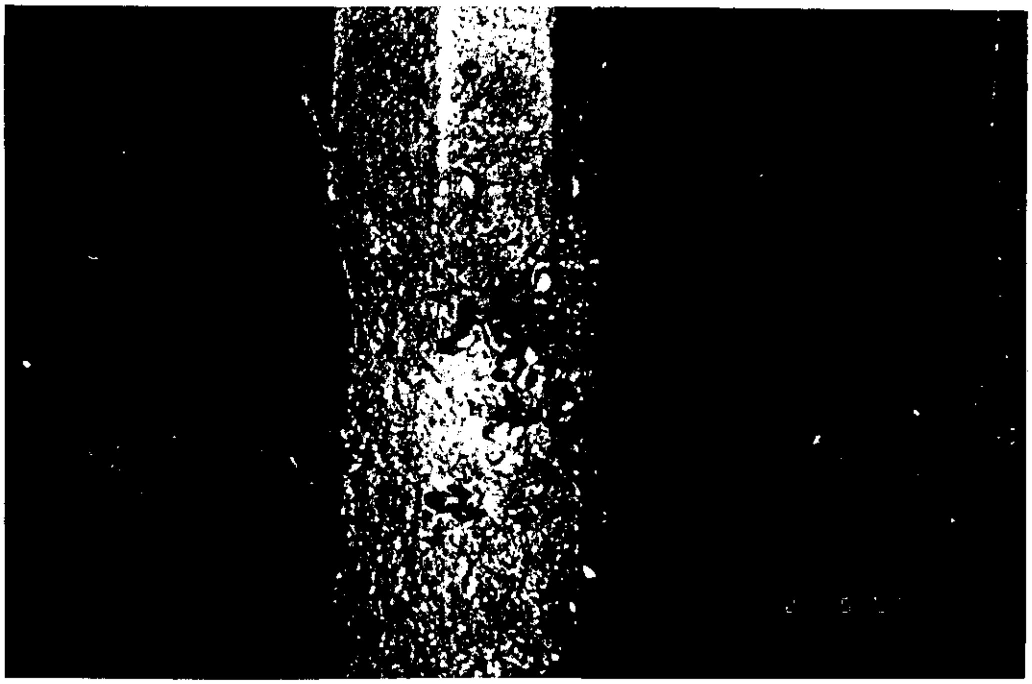


PHOTO 7. An open corrosion spall

PHOTO 8. Erosion in a non-prestressed concrete pile



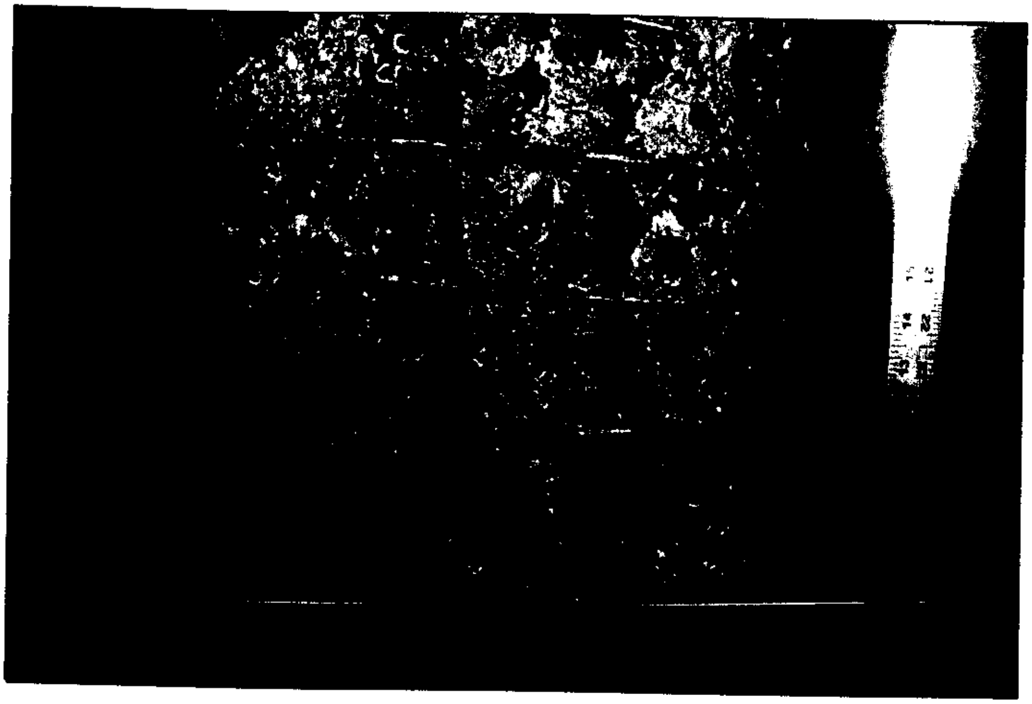
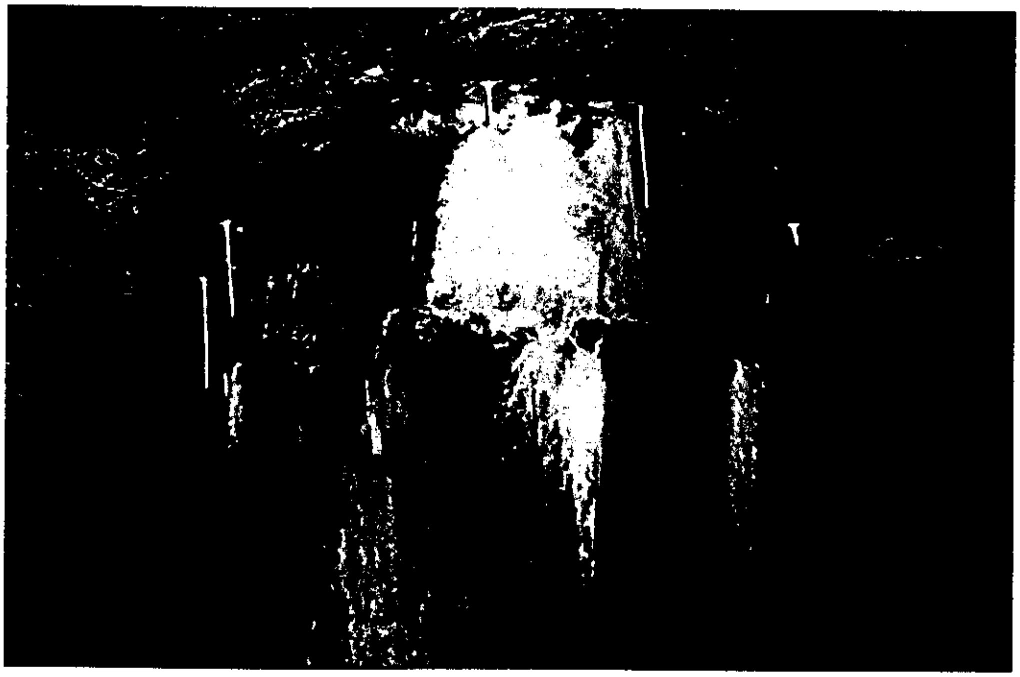


PHOTO 9. Erosion in a prestressed concrete pile

PHOTO 10. Built-up crack in a concrete pile



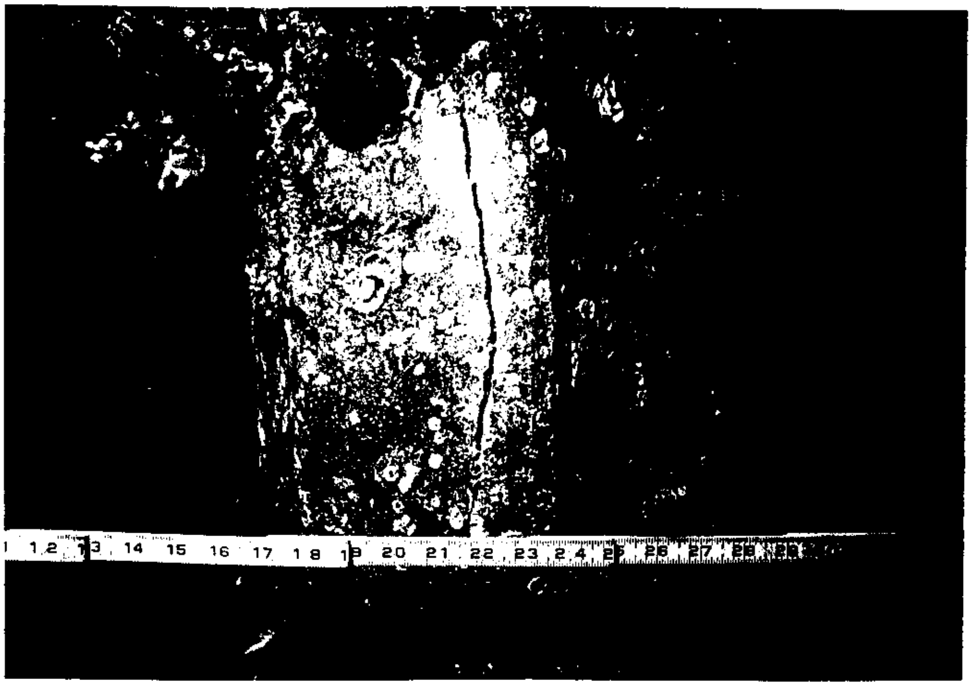


PHOTO 11. Underwater cracking of a prestressed concrete pile

PHOTO 12. Corrosion of a steel H-section pile

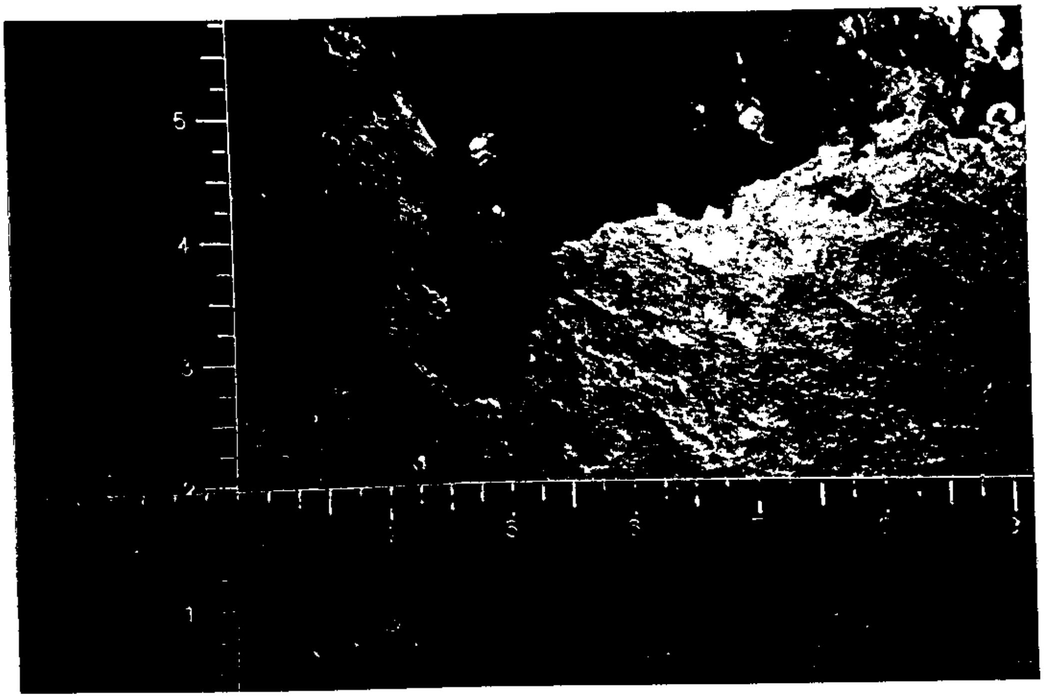
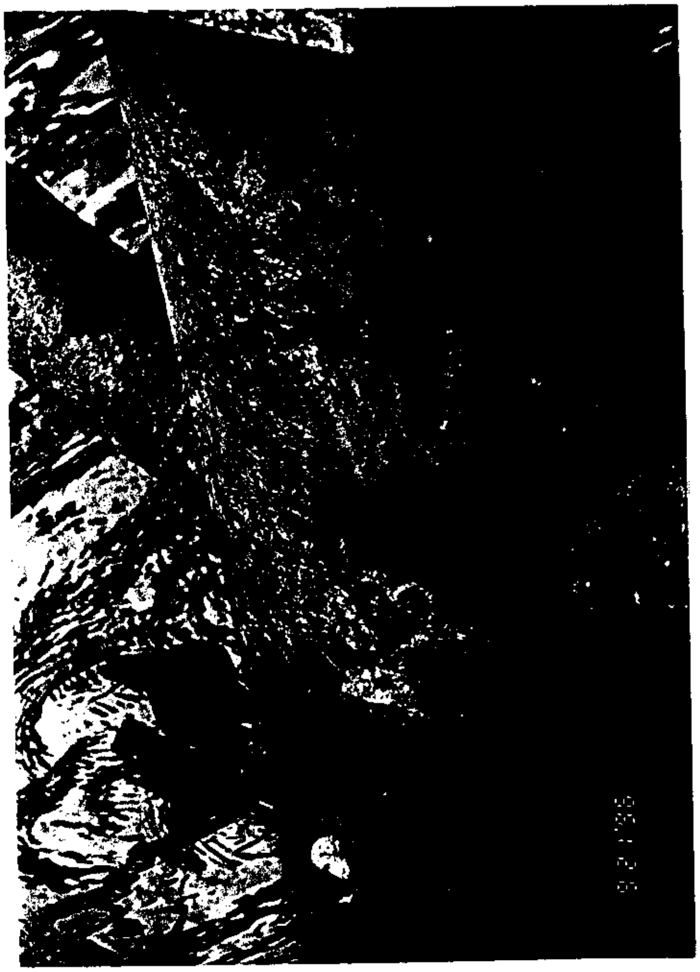


PHOTO 13. Corrosion of a steel sheet pile

PHOTO 14.
Corrosion of a steel tubular pile



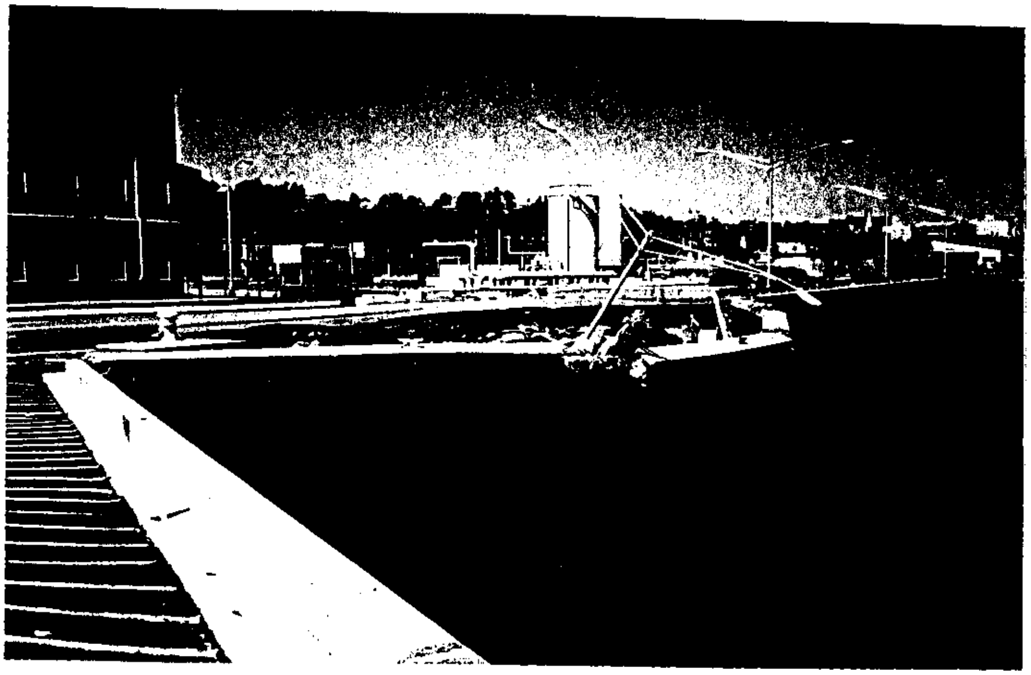
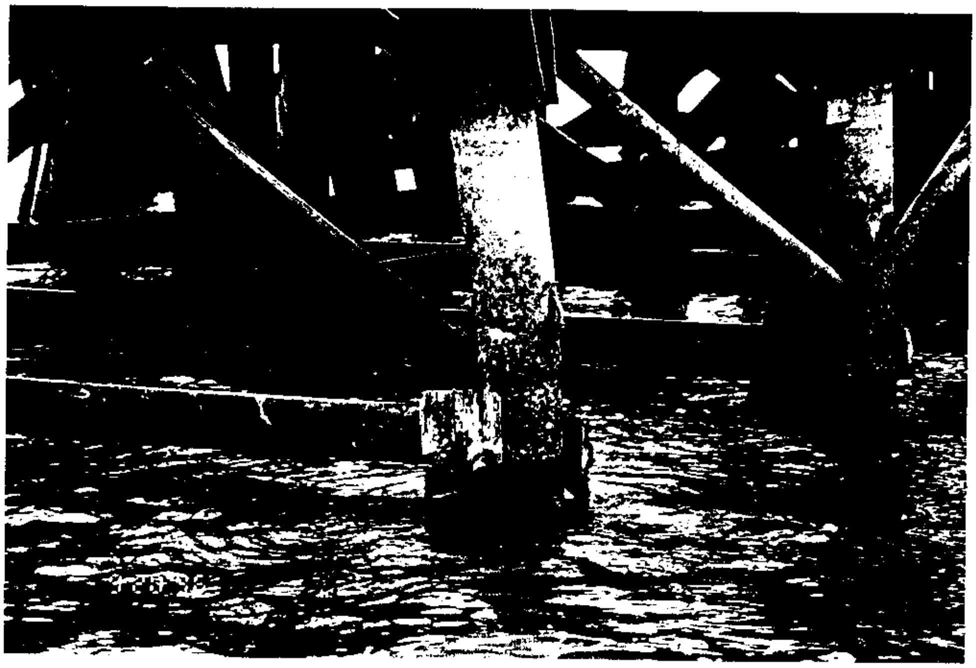


PHOTO 15. Overloading of a steel sheet pile bulkhead

PHOTO 16. Overloading of a tubular steel pile



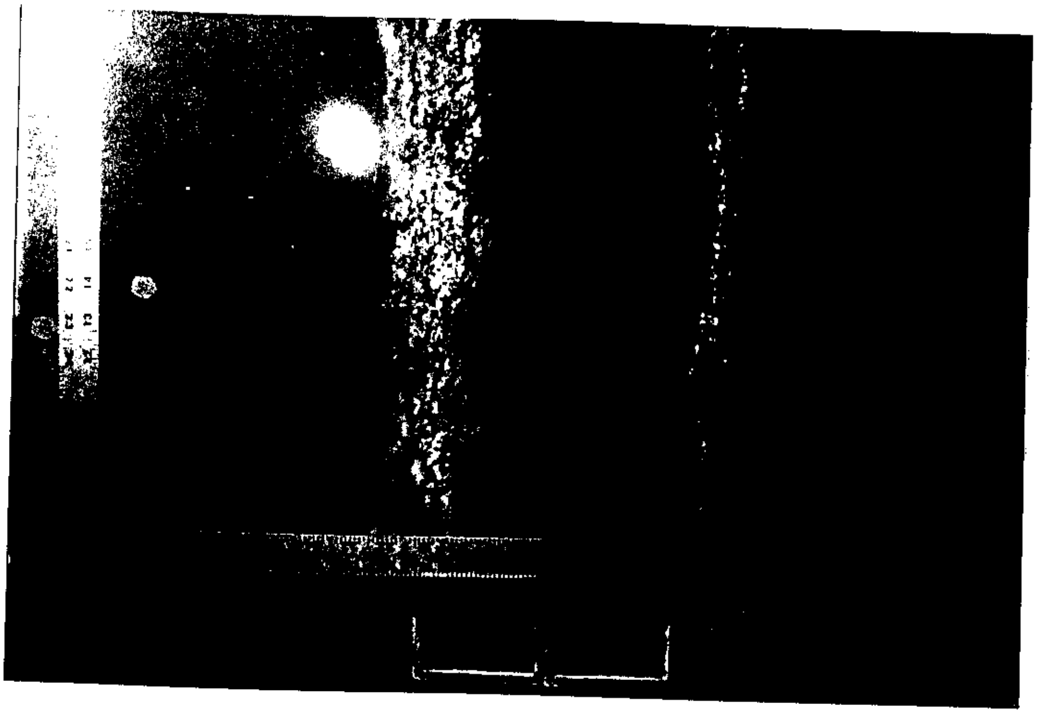


PHOTO 17. Marine borer attack of a timber pile

PHOTO 18. Close-up of a marine borer attack

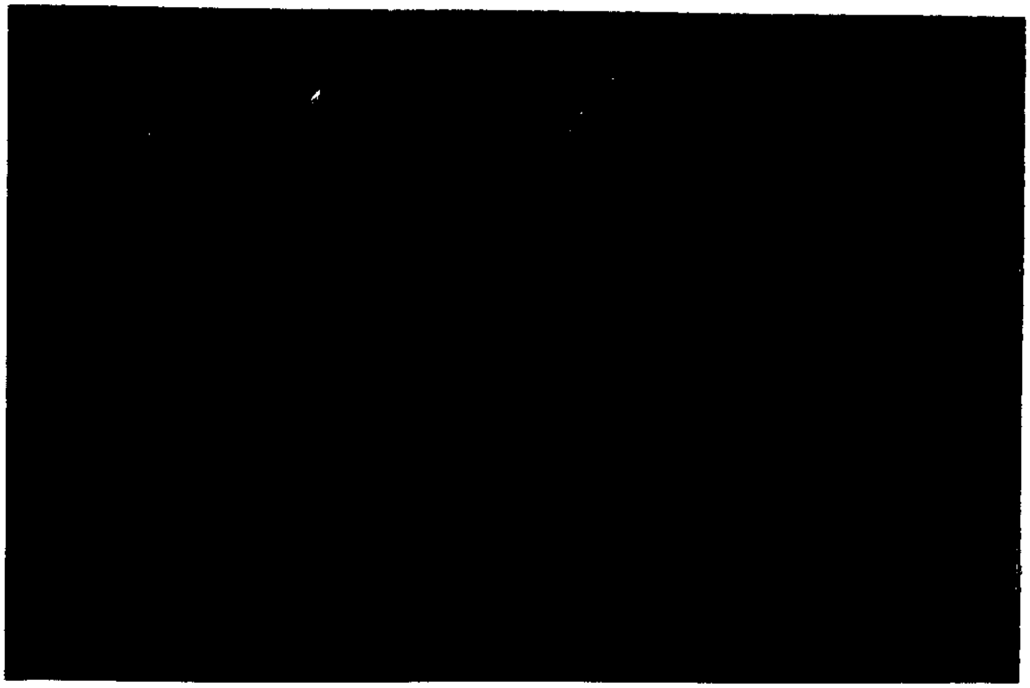


PHOTO 19. Fungi and rot damage to timber beams

PHOTO 20.
Overload damage to a timber pile

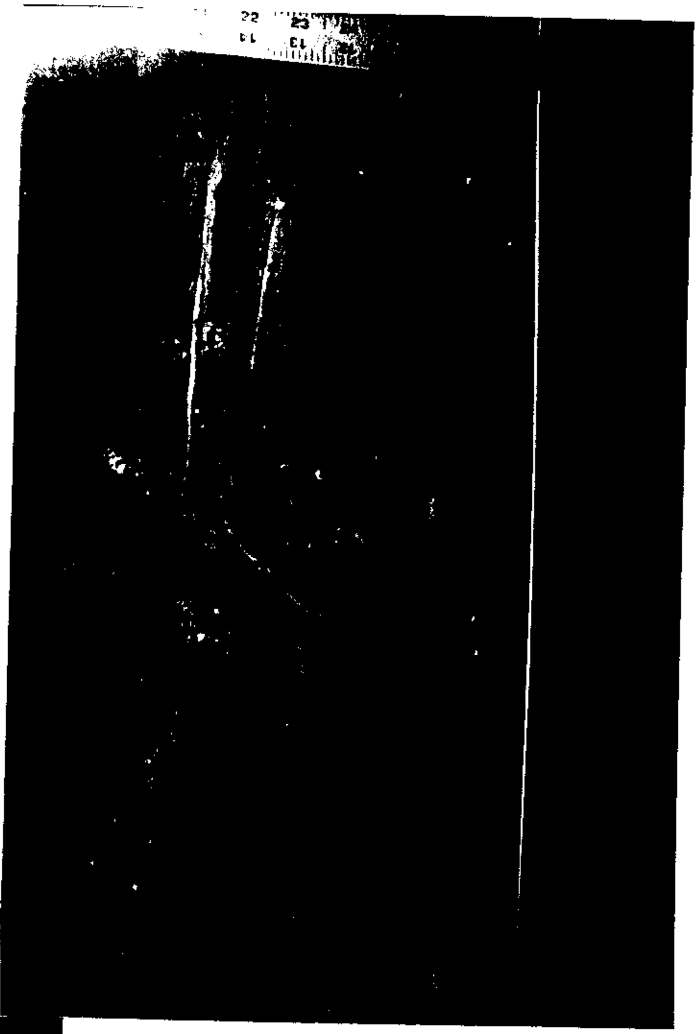


PHOTO 21.
Overload damage to a timber pile

PHOTO 22.
Abrasion damage to a timber pile

WHITE PAPER # 6

ADVANCED MATERIALS FOR OFFSHORE PROCESSING EQUIPMENT

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Introduction

This white paper assesses the material performance of offshore process equipment by identifying the equipment most often in need of repair or replacement, specifying the service or operating conditions for this equipment, and allowing the material producers to suggest material substitutions to the equipment manufacturers. The equipment will be classified in this paper as (1) pressure vessel equipment, (2) heat exchanger systems, (3) pressure piping, (4) rotary equipment, and (5) other processing equipment.

The three primary reasons for loss of service life for a specific piece of equipment or system is from corrosion, wear and erosion and fatigue damage. Even though there are other failure modes associated with the complex operations on an offshore processing platform these three forms of damage can be addressed by improvements in material properties and behaviors through better material selection. There are other advantages to make materials substitutions, such as the efforts to reduce the weight on the platform. There is also an effort of upgrading process equipment so that it can be operated remotely in order to reduce the number of personnel on the offshore platform. This goal will require more sensor technology, including monitoring the performance (extended service life) of the equipment and material remotely. It may suggest the use of the more expensive higher performance materials to take advantage of the safety and economic savings of remote operations.

Approach

This white paper addresses the following series of questions to promote discussions and to obtain the necessary information from the workshop participants. The questions addressed are as follows:

1. What specific material problems (failures) and suggested material improvements can be identified for materials in pressure vessel systems (ASME Section VIII). This area of interest would include separators, boilers, reactors and drums?

2. What specific material problems (failures) and suggested material improvements can be identified for materials in heat exchangers systems (ASME Section VIII)?

3. What specific material problems (failures) and suggested materials improvements can be identified for materials in pressure piping (ASME/ANSI B31.3)?

4. What specific materials problems (failures) and suggested material improvements can be identified for materials in rotary equipment?

5. What specific material problems (failures) and suggested material improvements can be identified for materials in other offshore equipment which the workshop participants feel needs to be addressed?

For each of the above questions the following considerations need to be addressed when assessing these specific problems and recommendations for improved material performance:

1. What is the mode of failure or cause of maintenance i.e., corrosion, fatigue cracking, wear or erosion?

2. Are there advantages in fabrication cost and weight reductions to be made through material selection?

3. What are the consequences of a change in material; i.e., difficulty in fabrication due to welding or during initial construction, or difficulty in maintenance and repair at later dates?

4. What are the economic trade offs in making a specific material selection?

5. What is the availability of material, welding consumables for fabrication, and skilled shop personnel?

6. What service requirements do materials need to satisfy for specific equipment and systems?

7. Can material changes in processing equipment increase the life cycles of the equipment and reduce maintenance costs?

8. Can careful and thoughtful engineering of the material selection process assist in achieving the goal of remote control of offshore processing?

Discussion

The working group met during various stages of the workshop. Representatives, from Conoco, Mobil, Amoco, Exxon, and Chevron, as well as representatives from the materials industry participated in discussions and made significant contributions. Each topic was discussed in detail, and it became apparent that the first three areas had so much commonality, that they will be considered together. The discussion will therefore incorporate these areas as; (1) Pressure vessels and piping, and heat exchangers, (2) Rotating Equipment, (3) Other Equipment

Pressure Vessels and Piping, and Heat Exchangers

Typically the material used for pressure vessels is A516 Gr 70 steel, a carbon steel grade with 70,000 psi minimum tensile strength This material has about 38,000 psi minimum yield strength, and is the workhorse of materials for pressure vessels throughout the industry. A516 Gr 70 steel is also used for the shells and heads of heat exchangers, with the exchanger tubes made of A106 Gr B steel, which is carbon steel, but with higher alloy compositions for higher corrosion service. The most common material used for pressure piping is A106 Gr B steel, when carbon steel is satisfactory..

The failure modes of all the equipment is very similar. The main causes of failure will depend on the type of well and it's products. However, in sour service (hydrogen sulfide) the hydrogen is the main cause of failure. Hydrogen sulfide combines with the iron to form iron sulfide to produce nascent hydrogen which can diffuse into the steel and cause hydrogen induced cracking. This type of cracking occurs in any area of a weldment which has high hardness, usually at the toe of welds in the heat affected zone (HAZ). Carbon dioxide (C02) causes accelerated general corrosion attack, especially on carbon steel equipment. Erosion, microbiological corrosion, crevice corrosion, chloride stress corrosion cracking, induced vibration and design defects were all identified as other causes of failures on offshore equipment.

Typical solutions for preventing the failures can be as simple as heat treating the carbon steel to lower the hardness in the HAZ below the NACE MR0175 requirement of HRC 22, or purchasing equipment with such a low carbon equivalent that the hardness the hardness after welding will not exceed the NACE limit. If the hardness values are acceptable after welding, no postweld heat treatment is necessary and the steel is immune to hydrogen induced stress corrosion cracking. Upgrading of materials is also important because it allows for materials that are able to withstand the environment proposed. Quench and tempered steels have higher tensile and yield strengths and have been used offshore to avoid thicker walled, heavier vessels. Weld overlay and rolled cladding of vessels is another important way to prevent failures and improve life of this equipment. Cladding allows for the use of higher strength, thinner walled materials. The corrosion protection of the cladding prevents the attack on the base metal. Metal and organic coatings can also be used to prevent corrosion, and many metal spray techniques have been developed that produce very high quality linings. The main obstacle for organic coatings being the temperature limitations.

There are new alternative solutions available for many of these corrosion problems. These alternative solutions include, the use of titanium alloys, as well as copper, nickel, aluminum, and stainless steels. Fiber reinforced plastics are also new alternative materials that are being used more and more in pressure vessels, piping, and heat exchangers.

There are many considerations that must be taken into account when using some of the alternative materials because many of these alloys are new and untested. These considerations are; (1) design issues, (2) manufacturing/fabrication/operations issues, (3) and costs issues.

There are several roadblocks that sometimes prevent the use of higher alloy alternative solutions. These roadblocks are the lack of knowledge about the materials. There is a need for more data on these materials to fill in the blanks on the materials properties so that they can be used confidently. Another roadblock is the lack of codes and standards for the materials. There is a need to upgrade or develop the codes and standards that facilitates the use of the materials. Finally there is very little experience in the use of many of the materials. Many fabricators shy away from using some of these materials because of their ignorance on the weldability and fabricability of these new materials. The lack of experience generally add a lot to the cost, even though the problems are not great.

Several strategies can be developed to overcome the roadblocks to the use of these materials. Technical data searches are needed to increase the knowledge now available. Testing of materials should be encouraged to facilitate the needed material property information and the updating of codes and standards to include the allowable stresses for the new materials. Finally, new material prototypes should be used and evaluated to establish the experience base for fabrication, and the service history for the materials.

Research and Development is another issue. Funding is essential for R&D to demonstrate the longevity of any new materials proposed for these systems. The transfer of the knowledge to industry should be made through publications or technical meetings.

Rotating Equipment

There are numerous offshore rotating systems using for compression and pumping of hydrocarbons. This equipment operates under a combination of both high static and cyclic stresses, and under corrosive environments. The failures involving rotating equipment usually are very high costly because of both loss of production, and the cost of replacement.

During the workshop sessions, different failure modes were discussed related to various applications and design considerations. The group developed similar flow charts for each category. Rotating equipment problems are usually related to turbine blade failures which can be caused by corrosion pitting and subsequent fatigue, by creep failures of blades, fatigue failures of shafts, and bearing surfaces. These problems are all unique for each type of equipment, and the type of materials used.

To apply new materials in these applications will require a thorough understanding by the material producers of the service conditions, mechanical requirements, and equipment manufacturers design concepts. Most likely, new materials will not be advanced unless the material producer works with the equipment manufacturer and at the same time the equipment manufacturer needs to understand the requirements of operating a specific piece of equipment in offshore conditions.

Other Equipment

The workshop participants realized that much of the equipment fell into the 'other' category. The equipment systems of concern were:

1. Ventilation systems
2. Equipment foundation and support structures
3. Key utilities such as water, air, and electricity.
4. Instrument control loops
5. Atmospheric storage tanks and vessels
6. Corrosion Control Systems.

The failures that occur for each of these are numerous and cover all those failure modes mentioned previously. The main learning is that rotating equipment and 'other' equipment requirements described here are so equipment specific that it will require manufacturers to work directly with the various materials producers to find improvements in performance. Better communications must be established with the manufacturers to produce improvements. Because of the complexities and numbers of different equipment systems, new methods to transfer materials knowledge is of utmost importance. It will be a challenge to the industry to provide specific technical information for all of the systems mentioned here.

MATERIAL REQUIREMENTS FOR OFFSHORE PIPELINES/FLOWLINES

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International Workshop on

Advanced Materials for Marine Construction

Report from Working Group #7 - Pipeline/Flowline

SUMMARY

The purpose of this white paper is to present the state-of-the-art regarding the design, materials selection, construction, commissioning, inspection and operation of offshore pipelines, flowlines and risers. The paper, as well as the conference, have the additional purpose of identifying requirements for future research and development work in these areas.

The paper begins with an overview of current design United States codes such as ASME/ANSI B31.4 and B31.8. Newer standards such as the ISO and the DNV Rules for pipelines are also treated. The paper continues with more detailed discussions of the design criteria, and utilization of materials by the different codes is explained. Older stress and strain based designs as well as newer limit state designs are discussed.

Next, design criteria for corrosive systems are dealt with followed by discussions of the special requirements for single phase, multi-phase and sour systems. Current methods for prevention of external corrosion such as coatings and cathodic protection are also presented.

Presently available grades, sizes and properties as well as the manufacturing methods applicable to carbon steels and corrosion resistant alloys (CRA) for pipeline applications is covered, and information concerning the weldability, corrosion resistance and future materials needs is included. The construction and commissioning portions of the paper cover pipelay methods such as S-laying, J-laying and reeling; pipeline bundles; non-destructive testing; hydrostatic or pressure testing; pre-service condition surveys; cleaning; preparation for long term service; and drying. The paper concludes with discussions of current methods of on-line corrosion/condition monitoring and intelligent pigging.

1. INTRODUCTION

Marine pipelines, flowlines and risers often represent a major portion of the capital investment required for the offhsore production of oil and gas. Moreover, given the increasing trends within the oil and gas industry towards production of reserves located in increasingly hostile marine environments, the economic and environmental success or failure of major offshore projects will, to a large degree, depend upon the proper design, construction and operation of marine pipelines. Thus, there is a clear imperative for owners, operators, as well as constructors of offshore pipelines, flowlines and risers to find new ways to improve their reliability and to lower their capital and operating costs.

The primary aim of this paper is to present the state-of-the-art regarding design, materials selection, construction, operation and maintenance of offshore pipelines, flowlines and risers. Additional goals are to identify present obstacles to progress in these areas and to identify areas that the contributors believe will require future research. It is hoped that the information contained herein and that is presented in this workshop will be used by owners, operators, contractors and regulators of offshore oil and gas production facilities to ensure future successes and growth within the marine construction industry.

2. PIPELINE CODES

2.1 Existing American Codes, Standards and Specifications

2.1.1 ANSI/ASME B31.4, B31.8 and B31G

2.1.1.1 ANSI/ASME B31.4, Liquid Petroleum Transportation Piping Systems

The ANSI/ASME B31.4 code is applicable to liquid transportation systems for hydrocarbons, liquid petroleum gas, anhydrous ammonia, alcohol and carbon dioxide.

The design temperatures covered by the code are between minus 20°F (– 29 °C) and 250 °F (120 C).

Requirements to materials are given in a separate chapter. The requirements are typically given as references to API and ASTM standards and specifications.

A word of caution is given to the designer about giving consideration to the significance of temperature on the performance of materials, and since the selection of material to resist corrosion is not within the scope of the code, the designer is referred to other sources of information for material performance in corrosive environments.

Brittle fractures are addressed in connection with carbon dioxide pipelines only, and by reference to API Specification 5L supplementary requirements for toughness.

Ductile fractures are addressed only in connection with carbon dioxide pipelines and propagation is to be minimised by selection of steel with appropriate fracture toughness and/or by installation of fracture arrestors.

In general the code does not establish any connection between design temperature and requirements to the materials properties, and it is left to the designer's discretion to select the material properties and testing temperatures required to ensure resistance against brittle and ductile fracture.

2.1.1.2 ANSI/ASME B31.8 Gas Transmission and Distribution Piping Systems

The ANSI/ASME B31.8 code is applicable to gas transmission and distribution systems. Gas is defined as any gas or mixture of gases suitable for domestic and industrial fuel, such as natural gas, manufactured gas or liquefied petroleum gas distributed as vapour.

The design temperatures covered by the code are between minus 20°F (– 29°C) and 250 °F (120 °C).

Requirements to materials are given in a separate chapter. The requirements are typically given as references to API and ASTM standards and specifications.

For materials for use in cold climates a warning is given to the effect that some of the materials conforming to the referenced specifications may not have properties suitable for the lower portion of the temperature band covered by the code. Engineers are cautioned to give attention to low-temperature impact properties of the materials to be used for facilities exposed to unusually low ground or atmospheric temperatures.

In cases where the pipeline is designed to operate at certain hoop stresses as given in the code, requirements to fracture control and arrest are imposed, either by specifying fracture toughness criteria or other methods to control fracture propagation.

Brittle fracture control is specified to be by assuring adequate ductility of the pipe by fracture toughness testing to API Specification 5L, Supplementary requirements SR5 or SR6. If the operating temperature is below 32°F, the test temperature is to be at or below the lowest metal temperature expected. Acceptance criteria are given as a percentage of shear value of the test specimens.

Ductile fracture arrest is to be assured by Charpy energy values calculated according to several formulae given in the code. No requirements to the test temperature are given.

A general requirement to protect the piping system from detrimental corrosion is stated, but no specific requirements to materials exposed to corrosive media are given.

A chapter of the code covers offshore gas transmission. Materials requirements are generally given by reference to other chapters in the code. In addition to the requirements of the referenced standards, other requirements may be considered.

It is required to design the pipeline against failure due to brittle fracture and ductile fracture, but only a general requirement to reasonably high resistance to propagating fractures for pipelines with high pressure is given.

In general the code does not establish any connection between design temperature and requirements to the materials properties, nor does the code address fracture initiation or collapse criteria which are important for deep water pipelines. It is left to the designer's discretion to select the testing temperatures for the material properties required to ensure resistance against brittle and ductile fracture.

2.1.2 API Specification 5L and other American Material Standards

2.1.2.1 API Specification 5L, Specification for Line Pipe

The most widely used specification/standard for line pipe is API Specification 5L, which is a specification exclusively for line pipe and covers seamless and welded pipe. The named grades covered are B, X42, X46, X52, X56, X60, X65, X70, and X80. The chemical composition and mechanical properties of intermediate grades that are subject to agreement between the purchaser and the manufacturer must be consistent with the corresponding requirements for the grades to which the material is intermediate.

Requirements for fracture toughness are not mandatory. However, the specification states that "when so specified on the purchase order, the manufacturer shall conduct fracture toughness tests in accordance with, Supplementary Requirement, SR5 or SR6 (Appendix F) or any combination of these, as specified by the purchaser, and shall furnish a report of results showing compliance with the supplementary requirements specified".

It should be further noted that the chemical composition requirements do not necessarily ensure optimum weldability. If the purchaser desires to obtain information about the weldability of the material, it is possible for grades up to and including X70 to specify SR18 and thus limit the carbon equivalent (CE) to a maximum of 0.43.

Mandatory non-destructive testing is limited to the weld seam of welded pipe. However, to ensure detection of longitudinal discontinuities in seamless pipe it is possible to specify SR4. Laminations in the pipe body are limited by the specification, but specific inspection for detection of laminations is not covered by any Supplementary Requirement and must thus be specified in the purchase order. Repair of defects in the pipe body by welding is permitted.

Although API Specification 5L is the most widely used standard for line pipe many purchasers impose requirements different from or in addition to API Specification 5L for specific applications, e.g. offshore or sour service. Consequently, an international system has been adopted defining three levels or classes of requirements for line pipe. The basic requirements are those minimum requirements of API Specification 5L and are classified as "Class A" pipe for general use (ISO 3183). Additional requirements, such as toughness or chemical composition necessary to avoid long running shear fractures in gas transmission lines are standardised in ISO 3183 - Class B. More stringent requirements for sour service and offshore applications are specified in ISO 3183 - Class C. The user of the pipeline must define the requirements for the line pipe as Class A, Class B or Class C.

2.1.2.2 API Specification 5LC, Specification for CRA Line Pipe

API Specification 5LC covers seamless, centrifugally cast and welded corrosion resistant alloy (CRA) line pipe. The alloys covered by this specification are similar to UNS S31603, UNS S41008, UNS S31803, UNS S31260 and UNS N08825.

Cold worked alloys are not addressed by this specification nor are any of the new weldable 13 Cr grades of line pipe.

2.1.2.3 API Specification 5LD for CRA Clad or Lined Steel Pipe

API Specification 5LD covers the manufacturing and testing of clad (metallurgically bonded) and lined (mechanically bonded) CRA pipe made by seamless, centrifugally cast, weld overlay and the lining process. Alloys for the CRA portion are the same as for API Specification 5LC with the exception of UNS S41008 but includes UNS N06625. Much of the nondestructive testing requirements are left to agreement between the purchaser and the manufacturer, thus requiring the purchaser to be knowledgeable in the manufacturing of clad products.

2.1.2.4 ASTM Standards

A number of ASTM standards are referred to in ANSI/ASME B31.4 and ANSI/ASME B31.8, namely;

ASTM A 53	Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless
ASTM A 106	Seamless Carbon Steel Pipe for High-Temperature Service
ASTM A 134	Pipe, Steel, Electric-Fusion (Arc)-Welded (Sizes NPS 16 and Over)
ASTM A 135	Electric-Resistance-Welded Steel Pipe
ASTM A 139	Electric-Fusion (Arc)-Welded Steel Pipe (NPS 4 and Over)
ASTM A 333	Seamless and Welded Steel Pipe for Low-Temperature Service
ASTM A 381	Metal-Arc-Welded Steel Pipe for Use With High-Pressure Transmission Systems

ASTM A 524	Seamless Carbon Steel Pipe for Atmospheric and Lower Temperatures
ASTM A 530	General Requirements for Specialized Carbon and Alloy Steel Pipe
ASTM A 671	Electric-Fusion-Welded Steel Pipe for Atmospheric and Lower Temperatures
ASTM A 672	Electric-Fusion-Welded Steel Pipe for High-Pressure Service at Moderate Temperatures

These standards are for general purpose pipe and not specifically intended for use in pipelines.

2.1.3 Welding, API Standard 1104, RP 1107.

2.1.3.1 API Standard 1104

API Standard 1104 deals with welding of carbon and low-alloy steel piping used in the compression, pumping and transmission of crude oil, petroleum products and fuel gases. Where applicable, it also covers welding on distribution systems.

For all materials in one group provided that the qualification test is made on material with the highest specified minimum yield strength in the group. When welding materials from different groups, the procedure for the higher strength group shall be used.

API Standard 1104 gives acceptance standards for non-destructive testing of girth welds. Alternative acceptance standards based on a fitness for purpose criteria allow more generous flaw sizes. Use of the alternative acceptance standards requires CTOD testing, stress analysis and inspection. The applied axial strain is limited to 0.5%.

The use of the alternative acceptance standards requires CTOD testing of the weld metal and the HAZ. The notch in the HAZ test specimen is to be a through thickness notch located at the point of the highest HAZ hardness. Since the highest hardness normally will be found at the weld toe adjacent to the cap, this requirement will result in the CTOD test being more representative of the unaffected base material than for the HAZ from vee grooves.

2.1.3.2 API RP 1107

The API RP 1107 is a recommended practice for pipeline maintenance welding practices. It covers practices that may be used when making repairs to or installing appurtenances on piping systems which are or have been in service in the compression, pumping, and transmission of crude oil, petroleum products, and fuel gases and, where applicable, when making repairs to distribution piping systems for these products.

2.2 New Codes

DNV's Rules for Submarine Pipeline Systems have been totally revised in 1996. These Rules apply to the design, materials, fabrication, construction, operation, maintenance, re-qualification and abandonment of submarine pipeline systems used in the Petroleum and Natural Gas industries, and are applicable to single pipelines, pipeline bundles of the piggy back type as well as pipeline bundles encased within a carrier pipe.

The requirements for materials are applicable to line pipe in Carbon Manganese (C-Mn) steel, clad/lined steel, non-ferrous metallic materials and Corrosion Resistant Alloys (CRA) including Ferritic/Austenitic (Duplex) steel, Austenitic stainless steels, other stainless steels and nickel based alloys.

The ISO Standard CD 13623 Pipeline Transportation Systems for the Petroleum and Natural Gas Industries gives requirements for the design, materials, construction, operation, maintenance and abandonment of pipeline systems used for transportation in the Petroleum and Natural Gas Industries. It applies to pipeline systems on land and offshore, connecting wells, production plants, process plants, refineries, and storage facilities, including any section of a pipeline constructed within the boundaries of such facilities for the purpose of its connection.

Concerning materials it refers to ISO 3183 Petroleum and Natural Gas Industries - Steel Pipe for Pipelines which specifies technical delivery conditions for unalloyed and alloyed (except stainless) seamless and welded steel pipe.

The DNV Rules and the ISO standard have in common that they both are a self contained set of rules, establishing defined requirements to material properties, non-destructive testing and corrosion resistance based on the environmental and service conditions and the commodity transported.

The main differences between American codes and ISO/DNV are that the American codes are functional in nature with regard to material selection, place a large responsibility on the designer for selection of appropriate material properties and give references to numerous material standards meant to cover a diversity of applications. The ISO/DNV standard/rules are much more detailed with relevant references and tailor-made requirements.

2.3 Expected/Needed Changes in Codes

A truly international standard related to pipelines has not existed prior to the introduction of ISO Standard CD 13623 Pipeline Transportation Systems for the Petroleum and Natural Gas Industries.

It seems reasonable to expect that ISO CD 13623 as well as the DNV Rules supplementing this standard, will set the standard for the development of other codes in the future and that the trend will be towards codes containing much more detailed requirements based on the environmental and service conditions and the commodity transported and containing tailor-made requirements to materials.

3. PIPELINE DESIGN CRITERIA

3.1 Pressure Containment

3.1.1 Background for Criterion

The most fundamental design requirement of an offshore pipeline or flowline is that of pressure containment. The requirement is formulated in terms of the following parts:

1. an internal design pressure;

2. a hoop stress formula for the cross section of the steel pipe; and

3. a design factor expressing the maximum allowable level of strength utilisation of the pipe steel for pressure containment expressed as a percentage of SMYS.

The design criterion for pressure containment is expressed as a maximum allowable pipe wall hoop stress level as given by the design factor.

This formulation of the design requirement for pressure containment is found in all national and (draft) international pipeline standards. However, when it comes to the actual hoop stress formula and the design factor used in the various codes they are found to vary somewhat from one code to another. In particular the variations are found in the most recent updates of the codes.

The widely referenced ANSI/ASME B31.8 (gas) or B31.4 (oil) pipeline codes have up to now used the nominal outside diameter and the nominal wall thickness in their formulas. The maximum allowable utilization of the steel is derived from two underlying requirements:

1. the minimum wall thickness shall not fall below 90% of the nominal wall thickness

2. a maximum design factor of 80%.

When these two factors are included in the pressure calculation they produce a factor of 0.72. A pressure test level of 125% of the design pressure has long been used for hydrotesting of offshore pipelines prior to operation. Thus, 72% of 125% gives an internal pressure corresponding to 90% of yield for the induced hoop stress in the pipe wall.

Historically the ANSI/ASME codes have played a dominant role - established for the first time in the 1930s starting from existing pressure vessel codes - by their long time record of use and world wide application. Later pipeline codes developed by industrialised countries all over the world have to a wide extent benefitted from them. The design criterion for pressure containment has mostly been copied from ANSI/ASME.

3.1.2 Present Status International Pipeline Standards

Over the last decade we have seen an updating of various existing national pipeline codes. Thus the BS 8010 and the

NEN 3650 of UK and The Netherlands respectively have recently been updated. Other countries are in the process of performing it or have plans to do so in the near future. The formulation of the design criterion for pressure containment as presented in these updated codes are slightly different from the ANSI/ASME formulation and leads to some variability of the essential steel strength utilisation allowed for pressure containment by the various codes. The following table illustrates the variability in hoop stress formula and design factors prescribed by various existing national codes.

Table 3.1.

Design factors and hoop stress formula for pressure containment as prescribed in various national pipeline codes. Safety approaches are indicated.

Country/Code	Offshore	Hoop stress formula	Remarks
Belgium	0.62 - 0.67	ODnom,WTnom	Factor depending on steel grade. Factor up to 0.72 by derogation
Canada	0.72	ODnom,WTnom	
Denmark	0.72	ODnom,WTnom	
Germany	0.67	ODnom,WTnom	Factor dependant on steel grade. Factor 0.60 for offshore risers
Italy	0.72	ODnom,WTnom	Factor 0.80 allowed in desert areas.
Japan	0.38-0.45	ODmean,WTmin	Factor dependant on steel grade.
Netherlands	0.72	Daverage,WTmin	
Norway	0.72	Daverage,WTmin	Formula as proposed for future use. Factor 0.60 for offshore risers and 500m zone at platforms.
Spain	0.72	ODnom, WTmin	
UK	0.72	ODnom, WTmin	Factor 0.60 for offshore risers.
USA	0.72	ODnom,WTnom	Factor 0.50 for offshore risers.
ISO (draft)	0.77	Daverage,WTmin	Factor 0.83 allowed in open sea offshore.
CEN (draft)	0.72	OD nom,WTmin	Onshore pipelines only.

Another remarkable trend within pipeline standardisation work is the establishment of international pipeline standards. The new CEN standard (draft) developed over the last three to four years by the European Community is applicable to gas pipelines onshore only. More or less in parallel, the International Standardisation Organisation (ISO) has developed a standard (draft) for world wide application covering pipelines onshore and offshore and for transportation of a wide variety of liquids or gases used by the petroleum industry.

The new ISO pipeline standard is expected to have a strong impact on future offshore pipeline industry. Its basic philosophy is that of giving minimum requirements for pipeline systems while strengthened requirements may be imposed by national authorities.

3.1.3 The Pressure Containment Design Criterion proposed by ISO

The basic premises laid down in the proposed pressure containment design requirement in the (draft) ISO standard are the following:

1. it should be based on the ANSI/ASME codes i.e. utilising the pipe steel to the same hoop stress level as allowed in these codes;

2. this utilisation level shall be the same for all design pressure levels (expressed in terms of the diameter to wall thickness ratio D/t) i.e. irrespective of the pipeline being onshore or offshore; and

3. wall thicknesses for pipelines installed on the seabed may be designed and hydrotested allowing the permanent external hydrostatic pressure to be part of the loadbearing capacity for internal pressure containment.

Taking the ANSI/ASME codes as the basis for the ISO requirement was an obvious choice due to their earlier mentioned long time and world wide use. The second premise requires a modified design formula that is able to express this requirement. The one chosen is the one already used by the new NEN 3650 and is based on the average pipeline diameter and the minimum wall thickness, as shown in Table 3.1. The modified formula requires a new design factor in order to give the same utilisation level as implied by ANSI/ASME and an allowable undertolerance of 8% (API).

This means that ISO and ANSI/ASME design requirements for pressure containment will give exactly the same pipeline for typical onshore pipeline pressure ranges when produced with the same negative tolerance of 8%. For offshore pipelines, where D/t typically in the range 20 to 40, the wall thickness will be slightly lower than according to ANSI/ASME. However, the pipe steel strength will be utilised to the same level as for the onshore line, Figure 3.1.

An inherent consequence of the ISO design requirement for pressure containment is that of more stringent fabrication tolerances for wall thickness are specified, the total amount of steel will be correspondingly reduced while the utilisation level of the pipe wall steel is maintained.

3.2 Stress and Strain Based Criteria. Limit State Design

3.2.1 Traditional Criteria

Traditional pipeline design is based on the concept of maximum allowable hoop stress (pressure containment) or equivalent stress (other static loads) levels. In addition criteria against fatigue, buckling, collapse, fracture and ovalisation are essential in offshore pipeline design. In particular buckling and collapse criteria will determine the pipeline wall thickness for offshore pipelines in deep water i.e. for more than about 500 m water depth, depending on pipe size.

3.2.2 Strain Based Criteria

Strain based criteria are used increasingly within present day pipeline design. The driving force is to minimize construction costs by maximum utilisation of the strength of modern pipeline steel. In practice the use of strain based criteria rests on two basic premises:

1. calculations of strains requires advanced computational tools and highly specialized personnel to use them, and

2. the planned strain levels must be fully controlled during construction and operation of the pipeline.

A consequence of the second premise is the necessity to establish a realistic and rational assessment of all relevant uncertainties in each particular case. From this fact a logical next step to take is to apply the reliability based methods of limit state design (see below) which in essence is a rational method for assessment and integration of all relevant uncertainties and technological improvements into the design and construction of offshore pipelines.

3.2.3 Limit State Design

Another clear trend in the pipeline industry today is an increased use of limit state methods in establishing design solutions. "State" here reflects the state of the pipeline with respect to each relevant failure mode in the actual situation and the "limit" means the highest level of exposure allowed towards the actual failure mode. The trend is partly due to an increased use of pipelines in new environments, use of new pipeline materials or use of any type of new pipeline technology. Another major driving force is the need to obtain maximum cost-effective design and installation solutions while retaining the full structural reliability of the pipeline. In all cases the limit state design method offers a rational approach.

Since the limit state design method also is a way to integrate technological improvements into pipeline design and construction it should obviously be used in regular updating of codes to provide updated design requirements that benefits from technological progress while controlling the structural reliability of the pipelines. Presently this is the case in updating of the DNV rules for offshore pipelines and will most likely be done in future updating of other national and international pipeline codes.

At the same time it offers a method to establish a safe design solution in cases where existing standards do not provide the necessary guidance due to unconventional premises for the project. The pipeline project from the Troll field to the western coast of Norway provides an example. A design for a 5 km multispanning section of the pipeline in an extremely rugged seabed area in more than 500 metre water depth and loaded by a strong and highly unconventional near seabed density current was required. The situation was not satisfactorily covered by existing design codes or guidelines. However, fully satisfactory solutions for both the installation and the operation phases of the pipeline were established by the reliability based limit state design principles.

Further reading on limit states is provided in the references at the back of this paper.

3.3 Corrosion Design

3.3.1 Internal corrosion

3.3.1.1 Single phase flow

Dry sweet gas will not lead to corrosion on carbon steel since there is no free water phase present. The water content in the gas is often defined in terms of a water dew point temperature which is recommended to be at least 10° lower than the operating temperature. Also relative humidity in the gas is used as a quantitative measure with a maximum limit of 50%. Yet another way to specify water content is in pounds per million cubic feet of gas or kilograms per million cubic metres. The maximum water content for truly dry gas is 3 lbs H_2O/MMCF. If the gas is defined as sour, the material must be qualified for sour service even if the gas is dry. In many gas pipelines, glycol-water is carried over from the drying process. In equilibrium with a dry gas, a water/glycol ratio is usually in the order of 5/95, and is not expected to lead to significant corrosion.

Single phase oil or condensate will usually contain some amounts of water as carry-over from the process or from condensation in the pipeline. The content of corrosive gases is usually low and water is in many cases expected to be emulsified in the oil phase. There are however several reports on severe corrosion, particularly in the welds in such systems. Hence, many operators tend to inject corrosion inhibitor in oil and condensate pipelines.

3.3.1.2 Multiphase flow

Multiphase flow is typically from unprocessed or partly processed hydrocarbons where water is not removed to such extent that corrosion is eliminated. The flow contains oil/condensate, gas, water and sometimes sand.

In a sweet system, only carbon steel is prone to corrosion and higher alloyed materials will usually be immune. For 13% Chromium materials, low pH, high chloride content and the possiblity of dissolved oxygen at higher temperatures may be a problem and testing under realistic conditions must be done.

There is no universally accepted prediction model for CO_2 corrosion on carbon steel. Although the models published by Shell are widely used, different operators usually have their in-house model. Some have models which calculate an absolute corrosion rate, whereas others use the models to define the conditions into regions; high, medium and low corrosivity.

In almost all cases, a corrosion inhibitor must be used to keep the corrosion rate of carbon steel at an acceptable value. These are usually film forming organic inhibitors, but also glycol and pH-stabilisers have been used in specific cases. In a design phase, many operators use a defined inhibitor reduction factor which is applied to the predicted corrosion rate. This factor (inhibitor efficiency) varies from 60 to 95%. Some operators use another approachs that it will always be possible to find an inhibitor which will reduce the corrosion rate to an acceptable value independent of the corrosivity in the system. This may be more difficult in the future as there is a trend to specify more environmental friendly ("green") inhibitors which in many cases are not as efficient as the traditional inhibitors. High gas flowrates are known to remove the inhibitor from the surface.

Traces of H_2S in combination with the CO_2 can influence the corrosivity, usually in a positive way by enhancing the formation of protective sulphide layers. There are however, reports of increased CO_2 corrosion rates due to trace amounts of H_2S. Presently, there are no accepted "rules" to include this effect.

In pipeline design a critical flow velocity is calculated. This is traditionally based on API RP 14E which is only based on the density of the fluid and does not considering parameters such as fluid composition, flow regime, sand content etc. This

RP was originally not made for sweet corrosion on carbon steel with inhibitors which is governed by other factors than pure erosion. Even if it is well accepted that the API formula is not suitable for these conditions, different operators have modified the C-factor based on their operational experience in order to define a value for specific conditions and materials. In practice, however, the pressure loss is in many cases the limiting factor with respect to flow rate. In cases where high flow rates and unfavourable flow regimes are expected, the focus must be on the corrosion inhibitor. The products have different properties with respect to erosion resistance, and products must be tested in the laboratory and in the field to be able to select the right product and the optimal concentrations. CRAs are known to have higher critical erosional velocity limits than carbon steel and are therefore often used for this reason alone.

When sand is present in a pipeline, critical components can be eroded. These components are typically bends, valves and other components which obstruct the flow. Pure erosion must be evaluated by models specifically made for this. In an oilfield material, protective corrosive products layers can be removed which can lead to erosion-corrosion.

H_2S partial pressure over a certain level will lead to sour conditions. The NACE limits are most widely used in the industry worldwide, but also EFC (European Federation of Corrosion) has published recommendation which includes the pH value in the evaluation. The primary concern with respect to H2S is stress cracking. This can be as Sulphide Stress Cracking (SSC) or Chloride Stress Corrosion Cracking (CSCC). Carbon steels are only sensitive to SSC which occurs predominantly at ambient temperature. Hardness requirements are used to qualify the materials for sour service and the value 22 HRC is widely accepted as the limit for carbon steels. Many operating test pipeline materials for HIC resistance through standardised testing (NACE) or through testing simulating the real conditions. However, HIC testing may not be necessary for some seamless pipe or some controlled chemistry steels (i.e. low sulfur, Ca treated, etc.).

Regardless of the steps taken to reduce SSC and HIC of pipeline steels these actions do not in and of themselves control corrosion from H_2S. Thus care must be taken to also consider H_2S corrosion as well as the potential for cracking.

3.3.2 External corrosion

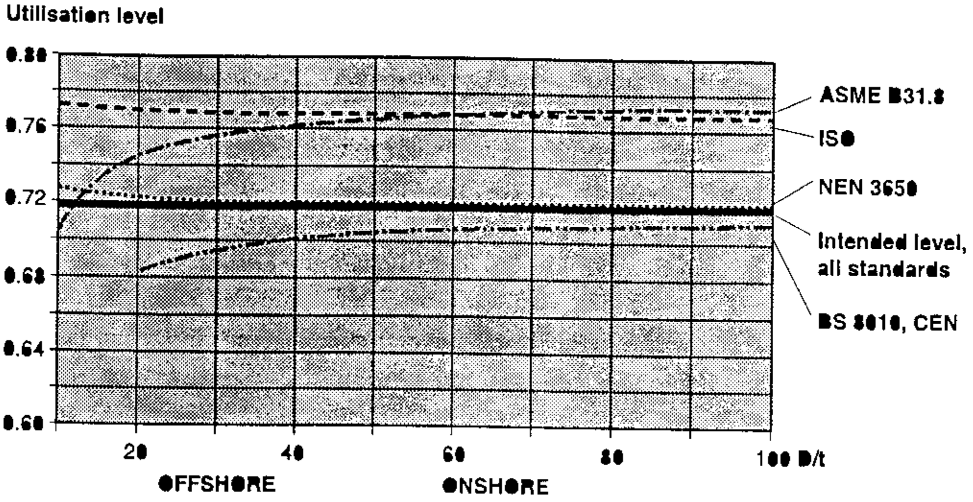
The most widely method used for external corrosion protection of subsea pipelines is use of sacrificial anodes in combination with a protective coating. In addition to the corrosion coating, a heat insulating layer is often applied on flowlines for wellstream. The insulation material is often based on polypropylene, polyurethane or rubber.

For pipelines which are thinwalled or have a low ratio between wall thickness and diameter, a concrete layer has to be used in addition to the corrosion coating for increasing the stability on the seabottom. The concrete also contribute to protect the pipeline from impacts caused by fishing gear (trawl boards) or anchor handling. The field experience over many years has shown that this type of protection is very reliable when applied correctly.

The way of designing a cathodic protection (CP) system varies from operator to operator. Local authorities may also require specific design values for the CP. Parameters which will influence the number of anodes are current demand, coating breakdown factors and anode capacity. Design values for these factors vary widely between the different specifications, and it is left to the designer to choose appropriate values for a given situation.
The same design criteria are usually used for stainless steels as for carbon steel. CP has proven to be effective in protecting critical crevices (flanges) in stainless steel pipelines.

Figure 3.1

Effective maximum allowable pipe steel strength utilisation as fraction of yield strength for pressure containment according to ANSI/ASME B31.8, NEN 3650, BS 8010, CEN (draft) and ISO (draft) pipeline standards.



4. PIPELINE/FLOWLINE MATERIALS

4.1. Carbon steels

Carbon steels are primarily used for pipelines where corrosion resistance can be controlled by cathodic protection, coatings and/or inhibitors. Sour service resistance can be considered, but for corrosive environments, corrosion resistant materials are needed (see Section 4.2).

4.1.2 Weldability

The API Specification for line pipe allows carbon contents up to about 0.30%. This coupled with elevated manganese levels can create weldability problems. Therefore, it is common in the industry for users to specify stricter composition limits than allowed by API Specification 5L to ensure good weldability. High carbon equivalents have become less of an issue in recent years with the increased production and use of micro-alloyed and TMCP steels.

One of the major advantages of using thermal mechanical control processed (TMCP) steels is that a certain strength level can be obtained with lower alloy content because the thermo-mechanical treatment and accelerated cooling contribute to the strengthening. This reduces the need for alloying elements which adversely impact weldability. This will in combination with the development of more efficient joining and installation technology contribute to more cost effective fabrication and installation of the pipelines.

In the development of more optimised solutions the treatment of scatter in steel properties is essential. Local variation in properties arise both in the pipe manufacturing process, in the welding and in the properties in the longitudinal and circumferential direction as well. This is attributed mainly to the pipe manufacture and is expected to be similar for different steel grades. This scatter can be treated and controlled by appropriate procedures for materials, processing and qualification testing.

4.1.1.1 Corrosion Resistance

Carbon steels are mainly used in transport pipelines and other applications where corrosion resistant alloys are not required. Steel to be used for sour service are typically tested for SSC and HIC and required to meet guidelines given by NACE Standard MR0175 or EFC publication No. 16. The trend in steel development is to establish steels with better resistance to CO_2 corrosion and sour service. Due to the need for additional alloying elements, such requirements affect the manufacturing of the steel, and lead to limitations on the dimensions and grades available.

4.1.2 Similarities/differences in mechanical properties and chemical composition

The API grade system has been adopted by the offshore industry to assign the strength grade of the steels. However, there are significant differences between API Specification 5L and Europe and ISO specifications for pipeline steels. Statoil specification R-SP-231 provides strict limitations for alloying elements in order to ensure sufficient weldability, fracture toughness and resistance against environmental cracking. The NORSOK standard does not specify grades above X52 class and the carbon content is 0.16% maximum.

4.1.3 Future steel grades and modifications of existing grades

The development of the pipeline steel by the steel manufacturers is utilising the TMCP and QT technologies to improve both strength and weldability. For onshore application, the strength has been focused, and steel grades up to X80 is already in use while X100 grades are available. Application of X100 is explored by oil/gas companies.

The strength and toughness properties of these new grades are promising both in base material and in the heat affected zone after welding. The limitations for offshore applications are related to the fabrication and structural behaviour and deformation capacity under installation and service. Aspects identified for further development are:

1. weld metal properties (strength and toughness) comparable with the base material;

2. softening of the heat-affected zone during the weld cycle;
3. deformation capacity in the case of deformation controlled loading under installation and service. Local variation of strength and toughness in the weld zone can be critical for the structural behaviour;
4. are yield strength limits required; and
5. yield/tensile ratio.

4.2. Corrosion resistant alloys (CRA)

When selecting a suitable material for offshore pipelines to handle wet corrosive fluids (oil, gas, and condensate containing CO_2,, H_2S and chlorides), the first candidate material considered is carbon steel. However, when the transported fluids cannot be effectively protected by corrosion inhibitors or is too expensive, the use of corrosion resistant alloys must be considered. The most common CRAs are; 13 Cr, duplex stainless steel and carbon steel clad with stainless steel or nickel base alloys. However, in cases of high content of H_2S in addition to CO_2 and chlorides, the use of duplex stainless steels becomes questionable due to the risk of sulphide stress cracking (SSC). The use of solid austenitic stainless steels or high nickel alloys is then a possible solution, but may be impractical due to their relatively low mechanical strength and/or high costs. In such circumstances, carbon steel pipe with CRA cladding may be the solution.

4.2.1. CRA Grades

Some examples of actual CRAs for flowlines and line pipe are given in Table 4.2.1. The international standard EN is the new European standard that in the future will substitute the European national standards: Great Britain's BS, Germany's DIN, France's NF, and Sweden's SS. API already has existing standards for solid CRA (API Specification 5LC) line pipe and clad (API Specification 5LD) line pipe.

The martensitic material called Super 13 Cr or weldable 13 Cr, is an example of a non standardised weldable steel which is introduced as an alternative to the more expensive duplex stainless steels for moderate aggressive conditions.

Table 4. 2.1

Nominal Composition

Structure	International Standards				Typical composition, wt %					
	EN	UNS	JIS	Name	C_{max}	N	Cr	Ni	Mo	Other
Martensitic	1.4028	42010		420L	0.2	-	13	-	-	
				Super 13Cr	<0.01	-	~12	~6	~2.5	
Duplex SS	1.4462	S32803		2205	0.03	0.17	22	5.5	3	-
	1.4410	S32750		2507	0.03	0.27	25	7	4	-
		S32760			0.03	0.3	25	7	3.5	W, Cu
		S31260			0.03	0.2	25	7	3.0	0.3 W, Cu
Austenitic SS	1.4432	S31603	SU5316	316	0.03	0.06	17	11.7	27	-
	1.4539	N08904		904L	0.02	0.06	20	25	4.5	Cu
	1.4547	S31254			0.02	0.20	20	8	6.1	Cu
Nickel alloys	2.4858	N 08825		Alloy 825	0.025	-	21.5	42	NB,Ti, A	Cu, Al, Fe Bal.
	2.4856	N 06625		Alloy 625	0.05	-	21.5	61	9.0	Nb, Ti, Al
	1.4563	N 08031		Alloy 28	0.05	-	27	31	3.5	Mn, Cu

Structure	International Standards				Typical composition, wt %
	EN	UNS	JIS	Name	
Titanium		R50400		Grade 2	Unalloyed Ti
		R53400		Grade 12	Ti-0.3Mo-0.8Ni
		R56320		Grade 9	Ti-3Al-2.5V

Table 4.2.2

Minimum Mechanical Properties

Structure	International Standards			Name	0.2 % Yield strength, MPa	Tensile strength, MPa	Elongation, Pct
	EN	UNS	JIS				
Martensitic	1.4028	42010		420L	450	650	18
				Super 13Cr	550[1)]	-	-
Duplex SS	1.4462	S32803		2205	450	620	25
	1.4410	S32750		2507	550	800	25
		S32760			550	750	25
	.	S31260			450	690	25
Austenitic SS	1.4432	S31603	SUS 316L	316	170	485	40
	1.4539	N08904		904L	220	500	30
	1.4547	S31254			300	650	35
Nickel alloys	2.4858	N08825		Alloy 825	240	550	30
	2.4856	N06625		Alloy 625	415	830	35
	1.4563	N08031		Alloy 28	220	500	35
Titanium	3.7035	R50400		Grade 2	276		
		R 53400		Grade 12	345		
		R56320		Grade 9	483		

1) In welded condition.

4.2.2. CRA Families

While typical CRAs used in the oil and gas industry tend to be fairly resistant to corrosion in the presence of CO_2 they are limited in the maximum temperature to which they can be exposed before localised pitting occurs in the presence of H_2S and chlorides. There is also a risk of stress corrosion cracking beyond certain limits of H_2S although this is chloride content, temperature and pH dependent for the different type of alloys, as well as dependent on the presence or absence of elemental sulfur.

13 % Cr.

13 Cr martensitic stainless steel (ASTM Type 420) has good resistance in CO_2 environments. However, the 13 Cr steel may be susceptible to sulphide stress cracking (SSC) in CO_2 environment with H_2S partial pressure higher than 0.0003 MPa, and the material has relatively low resistance to general and localised corrosion at elevated temperatures /1/. Stainless steel Type 420 and similar types has been used for flow line applications in the welded condition, however, post weld heat treatment is then needed to reduce the hardness in the heat-affected zone to an acceptable value.

Recently, a number of new 13 Cr steels with improved corrosion resistance at room temperature and at elevated temperatures have been proposed /1, 2/. The weldable super 13 Cr stainless steel indicated in Table 4.2.1, has been developed for applications in environments with small amounts of H_2S. By lowering the C content to less than 0.01 %, the susceptibility to SSC due to high hardnesses in the HAZ, is mitigated. However the upper limit for the H_2S content in the environment is not yet determined. Welding of the steel is accomplished with a consumable of super duplex stainless steel (25Cr-9 Ni- 3 Mo-2 W -0.3 N). A yield strength of 550 MPa for the welded joint was obtained /1/. Normally the martensitic stainless steels have the greatest susceptibility to SSC at ambient temperature, however when welded with a duplex material the most critical temperature for cracking is around 90 to 105°C in the weld metal.

When applying the material for subsea applications the pipelines has to be cathodically protected to prevent corrosion from the outside. Sulphide containing sediments will increase the hydrogen uptake thereby increasing the risk for hydrogen embrittlement from the outside.

As far as known, no welded pipelines or flowlines of 13 Cr steel without post weld heat treatment, have been attempted, but serious plans for application of this material or other materials of this class without post weld heat treatment for pipelines and flowlines, are under consideration by Statoil.

Duplex Stainless Steels

The duplex stainless steels which consists of about 50 % ferrite and 50 % austenite are stronger than either of the two phases considered separately. The duplex has a yield strength more than twice those of the common austenitic grades while retaining good ductility. In annealed conditions, the duplex grades have outstanding toughness and it is possible to retain good toughness and corrosion resistance after welding. However, as always by welding of stainless steels, reduction in the corrosion resistance may be observed / 3/.

For transportation of oil and gas 22Cr duplex stainless steel are applied to a large extent where the corrosiveness is too high for carbon steel. In fluids with CO_2 containing brine without oxygen and small amounts of H_2S, 22Cr duplex is corrosion resistant both with respect to SSC and pitting at temperatures at least up to 200°C /4, 5/, and therefore the CRA material group are frequently applied under such conditions.

The duplex stainless steels are susceptible to SSC for H_2S concentration over a certain limit. The risk for SSC is largest at a temperature about 80 to 100 °C and decreases both at higher and lower temperatures. According to NACE Standard MR0175-95 solution -annealed and cold worked UNS S31803 is acceptable for use at any temperature up to 232 °C in sour environments if the partial pressure of H_2S does not exceed 0.002 MPa, the yield strength of the material is not greater than 1,100 MPa and its hardness is not greater than 36 HRC. Wrought super duplex material UNS S32760 with hardness below 34 HRC is acceptable in sour environments containing up to 120,000 mg/l chloride for H_2S partial pressure up to 0.02 MPa. For low chloride concentrations and pH above 5.6, this material is acceptable up to 0.1 bar H_2S.

Austenitic Stainless Steels and nickel alloys

The austenitic stainless steels are very ductile materials with relatively low yield strength in annealed conditions. Type 316L is corrosion resistant in CO_2 containing brines without oxygen and with low content of H_2S. The maximum

H_2S level for Type 316L is rather low (about 0.001 MPa), but for UNS N08904 the maximum level is around 0.09 MPa /6/. The maximum temperature with respect to the internal environment is not well defined, but may be up to 200°C for both types. However, because of the risk of chloride stress corrosion cracking (CSCC) in the presence of oxygen and chloride on the outside of the pipe, Type 316 L is usually not applied at temperatures above 50 to 60 °C. The higher alloyed austenitic stainless steels have a much better resistance against CSCC and are therefor applicable at higher temperatures.

Titanium is unaffected by the CO_2 content in petroleum process streams, even at high flow velocities /7, 8/. Titanium is resistant when exposed to limited concentrations of H_2S. At higher concentrations, stress corrosion cracking may occur. Grade 2, Grade 12 and Grade 19 are approved for use in H_2S containing environments, which are listed in NACE MR-0175-95. Grade 19 has been successfully used as production liners and handling concentrated NaCl solutions containing H_2S at temperatures as high as 260°C /9/. Grade 9, Grade 18 and Grade 24 are not approved for sour service by NACE.

4.2.3. Clad Pipe

For CO_2 containing environments, which are too aggressive for carbon steel, without or with small amounts of H_2S, typically solid duplex stainless steel pipe are selected. As an alternative, for high concentrations of H_2S and particularly for high pressure lines requiring a heavy wall thickness or large diameter, clad pipe may be considered. The two types of materials most frequently used for cladding of pipe are Type 316 L stainless steel and Alloy 825. Clad pipe of 316L offers a comparable corrosion and cracking resistance to duplex steels in sweet environments. In solid form it suffers from low strength and poor resistance to external stress corrosion cracking, but as a cladding material these limitations are overcome. Alloy 825 has good resistance against SSC, the limits of cracking have not been established. However, many applications of Alloy 825 in extremely high H_2S environments have been reported /10, 11/.

Clad pipe have been used for more than 18 years in the oil and gas industry /6/ handling corrosive water with hydrocarbon mixtures. In total more than 200km of pipe have been installed and the service record of these lines has been excellent.

5. Pipe Products

5.1 Carbon Steel Line Pipe

5.1.1 Seamless Line Pipe

Seamless line pipe refers to those pipe products that are made without a longitudinal weld. Extrusion is an excellent method of producing seamless pipe, especially for metals which are difficult to work, however most steel seamless line pipe is typically manufactured by the Mannesmann process. In the Mannesmann process, billets first undergo rotary piercing, followed by plug rolling and reeling. Various improvements on these basic processing steps exist which produce pipe with improved dimensional tolerances and surface finish.

Seamless line pipe is generally available in outside diameters ranging from ½ to 26 inches and in wall thicknesses up to and including 1.500 inches. World-wide, manufacturers produce seamless line pipe in grades ranging from API Specification 5L Grade B (SMYS = 35 ksi) to Grade X80 (SMYS = 65 ksi). Recent trends towards microalloying and lowering the carbon content of steel line pipe for improved weldability have necessitated that many manufacturers employ quenching and tempering in the manufacturing process, especially for pipe with yield strength equal to or greater than 60 ksi. Modern microalloyed, low carbon steel line pipe offers greatly improved weldability and fracture toughness as compared to older, higher carbon steels.

Seamless line pipe is presently available world-wide from mills located in North America, Europe, Japan, Asia and South America.

5.1.2 Welded Line Pipe

Since about 1975 welded line pipe has been used increasingly for offshore pipeline construction. Its increased use has been due primarily to improved manufacturing and weld seam inspection methods. The use of welded line pipe in offshore construction is expected to increase, especially for large diameter, high-pressure pipelines when the wall thickness and/or diameter requirements exceed the capabilities of existing seamless mills.

5.1.2.1 Manufacturing and Welding Methods

Numerous methods have been devised for manufacturing welded line pipe. Generally speaking, however, all the methods consist of cold forming either plates or coiled steel strips called skelp into a cylindrical shape followed by joining of the abutting edges and sizing the welded cylinder or pipe to the specified diameter. The wall thickness of the finished pipe is approximately the same as that of the starting plate or skelp.

A number of fusion welding processes including submerged arc welding (SAW), gas metal-arc welding (GMAW) and gas tungsten-arc welding (GTAW) have been used successfully to manufacture welded line pipe. However, improvements in process controls have led to the increased use of electric-resistance welding (ERW) and electric-induction welding (EIW) in recent years. Laser welding (LW), which has been pioneered by certain Japanese manufacturers, promises further improvements in the strength, fracture toughness and resistance to various forms of environmentally assisted cracking (EAC), such as sulfide stress cracking (SSC), in the weld zone of longitudinally welded line pipe for offshore use.

Spiral welded pipe is manufactured by forming skelp into a helix. The abutting edges are continuously submerged arc welded from both sides. Therefore, spiral-welded pipe may be considered as a special form of submerged arc welded pipe with a helical weld line. Although spiral welded pipe offers more economically use of material than longitudinally welded pipe, especially for larger pipe diameters (>36 inches), it is seldom used in offshore service.

Theoretically, welded line pipe can be manufactured in any diameter or wall thickness, but practically speaking, the maximum diameter and wall thickness are limited by the available sizes of equipment used to form the initial cylinders. The highest combination diameter, wall thickness and grade of DSAW pipe made in the world to date was 26-inch O.D. x 1.785-inch W.T. API Specification 5L Grade X70. This pipe was made in Europe on an experimental basis for the now-defunct Oman-India Pipeline (OIP) project.

5.2 Corrosion Resistant Alloy Line Pipe (CRA)

5.2.1 General

Increased exploration and production of oil and gas from corrosive reservoirs that produce CO_2, H_2S, and/or chlorides has created a large demand for line pipe manufactured from CRAs such as 13 Cr steel, the austenitic and duplex stainless steels, the austenitic Ni-based alloys such as Alloy 825, Alloy G-3 and others. Although these alloys are significantly more expensive than carbon steel, the reduced risk of failure associated with their application often results in lower life cycle costs for many systems. Increased environmental concerns and increased need for transportation of corrosive oil and gas is expected to increase the demand for CRA line pipe in the foreseeable future.

5.2.2 CRA Line Pipe Product Forms

CRA line pipe is available in both solid and internally clad product forms. Internally clad pipe is characterised by a liner of CRA material that may either be mechanically or metallurgically bonded to the outer pipe, which is usually carbon steel. Liners or cladding vary in thickness up to 5mm with about 3mm being typical. Since applicable pipeline design codes do not typically allow designers to take advantage of the liner thickness in strength calculations, the outer pipe thicknesses are typically of nonclad system designed for similar operating conditions. Obviously, clad line pipe offers most if not all of the inherent corrosion resistance of solid CRA pipe of the same alloy class, but at a significantly reduced cost.

5.2.2.1 Solid CRA Line Pipe

Solid CRA pipe are available in either seamless or longitudinally welded forms. The range of available diameters and wall thicknesses is generally the same as carbon steel.

Seamless CRA pipe may be manufactured by the Mannesmann process but a combination of extrusion followed by either cold drawing or cold pilgering is more typical for hard to work alloys. Welded CRA line pipe is usually manufactured using GTAW, GMAW or a combination of the two. Owing to improved corrosion resistance, most CRA line pipe is supplied to end users in the solution annealed condition. However, for increased strength, some nickel-based CRA materials for sour service are supplied in the cold worked condition. The hardness limits for these and other CRA for sour service are found in NACE MR0175.

5.2.2.2 Clad CRA Line Pipe

Clad line pipe is characterised by a CRA liner that is either mechanically or metallurgically bonded to a carbon steel outer pipe. Mechanically-bonded liners have been successfully affixed to the outer pipe by shrink fitting and by a combination of expansion and auto-frettage. Metallurgically-bonded liners are typically affixed to plate steel either by conventional hot-rolling or explosive forming. The plates are subsequently formed into cylinders and seam welded to form pipe.

At least one European manufacturer and a North American affiliate produce internally weld metal overlayed line pipe and fittings in a variety of alloy combinations. Pipe and fittings produced by this method have been used successfully in the North Sea and the Gulf of Mexico, and usage is expected to increase in the future.

6. Pipeline/Flowline Construction and Commissioning

6.1 Pipelay Methods

6.1.1 Conventional S-Laying

The dominating laying method for offshore pipelines is the S-laying method performed by so-called "third generation" laybarges operating world-wide. The actual barges are large semi-submersible or ship hull vessels built for the first major offshore pipeline projects in the Gulf of Mexico and in the North Sea in late sixties and early seventies.

These are equipped with "stingers" at the stern to control the pipelaying and guide the pipeline gradually into the sea and onto the seabed. Stingers are normally sized for 85% SMYS but for deep water lays some installation contractors are utilizing high departure angle stingers that strain the pipe between 0.2 and 0.3%, slightly yielding the pipe. Some barges are equipped for full dynamic positioning during laying, and others use anchor system to control position and provide necessary holding force on the barge. Line pipe handling and storage facilities, welding stations, pipeline tension machines and field joint stations are organized along one production line on board the barge. The complete spread includes line pipe supply barges, necessary anchor handling tugs, ROV vessels and possible supplementary assistance vessels.

The largest S-lay vessels are presently capable of laying pipelines up to 42-inches diameter. One of the most demanding offshore pipelay project to date in terms of pipeline diameter and water depth was the laying of the ZEEPIPE 2A 40-inch pipeline across the Norwegian Trench from the western coast of Norway to the Sleipner Field in the central North Sea area. This project was highly challenging due to large water depths (365 m), large pipeline diameter and wall thickness and irregular seabed conditions (rock outcrops and pockmarks). However, the pipeline was made feasible by upgrading the tension capacity of the actual laybarge and was successfully installed during the 1994 and 1995 lay seasons.

Other demanding pipelay operations on smaller size pipelines but largest water depths during recent years are the installation of the TRANSMED pipelines across the Strait of Sicily (610 m), the installation of the oil line from the Auger Field in the Gulf of Mexico (900 m) and the Troll Oil Line from the Troll Field to the western coast of Norway (540 m).

6.1.2 J-Laying

This method refers to the escape angle of the pipeline from the laybarge the pipeline during laying being more or less vertical in contrast to the almost horizontal position on the barge during an S-lay operational. The method has been proven fully technically feasible and in deep water pipelaying the method is even technically attractive in minimizing the underbend tension. Hereby the pipeline can be installed in irregular seabed terrain with a maximum adaption to the seabed topography and thus a minimization of seabed preparation costs. However, the line pipe is typically welded in the vertical or 2G position, which is more complex and time-consuming than for traditional horizontal (5G) welding used in the S-lay method. Thus the J-lay method has up to now not proved economically attractive. Clearly the success of the method in future deep water pipeline installation will depend critically on further improvements in welding speed of the line pipe.

6.1.3 Reeling

In the reeling method the pipeline is welded and fully prepared for installation in lengths limited by the maximum reel dimensions at an onshore yard. The whole pipeline section is spooled onto the lay reel, on board the lay vessel. The laying is performed by pulling and straightening the pipeline from the lay reel in principally the same manner as laying of an offshore cable.

The method may be very effective when suitable for the actual project. A basic technical limitation is that the pipeline cannot have concrete coating when reeled. The method is thus limited to projects where concrete coating is not needed for negative buoyancy or pipeline protection purposes. Another technical limitation of the method is due to maximum strain capacity of the pipeline which so far has limited the application of the reeling method to pipelines of 16-inch diameter or smaller. Also avoidance of a short soft zone into which strain may be concentrated either in the HAZ or weld metal is important.

A third obvious drawback of the method is the limited length of pipeline to be carried by the spool. The consequence is basically economic in its dependency on effective supply of new reels with new pipeline sections, i.e., on a nearby suitable welding yard.

6.1.4 Bundles

Laying of pipe bundles wherein one or more lines of small diameter pipe are "piggybacked" or carried inside a larger diameter pipe have gained favor in recent years primarily due to increased economies of scale. These economies of scale are realized through more efficient use of available lay vessels and equipment as well as decreased spread costs when multiple lines are required to be laid to a remote offshore facility. Reduced trenching (where required) and disturbance of sensitive ecological areas has also been a benefit realized from the use of this lay technique.

6.15 Coiled Tubing

Coiled tubing pipelines have been laid in Egypt and the Ivory Coast. This method is similar to reeling but uses much longer lengths of pipe that have TIG bias welds to couple the lengths.

6.2 Welding and Fabrication

6.2.1 Arc Welding

Offshore pipeline welding started in the late sixties and has undergone constant development up to now. In the early days, welding was performed manually using electrodes with cellulosic coatings. That technique was commonly used also in the seventies and is still used to a wide extent. However, the oil and gas industry required larger diameter, higher-strength heavy wall thickness pipelines. At the same time stringent material requirements were established. As a consequence it became clear that manual SMAW welding would not always be the optimum welding technique for offhsore pipelines.

A substantial part of the new welding technique development has been led by the larger pipelay contractors. The development was to use mechanized GMAW welding systems. Such systems were used in the North Sea in the early eighties. This method has dominated in pipeline welding since.

For seamless pipe manual welding is still the mostly used method but is increasingly taken over by the mechanized GMAW welding.

The development over the coming years is expected to go into one station welding where radial friction welding RFW are present candidates. All three techniques are promising but will require considerable development efforts to be brought to an industrialized stage. Other welding techniques such as plasma keyhole, laser or electron beam techniques may also be used in the future. However, these techniques seem presently to have less potential than the above candidates during the first two decades.

Although recently the use of semi-automatic systems using the gas shielded metal arc welding process have proven to be very successful in certain conditions, the standard and quickest method to weld pipelines is to adopt the stovepipe method which is vertical down welding using cellulosic electrodes. Tie-in welds are usually welded using a composite technique, i.e. vertical up for the root passes and then downhill for the filler passes. Standard cellulosic electrodes are reaching their limit when welding X60/X65 grade materials (depending on properties required). Therefore with these and higher grades, alloyed cellulosic electrodes need to be used with the consequent higher risk of hydrogen cracking in both the parent material and weld metal. This has led to the introduction of low hydrogen electrodes which can be used vertically down to maintain high deposition and production rates.

Because higher grade materials and higher operating pressures are being increasingly adopted, and because skilled pipeline welders are becoming fewer in number, the incentive to introduce semi-automatic and automatic welding machines for pipeline construction becomes more attractive. These machines and the welding consumables they use are able to produce welds with the required mechanical properties together with production rates of between 150 to 180 pipeline butts per day.

6.3 Qualification, NDT and Mechanical Properties of Pipeline Girth Welds

6.3.1 NDT Qualifications

Girth welds, tie-in welds in new pipelines are typically subjected to radiography, ultrasonic inspection or a combination of the two. Radiographic techniques have not changed much in several decades of use, but development of more sensitive film and the development of "real-time" radiography through computer technology promises to make this old standby even more useful in the future.

Ultrasonic inspection techniques for pipeline girth welds have progressed rapidly in the last few years with the standard A-scan technique being replaced more and more by computer generated B-scans and C-scans. Time of flight diffraction (TOFD) technology also promises to improve the usefulness of ultrasonic inspection as regards offshore pipeline construction.

6.3.2 Acceptance Criteria

Historically the NDT acceptance criteria for pipeline girth welds have been based upon arbitrary workmanship standards such as those found in API Standard 1104 or ANSI/ASME B31.8. More recently, however, acceptance standards have been based on the allowable flaw sizes predicted by fracture mechanics based design criteria. The latter trend is expected to continue in the future.

6.5 Commissioning

6.5.1 Hydrostatic Tests

All pipelines, once constructed, should be hydrostatically tested to ensure structural integrity. The normal range of test pressures is from 1.25 to 1.50 times the design pressure. The length of a test section will depend on several factors, including:

1. the availability and disposal of test water;

2. pipeline is not under or overstressed as a result of the static water head created by rises and falls in ground levels; and

3. access to test points for tie-ins and reinstatement.

It is essential when introducing the test water to ensure that the minimum amount of air is entrained and this can be achieved by utilizing two swabbing pigs separated by a slug of water. Inhibitors (oxygen scavengers) and biocides are often used in hydrostatic test water to prevent significant corrosion from occurring.

Generally pipelines are hydrostatically tested after the pipeline has been backfilled, but in some countries it is permitted to test the pipeline with the trench still open. The test period is usually 24 hours after the pipeline has stabilized, but a longer period may be required. When the pipeline is tested with an open trench, then a shorter period of about four hours is usually adopted.

6.5.2 Pre-Service Condition Surveys

A caliper or gaging pig is often passed through a pipeline before and after hydrostatic testing to ensure that the pipeline has not been deformed during construction and/or backfilling/trenching operations. This is increasingly important as use of expensive intelligent pigs is expected to increase in the future.

For pipelines in corrosive service intelligent pigs are often run before the line is filled with product. These commissioning runs provide corrosion engineers/metallurgical engineers with baseline data on which they can judge the efficacy of corrosion control methods such as continuous inhibition, pigging and batch treatment. Periodic smart pig runs during the service life of a pipeline can also provide confirmation of the data obtained from real-time corrosion monitoring instruments or coupons, if present.

6.5.3 Cleaning and Long Term Storage

After the pipeline has been emptied of water it is usually necessary to dry it before the gas is introduced. There are various methods to do this:

1. using super-dry air or inert gas, where an air drying plan and compressor produce oil-free air to push a series of foam pigs through the pipeline collecting water until the required dryness is achieved;

2. Vacuum drying, where evacuation of a pipeline causes the water to boil off at the ambient temperature of the pipeline, the water vapor being drawn off until the required dryness is achieved. This method is also effective at drying any pressure reduction stations attached to the pipeline;

3. Operational drying, where a pipeline may be purged using an inert gas and then pressureized and operated at a pressure where hydrate formation will not occur at ambient temperature. When the dewpoint checks prove acceptable then the pipeline can be raised to full pressure. This is usually a very slow method of pipeline drying; and

4. Methanol swabbing, where two slugs of methanol preceded and separated by nitrogen are passed through a pipeline. This method is not effective for above ground installations and pipe work where pigging is not possible.

Methanol is particularly flammable and toxic and requires great care in handling. Because of this and concern for the environment its use is becoming less common.

7.0 OPERATION AND INSPECTION

7.1 Design and Operation Limits

7.1.1 Establishing/Verifying Safe Limits for Corroded/Damaged Pipelines

One widely used method for predicting the remaining strength of corroded pipelines is presented in ANSI/ASME B31G. The B31G method is able to calculate safe operating pressures as well as burst pressure of corroded pipe by accounting for the area (volume) of metal lost to corrosion and for support given to the corroded sections by surrounding undamaged metal. Therefore, the B31G technique is essentially an area averaging technique akin to similar techniques found in the ASME Boiler and Pressure Vessel Code. Laboratory and field experience have shown in B31G method to be conservative both in terms of remaining strength and burst pressure of pipelines.

The algorithms used by B31G have been in the public domain for some time and have been adopted and modified slightly by the commercial program Rstreng.

The remaining strength of pipe damaged by external forces resulting in dents, dents and gouges or gouges has been studied extensively by Keefner, Maxey and others at Battelle. Algorithms for calculating the strength of damaged pipe may be found in the open literature.

7.1.2 On-Line Corrosion Monitoring and Intelligent Pigging

Drives to reduce the capital costs of pipelines for transportation of corrosive produced fluids has resulted in increased use of on-line corrosion monitoring in recent years. To characterise the various forms of corrosion that can occur in pipelines operators rely on a number of devices, including electrical resistance (ER) probes, linear polarization resistance (LPR) probes and coupons. In sour systems, hydrogen patch probes or Beta-foils are used to detect hydrogen that diffuses through the pipe wall.

Electrochemical noise (ECN) monitors, a relatively new method for predicting the onset of corrosion, have come into limited industrial use in recent years. While ER probes, LPR probes, ECN probes and coupons may be mounted flush with the inside pipe wall or in the flow stream, depending upon the judgement and experience of the pipeline designers, hydrogen patches are always mounted on the outside surface of the pipe. Typically, the instruments are monitored locally, but the use of personal computers and software specially designed for the purpose of corrosion monitoring are being increasingly used. Several major operators have designed and built systems that are monitored continuously in plant or offshore control rooms and that signal operators when corrosion reaches levels that cannot be economically sustained.

Intelligent pigging (smart pigging) of pipelines is typically conducted using EMI and/or ultrasonic techniques. Smart pigging of systems has increased in recent years, primarily as a result of increased sensitivity and reliability of the smart pigs themselves. In addition, governmental regulatory agencies such as the USDOT are increasingly requiring data such as that provided by smart pig inspections to judge the safety and operability of new and existing pipelines. In combination with on-line corrosion monitoring equipment, smart pigging proves pipeline operators with a complete picture of the condition of pipeline systems.

7.1.3 Hydrostatic Test Pressures and Frequencies

All pipelines, once constructed, should be hydrostatically tested to ensure structural integrity. The normal test pressure is 1.25 to 1.50 times the design pressure. The length of a test section will depend on several factors, including;

1. the availability and disposal of test water;
2. the topography, since it is important to ensure that the pipeline is not under- or overstressed as a result of the static water head created by rises and falls in ground levels; and
3. access to test points for tie-ins and reinstatement.

It is essential when introducing the test water to ensure that the minimum amount of air is entrained and this can be achieved by utilizing two swabbing pigs separated by a slug of water.

Generally pipelines are hydrostatically tested after the pipeline has been backfilled, but in some countries it is permitted to test the pipeline with the trench still open. The test period is usually 24 hours after the pipeline has stabilized, but a long period may be required. When the pipeline is tested with an open trench then a shorter period of about four hours is usually adopted.

Because of the difficulty and expense of offshore repairs, offshore pipelines are not normally retested after commissioning unless significant damage has occurred or modification or repairs have been made. However, should regular testing become necessary, the test pressure and test frequency should be selected to minimize the probability of an in-service failure, while at the same time minimizing the number of and size of flaws that remain in the line after each test. There are many references in the literature that describe hydrostatic test methods that will help operators attain this goal.

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RESEARCH AND DEVELOPMENT NEEDS

1. Clarify effects of H_2S in CO_2 - containing environment.
2. Clarify LP requirements for deep water and shallow water pipeline installations and LP consequences for high strength steels like X100.
3. Develop suitable flanges, fittings, welding procedures, ect. for X100 steels.
4. Develop automated intelligent pigging for clad pipelines.
5. Clarify advantages and disadvantages of hydro-testing new pipelines.
6. Establish H_2S limits for weldable 13% Cr steels.

RECOMMENDATIONS

- Update current codes to include limit state design.
- Develop an API Standard for welding of solid and clad CRA pipelines.
- Specify yield strength ranges instead of minimum only yield strength for line pipe steels.
- Mechanized UT should be introduced as an acceptable alternative to RT in pipeline construction codes.

Material Requirements for Secondary Ship Structures

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Abstract

The pages to follow discuss material requirements for secondary ship structures which are defined to be surface warship superstructures. These structures have been developed over the years from wood (not discussed in this paper) to steel to aluminum and are now, with the development of fabrication methods and reduction in material costs, being investigated for composite material applications. Additional consideration for titanium, stainless steels, and nickel alloys will be investigated with a quantitative comparative study demonstrating the advantages and disadvantages of these structural materials.

Currently, ship superstructures are primarily fabricated from steel. The strength of steel lends itself well to withstand the rigorous conditions developed at sea. Its relative low cost and manufacturability make steel a good material choice for large scale production use, but the weight of steel presents some challenges to ship stability. Presently, surface combatants are being designed with advanced combat systems resulting in a topside weight growth. The substitution of aluminum provided a weight reduction/stability improvement, but the poor resistance to thermal damage was too great a detriment and steel again became the preferred material. For both of these materials, corrosion is an issue. With the investigation of the application of composite materials in ship structures research, corrosion is no longer an issue, but the ability to fabricate large ship structures in a shipyard environment at a reasonable cost requires further study. Additionally, the issues of fire resistance and ad hoc attachment of equipments have been only marginally investigated.

A quantitative study is performed to demonstrate the weight and strength of six structural materials as applied to a typical structure subjected to an arbitrary airblast load. Analyses are performed using ALGOR finite element analysis (FEA) software. Several factors need to be taken into account when designing structures for the marine environment. In addition to the static loads a structure would face in an ordinary environment, one must also design to shock, high temperature variations, corrosion, and impact loads due to wave slap or, for a naval ship, air blast. This must all be accomplished while attempting to optimize both cost and weight. The effort to achieve all these goals has driven the search for practical utilization of advanced materials for secondary ship structures.

Introduction

Steel, the original advanced material used to replace wooden construction, is now considered the standard for secondary structure construction. The strength of steel allows the structure to withstand the harsh loadings associated with the marine environment. It also lends itself very well to production in a shipyard environment. The ease with which steel is welded, either automatically or manually, allows for efficient and cost effective fabrication. However, it is far from the perfect material, especially in applications such as secondary structures. A major drawback to steel construction is the weight of the resulting structure. In the case of naval vessels, there are several advantages to reducing the weight of the vessel, especially above deck, in order to lower the KG, increase stability, decrease drag, decrease powering requirements, etc. Therefore, higher strength steels such as HY-80 and HSLA-80 were developed as the demand arose, particularly from the Navy, for hull scantlings which could maintain their load carrying capability at a reduced weight. In secondary structures the loads are not as severe as those on the hull, indicating that an even greater potential exists for superstructure fabrication using high strength-to-weight ratio materials. While there are even higher strength steels that would allow a lighter structure to carry the same loads, there are many advantages to seeking advanced materials to replace steel in secondary structures. These should be considered plausible alternatives to steel construction.

Much consideration has been given to the use of aluminum for many structural applications. While aluminum does not have the yield strength of steel, it is much lighter, resulting in an overall weight savings for similar structures. For this reason, aluminum became the preferred material for superstructure fabrication for several naval surface combatants. The combination of a lightweight structural material that is also easily welded seemed to be ideally suited to that application. There are, however, drawbacks to aluminum fabrication. An initial obstacle was the inability to weld aluminum directly to steel. This has been overcome through the use of an explosively bonded joint, or detacouple. However, this is an added expense and an additional step in the fabrication process. The cost of the raw material (plate and shapes) is significantly higher for aluminum than for steel, increasing the cost to fabricate a structure. Aluminum also has poor resistance to thermal damage. This was made tragically clear when an aluminum superstructure melted as the result of a missile attack during the Falklands War, causing the loss of several lives. This incident, as well as others, resulted in the return to steel for use in superstructures. Neither steel nor aluminum, however, is completely resistant to corrosion, which is a serious consideration for all marine structures. The prevention and repair of corrosion damage costs millions of dollars every year. In addition, the damage itself can have serious consequences.

Presently, attention has been focused on the use of composites for naval ship superstructures. At first glance, a composite structure would seem to have the perfect properties for use in the marine environment, particularly for secondary structures. A fiberglass cloth such as E-glass in a vinyl-ester resin has an extremely high tensile strength-to-weight ratio. When combined with a lightweight core such as balsa, the sandwich composite structure has excellent bending strength as well. It is, therefore, possible to achieve significant weight savings over the entire structure. In addition, corrosion problems would be completely eliminated, along with several of the steps in production related to preventing or treating corrosion. Additionally, a composite superstructure could greatly reduce the radar cross section of the vessel, which is high on the list of priorities for the next generation of naval ships. However, special considerations would need to be made to ensure long-term structural integrity in a marine composite structure.

While corrosion is not a factor, there are reductions in strength due to environmental conditions and random variations in cloth layup which must be taken into account. Additionally, fire resistance of a composite marine structure remains an area of concern. The components of a composite structure, except for the E-glass fibers, are organic and will degrade at elevated temperatures. Several methods of protecting the composite structure have been developed including fire resistant insulations and resin systems, but fire protection of marine composite structures continues to be an area of research.

Several other advanced materials have characteristics favorable for use in the marine environment. Titanium, for example, has an exceptional strength-to-weight ratio. Certain alloys have yield strengths comparable to the strongest steels at approximately one half the weight. In addition, titanium is practically inert to corrosion from seawater. However, these factors must be weighed against the drawbacks associated with its use, as is true for any of the advanced materials discussed in this paper. The relative cost of titanium compared to steel is high. Additionally, welding of titanium is more difficult than for typical shipyard steels. These obstacles, while not insurmountable, are certainly more limiting in a shipyard environment than in other industries.

Similar tradeoffs exist for materials such as stainless steels and nickel alloys. Several common stainless steels have essentially the same mechanical properties as mild steel. Therefore, when compared to higher strength steel normally used in naval shipbuilding, a stainless steel structure would be slightly heavier and have less load carrying capability for the same scantlings. However, stainless steels are not as susceptible to corrosion, which is a strong argument to justify their use for a particular application. Costs associated with other stainless steel alloys that possess strengths comparable to carbon steel may be difficult to justify.

Nickel alloys, like stainless steels, are also resistant to corrosion. In addition, several nickel alloys have yield strengths significantly higher than those for high strength steel. These attributes must again be compared with the drawbacks for this particular material. For example, there is little likelihood of weight savings through using nickel alloys, as they have a greater density than steel. In addition, the cost of these alloys relative to steel is comparable to that for titanium.

Technical Procedure

This paper will compare the use of several advanced materials chosen from those discussed above for the fabrication of a generic superstructure using a finite element model created in the ALGOR software package. Steel is used as the baseline for comparison in the initial model run. The model is then run for each additional material (except composite) with the baseline scantlings. A revised model is then analyzed to determine a realistic scantling arrangement. The revisions optimize the weight of the structure while ensuring structural integrity. A separate model was prepared for analysis of the composite structure due to the inherent differences in design and fabrication between metals and composites. Additionally, analytical procedures differ not only between metals and composites, but also depending on the type of composite. For this paper, a quasi-isotropic cloth layup consisting of E-glass in a vinyl-ester resin is assumed for the skins. In addition, structural knockdown factors are considered in determining the ultimate tensile failure for the composite. The properties for all of the materials analyzed are listed below in **Table 1**.

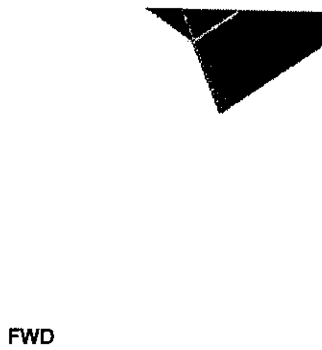
Table 1: Material Properties

Material	**Young's Modulus [1E6 psi]**	**Shear Modulus [1E6 psi]**	**Poisson's Ratio**	**Density [lb/cu. in.]**	**Tensile Stress [ksi]**	**Yield Stress [ksi]**
Steel ASTM A242	29	11.5	0.2609	0.284	70	50
Aluminum Alloy ASTM 5086-H116	10.3	3.9	0.3205	0.101	46	22
Titanium (CP) Grade 3	16.5	6.2	0.3306	0.161	65	55
Stainless Steel AL-6XN	28.3	10.9	0.3019	0.301	108	53
Nickel Monel 400	25	9.5	0.3158	0.319	98	85
Composite						
E-glass/Vinyl-ester Resin	2.747	1.07	0.2860	0.068	n/a	26*
Balsa Core	0.01	0.14	0.3000	0.0052	0.07	0.07

***Note: For composites the value listed is for ultimate tensile failure.**

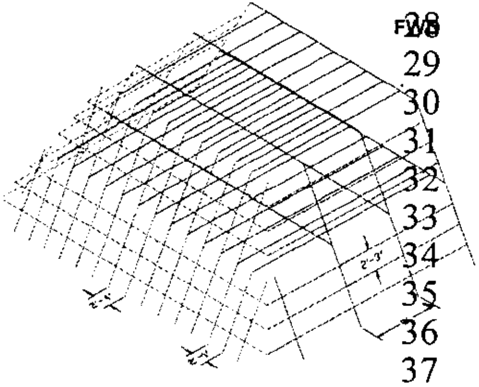
Model Description

The initial scantlings for the model were adapted from an existing ship design and are sized to ensure elastic response under the application of an arbitrary air blast load. The structure analyzed was developed from proposed deckhouse configurations and has a length of 29 feet, a breadth of 40 feet and a height of 16 feet. The aft and side faces taper inward 50 inches over the 8 foot vertical span of each deck. There is a centerline longitudinal bulkhead which runs the length of the structure, and a deck which divides the structure vertically. An isometric model of the structure is shown in **Figure 1**. The structure is designed with transverse frames every 8 feet. Longitudinal stiffeners are spaced vertically every 2 feet 3 inches on the shell plate. The aft bulkhead also has stiffeners running vertically along its slope. Additionally, there are longitudinal stiffeners which run beneath the two decks. The spacing for the lower deck and the vertical stiffeners is 28 inches, except for the outboard two on either side, which have a 25 inch spacing. The upper deck has a uniform 28 inch spacing. **Figure 2** provides a visual representation of the frames and stiffeners present in the model.



re 1: Structure Isometric

The baseline model, as well as those derived from it, has 1/4 inch plate throughout. In addition, the frame size was a standard 16 inch deep, wide flange section with a weight of 36 pounds per foot. The longitudinal stiffeners for the baseline model were 5 inch structural tees with a steel weight of 6 pounds per foot. The vertical stiffeners and the deck stiffeners were both 6 inch structural tees with a weight of 7 pounds per foot for the baseline model. While the models were revised to reflect the differences in the material characteristics, there was also an attempt to maintain some continuity. For this reason, only the sizes of the structural tees were changed. For analysis purposes, the bottom of the structure is considered translationally constrained. The centerline bulkhead is represented by fixing the vertical translation at the centerline along the length of the structure. The forward end of the structure is constrained such that there was no translation along the longitudinal axis and no rotation about the other two axes.



re 2: Stiffener Configuration

The composite structure was modeled slightly differently; however, the overall dimensions and attributes, including boundary conditions, were maintained.

The baseline model consisted of composite panels for the sides, the rear face, and the two decks. These panels had a 2 1/2 inch balsa core with 3/16 inch skins. Each skin is fabricated from several layers of E-glass in a vinyl-ester resin. The panels taper to a 1/2 inch solid flange in way of the intersection of two plates. The stresses would be compared to the ultimate tensile failure for the composite, which includes statistical, thermal , and moisture safety factors. Deflections are also a concern for composite structures, and these would be analyzed along with the stresses. If the model needed to be changed in order to handle the load, stiffeners would be added rather than increasing the size of the core or skins of the baseline model.

The simulated air blast load applied to the structure consists of a 3.0 psi uniform pressure on the starboard side with a 1.5 psi uniform pressure on both the aft face and the upper deck. The baseline model was analyzed with the properties of steel, and the stresses were analyzed. A Von Mises criterion was used for the plate stresses, and a beam bending theory that provided the stresses along the strong axis of the member was used for the stiffeners. The plate stresses averaged approximately 6.0 ksi (as indicated in **Table 2**), and the beam stresses were approximately 75 percent of yield for the steel chosen. The chosen scantlings were therefore acceptable for steel and would provide a very good baseline for the other materials.

The same loading conditions were applied to the composite model. The original stresses were 68% of ultimate strength which was acceptable. However, the deflections exceeded 3" and were considered too large. The model was revised to decrease deflections. Both models will be compared to the steel baseline in **Table 2.** For the composite model, the deflection rather than the stress would determine the final scantlings. Recognizing the impact of the low modulus of elasticity for composite materials, the natural frequency of the structure will be determined and compared to the natural frequency of the steel structure.

Material Analysis

A total of nine finite element models were analyzed. A baseline model of steel, as described in the previous section, was analyzed to provide a basis of comparison. With ship superstructures currently being fabricated of steel, this was the logical choice. For each of the alternative advanced materials, the material properties were substituted into the baseline model to determine a material baseline. The scantlings of the material baseline were then optimized for weight to withstand the applied load. Further discussions of stress characteristics are based on the beam stresses, which dominated the values of those in the plate.

Each of the models with the baseline scantlings had stresses nearly equal to those for the steel model, which agreed with the predicted results. The stresses in the baseline model were compared with the yield stress of the material. If the yield stress was exceeded, larger structural tees were used. If the material had a higher yield strength than that of steel, the scantlings were lightened.

As previously stated, the maximum stresses experienced in the steel model were bending stresses in the longitudinal beams on the order of 38 ksi. Referring back to **Table 1**, it is evident that the aluminum model, with material allowables below 38 ksi, would need to be strengthened, while the nickel model, with allowables much higher than 38 ksi, could be lightened. The stainless steel and titanium models would need no further optimization. While a complete optimization of strength and weight is not part of the scope of this paper, in general an effort would be made to keep the stresses in the revised models between 65 and 75 percent of yield in order to make more accurate comparisons. The approach was slightly different for the composite model since the deflections rather than the stresses were the driving factor. In this case, a goal of deflections less than 1 inch was set. A list of scantlings, stresses, and weight is provided in **Table 2** for each of the models.

Increasing the structural tees in the baseline aluminum structure by 2 inches resulted in a stress reduction from 38 ksi to 14 ksi, which is 65% of the yield point for this particular aluminum alloy. The overall weight of the structure was still only 41% that of the steel structure, primarily because the plate size remained the same.

The stresses for the nickel alloy model were initially well below yield. For this material, the lightest possible scantlings were sought. The horizontal, vertical, and deck stiffeners in the nickel alloy model were all reduced to 4 inch tees. The resulting stresses were just below 60 ksi, which is 31% below yield. Further optimization of the members could possibly reduce the weight to below that of the steel structure.

The original scantlings were kept for both the stainless steel model and the titanium model. The stresses in the titanium model were 69% of yield , and the weight was over 42% less than that of the steel model. The stainless steel model also had stresses just above 38 ksi, which is 72% of yield for the particular alloy chosen. The resulting weight of the model is slightly heavier (<6%) than that of the steel model.

The composite model required both horizontal and vertical stiffeners to achieve the desired results. Three vertical stiffeners divided the longitudinal span of the panels. One horizontal stiffener was required for each of the vertical spans between decks. The stiffeners consisted of a 6 inch deep balsa core with a 1/8" skin. In addition, each of the stiffeners had a 1/8" unidirectional cap for added strength. This reduced the deflections from 3.3" to 1.1" with the maximum deflection in a localized area. By reducing the deflection, the minimum natural frequency of the structure is approximately 11 cycles/sec compared to 36 cycles/sec for the steel model. This minimum natural frequency is found in the internal deck.

1

Table 2: Analysis Summary

Model	Transverse Frames	Longitudinal Stiffeners	Vert./Deck Stiffeners	Max Stress (Plate) [ksi]	Max Stress (Beam) [ksi]	% Yield	Max Deflection [in]	Weight [lbs]
Steel	**W16x36#**	**WT5x6#**	**WT6x7#**	**5.4**	**38.2**	**76**	**0.112**	**46446**
Aluminum Alloy	W16x36#*	WT5x6#*	WT6x7#*	5.3	37.9	172	0.319	16555
Aluminum Alloy	**W16x36#***	**WT7x13#***	**WT8x13#***	**5.3**	**14.2**	**65**	**0.274**	**19059**
Titanium Alloy	**W16x36#***	**WT5x6#***	**WT6x7#***	**5.8**	**38.1**	**69**	**0.208**	26882
Stainless Steel	**W16x36#***	**WT5x6#***	**WT6x7#***	**5.5**	**38.2**	**72**	**0.120**	**49226**
Nickel	W16x36#*	WT5x6#*	WT6x7#*	5.4	38.3	45	0.130	52288
Nickel	**W16x36#***	**WT4x5#***	**WT4x5#***	**6.0**	**58.6**	**69**	**0.208**	**50233**

	Core Thickness [in]	Skin Thickness [in]	Stiffener Depth [in]	Max Stress (Tensile) [ksi]	Max Core Shear (Out-of-Plane) [ksi]	% Yield	Max Deflection [in]	Weight [lbs]
Composite	2 1/2	3/16	0	17.8	116	68	3.309	15845
Composite	**2 1/2**	**3/16**	**6**	**7.2**	**102**	**28**	**1.118**	**17081**

2

***Note: Weights for structural members are for an equivalent steel section.**

Conclusions

The choice of materials for use in secondary structures for the marine environment is a very complicated procedure, and several factors must be taken into account. It has already been stated that high strength-to-weight ratio materials would be desired for this application. Material cost, corrosion, and resistance to thermal damage are also among the leading indicators for material selection.

Figure 3 shows the characteristics of each material relative to steel. The relative strength-to-weight ratio is defined as

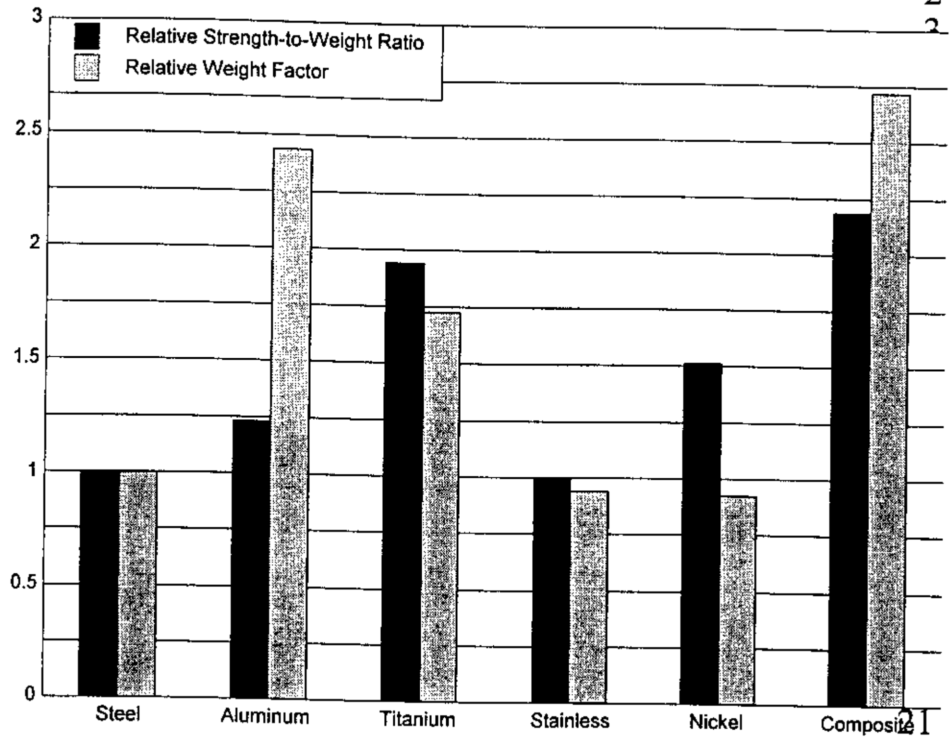
$$\frac{s_y(\text{material}) / r(\text{material})}{s_y(\text{steel}) / r(\text{steel})}$$

The weight factor is determined in accordance with the following equation:

$$\frac{\text{Weight}_{(\text{steel model})}}{\text{Weight}_{(\text{material model})}}$$

For each of these categories the highest number is the most desirable.

Initial indications can often be misleading. For example, it is surprising that while titanium has a very good strength-to-weight ratio, the aluminum model has a higher weight factor, and thus a lower weight, than the titanium model. This would seem contrary to predicted results. A comparison of these two quantities for the stainless steel and nickel models also yields interesting results. The nickel model has a better strength-to-weight ratio, suggesting that weight savings would be possible using this material. However, none of these weight savings are realized, and the stainless model is in fact slightly lighter than the nickel model. This indicates that the strength-to-weight ratio, while an important characteristic, is not the only basis upon which a material selection should be made. For these models, this can be attributed to the fact that the plate size was not changed since the stresses in it were far below the yield of all the materials. A combination of slightly larger stiffeners with a reduced plate thickness would reduce the weight of the revised models. However, due to discrete sizes of stiffeners and minimum plate thicknesses, it is very unlikely that the full potential for weight savings suggested by the strength-to-weight ratios would ever be realized.



re 3: Relative Material Characteristics

Finite element analysis programs such as ALGOR are very useful tools when analyzing and comparing various materials for use in structures of any nature. However, as discussed, the marine environment places demands on materials that require considerations beyond structural analysis to determine the proper material. In addition to stresses and weights, material choice must also take into account factors such as the cost of both the raw material and fabrication, resistance to corrosion and thermal damage, and the ability to fabricate the intended structure using the material. Additional considerations may affect the decision: the particular structure, its location in the ship, subjection to specific frequencies, etc. This is a classic trade-off study that will vary depending on the material choices, the budget, the technology currently available, and the type of structure under consideration. Even for the relatively narrow category of secondary structures for marine applications, there is no one perfect material to be used. There are, however, some general characteristics that are desirable. An intelligent decision can then be made based on the importance of each particular characteristic to the design in question.

For the particular example discussed in this paper, namely a section of a proposed superstructure for a surface combatant, the most basic characteristics which need to be considered are strength, weight, ease of fabrication, cost, corrosion resistance, and thermal resistance. Using finite element analysis, strength is able to be factored out of the equation since all of the structures were designed to the same load, and the resulting stresses were all roughly the same percentage of the yield stress for each material. The remaining characteristics are then assigned a relative importance based on the shipbuilder's perspective. The materials are rated in each category, with 10 being the best and 1 being the worst. The weighted score is obtained by multiplying the rating by the relative importance.

Ease of fabrication is essential to successful shipbuilding, as is minimizing costs. For this study, the category of material cost encompasses both of these factors and is given the highest relative importance. It is essentially a measure of the cost of the raw materials and the labor involved in generating the final product. Materials such as steel and aluminum are readily available and therefore relatively inexpensive. They are also easily welded, allowing production to flow smoothly from flat plates to complete assemblies. Titanium, on the other hand, can only be welded in a highly controlled environment, which a typical shipyard does not often provide. In addition, the cost of the raw material is much higher than that for either steel or aluminum. Composites are fabricated in a manner which is quite foreign to a typical "steel" shipyard. However, smaller shipyards specializing in pleasure craft or high performance vessels have been using composite construction successfully for years. Similarly, once the initial effort was made, composite construction could be achieved with relative ease in the large shipyard environment. However, the ratings will reflect the present state of production capabilities, as advances for other materials are possible as well. The following table represents the material cost ratios for a typical shipyard capable of fabricating structures from the proposed material.

Table 3: Material Cost Ratios

Material	**Steel**	**Aluminum**	**Titanium**	**Stainless**	**Nickel**	**Composite**
Material Cost	1 : 1	2.5 : 1	31 : 1	23 : 1	24 : 1	2 : 1

Table 2 displays the weight of all the structures, and the ranking is fairly simple, with the lowest weight receiving the highest score. It is based on the updated structures rather than the baseline models to ensure an accurate comparison. The weight is given the next highest relative importance because of the increase in performance which can be achieved through the reduction of weight.

Another characteristic being considered is the resistance of the material to thermal damage. The difference in the ability of two materials to resist thermal damage can literally be life and death. This property, based upon material melting points, is the greatest shortcoming of both composites and aluminum.

As discussed earlier, corrosion is an important consideration in marine design. Materials such as steel and aluminum have little defense against it, except for costly and labor intensive protective coatings. Titanium, on the other hand, is essentially inert to seawater corrosion. Composites are intrinsically resistant to corrosion as well, but they are susceptible to water absorption by the core, which can have the same structural effect that corrosion has on metals. For the purposes of this analysis, however, this was taken into account as a structural knockdown factor during the finite element analysis. For this reason, composites are considered equal to titanium. Nickel and stainless steel also have excellent corrosion resistance, but they can be susceptible to pitting and crevice corrosion. Both ranked much higher than aluminum because they are essentially inert in atmospheric conditions; their greatest susceptibility is when submerged. While this characteristic is important considering the environment of operation, it is considered less crucial than the other three criteria and is therefore given the lowest relative importance. Ranks are determined based on the following table extrapolated from **References 5 and 11**.

Table 4: Corrosion Rate Data

Material	**Steel**	**Aluminum**	**Titanium**	**Stainless**	**Nickel**	**Composite**
Corrosion Rate	$5^{\text{mils}}/_{\text{yr}}$	$0.1^{\text{mil}}/_{\text{yr}}$	Nil	Nil $^{\text{except pitting}}$	$<1^{\text{mil}}/_{\text{yr}}$	Nil

Table 5 provides a matrix of the materials and characteristics being considered. The total for each material is calculated simply by summing the totals for each characteristic after multiplying the rating by the relative importance (RI). Therefore, for this example, composites would be the preferred material. This table is an example of the type of approach which should be taken when choosing materials for any application in general, and for secondary structures for surface combatants in particular. It is not, however, a comprehensive listing of characteristics which need to be considered for all applications. For example, one significant area which this study did not investigate was the effect of the material on the radar cross section, or stealth characteristics, of the structure. Other characteristics which are more likely to be considered by the owner rather than the operator include life cycle cost, maintainability, and repairability.

Table 5: Material Comparison Matrix

Category	RI	Steel		Aluminum		Titanium		Stainless		Nickel		Composite	
Material Cost	**10**	10	**100**	8	**80**	1	**10**	5	**50**	4	**40**	9	**90**
Weight	**7**	4	**28**	9	**63**	6	**42**	2	**14**	1	**7**	10	**70**
Resistance to Thermal Damage	**5**	9	**45**	2	**10**	10	**50**	9	**45**	7	**35**	1	**5**
Corrosion	**3**	1	**3**	6	**18**	10	**30**	10	**30**	10	**30**	10	**30**
Total:			**176**		**171**		**132**		**139**		**112**		**195**

***Note: RI is the Relative Importance (RI) factor for each category**

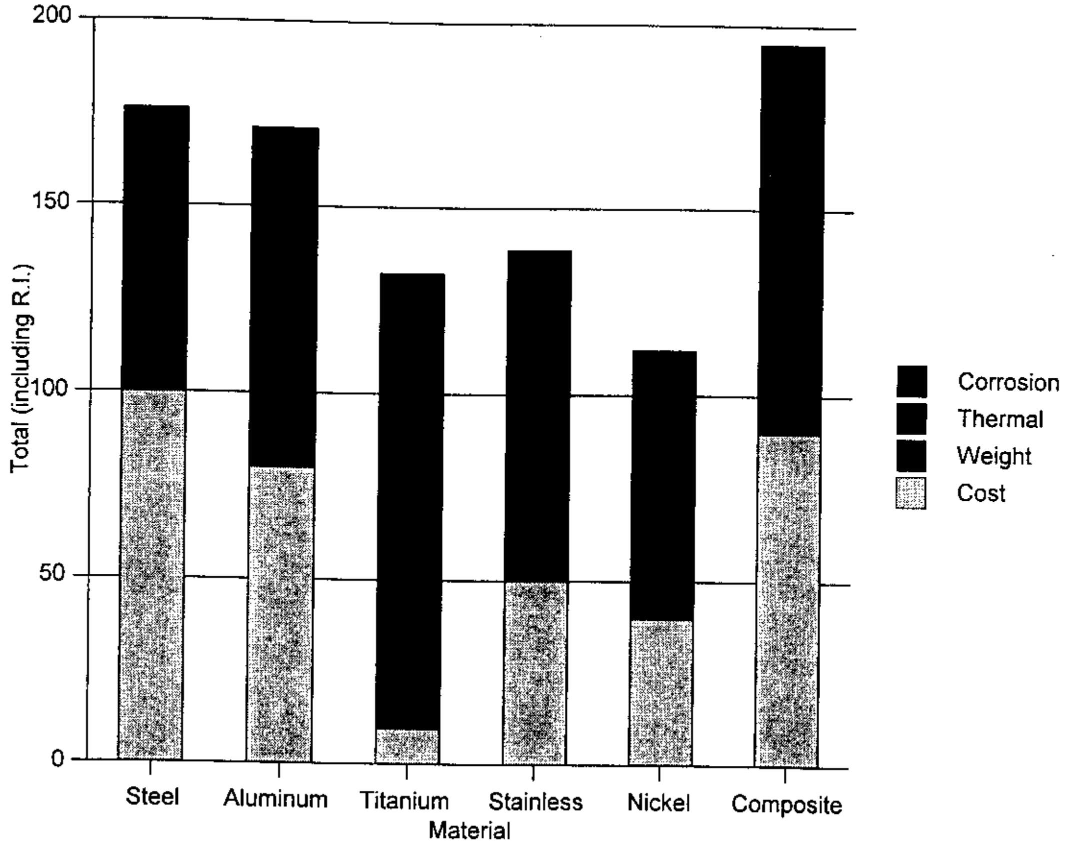
Figure 4 graphically indicates the particular areas in which each material needs to improve in order to be considered for this application. It can easily be seen that any narrow band is an area in which that material is deficient. Improvements in the relative area(s) of deficiency for a particular material could alter the choice for a given application.

Using the criteria selected for this example, it is possible to forecast the possibility of advanced material use for secondary structures. Each material proposed as an alternative can easily be compared with the material currently in use. In order to become the new standard, the material would need to surpass the characteristics of steel for this particular application.

Aluminum, in this example, compares very well in the weight and corrosion categories. It is very close to steel in the area of cost. The one category where it falls short is thermal resistance. An aluminum structure has little residual strength after prolonged exposure in a fire because the material softens at 400 degrees Fahrenheit and melts at 1100 degrees. If a high temperature aluminum alloy were to be developed such that the other properties (density, weldability, etc.) were not compromised, then the majority of naval vessels might once again feature aluminum superstructures. Unfortunately, all aluminum alloys are limited by the relatively low melting point of the base metal. Therefore other methods of preventing structural collapse in the event of a fire need to be examined.

Composites, along with aluminum, appear to have the highest potential for future use in secondary structures, especially where thermal damage is not a great concern. One of the largest obstacles to the use of composites is the lack of familiarity typical shipyards have with their production methods, resulting in increased fabrication costs. Once an initial effort is made, the barriers to the use of composites will be fewer and their use more readily justified. The low melting point of the matrix is another hinderance to marine composite construction. As with aluminum, steps must be taken to ensure structural integrity. Unlike aluminum, there are configuration options which, although they will burn, will remain structurally sound in the event of a fire. Research into higher temperature resins will further improve the marketability of composites for the marine environment.

Figure 4: Material Comparison Summary



Titanium far exceeds steel in the areas of weight and corrosion resistance. However, it is expensive and difficult to fabricate in a shipyard environment. In order for titanium to achieve large scale incorporation into secondary structures, a less expensive and more easily welded alloy would need to be developed. Alternatively, innovative joining methods and material configurations could result in more cost effective fabrication.

Presently, nickel alloys do not seem well suited to widespread use in marine secondary structures. Their strength and corrosion resistance are attractive characteristics, but their weight and cost do not justify their use in all but a few specialized applications. Of the two, cost is the greater drawback; thus a cheaper alloy with similar properties would be very desirable for several uses.

Stainless steel has minor drawbacks such as a higher material cost than steel, aluminum, or composites. However, the improved corrosion resistance and negligible weight difference make it a viable consideration for secondary marine structures. Another notable characteristic of stainless steel is the absence of any extreme deficiency of the material. Although stainless steel is not rated highest overall for use in marine secondary structures, it is not rated lowest in any of the individual categories. Therefore, it is a good compromise when no particular material characteristic is required. In addition, the typical shipyard would adapt most quickly to the use of stainless steel for fabrication. Its corrosion resistance and low cost relative to nickel and titanium make it a prime candidate for use in conjunction with composites in applications such as fasteners.

As mentioned previously, this study maintained the plate beam structure for all of the materials except composites. For some materials, particularly titanium, nickel alloys, and certain stainless steels, their relatively high strength and cost lend themselves to sandwich construction similar to that used for composites. The use of a corrugated or honeycomb core between two thin skins would reduce the amount of material used, and therefore reduce both the cost and the weight. In addition, because of the increased strength of the materials and the geometry of the sections, the structural integrity of the structure would not suffer. In addition, new and improved joining techniques for these materials, not necessarily limited to welding, can result in the cost effective production of large, complex, three-dimensional structures in a shipyard environment.

Greater interaction between shipyards, material producers, and regulatory bodies is also needed. As in this study, a shipyard may limit its material options based on previous experience. Therefore, for example, Monel is considered and then rejected as a choice for superstructure fabrication simply because the shipyard does not have the necessary experience with more suitable nickel alloys. Similarly, the use of composites may be limited because of the low melting point of the matrix and the fact that the core may burn. However, slight alteration of the regulations to focus on the ability of the structure to contain a fire may result in composites being favored because of the insulating effect the carbon in a balsa core provides when it slowly chars. Increased communication between these three groups will result in more knowledgeable material choices as well as increased safety of the structures. Finally, as more importance is placed on the life cycle cost of a structure rather than the initial expenditure, the use of advanced materials which are higher in price but have better corrosion resistance and maintainability will be more widespread.

Overall, the materials available for use in secondary structures for the marine environment are continually evolving, as are the methods for their fabrication. In some cases, increasing their use may mean overcoming cultural as well as technological boundaries. However, by taking advantage of these advanced materials today, it is possible to realize greater performance characteristics from the structures which they comprise. More importantly, the knowledge gained from the use of these materials will result in the advanced materials of tomorrow.

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Workshop on Advanced Materials for Marine Construction

Material Requirements for Ship Hulls

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Subject: Material Requirements for Ship Hulls

Beginning with the USS Constitution, the quest for a higher degree of performance for ship hulls has led to the use of advanced materials. This is true for all areas of seagoing vessels, from racing yachts to naval combatants. However, a certain equilibrium has been reached with steel being the primary material for naval and commercial vessel hulls.

Prior to determining the opportunities for the use of advanced materials in ship hull construction, it is important to first determine the requirements of the vessel and, therefore, its primary component, the hull. This brief overview will consider surface combatants, commercial vessels, high speed/high performance craft, and special application vessels.

Recognizing the wide range of requirements for these vessels, it is clear that no single material would be applicable to hulls for all of these configurations. It is necessary, therefore, to select a few materials for consideration, each of which may prove useful in a given application. Recognizing steel as the “material-of-the-day”, it naturally follows that consideration will be given for steel manufacture. Additionally, several hull types have been constructed of aluminum, with stainless steel and composites also receiving consideration. It is necessary to suggest that metal clad materials might prove to be an interesting consideration under the given parameters; however, this option will not be developed in this paper.

For the cost of steel, the strength of this material is unparalleled. With the development of high strength steels at a reasonable cost, resistance to unnatural attacks (ballistic, blast, fire, etc.) is feasibly designed. But the environment takes its toll on the lack of corrosion resistance of standard carbon steels. Additional systems have been developed to counter the initiation of corrosion, but these systems must be maintained and are an added expense and weight. There is also a magnetic signature associated with carbon steels which is undesirable for combatants. The stainless steel industry has responded to the need for high strength, corrosion resistant steel with the development of AL-6XN, a super-austenitic alloy containing nitrogen. This material choice is expensive in the material acquisition phases, but some studies have shown under certain hull configurations and life cycle cost considerations that hull manufacturing may be less expensive with this material. Naturally the lightweight features of aluminum and composite materials are appealing for high-speed, high-performance vessels, but in some arenas, the low thermal resistance and flammability of these materials may prove detrimental.

The surface combatant has a very unique set of "owner's requirements". A typical warship must exceed speeds of 30 knots, withstand intense shock requirements and have a service life in excess of 35 years. In addition, because of the expense of necessary combat systems equipment, structural costs must be minimized.

Threats to the hulls of surface combatants include ballistic penetration, corrosion, air blast, and wave slap. Recognizing the weakness of traditional carbon steels in the area of corrosion, stainless steels become appealing. While maintaining the admirable strength qualities of steel, the addition of chromium, nickel, molybdenum, and nitrogen to the AL-6XN stainless provides excellent resistance to the hull threats. But material costs are a deterrent to the evolution of ship hulls made of stainless steel. While some studies show combatant configurations that are cost efficient when built of this material, clearly the initial cost exceeds that of the carbon steel counterparts. With strength characteristics capable of resisting blast loading and wave slap, both composite materials and aluminum would seem a viable alternative;

however, both materials have deficiencies. The resins used in structural composites typically have melting points far lower than that for a metal. There are also smoke and toxicity concerns associated with the composite burning. For composite materials to provide ballistic protection, much thicker laminates must be used, resulting in a heavier and more expensive structure. Once the cost and weight are included in the fabrication, stainless steel becomes a more appealing option. Like composites, aluminum has poor thermal resistance. Even though the melting point far surpasses that of a typical organic resin, aluminum will soften at a much lower temperature, leaving the structure with little residual strength. The Belknap incident, among others, proved that material degradation under high heat loads can be catastrophic.

The recommendation for surface combatant hulls would, therefore, be stainless steel, such as AL-6XN, which meets all structural considerations. With each of the threats that were mentioned, failure of the hull is a serious problem. Stainless steel provides a high degree of resistance over the greatest range of hull threats mentioned. In order to justify the higher acquisition cost, therefore, a closer examination of the life cycle costs must be made.

High speed and high performance craft provide an excellent opportunity for realizing the full potential of several advanced materials. For example, there is a tremendous advantage to minimizing weight in racing sailboats. However, the weight savings must not come at the expense of structural integrity. While these boats do not face the threats to which naval combatants are designed, catastrophic failure is still a matter of life and death for those on board. Since the limits of performance are being challenged in this manner, all aspects of the design, especially the materials, will be as well. In this arena, composites have graduated from an advanced material to the norm. Within the realm of composites, there are a great many opportunities for experimentation with various cores, fibers, and resins. Recently, aluminum and titanium have also received serious consideration because of their strength to weight characteristics. One particular example involves an aluminum Whitbread entry sponsored by an aluminum company. This is an example of an aggressive approach to proving the capabilities of advanced materials.

As other high performance vessels are considered, it becomes clear that different rules govern the material selection. For both military and commercial issues, cost becomes much more important. As a result, a high-strength carbon fiber racing hull would most likely be replaced with a slightly less strong, but much cheaper, e-glass hull for use in these applications. In addition, fire issues become much more important. There are certain regulations which both naval and commercial vessels must meet. Currently, a composite structure would have a difficult time meeting current requirements. In order for composites to receive serious consideration for military applications in particular, one of two things must happen. Either the composite industry must develop a resin-fiber-core combination that is both structurally sound and capable of meeting the existing requirements, or the existing requirements must be changed to reflect the ability of the composite to contain a fire even when damaged. Currently, aluminum is used in the majority of naval and commercial high-performance vessels such as surface effect ships, hydrofoils, and fast ferries. While the thermal characteristics of aluminum are better than those of most composites in terms of melting point, it can not compete with steel. However, due to the weight constraints of these craft, steel construction is not feasible. Given the slightly better thermal resistance welded aluminum construction is favored over composite layup by many major shipyards. However, if a shipyard were to become comfortable with and proficient in a particular fabrication method, composite construction could easily replace aluminum for several of these hulls.

Similar to high performance craft, certain special purpose vessels have requirements well suited to the use of advanced materials. For example, it is required that the hull of a minesweeper be non-magnetic. Wooden and composite construction have both been historically used for this reason. However, with the advent of high strength, weldable stainless steels such AL-6XN, a stainless steel minesweeper is a realistic alternative. In addition to the combination of an easily fabricated, nonmagnetic structure, increased fire and ballistic protection would be realized, as would the benefit of increased resistance to underwater explosion damage.

Another special purpose vessel to be considered is the icebreaker. The main structural concerns are the high impact loads and low temperatures experienced by the hull. In particular, there is a drastic temperature gradient at the waterline; the hull immediately below the waterline is exposed to 32°F water while the hull immediately above the waterline is exposed to the ambient temperatures which can easily reach tens of degrees below zero. Additionally, this is the rare case where the addition of weight is desirable. Therefore, aluminum and composite structures would not be well suited for use in this application. A high strength, high toughness steel is traditionally used. A stainless steel with similar strength and toughness might be a possible alternative, and it would eliminate corrosion problems. However, shell plating in the ice belt region can exceed 1.5 inches and might result in welding difficulties. Any lessons learned from material experiments in icebreaker construction can also be applied to the many ice strengthened vessels which operate in Arctic waters and must be designed to similar requirements. In addition, Canada is currently exploring the allowable amount of plastic deformation which should be allowed in an ice-rated hull. This will have a great impact on the design of the hull, and quite possibly the material selection as well.

At first glance, commercial cargo vessels do not seem to be the best application for exotic, advanced materials. While weight and corrosion are two problem areas which commercial and naval vessels have in common, cost is the primary concern in their construction. Currently, mild steel is still the material of choice over higher strength steels simply because the weight savings do not make up for the additional money in vessels the size of tankers, bulkers, and container ships where light ship weight is a fraction of deadweight. In an arena where the lowest bid is usually the bottom line, it would be difficult to justify the additional expense.

However, if advances can be achieved so that acquisition cost is minimized or life cycle costs reduced, their use will definitely be considered. In fact, using a life cycle cost analysis, it can be argued that several advanced materials actually offer savings over traditional steel construction. While they are not designed to blast and ballistic loading scenarios that naval vessels must consider, commercial ship hulls are still subject to improper cargo loading procedures, coating system failures, fatigue, and extended periods between inspections and repairs. The combined effects of these threats can have serious consequences on the integrity of the hull and, therefore, the operating expenses. In particular, commercial vessels are extremely sensitive to ease of maintenance. Whereas military vessels generally have a relatively large time in port and a large crew to maintain the vessel, commercial ships have minimal crew onboard and spend most of their time at sea or dockside handling cargo. Life cycle costs of corrosion resistance for military vessels, therefore, concern primarily the cost of the coating or corrosion prevention system. Commercial ships must also factor in labor costs and lost revenue. The shift of the financial focus from the initial capital investment to the cumulative expenditures throughout the service life of the vessel will pave the way for the increased use of advanced materials.

With so many different hull arrangements and purposes, it is impossible to define a single "perfect" material. Clad materials, metallic composites, or such hybrid materials may provide the best solution for all of these scenarios, but even those hybrids would not be consistent for each situation. It is important to realize that the best application of an advanced material may not lie in a single industry. It is recommended that cooperation among the manufacturing industries may result in the best arrangement for each of the classes suggested. In addition, hybrid designs should be investigated further in order to utilize the best material(s) for each situation. Together this will maximize the benefits and minimize the risks of the use of advanced materials for ship hull construction.

Challenges in Using Advanced Materials in Marine Structures

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Three communities are involved in incorporating an advanced material in a marine application. One community is obviously the material supplier. These people have the expertise on the family of materials being considered. The other two communities are the end user and the builder. Both are active in the design effort.

The decision to use an advanced material in a marine application can be initiated by either of these entities. However, it should be realized by all concerned that the design and performance criteria differ drastically depending on which entity desires to use an advanced material.

The builder's concerns include cost, strength, density, strength to weight ratios, corrosion resistance, performance when subject to high heat or fire, fabricability and the builder's previous experience with the material.

The end users concerns also include cost, life-cycle cost, durability, maintainability, inspectability, reliability as well as the minimum performance criteria of the builder.

Because of the differences inherent in the concerns of the two communities, material substitution is the more likely route when the builder applies an advanced material. They are likely to replace a steel with a material that performs much like steel but at lower cost.

The end user has the opportunity to evaluate an application of advanced material as it pertains to the entire system. He can design the system or structure to capitalize on the features of the new material or combination of materials. Here a substitution of a structural steel with a structural aluminum or composite could be accomplished in such a way that, although the new materials may not perform exactly like the same quantity of steel, the design could incorporate a thermal barrier or cooling system which may exceed the performance of the original design at lower cost.

Material suppliers are anxious to be brought to the table in the earliest stages of design to be given the option of working with both the end user and builder to identify novel applications for advanced materials. Many of these solutions may mean a larger investment during fabrication, yet the life-cycle cost may indeed be greatly reduced from the traditional assemblies. These life-cycle cost, reliability and maintainability issues reflect the true design drivers of marine applications particularly because of the personnel safety, remoteness and harsh environment demands that are inherent in marine structures and systems.

Structures as Systems-LT. K. Moore

In designing marine structures, the temptation is to view the design challenge as limited to selecting the best material for the structure. In fact, a structure can and should be viewed as a system. The performance criteria do not have to be met by a single material. This is acknowledged inherently when a large ship hull is a steel with a hull coating. That is a system where two materials combine together to meet all the performance criteria. Design professionals are encouraged to view the incorporation of advanced materials in marine structures in the same way. Rather than simply desiring a structural material to substitute for another, review all of the features of the structure and seek to exploit the performance of the advanced materials as well as the features of the structure.

Workshop Critiques

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It was very nice to have this workshop in New Orleans in the deep south of the United States particularly at a really good time of Mardi Gras. The outside of the hotel was very exciting and enjoyable. Inside the hotel, this workshop has been held. Although we had only two and a half days, it was very successful with the participants of more than 120 persons from many fields such as material makers, manufacturers, universities, government and so on.

As the material advances, the exchange of information and knowledge between a material maker and a fabricator becomes more important. We say that "A good horse needs a good rider." Just like this, the advanced material must be used by the engineers with thorough knowledge of material.

However, they are generally so busy that they do not have enough time to study materials, and vice versa. I am a manager of research of steel. I all the time tell my young researchers to visit the manufacturers to talk and know how the material is used in what kind of application.

At this workshop, I had a chance to get knowledge on the materials other than steel. I am a steel man. So I know about steel, but do not know much about other materials. To know about the materials other than steel is very helpful to develop new steel.

Thus, this kind of workshop is very important and useful. Now the workshop is coming to the end, but this is a beginning of another exchange of information between the people in the different fields.

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Overall I would give this symposium a rating of excellent. I have been involved with preparation committees for 4 symposia and probably attended about 16 in the past four years so I have a recent basis for comparison.

One of the reasons for the success of this symposia was in it's sponsorship. Dave Olson (from CSM) and I were talking yesterday and he convinced me that sponsorship is a key to this. In becoming a sponsor a company or organization provides not just money but efforts as well. They are then much more likely to send personnel to attend as well. Finally, by having the sponsorships the costs to the attendees can be reduced greatly, which most likely allows more people from other organizations to attend.

Another key was the high degree of focus of the program. The direction was clear, the progression through the program was logical, and there was a job to complete. I am glad also that the focus of the program was made wide enough to include other than just the offshore industry. By bringing in port facilities and ships, the offshore community got some fresh viewpoints and the other industries were able to participate in a topic they may not have addressed for some time.

The facility was well suited to the situation. Although there was concern that the need to take elevators between the large meeting room and the work group rooms it did not turn out to be a problem. The location was a plus to attract anyone who could convince their boss that they wanted to attend for purely technical purposes. It was particularly nice of the host city to arrange the evening parades for our benefit. My biggest concern on arrangements was that I could have survived on less food.

The sequence of the program allowed things to flow smoothly and get good results out of the workshops. First high level representatives of four sectors stresses the need for advanced materials. Then, the "applications"were presented; this provoked thoughts of where improvements were needed and showed some fresh insights to the material persons. Then the materials sections made their presentation. The work group's meetings were separated by time so that questions that came up could be answered, new sections could be written, and so that side conversations could be held. By interspersing the work group sessions between technical presentations the pressure to finish the technical presentations exactly on time was reduced.

The makeup of the attendees was well balanced which made for a good transfer of information. A rough review of the attendees showed there to be roughly 20% government employees from Defense, Transportation, and Energy Departments. There were also roughly 20% of the attendees from foreign countries. It is always good to have the attendees from overseas so that we see new things which we normally would not. I hope they were able to gain as much out of attending as we here received from them. There were only about 10% of the attendees from academia; it would have been good to see more in this group. The universities can bring the recent results of research to these meetings which can result in the industry getting the research into applications. The rest of the attendees were well spread between materials providers and the users. This balance between these communities was a big factor in the results of the workshop.

It was noted that few small companies were able to participate in this and similar meetings. In future symposia it should be considered to approach the professional trade organizations that were involved to see if they would essentially provide "scholarships" to a few members from small firms, from organizational funds, to represent their internal committees.

The one possible weak link in this type of workshop is that which you cannot plan on; the participation of the attendees in the workshops. The work groups seemed to be well attended, some were larger than others but were generally appropriate to their topics. The "Floaters" session started out well but by the third meeting had lost most of the attendees. I assume this was because the people felt they had made their input and moved on to other topics to which they wanted to contribute. Originally some attendees felt that meeting should also address ship hulls as well as floating offshore facilities but, after further discussion, splitting ship hulls, into a separate paper was seen to be appropriate. Getting input from attendees is sometimes difficult. Often they come to the symposia to gain knowledge and do not feel they have anything to contribute. However, it is important that they be aware that they are an expert in their microcosm much more than anyone else attending. There may be other persons that work in their field but they may do things differently in their organization and could contribute. Generally when the work groups are asked for input there is often no one to step forward. But when specific problems are raised the members do identify problems and solutions. In order to get better involvement I would suggest a questionnaire or survey be sent to the attendees in advance so that they can consider the problems while still at their workplace. If the attendee identifies their area of interest for work groups the white paper for that group could be sent at the same time, giving the attendee more time to consider the content before they come. This does require additional work from the organizers but I think the payoff would be well worth while.

To sum I feel the meeting was a success because it was well orchestrated, well focused and well attended.

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