

Final Report

Accuracy of Polyester Subrope Damage Detection by ROV Inspection and Assessment of Remaining Rope Strength and Life

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Proposal Objective:

Item 2:

“Evaluate accuracy of polyester subrope damage detection performed by ROVs following hurricanes and other events (i.e., loop current) that exceed the 100-year design criteria. ROV inspections are used to detect damage to polyester mooring systems and estimate remaining fatigue life if damage exists.”

November 6, 2007

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Executive Summary

Background

In March 2007, the MMS contracted Stress Engineering Services, Inc. assisted by TTI, Ltd., to evaluate the accuracy and effectiveness of polyester subrope damage detection processes following hurricanes and other events (i.e., loop current) that exceed the 100-year design criteria for offshore structures. ROV inspections are used by the offshore industry to detect damage to polyester mooring systems and estimate remaining fatigue life if damage is found. This work was to address permanently moored floating production systems, rather than Mobile Offshore Drilling Units (MODUs).

Approach

The fundamental question to be addressed is: “What are the best ways to ensure the structural integrity of a polyester rope mooring system over the life of the project?” The specific objective is to **evaluate the accuracy of non-invasive damage-detection methods**. Toward meeting this objective, the following issues were considered for polyester rope mooring systems:

1. Structural mechanics
2. Factors that reduce structural integrity
3. Qualification for service
4. Characteristics of structural damage
5. Assessment of current and new methods for determining fitness for service

Scope of Effort

A variety of tasks were undertaken by the team to assess the state of the art in damage assessment for polyester-rope mooring systems. Significant tasks completed during the project included:

1. Performing “20-hurricane” cyclic wear testing of a subrope design
2. Assessing the effect of creep and cyclic wear on rope integrity and remaining life
3. Conducting a polyester mooring risk workshop with several participants from industry
4. Assembling a Failure Mode and Effects Analysis (FMEA) model to assist in semi-quantitative risk assessment, using results from the industry workshop
5. Developing concepts for non-invasive damage assessment, to improve industry’s ability to find damage and assess its impact on mooring system performance

The MMS solicitation identified the need for damage detection for subropes. A polyester mooring rope can contain from 10 to 70 individual subropes, depending on rope manufacturer and design. Large mooring ropes (of 10-12 in. diameter) with a load capacity of perhaps 5,000 kip are cumbersome and difficult to test. If a single rope test is conducted, all that is attained is the break test result of a single subrope. Alternatively, if multiple subropes are tested together, the testing is less cumbersome, testing options are more plentiful, and there is no risk of complete loss of data as would occur if there are difficulties with the test machine during the single rope test. This is the approach taken during this project. Test results with subropes can be converted to apply to complete rope systems by comparing pre-production full rope break test results with equivalent tests of multiple subropes.

Conclusions and Recommendations

The project team reached several important conclusions and recommendations based on project results:

1. The only major cause of rope structural integrity loss during a 20-year project life in which 20 repetitions of loads experienced equivalent to that of hurricane Katrina (20 hurricane Katrinas) was applied, was found to be third-party damage to the mooring system components. Only *in-situ* inspection of the mooring ropes by ROV video (not insert recovery/testing) can effectively discover this damage.
2. Because of the demonstrated structural integrity of polyester ropes, the major concerns of rope creep and cyclic wear damage have been proven to be unfounded.
3. Based on a risk/benefit analysis, insert recovery/testing has been determined to have no benefit in reducing the risk of normal operations. We recommend that the current practice of recovery and testing of inserts in installed mooring systems should be discontinued.
4. The accuracy of subrope damage detection using current methods (ROV video fly-bys) should be sufficient to detect rope jacket damage, which should in turn be inspected in more detail by methods recommended in this report.
5. A mooring rope found with jacket damage should be considered a critical inspection zone. Damaged rope segments should be replaced as soon as possible. For critical locations along the rope length, either digital video (2D or 3D) or LVDT measurements of local rope diameter are recommended to better assess the conditions.
6. A rope cycling test based on being subjected to 20 hurricanes with the strength of Katrina should be adopted as a “benchmark” for qualification testing of different designs and brands of polyester rope. Rope creep is less affected by the specifics of design and

more affected by the number of fibers resisting the load, so no specific test such as the 20-hurricane test is needed for creep.

7. A new strain-based hypothesis is presented for estimating the remaining life performance of a polyester rope, based on a prediction of major hurricane exposure and the design life of the mooring system.

1. Introduction

1.1 Background

In October 2006, the MMS solicited proposals from industry to accomplish the following objective:

Evaluate accuracy of polyester subrope damage detection performed by ROVs following hurricanes and other events (i.e., loop currents) that exceed the 100-year design criteria.

The solicitation stated that ROV inspections are currently used to detect damage to polyester mooring systems and to estimate remaining fatigue life if damage exists.

Stress Engineering Services, Inc., along with TTI Ltd., jointly submitted a proposal to the MMS to address that objective. The proposed team members have key experience with damaged rope testing and analyses (see References 1–3 in Section 10). A contract was awarded in March 2007 to Stress and TTI to perform the proposed work. The project objectives, scope of work and technical approach are summarized in **Appendix A**.

1.2 Approach

The fundamental question addressed by this project is: “What are the best ways to ensure the structural integrity of a polyester rope mooring system over the life of the project?” The specific request of the MMS is to evaluate the accuracy of (non-invasive) damage-detection methods. To meet this objective, the following issues must be considered:

1. Structural mechanics of polyester rope
2. Factors that reduce structural integrity of polyester rope mooring systems over the project life
3. Qualification of polyester mooring rope for service
4. Characteristics of structural damage to polyester mooring systems
5. Assessment of currently used and new methods for determining fitness for service of a polyester mooring system

After these tasks are complete, the specific project goal will be addressed:

6. **Determine the accuracy of polyester rope damage-detection methods**

1.3 Scope of Effort

A variety of tasks were undertaken by the team to assess the state of the art in damage assessment for polyester-rope mooring systems. It was assumed that the study was limited to

permanently moored floating production systems, rather than mobile offshore drilling units (MODUs). Significant tasks completed during the project included:

1. Performing “20-hurricane” cyclic wear testing of a subrope design using subrope samples provided by Samson Ropes
2. Assessing the effect of creep and cyclic wear on rope integrity and remaining life
3. Organizing and conducting a polyester mooring risk workshop on September 6, 2007 with 20 participants from industry. Items discussed included: (1) risks of failure associated with moorings during the operating life of a project, (2) risk and benefits of insert recovery and (3) risks and benefits of ROV inspection.
4. Assembling a Failure Mode and Effects (FMEA) model to assist in semi-quantitative risk assessment, using results from the industry workshop
5. Developing concepts for non-invasive damage assessment, to improve industry’s ability to find damage and assess its impact on mooring system performance

When the team developed the original proposal, it was believed that it would be necessary to assemble a mock-up of an ROV making measurements. However, as key ROV operators provided input on how they would detect and measure rope damage, it became clear to the investigators that an alternate approach would be preferred. Existing technology is merely to “fly” the rope segments with an ROV taking video, down one side and up the other. All participants agreed that this approach can be improved.

The MMS originally identified the need for damage detection for **subropes**. A polyester mooring rope can contain from 10 to 70 subropes, depending on rope manufacturer and design. Large mooring ropes of 10–12 inch diameter with load capacity of perhaps 5,000 kip are cumbersome and difficult to test. If a single subrope is tested, practically all that can be tested is the breaking test strength. This is not a useful predictor of the behavior of large assemblies of subropes. A more useful approach proposed and adopted by the project was to test multiple subropes (perhaps 3–6 ropes). These tests are far less cumbersome and the testing options are more plentiful.

Conversion between subrope testing and mooring rope performance can be made by comparing the five required pre-production rope break-test results (which are performed prior to the production of any new rope design) with equivalent tests of subropes:

$$(Break\ Load)_{Rope} = n K (Break\ Load)_{Subrope}$$

where K might range from 0.80 to 0.95, depending on rope design, and n is the number of subropes in the rope. The constant K is determined experimentally from the pre-production rope break test results and the subrope break test results.

This report describes subrope test results. Where appropriate, these can be converted and applied to mooring ropes using the equation above.

2. Structural Mechanics of Rope

2.1 *Undamaged Rope Mechanics*

A variety of issues are known to affect the integrity of undamaged rope, including environmental loads, operational loads, and design and materials technology. Provided that ropes are for well designed, manufactured using splice QA processes, installed properly (without twist), and have not been externally damaged by third parties; the following mechanical issues have been considered proven to be the most critical, but we have found even these are not be a significant issue:

- Exceeding maximum allowable rope tension at some time over rope life
- Failure due to rope creep caused by sustained tension loading over life
- Failure due to cyclic wear over project life

2.2 *Maximum Allowable Tension*

Floating production systems are designed such that extreme events, including both hurricanes and loop currents, will not cause rope tension to exceed the design maximum allowable value based on the minimum breaking strength (determined by testing) and the design safety factor (1.67 from API 2SK (Reference 4)). Meeting design requirements is determined by (1) on-board tension measurements and (2) whole-system analysis of the moored floater with risers and other ancillary equipment. Testing has demonstrated that occasional overloads to mooring ropes less than the breaking strength are not an integrity issue.

As part of this project, a whole-systems dynamic analysis was conducted using data from API RP 2SM. This analysis (see Reference 5) showed that cyclic amplitudes of force in the mooring ropes were smaller than that assumed for 20-hurricane testing (see Section 2.5), and that overloads of a properly designed mooring system will not be an issue. Details are presented in **Appendix B**.

2.3 *Rope Creep Over Time*

Full-scale rope creep tests are time-consuming and expensive unless some method is devised to accelerate the test. Two methods have been employed to accelerate creep testing:

1. Testing of yarns at elevated temperatures (which shortens test times) and then applying mathematical corrections to infer room-temperature creep over many years. This method is called the **SIM Method**, and has gained credibility for use in the geotechnical

applications where polyester is used to reinforce soil (similar to reinforced concrete). For more information, see Reference 6 and **Appendix C**.

2. Creep testing of yarns (and subropes) at higher than normal loads to reduce the time to failure to a practical period, and then applying mathematical corrections to the results to infer performance under normal loading conditions. This analysis and testing approach is called the **ARELIS Method** (see Reference 7).

One of the goals of this project was to further evaluate the creep mechanism. To that end, the team implemented the work of Higson (Reference 6), applied the SIM Method to room-temperature creep, and obtained the creep strain results shown in Table 1. See **Appendix D** for more details of the analysis.

Table 1. SIM Creep Elongation Test Results (% Elongation)

Creep Elongation Matrix						
Years	% of Ultimate Load					
	0.1	0.2	0.3	0.4	0.5	0.6
1	0.234%	0.372%	0.373%	0.308%	0.286%	0.386%
10	0.325%	0.517%	0.518%	0.428%	0.397%	0.536%
20	0.352%	0.560%	0.562%	0.464%	0.431%	0.582%
30	0.368%	0.586%	0.588%	0.485%	0.450%	0.608%
40	0.380%	0.604%	0.606%	0.500%	0.464%	0.627%
50	0.388%	0.618%	0.620%	0.511%	0.475%	0.641%
60	0.396%	0.630%	0.632%	0.521%	0.484%	0.653%
70	0.402%	0.639%	0.641%	0.529%	0.492%	0.663%
80	0.407%	0.648%	0.650%	0.536%	0.498%	0.672%
90	0.412%	0.655%	0.657%	0.542%	0.504%	0.680%
100	0.416%	0.662%	0.664%	0.548%	0.509%	0.687%

Table 1 shows the elongation in creep for decades of years. If we focus on 20–60% loads, elongation due to creep over time has a trend as shown in Figure 1. Typical preloads on polyester mooring systems in the Gulf of Mexico are 20% or less.

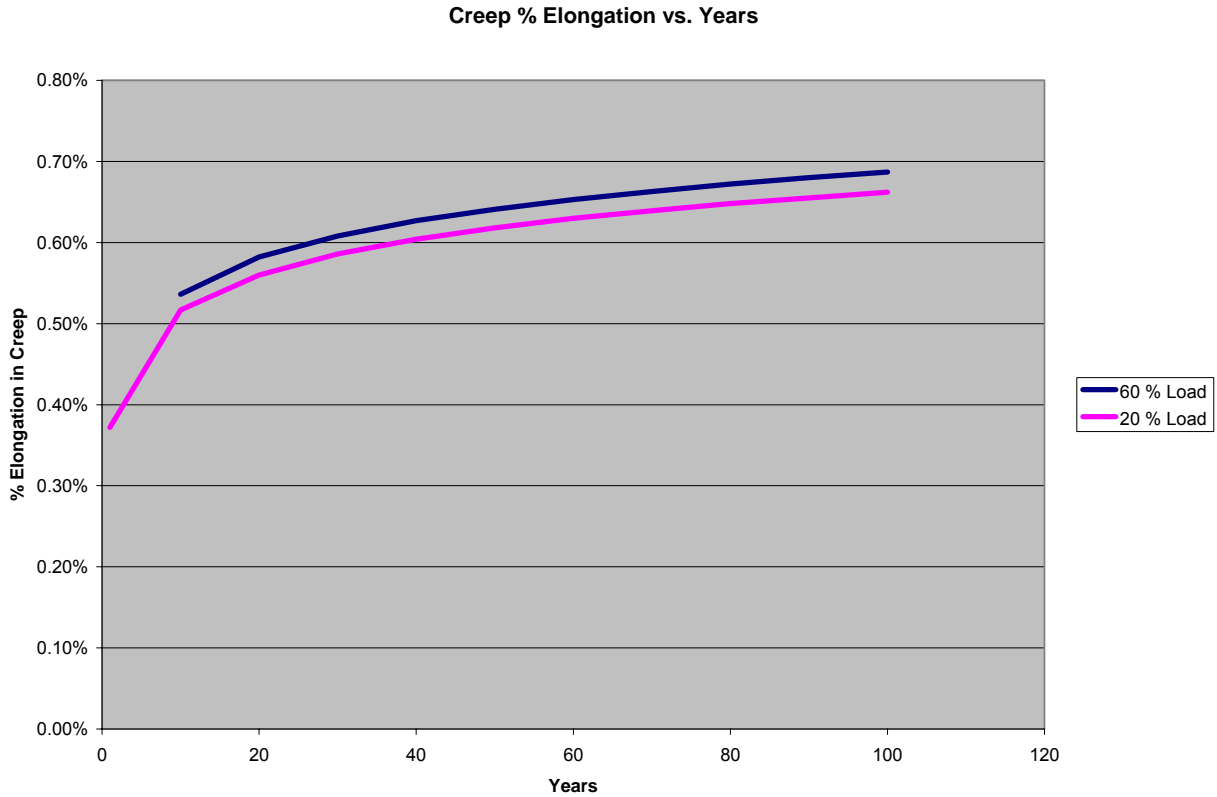


Figure 1. Elongation in Creep vs. Years

The next question that must be addressed concerns how long a rope can be maintained at a nearly constant load until it breaks. Calculated creep life times determined by Accordes (see **Appendix D**) are shown in Table 2.

Table 2. Rope Life Predictions

Creep Rupture - Diolen

Load	Lifetime (Years)	Consumed Lifetime after 20 years
50%	1.58925E+11	0.00000013%
55%	78,001,416	0.0000256%
60%	136,310	0.0147%
65%	633	3.16%

It is instructive to plot our estimates of creep life as shown in Figure 2. We have used Reference 8 to produce the Whitehill rope “calculated” curve using the Mandell equation, but we have

scaled it with perfect load sharing with respect to creep using the Chain-of-Bundles theory of Whitehill. Note that Mandell's creep equation was based on Dupont yarn of the 1980's vintage and is inferior to the Whitehill rope made from current vintage Honeywell yarn, which is a vastly improved rope fiber material. This means that the Whitehill curve is conservative.

The Parallel yarn rope data is from a private communication between TTI and Linear Composites, and is based on dead load creep tests of up to 13 years at 80% of nominal break load.

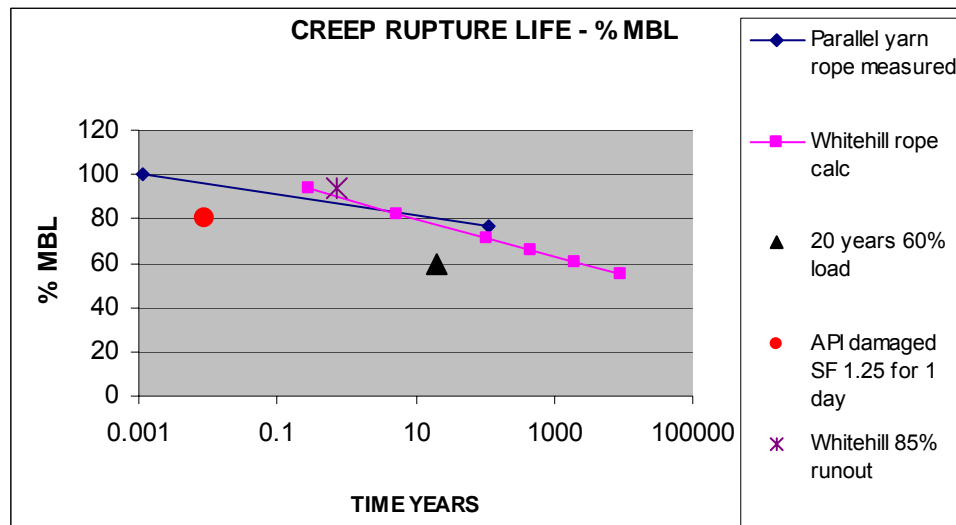


Figure 2. Rope Creep Life

The figure above shows that the rope (not yarn) data that we have is well above the plotted point for 20 years life for 60% load. Since typical pretensions used in the Gulf of Mexico for polyester mooring systems are 20% or less, there is a very large factor of safety against creep rupture failure. Hurricanes and loop current events over the 20 year life of a mooring system represent a relatively short duration, so the majority of creep occurs at 20% MBL or less. We have plotted the API RP 2SK load allowable (80% MBL) for a factor of safety of 1.25 on the remaining ropes, to show that even the one mooring leg damaged condition (of short duration until a mooring leg can be reinstalled) is not an issue with creep.

2.4 Cyclic Wear of Rope Over Time

In the analysis of fatigue life of structural materials, it is standard practice to use S-N curves (stress versus number of cycles to failure). API RP 2SM (Reference 5) suggests that polyester rope should be cycled at 30% MBL mean with 15% MBL cyclic amplitude. Thus, the

recommended cycling is from 15% to 45% MBL, and these cycles should be repeated 300,000 times. For a 30-sec test cycle period, this test would run over 104 days (at 24 hr/day). (With well designed polyester ropes, this API RP 2SM fatigue test is really testing the test fixture and hydraulic load application system, not the rope.)

In steel tubulars, for instance, resonant fatigue testing can be employed to cycle the samples in bending at a rate of 30 cycles/sec, allowing the tester to achieve about 0.25 million cycles every 24 hours. Unfortunately, polyester cannot be cycled rapidly because it will heat up. Based on these practical challenges for testing rope, the 20-hurricane test described below has merit for efficient rope qualification for cyclic wear.

2.5 *20-Hurricane Test Proposal*

Concept: Two years have passed since hurricanes Katrina and Rita struck various production structures in the Gulf of Mexico, and even now the memories of the destructive power of those storms is vivid in the industry. The authors propose that a useful and meaningful measure of the ability of a polyester mooring system to perform under the worst storm cycles would be to determine how the rope in a mooring leg would resist 20 hurricanes with the strength of Katrina, with a direct hit from one hurricane per year for a period of 20 years.

2.5.1 Background

In the literature there is a precedent for using number of hurricanes in rope-strength analysis. Hooker and Bosman (Reference 9) proposed a 20-hurricane test to more cost effectively test the cyclic wear of a proposed rope design. For cost efficiency, they tested a single subrope as summarized in Table 3.

Table 3. 20-Hurricane Test Conditions (Ref 9)

The test sample was submitted to the loading scenario in table 1 ten times whilst being continuously soaked in water. The cycle frequency was 1 Hz and the amplitude was randomized.		
Number of Cycles	Mean Load (%BS)	Maximum Amplitude (%BS)
4000	20	10
1000	40	15
4000	20	10
1000	11	10

Note that the sequence of load application was in the order shown in Table 4 (two hurricanes). The subrope was subjected to this sequence of cycles 10 times to simulate 20 hurricanes. They removed yarn samples and tested them separately (Table 4).

Table 4. Yarn Break-Strength Results (Ref 9)

Yarns were removed from the test rope after the test programme for analysis. It was decided that breaking the complete test sample would not reveal much due to the unusual potted terminations. The yarns were Acordis 2200 dtex 855TN Oceanic and the results are given in table 2. The number of test samples was 20.

Test	Samples before 20 Hurricane Test	Samples after 20 Hurricane Test
Breaking Strength (N)	167 ± 16	162 ± 10
Wet Yarn-on- Yarn Abrasion (CTF)	18000 ± 3000	17000 ± 6000

The yarn samples following the 20-hurricane test showed a 3% reduction in breaking strength over the uncycled yarns.

2.5.2 Simplification of 20-Hurricane Test

The author's experience (Reference 10) with testing damaged ropes for BP several years after the tests mentioned above, suggested that maximum damage due to wear occurred with the largest cycles, so **the 20-hurricane test proposed for this study is simply 20,000 total cycles at 30 to 60% of MBL.** Hindcast data from major hurricanes show that approximately 1000 cycles is a conservative estimate for a typical large hurricane.

2.5.3 20-Hurricane Test Results and Discussion

For this project four subropes provided by Sampson Ropes were loaded in parallel in Stress's L 2000 Test Fixture and subjected to 20,000 cycles simultaneously. The samples were all placed on the same pins as shown in Figure 3.



Figure 3. Test Setup for Cycling Four Subropes in Parallel

Maximum elongation was recorded versus the number of hurricane-level load cycles. Results showed that for 20 hurricanes, the elongation is nearly constant (Figure 4). Note that the maximum displacement shown is the displacement of the four subropes being cycled in parallel as shown in Figure 3.

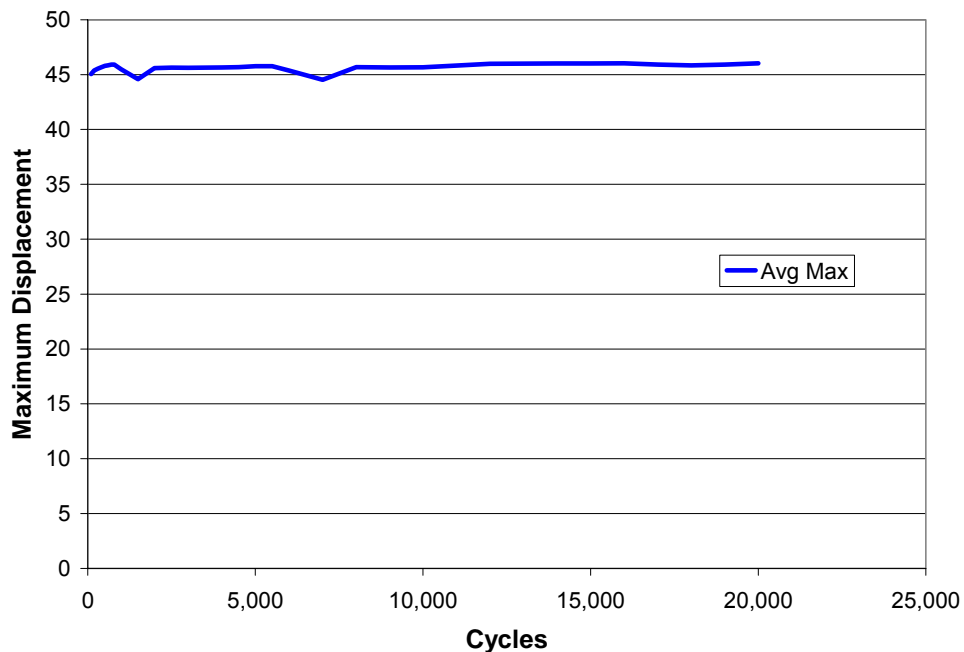


Figure 4. Maximum Displacement vs. Cycles

The elongation data appear constant, but in actuality, if the durability study curves of maximum elongation vs. number of cycles for four rope samples are considered, there is a slight positive slope indicated after thousands of hurricanes, as shown in Table 5.

Table 5. Minor Elongation in Cyclic Wear

*Effect of Cyclic Wear on Elongation Growth over Life
Based on Durability Study Data on Model Scale Ropes*

Cyclic Loading	Number of Hurricanes	Y at x=0 (%)	Y at Break (%)	Elongation increase per 1000 Hurricanes (%)
40% ± 17.5	13,425	0.62	1.26	0.0477
40% ± 20.	8,181	1.53	2.25	0.0880
40% ± 22.5	3,624	1.37	1.7	0.0911
40% ± 25	2,047	1.4	1.82	0.2052

However, for practical purposes, the elongation curve can be considered to be flat. The column Elongation increase per 1000 hurricanes is meant to show that the slope of the % elongation curve is extremely flat.

After the four subropes were subjected to 20,000 cycles at 30% MBL to 60% MBL, three of the samples were tested to failure and compared with break test results from new samples that were only bedded in for 60 cycles and then tested to break. Results are summarized in Table 6.

Table 6. Subrope Break Test Results

Sample	New Rope Break Strength (kip)	Cycled Rope Break Strength (kip)
1	79.19	75.56
2	80.45	74.21
3	80.36	76.24
Average	80.00	75.34
COV	0.88%	1.37%

The average break load for new subrope was 80.00 kip with a 0.88% coefficient of variation (COV); while that for hurricane cycled subrope was 75.34 kip with a COV of 1.37%. Thus, the equivalent of 20 hurricanes of cycling (20,000 cycles) reduced the average breaking strength by 5.6%. Since the COVs are small, this is a real and measurable difference.

The fourth subrope that remained was not subjected to a break test, but was used for forensic examination. Textile yarns were removed from that subrope and subjected to break testing. These yarn tests (Table 7) showed essentially the same results as those for the subrope break tests.

Table 7. Yarn Break Test Results

Textile yarn	Mean Breaking Strength N	SD N	CV %	Mean Breaking Extension %	SD N	CV %	Number tested
Inner	78.1	5.1	6.5	11.5	1.0	8.8	15
Outer	77.4	4.6	6.0	11.4	0.9	7.9	16

New Rope Results

Textile yarn	Mean Breaking Strength N	SD N	CV %	Mean Breaking Extension %	SD N	CV %	Number tested
Inner	74.0	7.3	9.9	10.2	1.1	11.1	15
Outer	78.9	6.4	8.2	11.0	1.0	9.2	11

Cycled Rope Results

The reason for the lower mean breaking extension for the inner yarns vs. the outer yarns is that the inner yarns are subjected to more yarn to yarn wear during cycling than the outer yarns.

To be accurate in our documentation of the results in Table 7, two un-cycled subropes, labeled tests 7 and 8 were conducted at Stress, but the COV of the “new rope”, cycled only 10 times as suggested in API RP 2SM, was much larger than the results shown for “new rope” in Table 7, and much larger than what is considered acceptable. We discovered (from the first hundred cycles of the hurricane tests) that the Samson splice needed bedding in of 60 cycles to display uniform cycling displacements, rather than 10 cycles as used. As a result, we asked Samson to re run the “new rope” tests for us, this time using 60 cycles of bedding in. Samson’s results are those shown in Table 7 for new rope.

The next question that the project team addressed was: “How does the reduction in break strength trend with the number of hurricanes?” To answer this, the current 20-hurricane test results were compared with results from the NEL/TTI Durability Study for which fatigue tests were run for millions of cycles. These data are compared in Table 8.

Table 8. Rope Strength vs Number of Cycles

Program/Source	Loading Conditions			
	Mean Load	Load Range	Cycles	Retained Strength
Stress/MMS – 35 tonne subrope	45%	40%	20,000	94%
Durability – 35 tonne subrope	20%	15%	1,000,000	71%
Durability – 10 tonne subrope	40%	40%	8,181,270	60%

The above results were converted into a format focused on the first 80 hurricanes (80,000 cycles) as shown in Table 9. As part of the Durability Study, Hobbs performed retained

strength testing on yarns from subrope tests and developed a correlation equation that can be compared to this project's rope tests (see **Appendix D**).

Table 9. Retained Strength as a function of Number of Hurricanes

<i>Combined Subrope Data from Stress (20 Hurricane) and Durability Study</i>		<i>Hobbs Equations on Subrope Yarns from Durability Study</i>	
Number of Hurricanes	Retained Strength	Number of Hurricanes	Retained Strength
0	100	0	100
20	94.4	20	95.6
40	90.5	60	94.7
60	88.2	1036	60
8000	60.4		

One might ask, why are we interested in 8000 hurricanes as shown in the table above? The answer is that we needed a “distant” data point on the x-axis to make the exponential curve fit equation give us a proper decay curve as shown next.

The results from these two methods are compared in Figure 5. It would be prudent to use the lower (blue) curve as a conservative estimate of retained strength as a function of number of hurricanes experienced.

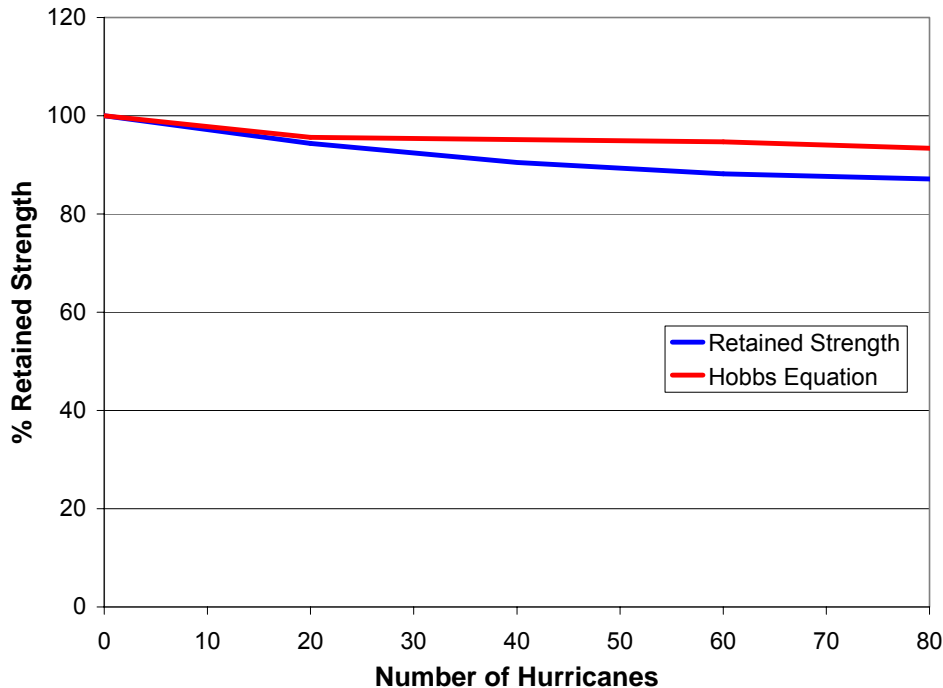


Figure 5. Retained Strength vs. Number of Hurricanes

An important conclusion is that for this particular (Samson) subrope design, **6% strength loss after 20 hurricanes is less than the 10% strength loss (for damaged rope) allowed by API RP 2SM**. In this case all damage is due to cyclic wear, not third-party damage.

2.6 Conclusions on Creep and Cyclic Damage

A typical rope sample reaches its breaking strength at about 10% elongation. Typical elongation due to creep over 20 or 40 years is only about 0.5%. Consequently, it can be estimated that the elongation to break for a rope test will be 10% minus 0.5 % or 9.5%. Creep follows a follows a stain (or % elongation) law. Further, at the loads being considered here—less than 60% MBL—creep strain to failure is measured in hundreds of years. Therefore, **creep is not an issue over the 20-year life of a polyester moored production system**. Cyclic wear is different from creep in that the maximum % elongation during cycling is almost constant, but the retained strength is diminished over thousands of cycles.

For the Samson subrope tested during this project, the loss of strength due to 20 hurricanes with the strength of Katrina was less than 6%, well under the 10% allowable. Any single polyester-moored production system is not expected to experience 20 hurricanes, or even five hurricanes, over its life. It should be noted that this test procedure is more severe than that adopted by Hooker and Bosman (Reference 2), which showed a 3% loss of strength, so the current result of 6% is consistent with the earlier results.

The bottom line is that **neither creep nor cyclic wear is a factor in the structural integrity of a polyester moored production system** during its 20 year life.

2.7 Qualification Method for Polyester Mooring Rope

Based on the discussion in this section, the project team believes that the 20-hurricane Katrina test should be adopted as a “benchmark” for qualification testing of different designs and brands of polyester rope. The test would measure both strength reduction and maximum elongation performance over a series of 20 hurricanes. A superior rope design would minimize cyclic wear, and a superior splice design would demonstrate no appreciable splice slippage after 20 hurricanes. A typical 20-hurricane test could be run continuously and completed in about three days, so testing would be economical.

3. Characteristics of Rope Structural Damage

3.1 *Rope Failure Mechanisms*

Rope inspection is typically conducted via ROV. Rope jacket damage may be indicated by jacket strands “hanging out” or “flying” in the water flow. For these types of cases, the damage will be visible from the ROV video. If jacket damage is observed by ROV inspection, a closer dimensional inspection of the rope is then required.

Reference 5 (based on Reference 4) describes the following subrope/rope failure mechanisms:

1. **Strain Concentration.** Strain is concentrated in the damaged portion of the subrope and causes the partly damaged portion of the subrope to reach failure strain (prematurely) before or at the time that the remaining undamaged subropes break.
2. **Unwind.** Subrope unwind can lengthen the damaged subrope due to unwinding of the damaged helical structure, and lessen the effect mentioned in item 1.
3. **Damaged Length.** The length over which damage can spread during loading, and can continue to cause unwind. Tight rope jackets limit the effect of damage propagation and unwinding.
4. **Recoil Damage.** The energy released when a partly damaged subrope fails completely, and the heat build up can melt adjacent subropes.
5. **Rope Jacket Tightness.** Tight rope jackets can reduce unwind (item 2).
6. **Subrope Pitch.** The design helix angle of the twisted subrope can (along with jacket tightness) affect load sharing between parallel subropes.

The team considered the relationship between initial rope damage and the corresponding reduction in rope break strength. Tests performed in California under the MMS JIP (and confirmed by shorter rope tests in Houston and Brazil) showed that:

1. A partially damaged (cut) subrope in the rope body will tend to break completely before the rope reaches its undamaged break strength. The best approach is to assume that a partly damaged subrope is fully damaged.
2. External damage, such a knife cut caused by rubbing wire rope, will tend to cause at least partial damage to 4 to 8 subropes in the rope body. Because of this, all of these subropes could break completely, if not while in service, then during a break test, if performed.

3. When subropes break, the strain energy released tends to heat up and melt adjacent subropes as the damaged subropes release strain energy, and convert it into heat energy. This can even occur in water.
4. Based on tests in California on long rope samples where ropes were intentionally damaged (cut) to 10%, a damage level of 10% will result in a reduction of approximately 35% or more in rope break strength when tested to failure. This is 3½ times the 10% reduction in rope strength permitted by API RP 2SM. Therefore, for all practical purposes, a rope with any damage to the rope core (the subropes) should be replaced. **So damage detection is merely a task of determining if the rope core subropes are damaged or not.**
5. Based on points 1–4 above, an ROV inspecting a rope with video would need to be able to discover either significant jacket damage that exposed partly severed rope core fibers, or a "necking down" of the rope, either with or without jacket damage.
6. If any discernible necking down is located, the rope segment affected should be replaced, because it is almost impossible (based on testing in the MMS JIP, Reference 2) to limit strength reduction to 10% or less.
7. End splices require special treatment. Splice damage inspection would have to be based on photographic documentation using the ROV, where the camera is directed toward the face of the splice. The original condition immediately after installation would be recorded and serve as the base case or reference. Future inspections should be compared and contrasted with the first.

Regarding point 4 above, the 53-meter rope tests at TMT in California (see Reference 4 for details) were significant because the rope samples were long enough to not affect the nature of strain concentration damage and of recoil heat damage. Strain concentration damage was not as prominent in the 15-meter tests at SES and CSL because of subrope unwinding that occurred with shorter ropes, but was not observed in the longer-rope TMT tests. Recoil damage was also not as apparent in the 15-meter samples as it was in the longer samples.

3.2 *Measuring Rope Damage*

During visits with three ROV companies, the project team was told by each that they would want to measure rope cross-section with a clamp-type traveling measurement "bug" attended by their ROV, if such a capability were developed. This concept is discussed in more detail in Section 7.3.

Dimensional inspection would entail placement of three or four displacement transducers positioned around the rope circumference. The traveling bug would be calibrated by running it on a newly installed rope, and documenting the results in detail with specific water depth location along with cross-section dimension. These data would be archived for future retrieval and comparison.

It was not considered prudent to perform mock-up dimensional measurements during the project. Although this task was originally planned, it was not undertaken since the inspection bug would be needed first, and it is not yet available. The ROV companies are reportedly willing to design, build and test a measurement bug for this application, but that represents a much larger effort than could be pursued during this project.

4. Methods for Detecting Rope Damage

4.1 *Rope Damage Mechanisms*

In its investigation of mechanisms that cause or contribute to damage of mooring rope, the industry has gathered experience dating back to 1995 with Petrobras offshore Brazil (See **Appendix G** and Reference 11) and continuing into the Gulf of Mexico with Mad Dog. Although many possible failure mechanisms have been considered (see **Appendix H**), industry has reached a general consensus that the most prominent concerns are:

1. **Third-party damage** such as down lines severing the polyester
2. **Poor quality splices** which reduce rope strength. The greater the number of inserts placed in the mooring spread, the higher the risk of a bad splice.
3. **Dropped rope** causing possible ingress of sand, which increases potential rope wear during cycling

Other issues, such as **rope overload** and **wear damage** caused by loop currents and hurricanes, have not been found to be critical in a properly designed polyester mooring system. (See discussion of creep (Section 2.3) and cyclic wear (Section 2.4) damage mechanisms.)

4.2 *GOM Inspection and Insert Recovery/Testing Requirements*

Based on MMS agreements with operators, current practice for polyester-rope mooring systems consists of:

1. ROV-based video inspections at regular intervals (for example, every 1 to 2½ years) to determine if any physical damage or other anomalies are visible on the rope segments or splices.
2. Recovery and testing of 15-meter inserts (that were designed into the mooring spread so that later recovery is possible). Intervals between insert recovery operations (and close inspection and testing) vary between 1 to 2½ years.

4.3 *Risks and Benefits of Insert Recovery*

As a part of this project, the authors conducted a **Polyester Mooring Risk Workshop** to conduct an open discussion of overall risks associated with the use of polyester mooring systems. The workshop discussions addressed questions about risks and benefits of rope damage detection. A variety of background information was captured and used for background in performing the Failure Modes and Effects Analyses (see Section 5).

Workshop participants were asked to brainstorm their ideas concerning the “pro’s” and “con’s” of Insert Recovery and Testing as applied to various production floaters. Complete discussion notes from the workshop are included in **Appendix E**. A summary of the pro’s and con’s offered by the participants follows:

Pro’s of Insert Recovery:

- Allows the operator to keep operating
- Checks on fiber degradation
- Discovers “unknown” degradation
- Provides a historical database – but no standard test
- Learn breaking strengths of rope or subropes
- Use extra subropes from each insert to perform research/testing

Con’s of Insert Recovery:

- Requires many more connections in rope mooring legs
 - Provides a sample for only one full rope test – what if the test result is bad?
 - High scatter in results for one insert makes it hard to make significant conclusions – can’t correlate with other data.
 - If test equipment fails, there are no test results.
 - Inserts are very short, and they are inherently more difficult to make than long segments – more probability of human errors during manufacturing.
 - Inserts are less tolerant than long segments – we observe “sawtooth” load results, usually due to improperly constructed splices.
 - For production testing (to qualify rope), there is more careful attention to detail for inserts, but later, inserts manufacturing is not as controlled.
 - During production testing, when results are bad, results can be discarded and the test performed again. This is not possible in recovery operations testing.
 - Length limitations of current testing machines (13–15 meters) results the insert test sections to be mostly comprised of splice and little mid-section.
 - In short inserts, deformation of the eye section causes problems in obtaining statistically consistent results.
 - Operators cannot extrapolate results from one recovered/tested insert to the rest of the mooring system.
-

The above list of advantages and disadvantages applies to existing types of polyester moored production floaters in the GOM.

At the workshop, Petrobras presented an additional consideration: Use of polyester inserts in the mooring lines of a disconnectable turret for an FPSO has an additional disadvantage—the FPSO needs to be totally disconnected from the turret before removing the inserts. This is due to the fact that, with the FPSO connected, the top part of the chain and the chain stoppers are not accessible. This one additional operation, if required for polyester moored FPSOs, can make an all-steel system more attractive, since this would be operated

passively. However, in ultra-deep water, an all-steel system must use submerged buoys, which poses an additional risk to be mitigated.

Appendix F is a concise statement of advice from Petrobras on the value of insert recovery, based on their extensive history of installing polyester mooring systems since 1995. Their conclusion, reproduced here, is:

“...our current thinking is that, provided tensions are monitored and found within the design limits recommended by current documents (like API RP 2SM), no additional information is obtained from the evaluation of inserts removed from service.”

Considering the three primary damage mechanisms listed in Section 4.1, **third-party damage** is inspected and evaluated by ROV-based video inspections at regular intervals to determine if any physical damage or anomalies can be observed on the rope segments and splices. *Insert recovery/testing is not efficient or effective in mitigating third-party damage, because it would only be useful if the damage were in the 15-meter length of the insert, rather than in the 20 to 30 miles of rope in the entire mooring system.*

Poor-quality splices can best be addressed during design and manufacturing by having an effective quality-assurance plan. If a poor-quality splice happened to be in one of the two splices in an insert that is recovered and tested, this would be unusual, because a complete mooring system might have four arrays of four ropes, and each mooring leg might have perhaps eight or ten splices. Consequently, there are about $3 \times 4 \times 9 = 108$ splices. *Insert recovery/testing is not an effective or efficient method for finding poor-quality splices.* Reference 13 provides more information concerning rope and splice quality assurance.

Problems cause by **dropped rope** are mitigated by designing into the rope an effective outer filter with the rope jacket that can exclude particles that might cause wear damage after invading the rope core. The filter system design for main rope and splices can be subjected to qualification testing to confirm performance in the event of a dropped rope. *Dropped rope is not an issue that intermittent insert recovery/testing can address.*

4.4 Insert Testing for Fitness for Service

The 4th objective in the detailed program scope shown in Appendix D was listed as determining the most reliable test to determine fitness for service. Based on the risk/benefit analysis our primary recommendation (as stated elsewhere) is to not recover the inserts for testing. If this advice is not acceptable, then the best insert testing methods to use would be:

1. Carefully disassemble the full insert to obtain undamaged subropes for testing. Unjacketed subropes are difficult to disassemble without disturbing the subrope structure.
2. Conduct 20-hurricane testing and “new rope” testing on the recovered “used” subropes. Compare the 20-hurricane results with results from new samples, but make sure that a sufficient number of cycles are applied to fully bed in the splice. When the first 100 cycles of the hurricane testing is evaluated, one can see when the splice becomes bedded in by looking at the change in maximum displacements for the cycles – the plot of maximum displacement vs. cycle number will level off at some point, and that marks the number of cycles required for bedding in. The most likely conclusion from the 20-hurricane testing is that results on the “used” subropes will be the same as that for uninstalled subropes. If not, first check for testing errors.
3. Using the formula in Section 1.3, convert the “new rope” subrope test results and compare that with the full insert break test. Alternatively convert subrope test results in the pre-production phase with subrope test results for the used (non-20-hurricane-tested) subropes.
4. Other subropes not needed for the 20-hurricane tests could be used for further experimental “research” as determined useful by the mooring system owner, or they could be stored for future use in the unlikely event that after 12 years of polyester rope industry experience a previously unknown rope structural degradation mechanism is discovered, and testing is warranted.

4.5 Conclusions on Damage Detection Methods

A significant conclusion from this discussion is that insert recovery and testing is not an efficient or effective method to minimize the major risks of an installed rope mooring system. On the other hand, ROV video inspection is the best available method of detecting third-party damage—the greatest risk in a mooring system—provided that the mooring system has (1) properly designed and built splices, and (2) a filter system to protect against particle invasion in the event of a dropped rope.

4.6 Recommendations for Determining Rope Fitness for Service

For rope that experiences damage in the core of the rope under the jacket, we would recommend replacement as soon as practical. We are taking account that the mooring system has been designed for one mooring leg lost. For rope that has not been damaged, our advice is

to make sure that 20-hurricane tests have been conducted on subropes used for the mooring system or subropes made identical to that used in the mooring system. One set of 20-hurricane tests will suffice for the life of the mooring system, unless the 20 hurricane figure is exceeded (an unlikely event). Considering allowable strength loss in the 20 hurricane testing, our Samson subrope tests showed 6% loss. Until 20 hurricane tests are conducted on other rope designs, we suggest that a limit of 8% loss should be considered a maximum allowable. If a currently installed mooring system strength loss exceeds 8%, then additional investigations should be undertaken to justify that larger strength loss. The 20-hurricane test is a very severe test, but it is useful on a relative basis to qualify various rope designs. The current version of API RP 2SM permits a strength loss of 10% due to damage, and the 20-hurricane test inflicts cyclic wear damage. The remaining 2% could be considered to cover creep and other miscellaneous losses. Please remember that the 20-hurricane test can also confirm that splice slipping is not occurring.

We must add that both a competent splice quality assurance program and a competent ROV inspection program should be a part of the overall mooring system integrity program.

If the requirement to recover/test inserts is lifted, there are some other alternative methods that should be considered to be of value in assuring mooring system integrity:

1. Use improved video systems (to be determined) for damage inspection by making the specification of "acceptable" video systems more rigorous. Using 3D digital video is an option.
2. Count chain links taken in. If there is a way to measure the number of chain links taken in over time in years, this becomes a measurement of stretch of the mooring system legs affected, or it could be indicative of a potential anchor movement problem.
3. Measure length and length change acoustically. Since a key measure of performance is % elongation, acoustic measurement technology, currently used to measure pipeline jumper lengths could be adapted to measure the length of a predetermined mooring segment (eye to eye) and compare it with previous measurements. Any unusual change in length would indicate a potential problem to be investigated.
4. Install "telltale" to discover excessive elongation of a rope segment. See Appendix K. This can be built into new mooring systems or added by ROV installation on currently installed mooring systems.
5. Special Eye Splice digital referencing as described in the measurement section of this report.
6. Develop and use a measurement "bug" as described in the measurement section of this report.
7. Develop and utilize a special insert having ROV-recoverable subropes. See Appendix L.

5. FMEA of Rope Damage-Detection Processes

5.1 Background

The project team was tasked with comparing the risks and benefits of rope damage-detection processes over the operational life of a mooring system. A **Failure Mode and Effects Analysis (FMEA)** was performed to quantitatively compare risks of each of the three operational processes:

1. Insert Recovery
2. ROV Video Inspections
3. Normal Operating Conditions for 20 year life of mooring system

5.2 Approach

The purpose of the FMEA was to discover and rank-order potential failure modes during the various operational steps, showing the highest risks and consequences of failure. Since processes were being compared, Process FMEAs were employed. The technical approach used in this risk analysis was to:

1. Conduct a Risk Workshop on polyester mooring system operations. Stakeholders included (1) operators (Shell, Chevron, BP, Petrobras, Anadarko), (2) contractors and consultants of mooring system design, installation and recovery (Intermoor, Delmar, Technip), and (3) regulators and certifying authorities (MMS and ABS). Stress and TTI were present to conduct the workshop and work with the results to build FMEAs. This workshop was focused on identifying and discussing various failure mechanisms, frequencies of occurrence, and consequences.
2. Use Workshop results and additional materials supplied by BP, Anadarko, and Intermoor, to construct the three FMEAs.
3. Use Intermoor (the contractor who has performed all insert recovery operations in the GoM) to review and improve the draft FMEAs assembled by the project team.
4. Finalize the three FMEAs and submit them to Workshop participants for comments and additions.

Appendix I presents details of the three FMEA analyses. For each FMEA, we considered each operational phase, or step of the process, in sequence and noted the failure modes and the respective causes that could manifest during that particular phase. Each **Failure Mode** was assigned a corresponding **Severity Index**. Each **Cause** was assigned an

Occurrence Index. A **Detection Index** (ranking the ability to detect a failure) was initially used, but this was not found to be useful, because all of the indices were about the same. The **Risk Priority Number (RPN)** is the product of the two indices and provides a quasi-quantitative value for overall relative level of risk corresponding to each Failure Mode and Cause.

Tables are presented in **Appendix J** that summarize the ranges (in terms of numeric scale, corresponding to a description) of the Severity and Occurrence Indices. A few examples of mooring operation events are provided within the Severity Index table to illustrate assumptions on the "typical" severity of Failure Modes. The higher the Severity Index, the worse the problem is. The Occurrence Index is a probability that a given Cause will occur. Thus, the higher the Occurrence Index, the more probable the specific Cause-based event.

5.3 FMEA Results

Table 10 presents a summary of the FMEA results. Insert recovery operations as a method to detect rope damage stand out from the results because there are 19 independent failure modes addressed. Both Normal Operations and ROV inspections have a much smaller number of failure modes: 6 and 5, respectively. The RPN is significantly larger for insert recovery (399), as contrasted with other methods. It should also be noted that the risk associated with normal operations occurs over a 20-year span, while the risk of insert recovery and ROV inspections will occur only over an estimated 75 days during the 20-year life of the project.

Table 10. FMEA Analysis of Damage-Detection Processes

Poly Mooring System Operational Processes	Number of Failure Modes	Approx. Exposure Time	RPN = Sum of Product of Severity and Occurrence Indices
Normal Operations	6	20 years	129
Insert Recovery Operations	19	75 days (20 times)	399
ROV Inspections	5	75 days (20 times)	112

Prior to drawing conclusions from these results, the types of risks considered in the FMEAs will be discussed.

5.4 Summary of Failure Modes and Risks—Normal Operations

No offshore operations are risk-free. For a typical mooring system design process, if performed properly, the only remaining risks are those that cannot be eliminated by design. For normal operations, risks of rope damage by third parties—such as uncontrolled vessels in a hurricane or loop current event dragging hanging loads through a mooring spread—cannot be eliminated. These risks can only be minimized. The risks of a load being dropped overboard that

severs a mooring leg can be minimized, but not eliminated. For normal operations without ROV inspections or insert recovery, the six failure modes are of high consequence (Severity Indices of 9 or 10), but of low frequency (Occurrence Indices of 1 to 3). The sum of the RPNs for normal operations is 129. As details of this FMEA were carefully considered, it was determined that none of the failure modes can be avoided, so this result is representative of normal and reasonable offshore operational risks for which insurance is purchased.

5.5 Summary of Failure Modes and Risks—Insert Recovery

As compared to normal operations, failure modes for insert-recovery operations are three times greater (three times greater RPNs than normal operations), and they occur only during a much smaller window (75 days total versus 20 years for normal operations). All failure modes for insert recovery result from risks of accidents vessels and ROVs operating inside the mooring system layout. These types of operations are not allowed during normal operations. Failure mode severities are the same as for normal operations. Occurrence indices are a little higher. This case can be compared with a hospital case of “elective” (though required) surgery in that it appears to have no beneficial value in terms of making the mooring system less prone to fail. The total RPN for insert recovery is 399, three times higher than that for normal operations. Based on field experience report by industry, it has been concluded that insert recovery and testing is not an efficient or effective method of minimizing the major risks of an installed and operating mooring system (see Section 4.5). **These risks can thus be totally avoided by removing the requirement for insert recovery;** and risks for normal operations are not increased as a result.

5.6 Summary of Failure Modes and Risks—ROV Inspection

ROV Inspection failure analysis defined only five failure modes, and indicates somewhat lower Severity Indices and higher Occurrence Indices than the other two processes. Typical failure modes are collisions of the ROV or ROV cage with the mooring legs during video photography. These risks can be greatly reduced by installing bumpers on the cages and ROVs so that impact does not result in rope damage. If it is assumed that impact causes rope damage, the sum of the RPNs and the average RPN is similar to that for normal operations. The period of risk exposure (75 days total) is much less than that for normal operations, however. Unlike insert-recovery operations, *ROV inspections provide a large added value in ensuring that there is no previously unknown third-party damage to the mooring system that might lead to a catastrophic system failure.* Stated differently, ROV inspection has the greatest value by

minimizing the largest risk (unknown third-party damage) of polyester mooring operations, and it does so with a reasonable and manageable risk of failure during the operation.

5.7 Opportunities to Reduce Risks During ROV Inspections

In considering FMEA results for ROV inspection, there are opportunities to further reduce risks. The highest single RPN is 36, assigned to the case where the ROV vessel rams the host. If the ROV vessel may lose DP, it is best if the vessel works down wind/current of the host, if feasible. It is seen that operational procedures can decrease that risk. Other risks pertain to the ROV cage or the ROV impacting the polyester rope and cutting it. The cage, ROV and tools can be padded such that impact with the rope will not damage it. Of course, a thicker rope jacket will provide additional protection as well. All of these risks can be addressed by a HAZOPS workshop held with the mooring system owner and ROV contractor prior to the ROV inspection.

5.8 Conclusions on the FMEA Analysis of Risk

1. Insert recovery, as a rope damage-detection process, shows no appreciable value but adds significant risk. Consequently, it is unnecessary and adds unnecessary risks.
2. ROV inspection, although it involves some risk of rope damage, is clearly valuable because it reduces the greatest risk to mooring ropes— unknown third-party damage.

6. Remaining Life Mathematical Model

The issue that the offshore industry has faced with polyester moorings is: What is the remaining life of polyester segments in a mooring system? When recovery of an insert is required, and when results of the insert break test are the same as for new rope, how do we know that the rope might not suddenly fail? It is proposed that these questions be answered by applying the remaining life hypothesis described below.

One of the objectives of this project was to develop and prove a unifying **remaining life model**. The hypothesis that was evaluated is a strain (or %-elongation) based model.

The first step is to determine the % elongation at break due to cyclic wear based on the 20 hurricane test. This is done by starting with the % loss in breaking strength due to cyclic wear taken from Figure 5. If there is a 6% loss in breaking strength due to cyclic wear from 20 hurricanes, then there is a 6% reduction in the breaking % elongation from that of a new rope. If the breaking % elongation for new rope is 10.5%, then the reduction is 10.5 times 6%, or 0.6%, and the breaking % elongation due to cyclic wear is $10.5 - 0.6 = 9.9\%$.

Next, one would subtract the creep strain that occurs due to 20 years of creep (say, 0.5% elongation). Project evaluations of creep (see **Appendix D**) support the concept that creep reduces (subtracts from) elongation at failure.

The **strain-based failure hypothesis** incorporating both cyclic wear and creep is then:

$$\% \epsilon_{\text{FAILURE}} = \% \epsilon_{\text{WEAR}} - \% \epsilon_{\text{CREEP}}$$

Where $\% \epsilon_{\text{WEAR}}$ varies between say 10.5% for an un-cycled but bedded-in rope to the % elongation associated with maximum cyclic wear at 60% load (shown as 40% with a range of 40% in Table 8) occurring at over 8 million cycles. The failure % elongation for this latter condition would be 60% of 10.5% (the new rope breaking strain), or 6.3%. We can then use the cyclic wear break load decay curve in Figure 5 to determine the $\% \epsilon_{\text{WEAR}}$.

For creep we can use $\% \epsilon_{\text{CREEP}} = 0.5\%$ for 20 years (for example), or see Table 1 for other values.

The team considered the load elongation curves of un-cycled rope to determine the failure elongation. However, the subropes tested at Samson were cycled 60 times for bedding-in, but the load was not reduced to zero (or the 2% reference load); rather, the load was

immediately from the maximum cycling load to failure. As a result the load elongation curve had an uncharacteristic shape for polyester, and the investigators could not easily select a % elongation at failure to compare with the cycled rope results. Note that this hypothesis does not agree with that proposed by Mandell (Reference 14).

7. Accuracy of Rope Damage Detection Methods

7.1 Current ROV Inspection Process

Currently inspection practice is to “fly” an ROV down each mooring leg, recording video as it travels downward to the anchor point, and then fly back up on opposite side, all the while looking for signs of damage. The video is then re-examined after the survey to ensure that potential damage was not missed. For chain and wire rope, the inspection is for one side only. The inspection of one mooring leg of perhaps 12 or 16 legs takes about 4 hours. It is sometimes necessary to scrape away marine growth attached to the rope jacket, using a ROV supported tool that will not damage the rope. (See References 5 and 12 for details.)

Following are several photographs selected from a typical video taken along the mooring leg. Figure 6 is a shot of the mid-length of a rope segment, showing the straight black marker line, which reveals that this rope segment has very little twist in it.



Figure 6. ROV Photograph of Rope Twist

Figure 7 is another view of the rope body. Note that visual clarity is fairly good, and that even small damage to the rope jacket would be visible.



Figure 7. Close-Up View of Rope Condition

Figure 8 is the eye splice joining the H-Link with a pin.



Figure 8. Photograph of Eye Splice and H Link

Figure 9 shows the H Link on its flat side.



Figure 9. Flat Side of H Link

Figure 10 shows the rope (upper left) approaching the toe of the eye splice (lower right) and the red tape covering the cut ends of the splice.



Figure 10. Photograph of Toe of Splice Region

These photos were recorded during a video fly-by. The ROV operator maneuvers the ROV so that the video is close enough to the rope to show any potential defects, yet far enough away from the rope to avoid any contact. Standard procedure calls for first lowering the ROV cage or hanger from the ROV support vessel, then flying ROV out of the cage to inspect all rope in range of the ROV umbilical. In this way, the video inspection is completed in segments.

7.2 Damage Assessment Process

If a potential damaged area is found by the inspection process described above, it can usually be located at a later time by referring to the mooring leg number and depth of the ROV on the video screen. The site can then be revisited for a more detailed inspection. Some ROV operators have 3D video (Sony product) such that a more accurate picture of the damage can be recorded. Digital video is superior to the common VCS format, since post evaluation of inspection results is less cumbersome in a more compact digital format. Investigators should be focused on the degree of jacket damage, and the presence of strands or yarns showing from the rope core. Polyester is so light that damaged elements tend to “flow about” (like a flag in the wind) in the localized currents around the rope. Above and below the damage site along the rope, the inspector should look for a necking down of the rope, which indicates missing strands or subropes at that location; or bulges under the rope jacket, which indicates the presence of recoiled rope.

ROV-supported calipers, if available, can be used to measure rope diameter at various points along the damaged region. Typical accuracy of an LVDT would be less than about 0.003 for a 1–2 inch stroke. Of course, an LVDT measurement system must be rated for the maximum

water depth of the inspection project. It is possible to make visual measurements of the rope diameter near a potential damage site. The project team discussed polyester rope diameter measurements with www.Welaptega.com. One of Welaptega's specialties is that they use a video measurement "jig" to measure chain links subsea, and they believe they could do something similar for this polyester rope application. We were referred to this company by Samson Ropes. For more information on Welaptega, please see their web site.

A simple but useful adaptation of ROV digital video is to use the ROV manipulator arm to hold a "rope" bumper against the rope so that the distance from the camera lens to rope surface can be temporarily fixed. If the bumper has a measurement scale on back, the camera will record a means to scale the rope on the photo. Distortions due to the camera depth can be accounted for when analyzing photos from the video.

Since a rope is comprised of many subropes in a parallel subrope construction, the rope diameter will be slightly different, depending on length along the rope and the rotational point around the cross section, so a difference in the diameter of a 12-inch rope could be $\pm\frac{1}{4}$ to $\frac{1}{2}$ inch or more. The key point here is that transducer accuracy of less than 0.005 inch will be small when compared with normal variations in rope diameter.

The key for measurement accuracy is to consider relative rather than absolute measurements. Always compare measurements of a suspected damaged area with the same measurements for unaffected areas of the rope.

7.3 New Measurement Concept

Each of the three ROV operators contacted during the project said that they could develop a rope measuring "bug" to traverse along the main segments of the rope, recording video from fixed points and recording rope diameter changes. Figure 11 is a profile of an ROV with a measurement bug tethered off.

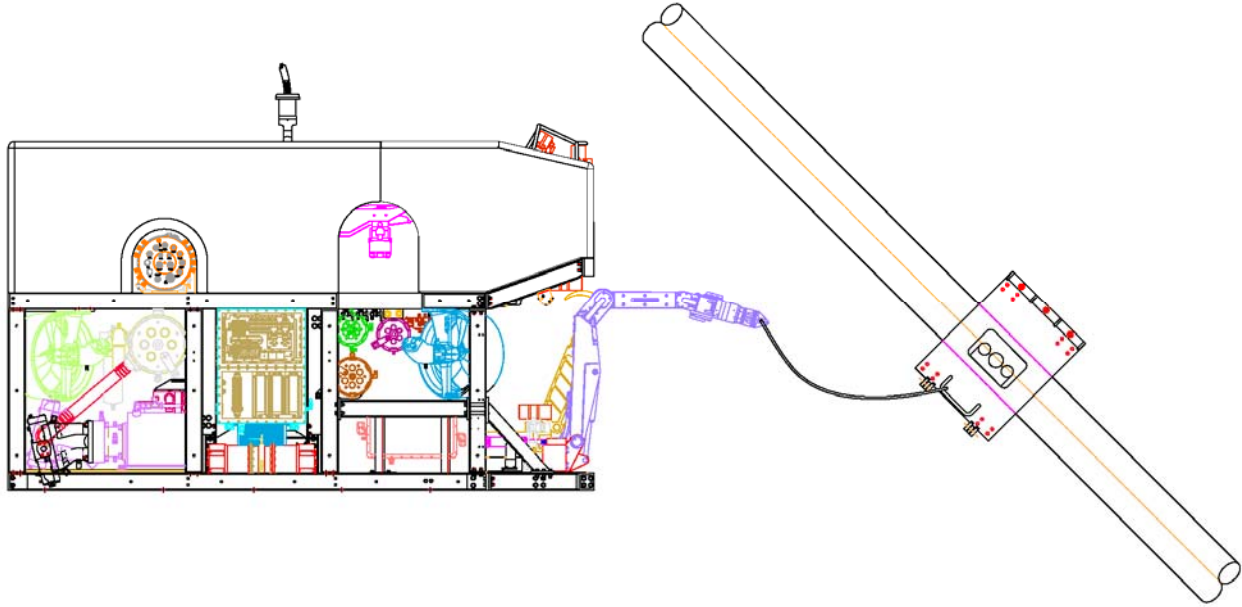


Figure 11. ROV-Supported Measurement Bug

The measurement bug might function as shown in Figure 12.

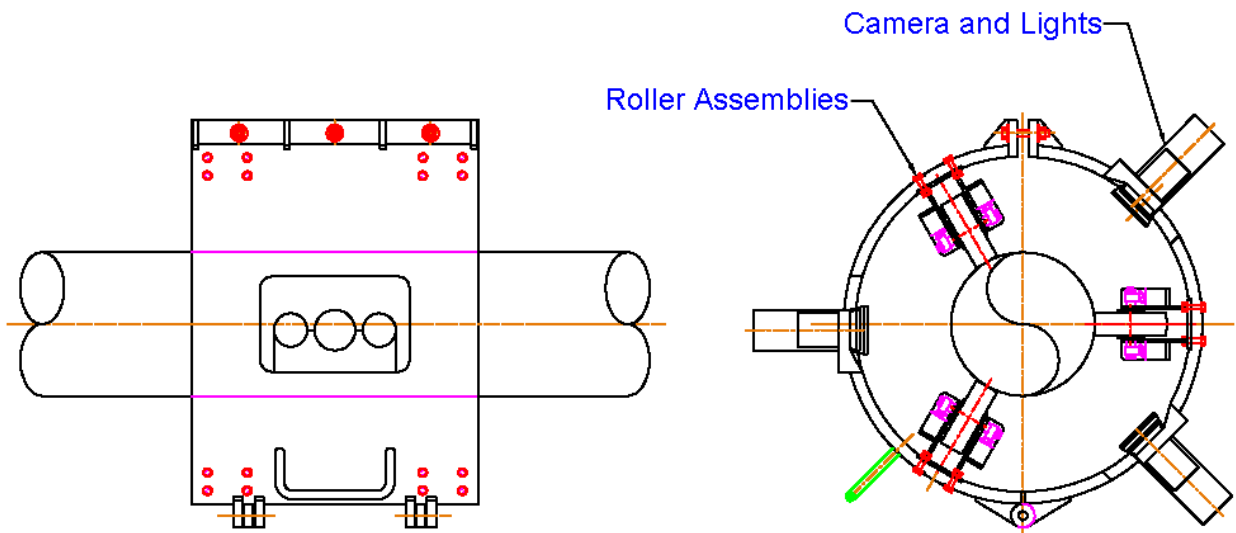


Figure 12. Measurement Bug Details

Other alternatives for the bug configuration are shown in Figure 13.

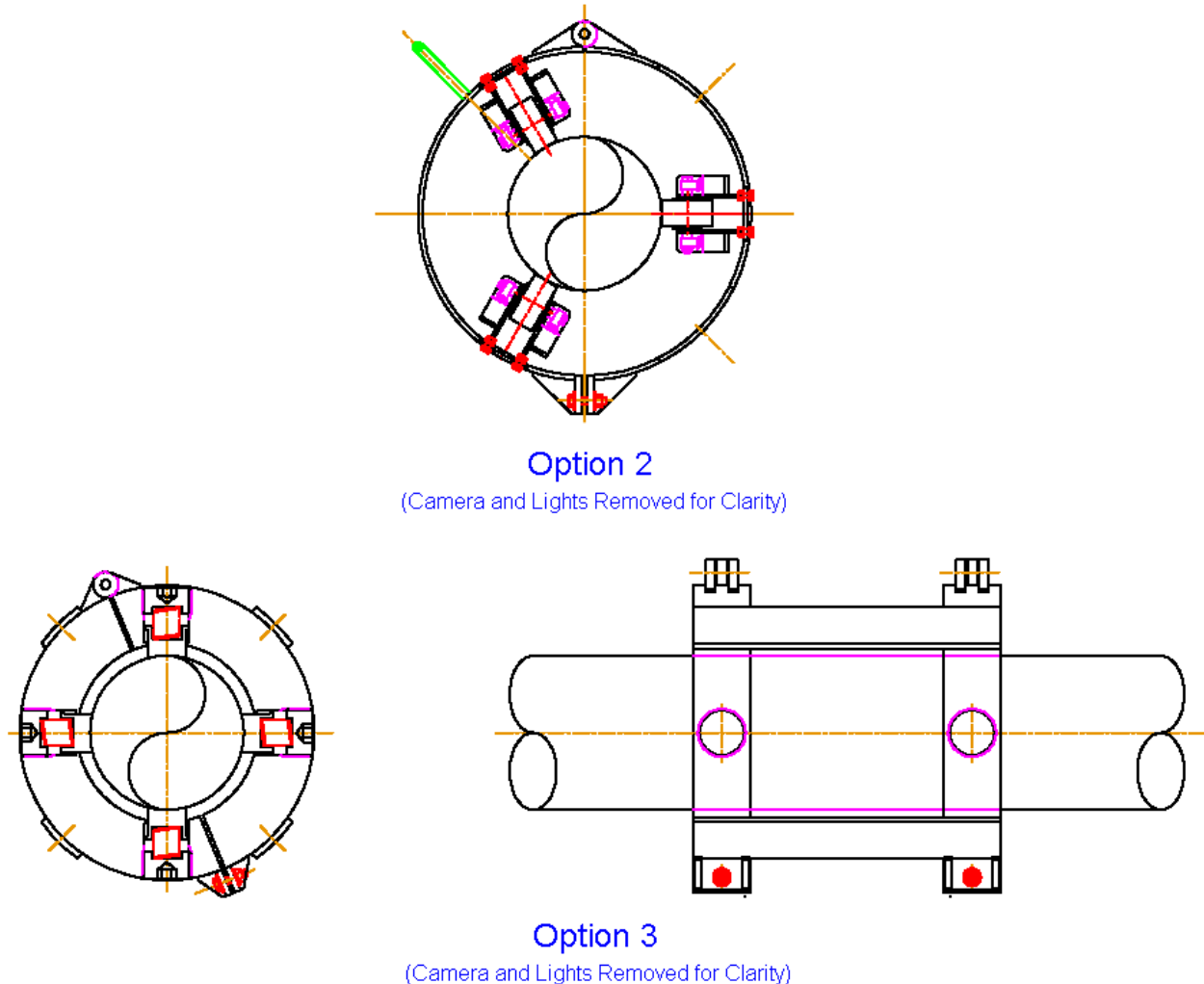


Figure 13. Alternate Bug Configurations

The design basis for the measurement system would include:

1. Rolling or sliding surfaces contacting the rope should not damage the rope.
2. The bug must consist of a split clamp to fasten around the rope in such a way that it will release quickly if there is an ROV drive-off if the tool gets stuck on the rope or in the damaged area.
3. Displacement measurement data and video should be coded with water depth, orientation, and rope segment so that it can be stored safely for future analysis.
4. The outer surfaces of the bug should be smooth, such that entanglement is not likely.
5. Design rope diameters would be from 8 to 16 inches.

7.4 **Conclusions on Measurement Accuracy**

1. Current ROV inspection methods are considered satisfactory by industry for discovering potential damage sites. Based on real-time video inspection plus a post-inspection

review of the digital video records, the possibility of missing a damage site of concern is small, provided the entire length of the mooring system is inspected. With sufficient lighting, even 2D video is clear enough to detect even minor jacket damage.

2. It is feasible to inspect suspected damage sites more closely using (1) 3D digital video, mechanical diameter measurement calipers supplied by the ROV operator, (2) a bumper/scale held in place by the ROV manipulator arm to allow making accurate measurements off of the video, or (3) a measurement “bug” containing both digital video measurement capability as well as LVDT measurements. Measurements made could be in the range of 0.005-in. accuracy for the large size (10–12 inch) mooring ropes being considering. Normal variations in rope diameter along the rope length and around the rope circumference at a given location could be of the order of ¼ inch.
3. The most significant point to consider regarding accuracy of rope measurement, is that if the rope core under the jacket shows any discernable damage, rope break strength (if tested) could be reduced by 35%, three times the API RP 2SM allowable limit. Consequently, that section of rope would need to be replaced. For this type of “Go/No-Go” situation, physical measurement accuracy is not critical.

8. Conclusions and Recommendations

The project team reached the following major conclusions and recommendations based on project results:

1. The only major cause of rope structural integrity loss during a 20-year project life in which 20 hurricanes of the strength of Katrina were applied, and 20 years of creep elongation has occurred, was found to be third-party damage to the mooring system components. Only *in-situ* inspection of the mooring ropes by ROV video (not insert recovery/testing) can effectively discover this damage. This assumes a competently designed, manufactured and installed mooring system.
2. Because of the demonstrated structural integrity of polyester ropes, the major concerns of rope creep and cyclic wear damage have been proven to be unfounded. Insert recovery/testing is not beneficial in this case. This conclusion also assumes a competently designed, manufactured and installed mooring system.
3. Based on a risk/benefit analysis, insert recovery/testing has been determined to have no benefit in reducing the risk of normal operations. Consequently, recovery and testing of inserts in installed mooring systems should be discontinued, and inserts should not be designed into future mooring systems.
4. The accuracy of subrope damage detection using current methods (ROV video fly-bys on front and back of each mooring leg) should be sufficient to detect rope jacket damage, which should in turn be inspected in more detail by methods recommended in this report. Using semi-quantitative risk/benefit analysis results, the team determined that ROV video inspection is of great benefit in locating third-party damage, and that the benefit is worth the added risk that was identified. Evaluation of the FMEA of the ROV inspection shows that the currently perceived risks can be reduced by performing a HAZOPS of the operation, involving the mooring system owner and the ROV inspection contractor.
5. A mooring rope found with jacket damage (cut ends waving in the current) should be considered a critical inspection zone. If the rope core (groups of subropes) appears to be damaged and affects less than 10% of the rope cross-section, it is prudent to assume that the rope will have a retained breaking strength of only 60% MBL (minimum breaking load). Damaged rope segments should be replaced as soon as possible. For critical locations along the rope length, either digital video (2D or 3D) or LVDT measurements of

local rope diameter are recommended to better assess the conditions. A measurement accuracy of 0.003 inches should be attainable in such measurements.

6. A rope cycling test based on being subjected to 20 hurricanes with strength of Katrina should be adopted as a “benchmark” for qualification testing of different designs and brands of polyester rope. The test would measure both rope strength reduction and maximum elongation performance after 20 hurricanes. A superior rope design would minimize cyclic wear, and a superior splice design is expected to demonstrate no appreciable splice slippage over 20 hurricanes. Rope creep is less affected by the specifics of design and more affected by the number of fibers resisting the load, so no specific test such as the 20-hurricane test is needed for creep.
7. A new strain-based hypothesis is presented for estimating the remaining life performance of a polyester rope, based on a prediction of major hurricane exposure and the design life of the mooring system.

Other more specific conclusions are provided at the end of various sections of this report.

9. Acknowledgements

The project team gratefully acknowledges the important contributions of the following individuals and companies:

1. The MMS for providing funding and Mrs. Lori D'Angelo, our Contracting Officer's Technical representative for her help in helping our interactions with the MMS work smoothly. The authors also thank Ms Christy Bohannon of the MMS Gulf Coast Region for her keen interest in this project and her valuable critique of this report.
2. Samson Ropes (Justin Gilmore and Danielle Stenvers) provided rope samples and performed pre-hurricane cycle break tests for the project on a gratis basis.
3. BP (Jeff Geyer and Dave Petruska) provided listings of insert recovery risks for the team to consider.
4. Intermoor (Todd Veselis) provided assistance by providing a generic insert recovery process and in collaborating with Stress in refining and verifying the FMEAs build for the three operational conditions.
5. Anadarko (Jenifer Tule) provided valuable risk information for input to the FMEA.
6. Anadarko (Jenifer Tule) and Technip (Kathy Marshall) provided valuable ROV video inspection information and photographs.
7. BP (Jeff Geyer) provided valuable risk information for input to the FMEA.

10. References

1. Ayers, R.R., Ward, E.G. and Smith, C.E., "Characterizing Polyester Rope Mooring Installation Damage," DOT Conference, New Orleans, 2002.
2. Ward, E.G., Ayers, R.R., Banfield, S.J., and O'Hear, N., "Full-Scale Experiments on Damaged Polyester Rope," for MMS and JIP Participants, May 2006.
3. Ward, E.G., Ayers, R.R., Banfield, S.J., O'Hear, N., Smith, C.E., and Laurendine, T., "The Residual Strength of Damaged Polyester Rope," OTC 18150, 2006.
4. API RP 2SK, *Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures*, American Petroleum Institute, 1997.
5. API RP 2SM, *Recommended Practice for Design, Analysis, and Testing of Synthetic Fiber Ropes in Offshore Mooring Applications*, American Petroleum Institute, 1999.
6. Higson, A., "Premature Failure of Fibre Ropes," Fourth Year Undergraduate Project Report, Emanuel College, 2007.
7. Bosman, R., "Test Method for Determining the Assured Residual Life Span (ARELIS) of Polyester Mooring Ropes," IEEE International Symposium, 2001.
8. Huntley, E.W., and Whitehill, A.S., Sr., "Creep-Rupture Models and Experimental Results for Polyester Rope," MTS, 1999.
9. Hooker, J., and Bosman, R.L.M., "Recent Investigations into the Physical Properties of Superline Polyester Ropes, Moorings and Anchors for Deep and Ultra Deep Water Fields," Aberdeen, November 1999.
10. Ayers, R. R., "Determining Interim Criteria for Replacing Damaged Polyester Mooring Rope," BP Report, December 2001.
11. Del Vecchio, C., "Light Weight Materials for Deep Water Moorings," Ph.D. Thesis, University of Reading, UK, 1992.
12. ABS, *Guidance Notes on the Application of Synthetic Ropes for Offshore Mooring*, ABS Publication, March 1999.
13. Petruska, D.J., Geyer, J.F., Ayers, R.R., and Craig, M.J., "Mad Dog Polyester Mooring – In Service Inspection and Rope Manufacturing Quality," OTC 16590.
14. Mandell, J.F., et al, "Fatigue and Environmental Resistance of Polyester and Nylon Fibers," MIT Department of Materials Science and Engineering, 1985.

11. Acronyms and Abbreviations

2SM	=	Section of API code addressing synthetic ropes
2SK	=	Section of API code addressing steel wire rope and chain
ABS	=	American Bureau of Shipping, a Classification Society
API	=	American Petroleum Institute, an industry-standards organization
ARELIS	=	Assured Residual Life Span, a high load method of creep testing
COV, CV	=	Coefficient of Variation, a statistical measure of the fit of data
CSL	=	Cordoario Sao Leopoldo, a Brazilian rope maker
FMEA	=	Failure Modes and Effects Analysis, a method of risk analysis
GOM	=	Gulf of Mexico
K	=	kips, 1000 lb, a measure of force
LVDT	=	Linear Variable Differential Transformer, an electronic measurement transducer
MBL	=	Minimum Breaking Load at two standard deviations below the mean
MMS	=	Minerals Management Service, part of the U.S. Department of the Interior
NEL	=	National Engineering Laboratory in the United Kingdom
N	=	Newton, the unit of force (metric system)
QA	=	Quality Assurance
ROV	=	Remotely Operated Vehicle
RPN	=	Risk Priority Number, a measurement means in FMEA risk analysis
SD	=	Standard Deviation, a statistical measure of fit
SES	=	Stress Engineering Services, Inc., Houston Texas (the prime contractor)
SIM	=	Stepped Isothermal Method, a method to speed up creep at high temperatures.
TTI	=	Tension Technology Incorporated (subcontractor)
Tonne	=	Metric Ton

APPENDIX A

Project Proposal Scope

INTRODUCTION

This final report, in response to the MMS solicitation, describes a technical project that was conducted to evaluate the accuracy of polyester subrope damage detection performed by ROVs following hurricanes and loop currents that exceed the 100-year design criteria and methods to estimate remaining fatigue life.

Background

The recent MMS-sponsored JIP determined how damaged subrope behavior affected full rope strength. The authors were responsible for the technical findings while OTRC served as the Project Manager. A DNV JIP also investigated damaged subrope behavior. Currently, API 2SM is finalizing the second edition of a Recommended Practice for Synthetic Mooring Systems.

This report contains our investigation of the accuracy of non-invasive deepwater subsea inspections performed by common ROV-supported inspection tools and provides the technology necessary to utilize the knowledge gained from the work cited above.

Recently SES and TTI conducted structural and fatigue tests on subropes and fibers taken from an insert to the BP Mad Dog polyester mooring system. Overall findings from these tests give us valuable insights that have made our work on this project more effective.

Objectives

Objectives of this project have been:

1. Evaluate accuracy of polyester subrope damage detection performed by ROVs following hurricanes and other events (i.e., loop current) that exceed the 100-year design criteria.
2. Perform a quantitative evaluation to determine if ROV survey results and resulting life damage estimates are acceptable.

3. Explore the viability of a newly conceived method for predicting remaining life based on adapting traditional methods for application for synthetic ropes, like polyester.
4. Identify non-invasive inspection methods other than ROV surveys and compare ROV inspections to physical insert testing to determine the level of accuracy that can be expected.
5. Identify the most reliable methods, including but not limited to insert tests, to verify that the mooring system is fit for purpose.

Scope of Work

We have fully utilized our knowledge recently gained on the large MMS JIP damaged polyester rope testing and evaluation project (see Reference 4), since this project is a natural follow-on to that work. The centerpiece of our proposed work consists of:

1. A carefully designed full-scale simulation of ROV-based tools, including quantitative measurements, of the effectiveness of currently available non-obtrusive inspection tools and methods (video, manipulator arm supported small tools). This simulation would take place in an ROV service company's shop. The second part of this simulation will be experimentation with newly-conceived inspection tools/methods developed as part of this project.
2. A recently-conceived model for predicting remaining life of a mooring rope or insert. Early results from work with two remaining life models, the SIM method and the Arelis model indicate significant scatter. We believe that a more straight-forward approach would be to employ a maximum strain failure law. This law would be applied by summing the creep strain over an elapsed time (t_1) and the strain due to direct loading at t_1 . This sum will be compared with the critical failure strain of the damaged, worn or as-new rope. This proposed remaining life hypothesis was conceived while working on integrity tests for BP of the recently recovered Mad Dog Insert. With our small and large scale damaged polyester rope testing experience coupled with the Mad Dog insert subrope testing experience, we will propose the most reliable insert test method(s) to not only determine fitness for service, but also to predict remaining life.

TECHNICAL APPROACH

Following are the representative tasks performed to achieve the stated objectives above:

1. Evaluate Damaged Rope (a) Remaining Strength, and (b) Remaining Life Methods: We know how strand and subrope damage affect full rope remaining strength (recent MMS JIP). Remaining life is difficult to determine, now that we have tested the subropes from the “used” an insert recovered from BP Mad Dog’s mooring system, we have what we consider to be a rational approach to quantify and verify. This task will consist of high load cyclic tests of subropes to quantify the critical strain reduction caused by wear between the subrope components. The algorithm concerning the effect of external damage to the rope and subropes is known from the prior MMS Damaged Rope Project testing program.
2. Non-invasive Inspection of Damage: We will determine how accurately ROVs can “measure” various types of damage, (1) by video, and (2) by use of a “go/no-go” gage sensing loss of rope diameter (held by the ROV manipulator arm). This task can be accomplished by simulating the ROV measuring operations and using a surplus polyester mooring rope segment, with assistance from an ROV company to provide manipulator arm and video equipment. SES’s Ray Ayers has testing, simulation and ROV knowledge and contacts to be valuable in this task.
3. Develop New Concepts for Non-Invasive Inspection: This task, intended to utilize experience from task (2) above, will be achieved by designing and conducting a small technical workshop to elicit potential new concepts for improved measurements. The concepts will ranked by potential of really working well. SES’s Ray Ayers is a prolific inventor (over 50 patents in deepwater technology), and he is an experienced small workshop designer and facilitator. Included in the workshop will be Ayers, Banfield and O’ Hear, as well as at least one ROV engineer, and others experienced in subsea mechanical and electronics design and invited mooring experts like Pierre Beynet or Dave Petruska from BP Mad Dog and/or Mark Huntly or Sim Whitehill, Sr. from Whitehill ropes.

4. Identify the Most Reliable Insert Tests to Determine Fitness For Service. Emphasis will be on remaining life predictions but we will describe and evaluate other methods. This task will primarily be a documentation of our collective (TTI and SES) knowledge and experience applied to the task requirement.

5. Determine the Value of Insert Recovery & Testing vs. the Risk. Use the result of task 4 as input for this task. Perform a Failure Mode Effects and Consequences Analysis (FMECA) on the relative risk of performing the insert recovery operations and performing integrity testing vs. not recovering and testing the insert and relying on mechanisms like “teltales” built into the rope jacket to indicate whether the combined strain in the mooring rope has reached a not-to-exceed value.

APPENDIX B FULLY COUPLED ANALYSIS OF A POLYESTER MOORED FLOATER

Extreme Storm Tension Loading Statistics
Taut Polyester Mooring
D. L. Garrett
July 2, 2007

Summary

Cyclic loading conditions representative of extreme storm loading for a polyester mooring are estimated. The method used to determine the representative loading is presented. The procedure determines the constant amplitude cyclic loading that yields the same calculated fatigue damage as calculated for stochastic tension loading during a storm. The recommended cyclic loading is from 30% MBS to 50% MBS. A total of 20,000 cycles represents 20 times the loading in a single storm.

T-N Curves

Fatigue of mooring components is calculated using T-N curves, which define the limiting number of cycles for a given range of cyclic tension. T-N curves are of the form

$$N \left(\frac{T}{RBS} \right)^m = K$$

N is the number of cycles

T is the range of tension

RBS is a reference breaking strength

m slope of T - N curve (experimentally determined)

K experimentally determined constant

For polyester, API RP 2SM recommended values are $m=9$, $K=7.5$. The reference breaking strength is the minimum breaking strength (MBS). The T-N curve is shown in Figure 1. T-N curves for studless chain and for spiral strand wire rope are also shown for completeness.

Stochastic Loading

Storm loading and response are stochastic processes and are modeled as stationary Gaussian processes. For a narrow band Gaussian process, the fatigue damage accumulated during a storm is

$$D = \left(2\sqrt{2}T_{rms}\right)^m \Gamma\left(1 + \frac{m}{2}\right) \frac{T_{storm}}{T_z} \frac{1}{K}$$

- D is the damage ($D = 1$ is failure)
 T_{rms} is the standard deviation of tension
 m is the slope of the T - N curve
 K is an experimentally defined constant
 T_{storm} is the duration of the storm
 T_z is the zero crossing period of the tension
 Γ is the Gamma function

A bandwidth correction factor (<1) can be used to account for the bandwidth. Thus, the narrow band fatigue damage formula provides an upper bound to the damage.

An equivalent tension range can be selected such that the damage with constant amplitude loading is the same as would be calculated for the Gaussian process. The equivalent tension range is

$$T_{eq} = 2\sqrt{2} \left(\Gamma\left(1 + \frac{m}{2}\right) \right)^{\frac{1}{m}} T_{rms}$$

The number of tension cycles during the storm is

$$n = \frac{T_{storm}}{T_z}$$

The calculated damage is

$$D = \frac{n}{N} = \frac{n}{KT_{eq}^{-m}}$$

Calculation of Test Parameters

Tension statistics for a mooring line loaded to design limits in an extreme storm can be used to develop constant tension range cyclic loading that represents the extreme storm loading. The case presented here is representative of a taut polyester mooring for a Floating Production System in deep water in the Gulf of Mexico.

The most probable maximum tension in the storm is

$$T_{MPM} = T_{mean} + \alpha T_{rms}$$

$$\alpha = \sqrt{2 \ln \left(\frac{T_{storm}}{T_z} \right)}$$

The most probable maximum tension is limited to 50% MBS for polyester. In storm loading, the dynamic component of tension represents up to about 15% of the total tension. The static tension with no environment (pre-tension) is typically about 15-20% MBS. Representative parameters are

$$T_{MPM} \leq 50\% \text{ MBS}$$

$$T_{rms} = 3 - 5\% \text{ MBS}$$

$$T_z = 12 - 18s$$

$$T_{mean} < 40\% \text{ MBS}$$

$$n < 1,000 \text{ cycles}$$

With these parameters, the equivalent tension range is approximately 20% of MBS. Loading from 30% to 50% MBS (mean = 40%) represents extreme loading conditions. The number of cycles to represent 20 storms is about 20,000. The test condition is plotted together with the design T-N curves for reference.

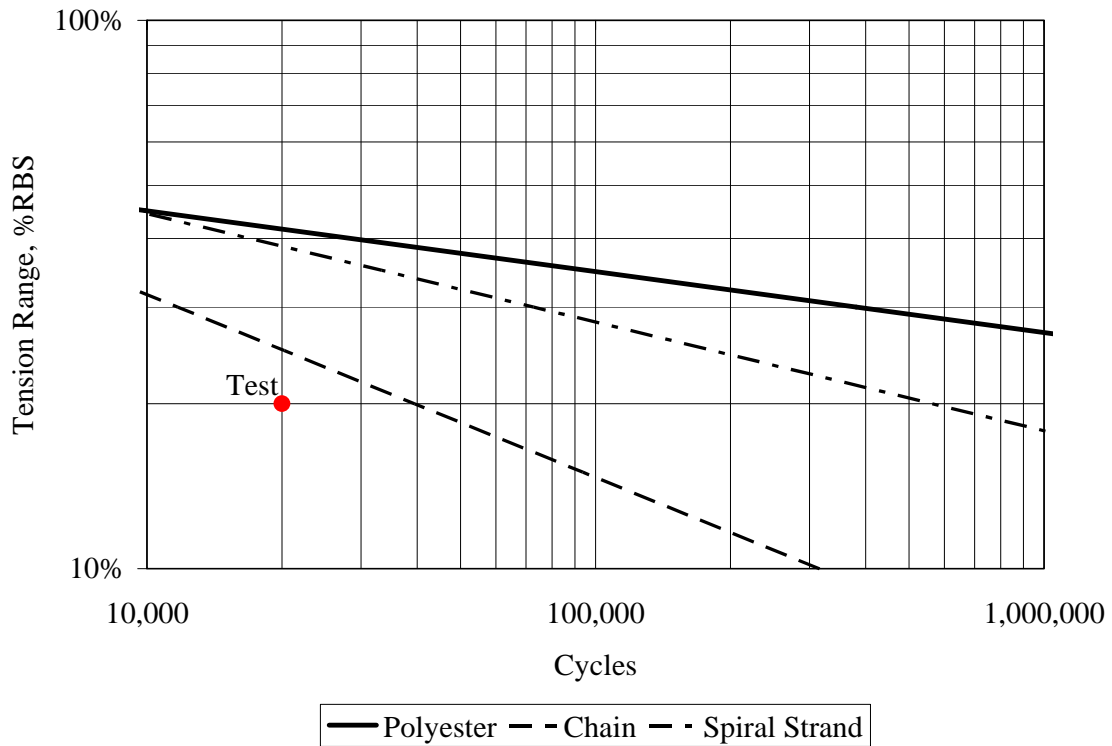


Figure 1. T-N Design Curves

APPENDIX C

The Stepped Isothermal (SIM) Method

Stepped Isothermal Method was developed from the Time-Temperature Superposition Principle; this states that the creep process in a viscoelastic material can be accelerated by increasing the temperature. In SIM testing the load is kept constant throughout the test, similar to a normal creep test. However, a sequence of temperature steps will be imposed on fibre during the testing method.

The main assumption used from TTSP is that one can superpose individual curves from a set of creep data, for which one parameter is changing, into a single reference curve for one specific value of that parameter. When testing non-linear viscoelastic materials a new specimen has to be treated for each chosen temperature, and tests on several specimens must be carried out for each temperature to reduce the uncertainty due to sample variation and handling effects. This variability is overcome in SIM testing by producing a master curve based on a test performed on a single specimen.

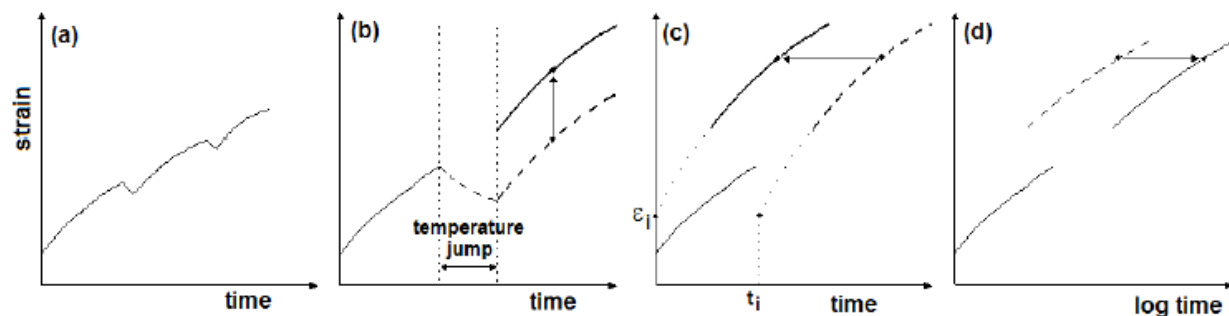


Figure 5: Schematic diagram for SIM procedure, based on Alwis' work [2].

Figure 5 shows a schematic diagram of the procedure for SIM testings and a graphical diagram of the mathematical treatment that is done from the original data collected. There are a number of different things that have to be accommodated in this process:

- (b) Compensation of shrinkage, there is a small decrease in strain caused by a reorganisation of the microstructure of the fibres during the temperature jump.
- (c) Shift along the linear time axis for each temperature step, this value of time should correlate with a "virtual" starting time of a simple creep test.
- (d) Shift along log-time axis, this occurs after the previous two manipulations, and is done so that a single master curve can be produced.

The results from the SIM testing showed a high amount of scatter and since there is little creep rupture data available for comparison it is hard to make comments about how successful this method is. Therefore, if possible, it would be desirable to perform long term creep tests for comparison to this theoretical method of prediction. Later the results from Lechat's testing will be compared to creep tests performed in this project.

This description of the SIM Method was extracted from Reference 6 of this Report.

APPENDIX D

TTI STUDY OF POLYESTER ROPE MECHANICS

PREPARED AS PART OF THIS PROJECT

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MMS Study

Date	Rev.	Description	Prepared by	Authorised by
2-Nov-07	R1	First Issue	N. O'Hear	S.J. Banfield
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Executive Summary

Polyester Parallel Strand Ropes have an exceptionally long lives as mooring lines. Testing at SES and analysis shows that, after the equivalent of 20 Hurricane Katrinas and 20 years static creep at 60% load (being the maximum in the fatigue load range 30% to 60%), the ropes retain 94% strength and have a residual life of 99.8% a new rope.

Work conducted by Higson at the University of Cambridge shows that elongation to failure is reduced by creep elongation. This allows us to set maximum permitted creep and a maximum permitted rope elongation or a critical elongation.

Creep progresses with wear but should not exceed 0.5%. Creep elongation greater than this heralds an unusual behaviour long before criticality is reached.

Rope elongation should not exceed a predetermined critical elongation of 7% to 8% depending on the rope.

The end point of tension-tension cycling is failure. The stiffness of the rope remains largely constant during cycling. After millions of cycles, the failure elongation can reduce to 6.5%. Although this behaviour is recognized it is shown not to be relevant to the mooring application where the actual fatigue is 0.2% of the rope's lifetime.

Elongation monitoring is proposed as a method to check the rope's behaviour, with a threshold elongation as the rope retirement criterion. This threshold elongation is gradually reduced in line with fatigue.

Introduction

This programme of work was undertaken to assess the utility of inserts in platform polyester mooring lines and an attempt to give guidance concerning an effective monitoring regime.

The work is divided into two parts; testing and analysis.

Testing

The tests were to subject mooring line sub-ropes to tension-tension fatigue, equivalent to 20 Hurricane Katrinas. After fatigue the sub-ropes were to be tested for residual strength and inspected for any possible wear. This would establish what impact, if any, tension-tension fatigue has on the lifetime of polyester mooring lines. If these tests could eliminate fatigue as a realistic wear mechanism in mooring lines, then overload, creep and external damage would become the only other possible life reducing mechanisms.

Analysis

Mooring lines have been subject to extensive fatigue studies, most recently in the Durability Study. The results from this study are examined in this report, particularly with respect to longevity and creep.

Yarn creep and its effect on tensile elongation has been studied at the University of Cambridge. The results show that, under constant load, creep elongation reduces the elongation to failure by that amount. An alternative way of expressing this is to say that creep plus elongation to failure is a constant. This study also provides the relationship between load and creep rate, so that creep can be calculated and, thus, the residual elongation to failure.

Finally the results are assembled into a simple concept, that provided a threshold elongation has not been exceeded, then mooring lines remain fit for continued use.

Rope Testing

The sub-ropes in this test programme were cycled at 45% +/-15% for 20,000 cycles. In the Durability Study, testing at NEL (see Tension-Tension Fatigue) was carried out at a mean load of 40%. This is slightly less severe than a mean load of 45%, however lifetime is mainly influenced by the load range. In any case, it is clear that, testing at 40% +/-20% is more severe than 45% +/-15%, We can be sure that the lifetime at 45% +/-15% will not be less than 8 million cycles, probably around 15 million cycles. Taking a conservative estimate of 10 million cycles to failure, we can say that 20,000 cycles, equivalent to 20 Hurricane Katrinas, represents 1/500th the lifetime of the rope and yet this is considerably greater abuse than the rope could possibly see in service.

Wear from 20,000 cycles

Previous experience has taught us that, in tension-tension fatigue, the very first cycles have the biggest displacements. The rope settles down as the components (sub-ropes and strands) adjust to share load evenly. This engenders some slight initial internal abrasion characterized by a minimal number of broken filaments.

Test carried out at Samson showed that the sub-rope residual strength after 20,000 cycles retained 94% strength with a modest increase in the coefficient of variation.

	New Rope Break Strength KIPS	Cycled Rope Break Strength KIPS
	79.19	75.56
	80.45	74.21
	80.36	76.24
Average	80.00	75.34
COV	0.88%	1.37%

Table 1 – New and fatigued sub-rope strengths

Yarn Examination

A short sample of a new sub-rope and a sample of a tested sub-rope, including an eye and its splice, were submitted for inspection and tensile testing.

Photograph 1 shows a general view of the new sample and Photograph 2 shows a general view of the tested sample



Photograph 1 - General view of new sample



Photograph 2 - General view of fatigued sample

The strands of the tested sample had a slightly 'crumpled' appearance but there was no sign of external damage to either sample.

Photograph 3 shows the strands of the tested sample, opened out to reveal their inner faces



Photograph 3 - Detail of fatigued sample

Only minor internal damage was seen, as raised filaments

The visual inspection revealed no significant difference between the two samples in terms of their general condition. Some minor internal abrasion was seen on the strands of the tested sample.

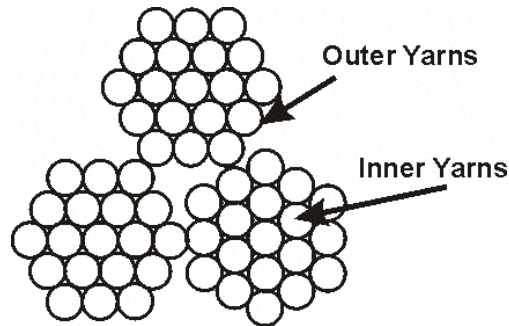


Figure 1- Schematic of Outer and Inner Yarns

Tensile Testing

A rope yarn was selected from each sample and divided into inner and outer textile yarns.

Tables 2 and 3 summarize the results from the new and tested samples respectively.

Textile yarn	Mean Breaking Strength N	SD N	CV %	Mean Breaking Extension %	SD N	CV %	Number tested
Inner	78.1	5.1	6.5	11.5	1.0	8.8	15
Outer	77.4	4.6	6.0	11.4	0.9	7.9	16

Table 2 - Tensile results for the textile yarns of the new sample

Textile yarn	Mean Breaking Strength N	SD N	CV %	Mean Breaking Extension %	SD N	CV %	Number tested
Inner	74.0	7.3	9.9	10.2	1.1	11.1	15
Outer	78.9	6.4	8.2	11.0	1.0	9.2	11

Table 3 - Tensile results for the textile yarns of the tested sample

It can be seen from Table 3 that the outer textile yarns of the tested sample have a higher average breaking strength than their inner partners. The breaking extension is also greater.

The increase in the Coefficient of Variation does follow the expected trend of being greater for the tested sample than for the new sample.

It would be expected that some change to the load extension curve of the tested sample would occur and that modulus changes would be detected. Figure 1 is a comparison of the load/extension curves of the inner textile yarns from the new and tested sub-rope

samples. The curves have been selected from the individual tests as having the closest breaking load and extension to the mean values shown in Tables 1 and 2.

Figure 2 is the same comparison but for the outer textile yarns.



Figure 2

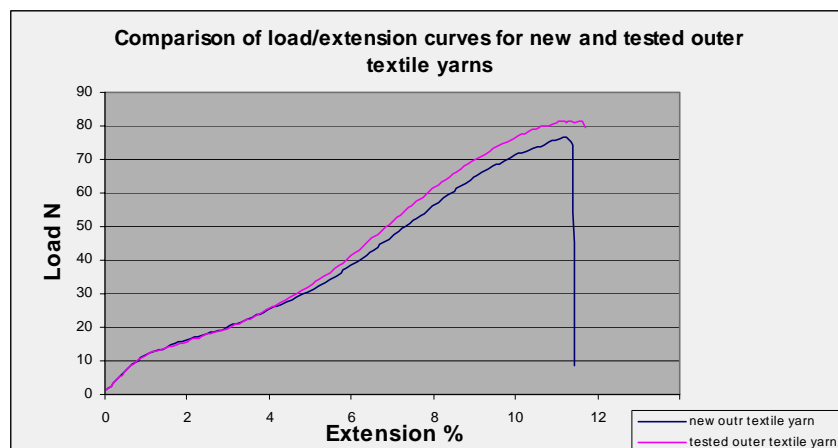


Figure 3

In both cases, it can be seen that beyond 2% extension, the two curves diverge, with the slope of the tested sample yarn being greater than that of the new sample yarn. Thus, there has been a change in the modulus of the polyester yarns, in that the yarns from the tested sample had 'stiffened' under the influence of the testing procedure. This stiffening is initial and occurs in the first few cycles. There is also a test related inaccuracy. Yarns are wrapped on capstans where the load decays before being clamped by the test machine grips. There is some slip on the capstans which may be less with used yarns. The slip increases the measured elongation. Worn yarns may slip less than new yarns and this will increase the measured stiffness.

In order to establish whether the splice zone is subject to greater wear, these tests were repeated with yarn taken from the tapered end of the splice.

Textile yarn	Mean Breaking Strength N	SD N	CV %	Mean Breaking Extension %	SD N	CV %	Number tested
Inner	76.5	8.5	11.1	11.1	1.5	13.1	20
Outer	68.9	7.3	10.6	9.8	1.1	11.3	20

Table 4 - Tensile results for the textile yarns of the tested sample, splice zone

The results show little difference in the splice area from the body of the rope. It should be noted that, due to entanglement, it was difficult to separate the textile yarns, particularly from the splice area. This entanglement occurs during rope manufacture and splicing.

Finally tests were carried out on the rope yarns. Rope yarns are easier to separate and show that no additional damage occurs in the splice region

Rope yarn	Mean Breaking Strength N	SD N	CV %	Mean Breaking Extension %	SD N	CV %	Number tested
Mid span	4858	237	4.9	NA	1.3	6.2	17
Splice zone	4818	259	5.4	NA	1.2	5.6	15

Table 5 - Tensile results for the rope yarns, tested sample, mid span and splice zone

The results of the yarn tests are in line with the results of the sub-rope tests and confirm the 94% retained strength. Since average strength is several percent higher than minimum rope break strength, this shows that, even after 20 Hurricane Katrinas, the mooring lines will still be operating within the design factors of safety for a new rope.

Durability Study

The purpose of the Durability Study was to demonstrate that polyester mooring lines had long fatigue lives. Elongation data was also captured continuously. The elongations were machine elongations and taken from pin to pin so that stiffness could be monitored. This necessarily included the spliced eyes which, to some extent, may distort the data as used for our purpose.

Absolute elongations were not recorded. The machine was set to zero with the rope load around 50% mean. For each cycle the load and elongation were captured some 50 times. By subtracting the first elongation at 40% load at the first cycle, zero elongation was reset to 40% mean.

The raw data gives a relatively wide band of elongations since the load varied from some 20% to 60% break strength. However the data allowed elongation to be extracted at any particular load (actually a small load range).

By examining data at the maximum load the elongation increase at failure could be determined

Data

The data is presented graphically for each fatigue test. It shows the increase in elongation measured between the mean load and the maximum load in each test i.e 40% load to maximum load.

For each load examined the elongation was extracted from each cycle

Test 1 40% +/- 17.5%, Endurance 13,424,920 cycles

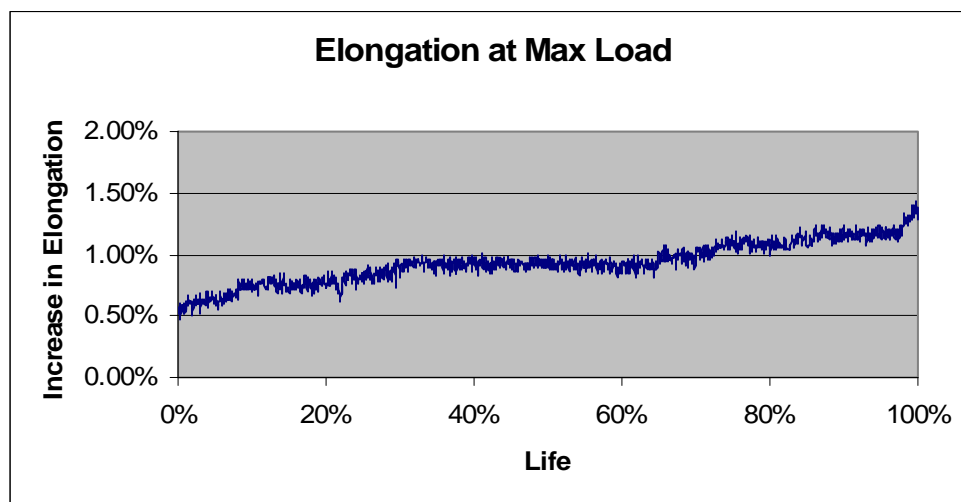


Figure 4 - Elongation at maximum load during 40% +/-17.5%

Test 2 40+/-20%. Endurance 8,181,270 cycles

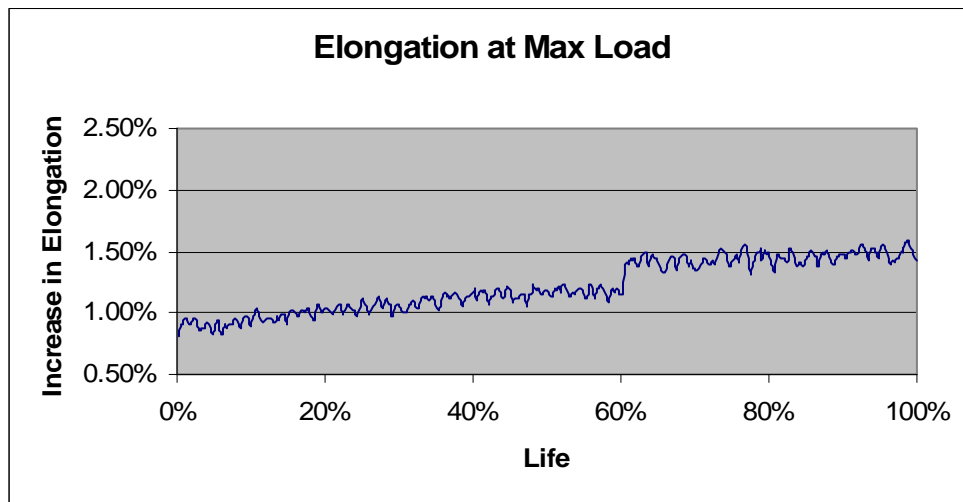


Figure 5 - Elongation at maximum load during 40% +/-20%

Test 3 40+/-22.5%. Endurance 3,624,620 cycles.

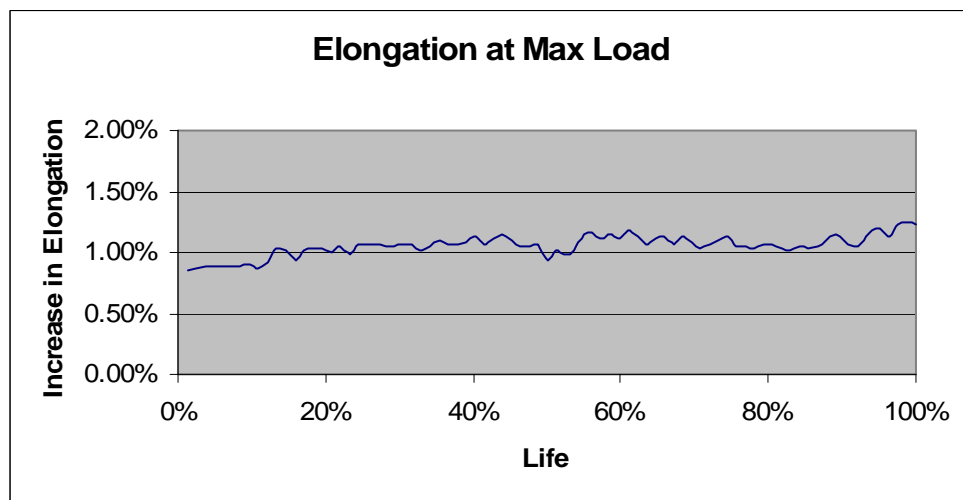


Figure 6 - Elongation at maximum load during 40% +/-22.5%

Test 4 40+/-25%. Endurance 2,046,520 cycles

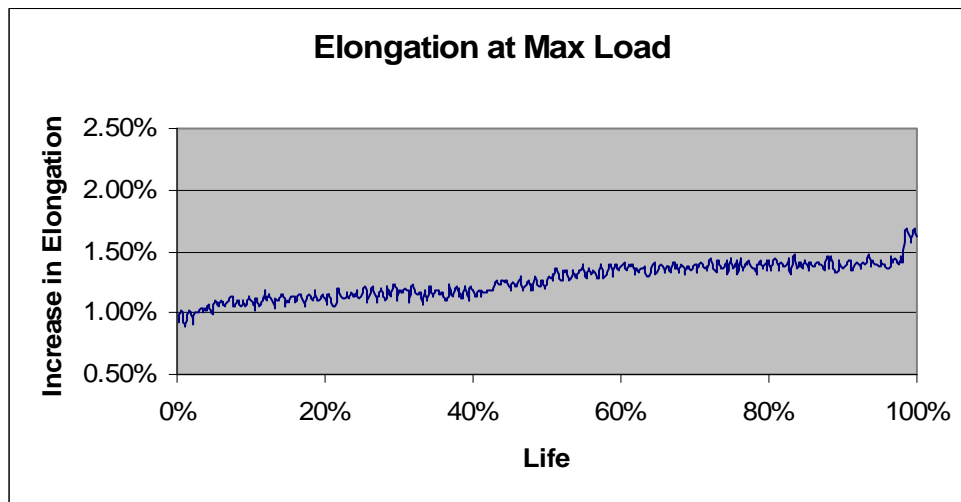


Figure 7 - Elongation at maximum load during 40% +/-25%

From these results, we can see immediately that polyester parallel strand mooring lines are capable of withstanding extreme abuse. Actual failure occurs after some 10,000,000 cycles which represents 10,000 Hurricane Katrinas. After 20 Hurricane Katrinas the ropes will be at the beginning of their fatigue lives (0.2%); virtually on the Y axis. Consequently, the ropes will have compacted to remove constructional elongation but without any long term creep.

The elongations in these results are pin to pin and include splices. It is not possible to determine the exact elongations over the body of the rope. It is reasonable to assume that after cycling the splices stiffen and become significantly stiffer than the body of the rope. Clearly creep precedes failure but the amount of creep may be somewhat larger than the 1% to 2% reported here.

Cycles to Failure vs Load Range

The log of the number of cycles to failure can be plotted as a straight line vs load range.

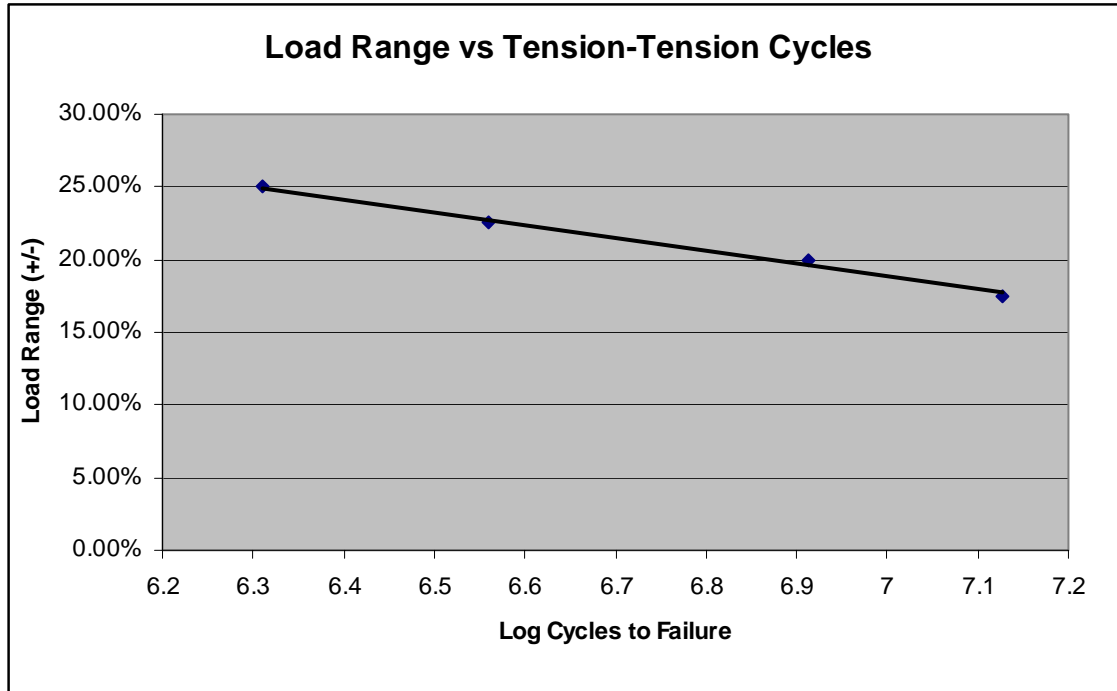


Figure 8 – Tension-tension fatigue cycles vs load range

It is worth noting that the 20,000 cycles, representing 20 Hurricane Katrinas represent the very early stages of the tension-tension fatigue cycling

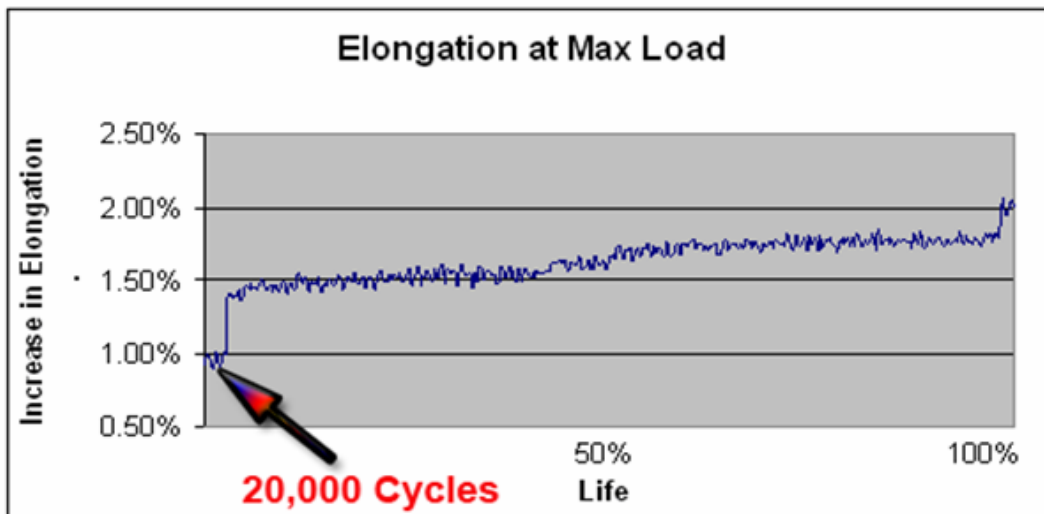


Figure 9 – 20,000 cycles vs 100% life

Break Elongations in Tension-Tension Fatigue

Referring again to the fatigue curves we see that there is a gradual increase in elongation. Taking for example the 40% +/- 25%

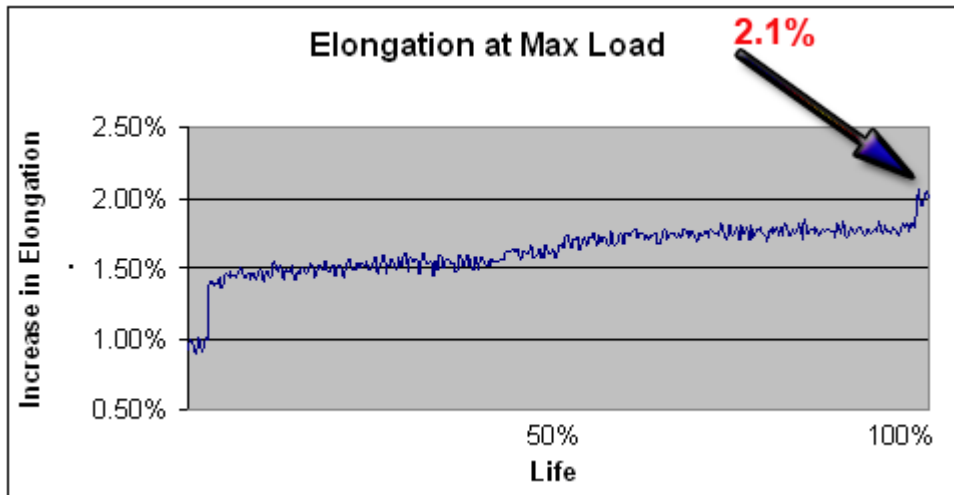


Figure 10 – Increase in Elongation at Failure (40% +/- 25%)

This 2.1% increase in elongation should be added to the elongation at 40% (the mean load). In the durability study this was not recorded. With a new rope elongation to failure of 11% , the elongation at mean load can be estimated to be 4.4%. In the example above this should be added to the 2.1% to give a failure elongation of 6.5%.

The actual rope load elongation curves were not recorded in the Durability Study. The curves for polyester ropes are not linear but, as a first order approximation, a straight line is reasonable and always fairly close to the actual elongation



Figure 11 – Straight Line Approximation for Polyester Yarns and Ropes

Thus in the durability study the actual elongations from new to failure were some 6% to 7%. These values are considerably lower than the nominal 11% to break of a new rope.

It also should be noted that there was no significant increase in stiffness of the rope. This is in slight contrast to the yarn results where some stiffening was measured. Initial stiffening, present in the yarn testing, but removed in the first few cycles is not available from the Durability Study. In ropes, this initial yarn stiffening can be masked by the rope constructional elongation

The step in elongation seen close to the start of the test was unexplained in the Durability Study. This was seen in 3 out of 4 tests and may have been an artefact of the test. If this is so, the actual elongations to failure can be reduced by some 0.5%.

The measurements made were pin to pin and include splices. Typically splices start with a stiffness some 10% lower than the body of the rope. The splice stiffness increases with cycling such that splices become 20% stiffer than the body of the rope.

Neither of these factors affect the general conclusion; elongations to failure reduce substantially with cycling.

In our case, however the cycling actually undergone in platform mooring is a tiny fraction of the rope's capability and, in the break test after cycling, the elongation to failure is only fractionally less than the new rope elongation to failure.

After 20,000 cycles the rope's break strength was reduced by 5.8%. This was reflected in the yarn testing and was due to some modest internal abrasion. If this strength loss is extrapolated linearly, we can calculate a lifetime of 138,000 cycles (i.e. to failure) or some 37,000 cycles to 10% strength loss. However, the rope is capable of more than 10,000,000 cycles. This demonstrates that the strength loss must be initial and not continued at the rate noted.

In practice, it seems that there is a small body of filaments that are vulnerable, for example, that cross over each other or are partially damaged in manufacture. These break early on and the remainder share the load and provide the exceptionally long lives we have come to expect with polyester mooring lines.

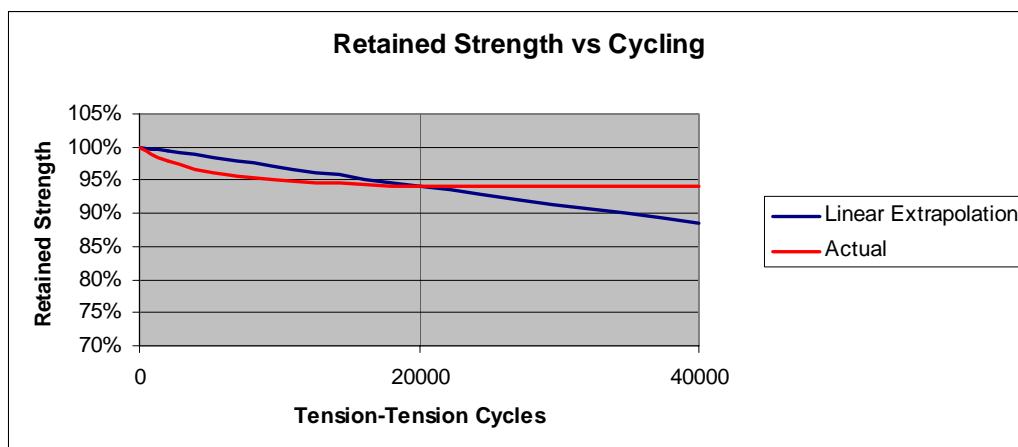


Figure 12 – Retained Strength vs Cycles

Cumulative Strain Model

Work was conducted by Angharad Higson at the University of Cambridge, which shows that creep reduces the elongation to failure by approximately the amount of creep. The entire thesis is provided as an appendix to this report.

Significantly, creep was carried out at a range of loads between 30% and 70% of break was measured using the Stepped Isothermal Method and the elongation to break subsequent to creep was measured. These results are presented in the following curves

The first curve (figure 13 from the thesis) shows the new yarn stress/strain curves with tensile failures typically around 10% to 12% elongation.

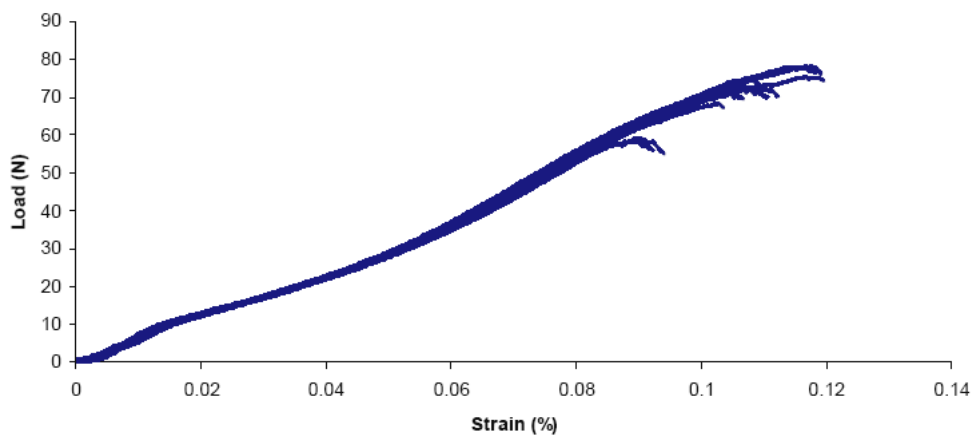


Figure 13 - Tensile curves for polyester fibres, tested at 20°C, of different gauge lengths, total of 12 curves on the plot.

Creep tests were then conducted on these yarns and the results are plotted in the following 2 figures

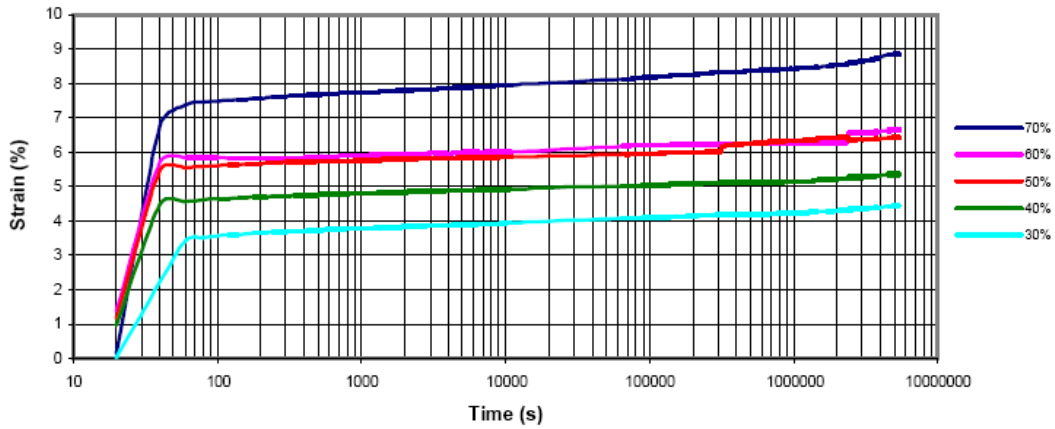


Figure 14 - Creep tests at varying loads

As can be seen, the reproducibility shown in these two tests series is good..

Finally the stress strain curves were measured after creep and the results are presented in the graph below. The starting point on the x-axis is the measured accumulated creep.

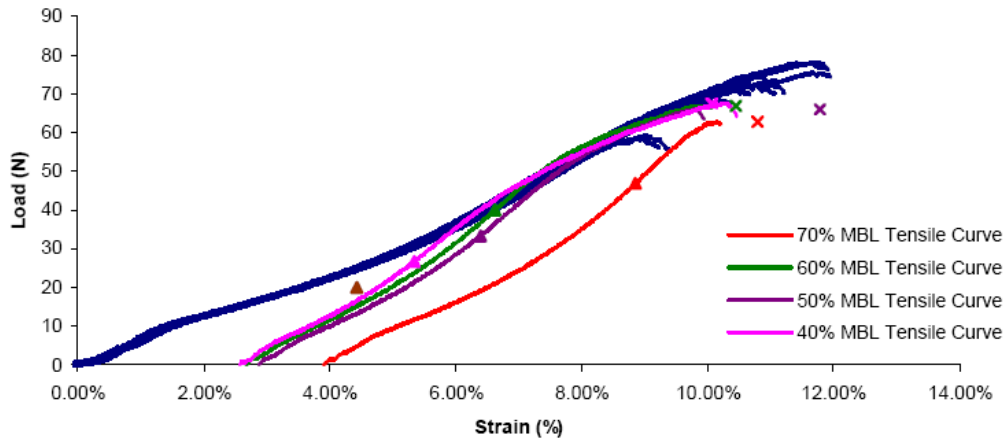


Figure 15 - Tensile test results after creep

The creep rates given in the Higson paper can be averaged and graphed. They show a good fit to a fifth order polynomial.

Creep Rates / Decade			
Load	Set 1	Set 2	Average
0.7	0.235	0.219	0.2270
0.6	0.153	0.148	0.1505
0.5	0.124	0.099	0.1115
0.4		0.12	0.1200
0.3	0.136	0.155	0.1455

Table 6 – Measured creep rates

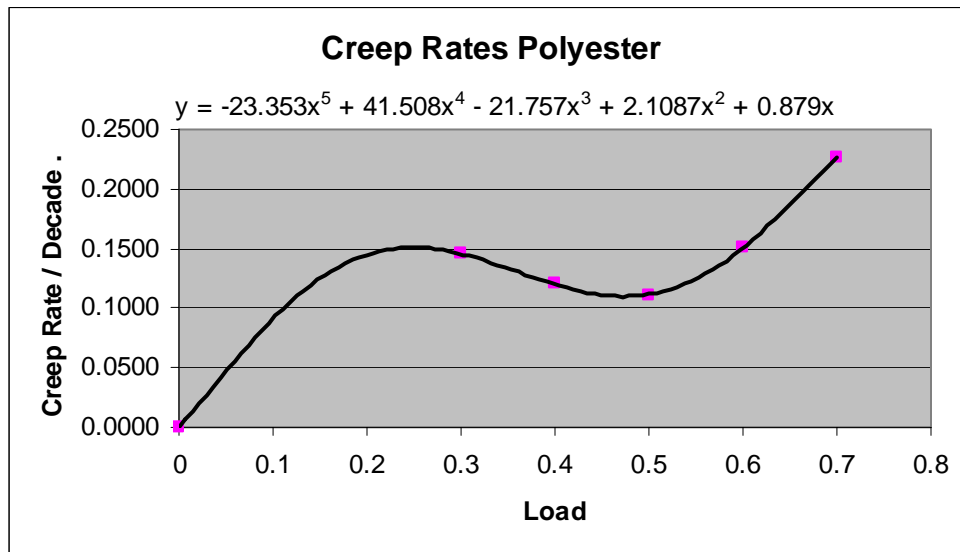


Figure 16 – Creep rates

Creep Elongation

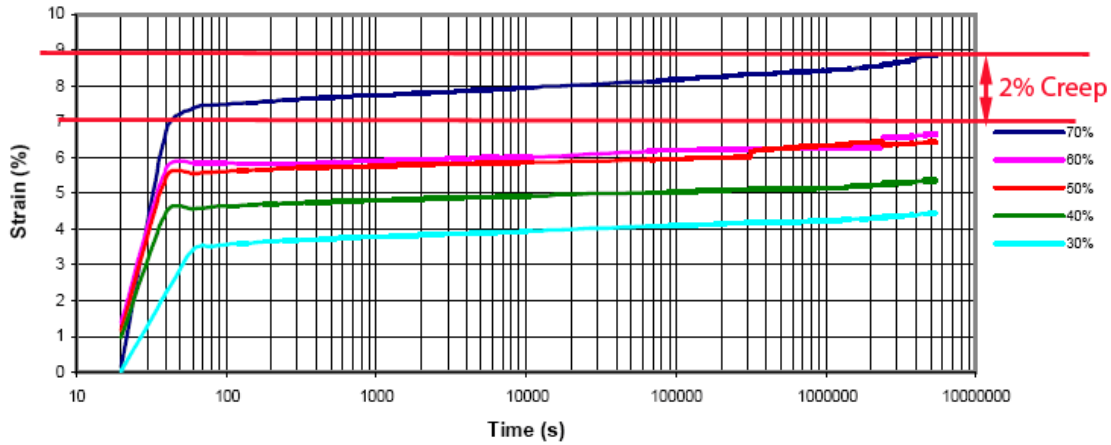


Figure 17 – 2% creep elongation at 70% load

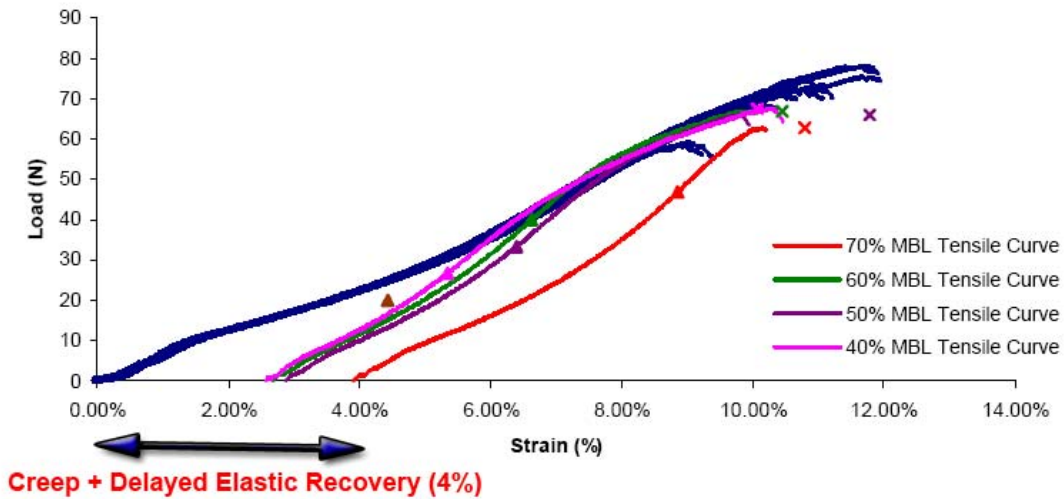


Figure 18 – 4% creep elongation plus delayed elastic recovery at 70% load

There is a difference between the creep recorded in the creep test and that shown on the subsequent tensile test curves. For example, the creep results for 70% load, show an elastic elongation to 7% strain followed by 2% creep to a total of 9%. The yarn was removed from the creep tester and then allowed to relax to zero load, when the length was measured and then immediately taken to break. This showed a 4% increase in length, or twice the apparent creep over the test period. All the results show the same trend; that is the apparent creep measured during the creep test is less than the residual elongation measured immediately after the test. After one week this residual elongation will have reduced, possibly even halved. This can be explained by “delayed elastic creep”. After unloading, yarns contract and continue to contract over a period of time, stabilizing after a week or so.

The final amount of creep is the increase in length at no load as shown in the final tensile tests. All these results demonstrate that the creep elongation added to the failure elongation lies in the range of the initial elongations to failure of new untested yarn.

Elongation to Failure

From these results we can now say that:

$$\text{Failure Elongation} = \text{New Failure Elongation less Creep Elongation}$$

Creep elongation can be calculated by multiplying the creep rate by the number of decades under load.

Creep Rate

The creep rate, up to 70% load, can be calculated from the polynomial

$$\text{Creep Rate} = aL^5 + bL^4 + cL^3 + dL^2 + e$$

Where L is the per unit load and a, b, c,d and e are constants.

Using the constants shown with the creep rate curve we obtain the following creep rates

Load	0.30	0.40	0.50	0.60	0.70
Calculated Creep Rate	0.146	0.120	0.112	0.151	0.227

Table 7 – Calculated creep rates

Creep is logarithmic. The number of decades is dependant on the tensioning time. In tensioning mooring lines this may be as much as 1 day.

This data represents creep over 70 days. There is some evidence to show that creep rates fall over an extended period of many years.

$$\text{Number of Decades} = \log_{10}(\text{Creep Period/Tensioning Time})$$

Decades (Tensioning Time = 1 Day)							
Period	10 days	1 Month	1 Year	10 Years	20 Years	30 Years	100 Years
Decades	1.00	1.48	2.56	3.56	3.86	4.04	4.56

Table 8 – Creep Decades

Given a tensioning time of 1 day, the number of decades in 20 years = 3.86

The calculated creep elongation after 20 years at 40% is then $3.86 * 0.12 = 0.463\%$

If the minimum new elongation to failure is 10%, then the current elongation to failure is now 9.537%

Stiffer polyester yarns have even lower creep rates. Work conducted by Celine Lechat at the Ecole des Mines in Paris produced the results shown in figure 23.

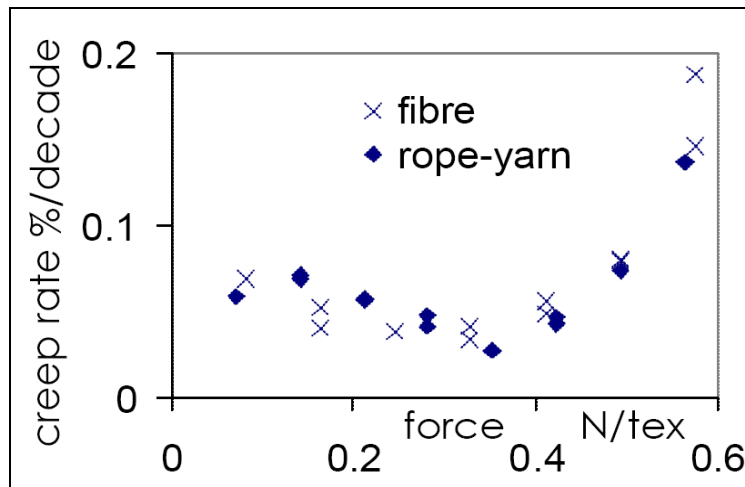


Figure 19– Creep rates for stiff polyester yarn (Celine Lechat)

Table of Creep Elongations

Using the polynomial given in Figure 13, a table of creep elongations can be drawn up against time and load.

Creep Elongation Matrix						
Years	P.U Load					
	0.1	0.2	0.3	0.4	0.5	0.6
10	0.325%	0.517%	0.518%	0.428%	0.397%	0.536%
20	0.352%	0.560%	0.562%	0.464%	0.431%	0.582%
30	0.368%	0.586%	0.588%	0.485%	0.450%	0.608%
40	0.380%	0.604%	0.606%	0.500%	0.464%	0.627%
50	0.388%	0.618%	0.620%	0.511%	0.475%	0.641%
60	0.396%	0.630%	0.632%	0.521%	0.484%	0.653%
70	0.402%	0.639%	0.641%	0.529%	0.492%	0.663%
80	0.407%	0.648%	0.650%	0.536%	0.498%	0.672%
90	0.412%	0.655%	0.657%	0.542%	0.504%	0.680%
100	0.416%	0.662%	0.664%	0.548%	0.509%	0.687%

Table 9 – Creep elongations vs time and load

The data can also be presented graphically showing the maximum expected creep.

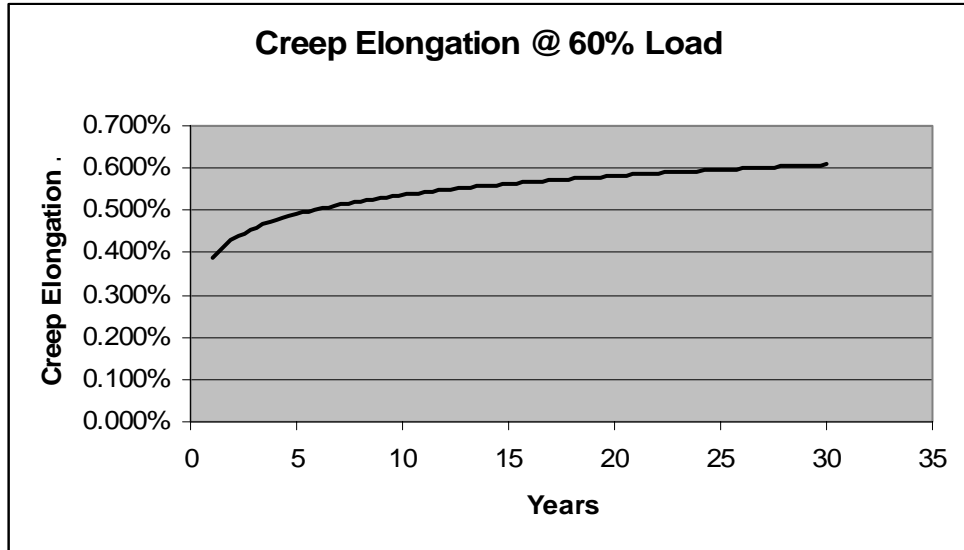


Figure 20 – Maximum expected creep

If the rope creep is greater than that of the curve in Figure 20, then the rope is exhibiting unusual behaviour and merits further investigation. This could trigger insert recovery and tests to confirm the residual lifetime.

Creep Rupture

The end point of creep is failure or stress rupture. The relationship between load and lifetime under load is given by the equation below.

Stress Rupture Log Life (s) = a + b/L		
Fibre	a	b
Polyester Yarn (Diolen)	-17.7	18.2

Table 10– Stress rupture constants

Where a and b are constants and L is the per unit load.

Based on these constants, a table of lifetimes and consumed life may be drawn up.

Creep Rupture - Diolen		
Load	Lifetime (Years)	Consumed Lifetime after 20 years
50%	1.58925E+11	0.000000013%
55%	78,001,416	0.0000256%
60%	136,310	0.0147%
65%	633	3.16%

Table 11 – Lifetime under load

Quite obviously, loads above 65% of the breaking strength are required for a very extended period of time to impact the strength in a 20 year period. This is a very remote possibility. However, should the rope become permanently overloaded, this will be evident from accelerated creep.

Strain Based Failure Method

An alternative way of using this data is to set a critical elongation that the rope is not allowed to exceed. This is made up of elongation under load plus creep elongation.

$$\epsilon_{\text{crit}} = \epsilon_{\text{load}} + \epsilon_{\text{creep}}$$

For example, we might say that the rope may never exceed 50% load with an elongation of 5%. Lifetime's creep is less than 0.5%

$$\epsilon_{\text{crit}} = 5\% + 0.5\% = 5.5\%$$

A more general expression that includes bedding elongation

$$\epsilon_{\text{crit}} = \epsilon_{\text{load}} + \epsilon_{\text{creep}} + \epsilon_{\text{cycling}} + \epsilon_{\text{bedding}}$$

allowing 3% for the bedding elongation and no cycling elongation

$$\epsilon_{\text{crit}} = 5\% + 0.5\% + 0\% + 3\% = 8.5\%$$

This method lends itself to the use of telltales which could be installed on the mooring lines.

Remaining Life

Taking a conservative approach,:

20 Hurricane Katrinas are equivalent to a 0.2% loss of life.

20 years creep at 60% load represents 0.0147% loss of life

Remaining life after 20 years is 99.785%

Applying the Cumulative Strain Model to Fatigue and Creep

In tension-tension fatigue, the rope's elongation to failure reduces. There is insufficient data to determine the exact relationship between fatigue and failure elongation.

Reasonably, the elongation may hold up for most of the life and decline most rapidly at the end of life. More conservative, but less likely, is a linear relationship.

This is illustrated in Figure 24

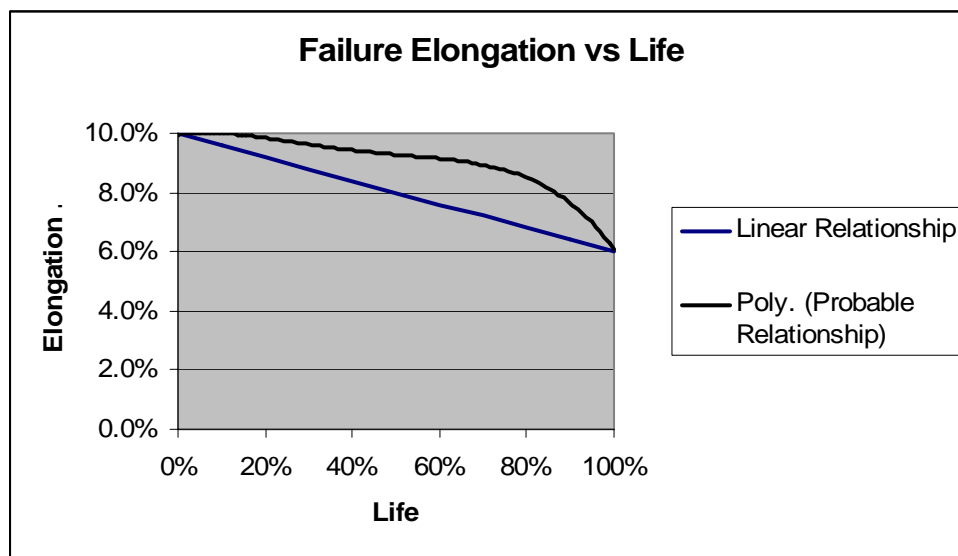


Figure 21 – Possible Failure Elongation Relationships

It should be emphasised that , in platform mooring, only a tiny fraction of the fatigue life is expended in fatigue during 20 or 30 years and the reduction in failure elongation is very small.

Taking the conservative linear relationship, the elongation to failure may now be calculated with respect to life.

Failure Elongation (wear) = Failure Elongation (initial) - 0.4* Remaining Life

The remaining life may be calculated from knowledge of the weather conditions and the calculated load range, using an equation of the type

$$\text{Log } N = a + bL$$

Where N = Number of Cycles to Failure

L = Load Range

a is a constant (= 10 for polyester ropes)

b is a constant (= 0.1 for polyester ropes)

A threshold elongation may now be set, which if exceeded, would require rope retirement.

Threshold Elongation = x% Failure Elongation (wear)

Actual Elongation = Elongation due to Load + Creep + Semi-permanent Elongation + Added Elongation from Tension-Tension Fatigue

Conclusions

In reality polyester parallel strand mooring lines can withstand a Hurricane Katrina every year for 10,000 years. Consequently tension-tension fatigue is not a candidate failure mechanism in this application.

Overload, although unlikely, does accelerate creep and creep rupture. If continuous overload were to occur this would be evidenced by creep elongation. The maximum creep elongation expected in 20 years is 0.58%. If creep exceeds about 0.5% (10m in a 2000m mooring line)or is greater than that shown in Figure 20, then the rope is exhibiting unusual behaviour. This is the right time to recover inserts and to determine residual rope lifetime and whether replacement is required.

Rope monitoring could be carried out by setting a threshold elongation, which, if exceeded would require the rope retirement. Because of tension-tension fatigue effects this would be a slowly reducing target.

APPENDIX E.

MMS Polyester Rope Risk Workshop

September 6, 2007

PARTICIPANTS

- | | |
|--------------------------------------|--------------------------------------------------------------|
| 1. Tom Fulton, Intermoor | 12. Evan Zimmerman, Delmar |
| 2. Todd Veselis, Intermoor | 13. Lori D'Angelo, MMS – Washington |
| 3. Kathy Marshall, Technip | 14. Ken Huang, ABS |
| 4. Jianan (Jay) Wan Technip | 15. Justin Gilmore, Sampson Ropes
(Supplied Test Samples) |
| 5. Hongbo Shu, Shell | 16. Nick O'Hear, TTI Ltd |
| 6. King Him Lo, Shell | 17. Ray Ayers, Stress |
| 7. Paul Devlin, Chevron | 18. Steve Banfield, TTI Ltd. |
| 8. Jenifer Gaulden, Anadarko | 19. Cesar del Vecchio, Petrobras |
| 9. David Petruska, BP | 20. Carlos Mastrangelo, Petrobras |
| 10. Christy Bohannon, MMS | 21. Jim Grant, BP. |
| 11. Robert Garrity, Delmar - Missing | |

AGENDA

- | | |
|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. 9:00 | Welcome, Introductions, Workshop Purpose - Ray Ayers, Stress (15 min) |
| 2. 9:15 | MMS Damaged Rope Inspection Project Overview – Ray (15 min) <ul style="list-style-type: none">a) Evaluate Damaged Rope Remaining Lifeb) Evaluate in situ non-invasive Inspection for Damage - propose conceptsc) Evaluate effectiveness of Insert Recovery/Testing & propose other methods.d) Determine risk of insert recovery. |
| 3. 9:30 | Results from 20 Hurricane Physical Testing – Macro and Micro – Ray (30 min) |
| 4. 10:00 | Analysis of 20 Hurricane Rope Damage based on API 2SM Dave Garrett (15 min) |
| 5. 10:15 | Break |
| 6. 10:30 | Workshop: Risk/Benefit of Recovering/Testing Inserts vs. Other Methods. Facilitator: Ray <ul style="list-style-type: none">a) Describe FMEA Methodb) Collect “data” from attendees. |
| 7. 11:30 | Lunch |
| 8. 12:00 | Continue Risk/Benefit Workshop - Ray |
| 9. 1:30 | The Fundamentals of Rope Life – Nick O' Hear, TTI |
| 10. 2:00 | Proposed Inspection Methods |
| 11. 2:15 | Meeting Summary and Action Items |
| 12. 2:30 | Adjourn |

RISK WORKSHOP SUMMARY

by Ray Ayers

Workshop Scope

Although the main project objective focuses on the accuracy of damaged rope NDT methods, a secondary objective deals with remaining rope life and the value of insert recovery. This summary deals with the latter objective.

Based on the Risk Workshop Results and the 20 Hurricane data we showed you, there are some conclusions that we are in the process of making.

CONCLUSIONS REGARDING THE BENEFIT OF INSERT RECOVERY:

1. The three highest risks that affect polyester mooring rope integrity are:
 - Third-Party Damage (like down lines severing the polyester)
 - Poor Quality Splices (reducing rope strength). The more inserts placed in the mooring spread the higher the risk of a bad splice.
 - Dropped Rope (causing sand particle ingress which increases rope wear during cycling)
2. Various sets of test data (this study, Durability Study, Whitehill, Accordis tests) show that rope creep and (hurricane) cyclic wear on well-constructed and well-installed rope are not an appreciable factor for a combination of 20 hurricane Katrinas hitting head on and 20 years of operation.
3. Poor quality splices can be minimized if not eliminated by effective quality assurance processes during manufacturing and before installation, and not by Insert Recovery..
4. Dropped rope after installation is a risk that can be minimized if Inserts are not recovered. The results of dropped rope can be simulated on land without Insert Recovery.
5. Insert Recovery does not improve any of the risks listed above. Industry has sufficient knowledge of cyclic wear and creep to know that they are not a credible structural integrity issues, and further, if they were, they cannot be solved by Insert Recovery.
6. ROV Inspection is a risk, but the value is in determining if there has been any 3rd party damage, the greatest risk of all. Thus, ROV Inspection is far more valuable than Insert Recovery.

CONCLUSIONS CONCERNING THE RISK OF INSERT RECOVERY

Background

FMEA charts were constructed for:

1. Normal Operations after Installation
2. Insert Recovery Process Based on Intermoor Process
3. ROV Inspection Process

And then they were reviewed in detail with Todd Veselis of Intermoor, making whatever changes were needed based on our discussion.

I have summarized the findings as follows:

Data:

POLY MOORING SYSTEM Operational Processes	Number of Failure Modes	Approx. Exposure Time	RPN = Sum of Product of Severity and Occurrence Indices
Normal Operations	6	20 years	129
Insert Recovery Operations	19	75 Days (20 times)	399
ROV Inspections	5	75 Days (20 times)	112

See the FMEA details in Appendix J.

Risk Conclusions from Workshop

1. Risks can never be eliminated. The question is: "What risks are prudent?"
2. The Normal Operations failure modes are small in number, high in severity and low in frequency of occurrence. They are failure modes similar to that of other non-polyester moored drilling and production systems in the GOM in which inserts are not recovered.
3. The Insert Recovery Process involves 19 failure modes. Three times the failure modes of that for Normal operations, and they are specific to perhaps only 75 days out of 20 years.
4. The ROV Inspection Process involves only 5 failure modes as contrasted to 19 for insert recovery. This too, is specific to perhaps 75 days over 20 years.

5. All of the products of Severity Index and Occurrence Index are similar, so nothing to be learned there.

Overall Risk/Reward Conclusions

1. Insert Recovery shows no appreciable value but it adds significant risk, and is not only unnecessary but it adds unnecessary risks.
2. ROV Inspection, although risky, is valuable, because it mitigates the greatest risk of all: 3rd party damage.

Valuable Help Provided Following the Workshop:

1. Intermoor and Todd Veselis provided assistance in the Insert Recovery Process and in the FMEA.
2. Anadarko (Jenifer Tule) and BP (Jeff Geyer) provided valuable risk information for input to the FMEA
3. Anadarko (Jenifer Tule) and Technip (Kathy Marshall) provided valuable ROV video inspection information.
4. Lori D'Angelo helped us get an extension on the project closing date so that we can deliver a better quality report.

MMS RISK WORKSHOP MEETING NOTES

Taken From The Flip Chart Sheets by Ray Ayers, Stress

Challenges

- Availability of adequate vessels
- Ability to disconnect connections (pins to remove-frozen)
- Simultaneous operations – producing while recovering
 - Offsets
 - Multiple vessels in close proximity
 - Rope contact from downlines
- Weather drive-off – mechanical damage
- Two Boats better than one for recovery - One to hold the ground chain
- Not monitoring ROV with hook at touchdown.
- Lines down in water
- Never allow work wires except during recovery
- Recovery is actually “uninstalling” - Reverse process
- Grouped moorings adds to congestion
- Risers to worry about as well

- Higher tensions on other side
- Use AHVs – smaller than installation vessels
- Complicated by hurricane
- Insert recovery needs to be covered in initial design
- Having enough chain between poly segments helps with the recovery operation
- Problems with loop currents
- FPS preparations: get winches, change offsets, ballasting
- Using normally unused components for the recovery adds the risk of component failure due to disuse (winches on deck)
- Chain runaway is a fear
- Loss of AHV position
- Lowering line cutting mooring legs
- ROV line as well
- Extra offshore operations
- “Exclusive zone” removed for insert recovery
- Can’t re-tension cable - Have vessel offset, and can’t get it back
- Risk of accidents and injury/death to deck hands

INSERT RECOVERY AND TESTING

Pros:

- By doing such, operator is permitted to keep operating
- Check on fiber degradation
- Discover “unknown” degradation
- Having a historical database – but no standard test
- Learn breaking strengths of rope or subropes
- Use extra subropes from insert to perform research/testing

Cons:

- Many more connections in mooring legs
- You only get one full rope test – what if you have bad result
- High scatter in results for one insert makes it hard to make significant conclusions – can’t correlate with other data
- If you have a failure of the test equipment, you have no test result
- Inserts are very short, and they are harder to make than long segments – human errors during manufacturing
- Inserts less tolerant than long segments – we get “sawtooth” load results, usually due to improperly constructed splices.
- For production testing (to qualify rope) there is more attention to detail on the inserts, but after this, making inserts during manufacturing is not as controlled.

- During production testing, when we get bad results, we throw out the result based on some problem. But you cant do this in recovery operations testing.
- Length limitations of testing machines (13 to 15 meters) results in the inserts being all splice and little mid section.
- In short inserts, deformation of the eye section causes problems with obtaining statistically consistent results.
- Can't extrapolate results from one recovered/tested insert to the rest of the mooring system.

Alternatives to Insert Testing:

- Perform simulated insert testing with onshore inserts subjected to real measured offshore loads.
- Use tension monitoring instead
- Count the links of chain on deck over time – rope elongation measurement
- If you bed in rope during installation, the tensions will remain the same over time.
- Concerned about accuracy of tension measuring equipment might be a problem, especially with zero drift over time
- Use API 2SM test – 100,000 cycles
- Use computer modeling plus load measurement to monitor mooring leg performance
- Can instrument chain stops and load pins
- Use 3rd party ROV inspection – 100% - down front side and back on rope backside, each leg.

MMS meeting notes 6 September 2007 *Notes Taken by Steve Banfield, TTI*

A. The Following Comments were offered during initial discussions:

1. Petrobras has left ropes in with damage for 1-2 years before replacement, because hey have ample margin. Normal Safety factor +25%.
2. Delmar has seen rope fusion in previously submerged mooring ropes due to a break. This confirms the value of the MMS JIP findings on rope fusion effects during break tests in California.
3. A GOM operator pointed out that fatigue loads are lower in Brazil when compared with the GOM, so there is a lower probability of a higher load.

4. One operator commented: If the rope necks down it is not possible to determine how much damage you have. When using ROV and looking through lens it is very difficult to assess damage along length
5. One operator pointed out that, statistically, the damage to a splice will be lower due to ratio of short length splices to long length mooring line
6. In some inserts, the polyurethane coating over splice penetrated through and stick to subropes. This should be addressed in future designs. Filter cloth should extend through slice to prevent PU penetrating into load bearing subropes.
7. For break tests, several operators use 100 cycles to 30% for bedding in, in accordance with ISO.
8. Another operator compared breaks tests using 10 cycles 1-50% and 100 cycles 10-30% and found no difference.
9. SJB stated that the Durability JIP used 10 cycles 1-50% and achieved a very low coefficient of variation around 1%.
10. One operator found in tests that strength increases with increasing rate of loading.

B. Risk Brainstorming Comments for FMEA

The audience was asked to list operational concerns during installation and recovery:

- Consensus that during installation there were not real concerns, it was mainly during recovery that concerns were prevalent.
- Availability installation vessels
- Ability to disconnect shackles/links etc
- H link pins corroded
- Typically have to cut connector to remove, could result in damage to mooring line
- Petrobras have a policy to cut off connectors and replace with new, as these items are the weak link in a mooring
- Simultaneous operational production whilst recovering, concerns are bottom contact while reducing tension and offset.
- Main mooring runs over stern, high risk to rope, say during vessel manoeuvring, sharks jaws, deck equipment operations etc.

- Have to stopper off on INSRT, 50 kips required to hold up the weight of the mooring system. Sometimes have to grab onto bottom chain to ease tension on stopper, this presents another danger to mooring line.
- Petrobras never allows work wire in same vicinity as mooring lines, but this does not always happen in practice.
- The D/d over stern roller should not be an issue. If it is too low, then you are using wrong vessel.
- Stern angle clearance could be an issue, it was reported by one operator that they had damage due to rudder contact.
- Mooring lines grouped close together, say 10 apart, give little space between lines for error when using grab.
- Operators design in a short chain length between mooring line segments, so easy to grab and hold in sharks jaws. Sometimes the grabs are on the H link.
- Preparations/concerns on FPS include
 - Run messenger chain
 - Ballasting
 - Offset
 - Winches may have seized, or will not have as “new capacity”
 - Winch fails, run out of mooring line
 - Loss of station keeping
 - ROV line contact
 - Work wire contact in tight mooring line cluster
 - Polyurethane coating damage over splice
 - Sling for stoppering failure biggest risk, use dual system

C. From brainstorming of Pros and Cons of Insert Recovery:

<i>PROS</i>
<ul style="list-style-type: none"> ❖ Measure any fibre degradation ❖ Discover an unknown ❖ Historical database, but needs standardised test method ❖ Subrope strength database ❖ Detailed internal examinations, research ❖ INSERT props ❖ Keep operating permit ❖ Main mooring higher strength than INSERT

CONS

- ❖ Handling damage
- ❖ Damage to facility/people
- ❖ More connectors increase risk failure
- ❖ Bad tests results/correlation
- ❖ Typically large scatter
- ❖ Bad test = no answer = get another INSERT
- ❖ INSERT is weak link, more splices = less reliable
- ❖ INSERT has low tolerance on subrope length variability
- ❖ Scaling of length does not lend to the short INSERTS
- ❖ Eye deformation over life increases subrope variability

Additional Comments:

- One operator found that during internal inspections, that 40% of splices were made incorrectly, splices are human made and in production more likely to have errors
- **If Petrobras removes an insert, they never break the whole insert, but take apart for detailed examination and testing subropes/yarns. They now test inserts every 5 years and plan to go to 10 year interval. All new installations in Brazil do not have inserts.**
- Tension range with polyester is around half or less than an equivalent steel mooring system.
- A hurricane passed directly over Red hawk, they measured environment and ran mooring analyses to confirm system is still performing to design. They then ran the loadings on a new sample of rope from this analysis to replicate any damage, but found none, so why remove and INSERT.
- One operator believes that - provided tension are monitored and found within design limits, there is no additional information obtained from the evaluation of INSERTS removed from service.
- But not all floaters have tension monitoring.
- When asked about having to re-tension a mooring, Red Hawk has not had to re-tension yet. However, they put a lot of effort to tension highly during installation to bed-in mooring lines.
- It maybe possible to count chain links to monitor creep.
- A 0.5% length change could not be picked up in a traditional catenary mooring, but should be possible in a taut mooring.

- One operator suggested that the angle change at top of mooring could be used to monitor length.
- Another operator said that tension monitoring and angle change could be used to check that mooring still operating within design limits.
- It was stated that INSERTS originally were designed to identify unknown mechanisms and are not needed. The highest risk is now external mechanical damage and this should be studied in preference to fatigue and creep.
- An operator pointed out that there is a high risk trying to run an ROV along a mooring line using a manipulator.

Appendix F:

Petrobras' Advice on Insert Recovery/Testing

Reasons for not using Inserts in Systems with Polyester Ropes

API RP 2SM recognizes the following factors as being possible to limit the life of synthetic fiber ropes: hydrolysis, heating and internal abrasion, tension-tension fatigue and axial compression fatigue (item 3.3.4). Creep rupture is also mentioned (items 3.3.3 and 4.6.3), however the Recommended Practice says that "Polyester and aramid ropes are not subject to significant **creep** at loads normally experienced in mooring applications".

For **Fatigue**, It has been already shown that:

- 1- high efficiency polyester fiber ropes outperform steel components of the mooring lines in fatigue (API RP 2SM);
- 2- systems incorporating polyester fiber ropes show typical wave frequency cyclic tension ranges which are half or less than the corresponding ranges in all steel systems (refs. Chaplin & Del Vecchio 1992 and API RP 2SK Appendix H)

Hydrolysis was certainly a concern in 1994 when 2 x 300m lengths were installed in P-22 and P-9 and in 1997 when full systems were installed in P-19, P-26, FPSO-II and P-34. Today there is no reason to believe that Hydrolysis will significantly reduce the strength of a high efficiency polyester rope in a deepwater application as shown by Petrobras experience. This is also recognized in API RP 2SM, provided rope temperature is lower than 30C (item 4.6.10).

Heating and internal abrasion have not been observed in any of the inserts and complete mooring lines recovered by Petrobras. Also it has not been observed in the test samples of high efficiency polyester fiber ropes in several JIPs, except for one sample cycled between 15 and 65% of Average BS for 3.3 million cycles which failed adjacent to a splice (Berryman). This condition is clearly not relevant for a DW moored permanent installation.

Axial compression fatigue is cause for concerned particularly in aramid ropes, fact that is known now for more then 20 years. API RP 2SM provides conservative guidance for polyester ropes restricting the number of cycles bellow a minimum tension to 5% of MBS while in service and 2% in pre-deployment. So far this failure mode has not been observed in moorings operated by Petrobras. Therefore we consider that limiting minimum tensions is an effective way of dealing with this failure mode. In addition to that Petrobras requires that polyester ropes have a minimum tenacity of 0.47 N/tex (ISO 18692). This ensures that rope construction has low twist or long braid pitch resulting in higher tolerance to cycling at lower tensions.

External abrasion and cut resistance clearly cannot be evaluated by removing samples since only by chance this kind of damage will happen in the inserts.

Conclusion

In this way it is our current thinking that, provided tensions are monitored and found within the design limits recommended by current documents, no additional information is obtained from the evaluation of inserts removed from service.

APPENDIX G

PETROBRAS POLYESTER MOORING HISTORY

POLYESTER ROPES IN PETROBRAS PROJECTS (5/01)

Unit	WD (m)	Supplier	MBL (tonne)	Date	Type	Field	Type	Anchor
<i>P-IX</i>	230	Phylistran	500	1995	FPS	Corvina	Cat.	DE
P-XXII	115	MRL	500	1995	FPS	Moréia	Cat.	DE
FPSO-II	1420	MRL/CSL	711	1998	FPSO	Marlim South	Cat.	DE
FPSO-II	1200	MRL/CSL	711	1999	FPSO	Marlim South	Taut	VLA
P-34	835	MRL	711	1997	FPSO	Barracuda	Cat.	DE
P-19	770	MRL	711	1997	FPS	Marlim	Taut.	SP
IMO-1	420	CSL	494	1997	Buoy	Bijupirá-Salema	Cat.	DE
P-26	990	MRL	711	1997	FPS	Marlim	Taut	SP
IMO-3	830	CSL	494	1999	Buoy	Marlim	Cat.	DE
P-27	530	CSL	630	1998	FPS	Marlim	Taut.	VLA
AVARÉ	550	CSL/MRL	490/630	1998	SSO	Marimbá Leste	DICAS	DE
P-47	850	CSL	711	1999	FSO	Roncador	Cat.	DE
P-36	1360	(1)	1000	2000	FPS	Roncador	Taut	VLA
Espadarte	800	CSL	1000	2000	FPSO	Espadarte	Cat.	DE
P-38	1080	MRL	711	2000	FSO	Marlim South	Cat.	DE
P-40>36	1360	CSL	1000	(P-36)	FPS	(Roncador)	Taut	VLA
MODU	750	CSL	630	2000	MODU	Bijupirdá-Sal.	Taut	VLA
P-43	800	(2)	1000 ⁽³⁾	2003	FPSO	Barracuda	DICAS	VLA
P-48	1000	(2)	1000 ⁽³⁾	2003	FPSO	Caratinga	DICAS	VLA

APPENDIX H:
DETAILED LIST OF FAILURE MECHANISMS
FACTORS THAT REDUCE ROPE STRUCTURAL INTEGRITY

Key Environmental Factors - Active over a 20-Year Life:

1. Hurricanes – These have been studied for decades, and knowledge has matured. Failure would occur to the mooring due to overloading or loss of residual strength to the polyester due either to fatigue or creep.
2. Loop/Eddy Currents – These are primarily found in deep waters of the Gulf, and can provide sustained high currents throughout the water column. Knowledge is maturing on this. Failure would occur to the mooring due to overloading or loss of residual strength to the polyester due either to fatigue or creep.
3. Growth and ingress of marine organisms in the rope core – “Barnacles” have been found on polyester mooring lines in Brazil in the upper section of the mooring line (up to 110 m below the water surface). If they enter the rope core, they could be damaging by causing yarn-on-yarn abrasion leading to yarn failure and thus loss of residual strength. Particle filter cloth below the jacket should prevent ingress to the load bearing core.
4. Ingression of solid particles in the rope core. Soils/solids particle ingression has been found to be damaging to the rope core. The filter material should prevent damage and a test will be conducted during the prototype testing to determine the effectiveness of the filter cloth. Failure or loss of residual strength would also result from yarn-on-yarn abrasion.
5. UV Attack – Once the moorings are deployed, this is not a problem below the water’s surface. UV rays can cause damage to the polyester resulting in loss of residual strength.
6. Attack by Known Chemicals - This should only be a potential problem while the moorings are in storage or on deck. In the water, any small amounts of dropped

chemicals should be diluted. Normal chemicals in the water column have not been found to cause problems by Petrobras or in laboratory testing as polyester is a good material for chemical resistance. Chemicals that are known to attack polyester (certain acids) would cause a loss of residual strength to the rope.

7. Hydrolysis/Heating - The principal concern is heating of the rope splices due to hysteresis during cyclic loadings. Presence of salty solution can enhance the problem especially for lines that are recovered and allowed to dry. When the mooring is submerged in water, heat build-up has been found by test to not be a problem for rope integrity. These tests have been conducted on model scale and full scale ropes at a cycling frequency much faster than any in service loading. Excessive heat build-up, should it occur, would cause the polyester yarn to melt and reduce the residual strength.
8. Fishbite - No solid evidence of a large fish biting 6 to 10-inch diameter ropes exists, although it is mentioned in all fiber-mooring codes. This is treated as “accidental” rope damage and as such causes loss of residual strength. We have very little reason to believe that this is a risk at all.

Key Rope Assembly Design/Construction & Material Factors - Established and Maintained over a 20-Year Life:

1. Rope tensile strength - This is a key design factor determined by testing multiple samples of the proposed rope design.
2. Residual tensile strength - When rope test samples are periodically removed from the mooring, they can be tested in tension, and the “used” rope sample results can be compared with the new results obtained during prototype testing. This does not address remaining rope life
3. Rope axial stiffness – This is a key design factor that will impact vessel offsets and maximum dynamic loads and thus safety factors. Prototype testing will

establish stiffness of the rope and this can be verified with recovered inserts over time.

4. Tensile fatigue strength - This is a design feature that is determined in new rope samples by testing. Accumulated material damage in the rope core can be caused by a combination of fatigue and creep loads. The cyclic loading causes slip/wear and thus fiber abrasion leading to fiber failure.
5. Tension/compression fatigue strength - Mooring lines that experience low tensions (by being on the leeward side of the FPS in a hurricane or in a loop current event) could be damaged by combined effects of slip/wear and z-kinking. This is a design feature that is tested before installation.
6. Fiber molecular damage accumulation due to creep and cyclic loading – When a rope experiences high loads (approximately 70 % of breaking strength or greater) the long chain molecules in the fibers can experience small but irreversible damage. Our design will avoid this not-well-understood-problem by using an increased safety factor.
7. Torque and twist - Severely twisted ropes, exposed to cyclic loadings can cause yarn-on-yarn abrasion, and thus cause accumulation of damage. This problem is avoided in design because it is a torque neutral design and can be monitored via a stripe marker built into the jacket of the rope during and after installation.
8. Splice slippage – If the individual subropes in a rope have different amounts of slack during the splice manufacturing, loadings in the splice can be unequal, and the splice will often readjust geometrically to equilibrate the subrope loads. This effect can be seen in tensile testing, and there is an abrupt discontinuity in the load-elongation curve. Marine finish, discussed below, makes splices more likely to slip, but is needed for fatigue strength. Proper splice design and quality assurance techniques should negate this issue. If equal or near equal sharing of subropes is not obtained, the more highly subropes could potentially be overloaded leading to a fatigue or creep rupture failure.

9. Wear and compression in the splice region – This represents normal conditions to consider in splice design and protective coverings are used in making the splice to avoid detrimental effects. Excessive wear will cause fiber failure and loss of residual strength.
10. Adequacy of marine finish – Marine finish is a waxy material that coats the yarns in the rope, reducing friction between yarns as they slip over each other under loading. The fatigue life of a polyester mooring rope is dependent on the presence of this finish. Although loss of marine finish over the life of the rope may be possible, there is no evidence of such occurrences (Ref. 5). It is also unclear of the role of the marine finish in a well bedded in rope. Nevertheless, if marine finish is lost, it could lead to additional wear or greater heat build-up resulting in fiber damage.
11. Adequacy of particle filter system - The particle filter layer resides just below the jacket, and filters out solid particles in excess of 20 microns. If during the life of the rope, this filter is damaged, solid particles could enter the core of the rope and cause fiber abrasion and loss of residual rope strength. There is additional concern about the particle filter application around the splice region. The filter material will be tested in the prototype testing by placing a sample of the rope in water filled with soil representative of the site and held at seafloor bottom pressure for a period of time and then removed and the core examined to determine if any particles got past the filter.
12. Rope jacket damage tolerance - The sole purpose of the rope jacket is to protect the rope cores against external damage. Since the jacket is not designed for resisting load, superficial damage to the jacket is not considered a problem. A secondary benefit of both the jacket and the filter system is to also protect the jacket from marine growth.
13. Defects in materials and construction - The yarns that are used to construct the rope are heavily tested. The rope body making process is accomplished through automated machinery, and hence, defects in the rope body do not generally occur. However, the splice making is hand-made, and thus is more subject to

quality assurance issues. To address this issue a splice QA/QC process is needed.. It is more efficient and effective to handle defects with a strong quality process, than to try to perform detailed inspections after installation.

Key Operational Factors Occurring over a 20-Year Life

1. External damage due to dropped items - There is always a possibility of dropped objects descending through the water column and damaging the mooring rope and thus reducing the residual strength. The likelihood of impact and the likelihood of damaging the polyester rope after impact are both considered very small, since the mooring legs use chain closest to the structure, where the dropping potential is highest. Further, dropped objects might brush along the side of the rope and be easily deflected away with only superficial damage to the jacket, a non-problem. In addition, the aerial extent of the actual mooring lines is minimal, making it a low-probability event of a falling object coming into contact with them.
2. External damage due to contact with other suspended objects – The most likely form of external damage is caused by other tension members (wire rope or chain work lines) rubbing against the polyester rope. After installation, this problem is minimized by creating and enforcing an exclusion zone around the mooring system to keep unwanted vessels away from the facility. Vessels that must approach the facility to provide services will be first cleared to do so and logged into the records with activities performed. Typically, this will only be supply and crew vessels that are servicing the facility that will need to come near the spar. These will all be DP vessels and thus will not need to deploy a mooring line while in the field. Additional SCRs may be installed in the future and if so will require work wires in the water column. After installation is complete, the neighboring mooring lines to the SCRs will be inspected with an ROV to confirm if any damage occurred. The use of fiber work wires is a practical method of significantly reducing the risk of damage due to in field activity. In the event any exposure could have occurred, the following will be conducted: (1) inspection and detection using an ROV, (2) using inspection results and available damage test

data to determine if an assessment can be made, and if not (3) using inspection results to simulate the damage on spare rope samples, and (4) performing tests to determine the structural adequacy of the damaged rope.

3. Particle ingestion due to dropped ropes or drill cuttings – Rope dropping or touching the seafloor, if it occurs, is most likely to occur during installation. The rope could either come in contact with the seafloor in a controlled mode or by accidentally dropping a line as a result of a work line failure during installation. In a controlled mode, the rope would be only in contact with the seafloor for a short period of time. The rope would be protected from particles by the filter cloth and in the splice region, the polyurethane coating provides additional protection. If under such condition, contact were made with the seafloor, the rope would be inspected with the ROV and if no damage is found to the jacket or filter cloth, installation will proceed. If the rope is accidentally dropped on the seafloor as a result of a work line breaking, the rope will be recovered and a spare will be used. Cuttings discharged from the drilling operation will also place particles in the water column that could reach the ropes although the distance between the discharge chute and the mooring lines should be adequate to prevent this from occurring. Inspection and testing of recovered inserts will also prove whether this is an issue.
4. Externally induced torsion or twist – This does not occur when a torsion-free rope design is used. Some twist may result during installation due to the rope slipping over the deployment winch drum instead of rolling. The ropes will be monitored during installation so if this is happening it can be corrected before the line is completely installed. This twisting will be minimal and kept below manufacturer suggested recommendations, and documented via the post installation video and the use of a stripe marker that will be built into the jacket. If additional twist (or untwist, depending if a left hand laid or right hand laid subrope breaks) is found in a future ROV inspection, this likely will indicate subropes have broken, creating a rope that is torsionally unbalanced. Levels of twist or untwists resulting from damaged subropes to be checked for will be based on results using a fiber rope analytical model and manufacturer supplied information/recommendations. Thus the intent would be to install the ropes while inducing no or minimum twist and

verify with the after installation ROV video inspection that this is the case. Then, if twist was found in the future, perform a more detail inspection since it may be an indication of broken subropes. Rope twist may create additional slip/wear in the rope thus leading to fiber failure or additional compression in the rope during low mean load conditions. Thus if additional twist is ever found in the rope beyond what is induced and allowed during installation, to the level the manufacturer specifies that would indicate one or more subropes have broken, the rope will be replaced.

APPENDIX I

FMEA Description of Method



Stress Reliability Method used for the Polyester Rope Mooring Operational Processes

*Failure Modes and Effects Analysis
Summary*

18 October 2007

Failure Modes and Effects Analysis - FMEA

- An engineering technique used to define, identify, and eliminate known and/or potential failures, problems, errors, and so on from the system, design, process, and/or service before they reach the customer.
- A procedure by which each potential failure mode in a system is analyzed to determine the results thereof on the system and to classify each potential failure mode according to its severity.
- A systematic method of identifying and preventing product and process problems before they occur.

FMEA References

- D.H. Stamatis, "Failure Mode and Effect Analysis," ASQ Quality Press, 1995.
- MIL-STD-1629A, "Procedures for Performing a Failure Mode, Effects and Criticality Analysis," 24 November 1980.
- SAE J1739, "Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA), Potential Failure Mode and Effects Analysis in Machinery (Machinery FMEA) Reference Manual," Aug 2002.



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FMEA Format

- Potential failure modes
 - The physical description of the manner in which a failure occurs
- Potential effects of failure
 - The outcome or consequences of the failure
- Causes of failure
 - The root cause of the listed failure
- Occurrence Index
 - The likelihood that failure mode will occur during the design life
- Severity Index
 - The ranking associated with the most serious effect for the given failure mode
- Detection Index – **Not Used**
 - The ranking associated with the best detection design control
- Risk Priority Number
 - The product of occurrence, severity, and detection



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Typical FMEA Process

- Select the team
- Review scope for details / limits

Qualitative FMEA

- Brainstorm potential failure modes
- List the potential effects of each failure mode
- List the root causes for each failure mode

Quantitative FMEA – Used for Polyester Mooring Project

- Assign a severity rating for each effect
- Assign an occurrence rating for each failure mode and/or effect
- Assign a detection rating for each failure mode and/or effect
- Calculate a risk priority number for each effect



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FMEA Form Example

FMEA Report	Equipment: Subsea Wells in GOM
Date: 22-May-2003	Phase: Completed Wells
Rev: 01	Activity: Sustained Casing Pressure

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Detection Method	Detection	Risk Priority Index	Comments
Typical subsea wells in GOM	Sustained pressure in "A" annulus								
Typical subsea wells in GOM	Sustained pressure in "B-1" annulus								
Typical subsea wells in GOM	Sustained pressure in "B-2" annulus								
Typical subsea wells in GOM	Sustained pressure in "B-3" annulus								



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APPENDIX J

FMEA RESULTS

INDEX CODES APPLIED

FMEA Criticality Analysis Index Codes

Severity Index		
Severity	Criteria	Ranking
Hazardous	Hazardous effect. Safety related. Sudden failure. Noncompliance with government regulations. Example: Blowout or deaths caused.	10
Serious	Potential hazardous effect. Able to stop product/service without mishap. Safety related. Time-dependent failure. Disruption to subsequent process operations. Compliance with government regulation is in jeopardy. Example: Need to shut in production for safety reasons.	9
Extreme	Customer very dissatisfied. Extreme effect on process/service; equipment damaged. Product/service incomplete but safe. Example: Mooring leg ruined; major damage to host or vessels.	8
Major	Customer dissatisfied. Major effect on service; rework on service necessary. Product/service performance severely affected but functional and safe. Example: Must operate with one leg missing.	7
Significant	Customer experiences discomfort. Product/process performance degraded, but operable and safe. Example: Long delay, waiting on parts, to complete recovery operation.	6
Moderate	Customer experiences some dissatisfaction. Moderate effect on product or service performance.	5
Minor	Customer experiences minor nuisance. Minor effect on product or service performance. Fault does not require attention.	4
Slight	Customer slightly annoyed. Slight effect on product or service performance.	3
Very slight	Customer more likely will not notice the failure. Very slight effect on product / process performance.	2
No	No discernible effect on product or subsequent processes.	1

Occurrence Index

Occurrence	Criteria	Ranking
Almost Certain	Failure almost certain.	10
Very High	Very high number of failures likely.	9
High	High number of failures likely.	8
Moderately High	Frequent high number of failures likely.	7
Medium	Moderate number of failures likely.	6
Occasional	Occasional number of failures likely.	5
Slight	Few failures likely.	4
Very slight	Very few failures likely.	3
Rare	Rare number of failures likely.	2
Unlikely	Failure unlikely. History shows no failures.	1

**RISK TABLES FOR (A) NORMAL OPERATIONS, (B) INSERT RECOVERY,
AND (C) ROV INSPECTION**

FMECA Report		Equipment: OPERATIONAL PROCESS FOR POLYESTER MOORING NORMAL OPERATIONS AFTER INSTALLATION						
Date:	24-Sep-2007	Phase:	Normal Operations After Installation					
Rev:								
Step	Operational Step	Potential Failure Mode(s)	Potential Cause(s) of Failure	Occurrence Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Product of Severity and Occurrence
1	Normal Operations	Chain or Poly Segment Damaged/Broken & Mooring Leg Dropped	Dropped Loads Overboard Adjacent to Host	3	Mooring Leg Dropped and Others in Cluster are severed and damaged. Loss of Mooring Causes Risers to Break, Oil Spill & Blowout.	9	Operations procedures to avoid Loads Dropped Overboard	27
2	Normal Operations	Mooring Legs or Clusters Cut or Severed	MODU Drags Anchors Through Clusters in Hurricane or Loop Current	3	Mooring Leg Dropped and Others in Cluster are severed and damaged. Loss of Mooring Causes Risers to Break, Oil Spill & Blowout.	10	Improved MODU Mooring System Design to Avoid Anchor Drags	30
3	Normal Operations	Mooring Legs or Clusters Cut or Severed	Other Vessels With Hanging Loads Pass Through Mooring System In Error or by Accident	2	Mooring Leg Dropped and Others in Cluster are damaged. Loss of Mooring Causes Risers to Break, Oil Spill & Blowout.	10	Proper Methods in Force to Avoid Mooring System Contacts by Other Vessels	20
4	Normal Operations	Mooring Lines Break	Mudslide Causes Anchor Movement, Tensioning Legs	1	Mooring Leg Dropped and Others in Cluster are damaged. Loss of Mooring Causes Risers to Break, Oil Spill & Blowout.	10	Proper Foundation Design Practices for Anchors	10
5	Normal Operations	Chains or Connectors Break	Corrosion Fatigue Design Issues	2	Dropping of One Leg, perhaps Damaging Cluster	9	Proper Corrosion Design and Inspection Techniques	18
6	Normal Operations	ROV Cuts Poly During Inspection	Loss of Control of ROV	3	ROV Damaged or Tangled, Poly Rope Cut/Damaged.	8	Durable ROVs, Trained Operators, Durable Rope Jackets	24
Total Number of Causes =		6					Total RPN	129
							Average RPN	21.5

FMECA Report		Equipment:	OPERATIONAL PROCESS FOR POLYESTER INSERT RECOVERY					
Date:	.	Phase:	Polyester Insert Recovery					
Rev:								
Step	Operational Step	Potential Failure Mode(s)	Potential Cause(s) of Failure	Occurrence Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Product of Severity and Occurrence
1	Offset Moored Vessel for Insert Recovery	Farside Mooring Legs are at Load/Displacement Limits and Break	Overloads, Increased Weather Loads	2	Multiple mooring legs break off from Moored Host	9	Proper Design and Installation Controls	18
1	Offset Moored Vessel for Insert Recovery	Drilling/Production Risers are at Load/Displacement Limits and Break	Overloads, Increased Weather Loads	2	Risers Break and Fall, causing Blowouts	10	Proper Design and Installation Controls	20
1	Offset Moored Vessel for Insert Recovery	Slack Side Mooring Lines touch mudline & are damaged	Not able to watch all lines at once	4	All poly segments touching the seafloor must be replaced	9	Proper Design and Installation Controls	36
2	Deploy AHT or ROV Vessel in Position for Insert Recovery	AHTS or ROV Vessel Loses Dynamic Positioning or Power	Control or Power Failure	4	AHTS or ROV Vessel Ram Host	8	Bumpers on Host	32
3	Deploy and Engage J Lock on Chain Below Insert using ROV	J-Lock or ROV Cuts Poly	Loss of Control of J Lock or ROV	3	Cut in Polyester leg	7	Poly Jacket Protects Core	21
3	Deploy and Engage J Lock on Chain Below Insert using ROV	J-Lock or ROV Cuts Poly	Loss of Control of J Lock or ROV	3	ROV Damaged or Tangled	6	Durable ROVs, Trained Operators	18
4	Host Pays Out Rig Wire or Chain	Winch Freewheels or Chain Jack Fails, making sudden loading on J Lock Assembly	Winch or Chain Jack Failure	3	Impact Loading on Mooring Leg Breaks Connection, dropping mooring leg, possibly impacting other lines in cluster.	9	Winches and Chain Jacks checked before Insert Recovery Operation Begins	27
5	AHTS Heaves in Work Wire, Bringing Mooring Line on Deck	Failure of AHTS Winch, J Lock or Connections	Winch not rated for service or not properly maintained	3	Impact Loading Breaks Connection, dropping mooring leg.	8	Winch and Connections Checked to Qualify for Service	24
5	AHTS Heaves in Work Wire, Bringing Mooring Line on Deck	Failure of AHTS Winch or Connections	Winch not rated for service or not properly maintained	3	Deck Personnel Injury, death, men overboard	9	Winch and Connections Checked to Qualify for Service	27
6	Mooring Line Secured on Deck for Removal of Insert	Line Slips from Chain Stoppers or From Chinese Fingers	Poor handling operations fails to secure line	3	Mooring Line drops overboard and to seafloor, possibly impacting other lines in cluster.	8	Components designed for this service and are properly maintained.	24
6	Mooring Line Secured on Deck for Removal of Insert	Handling and Load Transfer Mistake Causes Sudden Movements on Deck - Whiplash of Polyester	Improper handling and connection failures	4	Men Injured or Killed	9	Training of Deck Personnel	36
7	Mooring Line Secured on Deck for Removal of Insert	Chinese Fingers Damage Poly Rope Segment	Chinese Finger Design or Placement	2	Polyester Mooring Segment will be Unusable	8	Design and handling of Chinese finger Connections.	16
6	Poly Insert Removed and Secured on Deck	Insert is cut by sharp objects on deck	Improper handling and attention to moving sharp objects	3	Insert Damaged, preventing Testing	6	Insert has tough outer jacket	18
7	Removal of H Link from Insert	H-Link Pins Stuck	Corrosion Fatigue Design Issues	3	Men Injured trying to remove corroded pin.	9	Proper Corrosion Design	27
7	Removal of H Link from Insert	H-Link Pins Stuck	Corrosion Fatigue Design Issues	3	Heat Damage to the Poly when Torching off Pin	8		24
8	Connect J Lock and Lower the Mooring Line	Failure of AHV Winch or Connections	Winch not rated for service or not properly maintained	3	Deck Personnel Injury, death, men overboard	9	Winch and Connections Checked to Qualify for Service	27
9	Transfer Load from AHV to MODU	Connection or Winch Fails	Winch components or connection components get overloaded and break	3	Mooring Line drops to seafloor, possibly impacting other lines in cluster.	9	Proper design and Manintanance	27
9	Disengage J Lock and Retrieve it.	J-Lock or ROV Cuts Poly	Loss of Control of J Lock or ROV	3	Cut in Polyester	8	Poly Jacket Protects Core	24
10	AHVS and ROV Vessel leave Mooring Pattern area	AHV or ROV Vessel Loses Dynamic Positioning or Power	Control or Power Failure	3	AHV or ROV Vessel Ram MODU	9	None	27
Total Number of Causes		19					Total Product	399.0
							Average Product	21

Equipment:	OPERATIONAL PROCESS FOR ROV INSPECTION					
Phase:	ROV Inspection					
Potential Failure Mode(s)	Potential Cause(s) of Failure	Occurrence Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Product of Severity and Occurrence
ROV Vessel Loses Dynamic Positioning or Power	Control or Power Failure	4	ROV Vessel Rams Host	9	Bumpers on Host	36
Cage Damages Polyester Segment	Operator Error or Instrumentation Problems	3	Cage Cuts Poly Segment	8	Thick Protective Jacket on Rope	24
Cage Damages Polyester Segment	Operator Error or Instrumentation Problems	3	Cage Cuts Poly Segment	8	Thick Protective Jacket on Rope	24
ROV Cuts Poly	Loss of Control of ROV	2	ROV Cuts Poly Segment	7	Thick Protective Jacket on Rope	14
ROV Twists around Poly	Loss of Control of ROV	2	ROV must be Recovered from Entanglement by separate ROV	7	Unknown	14
					Total Product	112
					Average Product	22.4

Appendix K

Description of Strain Limit Indicator for Synthetic Fiber Ropes

TITLE OF IDEA: *Strain Limit Indicator for Synthetic Fiber Ropes*

DESCRIPTION OF IDEA:

Background - Current practice for deepwater mooring systems using synthetic fiber rope is to place 15-meter-long “inserts” in each mooring leg during installation of the mooring system. This practice was instigated in deepwater provinces by Petrobras in recent years, and has been now adopted in the U.S. Gulf of Mexico. On a predetermined schedule (years) certain inserts are removed and then tested to determine if the breaking strength has been reduced due to some failure mechanism. If the breaking strength determined by test is like that of a similar new (uninstalled) insert, then it is assumed that the rest of the mooring leg is like new in strength.

We have discovered problems with this methodology:

1. Tests of ropes can show breaking strengths like new, but in actuality they can be very near to failure. Creep under sustained loading can stretch the rope to a point where the strain limit of the rope is near. In short, break tests cannot be used to determine the remaining life of a mooring rope.
2. During the operation to recover an insert for testing, the dynamically controlled work vessel must maneuver close to other mooring legs without damaging them by contact. This is a risk-filled operation.
3. The inserts become the “weak links” in the mooring system. For a 16 leg mooring system, the inserts in each leg contribute 32 additional rope end splices that are not needed. Additionally the splices, unlike the rope body, are made by hand, and quality control of splicing is difficult.
4. Recovery of the insert is costly – perhaps \$250,000 to \$500,000 per recovery project

What is needed is a justification for eliminating the use of inserts. The regulators in the Gulf of Mexico will not permit eliminating inserts unless some other equal or better method of rope integrity monitoring is employed in place of the use of inserts. This IDEA can potentially provide that assurance of mooring line remaining life.

FEATURES OF THE IDEA:

First (Preferred) Concept:

1. A one or two meter length of bunched yarns, like that used to make the jacket of the rope, is firmly clamped to the rope at one end.

2. The other end of the bunched yarns is clamped such that the yarns can slip out if the rope stretches a predetermined amount.
3. Thus, the length of yarn beyond the second clamp is selected to be exactly the amount of allowable strain in the rope.
4. When the strain in the rope exceeds the allowable, then the bunched fibers slip out from the second clamp.
5. Since synthetic fiber yarns are light in water, the released bunched yarns will flutter like a “flag” in the local water currents around the rope. Using a color of yarn with best visibility will add to the effectiveness. One such color is yellow.
6. When a un-manned remotely operated vehicle (ROV) inspects the mooring leg, it will easily see the “flag” and will show ROV operators that the extreme load event has been experienced in this mooring leg. A backup method is to measure the distance between the clamps, to confirm that some permanent elongation has occurred. This will confirm that the flag has not been released prematurely by some other means.

Second Concept:

Another equally viable method of using this IDEA is to employ a ribbon that breaks (rather than slips out of the clamp (= tie-wrap) at the point of maximum allowable strain. This would be analogous to a common electrical fuse that destroys the element when excessive current is applied.

MAJOR ADVANTAGE OF THE IDEA

1. It is a reliable indicator of remaining life.
2. It is cheaper than the current insert method, and is elegantly simple
3. It eliminates the need for insert recovery and the attendant risks.
4. It does not detract from the strength of the rope and avoids use of additional splices that reduce quality assurance

5. MODELLING THE CONCEPT:

I used a “bunji” cord and a ribbon to simulate the IDEA. The bunji cord represented a synthetic fiber rope, and the ribbon represented the rope yarn used as the indicator flag. Tie-wraps were used to attach the ribbon to the bunji cord. On the left end (see pictures) the ribbon was wrapped around (tied to) the tie-wrap. On the right end the ribbon was passed under the tie-wrap so that it could slip. The remaining ribbon (rope yarns) right of the right hand tie wrap was exactly the length of the allowable strain (elongation) for the rope (bunji cord). See Figure 1 for layout.

As I pulled on the bunji cord, the ribbon slipped under the right tie-wrap, and when the excess ribbon had passed under the right tie-wrap, the ribbon popped free on the right hand side, while it maintained its attachment to the left tie-wrap. See Figure 2. Thus the allowable strain was exceeded and the ribbon deployed to show this fact.

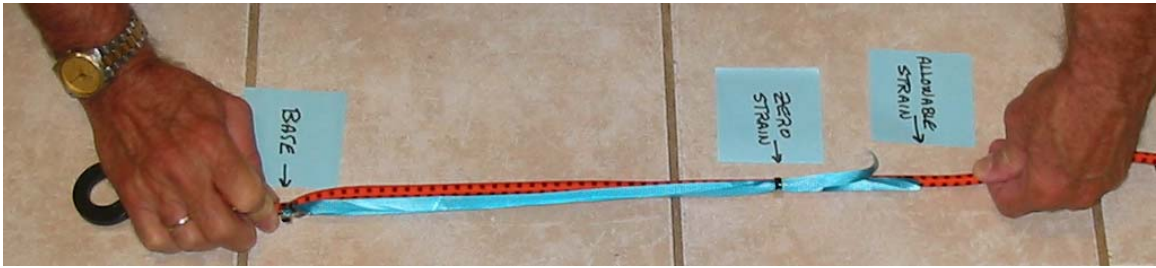


Figure K1. Model Test: Ribbon In Place – Zero Strain. Note that distance between Zero Strain and Allowable Strain is the Maximum Allowable Strain.

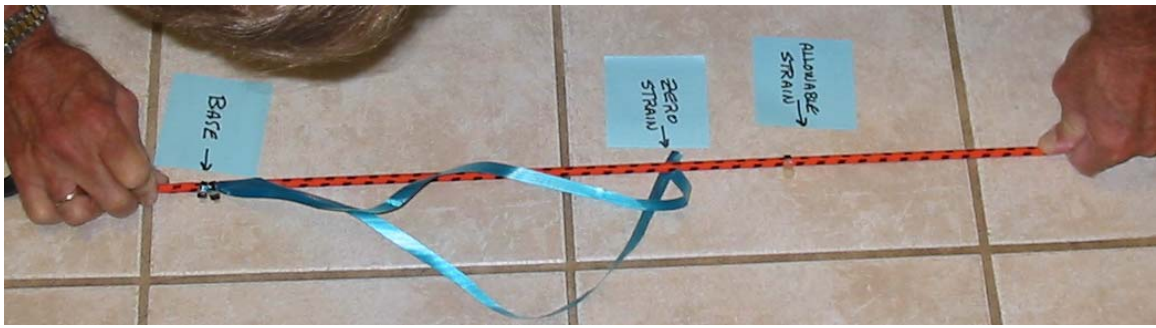


Figure K2. Model Test: Allowable Strain Has Been Exceeded by Stretching the Orange Rope. Now the Blue Ribbon is Loose, Indicating Allowable Strain Exceedance.

Appendix L

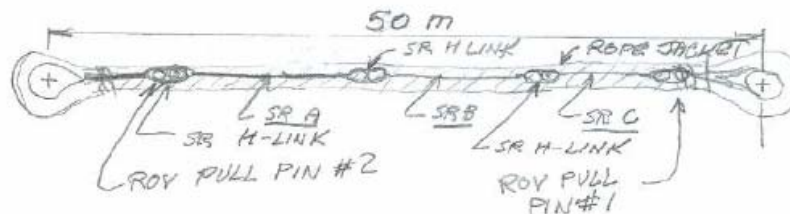
ROV-Recoverable Subrope Insert: The “Super Subrope Insert”

Problem

Currently –used rope inserts are too short to be representative of longer mooring legs (they are the weak link) and they are risky to recover. The MMS currently requires insert recovery and wants the ability to do future testing to evaluate a previously unknown failure mechanism that shows up.

Solution

1. Make a “special” 50-meter rope insert in which the number of subropes in the rope insert (n) is increased to $n+1$.
2. Cut the extra subrope say in the middle and temporarily coil each end and tuck it in the crotch of the rope splice.
3. Jacket the n subropes to form the rope, leaving the extra subrope out from under the rope jacket.
4. Re-terminate the added subrope by forming 3 shorter subropes in series (using compact subrope H links) as shown in this sketch:



Super Subrope Insert Concept

5. The 3 shorter subropes can be constructed with less rope yarns in order to increase the effective tension in the rope by the factor $(n+1)/n$. Decide on using a subrope jacket or otherwise having a covering on the subrope depending on the subrope design.
6. Design an ROV pullable pin so that once the super subrope insert is installed in the complete mooring system, an ROV manipulator can first pull the upper ROV pull pin (pull pin 2 in the sketch), causing some recoil clear of the ROV, but also causing the 3 connected subropes to fall by gravity and hang down by pull pin 1.
7. Have the ROV pull pins 2 and 1 in order and recover the 3 (15 meter) subropes to the ROV support vessel for transporting to shore and testing.
8. The Super Subrope Insert could be used as a test bed for testing PEN or HMPE subropes by designing the 3 subrope system to have at least one

subrope to be HMPE, and design the other 2 subropes to create the desired loading for the PEN or HMPE subrope.

Major Advantages of Super Subrope Insert Concept

The Super Subrope Insert concept can be used in place of the currently used rope insert, in order to:

1. Totally avoid short 15-meter full rope inserts that are a known weak link in the mooring system.
2. Totally avoid recovery of a full rope insert by the complex and risky two-boat insert recovery operation. Do this by recovering 3 equivalently loaded subrope inserts using only an ROV and support vessel as used for rope inspections. This is both a risk and a cost saver.
3. Recover the 3 subrope inserts simultaneously during the scheduled ROV Inspection. Only recover the subropes if there is a suspected failure mechanism that was previously unknown.
4. Being able to test 3 subropes for statistical significance, rather than one short full-rope insert.
5. The production system owner could perhaps install only 2 or three of these Super Subrope Inserts in a single mooring system, so that if - through the life of the mooring system - a previously unknown failure mechanism is suspected, structural testing is possible.