LIFE CYCLE COST ANALYSIS OF SUBSEA MULTIPHASE BOOSTER PUMPS

prepared for
Subsea Multiphase Booster Pump Joint Industry Project

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TECHNICHAL REPORT

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APPENDIX II

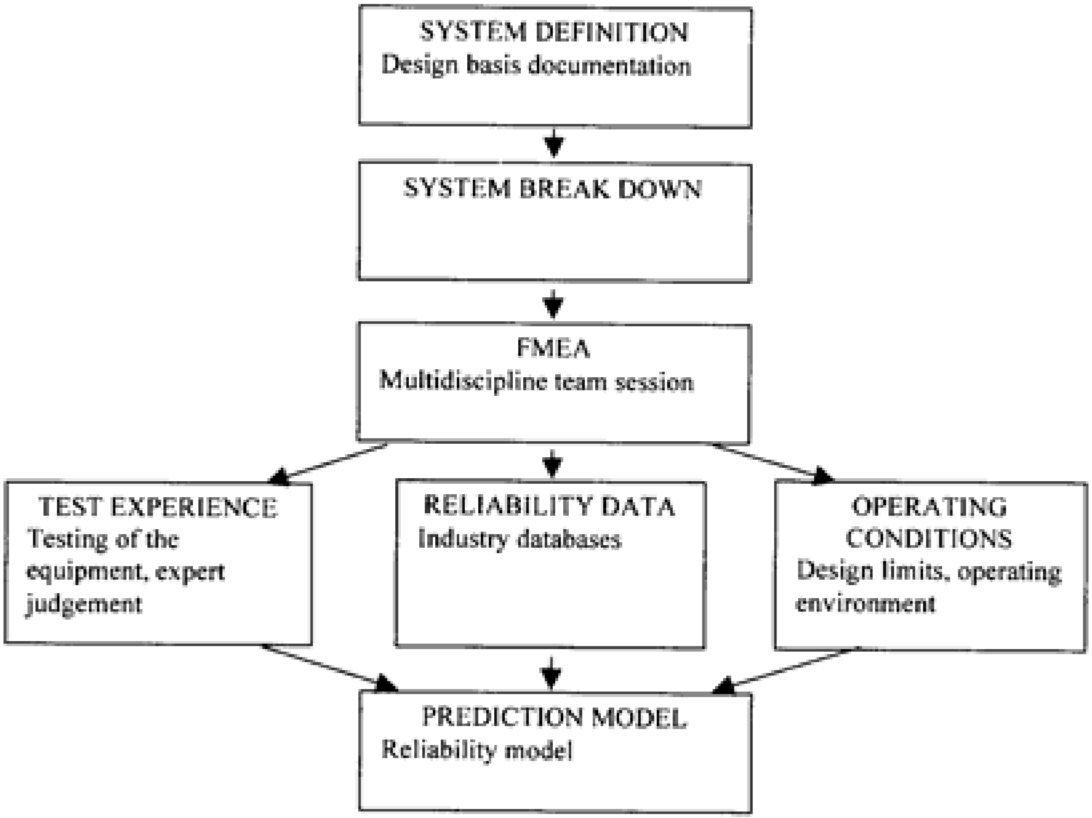
RELIABILITY ANALYSIS

II-1 Reliability Analysis

Reliability analysis involves an iterative process of reliability assessment and improvement, and the relationship between these two aspects is important. In some cases, the assessment shows that the system is sufficiently reliable. In other cases, the reliability is found to be inadequate, but the work reveals ways in which the reliability can be improved. It is generally agreed that the value of reliability assessment lies beyond merely obtaining the estimated system reliability. The greatest value lies in the discovery of ways to improve overall system reliability.

The methodology followed in the reliability assessment of the subsea booster pump system is illustrated in Figure II.1. The following sections give a detailed discussion of the reliability techniques applied in the assessment, including a description of failure modes and effect analysis, FMEA, reliability data and data ranking methods and some general reliability theory.

Figure II.1: Reliability Methodology Applied for this Study



II-1.1 Failure Mode, and Effect Analysis

Failure mode and effects analysis (FMEA) was one of the first systematic techniques applied in reliability analysis. It was developed by engineers in the late 1950s to study problems that might arise from malfunctions of military systems.

An FMEA is often the first step of a system reliability study. It involves reviewing components, assemblies, and subsystems to identify single point failure modes, causes, and effects of these failure modes. For each component, the failure modes and their effects on the rest of the system are written on a specific FMEA worksheet.

The benefits of using a failure mode and effects analysis are multifold. A failure mode and effects analysis is mainly a qualitative analysis, and is carried out during the design stage of a system. The purpose is to identify design areas where improvements are needed to meet reliability requirements. An FMEA is therefore an important basis for design reviews and inspections. An FMEA is beneficial to:

1. Assist in selecting design alternatives with high reliability and high safety potential during early design phase.
2. Ensure that all conceivable failure modes and their effects on operational success of the system have been considered.
3. List potential single-point failures, and identify the magnitude of their effects.
4. Develop early criteria for test planning and the design of the test and checkout systems.
5. Provide a basis for quantitative reliability and availability analyses.
6. Provide historical documentation for future reference to aid in analysis of field failures and consideration of design changes.
7. Provide input data for trade-off studies.
8. Provide basis for establishing corrective action priorities.
9. Assist in the objective evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics, and automatic and manual override.

II-1.1.1 FMEA Approach

The failure mode and effect analysis can be carried out either by starting at the component level and expanding upward (the bottom-up approach), or from the system level downward (the top-down approach). The bottom-up approach is also called the *hardware approach*, while the top-down approach is called the *functional approach*.

It is a general rule to expand the analysis down to a level at which failure rate estimates are available or can be obtained. However, it is often necessary to make compromises regarding the component level at which the analysis should be conducted, since the amount of detail could be overwhelming even for a system of moderate size.

II-1.1.2 FMEA Work Procedure

A failure mode and effects analysis is a systematic review, which is relatively simple to conduct. It does not require any specialized analytical skills from the personnel performing the analysis. It is, however, necessary to understand the system that is analyzed and the constraints under which it operates. The basic questions to be answered by an FMEA are:

1. How can each part conceivably fail?
2. What mechanisms might produce these modes of failure?
3. What could the effects be if the failures did occur?
4. Is the failure in the safe or unsafe direction?
5. How is the failure detected?
6. What inherent provisions are provided in the design to compensate for the failure?

II-1.1.3 FMEA Worksheet Format

The various entries in the FMEA worksheet are best illustrated by going through the worksheet column by column. The FMEA worksheet given in Table II.2 was used to evaluate the subsea booster pump system.

The heading in the FMEA worksheet documents the system and sub-system name and number, component name and number, component function, revision number and date of last revision.

The following columns are included in the FMEA worksheet to record data regarding the system:

Component Number (column 1). Identification number for each component in the sub-system.

Failure Mode (column 2). For each component's function all the failure modes are identified and recorded. Note the definition of a *failure mode*. A failure mode is the manner by which a failure is realized. All units are designed to fulfill one or more functions. A failure mode is thus defined as non-fulfillment of one of these functions.

Causes (column 3). The possible failure mechanisms (corrosion, erosion, fatigue, etc.) that may produce the identified failure modes are recorded in this column.

Local Effect (column 4). All the main effects of the identified failure modes on the component and sub-system are recorded.

System Effect (column 5). All the main effects of the identified failure mode on the primary function of the sub-system and system are then recorded. The resulting operational status of the system after the failure may also be recorded, that is, whether the system is functioning or is switched over to another operational mode.

Method of Detection (column 6). The various possibilities for detection of the identified failure modes are recorded. These may involve different alarms, testing, human perception, and so on. Some failure modes are called *evident failures*. Evident failures are detected instantly when they occur. The failure mode "spurious stop" of a pump with operational mode "running" is an example of an evident failure. Another type of failures is called the *hidden failure*. A hidden failure is normally detected only during testing of the unit. The failure mode "fail to start" of a pump with operational mode "standby" is an example of a hidden failure.

Corrective Action (column 7). This column may be used to record corrective actions required to get the sub-system up and running or pertinent information not included in the other columns. Maintenance actions suggested would be preventive activities that can be performed between or before drilling a well.

Comments (column 8). This column can be used to record recommended actions to be followed-up during the design process, or other relevant comments regarding the failure mode or component being evaluated.

II-1.1.4 Advantages and Disadvantages of an FMEA

The advantages and disadvantages of the FMEA are summarized in Table II.1.

Table II.1: Advantages and Disadvantages of an FMEA

Advantages	Disadvantages
Identifies and records systematically the cause and effect relationships	The output may be large even for relatively simple systems. Time consuming.
Gives an initial indication of failure modes that are likely to be critical, especially single faults that may propagate.	Can not conveniently deal with parallel or complex relationships. May be complicated and unmanageable unless there is a fairly direct relationship between cause and effect.
Searches for possible outcomes not previously known.	Can be difficult to deal with time sequences, restoration processes, environmental conditions, maintenance aspects, etc.
Highlights spurious outcomes as well as deviations from normal functional performance.	Does not, in itself, directly produce a model for quantitative evaluation.
Useful in the preliminary analysis of new untried systems or components.	Difficult to portray multiple dependencies or complex interactions between faults in different parts of the system.

Table II.2: The FMEA Worksheet Applied to Evaluate the Subsea Booster Pumps

FMEA **Report Form**	**System:** **Sub-system :** **Sub-system No.**	**Sub-system Function:**
Evaluated by: **Date:** **Client Reviewer:**	**Part/Component:** **Part/Component #:**	**Component Function:**

Id.	**Failure Mode**	**Causes**	**Local Failure Effect**	**System Effect**	**Method of Detection**	**Corrective Action**	**Comments**

II-1.2 Reliability Data

For much of the equipment, little or no statistical reliability data are available. The fact that the system evaluated will be applied in a new environment and under different operating conditions further complicated the establishment of reliability data. However, some sources do exist. Component and equipment reliability data have been obtained from the following sources:

1. Industry databases, OREDA, Wellmaster, MIL-HDBK-217
2. DNV in-house experience
3. Vendor data provided data
4. Expert judgement and synthesized data

Generic industry databases include data for many of the components within the subsea booster pump system. However, most of the information is based on experience with topside equipment, and modifications have to be made to relate to the equipment installed in the subsea environment. Some data is available for submerged pumps, but the application is different than the multiphase flow in the subsea booster pumps.

Data available in industry databases are often limited, and typically based on experience from other applications or operating environments. It is therefore important to be critical when selecting the reliability data, and use available vendor data in combination with expert judgment when required. Expert judgements can be used to establish or modify component reliability data where historical data are unavailable or sparse.

Reliability values may be based on ranking techniques that consider component characteristics and applications to compare with similar components for which reliabilities are more accurately known. For example, components that provide a pressure resistant seal may be ranked by considering: seal type (e.g., metal to metal seals generally are better than elastomeric seals), installation environment (e.g., downhole, subsea, rig floor or manufacturing shop) and operating environment (e.g., fluid exposure, mechanical stress, static versus dynamic). The component reliability is then estimated as an interpolated value between other component reliabilities based on similarities and differences in characteristics and applications.

When predicting the reliability of components, it is important to understand how and when failures typically occur. Failures that occur in a random manner are usually mathematically described with a exponential distribution that models a constant failure rate. Components that are exposed to aging effects, like corrosion, erosion or wear are modeled with a Weibull distribution in this study.

II-1.2.1 Failure Distributions in Reliability Calculations

When the system failure performance is modeled as a stochastic phenomenon there will always be uncertainties related to the relevancy of the statistical model applied. This section describes the failure distributions applied in this study, and explains some of the basic characteristics of these failure distributions.

Time to failure of a unit is defined as the time elapsing from when the unit was put into operation until it fails for the first time. Components are manufactured, installed and put into operation. Even though similar equipment is manufactured and installed exactly the same way, it is reasonable to assume some variation in the lifetime. It is therefore natural to interpret the time to failure as a random variable.

The state of a unit at time t is either functioning or failed. If time to failure T can be assumed continuously distributed with probability density function $f(t)$, the failure distribution function is defined by:

$$F(t) = P(T \le t) = \int_0^t f(u)du, \quad \text{for t > 0}$$

$F(t)$ denotes the probability that the unit fails within the time interval (0,t]. Depending on the selected statistical distribution function, the characteristics of a component will change significantly. When estimating the reliability of the subsea booster pumps, exponential and Weibull distributions were applied to describe the failure behavior of the equipment. These two distribution functions are described in the following two sections. The Excel spreadsheet allows the user to implement other statistical distribution functions, but these have not been applied when predicting the reliability of the booster pump system.

Exponential Distribution

The exponential distribution models the case where failures occur at a constant rate throughout a component's life. The exponential distribution is the most commonly used failure distribution in reliability analysis. It is mathematically simple and it leads to realistic lifetime models for certain type of units.

The time to failure T of a component is said to be exponential distributed with parameter λ (>0) if the distribution function is given by:

$$F(t) = P(T \le t) = 1 - e^{-(\lambda t)}, \quad \text{for t > 0}$$

The exponential distribution has only one parameter, λ, which is also called the failure rate or failure frequency of the distribution. It is easy to estimate an exponential failure distribution, as the failure rate can be established based on experience data, without going into detailed calculations. The failure rate is defined as the number of failures occurring over a defined period of time, normally the operational time or the time exposed to a certain stress.

Another term often used in reliability analysis is Mean Time to Failure (MTTF), which for the exponential distribution is defined as the inverse of the failure frequency. Most available reliability databases provide this information, making it easy to apply the exponential failure distribution.

To get a better understanding of the implication of the failure rate and relation to MTTF it could be useful to have the following relations in mind:

A. Conversion between failure rate (failure per 10^6 hour) and Mean Time To Failure (MTTF (years))

$$\text{MTTF [years]} = \frac{1}{(\text{Failure rate}) \times (8760)}$$

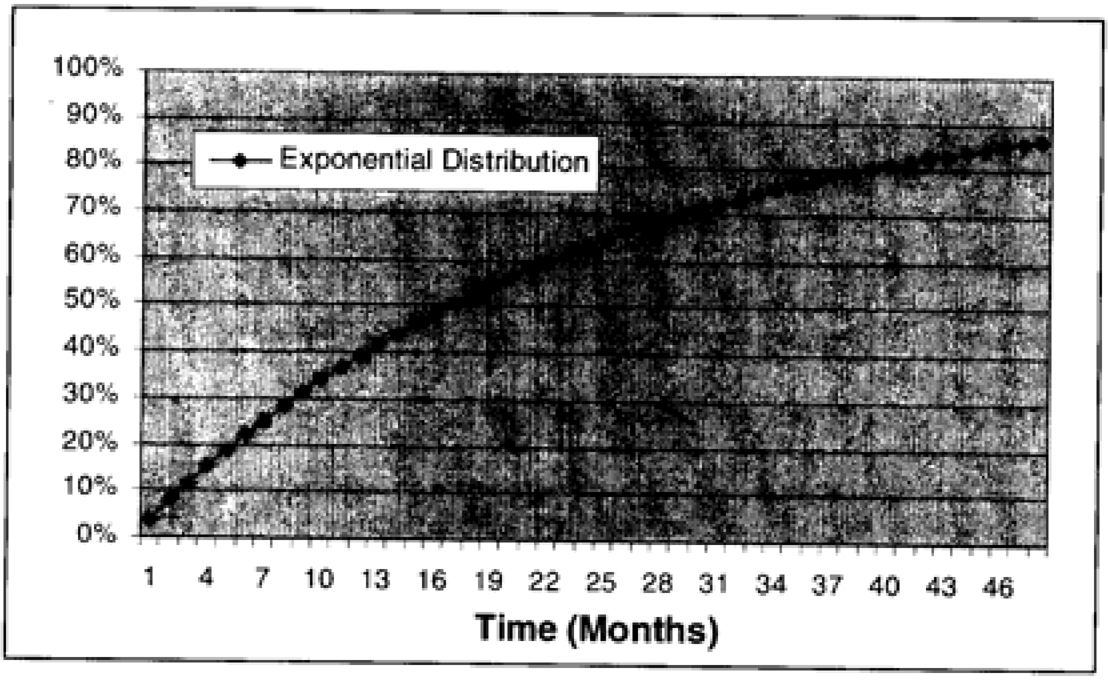
- The factor 8760 is representing the number of hours per year and serves as a conversion factor between *year* and *hour*.

B. Mean Time To Failure is the total observation period divided by the total number of failures within the period. For instance, if there has been 30 check valves in operation for, say, 2 years, 20 units for 4 years and 10 units for 5 years, and there has been 5 failures related to these units, an estimate of the MTTF would be:

$$\frac{(30x2 + 20x4 + 10x5)\,years}{5\ failures} = 38\ [years/failure]$$

An illustration of an exponential failure distribution is given in Figure II.2. The MTTF for the given distribution is two years (24 months). The Figure illustrates the probability of failure as a function of time *F(t)*.

Figure II.2: Illustration of an Exponential Failure Distribution



Weibull Distribution

Wear-out was considered to be one of the driving failure cause/mechanism for many of the mechanical parts in the subsea booster pump system. As the exponential distribution (constant failure rate) is not suited to model this phenomenon, the Weibull distribution was applied. The Weibull distribution allows modeling of lifetime distributions with increasing (or decreasing) failure rates.

The time to failure, T, of a component is said to be Weibull distributed with parameters **a** (>0) and λ (>0) if the distribution function is given by:

$$F(t) = P(T \le t) = 1 - e^{-(\lambda t)^{a}}, \quad \text{for } t > 0$$

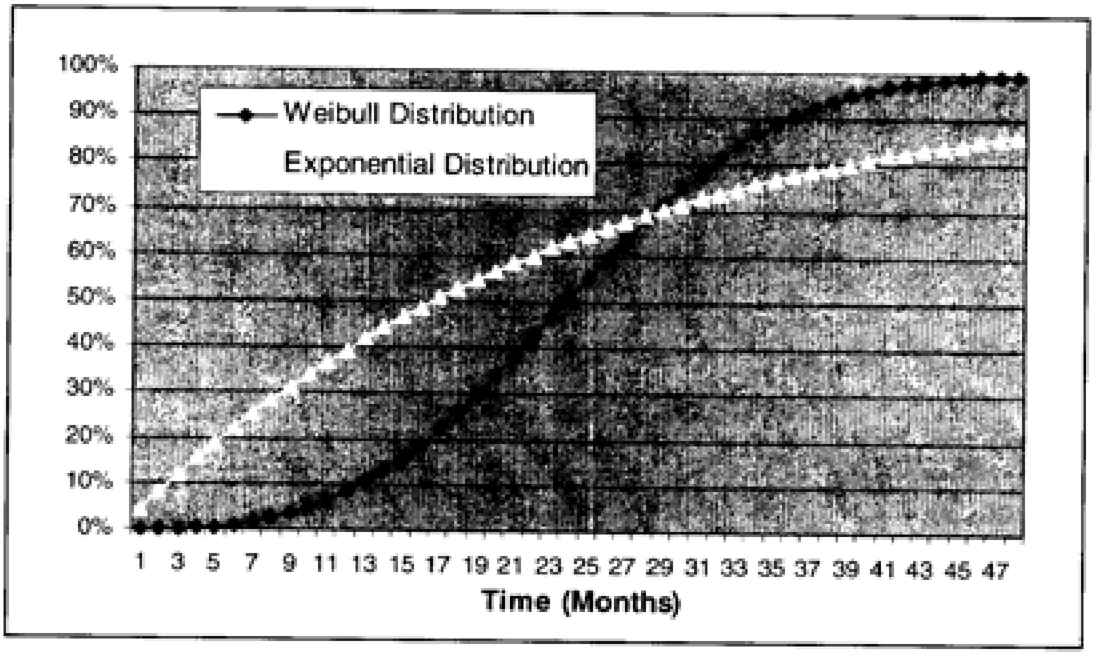
The use of the Weibull distribution is slightly more complicated than working with an exponential distribution. As seen from the equation above, the Weibull distribution is two-parametric (while the exponential distribution has only one parameter). Most reliability data sources do not provide sufficient information to allow estimates of the parameters that define the distribution in an easy manner. Therefore, some assumptions about the stochastic phenomenon have to be made.

In contrast to the exponential distribution, the two parameters in the Weibull distribution do not have a physical interpretation. However, given that a Weibull distribution realistically describes the lifetime for a certain component, the distribution can be determined based on two known observations. In this study, it was assumed that the MTTF for the component could be predicted. Further, based on testing results and quality control systems a guaranteed lifetime for the component should be possible to predict. It was assumed that less than 5% of the components would fail before this guaranteed lifetime.

An illustration of the Weibull distribution is given in Figure II.3. The MTTF was assumed to be two years (24 months). The exponential distribution was included to illustrate the different characteristics related to the Weibull distribution. Both failure distributions have a MTTF of two years, but a shape parameter "a" equal to 3 in the Weibull distribution changes the behavior of this distribution significantly.

Both exponential distribution (constant failure rate) and Weibull distribution (increasing failure rate) were used to model the Subsea MudLift Drilling system components. In general, mechanical components that were expected to wear-out from continuous or repetitious operation, such and the pump valves, hydraulic pumps and rubber diaphragm elements, were modeled with a Weibull distribution. Components that were expected to randomly fail were modeled with an exponential, constant failure rate, distribution. The Spreadsheet Tool model permits either the exponential or Weibull distribution to be used for any of the components.

Figure II.3: Illustration of a Weibull Failure Distribution



II-1.3 System Reliability

The purpose of this section is to describe some reliability modeling techniques, which takes into account the reliability performance of system entities and operational aspects. There are several analysis techniques and methods that can be used as a basis for RAM analysis. The most common techniques and methods are:

- Reliability Block Diagram (RBD)
- Flow Network Simulation (FNS)
- Fault Tree Analysis (FTA)
- Markov Chain Model (MCM)

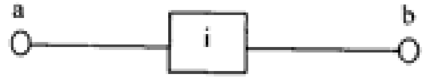
For the purpose of illustration, reliability block diagrams are explained in more detail in the following section.

II-1.3.1 Reliability Block Diagram

A reliability block diagram (RBD) analysis is a deductive (top-down) method. An RBD is the graphical representation of a system's logical structure in terms of sub-systems and components. The RBD allows the system success paths to be represented by the way in which the sub-systems and components are logically connected. An RBD is appropriate to model one system function only. If the system has more than one function, each function is considered individually, and a separate RBDs are necessary.

Consider a system with n different components. Each of the n components of system is represented by a block in the RBD as shown in Figure II.4.

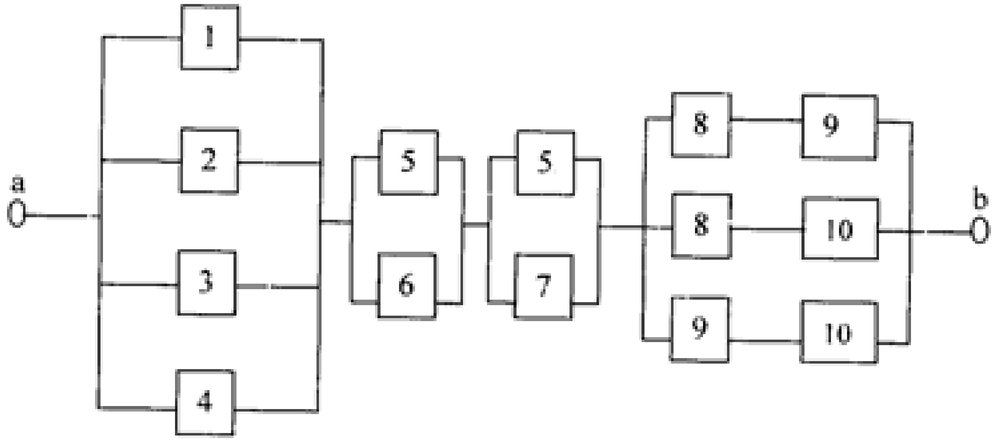
Figure II.4: Illustration of a Building Block in the RBD



When there is a connection between the end points (a) and (b) as in Figure II.4 component $_i$ is considered functioning as designed. This does not necessarily mean that component $_i$ functions in all respects. It only means that one, or a specified set of functions, is achieved (i.e., that some specified failure mode(s) do not occur). What functioning means must be specified in each case and will depend on the objectives of a particular study.

The way the n components are interconnected to fulfill a specified system function may be illustrated by a reliability block diagram, as shown in Figure II.5. The specific system function is considered achieved, when there is a connection between the end points (a) and (b), which means that some specified system failure mode(s) do(es) not occur.

Figure II.5: Illustration of a Reliability Block Diagram

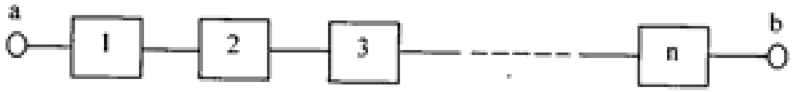


It should be emphasized that a reliability block diagram is not a physical layout diagram for the system. It is a logic diagram, illustrating one function of the system.

II-1.3.2 Non-repairable Series Structure

A system that functions only if all of its n components are functioning is called a series structure. In a series system the system fails to function if any one of the components in the series fails to perform its required function, over the specified period of time. It is not implied that the components are necessarily laid out physically in a series configuration. The corresponding reliability block diagram is shown in Figure II.6. "Connection" between the end points (a) and (b) (i.e. the system is functioning) is achieved only if there is "connection" through all the n blocks representing the components.

Figure II.6: A Reliability Block Model for a Series Structure



The reliability function of such a system is the product of the reliabilities, R_i, of the components.

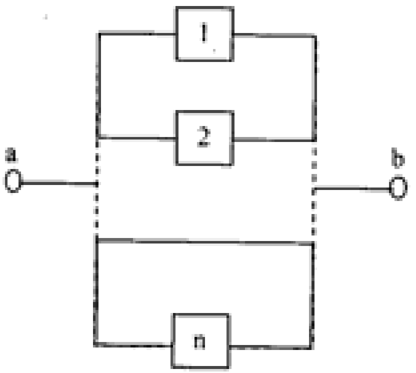
$$R_{system} = \prod_{i=1}^{n} R_i$$

In other words: "A chain is no stronger than it's weakest link".

II-1.3.3 Non-repairable Parallel Structure

A system that is functioning if at least one of its n components is functioning (or one which fails to operate only if all its components fail to operate) is called a parallel structure. A corresponding reliability block diagram is shown in Figure II.7. In this case "connection" between the end points (a) and (b) (i.e., the system is functioning) is achieved if there is "connection" through at least one of the blocks representing the components.

Figure II.7: The Fault Tree Model for a Parallel Structure



Again it is not implied that the components are necessarily laid out physically in a parallel configuration.

The reliability of a parallel system is:

$$R = 1 - \prod_{i=1}^{n} (1 - R_i)$$

Since parallel configurations incorporate redundancy, they are also referred to as "parallel redundant systems."

II-1.3.4 Repairable Systems

Usually one distinguishes between two types of maintenance: corrective and preventive maintenance. Corrective maintenance is usually called repair; it is carried out after a component has failed. The purpose of the corrective maintenance is to bring the component back to a functioning state as soon as possible. Preventive maintenance seeks to reduce the probability of failure of a component. It may involve procedures such as adjustment or replacement of components that are beginning to wear out. Periodic testing and maintenance based on condition monitoring are also regarded as preventive maintenance.

For repairable systems the term *"Availability"* is often used as the reliability performance factor. The availability is defined as the probability of functioning at a given time t. However, for practical purposes the *average* availability is normally used and is defined as the fraction of time an item is able to perform its intended function. In situations where the failure will be discovered immediately, the average availability is defined by:

$$A = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF}$$

where:

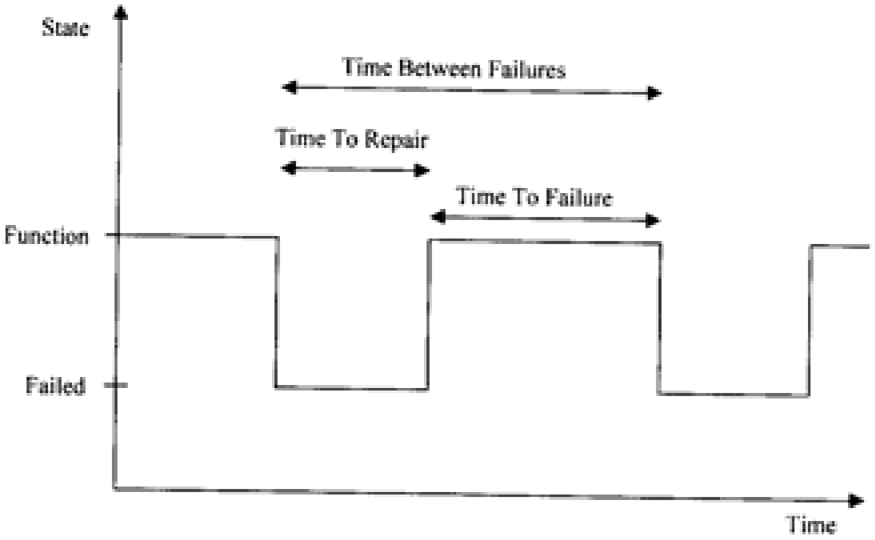
MTTF = Mean Time To Failure = the expected time an item is able to perform its intended function

MTBF = Mean Time Between Failures

MTTR = Mean Time To Repair

The graphical interpretation of this formula is given in Figure II.8.

Figure II.8: Failure and Repair Times



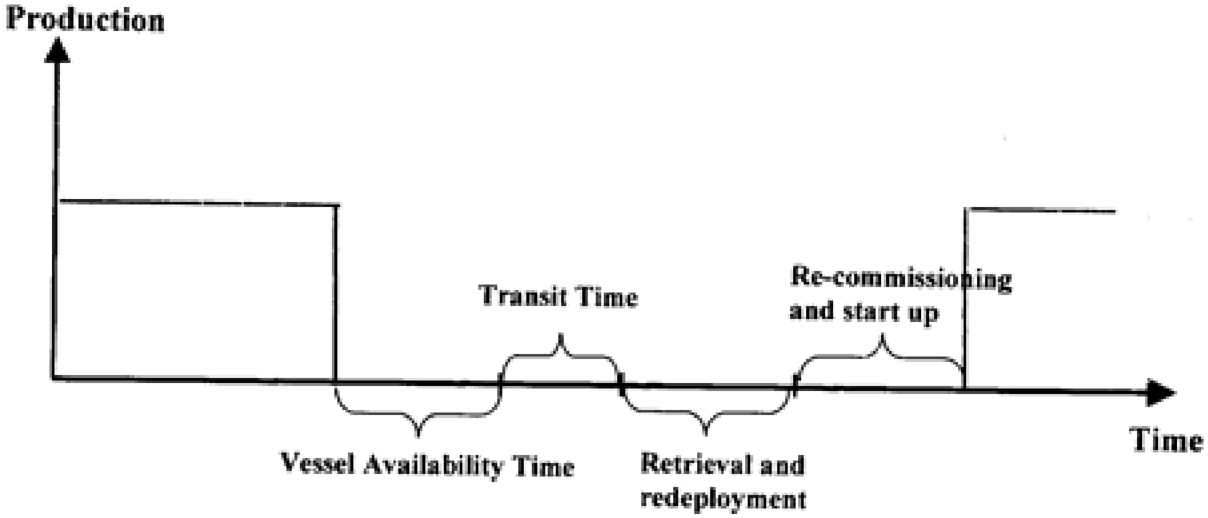
APPENDIX III

DOWN TIME MODEL

III-1 Down Time Model

Once the reliability performance of the subsea booster pump system and its components has been established, the next step is to associate appropriate downtime for each of the individual failure modes. Failures of subsea equipment require special intervention vessels to perform the repair operations, typically resulting in significant downtime. A total downtime evaluation therefore includes a complete development of the overall downtime through an evaluation of the individual operational steps including marine equipment mobilization, transit to site, equipment retrieval and redeployment steps, system re-commissioning and start up. An illustration of some of the parameters that will effect the total downtime of the booster pump system is given in Figure III.9.

Figure III.9: Illustration of some of the Parameters Effecting the System Downtime



The total downtime model is derived through the following key steps:

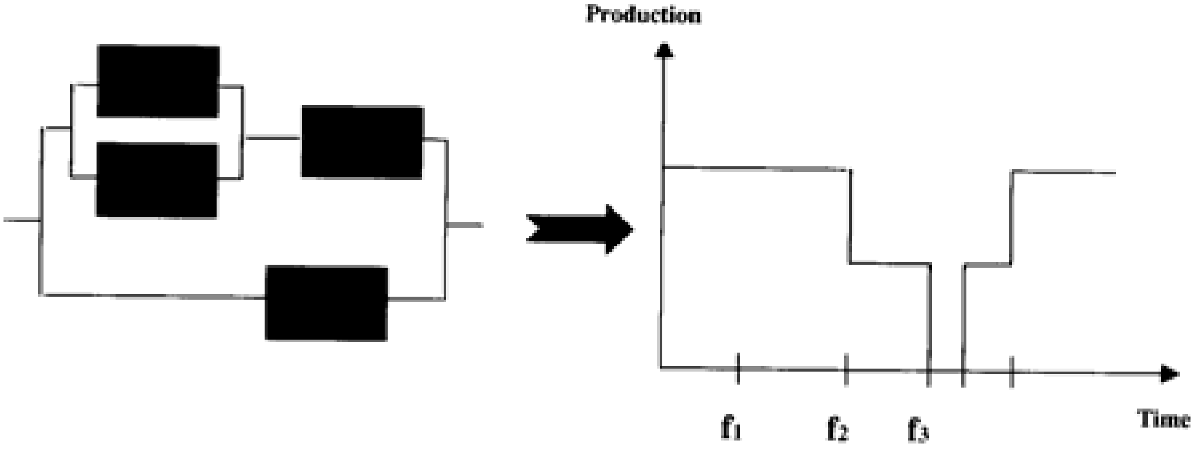
- Characterization of the effects on production continuity deriving from each class of events in terms of loss/reduction of production or loss/reduction of expected incremental production
- Characterization of the scenario of availability of marine equipment, in the region of interest, suitable to perform the intervention operations associated with each class of identified events.
- Development of a vessel availability model based on categorization of lead-time depending on vessel requirements for various failure events.
- Development of the overall downtime duration model through the breakdown and evaluation of individual operational steps including marine equipment mobilization, transit to site, equipment retrieval and redeployment steps, system re-commissioning and start up.

III-1.1 Effect on Production due to Equipment Failures

Depending on the configuration and the redundancy invested in the system, a failure may not have an immediate effect on production. The basic assumption when evaluating the subsea booster pump system, is that one pump is required in each of the two pipelines to maintain the desired boosted production profile, this can be referred to as the system demand. Most cases evaluated include redundant pumps to maintain full boosted production in case of failure in one module.

Figure III.10 gives an illustration of how equipment failures in a redundant system effect production. In the illustration the first failure did not effect production, the second failure however resulted in a fifty-percent loss. The third failure occurred before the previous failure had been repaired which resulted in complete loss of production.

Figure III.10: An Illustration of how Failures in a Redundant System Effect Production



To avoid failures resulting in long downtime and significant costs associated with production loss, it might be optimal to invest in a more redundant system. The spreadsheet tool allows the user to weigh the additional investment costs related to a more redundant system against the potential in future savings related to production.

III-1.2 Intervention Vessel Requirements

A detailed evaluation of the intervention vessels required for subsea repairs, including detailed specifications and requirements is therefore essential to predict a realistic downtime model. As different equipment may require different intervention vessels, an evaluation of the vessel requirements should be made on a component level.

Once the requirements have been established, the next question is the availability of the required resources. Typical questions that needs to be addressed include:

- Which vessels are available on the market that meets the given requirements?
- Where are the required intervention vessels located?

III-1.3 Intervention Vessel Availability Time

Availability time is defined as the time period from when a repair resource is needed until it becomes available to be mobilized for repair purposes. This includes the time required to locate and contract the intervention vessel and the time before it is released from another user. Transit time or mobilization time, is the actual time the vessel requires to get to the site. During the transit time the operator will have to pay full spread costs for the vessel. In some cases, the operator will also have to pay full spread costs for the time it takes the vessel to return to it's geographical location.

Based on the vessel requirements specified, the expected demand for the particular intervention vessels required can be estimated. If very few vessels are available, the availability time will increase. Geographic location is the driving factor for the transit time. Many of the required vessels will typically not be available in the Gulf of Mexico, and particularly not of the West Coast of Africa.

III-1.4 Total Downtime Model

In addition to the configuration and vessel availability, there are other issues that determine the total downtime related to equipment failures. These include:

- Availability of spare units/modules to replace failed equipment.
- Availability of spares and repair resources to maintain failed equipment.

The user, through selecting the system configuration and the repair philosophy can regulate the availability of spare units or modules. By setting rules for when a failed unit is to be replaced, the user automatically controls the risk of running short on available modules. By investing more on interventions and recover any failed unit, the risk of running short is reduced. Alternatively, the users can chose save the intervention cost and wait for more units to fail before recovering.

Most repairs can be performed in a local workshop located close to the installation, however some failures will require adjustments by the manufacturer. The downtime and logistic delay associated with a particular failure mode will therefore differ.

APPENDIX IV

LIFECYCLE COST MODEL

IV-1 Lifecycle Cost Model

This section documents the methodology developed to estimate the reliability based lifecycle cost of subsea booster pump systems.

IV-1.1 Introduction

Field development profitability is a function of many income and expense factors such as capital expenditures, CAPEX, operating expenditures, OPEX, production potential, product price and the frequency of component failures. Subsea booster pumping ultimately increases the production rate, and thus increases the field's profitability. This allows for development of marginal fields, and fields not previously economical to exploit, however to take advantage of the benefits related to this new technology requires successful management of reliability. Component failures will reduce the estimated field production potential and increase the OPEX, and could jeopardize the economics of a field development.

When moving into deeper water, the economic penalty for delayed/lost production becomes greater. Deepwater developments are characterized by high CAPEX with relatively low planned OPEX and high sustainable production rates - hence high costs for production interruption. The uncertainty related to whether "unforeseen" events will occur is also increased as prototype and novel technology is introduced into an operating environment not encountered in shallow water developments. Furthermore, subsea repairs and interventions become more expensive and are associated with longer delays due to availability and mobilization times for required repair vessels, particularly in ultra deep-water environments.

Until recently it was quite common for the decision making process used to evaluate deepwater ventures to focus on optimizing the balance between potential revenue, CAPEX and OPEX according to the equation 2.1. Little effort was put into evaluating the potential of lost revenue and expensive intervention costs due to component failures and unplanned interventions.

$$Profit = Max\ (Revenue - CAPEX - OPEX) \qquad (2.1)$$

Reliability, Availability and Maintainability, RAM, Analysis is a systematic approach to evaluate the uncertainty related to these "unforeseen" events. By associating economic values to the RAM calculations, introducing RAM Expenditures (RAMEX), the decision making process can strengthen. The RAM analysis consist of three important aspects of system performance:

- Reliability expresses the likelihood of surviving a certain time period under given operating conditions.
- Maintainability expresses the time to return a failed or shutdown equipment back to normal service. Influencing factors are working conditions, organization of work, procedures, and resources.

- Availability expresses the percentage of time the equipment is able to perform its intended function under given operating condition. It is a function of reliability and maintainability.

The inclusion of business interruptions caused by "unforeseen" events and failures of the equipment, by including the RAMEX, modifies the economic model as illustrated in equation 2.2.

$$Profit = Max\ (Revenue - CAPEX - OPEX - RAMEX) \qquad (2.2)$$

The methodology is developed to permit predictions of lifetime cost for a field development based on statistical and judgmental reliability data and assumed system parameters. It might be asked, "Why not simply estimate the lifetime cost for the development rather than estimating all these input parameters?" The answers are:

- The system is broken down to a level where some experience data is available and where it is possible to evaluate failure modes and their corresponding effect on system level.
- The quality of the input data (reliability of seals, bearings, electrical connectors, screws and couplings, production profiles, availability time for vessels, vessel spread costs, etc.) is independently evaluated to minimize bias.
- The methodology and spreadsheet tool "model" show the sensitivity to changes in specific input data that is not readily apparent otherwise.
- This model is especially useful to determine which parameters have the strongest influence on the total cost for the subsea booster pump system. The quality of data for these parameters can then be scrutinized to achieve the maximum practical quality. Likewise, time is not wasted by attempting to improve the quality of data that are of less importance to the overall reliability.
- Sensitivity analyses can determine the financial incentive for improving reliabilities of components.

IV-1.2 System Boundaries

The system analyzed and evaluated in this study has been the subsea multiphase booster pump system manufactured by Nuovo Pignone. Other booster pump concepts might include different components and modules, and require different intervention vessels to be restored and repaired. However, the spreadsheet tool allows the user to change and specify all these parameters, and thus relatively easy modify the tool to evaluate a different pumping system. To obtain realistic comparison between alternative pumping systems, it is however important to understand the process undertaken in this project to generate the input data.

The methodology applied when generating the input data for this study is generally applicable when evaluating the economical consequences related to application of new technology. The same challenges and problems apply when evaluating other concepts and solutions for deep-water developments, the methodology could therefore be applied to evaluate the performance other systems and equipment.

The system evaluated in this study is the Nuovo Pignone subsea multiphase booster pump system. The following sub-systems and components have been included:

DSBM Module:	The Nuovo Pignone subsea multiphase booster pump system includes an integrated module with includes the electrical motor, coupling chamber and the actual booster pump. By having an integrated unit the number of connections has been reduced to a minimum.
Control Module:	A conventional subsea control module is installed on each of the subsea booster pumps.
Main Umbilical:	The main umbilical includes lines to supply additional utility fluids and the main electrical power supply to the electrical motor. One umbilical can include power supply for a maximum of two pump modules.
Flowline Jumpers:	Flowline jumpers integrate the subsea booster pumps with the production pipeline.
Electric Flying Lead:	Electrical flying leads supply each of the electrical motors with power. It connects the motor to the subsea umbilical termination point.
Control Flying Lead:	The control system is integrated with the standard subsea control system. A flying lead from the filed subsea distribution unit connects to the control module on the booster pump.

IV-1.3 Life Cycle Cost Calculations

Generally, all the cost elements can occur any time during the filed-life. In order to compare the lifecycle cost for various alternative, each cost element is therefore discounted back to the given investment year. The lifecycle cost is calculated using the following formula:

$$\text{Lifecycle Cost} = \text{CAPEX} + \text{OPEX} + \text{RAMEX} = \text{CAPEX} + \sum_{k \in [1,N]} \frac{OPEX_k}{(1+r)^k} + \sum_{k \in [1,N]} \frac{RAMEX_k}{(1+r)^k}$$

where OPEX_k and RAMEX_k represent the OPEX, and RAMEX in year k respectively, r is the discount rate and N is the field-life in years.

IV-1.3.1 CAPEX

CAPEX, are costs related to actual hardware and installation of the subsea booster pump equipment. The system hardware includes the multiphase pump, electric motor, control system, electrical system, instrumentation and the utility systems. Installation includes vessel-spread cost multiplied by the estimated installation time and any rental or purchase of installation tools and equipment required.

IV-1.3.2 OPEX

OPEX are all costs associated with expenses required for continuos operation of the subsea booster pump system. Typically this includes expenses related to energy consumption, utilities and any other planned cost related to keep the system in continuos operation. To evaluate the cost benefits between frequent interventions and increased production potential, OPEX also includes the costs related to unplanned intervention due to failures in the system, including the spread costs for required intervention vessel and any repair expenses.

IV-1.3.3 RAMEX

RAMEX are costs associated with the economical consequence of component failures. For the booster pumps, RAMEX represents the potential in "loss of production" due to reduced or no boost of the production as a result of component failures. The costs associated with unplanned interventions have been defined as an unplanned intervention cost.

EXECUTIVE SUMMARY

The need for providing energy to the well stream to reach the treatment facilities is continuously increasing as exploitation of hydrocarbon reservoir moves into deeper waters. The ability to provide energy to the well fluids also has the potential benefit of increasing the ultimate recovery and/or accelerating the production. This motivates the interest in exploring the opportunities that some novel technologies like subsea multiphase boosting offers. Significant development and testing work has been undertaken in the effort of qualifying multiphase boosting technology as a viable option for the exploitation of hydrocarbon reserves. While the technology itself is perceived as mature, limited operational experience in subsea applications is available. As a consequence, the anticipated equipment performance and the associated operating costs are subject to uncertainty. In addition, moving into deeper water, subsea system interventions become more expensive and are associated with longer waiting times for the required intervention vessels.

The JIP demonstrates how systematic evaluation of the system, applying traditional risk and reliability techniques, can be used to proactively identify areas of uncertainty. These uncertainties are than quantified by combining economical parameters and reliability simulation techniques, to assist the decision-making process. An integrated probabilistic model for assessing the total reliability based lifecycle cost has been developed, and can be used to assist in finding optimal development solutions and making decisions.

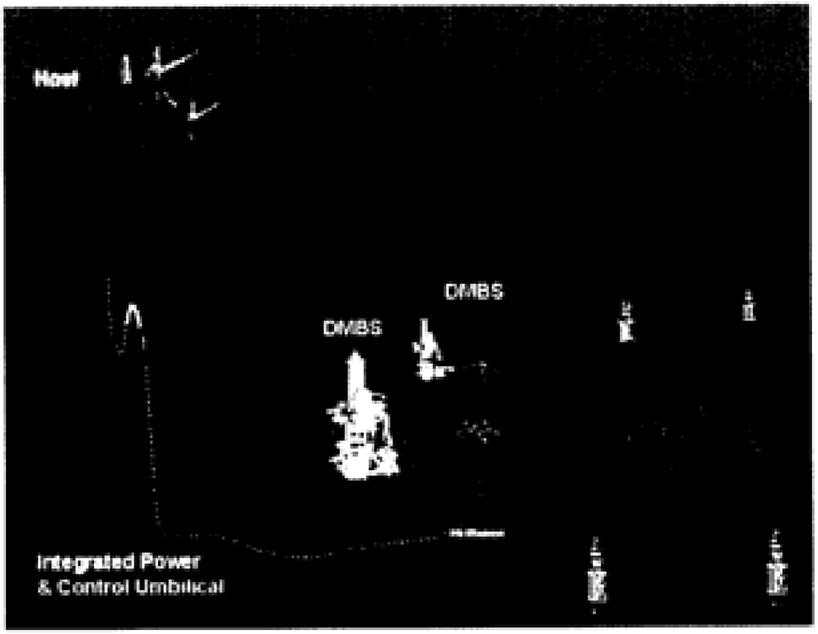
The project was executed in three different phases. Phase one of the project defines the design basis, sizing of the booster pumps and estimates the reference production scheme. Second phase of the project includes the reliability prediction of the subsea booster pump system and the evaluation of the downtime model. The third and final phase of the project includes the economical evaluation, including capital investment costs, CAPEX, operational costs OPEX and costs related to reduced production due to lost or reduced boosting capability. All the cost elements were than combined in a total lifecycle cost model. This lifecycle cost model is established by combining all the information generated in the individual project tasks. By using simulation techniques, all the elements are systematically linked together to generate the lifecycle cost for a booster pump development.

To demonstrate the spreadsheet tool and methodology developed in the JIP, two typical West of Africa and one Gulf of Mexico study case have been evaluated. The tool and methodology is however general, and can easily be modified to reflect and evaluate other study cases. The following three study cases were evaluated in the JIP:

1. A West of Africa development in 4500 ft. water depth, 9 miles tieback.
2. A West of Africa development in 7000 ft. water depth, 18 miles tieback.
3. A Gulf of Mexico development in 6000 ft. water depth, 7 miles tieback.

All study cases have a dual piggable flowline loop tying back to the host facility. For the long tieback, a floating buoy is located close to the pumping unit to support the electrical power supply. This will prevent some of the electrical power loss through the umbilical. For all study cases, the tool allows the user to evaluate the lifecycle cost for different sparing philosophies and maintenance decisions. An illustration of the short tieback scenario is given in Figure 1.

Figure 1: Illustration of the Subsea Booster Pump System



To evaluate the total lifecycle cost related to subsea booster pumping, the Excel based spreadsheet tool is applied. The tool is used to evaluate different redundancy configurations and maintenance decisions, and is applied to suggest cost optimal solutions for the different study cases. The different configurations implemented in the lifecycle cost tool, are illustrated in Figure 4, and include:

Full Redundant System:	A dedicated hot spare boosting module for each active one.
Redundant System:	A common hot spare module available to compensate a single module failure.
Subsea Spare System:	A dedicated cold subsea module not connected, available for each active module. (Has to be hocked-up by an ROV in case of demand.)
	A common cold subsea module, available to be hocked-up with an ROV to replace a single failed pump module.
Surface Spare System:	Spare pumping module available on surface, requiring a heavy lift operation to replace the failed module.

The tool allows the user to select the various options, and calculate the associated lifecycle cost. This gives the user valuable information in order to select a cost optimal configuration.

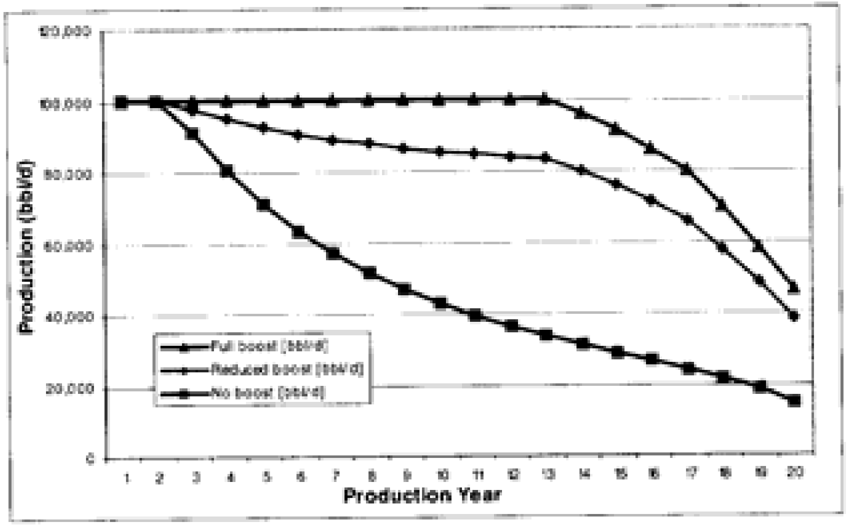
The key economic benefit of applying subsea booster pumps, is the potential for increased recovery and/or accelerated production. By providing energy to the well stream, the wellhead pressure is increased and the flow from the wells will increase until a new balance between the fluid pressure and the system resistance is achieved. This allows operators to exploit marginal fields with less wellhead pressure and opens the potential for longer tiebacks.

For the purpose of a rough screening exercise, several different booster pumps provided by Nuovo Pignone have been implemented in the Excel spreadsheet model. The characteristics of each pump is included, allowing the user to provide a desired boosted production profile and the tool will automatically check whether any of the available pumps will meet the specified requirements. To perform the brief screening of suitable booster pumps, the user is asked to provide the following information regarding the reservoir characteristics:

- Desired boosted production profile of oil.
- Boosted production profile of gas and water.
- Wellhead pressure.
- Wellhead temperature.

It is further recommended that the user provide information regarding the compressibility factor, oil formation factor and gas-oil-ratio. An illustration of the boosted and non-boosted production profile is given in Figure 2.

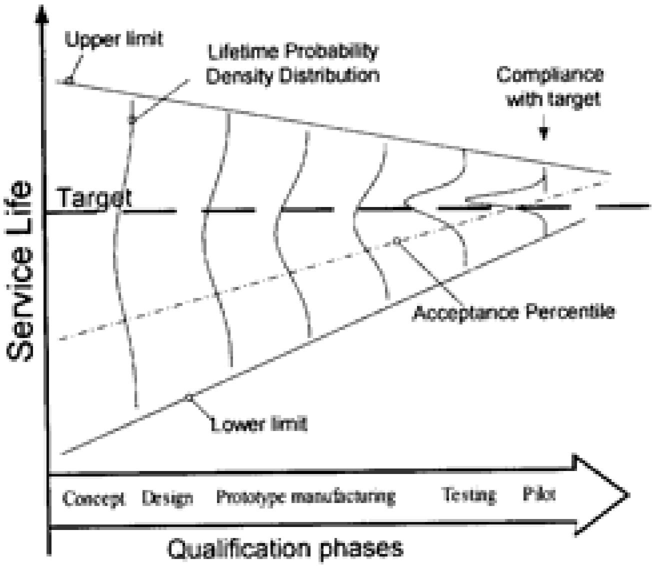
Figure 2: Illustration of the Boosted and Non-Boosted Production Profile



Due to the limited operational experience, particularly in deepwater, little or no reliability data of the overall performance of subsea multiphase booster pumps has been available. In order to predict the reliability performance of the subsea multiphase booster pump system, a complete review was performed applying traditional reliability techniques. The system was split into suitable sub-systems and components, and data was obtained from industry databases and experience with similar equipment. This in combination with test experience and expert judgement served as the basis for establishing the reliability performance of the booster pump system.

The reliability evaluation was based on the latest available documentation provided by Sonsub and Nuovo Pignone. This included detailed design drawings of the system, results from the factory acceptance tests, system integration test and the actual filed testing of the equipment in a subsea environment. Based on this documentation and discussions and meetings with the pump manufacturer, the system was evaluated and a reliability model was developed. An illustration of how additional information provides more confidence in the reliability prediction is illustrated in Figure 3. As more information is available, more confidence can be put into the predictions.

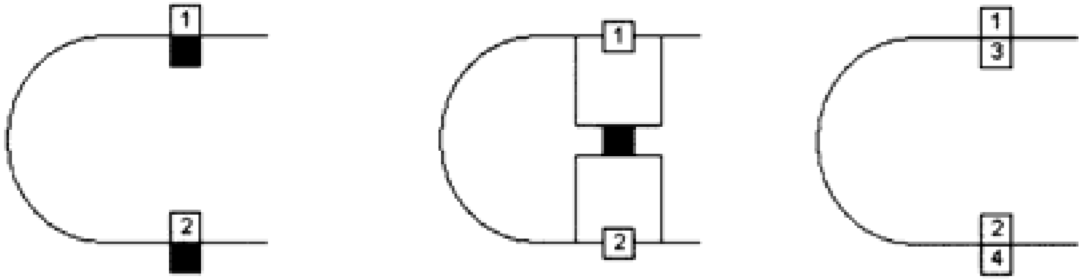
Figure 3: Illustration of the reliability prediction process



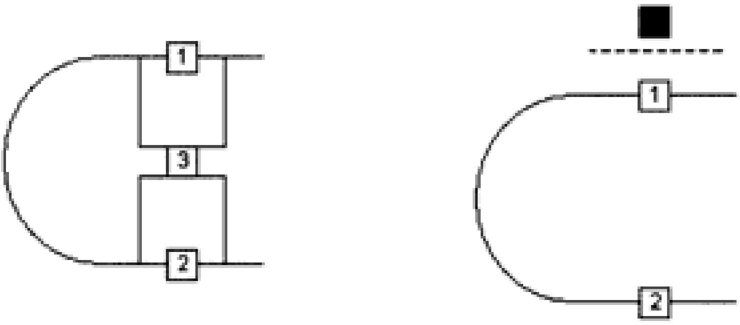
By applying Monte Carlo simulation techniques, the economical consequence related to equipment failures can be implemented in a total lifecycle cost model. Depending on the system configuration, a failed unit could either result in loss of redundancy or loss of boosting capacity. To restore a failed unit, the required intervention vessel will have to be allocated and a new module will be installed or hooked-up to replace the failed unit. Depending on the failure, the failed unit will either be repaired in a dedicated workshop or brought back to the manufacturer for overhaul. The lifecycle cost model will automatically incorporate all cost elements related to loss of boosting capacity and any costs associated with intervention vessels and spare parts.

The Excel spreadsheet tool allows the user to select between different configurations and choose different maintenance philosophies and calculate the associated lifecycle cost or economical consequence related to each particular case. Whether built-in availability increases or decreases the initial capital investments is not as important as whether the investment is beneficial from a revenue point of view. Additional investment costs can be justified based on increased revenue from a lifecycle cost evaluation. The different redundancy options are given in Figure 4.

Figure 4: Illustration of the Redundancy Options Evaluated



Full Redundant System (1.1b) Common Hot Spare (2.1b) Two Cold Spares (2.2b)

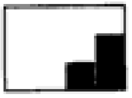
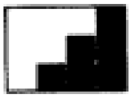
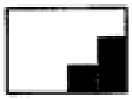
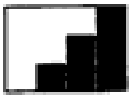
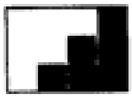
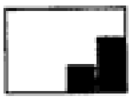
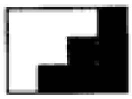
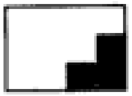
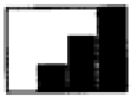
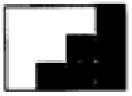
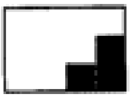
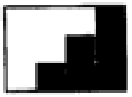
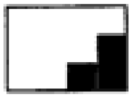
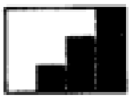
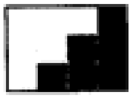
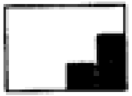


One Cold Spare (2.2c) Surface Spare (3.1a)

A number of simulations with different settings were performed to determine a cost optimal solution for each of the three study cases. In addition to the configuration, the intervention requirements can be changed. Early screening indicated that limiting the number of ROV interventions typically results in increased lifecycle cost for all the configurations evaluated. As a start, all the cases were therefore evaluated with the assumption that ROVs are allocated immediately after the first failure occur, and only the MSV criteria was changed when running the simulation screening.

Due to the high value of the boosted production, any settings that result in reduced or lost boost for a significant time will give a high lifecycle cost. As a consequence, only a limited number of settings are beneficial from a lifecycle cost perspective. These settings were determined and the cases simulated and evaluated in the next screening process. A complete list of the cases evaluated for the different redundancy configurations are listed in Table 1.

Table 1: Intervention Vessel Settings

Case	**Configuration**				
	1.1b	**2.1b**	**2.2b**	**2.2c**	**3.1a**
1					
2					
3					
4					

The intervention requirements specified in Table 1 were used to determine the optimal intervention requirement setting for each of the configurations. After this screening process, the best alternatives were evaluated in more detail to select a suggested configuration for each of the three study cases.

For both of the West of Africa study cases, the full redundant system has been selected as the most optimal configuration. The additional investment costs for a full redundant system, benefits from a lower production loss and less interventions resulting in a lower lifecycle cost. For the short tieback solution, the surface spare configuration was a good alternative, however as explained in the main report the decision will depend on the discount rate.

For the Gulf of Mexico study case the configuration with a surface spare module is the most beneficial. This study case only evaluates nine years of production, which makes it less vulnerable to operational costs and production losses. The lifecycle costs calculated for each of the study case is given in Table 2.

Table 2: Lifecycle Costs Generated for the Three Study Cases

	WA 4500	WA 7500	GoM
RAMEX	33.1	58.9	4.2
OPEX	43.9	55.4	11.8
CAPEX	68.5	59.4	30.3
Lifecycle Cost	**145.6**	**173.6**	**46.2**

Subsea multiphase pumping is expected to be one of the most efficient tools for economic exploration of deepwater marginal fields. The need to provide energy to the well stream to reach the treatment facilities is continuously increasing as exploitation for hydrocarbons moves into deeper waters. Further, increased energy to the well fluids has the potential to increase the ultimate recovery and/or accelerate the production.

The benefits of subsea booster pumping are evident, however there are major uncertainties related to the reliability performance of these systems. Significant development and testing work has been undertaken in the effort of qualifying multiphase boosting technology as a viable option for the exploitation of hydrocarbon reserves. While the technology itself is perceived as mature, limited operational experience in subsea applications is available. As a consequence, the anticipated equipment performance and the associated operating costs are subject to uncertainty.

Operators hesitate to be the first users of new technology before the benefits are fully understood, and subsea multiphase boosting technology has yet to demonstrated it's claimed merits. The main reason is the uncertainty associated with the operating expenditures and intervention costs related to "unforeseen" events and equipment failures. The JIP demonstrates how systematic evaluation of the system, applying traditional risk and reliability techniques, can be used to identify areas of uncertainty. These uncertainties are than quantified by combining economical parameters and reliability simulation techniques, to assist the decision-making process. An integrated probabilistic model for assessing the total reliability based lifecycle cost has been developed, and can be used to assist in finding optimal development solutions and making decisions.

One of the main results from this reliability evaluation is the potential cost saving related to focusing attention on critical areas, and improvement of solutions and concepts where the reward with respect to improved reliability is highest. The most critical components identified in this study include seals and bearings in both the pump module and the electrical motor. Effort has been made to improve the reliability of the seals and bearings applied in the booster pumps, however to provide confidence in the reliability predictions it is important that a reliability qualification program is established and testing in realistic conditions continue to define realistic and representative failure rates.

When establishing the reliability of the subsea booster pumps, available reliability data for similar equipment was reviewed and evaluated in detail. Further, the design documentation was evaluated and reviewed for system design specifications and requirements. Results from the factory acceptance tests, and the actual field application test were also made available to the JIP, and helped establishing more confidence in the predicted values. It is however important to realize the limitations of these predictions. It is strongly recommended to develop a detailed risk and reliability plan for any specific project to assure the reliability targets are met throughout the project development.

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1 INTRODUCTION

1.1 Purpose

The purpose of this JIP is to address uncertainties related to subsea multiphase booster pumping in deepwater application. Traditional risk and reliability techniques are applied to proactively identify shortcomings and uncertainties that may otherwise have gone unnoticed. These uncertainties are then quantified in a complete lifecycle cost model developed to assist in the decision-making process for selecting cost optimal subsea booster pumping solutions.

The JIP is based on the Sonsub/Nuovo Pignone subsea booster pump concept. Even though, the tool is developed for these specific pumps, the input can easily be modified to reflect other systems and configurations if required. The purpose of this JIP is to develop a model that can be applied to evaluate cost/benefit of different system configurations and maintenance strategies and find optimal field solution. An additional feature is to implement a selection of available booster pumps provided by Nuovo Pignone and make the tool a brief screening tool to select suitable pumps for specified applications.

1.2 Background

Technological improvements have essentially provided access to hydrocarbon resources increasingly difficult to reach and produce. The economical efficiency of these new achievements was never questioned as long as economical margins were high and the demand was growing. Over the last decades however, finding and producing quickly was no longer the only objective, companies were forced to cut costs and produce and explore more efficiently.

Today, access to the resources and cost reduction are combined efforts in the industry, and remarkable improvements have been made within different disciplines in order to meet the demand for faster and more cost efficient exploration and production. Subsea technology has allowed oil-and-gas developments to emerge into deep and ultra-deep waters. Further, fields not previously considered economical or even possible to exploit, are now being developed utilizing the potential from this new technology. Subsea multiphase boosting represents some of the latest technological achievements in subsea arena. Even though, multiphase pumps have been available for several decades for onshore and topside applications in the upstream petroleum industry as well as in the process industries, it is only during the last decade significant effort has been made to explore the potential for subsea applications.

Subsea multiphase pumping is expected to be one of the most efficient tools for economic exploration of deepwater marginal fields. By boosting the well fluid, the wellhead pressure is increased and the flow from the wells will increase until a new balance between the fluid pressure and the system resistance is achieved. Some of the main benefits related to subsea booster pumping include:

- Accelerated production rates and increased recovery, resulting in overall improved field economics.

- Increased potential to develop and produce remote fields to an existing or central host, and eliminate the need for surface facilities in the field.
- Reduced liquid slugging in the riser resulting in significant cost reduction as the need for large slug catchers has been eliminated.
- Improved flow assurance performance in general as higher flow rates result in higher flowing temperatures in the wellbores, flowlines, and risers.

The benefits of subsea booster pumping are evident, however there are major uncertainties related to the reliability performance of these systems. Significant development and testing work has been undertaken in the effort of qualifying multiphase boosting technology as a viable option for the exploitation of hydrocarbon reserves. While the technology itself is perceived as mature, limited operational experience in subsea applications is available. As a consequence, the anticipated equipment performance and the associated operating costs are subject to uncertainty. In addition, moving into deeper water, subsea system interventions become more expensive and are associated with longer waiting times for the required intervention vessels.

This study demonstrates how systematic evaluation of the system, applying risk and reliability techniques can be used to proactively identify uncertainties associated with subsea booster pumping. Further, having a better understanding of the uncertainties involved, ultimately result in possibilities to reduce these uncertainties and assist in the decision-making process when evaluating the application of subsea multiphase pumping.

1.3 Scope of Study

The objective of this JIP is to systematically identify uncertainties related to subsea multiphase booster pumping in deepwater application, and quantify these uncertainties in a complete lifecycle cost model.

Thus, the scope of work for the JIP is twofold:

- To address and identify uncertainties related to the subsea multiphase boosting operation in deepwater.
- To develop and demonstrate a probabilistic model for assessing the reliability based lifecycle cost for subsea multiphase boosting operation in deepwater.

Traditional risk and reliability techniques are applied to proactively identify shortcomings and uncertainties related to the subsea booster pump system. Quantitative reliability numbers associated with these uncertainties are based on a combination of experience from similar systems and applications, and detailed evaluation of the sub-systems and components in the current system design.

A probabilistic model for assessing the *reliability*-based lifecycle cost for subsea multiphase boosting operation in deepwater has been implemented in an Excel spreadsheet. This tool can be applied to evaluate the cost/benefit of different system configurations and maintenance strategies to find the most cost optimal solutions.

The JIP methodology is than applied to evaluate three specific development scenarios. The three study cases considered include:

- A West of Africa development in 4500 ft. water depth, 9 miles tieback.
- A West of Africa development in 7000 ft. water depth, 18 miles tieback.
- A Gulf of Mexico development in 6000 ft. water depth, 7 miles tieback.

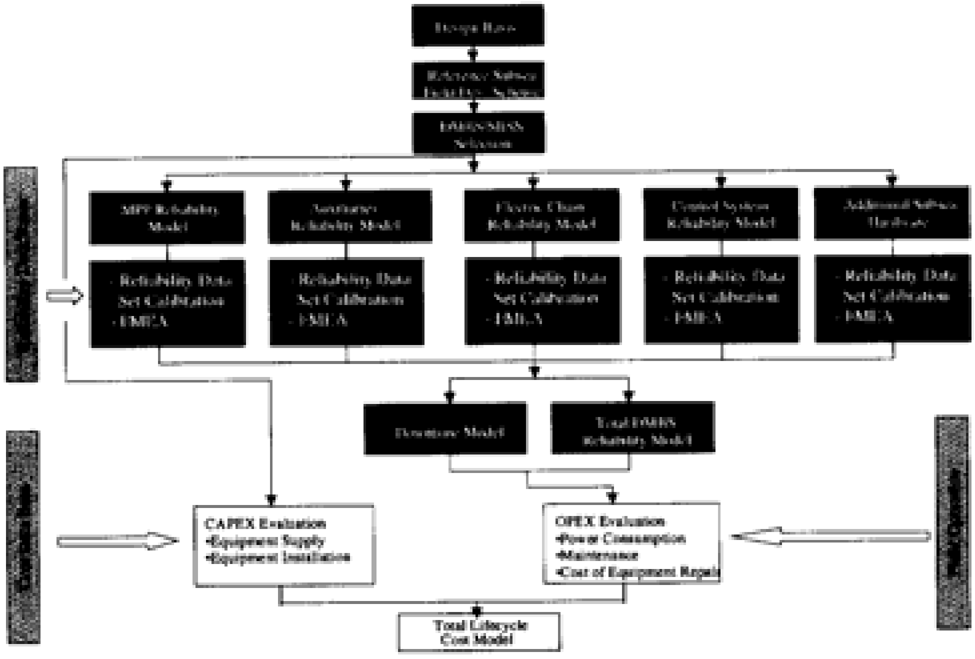
The study cases were all constructed in co-operations with the JIP sponsors, who provided production profiles and reservoir characteristics required to develop the study cases. Based on the provided information, the potential benefit of boosting the production was estimated, and booster pumps were suggested.

To evaluate the total lifecycle cost related to subsea booster pumping, the Excel based spreadsheet model is applied. The spreadsheet tool is used to evaluate different redundancy configurations and maintenance decisions, and is applied to suggest cost optimal solutions for the different study cases.

1.4 Methodology

The project is executed in three different phases. Phase one of the project defines the design basis, sizing of the booster pumps and estimates the reference production scheme. This initial phase of the project is represented by the blue boxes in Figure 1.1. The second phase of the project includes the reliability prediction of the subsea booster pump system and the evaluation of the downtime model. This represented by the green boxes in Figure 1.1. The third and final phase of the project includes the economical evaluation, tying all the cost elements together in a total lifecycle cost model.

Figure 1.1: The Work Process to Evaluate the Total Lifecycle Cost for the Subsea Multiphase Booster Pumps



The first step when considering subsea booster pumps is to estimate the potential related to increased production. Based on given reservoir characteristics, suited pumps have been selected from a list of available pumps provided by Nuovo Pignone. Details regarding the design specifications, sizing of the pumps and calculations of the reference production schemes can all be found in separate reports produced by the JIP.

Based on the design specifications, the reliability performance of the systems has been evaluated applying traditional risk and reliability techniques. The reliability model has been developed in close co-operation with the manufacture, and included:

- Splitting up the booster pump system into suitable sub-systems and components.
- Perform an FMEA analyses of the individual sub-systems and components.
- Predict the reliability through experience from similar systems and components in combination with expert judgement and actual test data.

Once the reliability model has been established, the downtime associated with various failures has to be determined. This downtime is based on the need for dedicated maintenance recourses, spare parts and potential repair times in addition to the actual time for the intervention or replacement operation. All these aspects are linked together in the downtime model.

The lifecycle cost model combines all the previous information and incorporates the cost elements. By using simulation techniques, all the elements can systematically be linked together to generate the total lifecycle cost for the particular development or concept evaluated.

The following cost elements are considered when evaluating the different subsea booster pump configurations:

- CAPEX, capital expenditures related to hardware and installation of the subsea booster pump system. The system hardware includes the multiphase pump, electric motor, control system, electrical system, instrumentation and the utility systems. Installation includes vessel-spread cost multiplied by the estimated installation time and any rental or purchase of installation tools and equipment required.
- OPEX, operating expenditures are expenses associated with required continuos operation of the subsea booster pump system. Typically this includes expenses related to energy consumption, utilities and any other planned costs related to keeping the system in continuos operation. In addition to the planned operational cost elements, in this study OPEX also includes costs related to vessels and repairs due to equipment failures.
- RAMEX, are costs associated with the economical consequence of a component failures. For the booster pumps, RAMEX represents the potential in "loss of production" due to reduced or no boost of the production as a result of component failures.

1.5 Deliverables

The main deliverable from the JIP project is an Excel based spreadsheet tool that allows the user to calculate the total lifecycle cost for different configurations and maintenance philosophies related to the subsea booster pumps. The spreadsheet tool ties all the cost elements together, and includes detailed assessment of:

- The reliability of the components and how this links to system reliability and performance of the booster pump system.
- The downtime associated to equipment failures.
- The OPEX both associated with planned and unplanned interventions.
- The CAPEX associated with the investment in the equipment and commissioning of the booster pump system.

This "modular" approach is also reflected in the development of the spreadsheet model making it sufficiently *flexible* to allow inclusion of reliability analysis of other subsea pumping equipment (i.e., equipment not covered by this JIP). In a similar way, reliability data sets relevant to different equipment can be specified and the related lifecycle cost predicted.

The JIP project is has also been aiming to actively contribute to the increased knowledge and awareness of subsea multiphase pumping design, reliability and operation.

1.6 Definitions

The following definitions were used:

Reliability:	The British Standard BS 4778 defines reliability as "the probability that an item will perform a required function under stated conditions for a stated period of time."
Availability:	The proportion of the total relevant time that a component, equipment or system is available to perform its intended function.
Failure:	The termination of the ability of an item to perform a required function.
Fault:	State of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, due to lack of external resources.
Probability of failure:	The likelihood that a component is in the failed state.
Frequency:	The average rate at which an event will occur.
Common Cause Failures:	Simultaneous failure of two or more system parts from a common cause.

Revealed Failures:	A failure that would reveal itself to the personnel e.g., control room alarm/ light. A failure of a component, equipment or system that is automatically brought to light in its occurrence is said to be a revealed failure.
Critical failure:	A critical failure has been defined as a failure of a component or sub-system requiring the drilling system to be retrieved and repaired.
Unrevealed failures:	Failure that would only be detected when testing the system. A failure of a component, equipment of system that remains hidden until revealed by some thorough proof testing procedure.

1.7 Abbreviations

FMEA:	Failure Mode and Effect Analysis
FTA:	Fault Tree Analysis
MODU:	Mobile Offshore Drilling Unit
OREDA:	Offshore Reliability Database
CIU:	Chemical Injection Unit
DCS:	Distributed Control System
DMBS:	Deepwater Multiphase Boosting System
EPU:	Electric Power Unit
HPU:	Hydraulic Power Unit
IM&R	Inspection Maintenance & Repair
SEHDU:	Subsea Electro-Hydraulic Distribution Unit
VSD:	Variable Speed Drive
UPS:	Un-interruptible Power Supply
ROV:	Remote Operated Vehicle
SCM:	Subsea Control Module
SBSS:	Subsea Boosting System Station
DMBS:	Deepwater Multiphase Boosting System

MPP:	Multiphase Pump
UTA:	Umbilical Termination Assembly

2 SYSTEM DESCRIPTION

2.1 Definition of the System

The current section gives a brief introduction to the Sonsub/Nuovo Pignone subsea booster pump concept. Both the subsea and topside equipment is described, and an overview of the key components and system configurations covered by the JIP is presented. A detailed description on the pumps can be found in the design specification documents provided for the JIP.

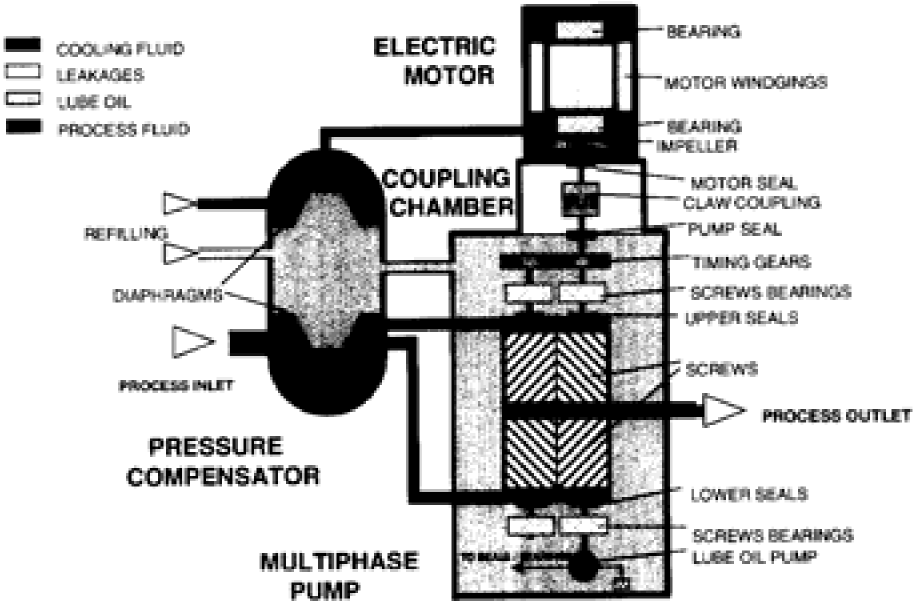
2.2 Subsea Pumping System

The subsea multiphase booster pump system evaluated includes a subsea screw pump in vertical configuration driven by a water-filled electric motor. The pump is equipped with an integrated lube oil system and the complete module is pressure balanced at the process pump inlet conditions by means of special pressure transfer vessels. A schematic overview of the system is given in Figure 2.1.

The current subsea screw pump design is a result a development project with emphasize on a number of key issues, including:

- Focus on developing an integrated unit;
- Simplicity, and minimizing the use of new and unproven technology;
- Self-regulation without any control requirements;
- Insensitivity to the water depth;

Figure 2.1: The Subsea Multiphase Booster Pump



Improvements have been made in the design of the components of the pump as well as in the fabrication methodologies and in the selection of the mechanical seals and hydrodynamic bearings configuration. Mechanical seals and bearings are continuously lubricated by a dedicated lube oil system. The lube oil system is a closed circuit connected to an integrated oil tank, which is pressure balanced to match the pump inlet conditions. A lubrication pump is installed within a pressurized lube oil vessel and is mechanically driven by the pump shaft. This pump provides the required differential pressure to enable the oil circulation and the oil supply to both the mechanical seals and the bearings. Such a differential pressure, which is the maximum load expected across the seals, is practically constant, in a range of 1.5 – 2 bars, and is totally independent from the pump inlet pressure.

The pressure balance of the whole system is obtained through a "primary transfer vessel" where an elastomeric diaphragm with a special designed shape separates the lube oil section from the process fluids at the pump suction side. In this way the lube oil is continuously maintained at the process pressure without contamination of the fluids. Due to the positive and constant overpressure across the pump seals, leakage of lube oil will occur pass the seals towards both the process and the coupling side. However, leakage of other fluids in the reverse direction potentially contaminating the lube oil will be eliminated due to the overpressure. The oil leakage is compensated by the translation of the primary diaphragm and, consequently by a net volume reduction of the oil reservoir that is maintained at a constant pressure. The oil reservoir is sized to allow the oil leakage and is refilling according to pre-defined calculations.

The lube oil section also transmits the process pressure to the remaining sections of the system, motor and coupling chamber, by means of two "secondary transfer vessels". These vessels are equipped with a standard bladder type compensator. The electric motor is hydraulically pressure balanced to the pump process inlet conditions through the secondary transfer vessel that separates the motor cooling-water from the lube oil. In addition, an auxiliary internal impeller provides an overpressure of 0.5 bar to the motor shaft seal chamber during running, to ensure leakage across the seals only occur from the motor to the coupling chamber. Any water leakage towards the coupling zone is compensated by a reduction of the water reservoir net volume, similarly to the primary oil circuit, until an external water refilling is required.

Water and oil leakage towards the coupling chamber is collected in another secondary transfer vessel, which is pressure compensated similarly to the water vessel. This leakage vessel requires an emptying operation in conjunction with the refilling of the other two vessels.

2.3 Surface Facilities

To accommodate the power demand from the subsea booster pumps, a topside power supply has to be provided. Further, a variable speed drive will be required to ensure the production flow variations as required due to the multiphase nature of the fluid and to the field production profile during the field life. All the equipment constituting the electrical system able to provide the mechanical power required by the multiphase pumps from the topside available power supply is commonly identified as the "Electrical Power Chain".

Other than the Electrical Power Chain equipment, the SBS will be constituted by a number of other sub-systems each designed to provide a specific functionality. Some of these sub-systems will be installed at topside, while the others will be installed subsea housed on suitable support frame.

The DMBS sub-systems located at topside facilities include the following equipment:

- The Variable Speed Drives (VSD);
- The Step-Up Transformer;
- The Hydraulic Power Unit;
- The Instrumentation and Control Electric Power Unit;
- The Lube Oil Refilling Unit;
- The Cooling Fluid Refilling Unit;
- Topside Control Unit(s) and Operator Station(s);
- Chemical Injection Unit (CIU);

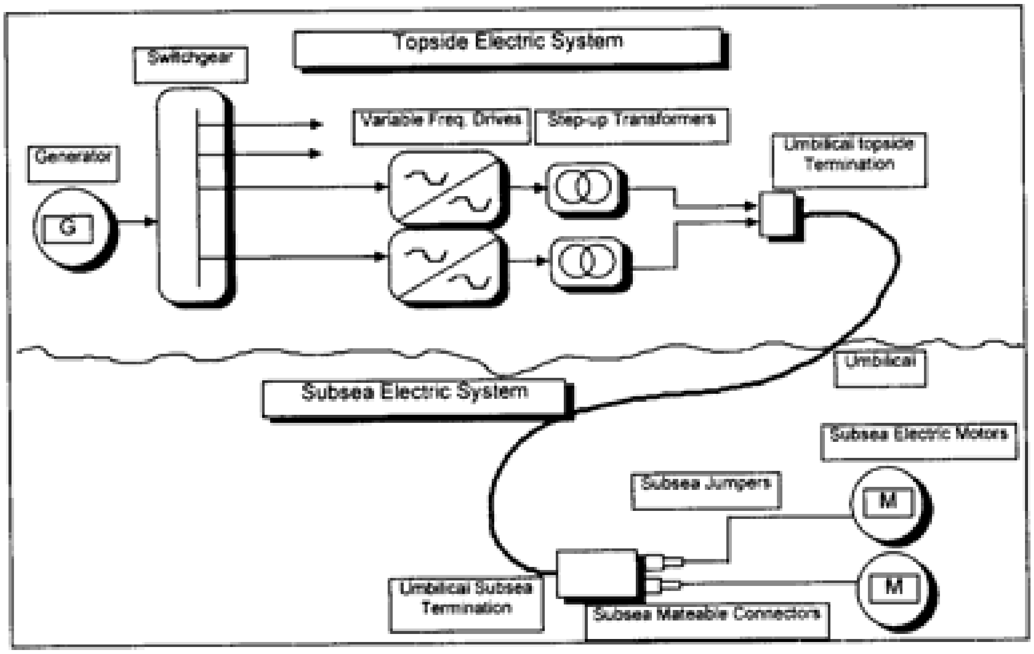
The SBS topside and subsea installed equipment are linked together by:

- A control/service umbilical carrying all the hydraulic power fluid, chemicals, low voltage electric power supply and communication signals lines.
- A power/service umbilical carrying the auxiliary fluids (lube oil and cooling fluids) and the high voltage electric power lines

The subsea multiphase booster concept has chosen a minimum subsea equipment approach. The electric distribution and speed regulation equipment are installed at the topside facility, and connected to the relevant subsea motors by means of individual electric cables housed inside one or more umbilical cables. If necessary subsea step-down transformers are used to match the subsea motor working voltage with the voltage level used for electric power transportation.

The key factor driving the architecture and requirements of the topside facility to support the subsea multiphase boosting system is the topside electrical power supply needed to provide the required power and functionality related to the subsea boosting equipment. The most general configurations for a Subsea Electric Power Distribution System are summarized in the Figure 2.2.

Figure 2.2: Illustration of the Subsea Electrical Power Chain



2.4 Sparing Philosophies

The concept evaluated in this study has been a dual piggable looped flowline, with dedicated booster pump modules in each of the two pipelines. In addition to the two pumps in operation, different sparing or redundancy options are evaluated. These different options are all implemented in the lifecycle cost tool, and include:

Full Redundant System:	A dedicated hot spare boosting module for each active one.
Redundant System:	A common hot spare module available to compensate a single module failure.
Subsea Spare System:	A dedicated cold subsea module not connected, available for each active module. (Has to be hocked-up by an ROV in case of demand.)
	A common cold subsea module, available to be hocked-up with an ROV to replace a single failed pump module.
Surface Spare System:	Spare pumping module available on surface, requiring a heavy lift operation to replace the failed module.

The tool allows the user to select the various options, and calculate the associated lifecycle cost. This gives the user valuable information in order to select a cost optimal configuration.

A more detailed system description can be found in the design basis report.

3 PROJECT EXECUTION

The following chapter explains the technical details related to the project execution. Focus is on the technical aspects implemented in the spreadsheet tool and specific details regarding reliability-based lifecycle cost tool are not included. A brief user manual of the tool however, can be found in Appendix V.

3.1 Definition of the System

Before starting the lifecycle cost evaluation of the subsea booster pump system, the study boundaries were defined in co-operation with the JIP participants. The main focus of the study was the evaluation of the reliability based lifecycle cost of the subsea booster pumps and the associated auxiliary systems. Several system configuration alternatives were evaluated, and different redundancy options implemented in the Excel spreadsheet tool.

3.2 Reference Production Scheme

The first calculation, when estimating the lifecycle cost related to subsea booster pumping, is to evaluate the expected effect on the production profiles. By boosting the well fluid, the wellhead pressure is increased and the flow from the wells will increase until a new balance between the fluid pressure and the system resistance is achieved. The effect of booster pumping will depend on the reservoir characteristics, and is explained in detail in a separate report where the production profile for the three stud cases have been evaaluated. It is strongly recommended that the exercise related to prediction the production profile and selecting suitable booster pumps is performed on a case to case basis.

For the purpose of a rough screening exercise, however, several different booster pumps provided by Nuovo Pignone have been implemented in the Excel spreadsheet model. The characteristics of these individual pumps are implemented, allowing the user to provide a desired boosted production profile, and the tool will automatically check whether any of the available pumps would be able to meet these specified requirements.

To perform the brief screening of suitable booster pumps, the user is asked to provide the following information regarding the reservoir characteristics:

- Desired boosted production profile of oil.
- Boosted production profile of gas and water.
- Wellhead pressure.
- Wellhead temperature.

It is further recommended that the user provide information regarding the compressibility factor, oil formation factor and gas-oil-ratio. The tool does however, provide *suggested* values for these parameters.

3.3 Reliability Model

Due to the limited operational experience, particularly in deepwater, little or no reliability data of the overall performance of subsea multiphase booster pumps has been available. In order to predict the reliability performance of the subsea multiphase booster pump system, a complete review was performed applying traditional reliability techniques. The system was split into suitable sub-systems and components, and data was obtained from industry databases and experience with similar equipment. This in combination with test experience and expert judgement served as the basis for establishing the performance of the booster pump system.

The reliability evaluation was based on the latest available documentation provided by Sonsub and Nuovo Pignone. This included detailed design drawings of the system, results from the factory acceptance tests, system integration test and the actual filed testing of the equipment in a subsea environment. Based on this documentation and discussions and meetings with the pump manufacturer, the system was evaluated and the reliability model was developed.

The reliability analysis was performed in a five-step process, including:

- A systematic breakdown of the system
- A Failure Mode Effect Analysis (FMEA)
- A review of available data sources
- Reliability prediction based on actual operating parameters
- Expert judgement based on experience with similar equipment

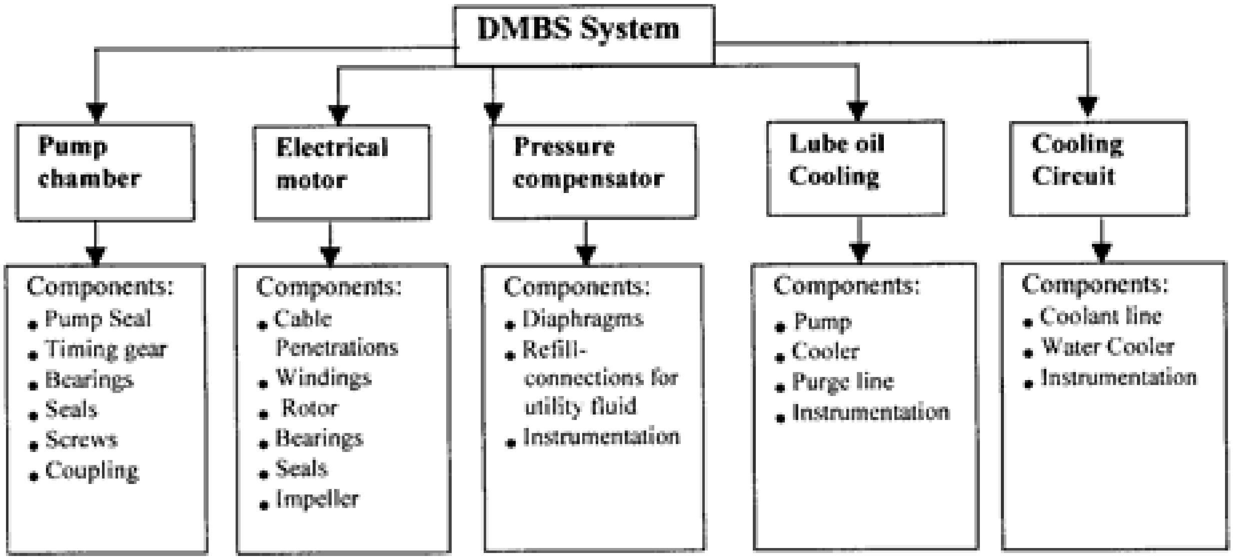
3.3.1 System Breakdown

The subsea multiphase booster pump system was split into the five sub-systems as follows:

- Pump
- Motor
- Pressure Compensator
- Lube Oil Cooling
- Cooling Circuit

Each sub-system was further split into their basic components as illustrated in Figure 3.1.

Figure 3.1: Overview of breakdown of the subsea multiphase booster pump



3.4 Performing the FMEA

In this study, the FMEA was used to systematically review the subsea multiphase booster pump system and identify any conceivable failure modes. The effects of these failure modes on successful operations were identified, and the FMEA further served as input to the quantification of the overall system reliability.

The purpose of the FMEA was to establish better understanding of the subsea booster pump, in order to predict the reliability performance. Focus was therefore on the subsea equipment and identified failures that would require the system to be retrieved to surface for repair. This is an expensive operation, resulting in possible reduced or lost production-boost and expensive intervention costs to restore the failure. Topside failures were also identified, but would be of minor concern as the repairs can be made on surface.

The basis for the FMEA was established during a one-week workshop between DNV and Sonsub. Additional information was included through a round of reviews. Competence, knowledge and expertise from many disciplines were consulted to establish the final FMEA worksheets.

Table 3.1 lists the sub-systems evaluated in the FMEA.

Table 3.1: Sub-systems evaluated in the FMEA

Sub-system	Function
Multiphase Pump Package	Provide the required boosting of the production flow
Electrical Motor	Generate the necessary power required to operate the booster pump
Pressure Compensator	Equalize the pressure between the lube oil, cooling water and process fluid
Lube Oil Cooling	Provide lubrication and cooling of the seals and bearings in the pump package
Cooling Water System	Supply cooling to the motor casing, to provide sufficient cooling of the motor windings
Electrical Power Chain	Transfer electrical power from the surface to the subsea electrical motor

The FMEA was performed based on a top down approach or a functional approach, starting from a system level and splitting up into sub-systems and components. The FMEA worksheet found in Appendix II in Table II.2 was used to record the failure modes and effects on the different components evaluated for the subsea booster pump system. The complete FMEA worksheets can be found in Appendix I.

3.5 Reliability Data

The next step in the process was to assign reliability data to the failure modes identified in the FMEA. Statistical reliability data are most valid when collected from a large uniform population. Industry databases provide reliability data for some of the components in the Subsea Booster Pumping System, however, many of the components are one-of-a-kind and service conditions vary greatly from the equipment recorded in the databases.

Industry databases, expert judgement and ranking techniques were used to develop the reliability data for the basic components comprising Subsea Booster Pumping System. Table 3.5 lists the failure data used in the reliability calculations.

Component reliability data were obtained from the following sources:

- Available industry databases
- DNV in-house experience
- Vendor data
- Expert Judgement and Synthesized data

3.5.1 Review of Industry Data

In order to understand existing systems associated with boosting operations an extensive literature survey was undertaken to determine if there were any data available that could be used to predict the reliability of the subsea booster pump system. Since information regarding subsea booster pumps is limited, data from similar systems on topside facilities was reviewed. These results have been summarized in Table 3.2.

Table 3.2: Failure Data on Pumps and Electrical Motors in Industry Databases

Component	MTTF (years) [Min]	MTTF (years) [Max]	Data source
Pumps	0.6	3.5	OREDA
Electrical Motors	0.8	1.5	OREDA
Electrical Motors	0.9	2.0	IEEE

The reliability data survey, of booster pumps applied in topside application, indicate that the failure rates for the pumps are more dispersed than the electrical motors. The reasons for the dispersed data on the pumps, and the more consistent reliability data for the motor, could be explained as follows:

- Failure data for pumps are sensitive to loading, mode of operation, and utilization rate.
- Failure rate of pumps is more sensitive to the operating environment.
- The failures in electric equipment are less sensitive to loading, mode of operation, and utilization rate.

Further, the reliability data survey provide important information on which components in the system are most vulnerable to failures Table 3.3 and Table 3.4 illustrate the percentage of the total failure rate relating to the main components in pumps and electrical motors respectively.

Table 3.3: Percentage of Failures by Components in Pumps

Pump Component	% Of Failures
Bearings	40
Seals	30
Mechanical	10
Other (auxiliary)	20

Table 3.4: Percentage of Failures by Components in Electrical Motors

Motor Component	% Of Failures
Bearings	45
Electrical	30
Other (auxiliary)	25

3.5.2 Expert Judgement

Data available in industry databases were found to be limited, and typically based on experience from other applications or operating environments. It was therefore critical when selecting the reliability data to use available vendor data and experience from prototype testing in combination with expert judgment.

Vendor data was supplied when predicting the reliability of the different components in the subsea booster pump system. Results from the factory acceptance tests, and the actual field application test were made available to the JIP, and helped establishing more confidence in the predicted values.

Another technique applied in this study was a prediction modeling technique selected for mechanical models published by the U.S Department of Defense. These models have been established by extensive testing conducted by the U.S Department of Defense on similar surface equipment, /1/. The advantages of this prediction modeling include:

- The direct impact of the base failure rate of an item based on the operating environment can be quantified.
- The impact of variations in dimensions and materials to increase the reliability could be quantified.

The techniques were adjusted to match the subsea booster pump design parameters and characteristics. Design documentation was evaluated and reviewed for system design specifications and requirements. Where applicable, references to any international standards were also evaluated with respect to their applicability, and taken into account in the prediction model. When applying these prediction methods, the base failure rate derived from existing databases combined with expert judgement can be adjusted to take more account of the actual operating environment. Physical parameters such as temperature, pressure and other operating characteristics can be taken into account and adjust the reliability data.

Once reliability estimates had been suggested for the failure modes identified in the FMEA, the vendor and equipment supplier were asked to review and evaluate the reliability data. An organized expert judgement session was conducted, which also served as input for selecting different statistical distribution functions to describe some of the failure modes.

When aging effects and wear were assumed to be likely failure mechanisms, the equipment suppliers were asked to provide a guaranteed lifetime. The guaranteed lifetime relates to a time that the vender would not expect any failures to occur. It has been defined as the time the component will survive with a 95% probability. This time would be given based on actual reliability testing of the components, and used to establish the shape parameter in the Weibull distribution. Table 3.5 gives the reliability data applied in the JIP. The combined system reliability performance is illustrated by the graph in Figure 3.2.

Figure 3.2: The Estimated Reliability Performance of the Subsea Booster Pump

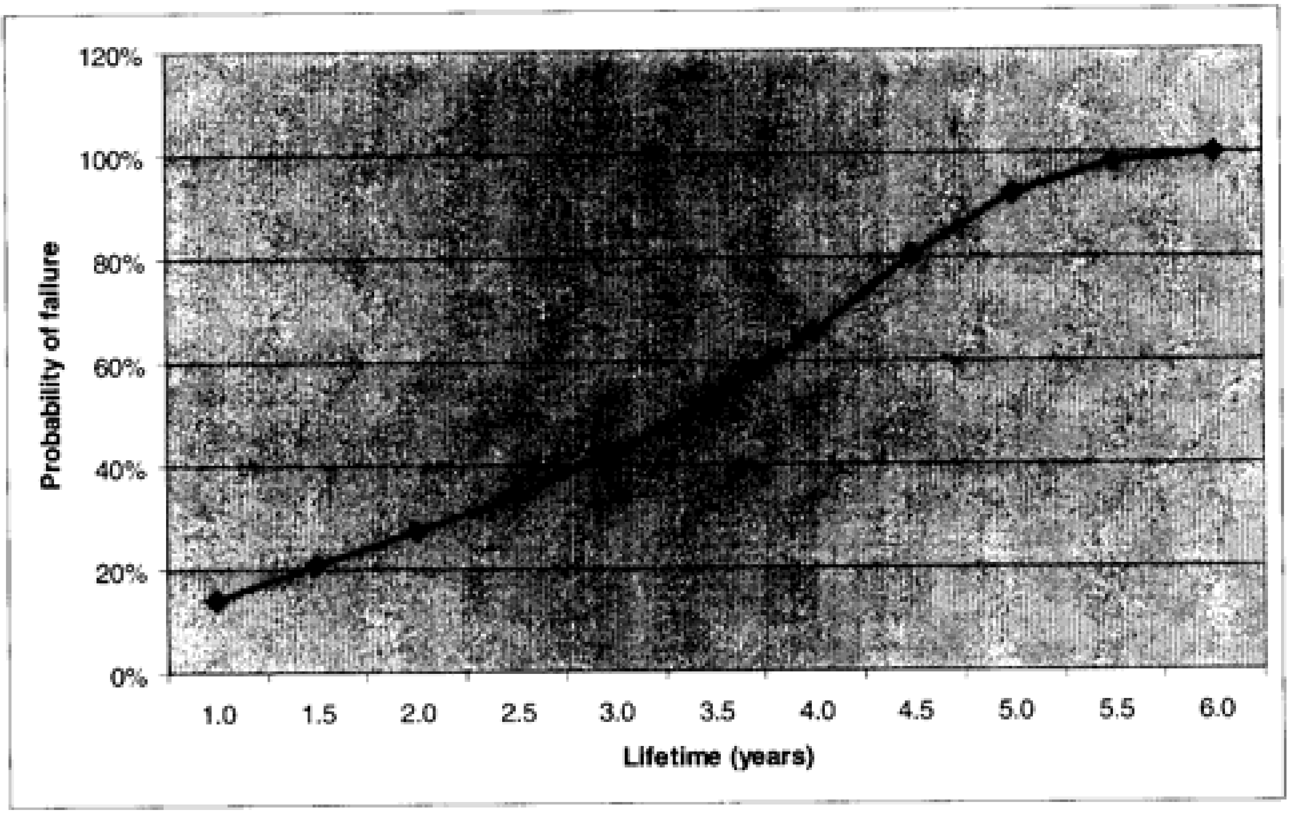


Table 3.5: Critical Failure Data Applied in This Study

Category	Equipment	Probability Distribution	Mean Time To Failures, MTTF (years)	Guaranteed Lifetime[1] (years)
Pump	Pump Seal	Weibull	6.0	3.5
Pump	Timing Gears	Weibull	20.0	4.0
Pump	Radial bearing (two)	Weibull	6.0	3.5
Pump	Thrust bearing (two)	Weibull	6.0	3.5
Pump	Upper Seals	Weibull	6.0	3.5
Pump	Lower Seals	Weibull	6.0	3.5
Pump	Screws	Weibull	20.0	4.0
Pump	Coupling	Exponential	75.0	
Motor	Cable penetrators	Exponential	150.0	
Motor	Windings	Exponential	200.0	
Motor	Rotor	Exponential	200.0	
Motor	Journal bearing (two)	Weibull	6.0	3.5
Motor	Thrust bearings (two)	Weibull	6.0	3.5
Motor	Impeller	Exponential	75.0	
Motor	Motor seal	Weibull	6.0	3.5
Motor	Shaft	Exponential	200.0	
Compensator	Pressure compensator chamber	Weibull	35.0	8.0
Lube oil	Lubrication oil pump	Exponential	75.0	
Lube oil	Lubrication oil cooler	Exponential	25.0	
Cooling	Cooling fluid supply line	Exponential	100.0	
Cooling	Heat exchanger	Exponential	25.0	
Power Supply	Umbilical	Exponential	250	
Power Supply	Flying leads	Exponential	125	
Power Supply	Topside Frequency Drive	Exponential	30	
Control System	Subsea Control Module	Exponential	15	
Control System	Control Jumpers	Exponential	125	

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[1] Garanteed lifetime has been defined as the time a component will survive with 95% probability.

3.6 The Reliability Model for the Subsea Booster Pump System

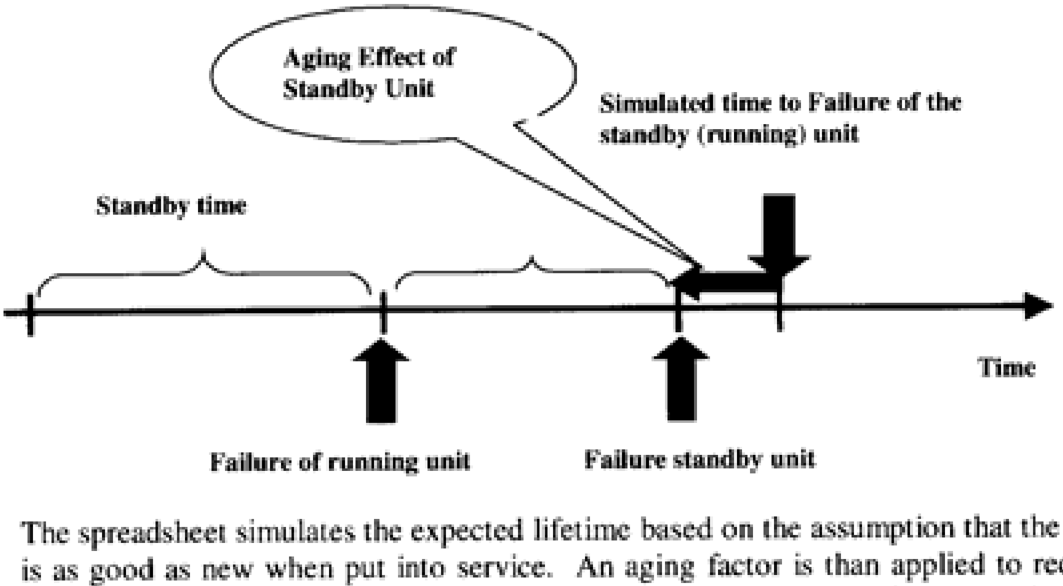
The Excel spreadsheet tool is using Monte Carlo simulation and next event techniques to sample the failure events. Instead of developing traditional reliability block diagrams or fault tree models, the failure modes are sampled independently. A critical failure of one of the components in the system will result in loss of the booster pump, making the system no more reliable than the weakest point.

The system has been broken down into maintainable modules. For the Nuovo Pignone pumps, the complete pump including the electrical motor and compensator is one integrated module. When a critical failure has occurred in one particular module, the complete module is brought back to surface for repair. All failure mechanisms are than restored and repaired to make the system as good as new before reinstalled into service. The control modules and electrical flying leads are independent retrievable.

Some of the booster pump configurations have subsea standby pumping modules. For these configurations, a probability of failure on demand can be implemented into the tool. The probability of failure on demand reflects the probability that start-up of the standby unit will not be successful. The probability of failure on-demand is applied during switchover to standby modules after failure of the running equipment.

Another feature implemented is the aging effect of subsea installed standby equipment. Figure 3.3 gives an illustration of how the expected lifetime of the standby unit is reduced by an aging factor.

Figure 3.3: Illustration of how the Aging Effect Reduces the Life Expectancy of a Standby Pump Module put into Service



The spreadsheet simulates the expected lifetime based on the assumption that the unit is as good as new when put into service. An aging factor is than applied to reduce this simulated value. The aging factor is defined as a percentage of the time the unit has been in standby.

3.7 Downtime Model

Failures of subsea equipment require special intervention vessels to perform the repair operations. For the Nuovo Pignone pumps, two different types of vessels have been applied depending on the type of work to be performed. An MSV is required for heavy lift to bring the pump module back to surface, however a DSV with ROV-capability is sufficient to retrieve the subsea control module, change out cables or flying leads and connect a subsea standby unit. Table 3.6 gives an overview of the required intervention vessels for the different subsea equipment.

Table 3.6: Required Intervention Vessel for Subsea Equipment

Equipment	Vessel Required
Booster Pump Module	MSV
Umbilical	MSV
Subsea Control Module	ROV
Flying leads	ROV
Control Jumpers	ROV

Large support vessels are not currently based on the West Coast of Africa and will only be available if they are working for a specific project. Generally if one is needed, it is brought in from the North Sea. Also in the Gulf of Mexico these vessels are not easily available, suited vessels are typically on long-term contracts. This has been reflected in the transit times, given in Table 3.8. While in the Gulf of Mexico an MSV will be available in 80-90% of the cases, for the West of Africa cases one will have to be transferred from the North Sea.

A major issue working in deepwater is the time for lowering and recovering of the ROV, line speed becomes a critical factor. This limits the number of ROV vessels applicable for this application. There are not that many deepwater ROV systems available in the industry. A total review of vessel requirements was performed in co-operation with Sonsub, and a list of suited vessels was generated. A suggested list is given in Table 3.7.

Table 3.7: List of Possible Intervention Vessels

Multi Service Vessel (MSV)	Diving Service Vessel (DSV)
FDS (Saibos)	Rockwater 1 (Rockwater)
Maxita (SonsubClough)	Rockwater 2 (Rockwater)
Regalia (Rockwater)	Orelia (CSO)
Semi 1 (Rockwater)	Wellservicer (CSO)
Semi 2 (Rockwater)	Seawell (CSO)
Polar Prince (Sonsub)	Northern Explorer
Norlift (J.Ray McDermott)	Mayo (CSO)

Based on our understanding of the vessel availability, the availability time, transit time and day-rates both for the two West of Africa study cases and the Gulf of Mexico study case are given in Table 3.8. The availability time, which reflects the time to get the vessel on contract, will be the same in both the geographical locations. The transit time however will differ, as vessels normally are available for operation in the Gulf of Mexico, they typically will need to be taken from the North Sea to serve West of Africa.

Table 3.8: Intervention Vessels Information

Resource Vessel	Availability Time (days)	Transit Time (days)	Spread Cost (US$/day)
MSV – West of Africa	30	20	120,000-140,000
DSV – West of Africa	14	10	80,000-90,000
MSV – Gulf of Mexico	30	5	120,000-140,000
DSV – Gulf of Mexico	14	0	80,000-90,000

All failures do not necessarily result in loss or reduced production. As pointed out previously, the consequence of a failure will depend on the configuration. In this study a dual piggable flowline loop has been assumed for all cases, with one booster pump in service in each pipeline. In case of lost boosting capacity through one pipeline it has further been assumed that more flow can be directed through the other pipeline to compensate some of the lost boost capacity.

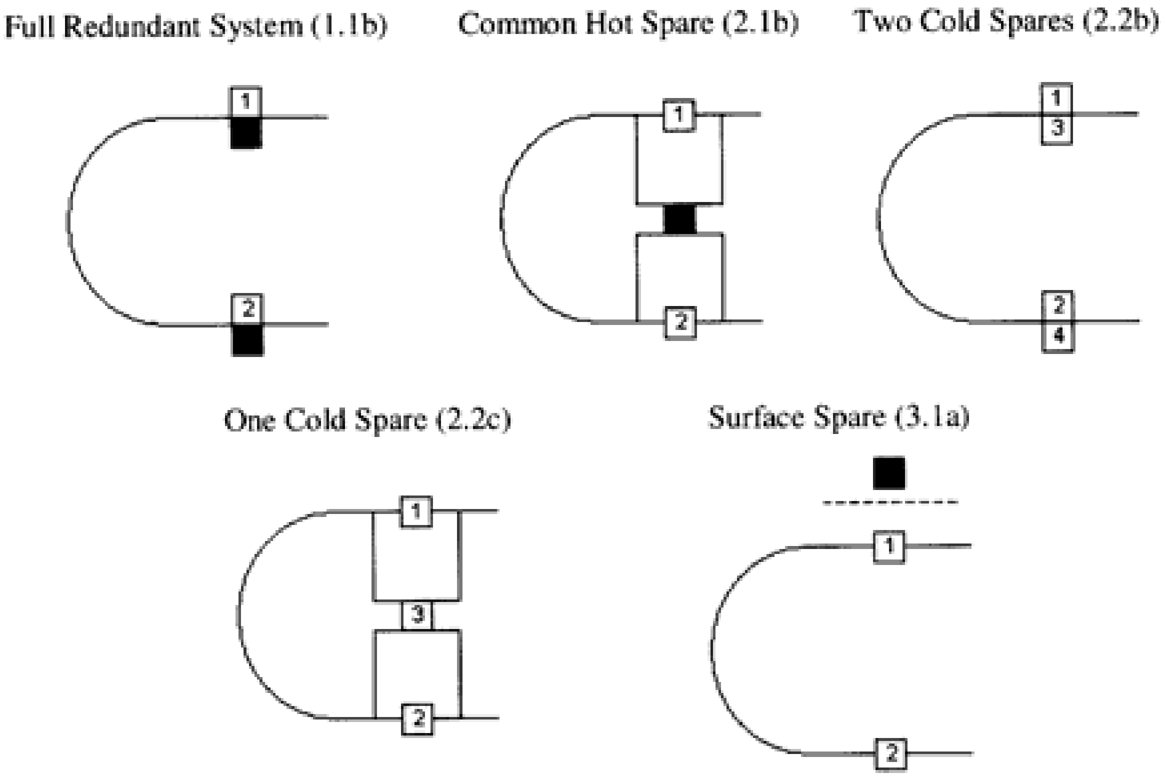
3.7.1 Sparing Philosophies

The concept evaluated in this study has been a dual piggable looped flowline, with dedicated booster pump modules in each of the two pipelines. In addition to the two pumps in operation, different sparing or redundancy options are evaluated to improve the reliability performance. These different options are all implemented in the lifecycle cost tool and include:

Full Redundant System:	A dedicated hot spare boosting module for each active one.
Redundant System:	A common hot spare module available to compensate a single module failure.
Subsea Spare System:	A dedicated cold subsea module not connected, available for each active module. (Has to be hocked-up by an ROV in case of demand.)
	A common cold subsea module, available to be hocked-up with an ROV to replace a single failed pump module.
Surface Spare System:	Spare pumping module available on surface, requiring a heavy lift operation to replace the failed module.

The tool allows the user to select the various redundancy options implemented, and calculate the associated lifecycle cost. This gives the user valuable to select a cost optimal configuration. Figure 3.4 gives an illustration of the redundancy configurations implemented in the spreadsheet.

Figure 3.4: Different Redundancy Configurations Evaluated


Full Redundant System (1.1b) Common Hot Spare (2.1b) Two Cold Spares (2.2b)

One Cold Spare (2.2c) Surface Spare (3.1a)

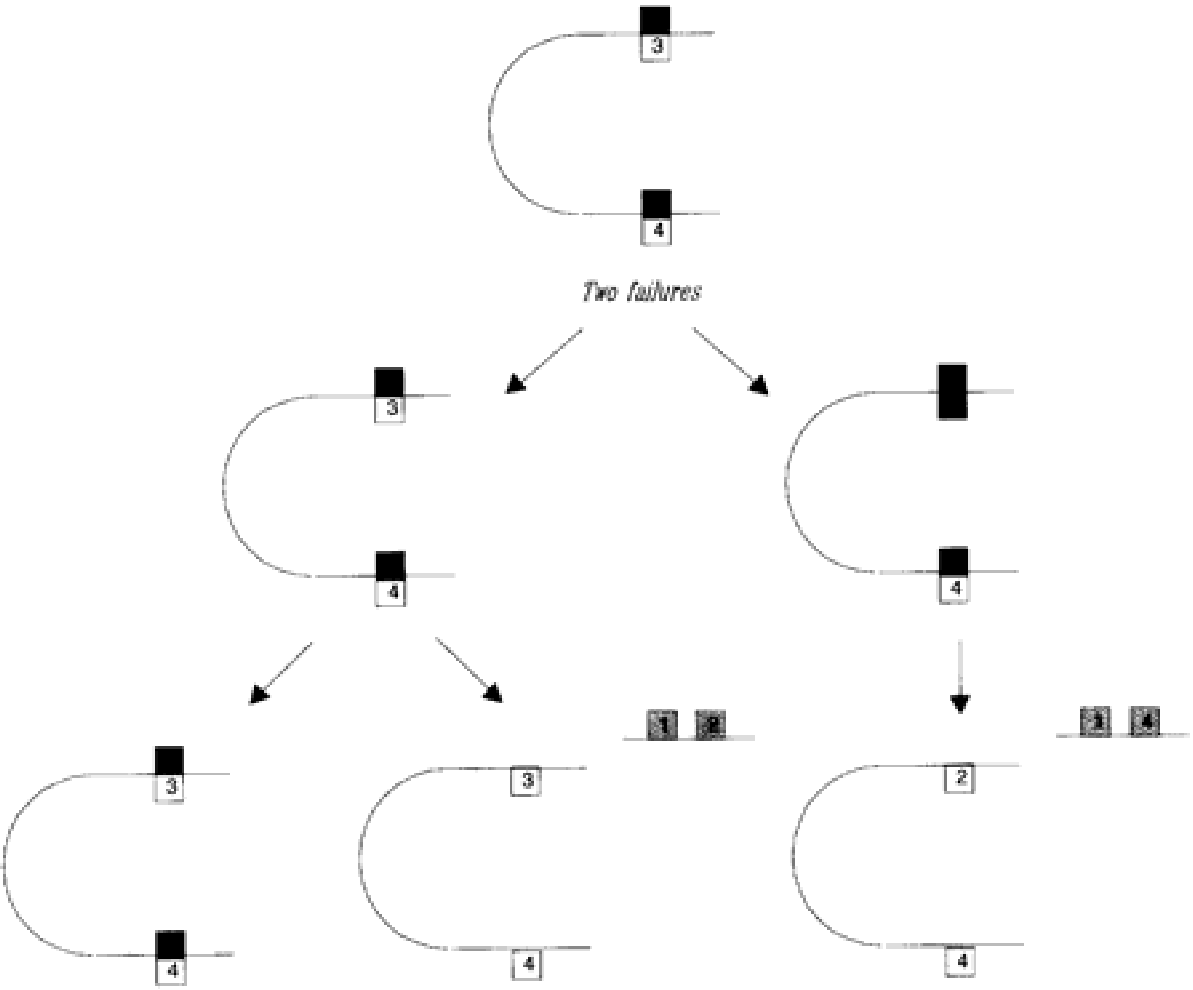
3.7.2 *Repair Philosophies*

For some of the sparing philosophies, there will be a various choices with respect to repair philosophies. For a full redundant system, as an example, there will be a choice of either to pull up a failed pump module or continue boosting without allocating recourses to repair a failure after the first module has failed. An illustration of various repair philosophies for the full redundant system is given in Figure 3.5.

At the top of the figure, the full redundant system is represented. As a first restriction the user has selected that no repairs should be performed before at least two failures have occurred. Two failures can result in a system configuration with one available pump in each pipeline, represented to the left in the figure, or both pumps failed in one pipeline.

The next criteria set by the user is that no repairs are to be performed before actual loss of boosting capacity. This will result in an intervention for the scenario with two failed units in one pipeline, represented to the right in the Figure 3.5. However, for the situation with one failed unit in each pipeline, operation will continue and intervention will be postponed until a third failure occurs. More strict criteria would have been to repair the system if two modules have failed unconditionally.

Figure 3.5: Illustration of Different Repair Philosophies for a Full Redundant System



The spreadsheet allows the user to define different philosophies related to the intervention vessels, and thereby control the intervention philosophy. This can be used in sensitivity calculation to determine a cost optimal repair philosophy for a particular system. Selecting a combination of how many failures and what system configuration will result in an intervention determines the intervention philosophy.

3.8 Life Cycle Cost

The lifecycle cost model combines the capital investment cost, the operational cost in addition to all the reliability or risk cost elements described previously in this chapter. By using simulation techniques, all the elements are systematically be linked together to generate the total lifecycle cost for the development or concept.

3.8.1 CAPEX

CAPEX is comprised of two cost elements, the actual equipment cost and the installation cost. Four different pump sizes have been implemented in the spreadsheet model, and equipment cost has been determined for all the four pump modules. An illustration is given in Table 3.9. As the required power system and the umbilical size will depend on the tieback distance, a database was implemented including specific cost values for different tieback alternatives. This database allows the user to select different pump sizes and tieback distances and determine the associated total life cycle cost.

Table 3.9: Investment Cost for Different Subsea Booster Pumps

Component	NPV 300	NPV 700	NPV 1000	NPV 1600
Umbilical	380,000 $/mile	400,000 $/mile	460,000 $/mile	480,000 $/mile
Power System	$700,000	$900,000	$1,000,000	$2,300,000
Control System	$2,520,000	$2,520,000	$2,520,000	$2,520,000
Pump Module	$1,310,000	$1,730,000	$1,920,000	$2,150,000
Structure & valves	$1,800,000	$1,800,000	$2,100,000	$2,100,000

The installation cost is estimated based on the estimated cost for the installation vessel and the number of equipment that needs to be installed for each of the study cases. A fixed installation cost associated with preparation and allocation the required installation vessel has been estimated. In addition a unit price related to the installation cost for the different subsea equipment has been generated. Table 3.10 reflects these installation costs for the main subsea equipment required in the subsea booster pump system.

Table 3.10: Installation cost for Main Subsea Equipment

Equipment	Installation Cost
Booster Pump Module	$480,000
Umbilical	$960,000
Flying leads and other axially equipment	$60,000

3.8.2 OPEX

OPEX is the estimated planned operational expenses associated with the subsea booster pumping system. This includes power consumption and use of other utilities. The power consumption has been calculated based on the expected power demand for the booster pumps, taking account for the power consumption from a specific pump, tieback distance and downtime of the specific booster pump. Similar to the investment costs, the estimated power consumption associated with a specific pump size and tieback distances is implemented into a database, to assure correct estimates are generated when the user is selecting alternative pump sizes and tieback distances.

In addition all costs associated with the unplanned interventions have been included in the OPEX estimate. This includes vessel-spread costs, repair costs and spare parts. This allows the user to evaluate the costs associated with setting a strict repair criteria, as the intervention cost will increase accordingly. By comparing how the additional costs related to increased interventions compare to the reduced costs for lost production, the user could optimize the intervention philosophy.

3.8.3 RAMEX

The Reliability, Availability & Maintainability Expenditures, RAMEX, are all costs associated with equipment failures and the reliability calculation. For the booster pump evaluation, RAMEX represents the potential for "loss of production" due to reduced or no boost of the production profile as a result of component failures. As explained, this will depend on the system configuration and repair/intervention philosophy. The costs associated with spread costs and repairs due equipment failure have been defined as an unplanned intervention cost.

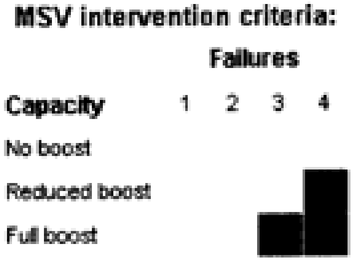
4 CALCULATION RESULTS

The Excel spreadsheet tool developed was used to evaluate three specific study cases. The three study cases considered include:

1. A West of Africa development in 4500 ft. water depth, 9 miles tieback.
2. A West of Africa development in 7000 ft. water depth, 18 miles tieback.
3. A Gulf of Mexico development in 6000 ft. water depth, 7 miles tieback.

A number of simulations with different settings were performed to determine a cost optimal solution for each of the study cases. In addition to the configuration, the intervention requirements can be changed. Figure 4.1 illustrates the intervention requirement setting implemented in the Excel spreadsheet tool. The black squares in the figure indicate that the particular scenario is not possible. A configuration with less than four pumps can never have two failures without having reduced boosting capacity. The white boxes indicate that the user will accept this particular configuration without allocating resources. For the settings selected in Figure 4.1, no intervention will be started until at least two units have failed or the system is delivering at reduced boost.

Figure 4.1: The Intervention Requirement for MSV



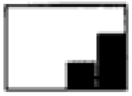
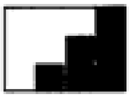
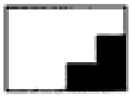
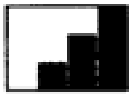
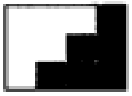
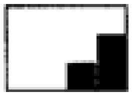
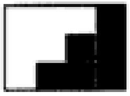
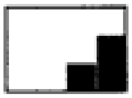
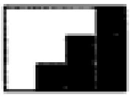
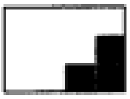
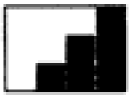
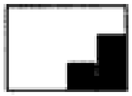
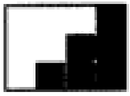
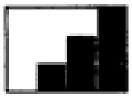
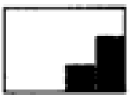
MSV intervention criteria:

	Failures			
Capacity	1	2	3	4
No boost				
Reduced boost				■
Full boost			■	■

During the early screening process it was discovered that limiting the number of ROV interventions typically results in increased lifecycle cost for all the configurations evaluated. As a start, all the cases were therefore evaluated with the assumption that ROVs are allocated immediately after the first failure occur, and only the MSV criteria was changed when running the simulation screening.

Due to the high value of the boosted production, any settings resulting in reduced or lost boost for a significant time will result in a high lifecycle cost. As a consequence, only a limited number of settings are beneficial from a lifecycle cost perspective. These settings were determined and the cases simulated and evaluated in the next screening process. A complete list of the cases evaluated for the different redundancy configurations are listed in Table 4.1. All the configurations were evaluated, including the full redundant system, one hot spare, two cold spares, one cold spare and the surface spare configuration, the configurations have been defined in Figure 3.4.

Table 4.1: Study Cases Evaluated for the Different Configurations

Case	Configuration				
	1.1b	**2.1b**	**2.2b**	**2.2c**	**3.1a**
1					
2					
3					
4					

The same intervention settings were applied for all the three study cases during the first screening, to determine the optimal intervention requirement for each of the configurations. In the next sections the results and conclusions generated for the three study cases are reported.

4.1 West of Africa 4500ft.–Short Tieback Distance

As explained in section 3.7, it has been assumed that intervention vessels will be transferred from the North Sea to serve West of Africa. The vessel availability, transit time and spread cost, is given in Table 4.2.

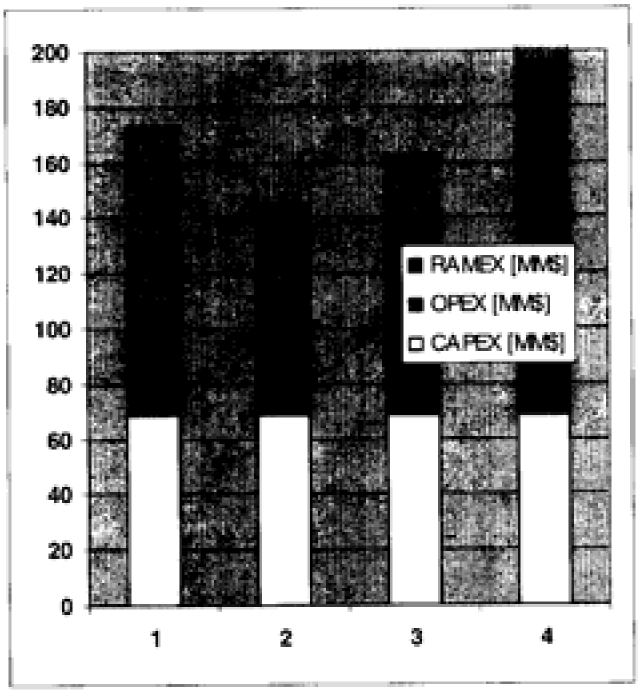
Table 4.2: Intervention Vessel Input

Resource Vessel	Availability Time (days)	Transit Time (days)	Spread Cost (US$)
MSV – West of Africa	30	20	120,000-140,000
DSV – West of Africa	14	10	80,000-90,000

After implementing the required boosted production profile and reservoir characteristics for this study case, the pump-screening tool suggests the largest pump as the only suitable pump for this operation. With some adjustments with respect to the required boosted production profile, the NPV1000 could possibly also mach the requirements.

In the screening process, the different repair philosophies established in Table 4.1 were simulated, and an optimal repair strategy was selected for each configuration. An illustration of the estimated lifecycle cost generated for the different repair philosophies for the full redundant system, 1.1b, is given in Figure 4.2.

Figure 4.2: Lifecycle Cost Calculations for the Full Redundant System



The capital investment cost, CAPEX, which is represented by the yellow bar in the bottom of each graph, will be the same as it is the same configuration that has been evaluated for all the cases. The only parameter that is changing, is the operational cost associated with interventions. By setting the criteria to allocate recourses more frequent the operational cost will increase and the estimated lost production will decrease.

When changing the settings from Case 1 to Case 2, as explained in Table 4.1, intervention vessels will be allocated more frequently and reduce the amount of time producing at reduced boosting capacity. This has a positive effect on the total lifecycle cost, which is reduced from approximately 175 million dollars to 145 million dollars. Additional interventions will further reduce the cost associated with lost production, represented by the blue bars on the top, however as seen in Figure 4.2 the total lifecycle cost will increase.

Similar, different settings with respect to intervention vessels were evaluated for the other configurations according to Table 4.1. The results from this first screening are quoted in Table 4.3.

Table 4.3: Lifecycle Cost Results generated when evaluating the West of Africa 4500ft. Case

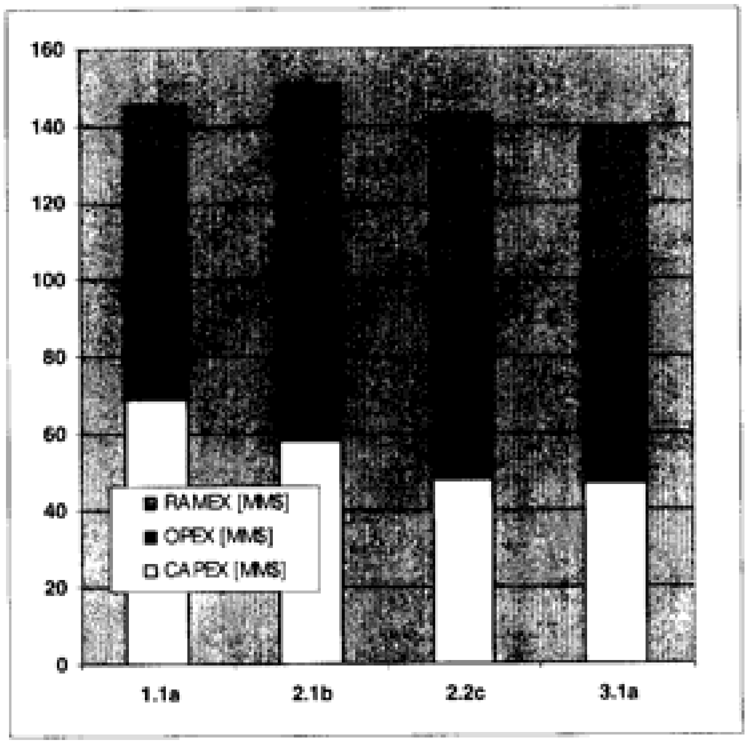
	1.1b			2.1b			2.2b			2.2c			3.1a		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
RAMEX	64.1	33.1	22.0	66.6	40.9	23.1	79.9	72.6	66.2	64.9	42.3	52.0	64.9	39.8	52.0
OPEX	40.6	43.9	72.4	51.9	51.4	114.7	39.3	60.9	65.1	50.4	53.1	130.7	50.4	52.8	130.8
CAPEX	68.5	68.5	68.5	58.2	58.2	58.2	57.9	57.9	57.9	47.6	47.6	47.6	47.0	47.0	47.0
Lifecycle Cost	173.2	145.6	162.9	176.8	150.5	196.0	177.1	191.4	189.2	162.9	142.9	230.3	162.3	139.7	229.8

Table 4.4: Lifecycle Cost Results generated when evaluating the West of Africa 7500ft. Case

	1.1b			2.1b			2.2b			2.2c			3.1a		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
RAMEX	115.4	58.9	50.1	116.5	71.6	43.6	140.6	127.4	116.5	116.3	72.4	93.8	115.9	69.0	94.1
OPEX	48.7	55.4	92.2	65.1	64.0	149.7	48.0	79.6	85.8	63.2	65.8	174.5	63.2	65.5	174.2
CAPEX	59.4	59.4	59.4	49.1	49.1	49.1	53.3	53.3	53.3	43.0	43.0	43.0	42.5	42.5	42.5
Lifecycle Cost	223.4	173.6	201.6	230.7	184.7	242.3	242.0	260.4	255.6	222.5	181.2	311.2	221.5	176.9	310.8

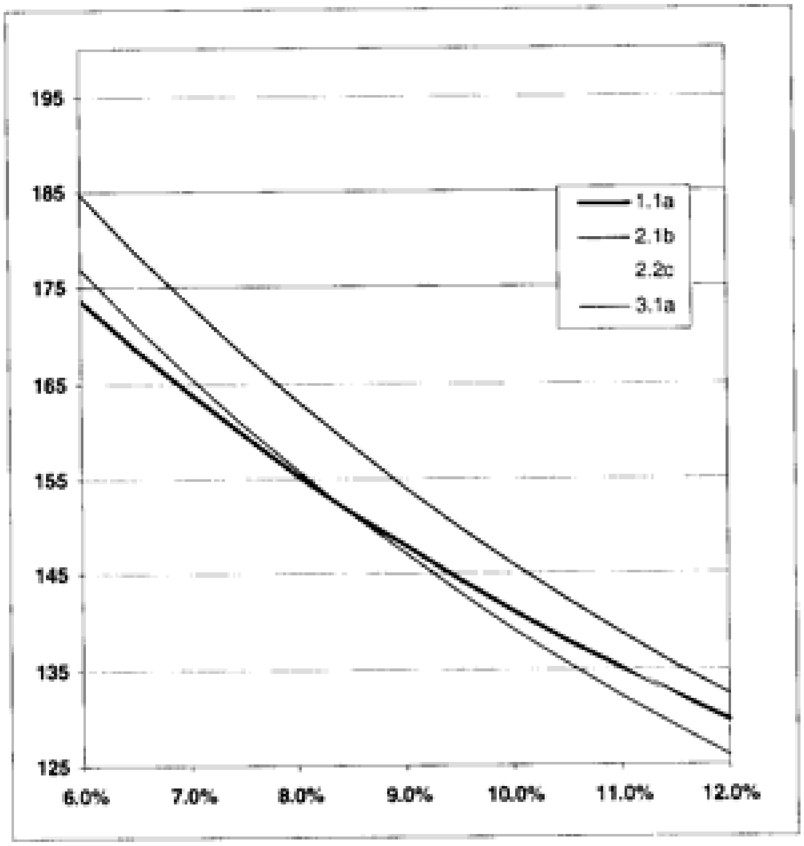
After the first screening, a more detailed evaluation of the best study cases was performed. Figure 4.3, illustrates the results generated after further evaluation of the full redundant system, the hot spare, the cold spare and the surface spare configuration. It is difficult to draw a distinct conclusion based on the results generated. Taking account for the uncertainty, all the study cases generate more or less the same lifecycle cost after optimizing the repair philosophy. The optimal intervention philosophy is represented by Case 2 in Table 4.1, for all the configurations.

Figure 4.3: Results generated after the first screening, West of Africa 4500ft.



One of the main differences between the four study cases evaluated in Figure 4.3, is the number of pump modules. The full redundant system includes four pump modules, while the other cases only have three pump modules. From the results, there seems to be very little value in installing the third spare module. The additional investment associated with the hot standby unit (2.1b) is not compensated with significantly higher availability compared to the case with a surface spare (3.1a). This trend is further strengthened after running sensitivities on the discount rate. While all the cases with three pump modules maintain the relative difference in lifecycle cost, the full redundant system will be a better solution with lower discount rates. The result from the sensitivity calculation is given in Figure 4.4.

Figure 4.4: Sensitivity Evaluation of the discount rate



As seen in Figure 4.4, the full redundant system gives the lowest lifecycle cost with discount rates lower than 8%. Further, the surface spare case will always return lower lifecycle cost values compared to the two configurations with subsea spare modules.

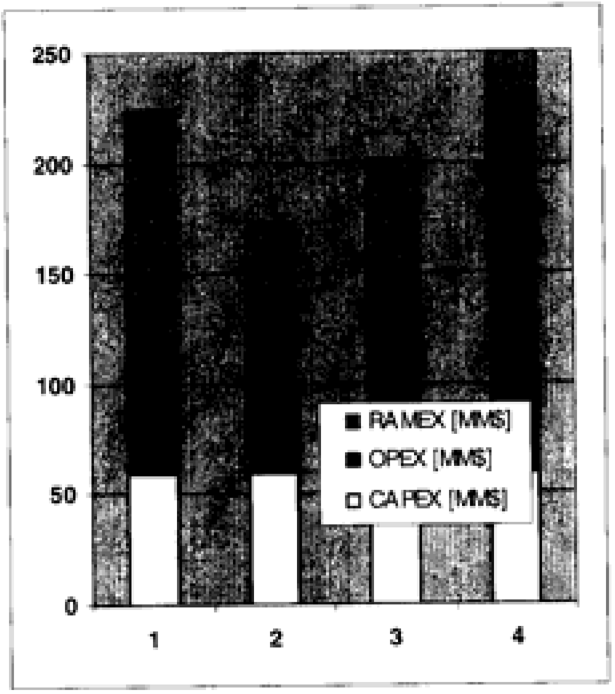
4.2 West of Africa 7500ft.–Long Tieback Distance

Intervention vessel requirements are the same for both the two West Africa development cases. It has further, not been possible to distinguish between the water depth when establishing the reliability data. Most of the equipment is in a closed operating environment, and the system will be designed to handle the ambient pressure and temperature.

Similar to the previous study case, the largest pumps have been suggested as the only suitable pump for the required operation. With some adjustments in the required boosted production profile, the NPV1000 could possibly also mach the requirements.

Again a screening process was performed to determine the optimal intervention strategy for each of the configurations. In the screening process, the different repair philosophies established in Table 4.1 were evaluated. An illustration of the results generated for the full redundant system, 1.1b, is given in Figure 4.5, which reflects the lifecycle cost estimated for the different repair philosophies.

Figure 4.5: Lifecycle Cost Calculations for the Full Redundant System

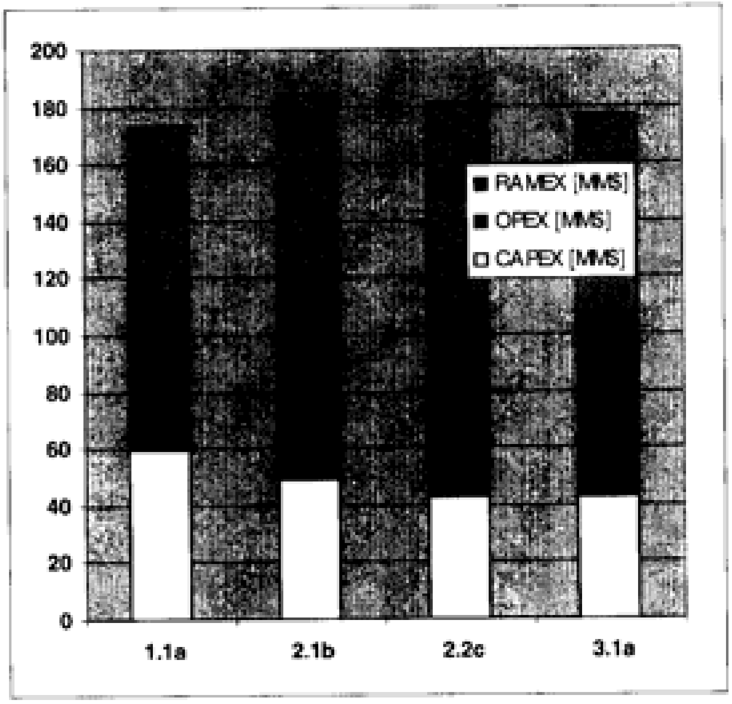


The first evaluation is to determine the optimal intervention requirements for the different configurations. The only parameter that changes, is the operational cost associated with interventions. By setting the criteria to allocate recourses more frequent the operational cost will increase and the estimated loss in production will decrease. As seen in Figure 4.5, the lifecycle cost drops from Case 1 to Case 2, due to the improved production availability as a result of more frequent interventions. Additional interventions will further reduce the cost associated with lost production, represented by the blue bars on the top, however as seen in Figure 4.5 the total lifecycle cost will increase.

Similar, different settings with respect to interventions were evaluated for the other configurations according to Table 4.1. The results after this first screening are quoted in Table 4.4.

When comparing the best cases for each of the redundancy configurations, there seems to be very little value in installing the third spare pump modules. As for the first case, the additional investment costs associated with the hot standby unit (2.1b) is not justified through higher availability compared to the surface spare case (3.1a). In this study case, however, the full redundant system seems to be the most cost efficient, even with a discount rate of 10%. Again this conclusion will increase with lower discount rates.

Figure 4.6: Results generated after the first screening, West of Africa 7500ft.



Another benefit related to the full redundant system, is more consistency in the results. When running with four pumps there is less chance for a complete loss of boosting capacity, which effects the uncertainty associated with the lifecycle cost estimate for the other three cases.

4.3 Gulf of Mexico Study Case

As explained in Chapter 3.7, it has been assumed that intervention vessels typically are available in the Gulf of Mexico. The vessel availability, transit time and spread cost, is given in Table 4.5.

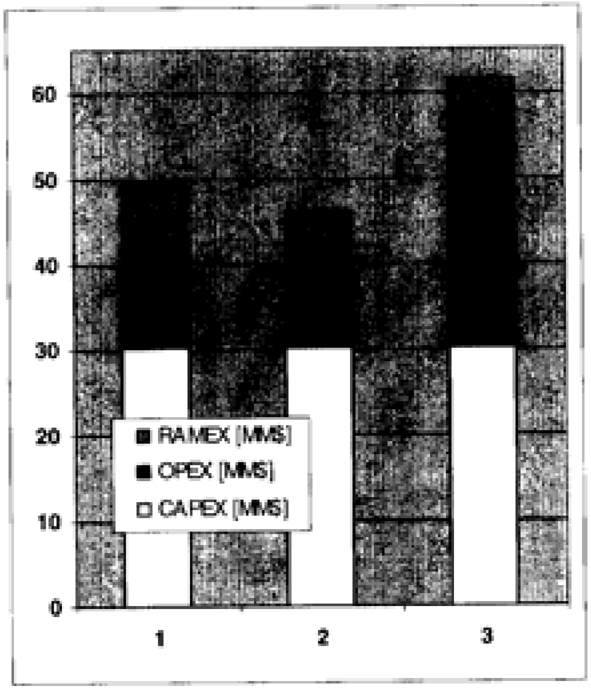
Table 4.5: Intervention Vessel Input

Resource Vessel	Availability Time (days)	Transit Time (days)	Spread Cost (US$)
MSV – Gulf of Mexico	30	5	120,000-140,000
DSV – Gulf of Mexico	14	0	80,000-90,000

After implementing the required boosted production profile and reservoir characteristics for this study case, the pump-screening tool suggests the NPV 700 as the smallest and cheapest pump that will meet the boosting requirements. This pump has therefore been selected for the Gulf of Mexico study case.

As a first screening process to determine an optimal intervention strategy for each of the configurations, the different repair philosophies established in Table 4.1 were evaluated also for this study case. An illustration of the results generated for the surface spare system, 3.1a, is given in Figure 4.7, which reflects the lifecycle cost estimated for the different repair philosophies.

Figure 4.7: Lifecycle Cost Calculations for the Surface Spare System



The only parameter that is changed during this first screening, is the operational cost associated with interventions. By setting the criteria to allocate recourses more frequent the operational cost will increase and the estimated loss in production will decrease. As seen in Figure 4.7, the lifecycle cost drops from Case 1 to Case 2, due to the improved production availability as a result of more frequent interventions. Additional interventions will further reduce the cost associated with lost production, represented by the blue bars on the top, however as seen in Figure 4.7 the total lifecycle cost will increase.

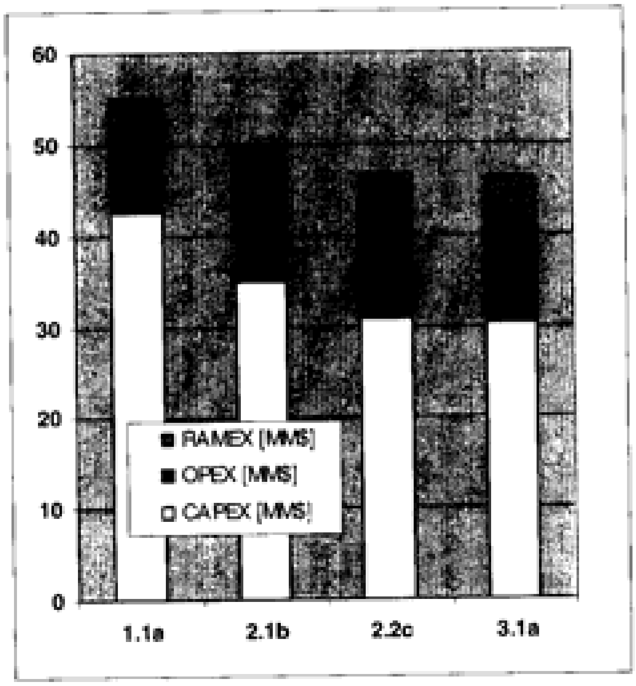
Similar, different settings with respect to interventions were evaluated for the other configurations according to Table 4.1. The results after this first screening are quoted in Table 4.6.

Table 4.6: Lifecycle Cost Results generated when evaluating the Gulf of Mexico Study Case

	1.1b			2.1b			2.2b			2.2c			3.1a		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
RAMEX	5.8	3.1	1.6	8.3	3.8	1.8	10.7	8.1	10.1	7.0	4.1	4.5	8.1	4.2	4.8
OPEX	8.8	9.6	15.6	11.0	11.1	25.6	8.5	13.0	13.5	11.2	11.7	25.2	11.1	11.8	26.5
CAPEX	42.5	42.5	42.5	35.0	35.0	35.0	38.3	38.3	38.3	30.8	30.8	30.8	30.3	30.3	30.3
Lifecycle Cost	57.1	55.2	59.7	54.3	49.9	62.4	57.5	59.4	61.9	49.0	46.7	60.6	49.5	46.2	61.6

After the first screening the most optimal repair strategy for each of the study cases was used to compare the alternative configurations, the results are given in Figure 4.8.

Figure 4.8: Results generated after the first screening for the Gulf of Mexico Study Case



As seen from the results generated, the full redundant system results in the highest lifecycle cost for the Gulf of Mexico study case. The contribution from operational expenditures and reduced production is significantly less in this study case due to the number of years evaluated. While the West Africa study cases all were evaluating 20 years of production, the Gulf of Mexico study case was only considering 9 years of production. The additional investment in a redundant system is therefore less likely to be beneficial for this particular study case.

4.4 Uncertainty in the Results

Most of the inputs and all the outputs from a reliability analysis are uncertain to some degree. In some cases, the uncertainties may be large, and the conclusions of the reliability analysis may be sensitive to possible variations in the inputs or modeling assumptions. These uncertainties form one of the main limitations of reliability analysis, and it is important that they are understood and accounted for explicitly.

Uncertainty, as applied in this study, is defined as the degree of imprecision that is attached to parameters in the reliability analysis. The "true" value of the parameter can not be known; only estimates are available. The uncertainty attached to the estimates explicitly acknowledges this difference.

Main sources of uncertainty are as follows:

1. *Uncertainty in the reliability data.* The information leading to a predicted likelihood of occurrence for a critical event (frequency of occurrence/failure rate) may be limited. The analyst, due to limited information, may be unable to attribute the identified events with the "correct" set of properties. This could be due to the use of data which are not representative for the type of equipment analyzed (design, technology, age, frequency trends, etc.), insufficient observation time, or the fact that the data have been extracted from operating and environmental conditions which is not representative.

   Example: The Subsea Multiphase Booster Pumps evaluated in this study is new technology with limited operating experience. The failure rate estimates are mainly based on generic data sources adjusted by equipment specialists and vendors to reflect equipment specifics. (Prototype testing results have provided the best source of reliability data.)

2. *Insufficient system information and modeling inaccuracy.* The reliability analysis must be based on a number of assumptions and conditions. Critical events that form the basis for the input to the reliability model do not represent the complete picture of all possible events that can influence the operation of the subsea booster pumps. Reliability analyses have to make assumption and modeling short-cuts to fit a models to a real situations. Omission of critical components/events leads to over-estimate of reliability and possibly to under-valuing reliability increasing measures.

   Example: The failure rate applied for the Subsea Multiphase Booster Pumps excludes external impact and failures that can occur during installation of the subsea equipment. Proper reliability management has been assumed for specific projects.

To achieve better control of the uncertainty, the study has adopted the following two strategies:

- **Conservatism:** This approach attempts to predict the reliability as accurately as possible, but where uncertainty is large, the study tries to provide values on the conservative side. Thus, uncertainty is addressed by using "conservative" estimates of input parameters and assumptions where there are lack of, or minimal knowledge/technology regarding the phenomenon modeled, or scarce databases. This implies using data and models that are believed to give the largest unreliability.

- **Sensitivity calculations:** Sensitivity is defined as the degree to which results of a calculation are affected by variations in the inputs. The sensitivity of the reliability results to the input parameter therefore illustrates the significance of uncertainty in those inputs.

5 CONCLUSIONS

Subsea multiphase pumping is expected to be one of the most efficient tools for economic exploration of deepwater marginal fields. The need to provide energy to the well stream to reach the treatment facilities is continuously increasing as exploitation for hydrocarbons moves into deeper waters. Further, increased energy to the well fluids has the potential to increase the ultimate recovery and/or accelerate the production.

The benefits of subsea booster pumping are evident, however there are major uncertainties related to the reliability performance of these systems. Significant development and testing work has been undertaken in the effort of qualifying multiphase boosting technology as a viable option for the exploitation of hydrocarbon reserves. While the technology itself is perceived as mature, limited operational experience in subsea applications is available. As a consequence, the anticipated equipment performance and the associated operating costs are subject to uncertainty.

Operators hesitate to be the first users of new technology before the benefits are fully understood, and subsea multiphase boosting technology has yet to demonstrated it's claimed merits. The main reason is the uncertainty associated with the operating expenditures and intervention costs related to "unforeseen" events and equipment failures. The JIP has demonstrated how systematic evaluation of the system, applying traditional risk and reliability techniques, can be used to identify areas of uncertainty. These uncertainties were than quantified by combining economical parameters and reliability simulation techniques. An integrated probabilistic model for assessing the total reliability based lifecycle cost has been developed, and can be used in the decision-making process to assist in finding optimal development solutions and concepts.

A detailed review of the Sonsub/Nuovo Pignone subsea booster pump has been performed to establish a reliability prediction model. Information from prototype testing and reliability input provided from the manufacturer and sub-contractors has been used to predict the reliability of the booster pump system. Based on the results generated in this study the following main conclusions can be made:

1. No serious reliability issues or problems were found with the design of the Subsea Booster Pump System. Based on test results and documentation provided, the system appears to be capable of deepwater application.
2. As long as redundancy is provided in for of subsea spares or a surface standby unit, the booster pump system can be expected to operate with high availability.

The methodology and results generated in this JIP have been implemented into an Excel based Spreadsheet tool. This tool allows the user to select cost optimal solutions and configurations based on a lifecycle cost evaluations. The lifecycle cost includes economic evaluation of unplanned events and interventions, and will assist the operator in evaluating a total lifecycle cost related to subsea booster pumping operation in deep water.

6 RECOMMENDATIONS

As operation and exploration moves into deeper water and more remote locations, the need for subsea booster pumping and subsea processing in general will increase to economically exploit these new developments. Following this trend it is important to understand the consequences. This is equipment that in a topside environment traditionally requires regular maintenance and intervention. Even if the component reliability is improved for subsea application, it must be expected that this equipment will fail. Compared to a conventional subsea production systems, to economically utilize subsea booster pumping technology, a full understanding of required intervention resources and spare parts is essential. These issues should be carefully evaluated for any project development planing to utilize subsea-processing equipment.

One of the main results from this reliability evaluation is the potential cost savings related to focusing attention on critical areas, and improve solutions and concepts where the reward with respect to improved reliability is highest. The most critical components identified in this study include seals and bearings in both the pump module and the electrical motor. Effort has been made to improve the reliability of the seals and bearings applied in the booster pumps, however to provide confidence in the reliability predictions it is important that a reliability qualification program is established and testing in realistic conditions continue to define realistic and representative failure rates.

When establishing the reliability of the subsea booster pumps, available reliability data for similar equipment was reviewed and evaluated in detail. Further, the design documentation was evaluated and reviewed for system design specifications and requirements. Results from the factory acceptance tests, and the actual field application test were also made available to the JIP, and helped establishing more confidence in the predicted values. It is however important to realize the limitations of these predictions. It is strongly recommended to develop a detailed risk and reliability plan for any specific project to assure the reliability targets are met throughout the development.

The Sonsub/Nuovo Pignone subsea booster pumps have been equipped with a number of monitoring equipment. This equipment could potentially give early warnings of failures, and assure that resources are allocated before the equipment fails. Further, preventive maintenance based on conditional monitoring could potentially improve the system availability and reduce the lifecycle cost. Based on the limited operating experience and information available with respect to this equipment, the full benefits related to conditional monitoring have not fully been accounted for. The current assumption is that this equipment will improve the understanding of the equipment failure mechanisms once the system is put into service, and assist in continuous improvement of the equipment and design.

In the JIP, the subsea booster pump system has been evaluated in isolation from the rest of the production equipment. It is strongly recommended that the reliability evaluation of the subsea booster pumps is included as an integrated part of a subsea production system. Intervention requirements and resources should be planned and allocated based on a complete evaluation of the equipment in a development.

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System: Deep Water Multiphase Booster System
Sub-system: Multiphase Pump Package
Sub-system No.: I

#	Part/Component
1	Pump Seal
2	Timing Gears
3	Upper Screw Bearings
4	Upper Seals
5	Screws
6	Lower Seals
7	Lower Screw Bearings
8	Claw Coupling

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Multiphase Pump Package **Sub-system No.:** 1	**Sub-system Function:** Provide the required boosting of the production profiles
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Pump seal **Part/Component #:** 1	**Component Function:** Prevent leakage from pump chamber to coupling chamber

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
I-1.1	Internal leakage	Seal fails due to material degradation	Loss of lube oil as it enters the coupling chamber	Leaks into the coupling chamber can be flushed back into the production system	Increased lube oil consumption	In case of temperature increase, shutdown the pump and repair the seal	Velocity of pump ranges 1200 to 3000 rpm. (Relatively low stress)No pressure difference or very little pressure difference due to the pressure compensator
		Pump shaft wears due to improper alignment of pump and motor shaft	Loss of lube oil as it enters the coupling chamber	Pump could trip due to increased pump casing temperature due to loss of lube oil to the coupling chamber	Increased lube oil consumption	In case of temperature increase, shutdown the pump and repair the seal	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Multiphase Pump Package **Sub-system No.:** I	**Sub-system Function:** Provide the required boosting of the production profiles
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Timing Gears **Part/Component #:** 2	**Component Function:** Maintains the clearance between rotors

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
I-2.1	Mechanical Failure	Wear of gears due to improper alignment	Increased loading of the motor	Motor trips	Temperature sensors in the pump casing	Pull the pump package out and realign the timing gears	Pump will be extensively tested on surface
		Overheating / Wear due to improper lubrication	Vibration increases in the timing gear	Pump will seize or trip	Temperature sensors in the pump casing	Pull the pump package and inspect the timing gears and pump chamber	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Multiphase Pump Package **Sub-system No.:** I	**Sub-system Function:** Provide the required boosting of the production profiles
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Upper and Lower Screw Bearings **Part/Component #:** 3, 7	**Component Function:** Support axial loads

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
I-3.1	Bearing Seizure	Improper lubrication	Bearing temp increases	Possible seizure of the motor	Bearing temperature indicators	Pull the pump package out and replace bearing	Pump will be extensively tested on surface
		Misalignment of the pump and motor shaft	Vibration of bearings could lead to temperature increase	Possible seizure of the motor	Bearing temperature indicators	Pull the pump package out and replace bearing	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Multiphase Pump Package **Sub-system No.:** I	**Sub-system Function:** Provide the required boosting of the production profiles
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Upper and lower seal **Part/Component #:** 4, 6	**Component Function:** Prevent mixing of lube oil with process fluid

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
I-4.1 I-6.1	Internal leakage	Seal fails due to mechanical degradation	Lube oil enters the process flow, or the process flow contaminate the lube oil	Pump load increases as it pumps a mixture of process fluid and lube oil to the production line	Lube oil consumption increases	Monitoring the flow and repair the pump depending on the extent of the leakage	It is a controlled fluid environment. Seal is designed for a much higher rating. No or limited pressure differential due to the Compensator
		Pump shaft wears due to improper alignment of pump and motor shaft	Lube oil enters the process flow, or the process flow contaminate the lube oil	Pump load increases as it pumps a mixture of process fluid and lube oil to the production line	Lube oil consumption increases	Monitoring the flow and repair the pump depending on the extent of the leakage	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Multiphase Pump Package **Sub-system No.:** I	**Sub-system Function:** Provide the required boosting of the production profiles
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Screw **Part/Component #:** 5	**Component Function:** Develop required pressure to boost production

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
I-5.1	Vibration	Sand deposits on the screw	Motor load increases	Pump shafts could shear which would lead to the loss of pump unit	Monitor temperature	Flush the pump with chemical inhibitors which will prevent deposits	Study composites of the well to decide the chemicals to be doused
I.5.2	Temperature increase	High gas content	Increase in contact with screw and liner	Pump would trip	Monitor temperature	Retention fluid flows into the pump casing	Retention fluid will flow to the pump. Gas tests have been conducted and have been found to operate satisfactorily over a period of time.
I.5.3	Reduced volumetric efficiency	Erosion due to sand deposit	Increase in contact with screw and liner	Motor load increases	Pressure tapping	Monitor pressure	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Multiphase Pump Package **Sub-system No.:** I	**Sub-system Function:** Provide the required boosting of the production profiles
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Claw Coupling **Part/Component #:** 8	**Component Function:** Transmit torque from motor to pump

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
I-8.1	Mechanical Failure	Coupling fails due to improper meshing between male and female hubs	Coupling fails to transmit torque	Temperature of motor increases which could cause the motor to trip	Temperature Indicator	Pull the pump package out and replace the coupling	The pump is extensively tested before installation.

System: Deep Water Multiphase Booster System
Sub-system: Subsea Electrical Motor
Sub-system No.: II

#	**Part/Component**
1	Cable connections
2	Primary Windings
3	Rotor
4	Upper Bearing
5	Lower Bearing
6	Impeller
7	Motor Seal
8	Motor Shaft

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Subsea Electrical Motor **Sub-system No.:** II	**Sub-system Function:** Provide the necessary power required to operate the booster pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Cable connections **Part/Component #:** 1	**Component Function:** Provides the electrical supply to the motor

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
II-1.1	No signal	Internal leakage	Motor trips	Loss of the booster pump	Obvious from the flow and pressure sensors	Send ROV down to repair the connector	Protection devices on the topside cable have been provided to avoid damage of the motor
II-1.2	Insufficient electrical supply	No power from the topside equipment	Motor can not operate	Loss of pump	Temperature tapping	Pull the pump package out and replace the motor	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Subsea Electrical Motor **Sub-system No.:** II	**Sub-system Function:** Provide the necessary power required to operate the booster pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Windings **Part/Component #:** 2	**Component Function:** Set up a magnetic field to generate the torque

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
II-2.1	Failure of the windings	Faulty signal from variable speed drive and cable connections	Voltage increase which increases stresses on the windings	Motor will fail	Temperature tapping	Pull the pump package out and replace the motor	Insulation Resistance measurement
II-2.2	Loss of insulation on the motor windings	Mechanical damage of the windings	Increased internal temperature	Increased stress of the electrical motor, possible trip	Temperature tapping	Pull the pump package out and replace the motor	Insulation Resistance Measurement
		Water intrusion	Short circuit	Motor will trip	Temperature tapping	Pull the pump package out and replace the motor	Insulation Resistance Measurement

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Subsea Electrical Motor **Sub-system No.:** II	**Sub-system Function:** Provide the necessary power required to operate the booster pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Rotor **Part/Component #:** 3	**Component Function:** Set up a magnetic field to generate the torque

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
II-3.1	Mechanical failure	Loss of one of the conductors	Imbalance of the three phase motor	Motor trips	Monitoring current flowing through the conductors	Pull the pump package out and repair the rotor	Monitoring current on a continuos basis

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Subsea Electrical Motor **Sub-system No.:** II	**Sub-system Function:** Provide the necessary power required to operate the booster pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Upper and lower bearing **Part/Component #:** 4, 5	**Component Function:** Absorb the axial loads and thrust loads

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
II-4.1 II-5.1	Bearings seize	Misalignment	Stress and wear of the electrical motor	This could lead to the failure of the pump unit	Temperature Indicators	Pull the pump package out and replace the bearings	Proper bearing selection
		Improper lubrication	Bearing temperature increases	Motor trips	Temperature Indicators	Pull the pump package out and replace the bearings	Proper bearing selection

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Subsea Electrical Motor **Sub-system No.:** II	**Sub-system Function:** Provide the necessary power required to operate the booster pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Impeller **Part/Component #:** 6	**Component Function:** Provide circulation of the cooling water, and maintain a marginal pressure differential to the coupling chamber

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
II-6.1	Mechanical failure	Cavitation	Loss of performance	Temperature in the motor casing increase due to reduced circulation	Temperature indicators an pressure transducers	Pull the pump package and replace impellers	There are two impellers to provide circulation of the cooling fluid.
		Worn Bearings	Increase motor temperature	Temperature in the motor casing increase	Temperature indicators an pressure transducers	Pull the pump package and replace impellers	There are two impellers to provide circulation of the cooling fluid

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Subsea Electrical Motor **Sub-system No.:** II	**Sub-system Function:** Provide the necessary power required to operate the booster pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Motor seal **Part/Component #:** 7	**Component Function:** Prevent the cooling water entering the coupling chamber

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
II-7.1	Internal leakage	Seal rupture	Loss of coolant to coupling chamber	Coolant will be drained from the coupling chamber. No effect as long as coolant is refilled.	Cooling water consumption increase	Depending on the level of leakage plan to pull the pump out and replace the seal	Proper material selection for seal
		Shaft wear	loss of coolant fluid to coupling chamber	Coolant will be drained from the coupling chamber. No effect as long as coolant is refilled.	Cooling water consumption increase	Depending on the level of leakage plan to pull the pump out and replace the seal	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Subsea Electrical Motor **Sub-system No.:** II	**Sub-system Function:** Provide the necessary power required to operate the booster pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Shaft **Part/Component #:** 8	**Component Function:** Converts the Electro-magnetic field into torque

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
II-8.1	Distortion	Coupling seizure	Increased motor temperature	Motor trips	Temperature indicators	Recover pump and replace motor	Proper material selection for shaft
		Defective material	Increased motor temperature	Motor trips	Temperature indicators	Recover pump and replace motor	

System: Deep Water Multiphase Booster System
Sub-system: Pressure Compensator System
Sub-system No.: III

#	**Part/Component**
1	Pressure Compensator
2	Instrumentation

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Pressure Compensator System **Sub-system No.:** III	**Sub-system Function:** Equalize the pressure between the lube oil, cooling water and process fluid
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Pressure Compensator Chamber **Part/Component #:** 1	**Component Function:** Equalize the pressure between the lube oil, cooling water and process fluid

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
III-1.1	Mechanical failure	Bottom membrane fails	Depending on the pressure, lube oil will enter the process flow or process fluid will enter the lube oil system	Contamination of the lube oil will reduce the cooling and lubrication effect and thus the reliability of the pump	Loss of lubrication fluid, or degraded pump performance	Plan to pull the pump package out and replace the membrane	No differential pressure across the system and the membrane. It has been tested and it is not exposed any cycles
		Top membrane failure	Depending on the pressure, lube oil will enter the electrical motor or cooling water will enter the lube oil	Possible contamination of the cooling water for the electrical motor. Overload and possible trip	Loss of lubrication fluid, or degraded pump performance	Plan to pull the pump package out and replace the membrane	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Pressure Compensator System **Sub-system No.:** III	**Sub-system Function:** Equalize the pressure between the lube oil, cooling water and process fluid
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Pressure Compensator Chamber **Part/Component #:** 1	**Component Function:** Equalize the pressure between the lube oil, cooling water and process fluid

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
III-1.2	External Leakage	Process inlet line leakage	Depending on the pressure, loss of process fluid to the sea or seawater entering the production line	Depending on the size of the leakage to sea, consider shut down of the booster pumps	Pressure indication of the process fluid	Consider repairing the booster pump	Pressure testing of lines before installation
		Lube oil inlet leakage	Depending on the pressure, loss of lube oil to sea or seawater ingress to the lube oil	Contaminated lubrication could result in reduced lubrication and cooling, thus reduced reliability	Lube oil consumption will be detected. Seawater contamination will be detected as reduced performance	Plan to pull the pump package out and replace the membrane	Pressure testing of lines before installation
		Cooling water Line leakage	Depending on the pressure, loss of cooling water to sea or seawater ingress in the motor cooling system	Seawater ingress in the electrical motor will reduce efficiency and could damage the motor	Loss of cooling water will be compensated by refill. Seawater ingress will be detected by reduced performance and sensors in the system	Plan to pull the pump package out and replace the membrane	Pressure testing of lines before installation

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Pressure Compensator System **Sub-system No.:** III	**Sub-system Function:** Equalize the pressure between the lube oil, cooling water and process fluid
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Instrumentation **Part/Component #:** 2	**Component Function:** Level indication

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
III-2.1	Complete loss of the level indication from the pressure Compensator	Cable connections fail	No level indication from the pressure chamber	The level indication is just for convenience. Other sensor in the system would probably detect loss of fluids.	No read-back to the control board	Opportunity based repair as the failure is not critical for operation of the pump	
III-2.2	Loss of a pressure level sensor	Sensor failure	No indication from the failed sensor	Loss of redundancy, there is a two level indication system (level low, level low-low)	Loss of one level of indication	Opportunity based repair as the failure is not critical for operation of the pump	

System: Deep Water Multiphase Booster System
Sub-system: Lube Oil Cooling
Sub-system No.: IV

#	**Part/Component**
1	Lube pump
2	Lube cooler
3	Lube purge line
4	Lube flow instrumentation

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Lubrication Oil System **Sub-system No.:** IV	**Sub-system Function:** Cooling and lubrication of the screw pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Lubrication oil pump **Part/Component #:** 1	**Component Function:** Supplies the oil to seals and bearings

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
IV-1.1	Mechanical failure	Gears of pump fail	Lube oil pump fails to deliver pressure	Bearing and seals heat up and pump could trip	Differential pressure and temperature tapings	Pull the pump package out and replace motor	The delivery lines are the integral part of the system

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Lubrication Oil System **Sub-system No.:** IV	**Sub-system Function:** Cooling and lubrication of the screw pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Lubrication oil cooler **Part/Component #:** 2	**Component Function:** Heat exchanger which cools the lubrication oil

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
IV-2.1	External leakage	Heat exchanger failure	Loss of efficiency	Bearings and seals heat up and the pump could trip	Temperature tapping	Pull the pump package out and repair the system	
		Line that supplies oil from pump to cooler leaks	Flow of oil reduces	Bearings and seals heat up and the pump could trip	Pressure differential	Pull the pump package out and repair the system	¾"pipe and ½"meter long
		Clogging	Loss of efficiency	Bearings and seals heat up and the pump could trip	Temperature tapping	Pull the pump package out and repair the system	
IV-2.2	Reduced flow	Clogging	Loss of efficiency	Bearings and seals heat up and the pump could trip	Temperature tapping	Pull the pump package out and repair the system	¾"pipe and ½"meter long

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Lubrication Oil System **Sub-system No.:** IV	**Sub-system Function:** Cooling and lubrication of the screw pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Lube oil purge line **Part/Component #:** 3	**Component Function:** Purge line of the lube oil to mix old lube oil with the production fluid

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
IV-3.1	External leakage	Corrosion	Crude from main line enters the seawater	Loss of production, depending on the size of the leakage pull or close of the booster system	Pressure loss in the main Production line	Pull the pump package out and repair the pipe	
IV-3.2	Internal leakage	Check valve fails	Crude from main line the purge line	The hydraulic isolation valve will prevent production fluid entering the pump chamber	Pressure loss in the main Production line	Pull the pump package out and repair the valve	The check valve and the hydraulic operated valve are in series
IV-3.3	Hydraulic valve fails to open	No signal from hydraulic distribution system	Unable to purge the lube oil tank	Aging of the lube oil could result in reduced efficiency and possible failure of the pump	Not able to change the lube oil, will be detected when trying to refill	Pull the pump package out and repair the valve	
		Mechanical failure	Unable to purge the lube oil tank	Aging of the lube oil could result in reduced efficiency and possible failure of the pump	Not able to change the lube oil, will be detected when trying to refill	Pull the pump package out and repair the valve	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Lubrication Oil System **Sub-system No.:** IV	**Sub-system Function:** Cooling and lubrication of the screw pump
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Lube oil Instrumentation **Part/Component #:** 4	**Component Function:** Pressure and temperature read-back of the lube oil condition

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
IV-2.1	Complete loss of the level indication from the pressure Compensator	Cable connections fail	No pressure or temperature read-back from the lube oil	The instrumentation is not critical to operate the pump, however deviations from normal operation can not be detected	No read-back to the control board	Possible pull the pump to repair the connections	
IV-2.2	Loss of a pressure level sensor	Sensor failure	Loss of reading from one single sensor	Loss of a single sensor is not considered critical	Loss of one level of indication	Opportunity based repair as the failure is not critical for operation of the pump	

System: Deep Water Multiphase Booster System
Sub-system: Cooling Water System
Sub-system No.: V

#	Part/Component
1	Coolant line
2	Water Cooler
3	Temperature tapping

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Cooling Water System **Sub-system No.:** V	**Sub-system Function:** Provide sufficient cooling of the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Coolant line **Part/Component #:** 1	**Component Function:** Supplies coolant to the motor casing via the water cooler

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
V-1.1	External leakage	Corrosion of the line	Increasing temperature of coolant in the motor	Pump trips due to increase in bearing temperature	Temperature tapping on the water cooler	Pull the pump package and repair the line	Proper testing techniques for heat exchangers
		Leakage in connections	Increasing temperature of coolant in the motor	Pump trips due to increase in bearing temperature	Temperature tapping on the lube oil cooler	Pull the pump package out and repair the line	Remote event

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Cooling Water System **Sub-system No.:** V	**Sub-system Function:** Provide sufficient cooling of the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Water Cooler **Part/Component #:** 2	**Component Function:** Cooling the cooling water circulating the electrical engine

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
V-2.1	External leakage	Corrosion	Depending on the pressure configuration, loss of cooling water to the sea or contamination of cooling water.	Increase in temperature of cooling water will in time would cause the motor failure	Temperature tapping on the water cooler	Pull the pump package and repair the cooler	Even if there is a contamination of 3% of the cooling fluid the manufacturer states that the motor will run for three years
V-2.2	Clogging	Contamination and aging effects of the fluid	Not able to circulate the cooling water through the cooler.	Increase in temperature of cooling water will in time would cause the motor failure	Temperature tapping on the water cooler	Pull the pump package and repair the cooler	Even if there is a contamination of 3% of the cooling fluid the manufacturer states that the motor will run for three years

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Cooling Water System **Sub-system No.:** V	**Sub-system Function:** Provide sufficient cooling of the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Instrumentation **Part/Component #:** 3	**Component Function:** Read-back of the cooling water temperature and pressure

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
V-3.1	Complete loss of the instrumentation	Failure in the electrical connections	No pressure or temperature read-back from the cooling water	The instrumentation is not critical to operate the pump, however deviations from normal operation can not be detected	No read-back to the control board	Possible pull the pump to repair the connections	
V-3.2	Loss of a single	Sensor failure	Loss of reading from one single sensor	Loss of a single sensor is not considered critical	Loss of one level of indication	Opportunity based repair as the failure is not critical for operation of the pump	Four points for the measurement of temperature are provided

System:	Deep Water Multiphase Booster System
Sub-system:	Manifold System
Sub-system No.:	VI

#	Part/Component
1	Production Flow Line Sled
2	Bared Tee
3	Main ROV Valve to pump production jumpers
4	Production jumpers
5	ROV Inlet Valve to pump package
6	DMBS unit inlet valve
7	Hydraulic Connectors
8	Main Production Valve
9	Non return Check Valve
10	Outlet valve for DMBS unit
11	Outlet valve from pump package

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Flowline sled **Part/Component #:** 1	**Component Function:** Transfer crude from production line sled to Main inlet ROV valve

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-1.1	External leakage	Internal wear of pipe or connection leakage	Loss of production fluid	Total loss of the system	No flow indication	Isolate the line and replace it with the help of ROV	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Bared Tee **Part/Component #:** 2	**Component Function:** Connection on the flow flow sled

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-2.1	External leakage	Internal wear of pipe or connection leakage	Loss of production fluid	Total loss of system	No flow indication	Isolate the line and replace it with the help of ROV	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Main ROV valve to the production jumper **Part/Component #:** 3	**Component Function:** Direct the production flow through the booster pumps

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-3.1	Fail to open	Mechanical failure of the valve such as broken spindle	Failure to transfer crude to the Pump units	Production cannot be boosted	ROV fails to operate it	Close main ROV outlet production valve and open main hydraulic valve in the flowline sled and plan to replace the ROV inlet production valve.	
VI-3.2	Fail to close	Mechanical failure of the valve such as broken spindle	Unable to isolate system	Can not isolate the booster pump	ROV fails to operate it	Shut down the total system and replace the valve	
VI-3..3	External leakage	Valve connections leak out	Loss of crude oil and seawater enters the system	Production cannot be boosted and corrosion increase	No flow indication	Close main ROV outlet production valve and open main hydraulic valve in the flowline sled and plan to replace the ROV inlet production valve.	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Production Jumpers **Part/Component #:** 4	**Component Function:** Prevent seawater entering the production system

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-4.1	External leakage	Wear of metal scals or flexible jumper	Seawater enters the system	Increase corrosion within the different components of the system	Monitoring Of samples in the outlet production flow line	Replace using ROV's	
VI-4.2	Clogged	Icing	Line blockage	Pumping units starve	Monitoring Of samples in the inlet production flow line	Replace using ROV's	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** ROV Inlet valve's to pump unit **Part/Component #:** 5	**Component Function:** Supplies the pumps with crude via the pump manifold

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-5.1	Fail to open	Mechanical failure of the valve such as broken spindle	Failure to transfer crude to the Pump units	Reduced recovery of the oil production, possible need for closure of the booster pumps	ROV fails to operate it	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	
VI-5.2	External leakage	Material degradation, installation failure	Depending on the pressure loss of crude oil or seawater leakage into the system	Reduced recovery of the oil production, possible need for closure of the booster pumps	No flow indication	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** DMBS unit inlet valve **Part/Component #:** 6	**Component Function:** Supplies the pumps with crude via the pump manifold

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-6.1	Fail to open on demand	Mechanical failure of the valve such as broken spindle	Failure to transfer crude to the Pump unit	Pump cannot boost production	Not able to operate valve	Plan to replace valve using ROV	
		No signal from the hydraulic distribution unit	Failure to transfer crude to the Pump unit	Pump cannot boost production	Not able to operate valve	Inspect regularly	
VI-6.2	Fail to close on demand	Mechanical failure of the valve such as broken spindle	Failure to transfer crude to the Pump unit	Pump cannot boost production	Not able to operate valve	Plan to replace valve using ROV	
		No signal from the hydraulic distribution unit	Failure to transfer crude to the Pump unit	Pump cannot boost production	Not able to operate valve	Inspect regularly	
VI-6.3	External leakage	Material degradation, installation failure	Depending on the pressure loss of crude oil or seawater leakage into the system	Reduced recovery of the oil production, possible need for closure of the booster pumps	No flow indication	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Hydraulic Connector **Part/Component #:** 7	**Component Function:** Prevent seawater entering the pump suction inlet

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-7.1	External leakage	Material degradation, installation failure	Depending on the pressure loss of crude oil or seawater leakage into the system	Reduced recovery of the oil production, possible need for closure of the booster pumps	No flow indication	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Main Production Valve **Part/Component #:** 8	**Component Function:** Used during start up and emergency as a bypass valve in order to prevent loss of production

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-8.1	Fail to open on demand	Mechanical failure of the valve such as broken spindle	Can not produce naturally, through the flowline sled	Bypass function is lost if valve fails	Not able to operate valve	Plan to replace valve using ROV	
		No signal from the hydraulic distribution unit	Can not produce naturally, through the flowline sled	Bypass function is lost if valve fails	Not able to operate valve	Inspect regularly	
VI-8.2	Fail to close on demand	Mechanical failure of the valve such as broken spindle	Production flow will continue through the flowline sled	Can not direct the production flow through the booster pumps	Not able to close the valve	Plan to replace valve using ROV	
		No signal from the hydraulic distribution unit	Production flow will continue through the flowline sled	Can not direct the production flow through the booster pumps	Not able to close the valve	Inspect regularly	
VI-8.3	External leakage	Material degradation, installation failure	Depending on the pressure loss of crude oil or seawater leakage into the system	Reduced recovery of the oil production, possible need for closure of the booster pumps	No flow indication	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Non-return check valve **Part/Component #:** 9	**Component Function:** Prevents the oil from flowing back after it has exited the pump outlet

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-9.1	External leakage	Material degradation, installation failure	Depending on the pressure loss of crude oil or seawater leakage into the system	Reduced recovery of the oil production, possible need for closure of the booster pumps	No flow indication	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Outlet valve for DMBS unit **Part/Component #:** 10	**Component Function:** Supplies crude to the main ROV valve

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-10.1	Fail to open	Mechanical failure of the valve such as broken spindle	Failure to transfer crude to the Main ROV valve	Total loss Pump unit	ROV fails to operate it	Pull the pump package and replace the ROV valve	
VI-10.2	External leakage	Material degradation, installation failure	Depending on the pressure loss of crude oil or seawater leakage into the system	Reduced recovery of the oil production, possible need for closure of the booster pumps	No flow indication	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Manifold System **Sub-system No.:** VI	**Sub-system Function:** Direct the production through the booster pumps
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Outlet valve from pump package **Part/Component #:** 11	**Component Function:** Supplies crude to the pump manifold

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VI-11.1	Fail to open	Mechanical failure of the valve such as broken spindle	Failure to transfer crude to the Main production valve	Total loss of the pump system and Isolate the DMBS by closing the main ROV inlet and outlet valve and opening the fail safe production valve	ROV fails to operate it	Pull the pump package and replace the ROV valve	
VI-11.2	External leakage	Material degradation, installation failure	Depending on the pressure loss of crude oil or seawater leakage into the system	Reduced recovery of the oil production, possible need for closure of the booster pumps	No flow indication	Close the main inlet and outlet valves and open the main valve on the sled. Plan and replace valve	

System: Deep Water Multiphase Booster System
Sub-system: Electrical Power Chain
Sub-system No.: VII

#	**Part/Component**
1	Cable connections
2	Power Umbilical/Subsea Umbilical Terminator
3	Topside Umbilical Termination
4	Hang off Junction Box
5	Step up transformer
6	Step down transformer
7	Variable Frequency Drive
8	VSD Power Components

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Cable connections **Part/Component #:** 1	**Component Function:** Transfer power from the subsea umbilical termination to the electrical subsea system

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII-1.1	No electrical supply	Break of the continuity between male and the female wet mateable connector	No electrical supply to the system	Loss of the booster pump	Obvious when the electrical motor fails	Send an ROV to replace the connection	The connection takes place in a oil-filled--environment. Connections can be made at least 50 times before refill of the oil.
		Seawater leakage through the connection	No electrical supply to the system	Loss of the booster pump	Obvious when the electrical motor fails		

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Main umbilical and termination assembly **Part/Component #:** 2	**Component Function:** Transfer power from the topside host to the seabed

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII-2.1	No electrical supply	Failure in the connection	No electrical supply to the system	Loss of the booster pump	Obvious when the electrical motor fails	Disconnect the detachable part of the power connection and pull the power umbilical	The connection takes place in a oil-filled--environment. Connections can be made at least 50 times before refill of the oil.
		Loose insulation, seawater ingress	No electrical supply to the system	Loss of the booster pump	Obvious when the electrical motor fails		

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Topside umbilical termination **Part/Component #:** 3	**Component Function:** Transfer power hang off junction box to the power umbilical

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII-3.1	No electrical supply	Failure in the connection	No electrical supply to the system	Loss of the booster pump	Obvious when the electrical motor fails	Perform the necessary repairs (topside)	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Hang off Junction Box **Part/Component #:** 4	**Component Function:** Transfers power from step up transformer to the topside umbilical termination

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII-4.1	No electrical supply	Failure in the connection	No electrical supply to the system	Loss of the booster pump	Obvious when the electrical motor fails	Perform the necessary repairs (topside)	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Step up transformer **Part/Component #:** 5	**Component Function:** Increase the voltage to be transferred to the electrical pumps

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII-5.1	Short circuit	Primary windings Fail	No power supply	Motors fails	No voltage indication	Disconnect and repair	
		Secondary windings fail	No power supply	Motors fails	No voltage indication	Disconnect and repair	
		Failure of cooling medium	No power supply	Motors fails	Temperature indicators	Disconnect and repair	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Variable Frequency Drive **Part/Component #:** 7	**Component Function:** Decrease the voltage from the mains

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII.7.1	Input power loss	Supply voltage level fails under a predefined set-point for a predefined time duration (e.g 80% for 5-10 seconds)	Power supply failure from step-up transformer	Motor trips	Monitor input voltage	Input transformer needs to be adjusted by means of tap setting	
VII.7.2	Stall	The feedback frequency exceeds the frequency command for a predefined Value for more than a predefined time	Motor load higher than the drive capacity	Motor trips	Monitor input voltage	Output frequency monitoring	
VII.7.3	Output current unbalance	The current on each phase differs from the nominal value more than a predefined value for more than a predefined time	Motor stator phase impedance are not balanced	Motor trips	Check current sensing element	Check connections status	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Variable Frequency Drive **Part/Component #:** 7	**Component Function:** Decrease the voltage from the mains

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII.7.4	Loss of speed command	The speed set point provided by the topside control system as a signal in the range of 4-20mA. If the signal goes out of range for more than a predefined time it is considered that communication is lost	Failure of VSD control interface	Alarm generation	Control from VSD local control console	Check cabling and wire integrity	

FMEA **Report Form**	**System:** Deepwater Multiphase Concept **Sub-system:** Electrical Power Chain **Sub-system No.:** VII	**Sub-system Function:** Supply of the main power to operate the electrical motor
Evaluated by: **Date:** 12-30-2000 **Client Reviewer:**	**Part/Component:** Variable Speed Drive **Part/Component #:** 8	**Component Function:** Decrease the voltage from the mains

Id.	Failure Mode	Causes	Local Failure Effect	System Effect	Method of Detection	Corrective Action	Comments
VII.8.1	Fault	Control section watchdog	Alarm generation	Motor trips	check VSD cooling system	Replace components	
		Rectifier bridge Components	Alarm generation	Motor trips	check VSD cooling system	Replace components	
		Inverter bridge Components	Alarm generation	Motor trips	check VSD cooling system	Replace components	