NTNU – Trondheim
Norwegian University of
Science and Technology

TECHNOLOGY QUALIFICATION OF EQUIPMENT IN SUBSEA PRODUCTION SYSTEMS

Eirik Horpestad

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Supervisor: Marvin Rausand, IPK

Norwegian University of Science and Technology
Department of Production and Quality Engineering

NTNU
Faculty of Engineering Science and Technology
Department of Production and Quality Engineering

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MASTER THESIS
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TECHNOLOGY QUALIFICATION OF EQUIPMENT IN SUBSEA PRODUCTION SYSTEMS
(Kvalifisering av teknologi for utstyr i undervanns produksjonssystemer)

Increased water depths, the associated high cost of conventional topside installations, and hostile environmental conditions have paved the way for increased used of subsea production systems (SPSs) for oil and gas. During the last decade, several new technologies (e.g., subsea separation, pumping, and compression) have emerged to increase the production from an SPS. Electrification of the control system, making control systems fully electrical, is a difficult and important development that will change the way the industry thinks about subsea equipment. An electrical control system will make subsea installations relevant for a number of new fields and reservoirs that are far from the shore, at deep waters, and in hostile environments, fields and reservoirs that have not been possible to develop with conventional electrohydraulic systems. Examples comprise reservoirs in the artic sector.

Many of the technologies that are considered to be used subsea are known, proven, and have been used topside for many years. To be able to use known topside technologies subsea, the equipment needs to be "marinized" such that it becomes, smaller, more robust, easily maintainable, and reliable.

To "marinize" equipment, the industry applies the DNV-RP-A203 recommended practice that describes the process of qualification of new technology. For safety-related equipment the industry also follows the methods described in IEC 61508 and IEC 61511. The process of qualifying new technology is referred to as a technology qualification program (TQP).

The main difficulty the industry sees in this context is the lack of correct documented input data for reliability and availability (RAM) studies.

As part of this Master's thesis the candidate shall:

1. Perform and document an in-depth study of relevant standards and governing documentation (e.g., IEC 61508, IEC 61511, DNV-RP-A203, Statoil TR 1622, TR 1233, ISO13628-6).
2. Analyze the TQP processes that are part of the manufacturer's scope in major subsea project execution, including:

- Use of FMECA as part of threat assessment in TQP.
- Use of reliability targets and RAM analysis as part of acceptance criteria in TQP.
- Use of probability of failure on demand (PFD) targets when SIL is relevant.

3. Analyze how the TQP processes in major subsea project execution comply with relevant standards and governing documentation and possible challenges to meet requirements.
4. Perform a case study and describe the TQP process for chosen equipment, including FMECA, and building and implementation of a RAM model.

Following agreement with the supervisors, the various points may be given different weights.

Within three weeks after the date of the task handout, a pre-study report shall be prepared. The report shall cover the following:

- An analysis of the work task's content with specific emphasis of the areas where new knowledge has to be gained.
- A description of the work packages that shall be performed. This description shall lead to a clear definition of the scope and extent of the total task to be performed.
- A time schedule for the project. The plan shall comprise a Gantt diagram with specification of the individual work packages, their scheduled start and end dates and a specification of project milestones.

The pre-study report is a part of the total task reporting. It shall be included in the final report. Progress reports made during the project period shall also be included in the final report.

The report should be edited as a research report with a summary, table of contents, conclusion, list of reference, list of literature etc. The text should be clear and concise, and include the necessary references to figures, tables, and diagrams. It is also important that exact references are given to any external source used in the text.

Equipment and software developed during the project is a part of the fulfilment of the task. Unless outside parties have exclusive property rights or the equipment is physically non-moveable, it should be handed in along with the final report. Suitable documentation for the correct use of such material is also required as part of the final report.

The student must cover travel expenses, telecommunication, and copying unless otherwise agreed.

If the candidate encounters unforeseen difficulties in the work, and if these difficulties warrant a reformation of the task, these problems should immediately be addressed to the Department.

The assignment text shall be enclosed and be placed immediately after the title page.

Deadline: June 11th 2012.

Two bound copies of the final report and one electronic (pdf-format) version are required.

Responsible supervisor at NTNU: Marvin Rausand
Phone: 73 59 25 42
E-mail: marvin.rausand@ntnu.no

Supervisors at AkerSolutions: Thomas Høyvik Garten
P.O.Box 94, 1325 Lysaker
Phone: +47 22945315
Email: thomas.garten@akersolutions.com

DEPARTMENT OF PRODUCTION AND QUALITY ENGINEERING

Per Schjølberg
Associate Professor/Head of Department

Marvin Rausand
Responsible Supervisor

Preface

This report represents the master thesis that is part of the mandatory subject Production and quality engineering - master thesis (TPK4900). The work with the thesis has been carried out during the 10th semester, spring of 2012, partly in Trondheim at the department of Production and Quality Engineering (IPK) at the Norwegian University of Science and Technology (NTNU), and partly at Aker Solutions headquarters at Fornebu.

The Master Thesis is performed in cooperation with Aker Subsea AS (business area within Aker Solutions), which has helped to define the thesis as well as shared information and knowledge. Due to confidential material, certain details are left out or anonymized.

The intended readers should have a basic knowledge of system reliability theory, as well as the terminology behind reliability, availability, maintainability and safety. A more detailed description of the abbreviations used, is presented in appendix A.

Trondheim, 2012-06-11

Eirik Horpestad

Acknowledgment

I will first of all thank my main supervisor, professor Marvin Rausand (NTNU), who at regular intervals has provided valuable support and technical assistance throughout the thesis. I would also like to thank the staff at Aker Solutions, especially my co-supervisor Thomas Garten (Aker Subsea AS) who has facilitated my stay at Aker Solutions, provided software guiding, information gathering and support to the thesis. In addition, Ingvild Bakken (TQP engineer), Felipe Lima (System Design) and Dag Morten Jahr (Concept & Technology) have contributed with valuable comments and inputs when this was needed.

E.H.

Summary and Conclusions

Development of new technology has always been an important activity for the oil and gas industry. New technologies can streamline the production, improve the recovery rate and provide economic benefits. The implementation cost may sometimes be high, but the end result may in total easily turn out to have great economical advantages.

The challenge is that new technology may involve potential threats with high uncertainty. These factors must be managed prior to implementation, and is achieved through technology qualification. The aim of technology qualification, is to provide sufficient evidence that the technology is fit for purpose without high risk.

In order to increase the understanding about qualification, the thesis introduces key terms, which are further discussed and compared. These are the qualification, verification and validation. In addition, different qualification methods are introduced and discussed. The methods describe how the qualification certificate shall be produced, through physical testing, analytical evaluation or integrated qualification.

An in-depth literature survey revealed relevant standards, recommendations and other guidance documents. General qualification documents provide guidance of how general qualification should be executed. Business-specific documents illustrate how the general documents are implemented into the business-specific procedures, as well as providing internal guidance. In addition, guidance for qualification of safety instrumented systems, and supplementary qualification documents are presented.

In the general qualification document, DNV-RP-A203, a qualification program for the new technology is introduced. This qualification program is a the framework of how a technology qualification process will be implemented. The process deals with a structured set of steps, which are intended to provide qualification evidence and to ensure that qualification requirements are met. These steps are: technology qualification basis, technology assessment, threat assessment, technology qualification plan, execution of the plan, and performance assessment.

Development of new technologies is usually performed by a technology provider on behalf of an oil operator. In such cases, several qualification procedures are involved. This master thesis discusses how and to what extent the different documents should be followed. In addition, challenges in projects where several parties are involved are discussed, more specific between Aker Solutions and Statoil.

In the last part of the thesis, a extensive qualification case study is documented based on the technology qualification process provided in DNV-RP-A203. A passive subsea inlet cooler unit is selected as case equipment. Such subsea technology are adopted from existing topside solutions, but modified to withstand other hostile operational and environmental conditions. Qualification requirements for the inlet cooler unit are identified in the technology qualification basis. The maturity of the unit is defined in the technology assessment, and critical failures found in the threat assessment. A qualification plan is developed with four different activities intended to reduce the critical failures. The plan is executed, and the performance assessment considers to what extent the qualification requirements are met. Due to insufficient material, the last process step is inadequately reached.

In addition, an extension of the case study is carried out in terms of a production assurance analysis. The analysis is conducted using MIRIAM Regina, where a model is modulated with respect to failure modes identified in the threat assessment. Each failure mode is assigned different parameters, like failure rates and restoration time. The model is validated by competent staff at Aker Solutions. The simulation is carrier out with a 25-years perspective, through 1000 replications. The simulated results show that the average technical availability for the inlet cooler unit is 98,93%. Since no availability requirement is stated for the inlet cooler unit, the thesis does not draw any qualification conclusions. However, it indicates that, if this simulated value is higher than the required availability, and additional requirements are met, then the inlet cooler unit is considered as qualified.

Sammendrag og Konklusjon

Teknologiutvikling har alltid vært en viktig satsningsområde for olje- og gassindustrien. Ny teknologi kan effektivisere produksjonen, gi høyere utvinningsgrad eller øke fortjenesten. Implementeringskostnaden er ofte høye, men innsparingen kan bli vesentlig større.

Utfordringen er at ny teknologi som regel innebærer potensielle trusler som fører med seg høy usikkerhet. Slike trusler må identifiseres og reduseres før implementering. Dette kan oppnås ved å kvalifisere teknologien. Målet med kvalifiseringen, er å frembringe tilstrekkelig bevis på at teknologien er egnet til formålet.

For å øker forståelsen rundt kvalifisering, introduserer masteroppgaven sentrale begreper, som videre blir diskutert og sammenlignet. Disse er kvalifisering, verifisering og validering. I tillegg blir ulike kvalifikasjonsmetoder introdusert og diskutert. Metodene beskriver hvordan kvalifiseringsbevis skal frembringes, gjennom fysisk testing, analytisk evaluering eller integrert kvalifisering.

Et dokumentert litteraturstudium presenterer relevante standarder, rekommandasjoner og andre styrende dokumenter. Generelle kvalifiseringsdokumenter gir veiledning om hvordan en generell kvalifisering bør utføres. Bedrifts-spesifikke dokumenter belyser hvordan de generelle dokumentene er implementert, men gir også interne veiledninger. I tillegg presenteres kvalifiserings prosedyrer for sikkerhets instrumenterte systemer og andre komplementerende kvalifiseringsdokumenter .

I den generelle kvalifiseringsdokumentet, DNV-RP-A203, blir et kvalifiserings program for ny teknologi introdusert. Dette kvalifiserings programmet representerer rammeverket for hvordan et teknologi kvalifisering prosess skal gjennomføres. Prosessen omhandler et strukturer sett med trinn, som har til hensikt å frembringe bevis på at teknologien møter bestemte kvalifiserings krav. Disse trinnene er: teknologi kvalifiserings basis, teknologi vurdering, trussel vurdering, teknologi kvalifiserings plan, utførelse av plan og ytelses vurdering.

Utvikling av ny teknologi, er vanligvis utført av en teknologi leverandør på oppdrag fra en olje operatør. I slike tilfeller er flere kvalifiserings prosedyrer innblandet. Master oppgaven diskuterer hvordan og i hvilken grad de forskjellige dokument skal følges. I tillegg identifiseres utfordringer i prosjekter der flere parter er innblandet, mer spesifikk mellom Aker Solutions og

Statoil.

Siste delen av masteroppgaven, inkluderer en omfattende kvalifiserings eksempel, basert på teknologi kvalifiserings prosessen presentert i DNV-RP-A203. Utvalgt teknologi er en passiv subsea innløps kjøler enhet. Subsea kjøleren er adoptert fra en topside-løsning, men modifisert for å tåle andre og mer krevende drifts-og miljømessige forhold. I teknologi kvalifiserings basisen er kvalifiserings kravene identifisert. Modenheten til teknologien defineres i teknologi vurderingen. I trussel vurderingen blir teknologien analysert, og kritiske feil funnet. En kvalifisering plan er utviklet, hvor fire ulike aktiviteter har til hensikt å redusere de kritiske feilene. Videre er planen utført og dokumentert, der ytelses vurderingen bedømmer i hvilke grad kvalifikasjonskravene er oppfylt. På grunn av utilstrekkelig materiale, er dokumentasjonen i siste trinn mangelfull, og ingen konklusjon dratt.

Som en utvidelse av eksempelet, er en produksjonssikrings analyse utført, ved hjelp av simulerings verktøyet MIRIAM Regina. En modell er modulert med hensyn til feil modi som er identifisert i trussel vurderingen. Modellen er basert på forskjellige parametere, deriblant feil raten og restaurerings tiden. Modellen er validert av et kompetente personer hos Aker Solution. Simuleringen er utført med et 25-års perspektiv, med 1000 gjennomkjøringer. De simulerte resultatene viser at den gjennomsnittlige teknisk tilgjengelighet for innløp kjøleren er 98,93 %. Grunnet ingen spesifiserte tilgjengelighets krav er identifisert for teknologi kvalifiserings basisen, er det ikke trukket noen kvalifisering konklusjon. Likevel, om den simulert verdien er høyere enn krevd for tilgjengelighet, samt at yttligere krav er oppfylt, kan innløps kjøler enhten betraktes som kvalifisert.

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Chapter 1

Introduction

One of the challenges in today's oil and gas production is to extract the reservoirs more efficiently. The potential of increasing the recovery rate can provide major economic benefits. In the report "Increasing production on the Norwegian continental shelf" the Norwegian Ministry of Petroleum and Energy, states that an increase in the production rate of 1% on the Norwegian continental shelf, will provide a gross value of about 270 billion NOKs[1]. Such an increase corresponds the annual subsidy that the petroleum activities contribute to the Norwegian state coffers every year (Hansen et al., 2011).

The focus area for increasing the recovery rate has in recent years moved from traditional topside production systems, to subsea production systems (SPS). New processing technology, faster and more reliable information and communication technology, and new technology for condition monitoring are some important subsea technology solutions that streamline the production. A common development trend is that the new technology often can be considered as an "marinization" of conventional topside equipment, but with a new twist since it must withstand other hostile operational and environmental conditions.

1.1 Background

Implementing new subsea technology involves significant financial expenses and uncertainties related to the technology. The uncertainty implies a risk that should be managed and reduced

[1] Oil price 70 dollars/barrel, 1 dollar = 5,5NOK

to an acceptable level, before the technology is implemented. This is done trough a TQP. The overall objective of the TQP is to provide a systematic approach of how the qualification should be carried out, in order to provide traceable evidence that the technology meets specified requirements for the intended use, and within an acceptable level of confidence.

The challenge in this master thesis is to introduce and analyze some of these TQP that are relevant for the subsea petroleum industry. In addition, how the industry implements the TQP and a qualification case with integrated RAM model shall be introduced.

Several different information channels have been used through the master thesis. The qualification documents are either developed on general terms, such as DNV-RP-A203 (2011) from by Det Norska Veritas, or more business-specific, developed by Statoil WR 1622 (2009), or the Subsea department in Aker Solutions (2006). A more detailed description of these and other supplementary documents are presented in Chapter 3. In addition MIRIAM Regina (2005) has been used in order to learn the program.

1.2 Objectives

The main objectives of this Master thesis are to:

1. Perform and document an in-depth study of relevant standards and governing documentation.
2. Analyze the TQP processes that are part of the manufacturer's scope in major subsea project execution, including:
   - Use of FMECA as part of threat assessment in TQP.
   - Use of reliability targets and reliability, availability, maintainability (RAM) analysis as part of acceptance criteria in TQP.
   - Use of probability of failure on demand (PFD) targets when safety integrity level (SIL) is relevant.
3. Analyze how the TQP processes in major subsea project execution comply with relevant standards and governing documentation and possible challenges to meet requirements.

4. Perform a case study and describe the TQP process for chosen equipment, including FMECA, and building and implementation of a RAM model.

1.3 Limitations

Many of today's technology solutions deal with both hardware and software technology. While hardware technology may be qualified through detailed design, this design does not exist for software technology until the final program code has been developed. The technology qualification processes are for that reason slightly different. Qualification of software technology is omitted in this thesis, but some general information is still provided.

In order to limit relevant actors, two key players have been selected to represent the oil industry. These are Statoil and Aker Solutions.

1.4 Approach

A Case study is presented in Chapter 6 and 7. It is important to emphasize that this case study is only a exemplification of the reality, and should not be read and used as a final version, but as a guide. Some of the input to the analysis has been generalized as the focus is on the processes described.

Although today's business-specific qualification procedures are based on DNV-RP-A203 from 2001, this thesis is focused on the 2011 version. This is since the most recent version is more user friendly providing better qualification flow, that most likely will be implemented at a later time.

This thesis uses the same notation as Rausand and Høyland (2004), unless otherwise is stated.

1.5 Structure of the Report

The rest of the thesis is structured as follows. Chapter 2 defines key terms and describes different qualification methods. Chapter 3 presents important qualification literature. The technology qualification process, defined in DNV-RP-A203, is presented in Chapter 4. The next chapter, Chapter 5 analyzes how a qualification program is carried out by the industry. In Chapter 6, a case study is introduced, where a inlet cooler unit shall be qualified in accordance with DNV-RP-A203. Outputs from some of the process stages are presented in Appendix B. In Chapter 7, a RAM analyst is accomplished on the same Case Study. Summary and recommendations for further work are provided in chapter 8.

Chapter 2

Technology Qualification

Technology is a generic term where scientific studies and applied sciences is applied in practical tasks in the industry. New technology arises when existing technology is developed to a new degree of novelty, or when technology is developed without any former characteristics.

A classic categorization of new technology is provided in Table 2.1. Here technology is categorised as unproven technology, or proven technology where the application area (environment for the suggested technology) is new (DNV-RP-A203, 2011).

Gathering of information is important to provide sufficient evidence that new technology will function within given operational conditions and meet specified requirement. This study is most often done through TQP. In addition to provide evidence TQP may be used for comparison of different technology solutions, inputs to reliability evaluation of large systems, and documentation of the development stages.

Table 2.1: What is new technology?

	Proven	Unproven
New environment	$\surd$	$\surd$
Known environment	$\times$	$\surd$

2.1 Definitions

Some relevant terms related to TQP are qualification, verification and validation. These terms are interpreted differently by different standard organizations. The presented definitions in this thesis are adopted from DNV-RP-A203 (2011), which in turn is based on ISO 9000 (2005).

The most central term is qualification. This is defined as follows:

☞ **Qualification**: Is the process of providing the evidence that the technology will function within specified limits with an acceptable level of confidence.

A qualification should ensure that people, products, processes or systems functions within specified confidence limits. This evidence may be provided by empirical evidence, predictions using proven models or expert judgement. The confidence decides roughly which decisions that further should be made, based on requirements that where set at the start of the qualification process. This should been seen in relation to what extent the new technology should be implemented, or in what extent to invest more to the new technology.

A similar term to qualification is verification. Verification is a analytical method defined as follows:

☞ **Verification**: Is confirmation, through provision of objective evidence, that specified requirements have been fulfilled.

Verification is intended to ensure that evidence through observations, measurement, tests or other means matches obligatory or implied expectations or needs. The main similarities between verification and qualification are that both terms concern a way to "approve" something. The difference lies in what extent the evidence needs to be provided. Verification is used in cases with lesser extent, and little novelty, while qualification is used when the degree of novelty is large, with correspondingly high risk of an error.

Due to the economic benefit of verifying versus qualifying, the industry does as far as possible, start with a verification. In cases where verification is not sufficient, qualification will be executed. This boundary is determined by expert judgment.

In the software technology, verification means to build the product right. Here are the objective evidence obtained through manual inspections and testing (Sommerville, 2010).

Guidance for performing a verification can be found in specific industry standards, such as ISO 13628 (2006) that covers general verification tests for subsea equipment.

The last term, validation, also deals with a way to "approve". Validating is another analytical method defined as followed:

☞ **Validation**: Is confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

Validation is intended to ensure in what extent that evidence through observations, measurement, tests or other means matches obligatory or implied expectations or needs for specific use or application area are met. The difference between verification and validation is how the objective evidence is compared. While evidence for verifications is compared with own requirements, the evidence for validation is compared with third party requirement. Validation is therefore an important process in technology qualification which ensures laws and rules to be followed.

In the software technology, validation means to build the right product. The objective evidence is ensuring that the software does that the user really requires (Sommerville, 2010).

2.2 Qualification Methods

In order to qualify technology, this can be done in three different ways. Either by analytical qualification, qualification by testing, or in combination like integrated qualification. The appropriate method is determined in each individual case and depends on the system.

The aim is to provide a better understanding of how to reduce and manage uncertainty of the technology.

2.2.1 Analytical Qualification

An analytical qualification shall provide evidence through analytical methods, carried out by suitable software solutions or expert judgment, that provide evidence based on estimated values . In recent years, many reliable software solutions have been developed to visualize different problems of a product. Examples of software solutions that can be used to visualize problems, are computational fluid dynamics (CFD) and finite element (FEM) analysis. CFD provides evidence for flow problems that equipment is exposed to, while FEM analysis provides evidence for complex elasticity and structural analysis problems.

The advantage of using analytical qualification, is that physical models not necessarily have to be built. In addition, qualifying through software solutions are time-efficient, since detailed analysis by the software is performed considerably faster that real physical testing. The disadvantages of using analytical qualification, is that the model that are analyzed must be built correctly to ensure proper estimate. In addition, the modulated software solutions is basis on reflections of reality, where misinterpretations designed in software can provide differences between real and estimated values.

Analytical Qualification is often used to qualify complex and expensive equipment, due to the time and cost savings. In cases where analytical qualification do not provide sufficient evidence, qualification by testing must be carried out. Analytical qualification is also associated with qualitative qualification.

2.2.2 Qualification by Testing

The most traditional way to provide evidence through qualification, is by testing. Testing is a time consuming and costly process, which is carried when analytical qualification is not sufficient. The advantage is that it provides improved and more accurate evidence of the technology. This evidence is also called empirical evidence.

The major disadvantage of qualification by testing, is cost which is very high compared to the analytical qualification. The extent of testing is determined by the uncertainty of the technology. A test program shall be developed in such a way that it provides necessary evidence that reduces the uncertainty to an acceptable level.

For hardware technology, testing shall be carried out on a physical prototype. The prototype may be a simplification of the end product, but the essential parts that shall be tested must be present. For software technology, the testing shall be performed after the final code has been developed.

Qualification by testing is also referred to as quantitative qualification.

2.2.3 Integrated Qualification

The combination of analytical qualification and qualification by testing are often described as integrated qualification.

In large and complex systems, it is rarely necessary to qualify after a particular method. In such cases it is advantageous to use integrated qualification. Since qualification by testing is often an expensive method of qualification, only equipment that really needs to qualify through tests, is carried out by qualification by testing. The remaining equipment is qualified through analytical qualification. Such implementation minimizes the necessary qualifications cost and time consumption.

The method can also be combined in other ways. In cases where physical testing is difficult to monitor, such as high pressure scenario, analytical qualification could be used to qualify this level. The analytical result on a low pressure scenario is combined and compared to fit the results from the physical scenario. The analytical model is validated by the physical model, and reflects the reality. The high pressure scenario may thus be qualified using the analytical model.

In a third case, both methods are used in parallel and evaluate the same problem. This method most often used when uncertainties are not permitted, and where the acceptable level of confidence shall be high.

Chapter 3

Technology Qualification Related Documents

To qualify new technology, several standards and governing documentation must be considered. These documents provide guidance, requirements, and input to the process. Figure 3.1 gives examples of such inputs, and shows that the TQP must meet both company-specific and general documentation.

The next sections discuss the scope and use of core documents. General documents are first presented. Business-specific documents follows, and describes how general documents are implemented by the companies. Qualification of safety instrumented systems (SIS) and supplementary documents are also presented.

3.1 General Qualification Documents

Implementation of new technology requires that the technology is sufficiently proven, for instance by a TQP. The program should introduce a systematic and structured process that identifies and sufficiently reduces the uncertainties to the technology.

Several documents have recently been made to provide guidance for the qualification. Such qualifications guidelines are for instance developed by Det Norske Veritas and the American Petroleum Institute. In addition, NASA has developed the technology readiness level (TRL) concept, that is a measurement system for systematically assessing the maturity of a particular tech-

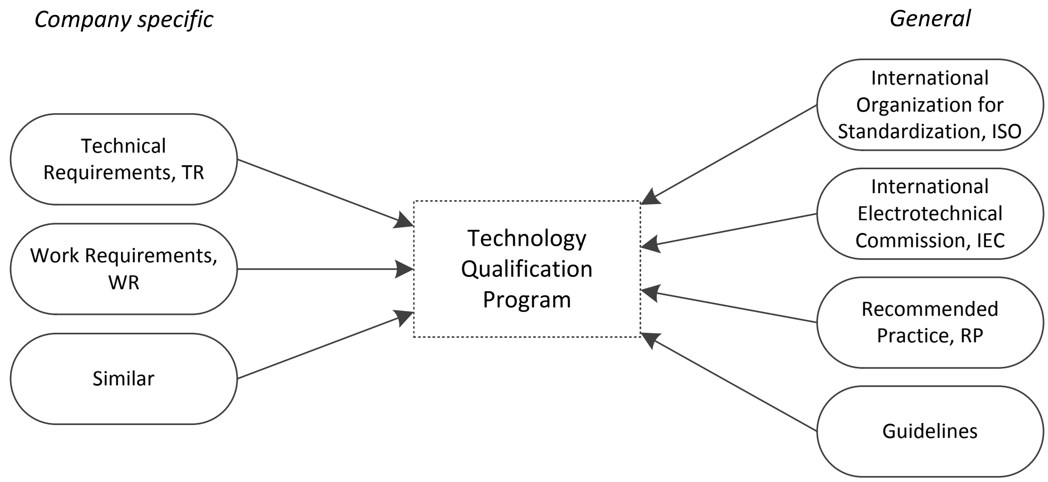

Figure 3.1: Relevant documents for the TQP.

nology.

3.1.1 DNV-RP-A203

DNV-RP-A203 (2011) is one of the most commonly used guidances for qualification of new hardware and software technology. The guidance, which is released as a recommended practice (RP), is developed by Det Norske Veritas and was first published in 2001. The current version was published in 2011, where better guidance was introduced based on 10 years of experience. The early version has been totally redesigned, provided better and more logical qualification flow, as well as improved and more specific examples and guidance notes. The 2011 version has become more user friendly than its predecessor, but does still have the same area of coverage. Today, the DNV-RP-A203 is considered as state of the art, by the oil industry.

DNV-RP-A203 introduce a TQP that represent the framework of the qualification. TQP is used to systematically exclude uncertainties and thereby provide technical evidence of the technology. The program is suitable for offshore components, equipment and assemblies, and used in exploration and exploitation of hydrocarbons on the Norwegian continental shelf, but may also be adopted for use other places. The objective to the TQP is to present a systematic approach on how to qualify and document new technology, through all stages of application. This is achieved by implementing a project execution model (PEM) (e.g., concept evaluation, pre-engineering and detailed engineering) within the TQP.

Within the TQP, a technology qualification process is introduced. The technology qualification process, illustrated in Figure 4.1, deals with a structured set of steps, assembled in series and connected to a modification stage, which ensures that uncertainties are reduced to an acceptable level and documented prior to approved qualification. The process steps presented in the current version are:

1. *Technology Qualification Basis:* The first stage is where the qualification basis is established. All facts to the new technology are identified such as its function, intended use, expectations to the technology as well as its qualification objectives.

2. *Technology Assessment:* This step performs an assessment of the technology and determines its degree of novelty where its key challenges and uncertainties are identified.

3. *Threat Assessment:* The threat assessment identifies the failure modes of the technology, and corresponding failure mechanisms as well as associated risk.

4. *Technology Qualification Plan:* The technology qualification plan is used to provide necessary qualification evidence on how to manage potential unacceptable failure modes.

5. *Execution of the Plan:* The planned activities are executed, and qualification evidence obtained through experience, numerical analysis and tests.

6. *Performance Assessment:* The last step concerns a review where the qualification evidence is assessed against the technology qualification basis.

   Modification: The aim of the modification is to reduces occurrence of non-acceptable elements, removes failure mode of concern, improve the confidence or reduce the cost.

If the technology in the performance assessment meets the requirements stated in the technology qualification basis, the technology is considered as qualified. If not, the technology must be modified to achieve these requirements .

A more detailed description of the technology qualification process is given in Chapter 4. In addition, Chapter 6 and 7 provide a case study, based on this process.

3.1.2 API-RP-17Q

Another qualification procedure, API-RP-17Q (2010), is released as a RP by the American Petroleum Institute. The current version, issued June 2010, is the first edition. API-RP-17Q provides a systematic method with a structured framework for qualification of subsea technology, but unlike DNV-RP-A203 that covers both hardware and software technology, API-RP-17Q is specific for subsea equipment.

The method starts with a breakdown of the subsea equipment into component-levels. These components are further categorized into classes of equipment or component functionality, which is used to identify the components. The qualification process is based on failure mode assessment (FMA) and product qualification sheet (PQS), where both supplier and operator in cooperation develop acceptance criteria and requirements for the technology. The FMA is a modified method of FMECA, and shall be presented in a FMA template (modified FMECA template). The PQS shall similarly be presented in component-specific templates, which contain information about each component, operating parameters, qualification requirements, interfaces and additional comments. The PQS shall be maintained through the qualification, and represents the final qualification documentation of a component.

The qualification takes place through exchange of the FMA and PQS, between the supplier and the operator. The technology is considered qualified when the acceptance criteria and requirements are met.

3.1.3 Technology Readiness Level

A common way to illustrate the progress in a TQP is by TRL. TRL is not a procedure, such as DNV-RP-A203 and API-RP-17Q, but deals with a systematic measurement system where the maturity of a particular technology is assessed.

The original TRL were developed by NASA in the middle of 1970s, for the aerospace industry. NASA needed a system to indicate how far a particular technology was developed, and whether or not it was ready to be used (NASA, 1995). The method was initially developed with seven levels, but over time it was expanded to include nine levels. These runs from TRL1 to TRL9, where the lowest level indicates the basic principles observed and reported for a technology,

Table 3.1: TRL adopted form WR 1622.

Level (TRL)	Development stage	Description
0	Unproven Idea	Paper Concept. No analysis or testing has been performed
1	Analytically Proven Concept	Functionality proven by analysis, reference to common features of existing technology or testing on individual subcomponents /subsystems. The concept may not meet all of the technical requirements at this level, but demonstrates the basic functionality with promise to meet all the requirements with additional testing.
2	Physically Proven Concept	Concept design or novel features of design validated by model or small scale testing in laboratory environment. The system validates that it can function in a "realistic" environment with the key environmental parameters simulated.
3	Prototype Tested	Full scale prototype built and put through product qualification test program. The prototype is tested in a robust designed development test program over a limited range of operating conditions to demonstrate is functionality.
4	Environment Tested	Full scale prototype (or production unit) built and put through a qualification test program in (simulated or actual) intended environment.
5	System Integration Tested	Full scale prototype (or production unit) built and integrated into intended operating system with full interface and functionality tests.
6	System Installed	Full scale prototype (or production unit) built and integrated into intended operating system with full interface and functionality test program in intended environment. The technology has successfully operated < 10% of its expected life.
7	Proven Technology	Production unit integrated into intended operating system. The technology has successfully operated with acceptable performance and reliability for > 10% of its specified life.

and the highest level proves the technology through successful operation.

Other industries have adopted and modified the fundamental idea behind TRL, such as API-RP-17N (2009) which presents a TRL for the subsea industry. Table 3.1 shows a version, modified by Statoil. The table indicates the maturity progressing through eight levels, where the levels are defined from a minimum of 0, corresponds to an unproved idea, to a maximum of 7, corresponding to a proven technology. Technology assigned with TRL≥4 is considered to be qualified.

3.2 Business-Specific Documents

The implementation of technology qualification in companies is done through own business-specific documents. These documents present company customized qualification programs, which is primarily based on interpretation of qualification specific documents and own reflections related to qualification. In this subsection, the business-specific documents of Statoil and Aker Solutions are presented.

3.2.1 Statoil - WR 1622

WR 1622 (2009) is a work process requirement (WR) developed by Statoil to provide guidance in qualification of new technology within the company and to vendors that offer new technology to Statoil. The current version is 5.05 and was released in December 2009. WR1622 is mainly based on DNV-RP-A203 and safety management practices from API-RP-17N, and describes how these documents should be implemented in Statoil. The current version of DNV-RP-A203 was released after version 5.05 became valid, so WR1622 is based on the 2001 version of DNV-RP-A203, with a process flow that is different from the one presented in section 3.1.1. The aim of the document is to define all additional activities that must be conducted in addition to the qualification activities adopted in DNV-RP-A203.

The qualification progress in WR1622 is based on Statoil's internal PEM, from the Statoil document, FR05. The model describes six stages that new technology within Statoil progresses. Between the stages, different decision gates (DG) are presented as milestones, from DG0 to DG4. In parallel with the PEM, the TRL is presented to show the maturity of the technology in various steps. A technology is considered to be qualified and ready to be implemented when all qualification activities are successfully completed in addition to TRL≥4 are met at milestone DG3.

The necessity of a qualification is identified in a technology assessment, that documents the risk and opportunity of the technology. The assessment classifies the technology as specified in DNV-RP-A203, but in a more strict way since it indicates to which extent the technology is new to Statoil, while DNV-RP-A203 classifies knowledge in relation to the industry. Technology in WR 1622, that is classified as 2 or higher shall be qualified through more activities. These activities follow the technology qualification process described in 2001 version of DNV-RP-A203.

WR1622 also presents requirements for qualification of new technology with and without fall-back solutions. Qualification based on fall-back solutions is less critical, since the fall-back solution can be used where qualification fails. Qualification without fall-back solutions is totally dependent on successful qualification, and therefore more critical. Qualification activities for no fall-back solutions are thus dependent on an earlier start to ensure that the technology can be developed.

3.2.2 Aker Solutions - Technology Qualification Procedure

The qualification guidance developed by Aker Solutions (2006) for the subsea department[1], is titled "Technology qualification procedure". The procedure was developed to ensure that requirement from the client as well as statutory rules and regulations are met through the qualification. The client is herein identified as Statoil. For other clients, the guidance shall be reassessed to ensure that requirements stated by the client are included. The current version was released September 2006, and is thus bases on the 2001 version of DNV-RP-A203 as well as a former version of WR 1622.

The guidance introduces a five steps qualification process, where each step indicates the work to be done, or which report that shall be made. A qualification is identified through the technology gap analysis, where TRL consideration and maturity classification is made. A technology where TRL≥4, or classified higher than 1 shall be qualified. The last steps deal with a formal qualification report, where sufficient qualification evidence shall be stated. The technology is considered to be qualified when the TRL≥4, and stated requirement is met.

3.3 Qualification of Safety Instrumented Systems

SIS can be installed to reduce the risk in a hazardous system. SIS is an independent protection system comprising sensors, logic, solver(s), and actuating items (also called final elements) which is designed to prevent and mitigate risk associated with safety-critical applications (Rausand and Høyland, 2004), and to maintain a safe state for the equipment under control (EUC).

[1] Original designed by Aker Kvaerner Subsea

For the subsea industry, SIS are usually grouped into process control (PC) systems and process shutdown (PSD) systems.

For new subsea technology that is categorized as SIS, there are several requirements that shall be followed. These requirements are generally stated in IEC 61508 (2010) and IEC 61511 (2003). In addition, the guideline, OLF 070 (2004), has adopted and simplified these standards for the Norwegian Petroleum Industry.

3.3.1 IEC 61508

IEC 61508 (2010), is the main standard for SIS that are based on electrical/ electronic/ programmable electronic (E/E/PE) technology. In IEC 61508 the E/E/PE safety-related system is referred to as SIS. The standard is generic, which means that SIS requirements for multiple industries are covered. The standard has two main objectives, where the first is to facilitate for development of sector specific standards[2]. The second objective is to serve as a guideline for development of SIS where no sector specific standard exists. The standard is mainly used for managing new technology, learning from previous accidents, and to standardize the application of SIS for safety application.

IEC 61508 is divided into seven parts. The initial tree parts (part 1 - 3) are normative parts which presents the requirements for the SIS hardware and software, while the remaining four parts (part 4 - 7) are supporting documents providing guidelines, examples and other informative annexes to the standard.

Part 1: General requirements

Part 2: Requirements for E/E/PE safety-related systems

Part 3: Software requirements

Part 4: Definitions and abbreviations

Part 5: Examples of methods for the determination of SIL

Part 6: Guidelines on the application of IEC 61508-2 and IEC 61508-3

Part 7: Overview of techniques and measures

[2]Examples of some sector specific SIS standards are IEC 61511(process industry), IEC 62061(machinery industry), IEC 61513 (nuclear power plant) and IEC 50126/IEC 50128/IEC 50129 (railway application).

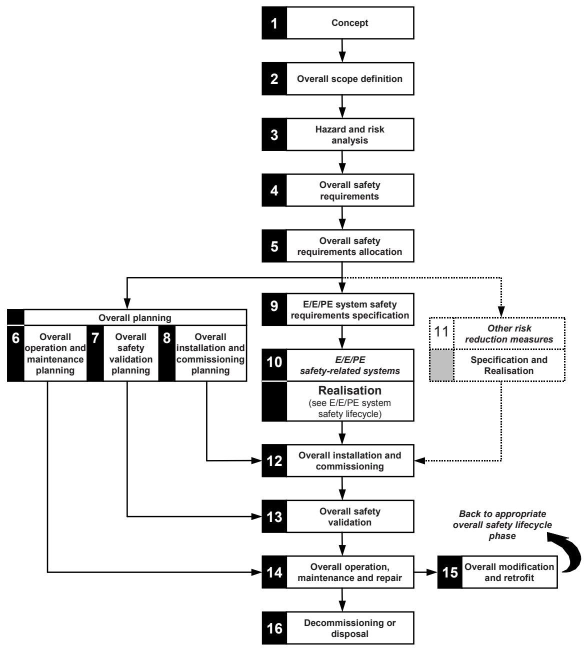

Figure 3.2: Safety life cycle adopted from IEC 61508.

IEC 61508 can also be used to develop and qualify SIS technology. This is done through the safety life cycle, illustrated in Figure 3.2. The cycle comprises 16 phases where the first five phases (phase 1 - 5) are risk analysis phases, which identify the safety functions requirements, reliability requirements and specifications of SIL requirements. In these phases risk analyses are conducted, reliability requirements are allocated, and SIL requirements are set based on tables.

The next phases (phase 6 - 13), are the design and construction phases. These phases describe how the SIS should be designed and constructed in accordance with SIL requirements and how the agreement with the requirements shall be verified.

The last phases (phase 14 - 16)are the operation and maintenance phases. These phases are intended to ensure that operation and maintenance are designing in such a way that the SIL performance is maintained. In addition, the actual SIL level is identified.

3.3.2 IEC 61511

One of the sector-specific standards, that is developed from the generic standard IEC 61508, is IEC 61511 (2003) for the process industry. The aim of the standard is to provide safety requirements and guidelines through the life cycle, which ensure that that the systems are in a safe state.

The standard customizes the requirements stated in the generic standard and makes them more process-specific. In addition, two fundamental concepts are adopted, safety lifecycle and SIL.

The standard is divided into three parts, where part 1 contains hardware and software requirements for SIS in the process sector. The other two parts (part 2 -3) are supportive parts providing guidelines for use of part 1.

Part 1: Framework, definitions, systems, hardware and software requirements.

Part 2: Guidelines for the application of IEC 61511-1.

Part 3: Guidance for the determination of the required SIL.

Although the standard is specific for the process industry, there are still some situations where the end user must use the generic standard, IEC 61508. This is when:

- The SIS technology is new, having no proven-in-use documentation.
- The proven technology is used in new not intended application areas
- The safety instrumented function (SIF) is assigned SIL4 requirements.
- Full variability language is used when programming the software technology.

Due to these situations, qualification of SIS technology must follow the requirements presented in IEC 61508.

3.3.3 OLF 070

OLF 070 (2004) is a guideline developed by the Norwegian Oil Association (OLF), intended for the Norwegian petroleum industry. The aim of OLF 070 is to provide the industry a guideline of how IEC 61508 and IEC 61511 should be used on the Norwegian continental shelf, and to ensure that the requirements made by the Norwegian Petroleum Safety Authority (PSA) are satisfied[3].

[3] For additional information, see: http://www.itk.ntnu.no/sil/

3.4 Supplementary Qualification Documents

In addition to the documents above, several supplementary documents are used through the qualification. These documents ensure that the technology is able to meet specified functional requirements and reliability targets in design and operation. Examples of such standards is ISO 13628, ISO 20815 and IEC 60300-3-4.

3.4.1 ISO 13628

The international standard ISO 13628 (2006) "Petroleum and natural gas industries - Design and operation of subsea production systems" is the main standard where requirements and overall recommendations for design and operation of SPS are provided. The standard is currently divided into eleven parts, but is continually expanded as new specific subsea equipment is standardized. The first part covers general requirements and recommendations, while the remaining parts concern more specific subsea equipment and systems, such as subsea umbilicals and subsea production control systems. The different parts of the standard are regularly updated and replaced, as new technology within a product group is developed and proven.

The standard shall be used to obtain information in design, fabrication, testing, installation and operation of the specific subsea equipment.

Part 1: General requirements and recommendations

Part 2: Unbonded flexible pipe systems for subsea and marine applications

Part 3: Through flowline (TFL) systems

Part 4: Subsea wellhead and tree equipment

Part 5: Subsea umbilicals

Part 6: Subsea production control systems

Part 7: Completion/workover riser systems

Part 8: Remotely Operated Vehicle (ROV) interfaces on SPS

Part 9: Remotely Operated Tools (ROT) intervention systems

Part 10: Specification for bonded flexible pipe

Part 11: Flexible pipe systems for subsea and marine applications

Part 15: Subsea structures and manifolds

In addition, several parts are under preparation (part 12,14, 16 and 17, stated in part 15)

3.4.2 ISO 20815

ISO 20815 (2010) is the production assurance and reliability management standard for the petroleum, petrochemical and natural gas industries. The aim of the standard is to provide processes and activities, requirements and guidelines that ensured available production for oil and gas production, processing or other similar activities. This is achieved through reliability and maintenance analysis of the equipment.

API-RP-17N (2009) may be used as guidance for implementation of ISO 20815 within a subsea project.

3.4.3 IEC 60300-3-4

IEC 60300-3-4 (2008) is the dependability management standard that provides guide to the specification of dependability requirements. The standard provides guidance on how to formulate and set reliability, maintainability and availability requirements for a system. In the oil and gas industry this standard is used by the operator and the technology supplier, which provides requirements to a new technology. In order to consider the technology as qualified, these requirements have to be met.

Chapter 4

Technology Qualification Process

The DNV-RP-203A that is presented in Section 3.1.1, provides a systematic approach to qualification of new technology. The technology qualification process that is illustrated in Figure 4.1, comprises six main steps, together with a modification stage that continually strives to improve the confidence in the technology.

Modification step deals with a modification that aims to reduce the critical failures to an acceptable level, in order to meet qualification requirements.

Each step in this process shall be sufficiently documented to arrive at the conclusion. This

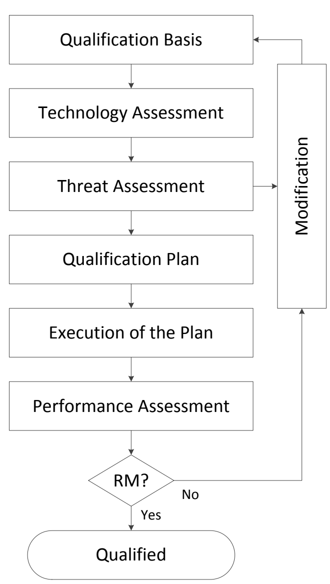

Figure 4.1: Technology qualification process modified from DNV-RP-A203. The technology is regarded as qualified, when the the requirements are met (RM).

implies that the level of detail increases with the progress of the TQP.

4.1 Technology Qualification Basis

The qualification basis is the first step in the TQP, and is considered to be the most important step, since information which forms the basis for the technology is stated here. The qualification basis defines where and how the technology is intended to be used, as well as expectations, requirements and acceptance criteria through the life cycle. DNV-RP-A203 divides this into technology- and requirement specification.

The technology specification deals with basic information related to the new technology, covering general descriptions, limitations and classification, as well as identification of relevant standards and governing documentation. The technology specification identifies to which degree the technology is new in relation to existing evidence and gives necessary expertise for developing and qualifying the technology.

The requirement specification is quantitative targets that the technology must meet in order to be qualified. Such targets are cost limits, schedules, RAM targets, SHE requirements and functional values.

In order to consider a technology as qualified, both the technology- and requirement specifications must be fulfilled through the technology qualification process.

4.2 Technology Assessment

The second step is the technology assessment which is a threefold analysis stage that determines the degree of novelty of the technology and a hazard identification. This is done through technology composition analysis, technology categorization and identification of main challenges and uncertainties. The assessment is carried out through inputs from the previous step.

Technology composition analysis is a top-down decomposition assessment where the technology is divided from system level into appropriate decomposition elements. This analysis is used to identify novelty in- and interfaces between- elements and systems to the technology.

The output from the technology composition analysis is further used in the technology cate-

Table 4.1: The level of technology novelty.

	Level of technology maturity		
Applicationa area	Proven	Limited field history	New or unproven
Known	1	2	3
Limited knowledge	2	3	4
New	3	4	4

gorization. The technology categorization is a method developed in DNV-RP-A203 to determine which, and to what extent the system level or separate elements of a technology are novel. The method is illustrated in Table 4.1, where the novelty is based both on the novelty of the technology itself, and what extent the technology is applied. The following categories are used:

1. No new technology uncertainties (proven technology).
2. New technology uncertainties.
3. New technology challenges.
4. Demanding new technical challenges.

Technology within category 1 is already proven. Previous qualifications are used to document the evidence. Technology within category 2, 3 and 4 are categorized as new technology with associated uncertainty. These technologies need to reduce the uncertainty through further steps in the TQP, before it may be considered as qualified technology.

Another novelty assessment is obtained by the TRL approach, which is described in Section 3.1.3. Although both TRL and technology categorization indicates novelty of a technology, it is important to emphasize that TRL is a complementary method, and not an alternative. This is because TRL indicates technology development stage, while technology categorization describes to what degree the technology needs to be qualified.

Identification of main challenges and uncertainties is the last analysis in the technology assessment. This analysis provides increased understanding of the unproved technology, through hazard identification (HAZID).

Table 4.2: Failure mode frequency categories.

Catrgory	Frequency Class	Description
A	Incredible	occurs once per 10 000 years or more seldom
B	Very unlikely	occurs once per 1 000 - 10 000 years
C	Unlikely	occurs once per 100 - 1 000 years
D	Occational	occurs once per 10 - 100 years
E	Probable	occurs once per 1 - 10 years
F	Frequent	occurs more often than ones per year

4.3 Treat Assessment

All new technology identified in the technology assessment shall be followed-up by a threat assessment. This step deals with identification of failure modes and failure mechanism, where associated risk is assessed and assigned criticality. This is carried out by expert judgment, through information gathered from the technology qualification basis. The assessment should identify all possible failure modes and mechanisms that can occur through the life of the technology. Several methods are designed to carry out this assessment, but the most common is Failure mode, effect and criticality analysis (FMECA) described in IEC 60812 (2006) "Analysis techniques for system reliability - procedure for failure mode and effects analysis (FMEA)". FMECA is a systematic method to use, but considers only one failure mode at a time which excludes combination of failures.

Frequency of failure is assigned in order to estimate frequency to each failure mode. These estimates shall be based on quantitative evidence provided from reliability data bases, test result or other approved sources. In cases where estimates are lacking, conservative estimates shall be assigned by expert judgment. The specified frequency classes are then assigned according to the frequency value. An example of such classes is show in Table 4.2, where every class deals with a frequency interval.

In the same way, the consequence of failure is identified for each failure mode. This identification is based on expert judgment where the severity level is assigned to the consequence to the failure mode. The consequence class must be chosen to suit the failure modes. An example of consequence categories is illustrated in Table 4.3. Each failure mode is categorized as strictly as possible, where the highest level of label is assigned where one or more of the descriptions fits.

Table 4.3: Failure mode consequence categories.

Category	Label	Description			
		Human Effect	Environment Effect	Component/ System Effect	Production Effect-System Level
1	Very minor	No or superficial injuries	Insignificant pollution	No function loss	Zero Production loss
2	Minor	Minor injuries, involving no loss time	Minor pollution with no impact	Loss of redundancy	Minor to zero production loss
3	Moderate	Injury involving some lost time	Moderate pollutions. Release above reportable limit or minor impact	Minor component breakdown/loss of minor functionality	Loss of a percentage of production for a short periode
4	Major	Serious injuries, less than 2 month absence	Large pollution. Significant impact, some remedation required	Loss of components major functionality	Loss of some precentage of production for a long period
5	Catastrophic	People- Fatality, serious injuries, invalidity, absence >60d	Very large pollution. Serious impact, significant remediation required	Total loss of components function	Complete loss of production for a long periode

At the end of the threat assessment, the frequency- and consequence- of failure are combined in a suitable risk matrix, illustrated in Table 4.2. The criticality to the specific failure mode are identified as Low- ((L) indicates acceptable risk), Medium- ((M) indicates unacceptable risk, ALARP-region) or High- risk ((H) indicates unacceptable risk). Failure modes with medium- and high- risk are considered as critical and unacceptable. These failure modes shall further be covered by a technology qualification plan.

4.4 Technology Qualification Plan

A technology qualification plan is developed to manage unacceptable failure modes identified in the threat assessment. The plan shall provide activities that shall obtain reliable evidence and meet requirements stated in the technology qualification basis. The activities shall first of all seek to reduce the failure modes with highest uncertainties. In order to execute the prioritized reduction in a good manner, a milestone plan should be developed. A milestone plan provides significant value to the qualification scheduling, since it determines whether or not

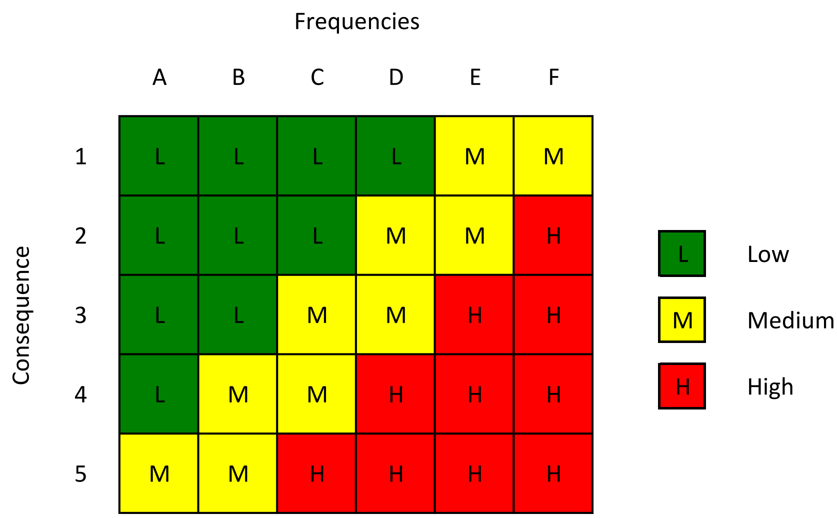

Figure 4.2: Risk matrix of the different failure modes.

the qualification is on schedule, through managing of various activities.

In order to ensure that every activity reaches sufficient evidence and requirements one or several qualification methods are used. How many and which qualification method that is suitable depends mainly on the characteristics of the failure mode, or the requirements stated in the technology qualification basis. For example will quantitative requirement call for a quantitative qualification method. The qualification method may be numerical or analytical analyses, experiments, testing, empirically justified trough previous experience or similar methods which are intended to build confidence. The qualification methods should in the same way as the failure mode cover the entire life of the technology. In cases which deals with technology with high cost frame multiple qualification method should be used, since this will strengthen the qualification evidence.

4.5 Execution of the Plan

After successfully developing a technology qualification plan, this may be executed and evidence provided through experience, analysis and tests. This step is the most time and cost consuming in the technology qualification process, indicating the importance of well-chosen and planned activities in the technology qualification plan.

Every activity with associated methods is carried out, where generated data is gathered, documented and organized in appropriate means, ensure traceability through the technology qualification process. The quality of the collected data should be evaluated during the data collection, ensuring reliable data.

In cases where undetected failure modes are detected during the execution, this shall be documented and evaluated, and given necessary actions.

4.6 Performance Assessment

The last step in the technology qualification process is the performance assessment. This assessment is intended to conclude whether or not a new technology may be regarded as proven. A proven technology shall confirm that both risk and uncertainty is reduced to an acceptable level through the life cycle, and where requirements from the technology qualification basis is met. In cases where technology does not meet stated requirements, further qualification activities can be identified. Such activities may be enhanced inspection, maintenance or other repair strategies. If the technology still does not meet requirements after the further activities, the technology qualification is considered as failed.

Chapter 5

TQP in Major Subsea Project

The willingness to develop and adopt new technologies on the Norwegian continental shelf has been one of the driving forces behind the strong international position to the Norwegian oil and gas industry. This is a result of good interactions between Norwegian oil operators, technology suppliers and research environments (Hansen et al., 2011), concerning safe and reliable solutions. This is achieved by qualifying the technology.

5.1 Valid Guidelines

Development of subsea technology is mainly initiated by oil operators or technology suppliers. The oil operators, performing oil and gas activities, need solutions for their activities. The technology suppliers frequently provide solutions for these activities and can also develop and offer new technology. When the supplier provides technology to oil operators, the operator requires that the supplier qualifies the technology using the qualification guideline provided by the operator. This is due to the fact that the operator is regarded as the responsible user, from the time the technology is being applied. When the suppliers develop technology for own purpose, no specific end user is identified, and the technology is qualified by own guidelines.

Two widely known oil operator and technology suppliers in Norway are Statoil and Aker Solutions respectively. Their business-specific documents are presented in Chapter 3. The extent of these documents varies, but a common feature is that they are based on the DNV qualifica-

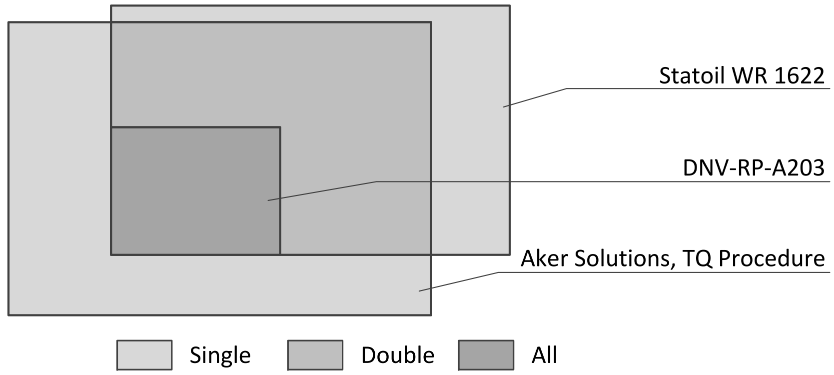

Figure 5.1: Coverage rate between selected documents. The size of the squares represents the scope of each document.

tion document, DNV-RP-A203[1]. Figure 5.1 indicates the extent and interactions between Aker Solutions procedure in relation to Statoil's procedure and DNV-RP-A203. The figure shows that the qualification procedures of both Aker Solutions and Statoil partially cover DNV-RP-A203, but in slightly different ways. Both procedures adopt, modify and extend the content of DNV-RP-A203, but in a way that it fits their business model. The technical part is similar, the administrative part is different. The figure also shows that the extent of Aker Solutions procedures, are somewhat larger than Statoil's WR 1622. This is due to the qualification procedures to Aker Solutions serves as a bridging document between DNV-RP-A203 and the client document WR 1622. This is also due to the fact that Aker Solutions as a supplier to Statoil, qualifies equipment by the technical part of the Statoil qualification guideline, and the administrative part of their own qualification guideline. Such an implementation is in accordance with the requirements of the operator. Consequently, Aker Solutions must modify and customize their own procedure when technology developed for other clients than Statoil shall be qualified.

The challenge of qualifying technology through these guidelines is that the documents are based on a previous version of DNV-RP-A203 from 2001, which is somewhat unsystematic. The latest version of DNV-RP-A203 was released summer 2011, and was developed with the intention to be more user friendly[2]. By implementing the 2011 version of DNV-RP-A203 into the Aker Solutions and Statoil documents, will provide better qualification guidance.

[1] 2001 version of the DNV-RP-A203

[2] Chapter 6 presents a case study based on this new edition.

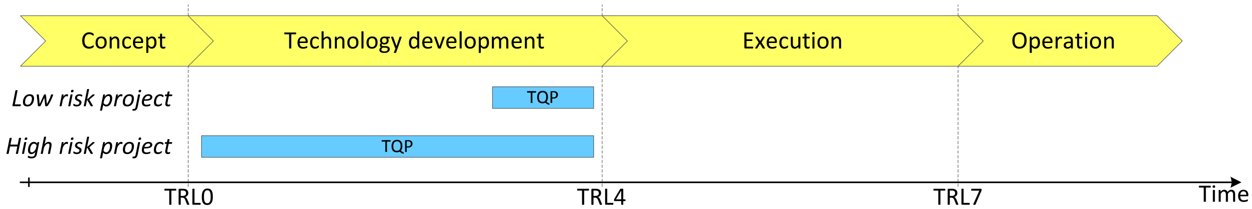

Figure 5.2: TQP in low and high risk projects.

5.2 Strategic Implementation of TQP in Projects

Implementation of TQP is dependent on the type of project. In the next section, different implementation strategies is discussed, in relation to some project types.

5.2.1 TQP in Low and High Risky Projects

Qualification and development are two terms that are closely related. During technology development, technology considered as new, needs to be qualified prior to implementation. This leads to the TQP session always is executed near the end of a technology development. The length and the starting point of the TQP however, is dependent on the type of the project.

Project types can roughly be divided into two, low risk projects and high risk projects. This is illustrated in figure 5.2. Low risk projects are recognized as projects with sufficient time, such as a pilot project where technology is developing without any specific end-user. In such projects, the technology is developed to a certain level prior to initiating the qualification program. This affects the project's duration, since development and qualification may be carried out in parallel towards the end. Due to long development it increases the likelihood of a successful qualification. The opposite is high risk project, which is recognized as a project with short duration. Reduced time consumption increases the efficiency of the project implementation. Development and TQP are conducted more or less in parallel all the time. Short horizon increase the likelihood of inadequate qualification.

Another disadvantages with short horizon is cost. In addition to the need of parallel processes, the activities within the processes should be performed more efficiently. In order to save time, these activities are run in parallel. Such a parallelization may lead to purchase of equipment prior to the end of the qualification. Such a purchase is only based on analytical qualification, where qualification through tests is lacking. This may be a risky decision, since the

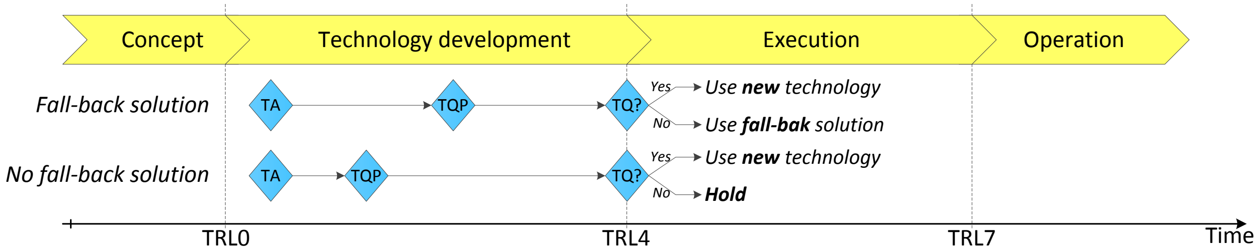

Figure 5.3: TQP in fall-back and non fall-back projects.

qualification program may require a modification prior to qualified equipment. In such cases, new equipment must be purchased, which implies that new costs are incurred.

This may be a risky decision, since the qualification program may require a modification of the purchased equipment. Ultimately, new equipment may be repurchased, forcing cost to be increased.

5.2.2 TQP in Delivery Projects

Delivery projects are recognized as projects where a delivery will take place within the time frame of the project. The specific delivery can be considered as a technology that is developed for another party. An example, is the relationship between Aker Solutions and Statoil, where Aker Solutions develops technology for Statoil. A delivery is expected to happen when the technology development is complete. If the technology has reached minimum TRL4, this indicates that the technology is qualified[3].

For a specific delivery, it is important to provide the required product within a time frame. For that reason, a fall-back solution is often required as back-up, should the qualification fail. This will increase the ability to deliver on time. In lack of fall-back solution, the technology is fully dependent on successful outcome of the qualification. If the qualification fails, no solution is available

The implementation strategy of the TQP, is dependent on weather a fall-back solution exists or not. This is due to the criticality of inadequate qualification, when fall-back solutions do not exist. As illustrated in Figure 5.3, the TQP have to start in an earlier stage for no fall-back solution, than when a fall-back solution exists.

[3]TQ?=Is the technology qualified?(DG).

When fall-back solution exists, the delivery is not fully depend on the result of the qualification. Therefore, the TQP should starts at the most optimal timing, in relation to time, cost and resources. For a non fall-back solution, no backup solutions exists, an the delivery is fully dependent on successfully outputs from the TQP. The TQP for non fall-back solutions should therefore start as early as possible in the technology development, to ensure that the technology will satisfy the qualification requirements.

Chapter 6

Case Study

This chapter presents a case study where a relevant subsea system is chosen to illustrate the TQP, described in the 2011 version of DNV-RP-A203. The chosen system is part of the Åsgard Subsea Compression Project (ÅSCP) which is a pioneering technology development in SPS. The Åsgard Subsea Compression Project was initiated by Statoil to maintain a stable production flow from the Midgard and Mikkel reservoirs. The engineering contractor and provider of technology is Aker Solutions, that develop the subsea compression system based on experience from the Ormen Lange Pilot project.

The compression system has two identical compression trains, which operate mainly in parallel. Each train is divided into several physical modules, including an passive inlet cooler module. The inlet cooler module consists of jumpers, valves, instrumentations, module frame, module pipes and inlet cooler unit. The inlet cooler unit is further selected for this case study.

The case study is conducted in collaboration with the technology supplier, where information is gathered through meetings with responsible engineers. Due to confidential material, certain details are left out or anonymized.

6.1 Description of the Inlet Cooler Unit

The inlet cooler unit has two functions, continusly cooling down the well stream and on an intermittent varies serving as anti-surge cooler for the compressor. The cooler is passive and heat is transferred to the surrounding seawater. The primary function and with the highest cooling

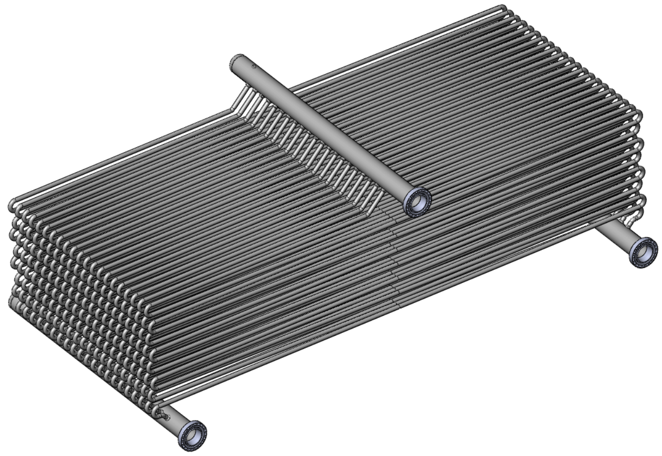

Figure 6.1: A simplified illustration of the inlet cooler unit.

duty is when the compressor runs in recycle when it protects the machine from overheating. This is the most critical operation phase, applicable to the start-up, shut-down and low production phases. The secondary function applies during normal operation, ensuring that the inlet multiphase flow is sufficiently cooled, thus increasing the compressor efficiency.

6.2 Technology Qualification Process

The ÅSCP is categorized as a delivery project where Aker Solutions is supposed to deliver the physical compression system within 2014 (Hansen et al., 2011). Due to the short deadline, the technology qualification process is carried out in parallel with the technology development throughout the entire project. As described in Chapter 5, this implies an additional high cost and uncertainty to the project, but the time consumption is reduced. In addition, the project is totally dependent on a successful outcome, due lack of fall-back solutions. However, expert judgment considers the project to be feasible, and the economic risk as low.

The expert team in this case study has both wide and narrow experience, but key players such as participation from manufacturer and operator are lacking. Since this is only a case study, it is judged acceptable. The team member's expertise is identified in Table 6.1.

A theoretical description of the qualification procedure is presented in Chapter 4. The process flowis visualised in Figure 4.1. The modification loop is used in cases of insufficient qualification.

Table 6.1: Qualification team.

Personnel	Subject	Responsibility	Company
Participant 1	TQP enginering	TQP follow up	Aker Solutions, Subsea
Participant 2	Project Engineer	Design Inlet Cooler	Aker Solutions, Subsea
Participant 3	RAMS enginering	NA	Aker Solutions, Subsea
Eirik Horpestad	Student	Facilitator	NTNU, IPK

6.2.1 Qualification Basis

The purpose for the qualification basis is to present the requirements to the inlet cooler unit.

Technology Specification

One of the challenges during operation of the inlet cooler unit is the risk of hydrate formation. Hydrate formation is like ice and is hydrocarbon gas and water formed at high pressure and low temperature, higher than normal freezing point for water. During operation, the multiphase well stream is cooled, and the hydrate condition may be reached inside the cooler. The design of the inlet cooler unit must therefore deal with hydrate control. By mixing mono-ethylene glycol (MEG) into the process stream the freezing point will be reduced, and the hydrate formation prevented. The design philosophy of the inlet cooler unit is thus to guarantee that the liquid flow remains mixed with MEG, and ensures that the mix is optimally distributed in all the cooling pipes.

The design philosophy states that no fall-back solution exists, and the inlet cooler unit shall be built with completely new design. The feasibility of the project as whole is thus partially[1] dependent on a successful outcome of the qualification to the inlet cooler unit. Expert judgment considers the associated risk of insufficient qualification to be low.

A simplified arrangement of the inlet cooler unit is illustrated in Figure 6.1. The figure shows a passive heat exchanger which primarily consists of:

- A 16" Inlet header (upper) which distributes the fluid to the cooling pipes.
- 42 x 3" 90,4 meter cooling pipes which cool down the fluid.
- 2 x 16" Discharge headers (lower) which collect the fluid from the cooling pipes.

[1] Also depends on other modules and devices with similar assessment.

Table 6.2: Functional requirements for inlet cooler unit.

Parameters	Functional Requirements	
Design life	25	*years*
Design Water Depth	240 - 300	*m*
Max. internal design pressure	220	*bar*
Min. internal design pressure	0	*bar*
Max. internal fluid temperature	110	$C°$
Environmetal temerature	7	$C°$

- Two inlet divides (confidential).
- Protection system (anodes and coating).
- Mechanical supports (pipe support and cooler unit structure).

Functional Requirements

The governing requirements for successful qualification of the ÅSCP are stated in the "Functional design requirements - Åsgard Subsea Compression Project", presented by Statoil. The document presents qualitative and quantitative statements such as functional requirements, contractually parameters and limitations for the ÅSCP, including the inlet cooler unit. These factors are mainly identified as performance, installability, reliability, intervention, availability targets and similar. Two vital qualitative requirements for the inlet cooler unit are described as:

- Liquid and gas flow mal-distribution should be avoided in the multiphase cooler during all operating scenarios including turn-down, and this must be verified during the engineering phase.
- Equal distribution of liquid from the cooler inlet header into the separate cooler pipes shall be secured and documented for the selected cooler design.

Table 6.2 presents examples of some selected quantitative requirements for the inlet cooler unit. Here both general and operational requirements are present, such as the unit shall be designed for minimum 25 years of continuous service, without any needs for maintenance or replacement.

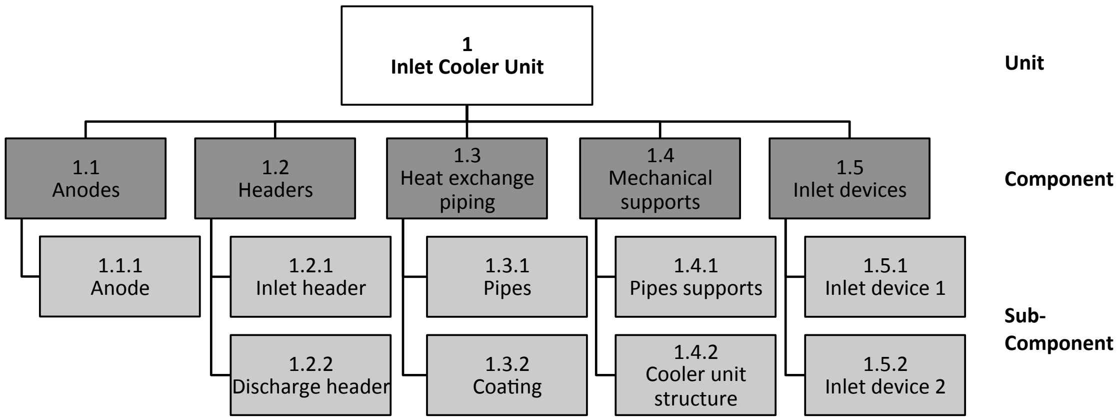

Figure 6.2: System Breakdown of the inlet cooler unit.

If the technology qualification basis is not fully met, expert judgment may determine whether to adopt it as it is or alter, in order to satisfy the project.

6.2.2 Technology Assessment

To assess which elements that involve new technology, the inlet cooler unit is broken down into manageable components and sub-components[2] through a Technology Composition Analysis. Each element is assessed and categorized in a Technology categorization, and relevant challenges identified in functional uncertainties. The complete assessment is provided in Appendix B.1, where an extract is shown in Table 6.3. The complete assessment contains some cells that are marked with an X. This is due to confidential information that has been anonymized.

Technology Composition Analysis

The Technology composition analysis is presented in Figure 6.2. The figure shows a top-down decomposition assessment that divides the inlet cooler unit into elements. Each element is identified and numerated to manage the elements through the TQP. This assignment covers the first two columns of the Technology assessment table.

[2]Both unit, component and sub-component describes the degradation level to the technology, and is further described as an element.

Table 6.3: Extract from the Technology assessment sheet.

El. ID	Element name	Functional Requirements	Challenges/Uncertainties	Classification	Current TRL	Comments
1	**Inlet cooler unit**			**4**	**1**	
1	Inlet cooler unit	Secure construct ability, assembly and inspection	Welding, inspection, dimensional control, assembly	2	5	Based on knowledge from Ormen Lange. Constructability review shall be performed.
		Cleaning and pressure testing	NA	3	5	Relatively similar design as Ormen Lange Shall be based on experience and facbrication methods for Ormen Lange.
1.1	**Anodes**			**1**	**7**	
1.1.1	Anode	Provide cathodic protection to the subsea equipment	Cathodic protection design	1	7	NORSOK M-503 Cathodic protection DNV-RP-B401 Cathodic protection design Extensive field history
1.2	**Headers**			**4**	**2**	
1.2	Headers	Secure flow rate within acceptable limits to prevent excessive pressure loss and erosion	Line sizing	1	7	NORSOK P-001 Process design Extensive field history Acoustic generated by flow specially in the header tees shall be evaluated.
		Secure material suitability for the purpose and compatibility with seawater and produced/injected fluids	Material selection	3	5	NORSOK M-650 Qualification of manufacturers of special materials Some field history topside. System integrated in Ormen Lange Pilot. 6Mo is selected to avoid HISC related concerns.
1.2.1	Inlet header	Minimise liquid distribution variance between the cooling pipes	2-phase fluid dynamics - liquid distribution	4	2	CFD simulations in Åsgard project. The selected design is based on tests and redesign.
1.2.2	Discharge header	Collect the multiphase flow from all cooling pipes and route it to the cooler discharge	Basic fluid mechanics and manifold design.	1	7	Extensive field history.
		Secure constructability	Fabrication (cutting, machining, welding)	3	5	Relatively similar design as Ormen Lange Focus on risk of distortion, risks to be assessed and managed (FMECA).

Technology Categorization

In column three relevant functional requirement is identified. This requirement represent the main purpose of the element. Some elements may have several requirements. The Technology categorization is based on these requirements. For each functional requirement two different categorization methods are carried out, the level of technology novelty and TRL.

The level of technology novelty focuses on where the uncertainty to the element is greatest. The allocation follows the classification presented in table 4.1. The allocation for a particular element is based on the highest value to the sub-element. Overall, the inlet cooler unit is classified as 4, indicating demanding new technology challenges.

The TRL indicates to what extent the functional requirement is met, and how the technology is ready to be used. The allocation is described in table 3.1. The allocation for a particular element is based on the lowest value to the sub-element. Overall, the inlet cooler unit is allocated TRL 1, indicating that the maturity of the technology is low, and extensive qualification work is required before it may be used.

Functional Uncertainties

The main challenges and uncertainties are also presented in the table. The column represents which challenge or uncertainty that may cause problem in order to reach the functional requirement. The comments column is created to indicate where the focus should be to provide sufficient qualification proof.

Summary of Technology Assessment

For technology elements that are classified as 2 or higher, or where TRL$<$4, there is a need for further qualification. Table 6.4 sums up the technology assessment, and highlights the allocations with unsatisfied values. These elements are categorized as new technology and are included in the Threat assessment, for further qualification. For the remaining elements sufficient qualifying evidence are available. Traditional engineering shall ensure that this evidence is followed.

Table 6.4: Technology assessment summary.

Element		Classification	TRL	Further qualification	Comment
1	Inlet cooler unit	**4**	**1**	Yes	Due to sub-element
1.1	Anodes	1	7	No	
1.1.1	Anode	1	7	No	
1.2	Headers	**4**	**2**	Yes	Due to sub-element
1.2.1	Inlet header	**4**	**2**	Yes	TCl[a]> 1, TRL≤ 3
1.2.2	Discharge header	**3**	5	Yes	TCl> 1,
1.3	Heat exchange piping	**3**	**3**	Yes	Due to sub-element
1.3.1	Pipes	**3**	**3**	Yes	TCl> 1, TRL≤ 3
1.3.2	Coating	**2**	5	Yes	TCl> 1,
1.4	Mechanical supports	**4**	**3**	Yes	Due to sub-element
1.4.1	Pipe supports	**4**	**3**	Yes	TCl> 1, TRL≤ 3
1.4.2	Cooler unit structure	1	7	No	
1.5	Inlet devices	**4**	**1**	Yes	Due to sub-element
1.5.1	Inlet device 1	**4**	**2**	Yes	TCl> 1, TRL≤ 3
1.5.2	Inlet device 2	**4**	**1**	Yes	TCl> 1, TRL≤ 3

[a]TCl = Technology Classification

6.2.3 Threat Assessment

For those elements in the inlet cooler unit that was categorized as new technology, relevant failure modes with associated mechanisms are identified and evaluated. A modified FMECA type methodology was selected to carry out this assessment. The method involves a spread sheet where each element on the lowest level represents a row. Each row is divided into differentcolumns that describe the element and associated failure. The complete FMECA sheet is provided in Appendix B.2, where an extract is shown in Table 6.5. The FMECA also includes the elements that strictly speaking did not need to be there, but has been included due to traditional engineering. The table contains some cells that are marked with an X. This is due to confidential information that has been anonymized.

Table 6.5: Extract from the FMECA sheet.

Description of element				Description of failure			Risk ranking				
El-(FM) ID	Element Name	Main function of element	Operational Mode	Failure mode	Failure cause or mechanism	Detection of failure	Con	Freq	Crit	Comments	Action Item
1.1.1 (a1)	Anode	Provide cathodic protection to the subsea equipment.	Normal	Corrosion	Insufficient cathodic protection (current distribution)		4	C	M	If coating is damaged local corrosion might develop quickly once started.	a. Design verification by third party using simulation. b. Include in ROV inspection instructions. c. Evaluate if HC leakage detection covers coolers.
1.2.1 (b1)	Inlet header	Secure flow rate within acceptable limits and distribute liquid to all cooling pipes.	Normal	Clogged	Hydrate formation		4	B	M	Very unlikely to occur before hydrates have clogged the cooling pipes. Occures by lack of MEG.	a. Assess sufficient amount/quality (salt content concerns) of MEG.
(b2)					Sand accumulation		1	C	L	Very unlikely to occur, since the sand will follow the gas.	
(b3)				Pipes uninhibited	Too uneven distribution		4	E	H	CFD simulations in Åsgard project. The selected design is based on tests and redesign.	a. Monitoring and operational experience. b. Liquid distribution simulation and testing.
(b4)			Intervention	HC accumulation							a. Input to operational manual.
(b5)		Mechanical integrity. Withstand operational loads.	Normal	External Leakage	Mechanical failure. Weld between small bore pipes and header possible weak points. . Vibration issues		4	D	H	NORSOK M-650 qualification of manufacturers of special material. Some field history topside. System Integrated in Ormen Lange Pilot. 6Mo is selected to avoid HISC related concerns.	a. Performed a FEM analysis. b. Evaluate the impact of slug induced loads on the inlet cooler unit.
(b6)			During construction	X	X		n/a	n/a	n/a		a. Evaluate and verify welds. b. X
1.2.2 (c1)	Discharge header	Secure flow rate within acceptable limits.	Normal	Clogged	Hydrate formation		4	B	M	Very unlikely to occur before hydrates have clogged the cooling pipes. Occures by lack of MEG. Temperature and pressure expected lower than in the inlet header.	a. Assess sufficient amount/quality (salt content concerns) of MEG.
(c2)					Sand accumulation		1	C	L	Very unlikely to occur, since the sand will follow the gas.	

Description of Element and Failure

The first two columns identify the item and associated failure mode (FM). The main function of the element introduces all functions that the element may have through the life cycle. The operational mode points out the operation phase of the function. Most of the functions are presented in normal mode, indicating that the inlet cooler unit cools down the multiphase flow. For each function and associated operational mode failure mode and failure cause/mechanism is identified through brainstorming by the expert group. The failure mode is related to the corresponding main function of the element, where the mode defines a non-fulfillment of the function. The root cause of the failure is described in the failure cause or mechanism column. The column describes which actions that produces or contributes to the failure mode. In addition, a column identifies the various possibilities for detecting a failure.

Risk Ranking

Each failure to the inlet cooler unit is considered in a risk ranking. The frequency of a specific failure is estimated by the expert group assign conservation estimate. The frequencies are based on a suitable frequency categorization, presented in Table 4.2. The consequence of a failure is also identified, where the expert group studied one-by-one failure and assigned a severity level. The suitable consequence classes described in Table 4.3 was used. The risk matrix presented in Figure 4.2 combines the consequence with the frequency, and assigns a criticality to the failure.

In addition, each failure has been assigned a comment and an action item column. These provide additional information and actions that should be implemented to reduce the risk to the failure.

Summary of Threat Assessment

A summary of the failures are presented in Figure 6.3. A total of 26 failure modes was detected, where 24 was further considered, due to the categorization of new technology. A total of 5 high, 9 medium and 3 low risk elements were identified, in addition to 7 failure scenarios that was unranked. One of these seven was assessed to be high risk, but without specific consequence and frequency. The other six are intended to be inputs to the design and operation, and are

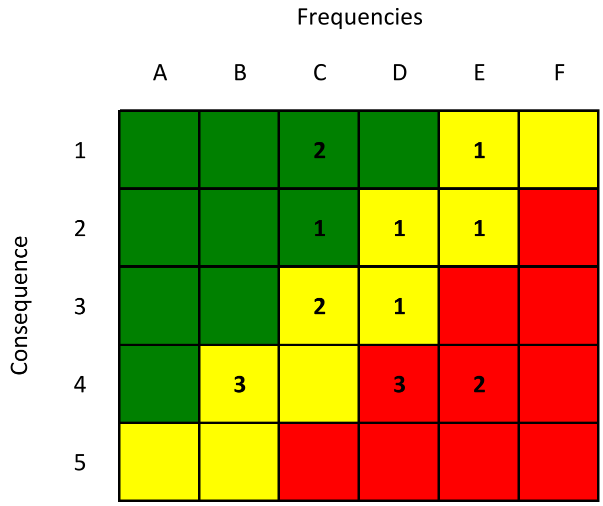

Figure 6.3: Failure scenario summary - Inlet cooler unit.

hereby considered to be low. Totally, there are 15 failure scenarios[3] with unacceptable risk[4], and considered as critical. These failures shall further be covered by the technology qualification plan. The rest of the failure scenarios, related to low risk, is concluded based on qualitative assessment by the expert group. The critical uncertainties can mainly be divided into four areas:

- Hydrate formation due to insufficient liquid distribution or where the amount of MEG in the production flow is insufficient.
- Fail to maintain cooling capacity throughout the intended lifetime.
- Rupture in welds due to vibrations.
- Combination of damaged coating and malfunction of cathodic protection can cause excessive corrosion.

6.2.4 Qualification Plan

The aim of the Qualification Plan is to develop a strategy where desired TRL and classification are met for the inlet cooler unit. This is managed by reducing the uncertainties and provided sufficient documentation to those failure modes of concern.

The technology qualification plan is organized into a milestone plan, shown in Figure 6.4, with four separated verification activities, where each activity is created to manage one or more

[3] 14 from the risk matrix and 1 unranked. Applies to: b1, b3, b5, c1, c3, d1, d2, d3, d4, d5, e1, e2, f1, h2, i1
[4] Failure with medium and high risk

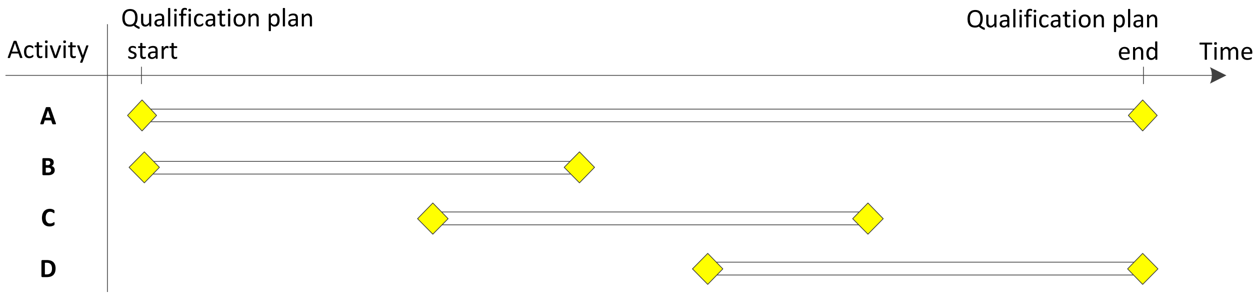

Figure 6.4: Milestone plan for execution of activities.

of the fifteen failure scenarios with critical uncertainties identified in the Threat assessment. The activities are:

A) Liquid distribution verification

B) Heat transfer capacity verification

C) Mechanical rupture of critical weld verification

D) Pipe support corrosion resistance verification

Unless these verification activities do not provide sufficient evidence, new activities shall be developed in order to secure enough evidence.

A) Liquid Distribution Verification

The activity shall prove that the final design distributes sufficient liquid properly to all cooling pipes. This includes multiple elements, mainly the Inlet header (1.2.1) and the Inlet device 1 (1.5.1) and Inlet device 2 (1.5.2). The activity covers the critical failures b1/b3/h2/i1. Several of these can cause vital feature failure, making this activity a priority, with high time consumption.

The verification activity is a twofold activity where CFD are combined and compared with results from a conservative physical test. The CFD model is validated by comparing results from the physical tests with the CFD model at low pressure. When the CFD model corresponds to the physical test, the model shall verify a high-pressure scenario. Such scenarios are impossible to verify by tests. However, the low pressure test is regarded as the most critical scenario, since the separation ability increases with reduced pressure.

The physical test is conductet by a scaled-down rig at near by ambient pressur. The flow regime in the test is expected to correspond to the flow regime in the final inlet cooler unit. By testing different liquid content and flow rates, observations can be used to predict the real operation condition.

A more detailed description of the test is not given, due to the scope of the test. Specified requirements stated in the technology basis shall be followed through the testing. The activity is considered as verified when expected distribution of different liquid content and flow rates meets stated requirements

B) Heat Transfer Capacity Verification

The objective of this activity is to ensure that Inlet Cooler unite meets the heat transfer capacity requirements. More specific, the activity provides evidence for the critical failure modes, d1/d2/d3, to the Pipe (1.3.1).

The verification is based on empirical correlation models where CFD simulations and calculations are carried out. This comprises calculation of overall heat transfer coefficient (OHTC) by both the CFD method and the applicable empirical correlation models method. More advanced full scale testing are assumed not necessary, since the current uncertainty level is considered as low as reasonably practicable. Instead, similarities to the inlet cooler unit on Ormen Lange Pilot may be used for further uncertainty reduction.

The activity is considered as verified if the results from both CFD and empirical correlation models are reasonably comparable within the process requirements.

C) Mechanical Rupture of Critical Weld Verification

The risk of mechanical rupture in critical welds is reduced through design verification using FEM analysis. The activity provides evidenc for critical failures identified in the inlet header (1.2.1), discharge header (1.2.2) and pipes (1.3.1), respectively b5, c3 and d4.

The FEM analysis shall provide feedback to design optimisation. Test welding shall be carried out on equipment with similar dimension, where x-ray technology will evaluated and verify the weld method. A verified weld will withstand mechanical failures and vibrations.

D) Pipe Support Corrosion Resistance Verification

The aim of the last verification activity is to ensure that the boundary between the pipes and pipe support is not exposed to excessive corrosion. The activity provides evidence for the critical failure f1 in the pipe supports (1.4.1).

The verification activity is a twofold activity, where the first evaluates the coverage to the cathodic protection system. This individual verification shall be done using established computer modelling and simulation tools. The second activity evaluates the potential for excessively high temperatures in the boundary between the pipes and pipe support. The verification is based on participation of specialists from relevant discipline.

The total activity is verified if the cathodic protection system covers sufficiently, and no high temperature in the boundary is found. In such cases the uncertainties is reduced due to the local corrosion is ruled out.

Verification of the remaining critical failures

In addition to the critical failures that are covered by the verification activities, four failures are not directly covered. These applies c1, d5, e1 and e2.

For the failures c1 and d5, no directly activities will be provided to avoid hydrate formation. As described in the technology assessment, to secure the flow rate in the pipes or collecting the flow from the pipes are well known technology, A hydrate formation will only occur when the inlet header fails to distribution sufficient. Verification of activity A will thus ensures that failure c1 and d5 is also verified.

Failures e1 and e2 deals with coating of the inlet cooler unit. These failure issues is managed by following TR0042 (Surface preparation and protective coating) and NORSOK M-501 (Surface preparation and protective coating). Additional experience should be transferred from Ormen Lange.

6.2.5 Execution of the Plan

All the verification activities identified in the qualification plan are carried out in the execution of the plan. The starting point and the length of each activity follow the milestone plan, illustrated in Figure 6.4.

Throughout the execution of the plan, the documentation of the qualification is essential to ensure traceability and evidence to the technology. The execution of an activity shall allways follow stated requirements.

6.2.6 Performance Assessment

In the performance assessment, the documented qualification evidence, obtained trough the execution of the plan, shall be compared with the technology- and requirement specifications stated in the technology qualification basis.

In this case study, real qualification evidence were difficult to obtain so no qualification conclusions are drawn. If qualification evidence had been available, these would have been analyzed and compared with the governing document "Functional design requirements - Åsgard Subsea Compression Project", presented by Statoil. The technology would have been considered as qualified when the qualification evidence meets all requirements. In cases where the technology does not meet the requirement, a modification loop could be used for trying to meet the requirements.

Projects with higher extent addition parameters may be examined to ensure that the technology meets all requirements. One of these parameters may be availability. In the Åsgard project, only availability requirements on an general level are stated, and not on sub-levels. This is due to the availability of sub-levels are rarely of interest, as it only represent a fraction of the total availability. The total availability is based on the availability of all sub-level. Chapter 7 provides availability measure of the inlet cooler unit.

After successful completion of the qualification, a qualification report shall be developed. This document shall provide evidence of the qualification, based on the documentation gathered through the TQP. The document shall be preceded by a summary of the qualification, where responsible manager provides approval.

Chapter 7

RAM model

A production assurance analysis provides valuable insight about the operational performance to all industries within production, processing and transportation (ISO 20815, 2010). This can subsequently be used to estimate income and to determine the profitability. Another, and widely used name for this analysis is RAM analysis.

A RAM analysis is a network study, where available equipment, production capability, and maintenance requirements are calculated. For complex systems, such calculations may be very complicated. For this reason appropriate software tools have been developed, such as MIRIAM Regina that is commonly used in the Norwegian oil and gas industry. MIRIAM Regina is developed in close cooperation with Norwegian oil companies (Statoil), and is used to verify development options for the Norwegian continental shelf. The calculations in MIRIAM Regina are based on a logic network where probability distributions are used as input to simulations in order to estimate the operational performance. The logic network must be modulated in such a way that it represents a physical system.

MIRIAM Regina is used to estimate the technical availability of the Inlet Cooler Unit in this case study. The estimated values presented in this chapter are not directly used as inputs to the performance assessment. This is because there is not stated any specific technical availability requirements for sub-system[1], only for the system as a whole[2]. The inlet cooler RAM model presented here can further be used as input to availability calculations for the whole system.

[1]Unit, Component, Sub-Component, ect.

[2]Åsgard Subsea Compression Project (ÅSCP)

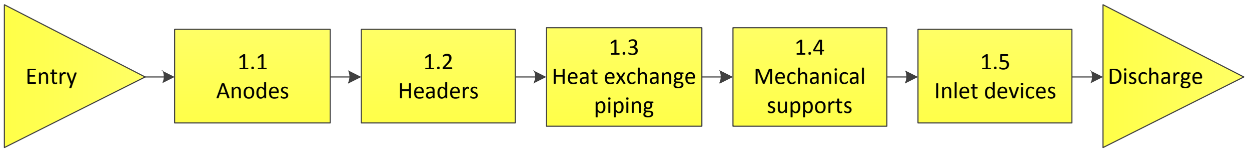

Figure 7.1: Inlet cooler unit modulated in MIRIAM Regina.

7.1 Building the model

An appropriate network for the inlet cooler unit was modeled in MIRIAM Regina. The network, which is shown in Figure 7.1, has two boundary points and five process stages. The boundary points, presented as triangles (entry and discharge), are the edges of the system. The process stages are presented as rectangles. Each process stage represent one of the five main components in Figure 6.2. For each process stage the associated failure modes are presented as items. These failure modes, associated with the sub-components, are not visualized in the network. Overall, the network can be regarded as failures modes combined in series.

A flow is used to visualize the production performance to the inlet cooler unit. The flow enters and leaves the system though the boundary points. In our context the flow rate can be seen as the availability of the system studied, where the entry boundary point is stated with 100% availability. Through the process, the technical availability is reduced by the random events initiated by the items in each process stage. The end boundary point may thus indicate a lower availability than the start, and represent the final performance of the system.

The magnitude of the reduction is determined by the failure rates of the failure modes in combination with their repair time. Due to testing, maintenance, and replacement policies[3], the failure rate in the burn-in and the wear-out periods of the bath-tube curve is ignored. The failure rates are then considered to be constant ($Z(t) = Z_C(t)$) where all failures will occur in the useful life period of the bath-tube function. Consequently, the failure rate is exponentially distributed. Required parameter for exponentially distributed is mean failure.

[3]Preventive maintenance activities in form of planned maintenance is not planned. Only condition based maintenance is continuously performed in terms of tests, measurements and observations with ROV

Table 7.1: Inlet cooler unit model data.

			Failure rates			Item restoration time								
						T_{RD}	T_M	$MTTR_S$	$MTTR_W$	T_{RU}	MDT_S	MDT_W	$MTTR_F$	
Item	**FM id**	**Failure mode**	$\frac{Failures}{10^6 Hour}$	$\frac{Failures}{Year}$	$\frac{Years}{Failure}$	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Days*	**Comments**
1.1.1 Anode														
A1	a1	Corrosion	0,15		761,04	0	120	200	277	6	206	283	30	Data based on risers
1.2.1 Inlet headers														
B1	b1, b2	Clogged	0,78		146,35	0	120	200	277	6	206	283	30	Data based on manifold
B2	b3	Pipes inhibited		$\frac{1}{10}$	10	0	120	200	277	6	206	283	30	Optimistic range
B3	b5	External leakage	0,23		496,33	0	120	200	277	6	206	283	30	Data based on manifold
1.2.2 Discharge header														
C1	c1, c2	Clogged	0,78		146,35	0	120	200	277	6	206	283	30	Data based on manifold
C2	c3	External leakage	0,23		496,33	0	120	200	277	6	206	283	30	Data based on manifold
1.3.1 Pipes														
D1	d1, d2	Scaling		$\frac{1}{10}$	10	0	120	200	277	6	206	283	30	Conservative range
D2	d3	Cools too much		$\frac{1}{1000}$	1000	0	120	200	277	6	206	283	30	Conservative range
D3	d4	External leakage	0,23		496,33	0	120	200	277	6	206	283	30	Data based on manifold
D4	d5	Clogged	0,78		146,35	0	120	200	277	6	206	283	30	Data based on manifold
1.3.2 Coating														
E1	e1, e2	Damage or deterioation	0,09		1268,39	0	120	200	277	6	206	283	30	Data based on flowlines
E2	e3	Reduced heat conductivity		$\frac{1}{100}$	100	0	120	200	277	6	206	283	30	Conservative range
1.4.1 Pipe supports														
F1	f1, f2	Fail to provide support	0,16		713,47	0	120	200	277	6	206	283	30	Data based on manifold
1.4.2 Cooler unit structure														
G1	g1	Mechanical failure		$\frac{1}{10000}$	10000	0	120	200	277	6	206	283	30	Conservative range
1.5.1 Inlet device 1														
H1	h1, h2	Fail to function		$\frac{1}{100}$	100	0	120	200	277	6	206	283	30	Conservative range
1.5.2 Inlet device 2														
I1	i1	Fail to function		$\frac{1}{100}$	100	0	120	200	277	6	206	283	30	Conservative range

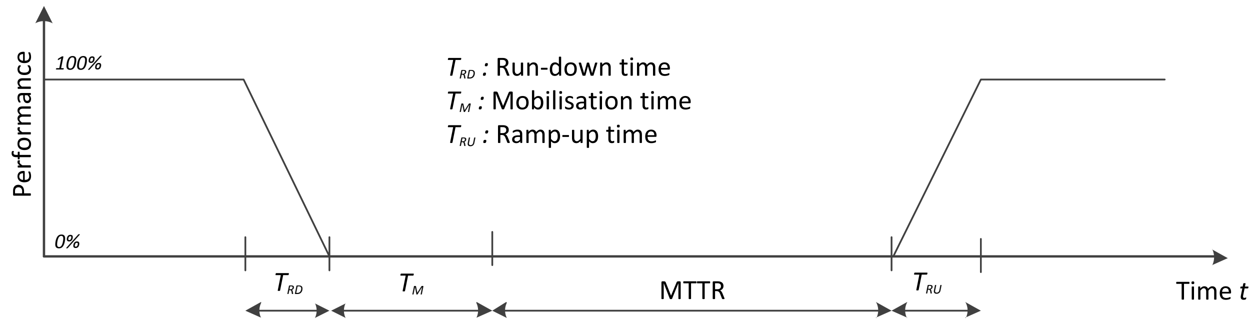

Figure 7.2: System restoration time.

The mean failure parameters are mainly obtained from the reliability database, OREDA[4]. OREDA is an extensive failure data source developed to predict the performance of systems in subsea and topside environments. The data given in OREDA describes already qualified equipment, where uncertainty is reduced and documented. The availability calculations to the inlet cooler unit are thus based on a system where the uncertainty is reduced. Since the inlet cooler unit technology is new, OREDA does not have data for identical equipment. The used data is thus obtained from similar equipment. In cases with lack of similar equipment, or where the similarities are considered too small, estimations from the FMECA work sheet are applied. The conservative end of range is used for all failure rates except B3, where the optimistic end of the frequency range is used based on expert judgment.

The applied data is presented in Table 7.1. The failure modes are obtained from the FMECA work sheet, modified and combined in order to avoid duplication of failure rates. The item column identifies the overall failure mode, while the FM id indicates which failure modes are combined. Several failure modes are omitted[5], due to no relevance to the availability calculation. The associated failure rates obtained from OREDA are shown in the first failure rate column. The second column gives the failure rate obtained from the FMECA work sheet. The final failure rate column shows a conversion of the first two columns in the way it is plotted in MIRIAM Regina. The source of the data is given in the comment column.

The item restoration duration is understood as the duration from an occurrence of the failure mode, up to the restoration of normal operation. Figure 7.2 illustrates relevant time elements that are considered for each item. Some of the time elements are dependent on seasonal varia-

[4]The OREDA (Offshore Reliability Data) is one of the most reliability data source for offshore and onshore use.
[5]non critical failures or non relevant operational mode

tions, and are marked by summer (S) and winter (W). All the item restoration duration elements are considered to be constant. In MIRIAM Regina, the mean down time (MDT) is composed[6] of run-down time (T_{RD}), mean time to repair ($MTTR$) and ramp-up time (T_{RU}). The mobilization time (T_M) is implemented separately, since each item may require different resources with different durations. The $MTTR$ is in this context regarded as the time it takes to replace a module with a spare module[7]. For this reason, all the various parameters are allocated the same values for each failure mode, as all failures requires a replaced module.

The time it takes to restore a failed item to it's original state, is denoted main time to repair failure ($MTTR_F$). The time parameter includes all aspects from transporting the module on-shore, to the specific failure on the module is fixed. In MIRIAM Regina, this is modeled by repairing individual sub-components. Due to lack of estimates, $MTTR_F$ is considered to be constant 30 days for all failures, based on expert judgment.

Due to time limitation in this assignment, it is assumed that all the failures included in the RAM model lead to 100% loss of function, and that common cause failures do not occur.

7.2 Validation and Simulation

The model has been validated through meetings with Aker Solutions reliability and cooler engineers, as well as MIRIAM Regina validated the module, with successful outcome. The simulation was specified with a 25-year perspective (219000 hours), since this is the duration Statoil has determined that the compression system shall operate. The tolerance calculation was set to 0,001. This indicates that the results are rounded to three decimals when this is required. The simulation was carried out with 1000 replications, in order to obtain reliable answers.

7.3 Results

The average technical availability (A_{sim}) for the inlet cooler unit was found to be 98,93%, giving a production unavailability of 1,07%. The overall technical availability is relatively high, due

[6] $MDT = T_{RD} + MTTR + T_{RU}$

[7] Since both compression trains can request only one spare module, will this calculation differ slightly with the reality

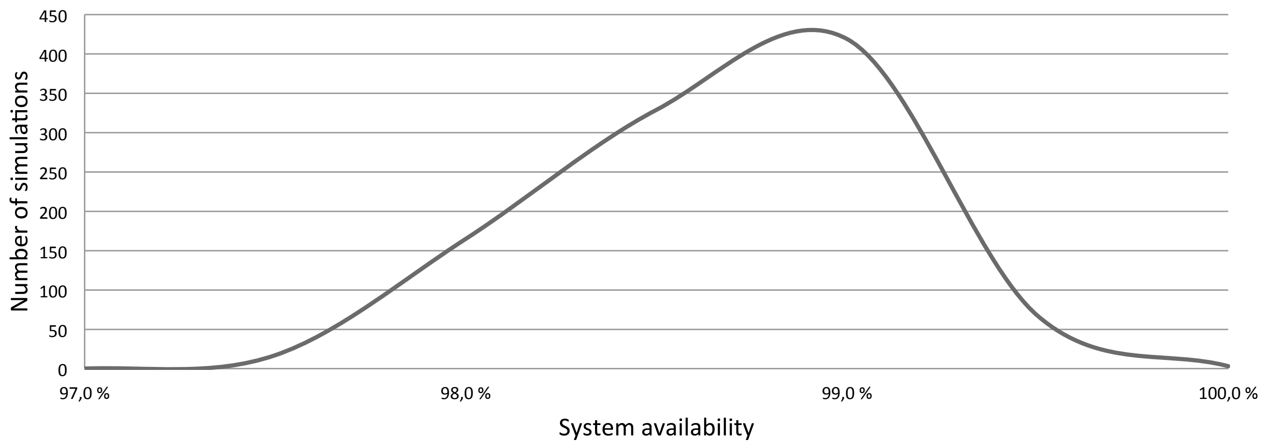

Figure 7.3: Variability distribution for 1000 simulation replications.

to effective modularization (i.e., the cooler module is separately retrievable) and effective spare philosophy. Figure 7.3 illustrates how the availability is distributed for 1000 simulation replications.

The output from the simulation is presented in Table 7.2. The simulation predicts the mobilizations frequency of the subsea processing intervention vessel (SPIV) to be 6,3 times during the 25 years of operational lifetime. This gives an annual SPIV mobilization of 0,25 times. The total average duration of repair with SPIV is found to be 1586 hours, such that the annual duration is 63,4 hours. The sub-components that represent the most frequent failures are the Inlet header (due to failure mode id B2) and the Pipes (due to failure mode id D1), where interventional intervals (T_{II}) are estimated to be 9.3 years and 9,0 years, respectively. This predominant trend may have been predicted, partly since their failure rate (number of failures per time unit) is low and due to the simplicity of the model. The estimated intervention interval for the inlet cooler unit as a whole is 4,0 years.

7.4 Performance Assessment, TQP

Specific availability requirements are, as previously mention, not stated for the inlet cooler unit. However, if a possible technical availability requirement (A_{basis}) had been stated to 98,5% in the technology basis, the simulated values to inlet cooler unit could have been used as evidence in the Performance Assessment. In this case, the inlet cooler unit would have been considered as qualified, due to $A_{basis} < A_{sim}$.

Table 7.2: Inlet cooler unit simulations.

Item	FM id	Failure mode	Observed No. used	No. used	MDT$_S$	MDT$_S$	MTTR$_S$	MTTR$_S$	T$_{II}$	A$_{sim}$	Comments
			$\frac{hours}{Cycle}$	$\frac{hours}{Year}$	$\frac{hours}{Cycle}$	$\frac{hours}{Year}$	$\frac{hours}{Cycle}$	$\frac{hours}{Year}$	*Years*	%	
1.1.1 Anode			**0,032**	**0,00128**	**356,719**	**14,269**	**240,469**	**9,619**	**781,250**		
A1	a1	Corrosion	0,032		356,719		240,469		781,250		
1.2.1 Inlet headers			**2,697**	**0,10788**	**1080,834**	**43,233**	**724,359**	**28,974**	**9,270**		
B1	b1, b2	Clogged	0,159		359,242		242,478		157,233		
B2	b3	Pipes inhibited	2,489		364,163		244,452		10,044		
B3	b5	External leakage	0,049		357,429		237,429		510,204		
1.2.2 Discharge header			**0,234**	**0,00936**	**726,896**	**29,076**	**492,029**	**19,681**	**106,838**		
C1	c1, c2	Clogged	0,170		364,802		249,935		147,059		
C2	c3	External leakage	0,064		362,094		242, 094		390,625		
1.3.1 Pipes			**2,768**	**0,11072**	**1487,798**	**59,512**	**1009,048**	**40,3622**	**9,032**		
D1	d1, d2	Scaling	2,515		382,307		262,771		9,940		
D2	d3	Cools too much	0,028		375,500		255,500		892,857		
D3	d4	External leakage	0,065		365,491		246,277		384,615		
D4	d5	Clogged	0,160		364,500		244,500		156,250		
1.3.2 Coating			**0,019**	**0,00076**	**344,121**	**13,765**	**242,474**	**9,699**	**1315,789**		
E1	e1, e2	Damage or deterioation	0,019		344,121		242,474		1315,789		
E2	e3	Reduced heat conductivity	0		0		0		-		No failure observed
1.4.1 Pipe supports			**0,038**	**0,00152**	**364,500**	**14,580**	**244,500**	**9,780**	**657,895**		
F1	f1, f2	Fail to provide support	0,038		364,500		244,500		657,895		
1.4.2 Cooler unit structure			**0**	**0**	**0**	**0**	**0**	**0**	**-**		No failure observed
G1	g1	Mechanical failure	0		0		0		-		No failure observed
1.5.1 Inlet device 1			**0,254**	**0,01016**	**363,287**	**14,531**	**243,287**	**9,731**	**98,425**		
H1	h1, h2	Fail to function	0,254		363,287		243,287		98,425		
1.5.2 Inlet device 2			**0,257**	**0,01028**	**361,434**	**14,457**	**242,650**	**9,706**	**97,276**		
I1	i1	Fail to function	0,257		361,434		242,650		97,276		
1.1 Inlet cooler unit			**6,299**	**0,25196**	**5085,589**	**203,424**	**3438,816**	**137,553**	**3,969**	**98,93**	

Chapter 8

Summary and Recommendations for Further Work

So far in this thesis, technology qualification has been described in a general term and more subsea specific term. This final chapter summarizes the various sections in the thesis and briefly introduces the obtained results based on the objectives. Finally, some recommendations of possible extension for further work is given based on the findings through this master thesis.

8.1 Summary and Conclusions

Implementing new subsea technology involves significant financial expenses and uncertainties related to the technology. The uncertainty implies a risk that should be managed and reduced to an acceptable level, prior to implementation.

In Chapter 2 of this thesis, relevant definitions related to qualification have been presented. Understanding similarities and differences of these definitions is essential for further understanding of qualification. Three different qualification methods have been introduced, analytical qualification, qualification by testing, and a combined integrated qualification.

In Chapter 3, an in-depth literature survey was documented, where relevant standards and governing documentation were presented. General qualification documents have been analyzed and the TQP from DNV-RP-A203 was briefly introduced. TQPs for two Norwegian offshore companies, the oil operator Statoil and the technology provider Aker Solutions, have been analyzed and their implementation of general qualification documents were described. Relevant standards for qualification of SIS were also introduced, along with various supplementary standards.

A more detailed description of the technology qualification process related to the TQP in DNV-RP-A203 was described in Chapter 4. This process was updated in 2011, given improved and more logical qualification flow, resulting in improved usability. The new technology qualification process is currently considered as state of the art by the oil industry. The process consists of six systematic steps that reduces uncertainty and provide evidence for the qualification. These are, technology qualification basis, technology assessment, treat assessment, technology qualification plan, execution of the plan, and performance assessment.

Governing documents in major subsea projects, have been presented in Chapter 5. In major projects, several players are often represented, and each of them has different guidelines for qualification. The chapter has discussed the relationship between these procedures, more specifically for Aker Solutions, Statoil, and the overall qualification document DNV-RP-A203. Various implementation strategies for TPQ were also presented in Chapter 5.

Further, in Chapter 6, an extensive qualification case study was performed. The aim of the case was to describe and carry out a qualification through the technology qualification process provided in DNV-RP-A203. A new subsea inlet cooler unit was chosen as the case equipment. The heat exchanger technology is well known within topside production systems, but for SPS the technology is new. Basic qualification requirements were identified in the technology qualification basis. Maturity of the technology has been analyzed in the technology assessment, and critical failure modes identified in the threat assessment. For those failure scenarios with an unacceptable risk, four verification activities were designed in the technology qualification plan. The aim of each activity was to reduce the uncertainty to the critical failures. The qualification plan was further carried out by execution of the technology qualification plan. Verification results were collected and documented. The last step concerns the performance assessment. Here, the verification values were compared with qualification requirements stated in the technology qualification basis. If the requirements had been met, then the values could have been used as evidence of qualification. Due to insufficient material, the last process step was inadequately reached.

An extension of the case study was carried out in Chapter 7. The chapter presented a production assurance analysis of the inlet cooler unit. The analysis was carried out using the simulation software MIRIAM Regina. A suitable failure mode model was applied based on a decomposition of the inlet cooler unit. The model was constructed with different parameters such as failure rates and restoration times, and was validated by representatives of Aker Solutions. The simulation was carried out with 25 years perspective, through 1000 replications. The result shows that the average technical availability (A_{sim}) for the inlet cooler unit was found to be 98,93%. Since no availability requirements exist for the inlet cooler, the chapter does not conclude whether the technical availability is sufficiently high to be qualified, or not. Instead, it indicates that availability requirements (A_{basis}) stated in the technology qualification basis, must be $A_{basis} < A_{sim}$ in order to considered the inlet cooler unit as qualified.

8.2 Discussion

The main conclusion and key finding from this master thesis were that technology qualification is an important step prior to implementation of all new technology. A qualification should be conducted with a TQP, which represents the framework for the qualification. Within the TQP a technology qualification process should be implemented. The process identifies the necessary qualification, and seeks to reduce the risks and uncertainty associated with the technology. A technology is considered as qualified when specified requirements are met, ensuring safe and more reliable technology to health and environment.

8.3 Recommendations for Further Work

For recommendations to further work, the author suggests revising the presented business-specific documents to ensure that the new and more user-friendly technology qualification process presented in the 2011 issue of DNV-RP-A203 is followed. Another recommendation is to develop a more detailed flowchart of the qualification process, to ensure better overview of the activities within each process step. In addition, qualification templates should be developed for all mandatory documents through the TQP. This provides both time and cost savings through the qualification.

Appendix A

Acronyms

CFD Computational fluid dynamics

DG Decision gate

E/E/PE Electrical/Electronic/Programmable Electronic

FEM finite element

FM Failure mode

FMA Failure mode assessment

IDC Inter discipline check

MEG Mono-ethylene glycol

PEM Project execution model

PQS Product qualification sheet

RAM Reliability, availability, maintainability

RP Recommended practice

SIL Safety integrity level

SIS Safety instrumented systems

SPS Subsea production systems

TCl Technology classification

TRL Technology readiness level

TQP Technology qualification program/procedure

ÅSCP Åsgard Subsea Compression Project

Appendix B

CASE, Technology qualification

B.1 CASE, Technology Assessment

Table B.1: Technology Assessment sheet.

El. ID	Element name	Functional Requirements	Challenges/Uncertainties	Classification	Current TRL	Comments
1	**Inlet cooler unit**			**4**	**1**	
1	Inlet cooler unit	Secure construct ability, assembly and inspection	Welding, inspection, dimensional control, assembly	2	5	Based on knowledge from Ormen Lange. Constructability review shall be performed.
		Cleaning and pressure testing	NA	3	5	Relatively similar design as Ormen Lange Shall be based on experience and facbrication methods for Ormen Lange.
1.1	**Anodes**			**1**	**7**	
1.1.1	Anode	Provide cathodic protection to the subsea equipment	Cathodic protection design	1	7	NORSOK M-503 Cathodic protection DNV-RP-B401 Cathodic protection design Extensive field history
1.2	**Headers**			**4**	**2**	
1.2	Headers	Secure flow rate within acceptable limits to prevent excessive pressure loss and erosion	Line sizing	1	7	NORSOK P-001 Process design Extensive field history Acoustic generated by flow specially in the header tees shall be evaluated.
		Secure material suitability for the purpose and compatibility with seawater and produced/injected fluids	Material selection	3	5	NORSOK M-650 Qualification of manufacturers of special materials Some field history topside. System integrated in Ormen Lange Pilot. 6Mo is selected to avoid HISC related concerns.
1.2.1	Inlet header	Minimise liquid distribution variance between the cooling pipes	2-phase fluid dynamics - liquid distribution	4	2	CFD simulations in Åsgard project. The selected design is based on tests and redesign.
1.2.2	Discharge header	Collect the multiphase flow from all cooling pipes and route it to the cooler discharge	Basic fluid mechanics and manifold design.	1	7	Extensive field history.

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Table B.1 – Continued from previous page

El. ID	Element name	Functional Requirements	Challenges/Uncertainties	Classification	Current TRL	Comments
1.2.2	Discharge header	Secure constructability	Fabrication (cutting, machining, welding)	3	5	Relatively similar design as Ormen Lange Focus on risk of distortion, risks to be assessed and managed (FMECA).
1.3	**Heat Exchange piping**			**3**	**3**	
1.3.1	Pipes	Maintain heat conductivity within the expected limits throughout the intended lifetime	Scale management - calcareous deposit and biofouling	2	4	Based on Seawater sampling and analysis for evaluation of scale potential. Not possible to test and verify in advance. Uncertainty needs to be accepted and mitigating actions initiated.
		Secure flow rate within acceptable limits to prevent excessive pressure loss and erosion	Line sizing	1	7	NORSOK P-001 Process design Extensive field history. Acoustic generated by flow, shall be evaluated
		Secure material suitability for the purpose and compatibility with seawater and produced/injected fluids	Material selection	3	5	Some field history of 6Mo use in topside equipment. NORSOK M-650 Qualification of manufacturers of special materials. System integrated in Ormen Lange Pilot. 3" Sch 80 pipes selected for Åsgard are considered more robust than Ormen Lange Pilot 1 ½" 6Mo is selected to avoid HISC related concerns.
		Secure constructability	Fabrication (cutting, machining, welding)	1	7	Extensive field history. Dimensional tolerance requires special focus.
		Secure that actual heat transfer capacity meets the requirement	Thermodynamics , natural convection, CFD	2	3	Evidence through tests CFD simulations in Åsgard project, report in IDC

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Table B.1 – Continued from previous page

El. ID	Element name	Functional Requirements	Challenges/Uncertainties	Classification	Current TRL	Comments
1.3.2	Coating	Reduce the amount of anodes needed.	Coating materials, surface preparation, application procedures and inspection	2	5	TR0042 Surface preparation and protective coating NORSOK M-501 Surface preparation and protective coating Extensive field history. Painting experience should be transferred from Ormen Lange. Both minimum and maximum coating thickness requirements.
1.4	**Mechanical support**			**4**	**3**	
1.4.1	Pipe support	Provide mechanical support to pipes securing necessary robustness and flexibility	Solid mechanics - piping	1	7	Extensive field history. FEM should verify effects of vibrations.
		Secure suitability for the purpose and compatibility with pipe material and structural material	Materials	4	3	Extensive topside experience, lacking for subsea. Main concern is corrosion between the support and the pipe.
		Secure constructability	Fabrication (cutting, machining, welding)	1	7	Extensive field history
1.4.2	Cooler unit structure	Provide mechanical support to pipe supports and facilitate transport and handling	Solid mechanics - structures	1	7	Extensive field history
1.5	**Inlet devices**			**4**	**1**	
1.5.1	Inlet device 1	X	X	4	2	CFD simulations in Åsgard project, report in IDC. X
		Secure constructability	Fabrication (cutting, machining, welding)	1	4	Relevant construction techniques are proven, however in different designs
1.5.2	Inlet device 2	X	X	4	1	CFD simulations in Åsgard project. X

B.2 CASE, Threat Assessment

Table B.2: FMECA sheet.

Description of element				Description of failure			Risk ranking			
El-(FM) ID	**Element Name**	**Main function of element**	**Operational Mode**	**Failure mode**	**Failure cause or mechanism**	**Detection of failure**	**Con**	**Freq**	**Crit**	**Comments**	**Action Item**
1.1.1 (a1)	Anode	Provide cathodic protection to the subsea equipment.	Normal	Corrosion	Insufficient cathodic protection (current distribution)	HC leakage, Pressure instrumentation, and ROV inspection.	4	C	M	If coating is damaged local corrosion might develop quickly once started.	a. Design verification by third party using simulation. b. Include in ROV inspection instructions. c. Evaluate if HC leakage detection covers coolers.
1.2.1 (b1)	Inlet header	Secure flow rate within acceptable limits and distribute liquid to all cooling pipes.	Normal	Clogged	Hydrate formation	DP/DT and liquid content measurement.	4	B	M	Very unlikely to occur before hydrates have clogged the cooling pipes. Occures by lack of MEG.	a. Assess sufficient amount/quality (salt content concerns) of MEG.
(b2)					Sand accumulation	DP measurement.	1	C	L	Very unlikely to occur, since the sand will follow the gas.	
(b3)				Pipes uninhibited	Too uneven distribution	DP/DT measurement.	4	E	H	CFD simulations in Åsgard project. The selected design is based on tests and redesign.	a. Monitoring and operational experience. b. Liquid distribution simulation and testing.
(b4)			Intervention	HC accumulation							a. Input to operational manual.
(b5)		Mechanical integrity. Withstand operational loads.	Normal	External Leakage	Mechanical failure. Weld between small bore pipes and header possible weak points. . Vibration issues	DT measurement, HC leakage detection.	4	D	H	NORSOK M-650 qualification of manufacturers of special material. Some field history topside. System Integrated in Ormen Lange Pilot. 6Mo is selected to avoid HISC related concerns.	a. Performed a FEM analysis. b. Evaluate the impact of slug induced loads on the inlet cooler unit.
(b6)			During construction	X	X	Inspection during construction.	n/a	n/a	n/a		a. Evaluate and verify welds. b. X
1.2.2 (c1)	Discharge header	Secure flow rate within acceptable limits.	Normal	Clogged	Hydrate formation	DP/DT and liquid content measurement	4	B	M	Very unlikely to occur before hydrates have clogged the cooling pipes. Occures by lack of MEG. Temperature and pressure expected lower than in the inlet header.	a. Assess sufficient amount/quality (salt content concerns) of MEG.
(c2)					Sand accumulation	DP measurement	1	C	L	Very unlikely to occur, since the sand will follow the gas.	

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Table B.2 – Continued from previous page

Description of element				Description of failure			Risk ranking				
El-(FM) ID	**Element Name**	**Main function of element**	**Operational Mode**	**Failure mode**	**Failure cause or mechanism**	**Detection of failure**	**Con**	**Freq**	**Crit**	**Comments**	**Action Item**
1.2.2 (c3)	Discharge header	Mechanical integrity. Withstand operational loads.	Normal	External Leakage	Mechanical failure. Weld between small bore pipes and header possible weak points. Vibration issues.	DP measurement, HC leakage detection.	4	D	H	NORSOK M-650 qualification of manufacturers of special material. Some field history topside. System Integrated in Ormen Lange Pilot. 6Mo is selected to avoid HISC related concerns.	a. Performed a FEM analysis. b.Evaluate the impact of slug induced loads on the inlet cooler unit.
(c4)			During construction	X	X		n/a	n/a	n/a		
1.3.1 (d1)	Pipes	Maintain heat conductivity within the expected limits throughout the intended lifetime.	Anti-surge	Scaling	Calcareous deposit and biofouling.	Instrumentation and inspection.	3	D	M	Design criterion is max 25 C at full and continuous recycle. In reality it is unlikely to run the compressor in full recycle for a long period. Based on seawater sampling and analysis for evaluation of scale potential. Not possible to test and verify in advance. Uncertainty needs to be accepted and mitigating actions initiated.	a. Assess seawater temperature monitoring to monitor cooler duty over time.
(d2)			Normal	Scaling	Calcareous deposit and biofouling.	Instrumentation and inspection.	2	D	M		a. Assess seawater temperature monitoring to monitor cooler duty over time.
(d3)				Too much cooling.	Too conservative design, high seacurrents, low seawater temperature.	Pressure and temperature instrumentation.	4	B	M	CFD simulations in Åsgard project.	
(d4)		Mechanical integrity. Withstand operational loads.	Normal	External Leakage	Vibration can potenitally damage welds.	DP measurement, HC leakage detection.	4	D	H	Some field history of 6Mo use in topside equipment. NORSOK M-650 qualification of manufacturers of special materials. System integrated in Ormen Lange Pilot. 3" Sch 80 pipes selected for Åsgard are considered more robust than Ormen Lange Pilot 1 ½". 6Mo is selected to avoid HISC related concerns.	a. Perform a FEM analysis. b. Evaluate the impact of slug induced loads on the inlet cooler unit. c. Use X-ray technology.
(d5)		Secure flow rate within acceptable limits to prevent excessive pressure loss and erosion.	Normal	Clogged	Hydrate formation.	Pressure and temperature instrumentation	4	E	H		a. Liquid distribution CFD simulation and physical tests.

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Table B.2 – Continued from previous page

Description of element				Description of failure			Risk ranking				
El-(FM) ID	**Element Name**	**Main function of element**	**Operational Mode**	**Failure mode**	**Failure cause or mechanism**	**Detection of failure**	**Con**	**Freq**	**Crit**	**Comments**	**Action Item**
1.3.2 (e1)	Coating	Reduce the amount of anodes needed.	Normal	Damage or deterioation of coating.	Vibration of piping, damage during installation.	Inspection measurement.	2	E	M	Damaged/deteriorated coating and insufficient cathodic protection is dangerous and critical. Both minimum and maximum coating thichness requirements.	
(e2)		Counteract fouling and calcarious deposits.	Normal	Damage or deterioation of coating.	Vibration of piping, damage during installation.	Temperature measurement.	1	E	M		a. Evaluate coating color to create contrast with possible fouling and calcarious deposits.
(e3)		Maintain heat conductivity within the expected limits throughout the intended lifetime.	Normal	Reduced heat conductivity.	Excessively thick layer of coating.	Temperature measurement.	2	C	L	Ensure that the maximum thickness is not excessively.	a. Ensure inspection during fabrication. b. Measure conductivity of coating.
1.4.1 (f1)	Pipe supports	Provide mechanical support to pipes securing necessary robustness and flexibility.	Normal	Fail to provide robust and flexible pipe support.	Vibration. Design errors.	HC leakage, DP instrumentation.	n/a	n/a	H	FEM analysis is recomended to verify effects from vibrations.	a. Inspection of toleranses during construction. b. Re-assess risk ranking after final design. c. Perform vibration analysis and mitigate findings.
(f2)		Secure material suitability for the purpose and compatibility with pipe material and structural material.	Normal	Too high friction towards pipes.	n/a	n/a	n/a	n/a	n/a	Extensive topside experience, lacking for subsea. Main concern is corrosion between the support and the pipe.	a. Re-assess after final design.
(f3)		Secure electrical contact between fixed pipe support points and pipe.	Normal	n/a	n/a	n/a	n/a	n/a	n/a	Extensive field history.	a. Re-assess after final design.
1.4.2 (g1)	Cooler unit structure	Provide mechanical support to pipe supports and facilitate transport and handling.	Normal	Mechanical failure.	Shock, vibration.	On secondary effects	4	A	L	Sufficient strength regarding supportability.	

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Table B.2 – Continued from previous page

Description of element				Description of failure			Risk ranking				
El-(FM) ID	**Element Name**	**Main function of element**	**Operational Mode**	**Failure mode**	**Failure cause or mechanism**	**Detection of failure**	**Con**	**Freq**	**Crit**	**Comments**	**Action Item**
1.5.1 (h1)	Inlet Device 1	X	Normal	X	Weld failure due to fatigue.	X	n/a	n/a	n/a		a. Focus in design and material selection. Account for possible fatigue. b. Re-assess after final design.
(h2)				Fail to function	Mechanical failure, design failure, wear.	None	3	C	M		a. X
1.5.2 (i1)	Inlet Device 2	X	Normal	Fail to function	Mechanicak faikure, design failure, wear.	None	3	C	M		a. X b. X

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