Risk reduction by use of passive fire protection – A study regarding implementation of new installations offshore

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Abstract

The offshore industry means high risk activities on a daily basis and with a location far away from solid ground and handling large amount of flammable substances, these are two strong reasons that make it important to keep a high level of safety onboard. One of these safety measures is passive fire protection (PFP), in this report this means the surface coating (Chartek) protecting the load bearing structure, which is used extensively in this industry. A common way of handling issues concerning the protection of load bearing structures is to apply PFP because it always has been applied and often without examining the necessity regarding the risks that apply for a given section or new installation. This thesis studies risk reduction by use of passive fire protection for new offshore installations or modifications. To investigate this issue further an installation of a new low pressure production module has been used as a base for this work. The different risk levels for the installation with PFP is compared to the same installation without PFP and this difference is quantified. The quantification is made due to the interest of presenting the PFP risk reduction in numerical figures. Depending on how to measure the risk level difference, the risk reduction differs. Risk reduction, when taking the ignition probability into consideration as well as making a cost-benefit analysis for the implementation, shows that the use of PFP is not cost effective.

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Foreword (Acknowledgement)

This paper is the result of the master thesis for obtaining a Master of Science degree in Engineering Risk Management and Safety Engineering at Lund University (LTH) and the work corresponds to 60 ECTS points. The work has been carried out at Aker Offshore Partner AS in Norway in connection with their work to design a Low Pressure Production Module as a modification to an existing oil platform.

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Christian Andersen & Christofer Lindholm

Summary

The purpose of this paper is to evaluate whether an acceptable risk level can be sustained without using passive fire protection (PFP) on new installations or modifications in the offshore industry. The purpose is also to try to quantify how much risk reduction PFP contributes with as an individual barrier i.e. with what frequency rate is PFP really needed. Further on an evaluation about how cost efficient the use of PFP really is on new installations will be investigated. The implementation of a new module on the Troll C platform will serve as investigative material for this task.

The paper will start with a short introduction to the offshore industry and why there is a need for a high safety level on a platform. It is in the industry today debated if the safety levels might be set too high. The paper will try to meet this debate and see if the conservatism is justified.

The offshore industry has a long list of regulations and principles they need to follow. These also include how risk assessments are to be performed. The regulations and principles as well as the concepts of “quantitative risk assessment”, “uncertainty”, “risk acceptance criteria”, “cost-benefit analysis” and “common assumptions” will all be explained. An understanding of these is important because they set the limitations for the whole activity offshore.

The concept of risk as well as the risk management model used in this paper will be presented in a chapter of its own. This will be followed by a theoretical background for steels load bearing abilities and how the assumed temperature that causes collapse to the observed module has been established. The different fire models as well as the PFP type *Chartek* will also be explained.

To get a step closer to the answers of the pre set questions a risk estimation must be made. The different steps and the reasoning behind them are explained and the values for the frequency and consequence analysis will also be presented.

Four scenario types that directly can threaten the structure of the module will be used to be able to present a total risk picture for the new module. Then, to be able to answer the question of how much risk reduction PFP contributes with, as an individual barrier, a quantification needs to be performed.

For a more realistic risk picture as well as to enable quantification of how much risk reduction PFP really gives fault trees and an event tree have been helpful tools in providing the needed information about how often the dangerous events are bound to happen.

The evaluation of the different scenario types show that PFP is needed with a total frequency rate of $1,3*10^{-5}$ per year to avoid a collapse of the module that can lead to 80 persons losing their lives. This is well below the set RAC of $1*10^{-4}$ per year for a type of accidental load that can threaten the main safety function, meaning that the risk level can be seen as acceptable for this accidental load. The contribution of $1,3*10^{-5}$ will lead to a total accumulated risk, for more than 51 persons losing their lives, of $5,3*10^{-5}$ for the whole platform Troll C and this is still below the risk acceptance criteria (RAC) presented before.

If just leaks are taken into consideration the risk reduction, that PFP as a single barrier contributes with, will be approximately 0,15% and if taking the ignition probability into consideration, the risk reduction will be approximately 4%. The first quantification approach is the one chosen for further evaluation and a cost-benefit analysis shows that the cost of the implementation of PFP is 26 times higher than the benefit gained and if including the estimated costs for the Troll C platform the cost-benefit relation will still be 5 times higher in favour of the cost.

Sammanfattning (Summary in Swedish)

Syftet med detta examensarbete är att utvärdera om en acceptabel risknivå kan bibehållas utan att använda passivt brandskydd på nya installationer eller modifikationer offshore. Syftet är också att försöka kvantifiera hur stor reduktionen som passivt brandskydd bidrar med som en individuell barriär. Vidare kommer en undersökning om hur kostnadseffektivt användandet av passivt brandskydd är på nya installationer. Installationen av en ny modul på Troll C plattformen kommer att användas som material för att svara på dessa frågor.

Arbetet börjar med en kort introduktion till offshore-industrin samt gå in på varför det finns ett behov av säkerhet ombord på en plattform. Det föregår en debatt om huruvida en alltför hög säkerhetsnivå hålls idag. Detta arbete vill möta denna debatt och se om denna konservatism är befogad.

Offshore-industrin har många olika lagar, rekommendationer och riktlinjer som ska följas. Dessa samt uttrycken ”kvantitative risk analys”, ”osäkerhet”, ”risk acceptans kriterier”, kostnad-nytta analys” och ”vedertagna antaganden” kommer att bli genomgångna. En förståelse för dessa är viktig då det är dessa som sätter begränsningarna för all offshore-verksamhet.

Begreppet risk samt riskhanteringsmodellen som används i arbetet presenteras i ett eget kapitel. Detta åtföljs av en teoretisk bakgrund för ståls belastningsförmåga samt hur den antagna temperaturen som orsakar kollaps för modulen har tagits fram. De olika brandmodellerna och det passiva brandskyddet *Chartek* blir också förklarade.

För att komma närmare svaren på de ovan nämnda frågorna måste en riskevaluering genomföras. Dess olika steg och resonemanget bakom dem beskrivs och värdena för frekvens- samt konsekvensanalysen presenteras även här.

Fyra olika typscenarier som direkt kan påverka modulens struktur används för att få reda på den totala riskbilden som föreligger för den nya modulen. För att sedan kunna svara på frågan om hur mycket riskreduktion som det passiva brandskyddet bidrar med som individuell barriär, genomförs en kvantifiering.

För en mer realistisk riskbild och för att möjliggöra kvantifieringen för hur stor riskreduktionen med passivt brandskydd innebär, har fel- och händelseträd använts som hjälpfulla verktyg för att få information om hur ofta farliga händelser förväntas hända.

Utvärderingen av de olika typscenarierna visar att passivt brandskydd behövs med en total frekvens på $1{,}3*10^{-5}$ per år för att undvika en kollaps som leder till att 80 personer mister sina liv. Detta värde är väl under riskacceptanskriteriet $1*10^{-4}$ per år för en typ av olyckslast som kan hota den övergripande säkerhetsfunktionen, med andra ord kan risknivån anses som acceptabel för denna olyckslast. Tillägget av $1{,}3*10^{-5}$ leder till en total ackumulerad risk, för att mer än 51 personer mister sina liv, på $5{,}3*10^{-5}$ för hela plattformen Troll C och detta är fortfarande under riskacceptanskriteriet som presenterades tidigare.

Om endast läckage tas med i beräkningarna blir riskreduktionen, för det tillägg som det passiva brandskyddet ger som en enskild barriär, ca 0,15% och tar man hänsyn till sannolikheten för antändning blir istället riskreduktionen ca 4%. Den första kvantifieringsmodellen har valts för ytterligare utvärdering och en kostnad-nytta analys visar att kostnaden för att installera passivt brandskydd är ca 26 gånger högre än den förväntade nyttan och tas även kostnaden för hela Troll C plattformen med blir kostnaden ca 5 gånger högre än den förväntade nyttan.

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1. Introduction

The purpose of this paper is to evaluate whether an acceptable risk level can be sustained without using passive fire protection (PFP), meaning the surface coating (Chartek) protecting the load bearing structure, on new installations or modifications in the offshore industry.
The purpose is also to try to quantify how much risk reduction PFP contributes with as an individual barrier i.e. with what frequency rate PFP really is needed. This will be investigated by following the different steps of a risk management model that will lead to a numerical expression of the risk reduction, i.e. the quantification of the risk reduction PFP is contributing with. Further on an evaluation about how cost efficient the use of PFP really is on new installations will be performed.

To be able to do the quantification of how much risk reduction PFP contributes with an estimation of the risk towards the new installation when PFP is not used must be made. This will be done by combining the results of the consequence analyses and frequency analyses to investigate with what frequency rate PFP would be needed.

These analyses are the result of different scenario types that are estimated to be the most representable concerning threats to the structural integrity of the new installation. The scenario types represent different segments, located in the vicinity of the new installation that contains large amounts of hydrocarbon. These scenario types are events commencing from the installation itself but also from the surroundings of the installation.

The consequence will primarily be regarding structural collapse and secondly personnel. However, the lives of the personnel will be considered in a cost-benefit discussion when the evaluation is to be made about the cost efficiency of using PFP. In this paper a new module that will be installed on the platform Troll C will serve as evaluative material of a new installation. The module will enable low pressure production and is a modification to the present platform.

1.1 Method

This paper has been made for Aker Offshore Partner AS at location in Bergen, Norway, in order to present a methodology, if possible, on how to measure the impact the implementation of PFP have compared to no PFP at all. This especially for new installations or modifications to already existing offshore platforms.

To be able to investigate the above question and the questions at issue a “real world installation” was the perfect base to stand on. The offshore platform, Troll C, is going to be modified with a module to enable low pressure oil production and this new module will function as a ground for the investigation in this report.

To present a solid base of information and to be able to present a reliable work, a lot of different aspects must be taken into consideration. At the beginning of this project the offshore industry was quite a new area for both writers of this paper. This has necessitated gathering a lot of basal information to be able to create a realistic picture of the task at hand. The gathering of information has been directed towards areas like for example:

- Rules and regulations in the Norweigan offshore industry.
- How steel and structures behave in the influence of a fire.
- Information and values about failure frequency rates in the process and offshore industry.

When doing the risk assessment, as a part of the risk management model, the task is to see what the risk level towards the module will be if no PFP is used. This means that the risk assessment will not investigate the risk contribution that the module has for the platform as a single unit. The risk assessment will on the other hand use the consequence of a possible collapse of the module as a contribution that could threaten the whole platform as a unit. To measure the risks towards the installation of the new module, a group of relevant scenario types needs to be evaluated. These scenario types constitutes of different segments where estimated and relevant leak sizes could occur. These segments are located in the immediate surroundings of the module. The potential hazards are if these leaks ignite and thereby start a fire that can threaten the module.

First a scenario type illustrating whether the production per se on the new module constitutes any danger to the module itself if anything should go wrong in the process is analysed. Since the location where the module is placed on the platform are filled with already existing production, it is estimated that some dangerous scenario types could develop from Troll C. The scenario types have been chosen considering processes in the vicinity of the module and the large amounts of hydrocarbons present here. They should represent the worst scenario types and thereby serve as a good base for the risk assessment. The expected fire load and its duration in each scenario type express the hazards for the scenario types, hazards that could cause a collapse, i.e. the consequence.

For a complete risk picture it is important to know how likely it is that a hazardous event will happen. To be able to calculate frequency rates for different outcomes of possible events, event- and fault tree analysis will be made. Every scenario type will end up in showing its own risk picture but for a total risk evaluation a summary of all the scenario types and their risk pictures will be made, showing the total risk picture that the module is exposed to.

The scenario types will be calculated without considering any PFP on the structure. With the total risk picture at hand it is possible to investigate how much risk reduction an application of PFP actually gives versus no application at all. This investigation will function as the basic method for the quantification of how much risk reduction the use of PFP gives as an individual barrier and an estimation of the costs for this will further be discussed together with a cost-benefit analysis.

Consideration will be taken for the ALARP (As Low As Reasonable Practicable) concept and other forms of risk acceptance criteria. These should have their starting point in the activity and the investment cost to determine if conservative thinking is justified.

Finally conclusions will be made which may result in recommendations to the decision makers. For a step-by-step description of the structure in this paper see section 1.5.

1.2 Purpose and goal

The purpose of this report is to evaluate if PFP always has to be applied on new installations and modules and propose recommendations if to use PFP or not.

The primary goal and the question at issue in this paper is to answer the question: Is it possible to measure the risk reduction the use of PFP gives as a single barrier and can an acceptable risk level be maintained if no PFP is applied on new installations and modules? Additional questions to be answered in this paper are: Makes PFP any essential difference considering the already high safety standard onboard offshore installations? If measurable, will the total risk reduction given by implementation of PFP be needed and will it be cost efficient?

One of the aims with the paper is to wound up with a methodology for future similar investigations of how cost efficient PFP really are for new installations or modifications to already existing offshore platforms.

1.3 Limitation

The work is based on Norwegian laws and regulations constituting the standards that are required for the offshore industry. The chosen scenario types present different hazards for the module. The focus of these hazards is directed towards the structure of the module and do not consider danger directed towards personnel which will be dealt with second handily. It is assumed that the weight distribution is even through all the steel beams so that no beam is more important than the others.

Only combustible materials (hydrocarbons) in the actual process will be taken into consideration when designing the scenario types, since these are assumed to be the greatest threat due to the great amount present. The paper only treats pool- and jet fires as possible fire events on the platform and the module. This limitation has been made because these types of fires are estimated to be the most representative to use when investigating whether PFP is necessary on the module or not. This is also because of the possibly elongated burning times compared to for instance a gas explosion.

A gas explosion or a rapid fire ball is not estimated to be any greater threat to the structural integrity of the module, because of the short duration involved in these phenomena (Pula et al, 2005). These phenomena have an average duration of 10-20 seconds and despite the powerful heat load they deliver during this time, they are not estimated to heat up the steel structure to its critical temperature. The only structural damage these phenomena could accomplish is if they wreck the steel structure apart by force. This is something that not will be looked into in this paper, because it is not estimated that the PFP will have a big influence in the protection against the force that an explosion will deliver to the structural integrity. Simplifications regarding the structural response, i.e. a collapse of the module if the steel reaches a critical temperature, have been made because the structural response is beyond the scope of the work.

To be able to quantify a possibly noticeable risk reduction by use of PFP or not, a number of scenario types involving different types of fires (jet- and pool fires), will be used to estimate whether a reduction is acceptable. Since all conceivable scenario types cannot fit in this paper, only a selection of the most representative scenario types will be used. The selected scenario types will be the ones estimated to directly threaten the module and no indirect threats like for instance escalating events will be included.

It is said that only scenario types that directly can threaten the module shall be included in this quantification, if no other barriers, active or passive (whose main purpose is to act as a barrier), are present.

Process equipment can work as a barrier but this will be disregarded to direct the focus towards the investigated barrier, the PFP. When estimating whether PFP is needed or not, it is assumed that if PFP has been applied onto the structure, the structure will always manage a possible fire load and cracks in the PFP etc. will not be considered.

1.4 Methodology in this paper

To better understand the structure of this paper and the different steps performed throughout the work, a short presentation of the different parts in this paper will follow below.

- **Chap 2.** Background information to give the reader a short introduction to the offshore industry as well as to give a short description of why a modification will be made, i.e. installing a new module on the platform.
- **Chap 3.** Presents some of the rules and regulations as well as the principles for the Norwegian offshore industry that must be regarded when performing new installations but also to see if a reduction of PFP is viable. Standards for how a risk assessment can be made will also be presented.
- **Chap 4.** A short explanation of the concept risk is explained to gain approval for the risk management model used in this paper. This model is presented, first as a whole and then in its different parts to inform the reader how the process is to be done.
- **Chap 5.** To give a theoretical background for how the load bearing abilities of the steel structure change during a fire and present the assumed critical temperature for collapse and why this temperature has been assumed and why it is used. Background information about the fire models used as well as basic information about the PFP type Chartek.
- **Chap 6.** The core in the risk management model is the risk estimation. This risk estimation includes both a frequency analysis as well as a consequence analysis. The frequency analysis in this paper is based on event- and fault trees that are presented together with the different inputs used in the trees. The consequence analysis as well as the risk acceptance criteria used are also presented here.

The first six chapters present the theoretical background that will serve as input for the remaining chapters that investigate how safe the module really is. Further investigation about if an acceptable risk level can be sustained without the use of PFP on the structure, will be performed. Also a quantification of how much risk reduction PFP gives as an individual barrier and the cost efficiency of the PFP is also investigated.

- **Chap 7.** Next the different scenario types are presented in detail. Each scenario type will have the potential of a number of different leak sizes and thereby different frequency rates. Each scenario type will also have its own consequences and these will end up in a risk picture. These scenario type specific risk pictures are then summarized to a total risk picture and risk assessment in accordance with the risk management model to see if an acceptable risk level can be sustained if no PFP is used.

- **Chap 8.** Further on an explanation of how the quantification, of how much risk reduction PFP really gives as an individual barrier, has been done and the ideas behind it will be explained. This risk reduction will be presented in numerical figures.
- **Chap 9.** Different ways of observing costs associated with safety are presented. The total frequency rate when PFP is needed is used when performing the cost-benefit analysis.
- **Chap 10.** The end of the paper will include a discussion with the answers the writers has concluded for the problem formulations. Together with personal thoughts and aspects regarding the conclusions, recommendations with regard to the theoretical models used in this paper as well as the stated limitations, are presented.

2. Background

A short introduction to the offshore industry as well as why a high safety level has to be maintained on a platform is to be clarified. But can this safety level become too high and conservative and is this conservatism always justified? The implementation of the new module will help clarify these issues at hand and this chapter will try to give these inputs to the readers.

2.1 Introduction to the offshore industry

The offshore industry is a business filled with different risks and the systems onboard must live up to certain standards and safety levels. These safety levels have to be met in order to provide a safe and efficient working place, as well as to minimize the possibility of an accident. To further increase the possibility of a safe working environment, special rules and regulations have been established that ensures that certain criteria are being met. These rules and regulations are for instance available in the NORSOK standard published by the Norwegian Technology Standards Institution (NTS). These standards cover both technical and operational safety issues. What this means is that equipment must have a certain level of reliability in order to be approved for offshore activity. It also means that personnel must perform their duties in certain ways and have a certain level of knowledge before they are allowed to work offshore.

The loads and stresses that arise due to the daily activities in an offshore environment put high demands on a durable construction, especially if some form of fire should start. A fire scenario that generates a fire load onto the construction can weaken its strength but also aggravate the situation for personnel on board. To prevent this kinds of hazards from happening the platforms are equipped with different security systems or “barriers”. These safety barriers function as protective shields against the hazards. The hazard is the hydrocarbons that are present but not dangerous until a leak has occurred. The barriers help preventing that for instance a small accident, like a minor leak in the process system, from escalating into a scenario that affects the whole platform with catastrophic consequences. The safety barriers can be both active and passive. In this paper the PFP is seen as a barrier that only protects the structure.

The loads and stresses mentioned before makes it important to take certain demands into consideration when investing in new systems. These demands are among other things the characteristics of the materials used and the different systems life-span. The strength to withstand a possible fire load and the maintenance needed to keep the system operational during the calculated life-span are also factors that need to be evaluated. Total risk elimination is hard to accomplish and to anticipate all conceivable risks that could lead to an accident is not practically viable or cost efficient. For that reason, risk reducing measures will be given priority so that an acceptable risk level can be maintained in order to let the onboard activity carry on under secure conditions.

Today’s safety barriers, when added up, withhold a rather high safety level including the barrier, PFP. But is this barrier always needed or can this barrier be ignored on some parts of a platform? This considering both that the steel structure itself has a resistance against fire loads but also the fact that most fires that occur offshore have a short duration.

The long tradition of working under high risk has forced the offshore industry to develop ways of handling risks as well as developing a high level of safety thinking, i.e. using more and more barriers. This way of thinking has lead to accepted assumptions for reduction of risks in the industry. In some scenario types these assumptions can be considered to be conservative to guarantee a high level of security, but is this conservatism always defendable? Is it defendable when observing the platform as a whole, both for its ability to preserve its structural ability in case of a fire and also from an economical point of view?

2.2 Implementation of new module on the Troll C platform

Troll C is the name of the platform observed in this paper and it is located in the Troll field in the North Sea. The field was discovered as early as in 1979 but the production did not start until the mid 90's (NPD, 2008). As the oil reserves in this area are getting depleted the main reason for implementing this new module is to be able to extract oil from the low pressure fields. This depletion makes the platforms pump up a lot of water instead of oil since the oil quantity is so low. A couple of years ago this was not an alternative because of the high costs associated with this type of production but the rising oil prices and the wish to achieve long term oil production has now made this a thinkable option (Aker Kværner AS, 2007a).

A modification with a module might sound like a small operation but this new installation has the dimensions 16,3 x 10,0 x 11,0 meters standing on beams 6,5 meters tall with the approximate total weight of 630 tonnes (see Figure 2.1, 2.2 and 2.3 below) (Grande, 2008). The total cost for this installation is approximately 500 million NOK (Grande, 2008).

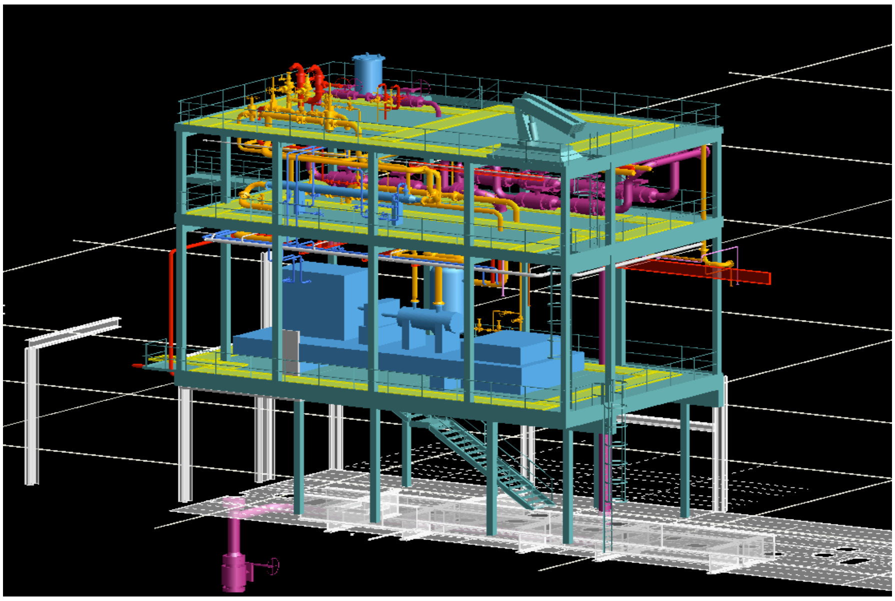

Figure 2.1 Illustration of Low Pressure Production Module (Aker Kværner AS, 2007a)

The module will be placed in the aft of the platform on its upper deck, see Figure 2.2 and 2.3 below.

Figure 2.2 Troll C platform, square marks location for the new module (Aker Kværner AS, 2007a)

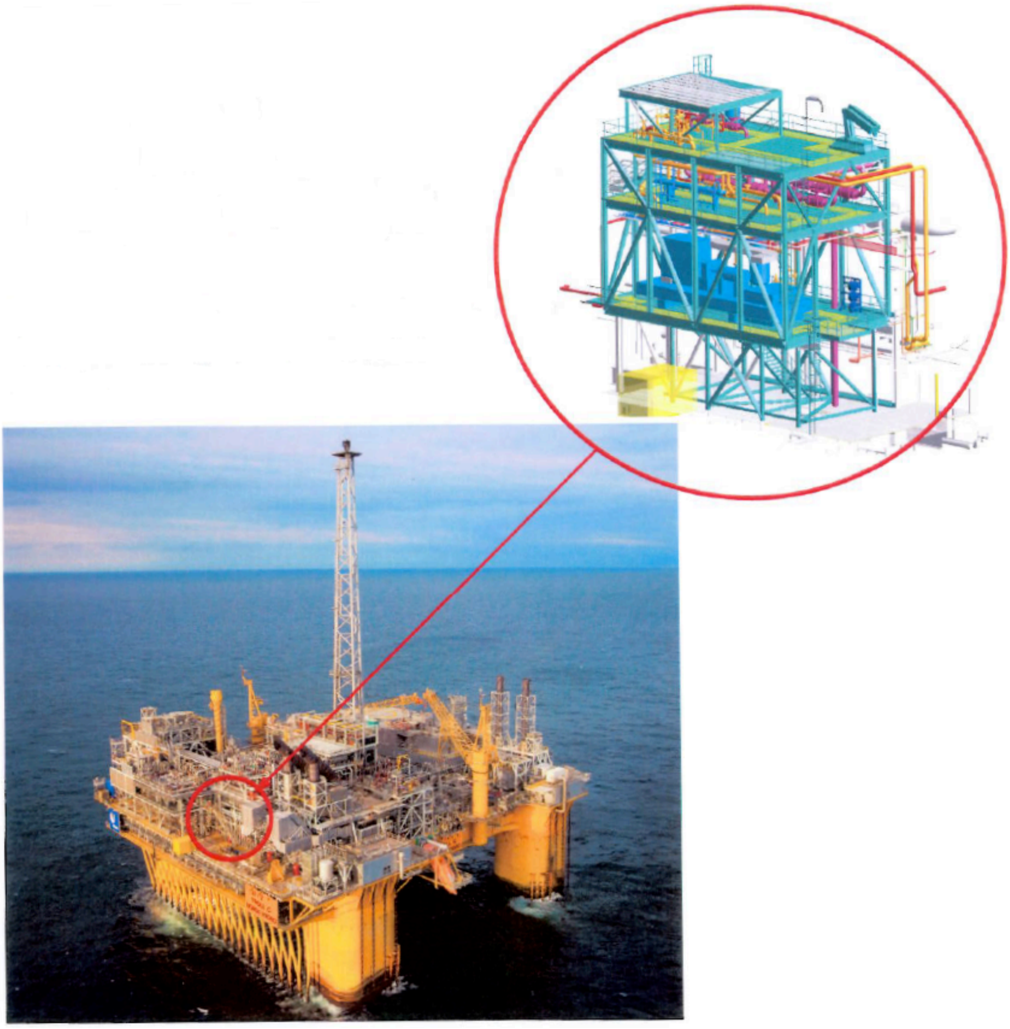

Figure 2.3 Troll C, marks location for the new module (Aker Kværner AS, 2007a)

3. Regulations and principles in Norwegian offshore industry

In this chapter the regulations and principles concerning fire protection used in the offshore industry in Norway are presented. These are the foundation for how the platforms are established, constructed and designed. Consequently there are special requirements concerning how risk assessments are to be performed and it is also here one can find what demands and possibilities there are for reducing the PFP. The concepts of “quantitative risk assessment”, “uncertainty”, “risk acceptance criteria” and “cost-benefit analysis” will be explained in this chapter. Furthermore, common assumptions when dimensioning PFP for different parts of a platform are presented. These assumptions can in some cases be a bit conservative according to the writers of this paper and a discussion will try to clarify why this is the case.

Laws, regulations, guidance and standards for the offshore industry

The offshore industry involves working in a high risk environment. Weather conditions, the location far away from land together with the dangerous products that are extracted on a platform are some of the things that can cause serious effects if not dealt with properly. To be prepared for hazardous events, rigorous safety preparations must be made. Therefore regulations, guidelines and standards have been established to better ensure a safe working environment.

The hierarchy for controlling the offshore industry is constituted by:

- Laws
- Regulations
- Guidance
- Standards

3.1 Laws

Laws like the fire and explosion law (LOV 2002-06-14 nr 20) under the area of the Petroleum supervision authority (Petroleumtilsynet) are generally about how things are decided overall and no specification is made about offshore industry.

3.2 Regulations

The establishment regulation (Innretningsforskriften) generally describes, amongst other things, how PFP are to be used and for what purpose. This regulation also describes other physical barriers like detection systems, deluge systems and so on.. The regulation states the following about PFP:

> **Passive fire protection**
>
> *Where passive fire protection is used, this should be designed so that it gives the current construction and equipment components sufficient fire resistance with consideration to load bearing properties, integrity and insulation properties during a dimensioning fire. When designing passive fire protection no account shall be taken from the cooling effects of fire fighting equipment.* (Petroleumtilsynet, 2008a)
>
> (Note: The regulation has been translated from Norwegian to English)

According to the writers of this paper the following statement about PFP should be a form of guarantee that, if PFP is used in a correct way, the construction should have sufficient fire resistance and thereby be able to handle a fire without any severe consequence. This statement is rather important for the quantification made in this paper because the attempt, with the quantification, is to measure how much protection PFP gives if used versus not used on the module.

The regulation also states that: "Accidental loads with a yearly frequency rate of more or equal to $1*10^{-4}$ should not lead to loss of the main safety function". The main safety function can for instance be prevention of accident escalation so that personnel are not located in the immediate surroundings of the accident and thereby preventing injuries. Maintaining the main bearing structure until the platform is evacuated is also a part of the main safety function. In the case of this paper the module is not a part of the main bearing structure, but the consequence for a collapse of the module could be seen to threaten the main bearing structure of Troll C.

3.3 Guidelines

Guidelines regarding the use of PFP are found in the establishment regulation (Innretningsforskriften) under guidance (Petroleumtilsynet, 2008a). It states that for decisions about dimensioning fire and sufficient fire resistance, that this must be established to meet the requirements for the main safety functions through known norms and calculation models. The guidelines are in many cases referring to standards, and the standards that are used in Norwegian offshore industry are gathered in a publication called NORSOK. Every single area of interest, from materials that should be used to safety regulations and risk analyses to name a few, are all covered here.

3.4 Standards

The standards are mostly not mandatory in their nature, meaning that they give directions to the level of, for instance fire safety, that has to be achieved but the performing, i.e. how they choose to do the safety enhancing procedures, is left to the producer/company of the platform. But it is not only the choice of materials or the number of risk analyses performed that provide a safe work environment. For this *Det Norske Veritas* (DNV) have published the ”DNV Recommended Practices” which presents recommendations for how to perform the tasks offshore in a safe way and, if followed, should lead to a safer working environment.

Below a closer description of the most relevant parts of the NORSOK standard according to this paper will be made.

3.4.1 NORSOK Standard S-001 – Technical safety

The purpose of this standard is to describe the principles and requirements for technical safety design on offshore installations were production and handling of hydrocarbons like oil and gas are taking place (NTS, 2000).

For the purpose of this paper the use of the technical safety standard will only be used considering the establishment of the new module and no consideration will be taken for other parts of Troll, regarding technical safety. The general principle for management of technical safety according to NORSOK S-001 is:

> *Technical safety management in project development and design processes comprises activities to identify risks, develop safety strategies and performance requirements for safety systems and barriers. Technical safety management shall also facilitate the design process to ensure that studies, analysis and reviews are performed in due time and properly documented with due consideration of the needs for timely input to design and procurement processes.* (NTS, 2000)
>
> *For modification projects (e.g. upgrading of existing installation/module, tie-in of satellite field), technical safety management activities adjusted to project scope and complexity shall be performed, including new analyses or updating of existing*

> *analyses for factors that are considered to be affected by the modification.* (NTS, 2000)
>
> *The individual project or installation shall perform specific hazard identification and risk evaluation process, and supplement the requirements as necessary to manage the actual risk picture.* (NTS, 2000)

As the general principle of management states, new analyses for modifications or installations shall be made. This means specifically that hazard identification and risk evaluation shall be made to update the actual risk picture. This will be done and the actual risk picture will show first of all the risk the module is exposed to. Secondly the risk picture for the platform Troll C will be shown.

This standard targets and deals with consequences of a potential scenario, especially when dealing with PFP as a barrier. The risk reduction principles and concept of NORSOK S-001 is to always give priority to the use of preventive measures/exposure barriers and inherent safe design principles. The objectives with risk reduction principles and inherent safety design are according to NORSOK S-001 to:

- *reduce potential hazards,*
- *reduce probability of unwanted events,*
- *reduce inventory and damage potential,*
- *strive for simplicity and reliability,*
- *prevent escalation, e.g. by safety barriers.*
  (NTS, 2000)

Passive fire protection

To ensure that technical safety like passive fire protection on offshore platforms is fulfilled the standard states to what extent the protection is required to fulfil a safe working environment onboard a platform.

The role of the passive fire protection according to the NORSOK standard S-001 is that it:

> *...shall ensure that relevant structures, piping and equipment components have adequate fire resistance, with regard to the load bearing properties, integrity and insulation properties during a dimensioning fire and to contribute in reducing the consequences in general.* (NTS, 2000)

When it comes to in what extent the PFP is required when used on safety systems/functions the NORSOK standard S-001 states that:

> *No specific interfaces, but the extent and requirement for passive fire protection is dependent on the design and performance of the following safety systems/functions:*
>
> - *Containment*
> - *Emergency shut down*

- *Blow down system*
- *Emergency power*
- *Fire fighting systems*
- *Escape and evacuation*
- *Structural integrity* (NTS, 2000)

The demand of the structural integrity is that the load bearing structure shall be able to keep its integrity during eventual accidental events that it has been designed to handle. This means that depending on how much damage the structure is designed to handle, some form of PFP might be needed to be able to maintain its structural integrity during accidental events like a fire.

Load bearing structures

Load bearing structures onboard the offshore platforms have specific requirements according to the S-001 standard, when it comes to withstanding a dimensioning fire:

> *Load bearing structures/important elements shall have adequate fire resistance to maintain required integrity during a dimensioning fire.* (NTS, 2000)

Adequate fire resistance for load bearing structures is not only dependent on PFP, but also on the resistant of the load bearing structure itself. This means that PFP not always is necessary if it can be shown that the load bearing structure can keep its integrity during a dimensioning fire.

When it comes to load bearing structures, the standard is clear on the subject of fire fighting equipment and that this equipment can not be taken into account when dimensioning for a sustainable integrity of the structure during a fire.

> *No account shall be taken from possible cooling effect from fire fighting equipment.* (NTS, 2000)

3.4.2 NORSOK Standard Z-013 – Risk and emergency preparedness analysis

This standard is mainly intended to provide information and check lists for personnel doing risk and emergency preparedness analyses. Another purpose of the standard is to act as a tool for planning and execution of these analyses (NTS, 2001).

The overall goal in this paper is to try to quantify how much risk reduction PFP really gives and to see if an acceptable risk level can be sustained if no PFP is used on the module. This means that the investigation concerning threats to the module will be investigated first hand and a consequence of these threats could end up threatening the whole platform Troll C. A total risk picture will be established for the module and this risk picture can affect the platform Troll C.

Quantitative risk assessment

The base for the analysis is a Quantitative Risk Assessment (QRA) divided in three parts:

- Risk analysis
- Risk assessment
- Health, safety and environment management

The risk analysis is meant to be a part of the whole activity. This means both during development and operation of the platform. This is to make sure that the analysis is a part of the decision-making process as well as being used in possible major modifications and changes of application areas (if major changes in organisation or manning level takes place) (NTS, 2001).

Risk analysis shall be carried out in connection to major modifications and serve as an integrated part of the developments of a project. This is so that the studies can be used in the decision-making process for design of safe technical solutions for the activity in question. The module is a major modification and as mentioned before the risk assessment is not used to see how much more risk the module is contributing with for the platform as a whole. The risk assessment will instead try to clarify the risk against the module, if no PFP is used, first hand. Then as a second step to try to clarify the risk against Troll C if the module collapses into the ocean. The two steps will be analysed to see if it is acceptable to exclude PFP on the module.

Uncertainty

Uncertainty is present in all different kinds of business and a certain amount of risk also comes with it. You cannot always predict what is going to happen and what consequences a possible event will cause. This makes assuring a totally risk-free environment impossible because the costs for this will at some point exceed the benefits gained. But this does not mean that high risk is acceptable. Instead a reasonable risk level must be obtained, which in some cases can be a balancing act.

The Z-013 standard states that reflection shall be made in the phases where risk acceptance criteria (RAC) are being used. This to judge the results of the QRA and the requirements may be satisfied in either of two possible ways:

- Apply more conservatism in the risk analysis.
- Make sure that RAC are satisfied with some margins.

Risk acceptance criteria

To achieve acceptable safety levels on the platform it is required that standards, specifications, procedures etc. each work for an adequate level of safety. Therefore specific risk acceptance criteria (RAC) have been set to ensure this. The definition of RAC according to NORSOK Z-013 is:

> *Criteria that are used to express a risk level that is considered tolerable for the activity in question.* (NTS, 2001)

It should be noted that RAC are used in relation to the risk analysis and express the level of risk that will be tolerable for the activity, and are the starting point for further risk reduction according to the ALARP-principle. The ALARP definition in NORSOK Z-013 is:

> *ALARP expresses that the risk level is reduced (through a documented and systematic process) so far that no further cost effective measure is identified.*
> (NTS, 2001)

It should be noted that the requirement to establish a cost effective solution implies that risk reduction is implemented until the cost of further risk reduction is grossly disproportional to the risk reducing effect.

A frequency of $1x10^{-4}$ per year for each type of accidental load has been used frequently as the limit of acceptability for the impairment of each main safety function, according to the example given in NORSOK Z-013 (2001). This value is also stated as acceptable according to Innretningsforskriften (Petroleumtilsynet, 2008a).

According to Norsk Hydro (Scandpower Risk Management AS, 2006a), the acceptance criterion for the platform as well as the new module has been set to between 1 fatality per 100 years and 100 fatalities per 10000 years (NTS, 2001).

To attain information about what risks that qualify as acceptable or not, NORSOK suggest a risk matrix for qualitative risk estimation as one way of presenting in what order to deal with each risk. The risks presented and investigated in this paper, however, have been chosen with regard to the comparatively large amounts of hydrocarbons available in the actual segments but also due to the nearby location to the module where an eventual fire actually could affect the module.

Analysis of cause and consequences of various accidents

This section of the NORSOK Z-013 standard covers a whole set of different causes that can lead to an accident as well as what consequences that could be expected if such an event occurs. All this information is a great asset when collecting statistical input whatever the risk, as well as providing valuable information about how to protect the platform and its personnel.

Guidelines for cost benefit analysis

As mentioned before in the uncertainty section it is not economically acceptable to spend enormous amounts of money on risk reducing solutions if the reduction isn’t adequate. This makes cost benefit analysis an important tool when deciding what strategies and solutions to choose. This is why NORSOK Z-013 provides an informative chapter on this matter and this permeates the safety-cost discussion in section 8.1 in this paper.

3.5 Common assumptions

Many of the assumptions made in offshore industry are conservative in their nature. In an environment associated with high risk like the offshore industry this can seem to be reasonable. When oil and gas industry first commenced, the high risks associated with this type of activity rapidly became a fact. This is one of the reasons why main structures and fire defence solutions have been designed using conservative assumptions, another one is uncertainty (HSE, 2008b).

For reasons like this the offshore industry has provided some common and conservative assumptions when it comes to dimensioning accidental load (DAL). According to NORSOK S-001 standard DALs shall:

> *…be established based on quantitative risk analysis and the comparison of estimated risk with risk acceptance and/or design criteria.* (NTS, 2000)

The definition used by NORSOK S-001 for DAL is *"…most severe accidental load that the function or system shall be able to withstand during a required period of time, in order to meet the defined risk acceptance criteria."* (NTS, 2000), see section 6.3 for the defined risk acceptance criteria for the new module. Unless any specific fire analysis is performed table values for fire loads (e.g. heat loads) shall apply. These values are presented in Table 3.1 below.

Table 3.1 Values of heat flux

	Jet fire		**Pool fire**
	For leak rates m> 2 kg/s [kW/m²]	**For leak rates 0,1 kg/s < m <2 kg/s [kW/m²]**	**[kW/m²]**
Local peak heat load	350	250	150
Global average heat load	100	0	100

The local peak heat load and global average heat load are defined in the NORSOK standard S-001 as:

> *The local peak heat load exposes a small (local) area of the process segment or of the structure to the peak heat flux. The local peak heat load, with the highest heat flux, determines the rupture temperature of different equipment and piping within the process segment. The local peak heat load has marginal influence on the pressure profile within the process segment.* (NTS, 2000)
>
> *The global average heat load represents the average heat load that expose a significant part of the process segment or structure. The global average heat load provides the major part of the heat input to the process segment and, hence, affects the pressure in the segment.* (NTS, 2000)

The NORSOK S-001 standard declares that there are alternative approaches when it comes to assessing other different heat fluxes and sizes of fires. These should be based on probabilistic analyses in combination with relevant acceptance criteria, which is the approach used in this paper except for scenario type 3 where tabular values are used.

Why the use of passive fire protection?
Passive fire protection is by definition a system designed to protect against fire in a static way, i.e. by just existing and without any moving parts. The oil platforms consist mainly of steel structures that are affected by wind and weather as well as an eventual fire load. A basic protection to prevent a rapid temperature elevation that affects the steels load-bearing abilities can be attained through the use of PFP.

3.6 ISO 13702 & ISO 17776

The International Organization for Standardization (ISO) has two important standards directed towards the offshore industry. The first, ISO 13702, contains requirements and guidelines for the control and mitigation of fires and explosions on offshore production installations and the other one, ISO 17776, contains guidelines on what tools and techniques for hazard identification and risk assessment are recommended. Both standards are applicable to fixed and floating offshore structures and many reviews in offshore literature are made in accordance with these standards. The standards state that the use of standards, like for instance the NORSOK standard, is a good way of ensuring the high and required safety level, especially for previously done applications or modifications since this is what the standards mainly are based on. If the modifications are more complex in their nature a more detailed study needs to be performed (ISO, 1999).

3.7 Summary

In the offshore industry there are a lot of different guidances available. The writers of this paper have decided to use the ones written in NORSOK. This choice has been made for two reasons. The first reason is that Aker Offshore Partner mainly uses NORSOK when establishing new modifications or installations. Since Aker Offshore partner wanted the issues, presented in this paper, investigated it was a convenient and natural choice. The second reason is that the ISO standards presented in this chapter refer to the use of NORSOK "as a good way of ensuring the high and required safety level" which further imply that NORSOK is a good standard to use. This is also why the ISO standards are not referred to further on in the paper but instead the NORSOK standard.

The risk assessment will consist of three parts that will be further explained in the next chapter, chapter 4, where the risk management model used in this paper will be presented and explained. The risk analysis will serve as a base for the assessment part and together with the risk acceptance criteria (RAC) making it possible to evaluate the risk situation that exist. If the risk level is below the set criteria the risk is acceptable and the assessment is complete. However, if the risk level is above the set criteria, risk reducing measures must be applied to lower the risk level and hereby assessing the situation.

It is important that accidental loads must not occur more than the given frequency of $1*10^{-4}$. It is also important that an acceptable risk level is below Norsk Hydros risk acceptance criteria. The effect of fire fighting equipment shall not be taken into account when designing the load bearing structure. When performing major modifications like the installation of the new module it is important to perform a risk assessment to be able to present all aspects of hazards and ways to handle these. This is to get an adequate safety level to the new installation and the platform as a whole.

4. Risk management model

This chapter will begin with an explanation of the concept of risk and connect this with the risk management model being used in this paper. This will enable the reader to better understand why this process is so important and how decisions can be made on the basis of this model. The different steps in the model, the risk analysis, the risk assessment and any decisions that will be made out of the basis of the risk assessment, for example a cost benefit analysis, will help form the overall risk management model. The model will also be of help when making the quantification of how much risk reduction PFP contributes with.

4.1 An explanation of the concept risk

The concept of risk is not so easy to explain and is very much dependent on the situation that should be described. The definition of risk used by the offshore industry according to NORSOK Z-013 is: *"…a combination of the probability of occurrence of harm and the severity of that harm."*.

According to Kapland & Garrick (1980) the definition of risk consists in answering three questions, namely:

I. *What can happen? (i.e. what can go wrong?)*
II. *How likely is it that it will happen?*
III. *If it does happen, what are the consequences?*

To be able to answer these questions a list of relevant scenario types should function as a base for the analysis. In question II, "*How likely is it that it will happen*?", the word *likely* can mean what the probability is or what the frequency is. These two words however, do not mean the same thing. **Probability** according to Kapland & Garrick (1980) is what the subjectivists are talking about, in other words a form of measuring knowledge. The probability can only enact values between 0 and 1. **Frequency** on the other hand is outcomes in experiment that involves repeated trials. The frequency can enact both very small numbers but also very large ones.

The risk definition used by Kapland & Garrick (1980) could schematically be described as; the product of the probability/frequency of an event together with the consequence for this event, which goes very well in hand with the definition used in NORSOK Z-013 (NTS, 2001).

Uncertainty is a term that also should be included when discussing risk. The uncertainty itself does not pose a risk but uncertainty plus some form of damage can equal a form of risk, according to the authors mentioned above. This means that uncertainty in results that leads to damage can be seen as a risk.

Finally some form of **decision** will be taken from this foundation, decision regarding how to deal with the risk, i.e. accepting or not accepting the risk. This reasoning about the decision can for instance be based on a cost benefit analysis, see section 9.3. For the purpose of seeing how much risk reduction the use of PFP really gives, one way of doing this can be by quantifying the risk reduction made by PFP, see chapter 8.

4.2 Safety management and risk control according to NORSOK Z-013

The model being used in this paper is the one given in the NORSOK Z-013 standard as Figure 4.1 is showing below. NORSOK Z-013 refers to the model as a quantitative risk analysis (QRA), however the term QRA being the right name for the model can be discussed when the model also contains a risk assessment part. The steps in this QRA are however:

- Inner level: Risk estimation
- Second level: Risk analysis
- Third level: Risk assessment
- Outer level: HSE (Health, Safety and Environment) management

The NORSOK Z-013 does not cover HSE management, but this is still considered a part of the QRA. The HSE management will however not be dealt with in this paper. The different steps in this QRA will be described in more detail below.

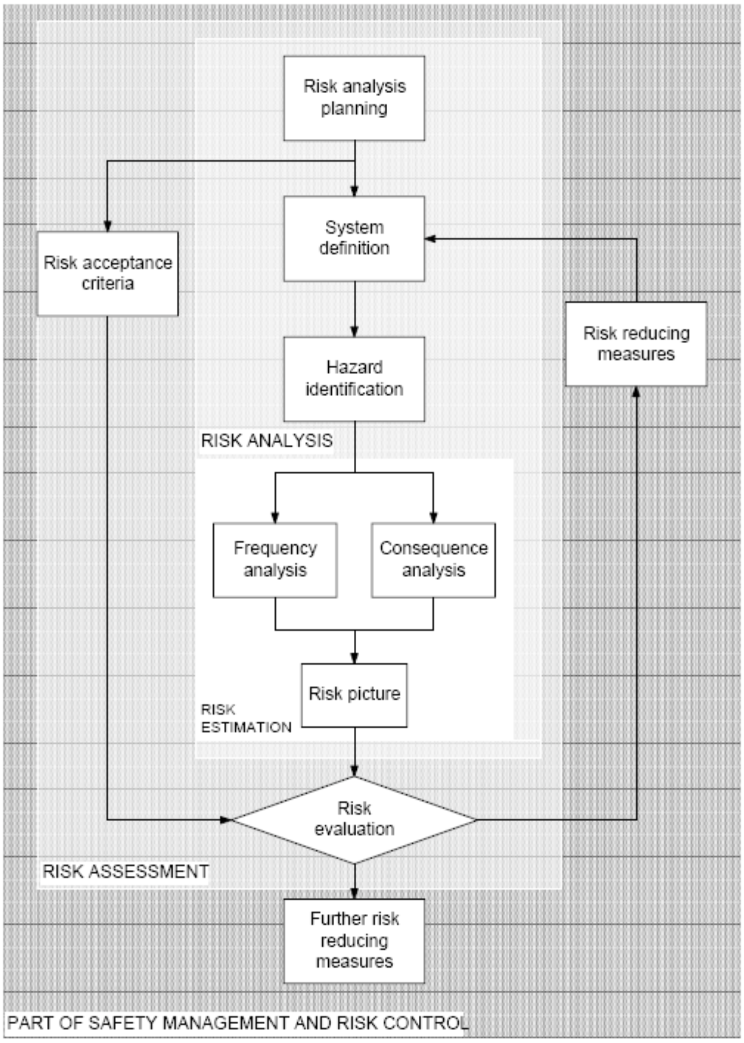

Figure 4.1 The risk assessment model used in this paper (NTS, 2001)

4.2.1 Risk analysis

The first step to take according to in this model is to perform a risk analysis. NORSOK Z-013 defines risk analysis as: *"…use of available information to identify hazards and to estimate the risk.*" (NTS, 2001). This definition goes well with the one given by Kapland & Garrick (1980). The aim of the risk analysis is to describe a system that can be considered to constitute a threat to the object being protected. The aim is also to identify any hazardous scenario types that can develop from this system. To get a better understanding of the relative danger for the hazardous scenario types, some form of calculation has to be made that shows the consequence the hazardous scenario types can have on the protected object if something goes wrong. If these calculations show that the object is not safe, calculations should be made that define the probability or in what frequency rate this scenario type could develop. However, if the calculations show that the object is safe the analysis should of course stop here. The two outcomes, the consequence and the probability/frequency rate should be weighted in together to try to establish if the risk is acceptable or not.

In this paper different scenario types that are estimated to have the potential to constitute a threat to the investigated object, the module, will be presented. Every scenario type will include;

- A system definition of both the system threatening the object and the system being threatened.
- A hazard identification that presents which hazards that can possess a threat towards the module.
- A risk estimation describing the consequence and the frequency rate/probability of a hazardous outcome.

The consequence analysis and the frequency analysis will together form the risk picture for each scenario type, which will be used when describing the total risk for the module.

System definition

The system definition is used to describe both the system that constitute a threat, but also the system that is exposed to the threat. In NORSOK Z-013 it is stated that the system definition (or description) shall include:

- *Description of the object of the analysis, i.e. the technical system (process, structure, utility, safety, emergency preparedness systems), including the relevant operations and phases.*
- *Statement of the period of time to which the analysis relates.*
- *Statement of current condition (in relation to possible degradation) for essential safety systems and safety functions (applies in particular to analyses in operations phase).*
- *Statement of the personnel groups, the external environment and the assets to which the risk assessment relates.* (NTS, 2001)

> *The system description should for a QRA in addition to the general requirements above, include capabilities of the system in relation to its ability to tolerate failures and its vulnerability to accidental effects.* (NTS, 2001)

Mainly, when describing the system constituting a threat, the system where a hazardous scenario type can develop is the one described. In this work, considering the system being a petroleum process industry, the different components and equipment where some form of failure can occur are being described. The system described in each scenario types is defined as its own segment. A segment can be described as one redundant part of the overall process i.e. the whole process that goes on on the platform is divided into smaller parts called segments, each one of these segments are described as one system. So when describing a system in a scenario type this system is a segment. The amount of different components or equipment that can fail in each segment, and thereby each scenario type, will be described in more detail in chapter 7. The failures often include leakages or that the functionality of the component or equipment is reduced for some reason.

When describing the system of the threat-exposed object, it is mainly the objects that are of interest to protect that have to be described. In this paper this will only include the structural system of the module and this is also described in more detailed in chapter 7.

Hazard identification

The hazard identification mainly describes, as the name implies, the hazards that can arise in the system (segment) and constitute a threat to an object if something goes wrong. This hazard identification can be compared with the first question in Kapland & Garricks (1980) definition of risk *"What can happen? (i.e what can go wrong?)"*. In this paper the hazards being evaluated are somewhat different from the "What can happen"-question. The hazardous segments of the process that contain large amounts of hydrocarbons and with the location of these segments in a way, that if released, can constitute a direct threat to the module are considered in this paper. These are the hazards considered relevant when observing the threats towards the module. In NORSOK Z-013 it is stated that the hazard identification shall include:

- *A broad review of possible hazards and sources of accidents, with particular emphasis on ensuring that relevant hazards are not overlooked.*
- *Internal/external incident reports that are applicable.*
- *A rough classification into critical hazards (as opposed to non-critical) for subsequent analysis.*
- *Explicit statement of the criteria used in the screening of the hazards.*
- *Explicit documentation of the evaluations made for the classification of the non-critical hazards.* (NTS, 2001)

It should be mentioned that relevant scenario types has been chosen after best ability and that other scenario types could have been overlooked. It is however more likely that these overlooked scenario types are not that relevant. This is because smaller amounts of hydrocarbons are present in the other segments and due to the fact that these systems are located at even greater distances from the observed object. For this reason their contribution to the overall risk picture will be neglected.

4.2.2 Risk estimation

Answering the questions; *"How likely is it that a hazardous scenario occurs and what is the consequence of it?",* will define the risk analysis according to Kapland & Garrick (1980). These two questions are to be answered in the risk estimation, according to NORSOK Z-013 (NTS, 2001), that is a part of the risk analysis. The risk estimation will help form the risk picture that will be used for further risk evaluation. In this paper the questions in the risk estimation according to Kapland & Garrick (1980) are rearranged so that, *"If it does happen, what are the consequences?"*, will be investigated and answered first. Then if the consequence is unacceptable, the question about, *"How likely it is that it will happen?",* will be investigated and answered. The rearrangement has been done because in our opinion, there is no reason to evaluate the probability of occurrence if there is no consequence directed towards the object investigated, at least in the risk estimation used in the risk analysis.

The consequence of a developing fire will be calculated in the risk estimation. To be able to define the consequence, some forms of assumptions have to be made. In this paper the assumption is that if the steel of the module reaches a certain temperature, the critical one, a collapse of the module will be the result, more about this in chapter 5. This assumption is made for two reasons. To maintain a strong and stable structure, no load bearing steel beam on the module can be "taken away" and this is due to the high load that the compressor on the module contributes with. The second is that an assumption like this will be conservative as well as simplifying the calculations. In those scenario types where the calculations show that the consequence will be unacceptable, further analysis in form of a frequency analysis has to be made.

The aim of the frequency analysis is to calculate in what frequency rate or what the probability is that a failure occurs that can cause a hazardous event. In this paper the main hazard is leaks of hydrocarbons from the process that ignites. Therefore the frequency analysis will help determine what the probability is for such a development. The frequency analysis will also help determine how much the different barriers will help preventing the consequence of a hazardous event to develop.

For this purpose an event-tree will form the basis of the frequency analysis. In some of the different steps in the event-tree, fault-trees will be connected to help evaluate the frequency rate or what the probability is that a threatening scenario outcome still can occur. A more detailed overview of how the risk estimation has been done is presented in chapter 6 and appendix 5. The data used in the fault-trees are based on accident and failure statistics taken from different sources. NORSOK Z-013 states that:

> *The modelling of the potential incident/accident sequence shall be detailed enough in order to suit the purpose of the analysis, e.g.:*
>
> - *Estimate the risk picture.*
> - *Estimate the performance of the barriers.*
> - *Establish performance standards for the essential safety systems.*
> - *Show the dependency between the physical barriers.*
> - *Reflect explicitly common cause and mode failures.* (NTS, 2001)

As mentioned before, the aim of this risk estimation is to investigate the risk reduction that PFP contributes with. So for that reason, when describing the reality in form of a model, only considered relative data will be part of this estimation.

All the different steps in the risk analysis will lead to an evaluation of the risk, and this evaluation is a part of the risk assessment as Figure 4.1 shows.

4.2.3 Risk assessment

The risk evaluation is part of the overall risk assessment and is used to investigate if the risk is acceptable or not. To be able to evaluate if the risk is acceptable some form of risk acceptance criteria (RAC) has to be set i.e. how much risk can be accepted before the risk is considered to big. If a risk reducing measure exist that lower the risk below the RAC this risk reduction has to be observed through an ALARP point of view, according to the NORSOK standard (NTS, 2001). This is in order to see if the risk reducing measure is to be taken into consideration.

To complete the risk management model a numerical quantification will be done to show how much risk reduction PFP contributes with as an individual barrier. Also a cost benefit analysis will be provided. This quantification and the cost benefit analysis will be of help when a decision has to be made regarding if PFP is going to be used or not.

5 Theoretical backgrounds

This section is meant to provide the theoretical background for load bearing abilities during a fire and what temperatures that can cause the structure to collapse. It will also present what choice of models that has been used and what different types of fires that are taken into consideration in this paper. The section starts with some basic definitions for fire resistance in materials and thereafter more specifically for carbon steel. The chosen fire models are hereafter presented and the chapter ends with describing PFP and specifically the PFP type "Chartek" that is used and how it works.

5.1 Basic definitions for structural integrity

When dealing with structures being exposed to fire it is important to have a basic understanding of different definitions. All materials have some sort of fire resistance. How large this resistance is depends on the material but the basic rule for a material to withstand the impact of a fire can be described with this expression (Buchanan, 2001):

$$\text{fire resistance} \geq \text{fire severity}$$

This means that if the fire severity is as large as or greater than the fire resistance either the material will ignite or the structure can collapse. Buchanan (2001) describes three different aspects, or domains, that each one plays an important role for the materials and hence the structures ability to withstand a fire load. These domains are; the time, temperature and strength domains. The time domain states that the failure time of the material or structure should exceed the duration of the fire in order to avoid a collapse. If not, a collapse is imminent and some preventive action against it should be taken like for instance the use of PFP.

$$t_{fail} \geq t_s$$

Another important aspect is the temperature domain described in the expression below, that states that if the temperature raise caused by the fire is greater than or equal to the temperature when the material or the structure will fail, there could also be a possibility for a collapse (Buchanan, 2001). If the temperature rises above the critical temperature for for instance steel, the load bearing properties change, which can result in permanent deformation of the structure but not necessarily a collapse. However, the physical properties of the steel will have changed as well due to the heat exposure, which probably can necessitate for instance switching a fire deformed steel beam (Franssen & Zaharia, 2005).

$$T_{fail} \geq T_{max}$$

The last domain that Buchanan (2001) mentions is the strength domain which is described by this expression:

$$R_f \geq U_f$$

R_f stands for the minimum load capacity during fire and U_f for the applied load at the time of the fire. This means that the reduced load capacity must be greater than the applied load in order to maintain the structural strength. If verifications are made with one of these domains in consideration the results should give identical results (Buchanan, 2001). This also means that if the described domains are fulfilled a collapse can be avoided.

5.2 Load bearing abilities for steel during fire

If steel is exposed to heat, through for instance fire, its structural abilities start to change. The structural load bearing abilities are dependent on the strength and stiffness of the steel and these factors decrease during high temperatures (Living Steel, 2008). These factors are included in the "effective yield strength", which is a commonly used expression when dealing with structural abilities and depending on the existing temperature the effective yield strength decreases with increasing temperature. When designing steel structures this is being dealt with with the help of reduction factors implemented in the calculations. For carbon steel this reduction factor is implemented for steel temperatures of approximately 500°C and above because this is where the yield strength of the steel start to change (Franssen & Zaharia, 2005). Several fire resistance tests conclude that the critical temperature for steel lies between 450 and 650°C (Living Steel, 2008). This is why the offshore industry is required to be able to keep temperatures below a certain temperature (often 450°C) in the steel for a time period that is sufficient for safe evacuation (NTS, 2001). Different time frames apply for the structure for different types of fire loads. For jet-fires 20-40 minutes apply, and for pool-fires 20-60 minutes, depending on which area that's observed and these time-frames also apply in this paper because Troll C has these requirements (UMOE, 1999). The thermal expansion for steel is linear up to the temperatures 700 and 800°C. Because of this it is usually not necessary to include thermal strain calculations when designing single steel beams and columns but it must be considered for frames and complex structural systems (Buchanan, 2001).

5.2.1 Temperature causing collapse

The calculations for stress-strain relationships in carbon steel during elevated temperatures are very advanced and to simplify the calculations the temperature for collapse in this paper is assumed to be 450°C. According to UMOE (1999) the steel temperature must always be kept below 450 °C and this limit has been the guideline throughout the designing and building process of the Troll C platform. The same guideline also applies for the design of the new module because it is going to be implemented on Troll C (Grande, 2008). The temperature limit depends on the load applied to the steel structure but the 450 °C limit always applies to primary load bearing structures (UMOE, 1999). This means that, independently of the applied load to the steel structure, the temperature must always be kept below the temperature limit.

5.3 Choice of fire models

The equations used for calculating jet- and pool fires have been collected from Fischer et al (1998) because they give good estimations of possible events that can cause such scenarios and are well suited for the process industry as well. The same equations are also used by Scandpower

(2006d) who has done the risk analysis for the Troll C platform where the new module is being installed. To calculate the different time intervals for the steel to reach a specific temperature, equations presented by Magnusson et al (1974) have been used. The different equations will be presented in more detail in each of the appendices.

The paper will only consider scenarios with jet- and pool fires like stated in the limitations section. Below follows a description of the different fire types.

5.3.1 Jet fire

A jet fire can be the result of a combustible material under high pressure being released because of for instance a leak that thereafter gets ignited (Fischer et al, 1998). Depending on the conditions the jet fire can reach lengths up to 50 meters with high flame temperatures of up to 1500°C. The high temperature is very common for hydrocarbon fuels and this is due to the high entrainment of air which leads to very good mixing conditions for the gas together with air for complete combustion. Because of this the heat radiation zone near the flame can get very high (Scandpower A/S, 1992). When flame lengths up to 50 meters are possible with very high heat intensity the flame can affect objects not just nearby but also at a fair distance. A somewhat positive feature with the jet fire is that the fire stops when the leak is contained. SINTEF have performed tests for jet fires with a mixture of gas and oil which often is the kind of mixture one can find on offshore installations. In their report (SINTEF NBL A/S, 2008b) they present the special characteristics for these types of jet fires where some of their observations are mentioned below:

- The amount of liquid dripping from the hole is so small that it can be neglected.
- The heat flux from the flames was high with intensities between 352-409 kW/m^2.
- Significant amounts of heat radiation could be measured in areas beyond the visible flames.
- The higher the amount of gas in the oil-gas mixture the higher the heat load was, compared to just oil.
- The heat flux measured in the front of the pipe being hit by the jet flame was almost the same independent of the distance from the leak source while the measured heat flux was lower on the backside of the pipe when the distance from the leak source increased.
- Heat flux contribution to the surroundings was greater with just oil compared to the oil-gas mixture.

5.3.2 Pool fire

When a combustible liquid is released onto a solid surface, the liquid may form a pool. If the combustible liquid slowly starts to evaporate and thereafter ignites, the result is a pool fire. The size of the pool fire, regarding the area the pool covers, obviously depends on how much liquid that is released but the intensity of the fire also depends on factors like burning rate for the specific fuel and what energy values that can be expected for it (Fischer et al, 1998). A large pool fire has the possibility to engulf many objects in its flames as well as its radiation can affect areas in the vicinity of the pool. The amount of radiation depends on what type of fuel that is burning and it also depends on how much soot the flame produces (Drysdale, 1998). In the SINTEF report mentioned above (SINTEF NBL A/S, 2008b) they also made some observations about pool fires mentioned below:

- The heat load from the flames engulfing an object is greater in the lower half of the flames because of greater heat intensity in the lower half of the flame due to that no soot screen in this part is present.
- The expected evaporation increases for flowing fluids compared to horizontal pools with fluids.

5.3.3 Different models give varying results

When performing calculations for jet fires in this paper and more specifically the length of the flame, different methods turned out to yield a great deal of differences. This is obviously partly due to different calculation methods and methodologies but also to the accuracy during tests. Equations for the same type of fires presented by Fischer et al (1998) were compared to equations provided by Scandpower A/S (1992) and Cowley & Johnson (1991), and the span of the results turned out to be huge, so huge that the authors chose another approach for these fires. Instead of considering the different flame lengths the focus was directed towards whether or not the module could get hit by the jet fire and how this affects the given scenario and the probability of this happening. Hitting the module is partially depending on the flame length but more important if there are objects in the way that hinders the flame from hitting the module.

5.4 Passive fire protection

Passive fire protection is, as stated before, a fire protection system that does not involve moving parts. For load bearing structures it is important to be able to maintain a great part of the original strength in case of a fire. Steel is the material of choice when building most of the structures on an offshore platform and it loses about 75% of its strength at 600°C, making collapse imminent if the load applied also should be high. Because of this, temperatures above 450°C are not allowed, as stated before (Akzo Nobel, 2008b). To be able to suppress the temperature rise in the steel structures some form of PFP can be needed. In the offshore industry a coating with heat reducing properties is applied to the structure. This coating is called ’Chartek’ and is further described in section 5.4.1.

5.4.1 Structural fireprotection - Chartek

Chartek is a kind of epoxy that is painted on the surface that one wants to protect. If a fire is directed towards the protected material the fire starts a chemical reaction in the material. This reaction makes the epoxy combust and it converts to carbon and gas. The outer part of the layer consists of char, the middle part is the reaction zone and the inner part consists of unreacted material. During this process the protective layer expands and hence it insulates the protected material. The process continues as long as there is unreacted material left but even if the process stops because of prolonged fire exposure it still works efficiently with retarding the heat transfer (Akzo Nobel, 2008a), Figure 5.1below shows schematically how Chartek works.

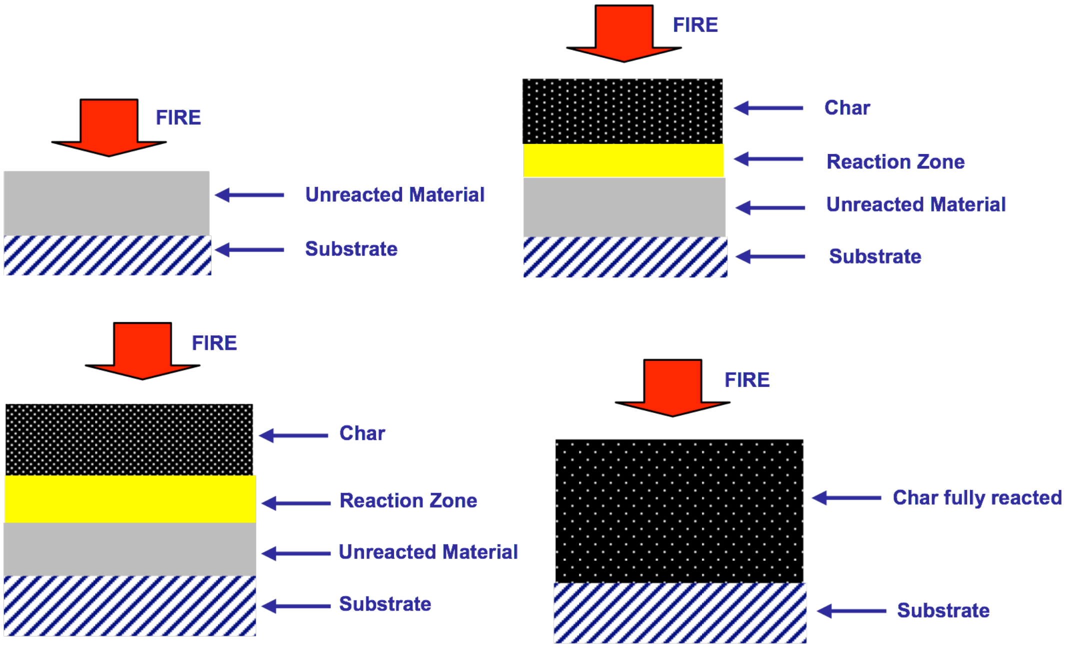

Figure 5.1 Step-by-step description of how chartek works (Akzo Nobel, 2008a)

Depending on the designers wishes on how to design the structure, specific requirements and different ratings for insulation are set. The performance criteria for Chartek are that the temperature of the structure being protected shall not exceed 139°C within the designated time period and the temperature rise must never in one point exceed 180°C (Akzo Nobel, 2008b). This means that the required thickness of the Chartek layer changes depending on the expected fire load as well as the required time frame that apply. Different time frames apply depending on what type of hydrocarbon release that is expected in the observed area and these time frames are presented in order to be able to safely evacuate the personnel onboard (NTS, 2001). Hydrocarbon fires cause rapid temperature rises to high levels, as high as in excess of 1000°C (Akzo Nobel, 2008a). To defend the steel structure against temperature rises up towards 450°C a layer of Chartek can be applied. The layer thickness depends on how the beam is constructed, as variation in steel thickness affects the heat transfer, but also which types of fires and time-frames that apply, as stated in chapter 5.2.

If a jet fire occurs and hits the steel the temperature elevation increases faster than the ordinary hydrocarbon pool fire and as the jet constantly "sprays" the material it also affects the Chartek layer in an erosive way. This makes it important to apply a couple of more millimetres chartek when applied, or the fire protection will be lower than it was designed to be (Akzo Nobel, 2008a). Other factors that also affect the quality of the protection is the aging of the protective material and the strain due to weather and mechanical stress (SINTEF NBL A/S, 2008a).

5.4.2 Chartek – Actual events

The company that produces Chartek has presented a case study with three actual fire events where chartek played a role in protecting the fire exposed structure (Akzo Nobel, 2008a). Two of the three events were actually offshore platform accidents and the third event was a fire exposed tank containing ethylene chloride. Only one of the offshore events as well as the tank event provided the duration of the fire exposure. The fire in the offshore event is not a hydrocarbon fire but a fire with construction material as fuel. The heat flux for such a fire should not be as high as the one of a hydrocarbon jet fire but the duration of 4 hours, compared to that the protective layer was designed to manage a 2 hour jet fire, could be assumed to be about the same total fire load. Akzo Nobel (2008a) also presents the results of the post fire inspection that shows, for the offshore accident, that the protected material temperature had been kept below 100°C. The tank event was a tank subjected to a hydrocarbon fire where the tanks critical temperature was 427°C and was not allowed to exceed that temperature for 2 hours. In this event the fire duration was 1 hour and 40 minutes and the post fire inspection, provided by Akzo Nobel (2008a), showed that the tank temperature had not been higher than 200°C. These events show that the material has high fire protecting abilities.

5.4.3 Life Cycle Cost Issues - Chartek

To maintain the required protection it is important that the thickness of the paint is held as specified. Therefore frequent checks are essential as well as increasing the layer thickness at locations where it is needed (Akzo Nobel, 2008b). This kind of work is expensive (see chapter 8.2) because of the tough conditions offshore as well as the special permits that are needed to be able to perform the work. This makes it important to apply the right amount of paint from the start so that the requirements are fulfilled and to keep maintenance costs at a low but reasonable level. To calculate the ”right” amount of paint it is essential to account for the economic life cycle versus the physical life cycle to ensure a high efficiency. If the different life cycles are equal the optimal efficiency level has been reached, which, however, might not always be the case. If the economic life cycle exceeds the physical the investment is not good and such an outcome should if possible be avoided (Persson & Nilsson, 1999).

5.5 Summary

All materials have some sort of fire resistance and the size of this resistance depends on the material. Steel is the material used for building the main structures offshore and the steels characteristics change due to influence of heat. Jet- and pool fires can easily elevate the steel temperature if the steel is exposed to the heat flux induced by these types of fire.

The steel properties are somewhat the same up to approximately 500 °C, which is why temperatures must never reach beyond 450 °C in primary structures independently of the load the structure is exposed to. This critical temperature will be used in the calculations and are considered to be a conservative assumption. It is also assumed that if the steel reaches 450 °C the structure collapses.

The PFP used for protection of steel structures offshore is most commonly the epoxy based paint “Chartek”. It has very good protective abilities for temperature elevation in the material it is supposed to protect. Depending on the expected heat flux load for eventual accidental events the Chartek layer thickness differs. The layer thickness will not be taken into consideration because the exact specifications for the material are company kept secrets which is why the assumption is made that if Chartek is applied, regardless of its thickness, the structure will be “safe”.

6 Risk estimation criteria for the risk analysis

For the purpose of evaluating what the risk is for the new module different scenario types with different leak sizes has to be investigated through a risk estimation. These risk estimations includes a frequency analysis that describes how often errors might appear in different components (for instance, piping, vents and barriers) and a consequence analysis that describes what the outcome will be due to failure of these components. These two analyses will describe the risk picture for each scenario type and for a total risk picture including all scenario types, see chapter 7. The risk pictures will be further evaluated in the risk evaluation together with the RAC. The total risk picture, describing the extent of the frequency when PFP is needed versus not needed, is going to be used when quantifying the risk reduction the use of PFP gives as a barrier, see section 8.

This chapter will help explain the steps and the reasoning behind the risk estimations done in this paper as well as the values used in the frequency analysis and consequence analysis. In this paper, where process hazards in offshore industry environment are being dealt with, event and fault trees are used for the purpose of analysing the frequency rate that something can go wrong i.e. the frequency analysis

The structure through the entire frequency analysis is built around an event tree, see Figure 6.1, that will make the basis for this analysis. The design of the event tree has been made on the basis of the chain reaction that can happen on a platform if a leakage occurs in the process system. The steps in this event tree are:

- Leak frequency (start event): The event-tree starts with the frequency rate a leak occurs in a scenario type (segment). For the purpose of calculating the frequency rate for how often a leak in a segment can occur all the leaking points in the segment have been included. There are different leak sizes in each scenario type and the leak sizes that can occur are (small, medium, major and large).
- The “Detection and closure”-part of the leak is a result of using a fault tree that describes the frequency rate and the possibility that different barriers do not work as they should. This fault tree is shown in Figure 6.2 and the basic events are described in section 6.1.3.
- The ignition probability of a leak has been estimated for different leak sizes and is described more in detail in section 6.1.2.
- The “Fire detection and closure”-part is a result using yet another fault tree describing the frequency rate and the possibility that fire detection barriers do not work and detect a fire as they should. This fault tree is shown in Figure 6.3.

These above steps will be further explained in this section but the decision made for one of these steps can already be explained here. The fire detection and closure is only evaluated if no other detection has been made earlier in the event tree.

A new event tree and the connecting fault-tree are used for every leak size in every scenario type. For a demonstration of how the frequency analysis is to be made using the event tree and fault tree, see appendix 5.

As can be seen in scenario outcome 3, 4 and 5, if the leak or fire is detected and the segment closes this will be done in approximately 1,5 minutes. This has been calculated by summarize the detection time in Table 6.12 (not including detection of a small liquid leak) and the time to full closure which is said to take about 30 seconds, for this kind of equipment size. The frequency rate, when PFP is needed and is not needed for each scenario type, are shown in chapter 7

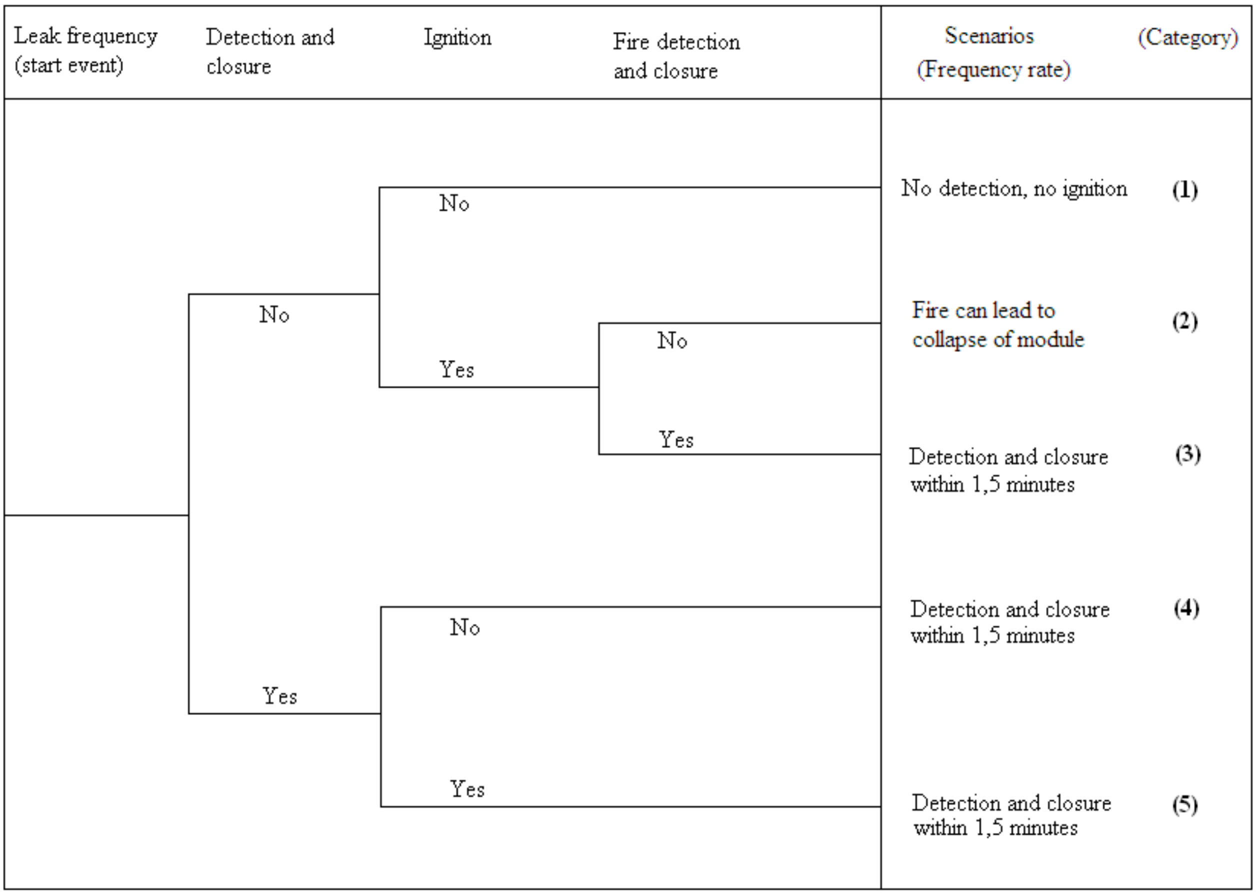

Figure 6.1 Event-tree for different scenarios for each scenario type

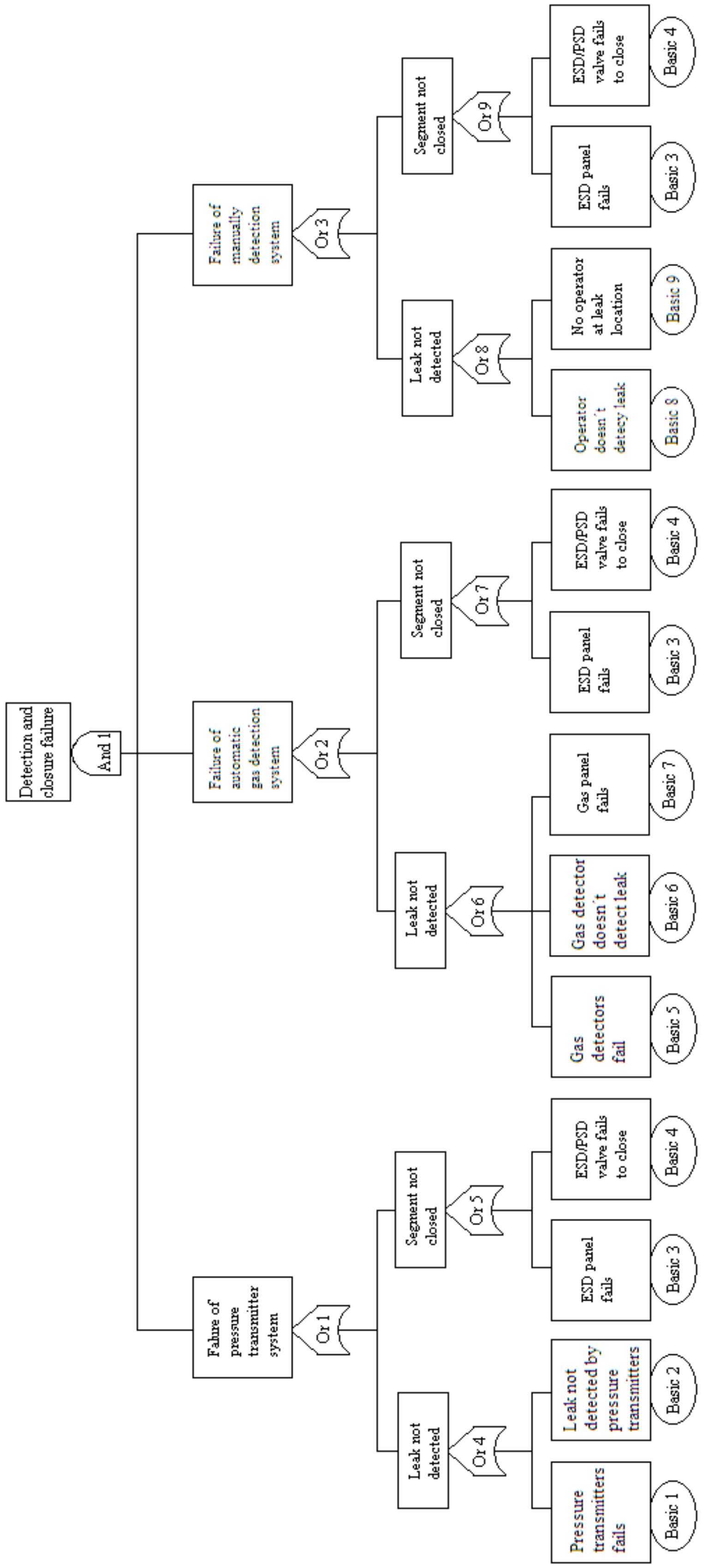

Figure 6.2 Fault-tree for detection and closure

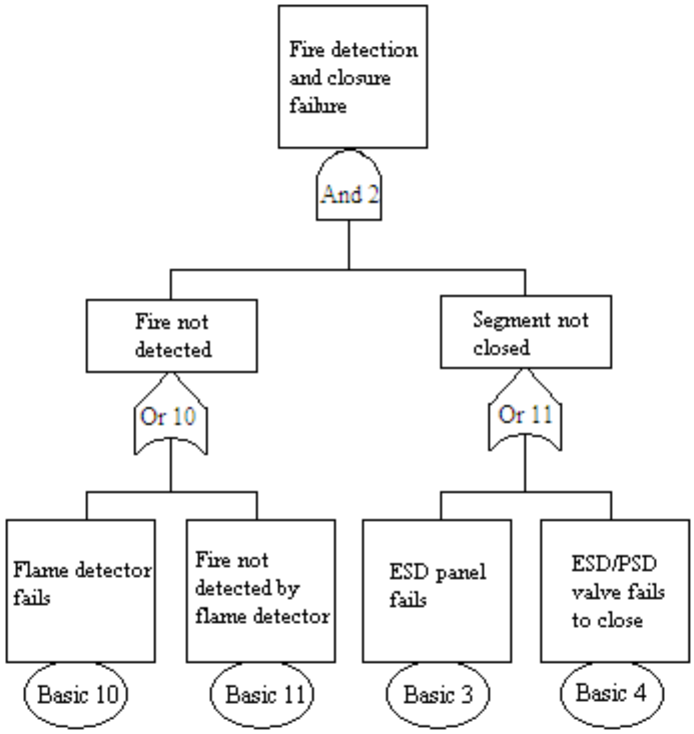

Figure 6.3 Fault-tree for fire detection and closure failure

6.1 Probability and frequency rates for the frequency analysis

The probability and frequency rates will be used in the event and fault trees to describe what frequency rate or what the possibility is that components, equipment and barriers fail or does not work. These values will be further explained and showed in this section. A guide to how to use these values in the frequency analysis, see example in appendix 5.

6.1.1 Leak sizes and leak frequencies

This section intends to clarify how the start event (leak frequencies) in the event tree is calculated. To make it easier for the reader to see how this is done, two different definitions of “sizes” have to be explained, see also Table 6.1 and 6.2. The first size is the distribution size and from this size comes the frequency rates for the component failures and the hole sizes that a leak can have. From the distribution size a transformation to the different leak sizes (amount of medium released) that can start in the segment is made. This transformation is made because the calculations in the event tree originate from the leak size terminology; small, medium, major and large.

Table 6.1 Distribution sizes

Distribution size
Minor
Major
Rupture

Table 6.2 Leak sizes

Leak size
Small
Medium
Major
Large

When calculating the leak size i.e. transforming the “distribution size” to “leak size”, one must first know the different sizes of components in the segment i.e. in each scenario type. The different components can, if they start to leak, have different mass rates, out of the leaking hole, depending on the sizes of the components. This is decided, among other things, on the area or hole size that the leaking component has. A distribution for different hole sizes are presented below.

Minor: a leak from a 1mm^2 hole.

Major: a leak from a 2 cm^2 hole for a diameter for 8 ¾ inch or: $A = \frac{\pi \cdot D^2}{4} \cdot 0{,}0081$

Rupture: a full size leak where $A = \frac{\pi \cdot D^2}{4}$

The hole size distribution is taken from Scandpower (2006c). For the diameter (D) for pipes and components, the values of the different component sizes are used when calculating the areas for the major and rupture leakages. These different calculated leak hole areas are then used to calculate the gas or oil release rate (mass rate). For gas release rate “Equation 1” has been used and for oil release rate “Equation 2” has been used.

$$Q = 0{,}667 \cdot C_d \cdot A \cdot \frac{P_0}{\sqrt{R \cdot T_0}} \qquad \text{[kg/s]} \qquad \text{Equation [1]}$$

$$Q = C_d \cdot A \sqrt{\frac{2(P_0 - P_a)}{v_f}} \qquad \text{[kg/s]} \qquad \text{Equation [2]}$$

The gas and oil release rates that are given by Equation [1] & [2] (Fischer et al, 1998), are to be used when defining the leak size in the segment. The sizes of the leakages are divided into categories with an upper and lower limit. These categories are used to better distribute and define the leak sizes, see Table 6.3 below.

Table 6.3 Leak sizes (Scandpower, 2006c)

Category size	**Lower limit Q (kg/s)**	**Upper limit Q (kg/s)**
Neglected		0,05
Small	0,05	1
Medium	1	10
Major	10	30
Large	30	10000

To summarize the steps when transforming the distribution sizes (minor, major and rupture) into the leak sizes (small, medium, major and large), this is done by:

- First knowing the component sizes in the segment
- Then calculating the mass rates for each distribution size using the hole size distribution and equation [1] or [2], depending on the medium inside the segment.
- And finally categorizing the distribution sizes, after amount of hydrocarbons being released, into the different leak sizes using Table 6.3.

When calculating the leak frequency for different leak sizes, values of different failure rates from distribution sizes are used. Leak frequencies for components and their distribution sizes have been taken from Scandpowers risk analysis for Troll C (see Scandpower, 2006c, 2006d). These values originate from a database called OREDA phase 3. This database is prepared by SINTEF Industrial Management and distributed by Det Norske Veritas (DNV). The database provides failure frequencies for the process industry, both offshore and onshore. Failure frequencies leading to leakages for different components have been recalculated for major and rupture leakages by the use of different distribution factors (see Scandpower, 2006c). The different components on the module and the Troll C platform include for instance valves, flanges and piping. The failure rate values for components used in this paper are presented in Table 6.4 below.

Table 6.4 Failure rates for different components and their distribution size (Scandpower, 2006d)

	Failure rate per 10^6/hour			**Failure rate per year**		
Component	Minor	Major	Rupture	Minor	Major	Rupture
Valve	1,2	0,02	0,002	$1*10^{-2}$	$1,7*10^{-4}$	$1,7*10^{-5}$
Flange	0,3	0,015	0,0015	$2,6*10^{-3}$	$1,3*10^{-4}$	$1,7*10^{-5}$
Piping per 10m	0,0048	0,0006	0,00006	$4,2*10^{-4}$	$5,2*10^{-5}$	$5,2*10^{-6}$
Heat exchanger (S&T)	7,6	0,3	0,0058	$6,6*10^{-2}$	$2,6*10^{-3}$	$5,1*10^{-5}$
Compressor	10	0,5	0,05	$8,7*10^{-2}$	$4,4*10^{-3}$	$4,4*10^{-4}$
Vessel			0,0048			$4,2*10^{-5}$

The frequency rate for different leak sizes is calculated knowing the amount of different components and pipe lengths in the segment. The distribution sizes (minor, major and rupture) and their failure rates are used when calculating the failure frequency for different leak sizes. For example, this can be done by knowing what the distribution size "major" together with a specific component size equals in mass rate and thereby knowing the leak size by using Table 6.3.

Petroleumtilsynet (2008b) shows that during the last five years leaks have decreased by more than a half, especially when it comes to leakage rates between 0,1-1 kg/s. The total leak frequency is around 0,2 per activity year and platform. For comparison about leak frequencies for Troll C, if the platform could be included in this statistics and have a leak frequency rate around 0,2 per activity year, this would give a mean value of 0,0074 per segment and activity year (including all 27 segments on Troll C). This value goes well with the leak frequency rates that have been calculated in this paper. To just calculate a mean value for all the different segments on a platform could be discussed because some segments have higher leak frequencies than others. On the other hand the leak frequency 0,2, per activity year and platform, is a mean value for a platform that includes different segments.

6.1.2 Probability of ignition

When it comes to information and statistics about ignition probability in the offshore industry, it should be noted that the probability on this topic is very uncertain. The probability of ignition will depend on many things but overall it will depend on:

- The number and nature of potential ignition sources present.
- The probability that the released medium is exposed to the ignition source.
- The probability that an exposed source of ignition will ignite the leaking medium (Scandpower, 2006c).

This means that the ignition itself will depend on different parameters like the nature of the installation (maintenance, age etc.) and the type of activity. The probability of ignition will also depend on the amount released (size of leakage, area being covered in flammable substance and the duration of the leak). In many scenario types there are large amounts of water involved in the leakage and the degree of involvement of water also makes it difficult to calculate the probability of ignition.

When it comes to Norwegian offshore platforms the ignition probability is lower compared to British platforms. Considerable recourses have been used to build in more security into the Norwegian platforms to prevent and hinder that hydrocarbon leaks will ignite and in recent years, special attention have been directed towards better control of ignition sources (Petroleumstilsynet, 2008). It should be mentioned that no leakage over 0,1 kg/s has been ignited for the last 11 years on a Norwegian platform. The last ignition of a leakage greater than 0,1 kg/s on a Norwegian platform was in 1992 and on British platforms this was in 2006. The leak on the British platform released 7000 kg of gas and the duration was about 15 seconds.

Ignition sources
Depending on the medium released the ignition probability will vary a great deal. If a gas is released the probability of ignition is higher than if crude oil is released. This is because a smaller amount of energy is needed to ignite the gas than the crude oil. It is also more likely that a gas cloud can fill a larger volume and therefore involve more ignition sources. Known ignition sources for vapour mixtures are:

- Electric sparks and arcs (from electrical circuits, motors, switches etc.)
- Mechanical sparks (from friction and falling objects)
- Static electrical sparks
- Lightning
- Flame (including flaring, boilers, smoking)
- Hot surfaces (including hot work, hot processing equipment, electrical equipment)
- Heat of compression
- Chemical reactions (e.g. auto-ignition of oil-soaked lagging on hot piping)
- High energy radiation, microwaves etc (HSE, 2008a).

For non-vapor mixtures like crude oil, little data is available about ignition sources. The reservoir where Troll C is located now produce high water cut fluids i.e. a great deal of what is being pumped up, is water. This means that probability calculations for ignition has to be for oil-water mixes and the ignition probability for this mixture is not so well understood or documented (HSE, 2008a).

Ignition Data
To be able to say anything about the ignition probability related to the size of the leakage, a larger leak will in most scenario types reach and spread out over a greater area. This could mean that a large leak has a greater probability to ignite than a small one because it covers a bigger area where the amount of ignition sources can be greater.

The mechanical energy produced from a severe and powerful gas leak that develops into a rupture could also be sufficient enough to cause an ignition. A severe rupture is also likely to cause pipes and other components to be thrown away like projectiles causing both sparks and other damages on electrical devices, which also increases the probability of an ignition. Scandpower (2006c) has in their safety and emergency preparedness analysis for the Troll C platform concluded that the probability for a large gas leak to ignite immediately is about 3% and for a major gas leak 0,3%. For medium and small leaks the probability has been estimated to be 0,1% and 0,01% respectively, see Table 6.5 below. These conclusions are based on the geometry and type of equipment available on Troll C.

The total ignition probability for a gas leak (Table 6.5) will, as mentioned before, depend on the amount of ignition sources. On the upper process deck on Troll C where the module is going to be placed the total probability for ignition has been calculated with consideration to four different ignition sources. These sources include:

- Hot work
- Rotating machinery

- Electrical equipment
- Turbines

Table 6.5 Leak sizes and probability of ignition (Scandpower, 2006c)

Size of leak	Probability of immediate ignition, gas (%)	Total ignition probability for gas (%)	Probability of immediate ignition, oil (%)	Total ignition probability for oil (%)
Large	3	3,3	1,5	1,8
Major	0,3	0,75	0,15	0,34
Medium	0,1	0,15	0,1	0,15
Small	0,01	0,032	0,01	0,032

The probability of ignition for released crude oil is lower than for gas. For small and medium leaks the probability can be assumed to be the same as for gas leaks of the same size. But for major and large leaks the ignition probability can, due to the differences between the two mediums ignition probabilities mentioned above, be reduced to half of what the gas ignition is according to Scandpower (2006c), see also Table 6.5.

Despite the efforts to calculate the probability of ignition on upper deck it is not mentioned in Scandpowers report how many ignition sources a leak in each segment is capable to reach. The total ignition probability is considered the same regardless of the location of the leakage and works as a mean value. This could be discussed especially when it comes to small and medium leak sizes that not covers any greater areas.

Other data presented by Health and Safety Executive (HSE) shows that the ignition probability on platforms lies around 6-7% (HSE, 2008c). The data for ignition presented by HSE is for British platforms and is likely to be higher than for Norwegian platforms like stated before. This probability represents the mean value for all hydrocarbons that are located on platforms and includes gas, liquid and two phase leakage.

The statistical data can be divided into the three different kind of liquid categories mentioned above: gas, liquid and two phase leakage. The leakage frequencies are shown in Appendix 5. The ignition probabilities for the different types of hydrocarbons are shown in Table 6.6. This table does not make a distinction between leak sizes for different types of hydrocarbons released and represent a mean value for each hydrocarbon type. The two leak sizes minor and significant in the HSE (2008c) report could be compared to a small size gas leak and a medium size oil leak in this report. In the report from HSE none of the major leaks have been ignited.

Table 6.6 Ignition probabilities for different hydrocarbon types (HSE, 2008c)

Hydrocarbon types	Share of leakage of total 725	Amount ignited of total medium	Ignition probability per year and platform (%)
Gas	394	16	0,0144
Liquid	242	27	0,04
Two phase	89	No ignition during this period	0

It should be noted that for liquids there are three categories; non process, oil and condensates. The category “non process” represents almost 93 % of the total ignition probability for liquids and oil represents the rest. The total amount of leaks for liquids is not divided into the three subgroups so further analysis can be made about the ignition probability. This makes it hard to comment the probability for just crude oil to ignite.

The report from Petroleumstilsynet (2008b) states that for British platforms there have been 501 gas/two phase leakages over 0,1 kg/s over a period of 14 years and seven of these ignited. 192 of these leakages were over 1 kg/s and one of these ignited. However they do not mention for how many of the British platforms that are considered when these ignited leakages occurred.

The ignition probability that Scandpower presents in their report and their argument that a larger leak have a greater probability of ignition than a small, is the opposite of the statistic data provided by HSE (2008c), where the probability of ignition for a minor leak is greater than for a significant one. This could depend on for example that small leaks occur more frequently and thereby have a higher ignition probability. However there haven’t been any major or large leaks ignited in the HSE (2008c) report, so it is hard to say anything about how often major and large leaks ignites on the basis of that report. In the HSE report there is a distinction of ignition probabilities for minor and significant release sizes. But because these two sizes both represent a small release size in this report no difference will be made for the ignition probability.

Summary ignition probability

In this report the ignition probability for the different scenarios will be the same as the ones Scandpower use, see Table 6.7. There are two more ignition sources that will be added to the already existing ignition sources (not including more hours of hot work) when the module is placed on the upper deck. These are a compressor and an electrical motor. The contribution that these two ignition sources make to the already calculated total ignition probability for the whole upper deck on Troll C will be neglected.

Table 6.7 Ignition probability used in this paper for different mediums

Size of leak	Total ignition probability for gas (%)	Total ignition probability for oil (%)
Large	3,3	1,8
Major	0,75	0,34
Medium	0,15	0,15
Small	0,032	0,032

The fact that the ignition probability used by Scandpower is a mean value for one deck and the statistical value from HSE is a form of mean value for an entire platform should be considered. It should also be considered that these platforms do not look the same, both when it comes to sizes but also when it comes to equipment that can start an ignition. It is also stated that the Norwegian platforms have a smaller potential for ignition of a leak than British platforms, this statement makes Scandpowers ignition probability realistic but also a bit conservative when describing the probability of ignition on the module as well as on the platform Troll C when comparing ignition probabilities between Norwegian and British platforms.

6.1.3 Probability of detection

The detection of a leakage is very important because the sooner it is detected the shorter the duration will be. Therefore different so called barriers are used to detect, prevent and reduce an eventual damage escalation and limiting the consequence a leakage can have. The definition of a barrier used by ISO (2000) is:

> *Barrier – measure which reduces the probability of realizing a hazard's potential for harm and which reduces its consequence.*

There are two different detection phases used in the event-tree in this paper; the first one is the detection of any kind of leakage, gas or liquid. The second phase is detection of a fire as the result of the ignition of a leak. In the first phase the detection will probably be due to some form of pressure drop in the system that the pressure sensors will detect or in the form of gas detection from and around the leakage point. The detection can also be made by an operator that observes and manually shuts down the segment where the leak has occurred. In the second phase the detection will be made through the fire detection systems.

When it comes to barriers, they are being tested in different time intervals to see if they function as they should. The time interval between the tests is essential. When calculating with test intervals, the main estimation is that when the component has been tested the functionality is known to be very high. This high functionality is being reduced with time, until the next test. By doing this assumption one can calculate the frequency rate of failure for this period of time. This value will be a mean value for the time between the tests. The mean value of frequency rate failure between the test intervals is used when calculating the failure frequency during a year. This mean value is calculated using the equation below:

$$PFD_{UK} = \lambda_{DU} * (t/2)$$

PFD_{UK} : Probability of failure on demand quantifies the unavailability due to dangerous undetected failures.
λ_{DU} : Dangerous failure rate, not detected by automatic self-test or personnel i.e. only detected by a functional test.
t : Time between test interval.

This means that the highest fault frequency a barrier can have depends on the time between the test intervals SINTEF (2004).

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The detection of a leakage is very important because the sooner it is detected the shorter the duration will be. Therefore different so called barriers are used to detect, prevent and reduce an

eventual damage escalation and limiting the consequence a leakage can have. The definition of a barrier used by ISO (2000) is:

> *Barrier – measure which reduces the probability of realizing a hazard's potential for harm and which reduces its consequence.*

There are two different detection phases used in the event-tree in this paper; the first one is the detection of any kind of leakage, gas or liquid. The second phase is detection of a fire as the result of the ignition of a leak. In the first phase the detection will probably be due to some form of pressure drop in the system that the pressure sensors will detect or in the form of gas detection from and around the leakage point. The detection can also be made by an operator that observes and manually shuts down the segment where the leak has occurred. In the second phase the detection will be made through the fire detection systems.

When it comes to barriers, they are being tested in different time intervals to see if they function as they should. The time interval between the tests is essential. When calculating with test intervals, the main estimation is that when the component has been tested the functionality is known to be very high. This high functionality is being reduced with time, until the next test. By doing this assumption one can calculate the frequency rate of failure for this period of time. This value will be a mean value for the time between the tests. The mean value of frequency rate failure between the test intervals is used when calculating the failure frequency during a year. This mean value is calculated using the equation below:

$$PFD_{UK} = \lambda_{DU} * (t/2)$$

PFD_{UK} : Probability of failure on demand quantifies the unavailability due to dangerous undetected failures.

λ_{DU} : Dangerous failure rate, not detected by automatic self-test or personnel i.e. only detected by a functional test.

t : Time between test interval.

This means that the highest fault frequency a barrier can have depends on the time between the test intervals SINTEF (2004).

Detection phase 1 – leak detection

Pressure transmitter fails

For the system to be able to sense a pressure drop, pressure transmitters have been integrated into the system. The following failure rates have been taken from SINTEF (2004):

For conventional pressure transmitters the failure rate is $0.3*10^{-6}$ per hour.

The pressure sensors are monitored from the control room and defect sensors can thereby be detected early. A test interval of 24 hours has been used due to this monitoring of the sensors.

The failure rate on demand is $3,6*10^{-6}$.

Leak not detected by pressure transmitters

These pressure transmitters are attached to different valves that when given a signal should shut down the segment where the leakage is situated. The time between when the signal is given until the valves are fully closed and the segment is shut down should not take more than 25 seconds. Emergency shutdown valves (ESV) should have a closing time of 2 seconds per inch if nothing else is specified. This means that a 12 inch valve will be fully closed in 24 seconds.

In the system for both the module and Troll C there are pressure regulators built in. These regulators are there to ensure that the system is operating optimal and works as pressure release for the system. If the pressure in the system is starting to get too high these open and release the overpressure. The disadvantage is that the regulators are trying to keep the pressure constant in the system, which means that the probability for the pressure transmitters to detect a pressure drop is small for a small leakage. The probability values for a pressure transmitter not to be able to detect a pressure drop have been taken from Scandpowers (2006c) risk analysis and are as follows, see Table 6.8.

Table 6.8 Probabilities that pressure transmitters do not detect a leak (Scandpower, 2006c)

Leak sizes	Probability of not detecting a leak (%)
Large	50
Major	65
Medium	75
Small	97,5

ESD panel fails

There is also a possibility that the emergency shut down panel fails to function (this is the connection between the gas panel and the valve that is supposed to close) and the failure rate for this has been taken from Scandpowers (2006b) analysis.

The failure rate for this kind of panel is $3,9*10^{-6}$ per hour.

These are assumed to be tested with an interval of 60 days for the probability of failure on demand.

ESD panel fails $2,8*10^{-3}$.

ESD/PSD valve fails to close

To be able to stop or reduce a leakage the segment where the leak is located must be closed to prevent more hydrocarbons to participate in the leakage or fire. This is done with emergency shutdown valves (ESV). The following values for failure rates have been taken for ESD/PSD ball valves from OREDA (DNV, 2002).

The failure rate for these kinds of valves is $3,36*10^{-6}$ per hour.

These are assumed to be tested every three months and the failure rate on demand will be the following:

ESD/PSD ball valves $3,6*10^{-3}$.

These two systems play an important role in how long the duration will be. If the ESV's for some reason do not close the duration could last for as long as hydrocarbons are entering the leaking system.

Gas detectors fail
There are also gas detectors operating in the process area. These gas detectors are arranged so that at least two gas detectors have to be activated to initiate automatic shutdown of the segment, if only one detector is activated this will result in an alarm. The detectors indicate when a level of 20 % or more of the lower explosion limit has been reached (Rew et al, 2000). There are some factors that influence the probability of gas reaching the gas detectors. In the process area these are mainly:

- Wind speed and direction.
- The ratio between gas and oil but also the leak rate.
- The location of the leak in relation to the detectors position.
- The type of gas detector.

The following value for failure rate of IR point gas detector has been taken from SINTEF (2004):

The failure rate for conventional IR point gas detector is $0,7*10^{-6}$ per hour.

With a test interval of six months the failure rate on demand will be the following:

IR point gas detector $1,5*10^{-3}$.

Gas detector does not detect leak
As mentioned before the gas detectors have some form of probability for not detecting the gas. The values presented for this probability has been collected from HSE (2008c). There are some differences between detecting gas from an oil leak and detecting gas from a gas leak. When analysing the leaks detected by gas detectors it is shown that only half of the detection was made for liquids in relation to gas. Of a total of 1267 gas leaks 735 was detected by gas detectors, making it a 58 % detection probability when gas is released in small and medium leakage. This could be compared to gas detection for liquid leaks where only 160 leaks of a total of 840 was detected by gas detectors, making the probability of detection 20 %. It is however hard to estimate what the probability would be for just gas detection of oil, due to that the theoretic material only present gas detection for all liquids (non process, oil and condensate). The values presented in Table 6.9 below are the probabilities that detectors will not detect a gas leak.

Table 6.9 Probabilities of gas not detecting gas and oil leaks (HSE, 2008c)

Leak sizes	Probability of no gas detection given a gas leak (%)	Probability of no gas detection given an oil leak (%)
Large	1	5
Major	10	20
Medium	30	65
Small	65	90

Gas panel fails

For the gas panel (the node between the gas detectors and the close down system) the failure rate has been taken from OREDA 92.

The failure rate for the gas panel to fail on demand is $5{,}7*10^{-6}$ per hour.

With a test interval of three months the failure rate on demand will be the following:

Gas panel $6{,}2*10^{-3}$.

Operator does not detect leak

Operators play a big role in detecting leaks. In the statistic report from HSE (2008c) it is shown that of the total of 2312 leaks 1411 were detected by operators onboard the platform. This will lead to a total of a 61 % probability that an operator detects a leak. The probability that an operator detects a leak is of course depending on where the leak starts. Despite this the authors have chosen to use this value when estimating the probability that an operator detects a leak for this area. This value is for all hydrocarbon phases and does not make any difference between the sizes of the leaks. It is likely that the probability for an operator to detect a leak becomes greater if the leakage is bigger. It is estimated that the probability for an operator to detect an oil leak is the same as for a gas leak, due to the fact that the oil leaks are more visible and a gas leak on the other hand is easier to smell or hear. For this reason the probability for an operator to not detect a leak is distributed as Table 6.10 shows.

Table 6.10 Probabilities for an operator not to detect a leak at location (HSE, 2008c)

Leak size	Probability that an operator will not detect a leak if present at the location
Large	0,2
Major	0,3
Medium	0,4
Small	0,7

No operator at leak location

It is also estimated that an operator is only present at the leak location 50 % of the time (Scandpower, 2006c).

Detection phase 2 – fire detection

If a leakage occurs, it could ignite immediately or there could be some form of delay time before ignition. If there is a delay time to ignition involving gas leakage this delay time will probably make the formation of a gas cloud possible and when ignited there could be an explosion with a following fire. As mentioned before no consideration will be taken to explosion risks in this paper.

Flame detector fails

There are three different fire detectors used on the Troll C platform; flame, smoke and heat detector. In the process area only flame detectors are used. These flame detectors are linked together so if one detector gives a signal an alarm will go off, but if two detectors give a signal an automatic shutdown will be initiated. The following values have been taken from SINTEF (2004).

The failure rate for a conventional flame detector is $1,6*10^{-6}$ per hour

With a test interval of six months the failure rate on demand will be the following:

Conventional flame detector $3,5*10^{-3}$.

Fire not detected by flame detector

The failure rate is not the biggest problem when calculating the probability of flame detectors not detecting a fire. The biggest problem is to estimate the probability of detection. The smaller a flame is the likelier it is that the detectors will not register the fire. By using data from HSE (2008c) a form of estimation can be made according to how efficient the detectors can detect a fire, see Table 6.11. The data show a slight difference between detection of a gas or oil fire. This difference is not that relevant and will not be taken into consideration in this report.

Table 6.11 Probability of no detection for flame detectors (HSE, 2008c)

Leak sizes	Probability of no detection (%)
Large	10
Major	30
Medium	50
Small	60

6.1.5 Time to detection

This information is good to have when estimating the closure and duration for a leak in the segment. The detection time is very hard to estimate because there is very little material concerning this subject. There are still some parameters that should be included into the discussion about detection time. The leak size should have some effect on the detection time, such as the bigger the leak is the earlier it will be detected. The time is also dependent on how many systems that are able to detect a leak or a fire, including operators. The location of these systems is another factor that affects detection time. For this reason, the times to detection for different leak sizes will be taken from accepted times that have been used before by Scandpower (2006b), see Table 6.12.

Table 6.12 Time to detection for different leak sizes (Scandpower, 2006c)

Leak sizes	Time to detection (seconds)	
	Gas	Liquid
Small	60	240
Medium	30	60
Major	10	20
Large	5	10

6.1.6 Duration for leaks

How long a fire will go on depends very much on the duration of a leakage i.e. how long there will be hydrocarbons leaking from the system. When detection is made and if the segment is shutting down the total mass and volume in the segment will decrease as the leak decreases or because the medium burns off. As soon as detection is made the valves, if they function, in the segment closes and the pressure inside the valves and pipes is reduced. The closing time for valves and reduction time for the pressure relief depends on various things and are somewhat different for the different segments on a platform.

Duration for gas leaks

The gas rate will be reduced as a function of time as soon as the segment is fully closed due to the reduction of gas in the system. For a faster pressure relief the blow down function will be initiated and reduce the leak rate even further. In this report the duration of leaks will be calculated from the leakage start until the time where the leak rate is reduced to 0.05 kg/s. A leak rate smaller than 0.05 kg/s are estimated to generate a jet fire that does not cause any greater danger which is why leak rates below 0,05 kg/s are neglected.

Duration for liquid leaks

For leaks including liquids the leak rate is reduced as a function of time and the duration of this kind of leakage is therefore dependent on the amount of liquid in the segment. The duration is calculated with the following formula (Scandpower, 2006c):

$$\text{DUR}=\frac{Mass}{Q_{initial}} + \text{Time to detection and full closure of section}$$

Mass = Total amount of liquid mass in the sector (kg)
Q_{initial} = Initial rate for liquid (kg/s)

If the leak is involving liquids, it is important to keep in mind that the liquid will remain on deck after it has been released unlike the gas that will "vanish". Accordingly, when calculating with liquid leaks, this has to be taken into consideration.

6.1.7 Deluge systems

To be able to describe the reality through a model like the risk analysis made in this paper all relevant inputs has to be considered to make the model as realistic as possible. This risk analysis has however not included the influence the presence of a deluge system will have on a fire. This decision has been made on the following grounds; first the regulation states that no account can be taken from any possible cooling effects from fire fighting equipment. This statement could both mean the cooling effect that is directed against the fire but also the cooling effect on the steel. The second ground is that estimation on how probable it is for a deluge system to control or put out a fire has been considered too hard to estimate, especially when it comes to different sizes of the leaks that develop into fires. It has also been considered hard to estimate the cooling effect that the water has on the steel structure. By not including the deluge systems into the risk estimation the result of the overall risk analysis will be a bit more conservative.

6.2 Consequence analysis

If a fire should occur the critical temperature for the steel structure has been set to 450°C. This is because the present standard at the main platform uses this as highest allowance criteria (UMOE, 1999). Steel gets affected by a temperature rise but it is not until the steel reaches this critical temperature that the changes are of such degree that it can give the structure permanent damage. The temperature 450°C is actually the temperature where the yield strength of the steel starts to diminish so any eventual load is not taken into consideration since it is only above this temperature the load can make a significant impact on the structural abilities during a fire (Franssen & Zaharia, 2005). A collapse is not the most likely scenario at this temperature but the calculations uses the temperature span up to 450°C as acceptable and if the temperature gets above this temperature the module is assumed to collapse. This is done to simplify the calculations but the results will on the other hand be conservative.

In order to calculate the time interval for the steel beam to reach 450°C the heat flux from the fires must first be established. The equation for the heat energy needed to increase the steel temperature to a certain temperature is then used in order to see the expected time interval to reach 450°C given the presented fire heat flux. The start temperature will be set to 15°C given the North Sea weather conditions. When doing these calculations, it is assumed that only one side of the beam is exposed to the heat flux unless the beam is engulfed in flames where all four sides will be exposed. See the Appendix section for each scenario (Appendix 1-4) for calculations and equations used.

For the overall consequence analysis it has been roughly estimated that if the temperature reaches the critical one for steel a collapse of the module will be the consequence. If the module collapses into the ocean this could threaten the whole platform Troll C. It has however been estimated that if a collapse of the module occurs it is a 50 % probability that it collapses into the ocean instead of into the already existing Troll C. There is however more likely for the module to collapse inwards, i.e. towards the existing platform, because the beams closest to Troll C are the ones affected first hand if a fire develops on Troll C. If a fire develops on the module it has been assumed that there is a 50 percent chance that this fire also affects the beams closest to Troll C.

This assumption has been made on the basis on which direction the jet flame can have and it is estimated that the jet flame can be directed either towards Troll C or the opposite way.

If collapsing into the ocean, instead of in to the already existing platform, it has also been said that this collapse will destroy the riser pipes that deliver hydrocarbons from the bottom of the sea up to the platform. If these riser pipes start a substantial leak of hydrocarbons a pool fire is expected to develop onto the sea and under the platform Troll C. This pool fire is estimated to threaten all the personnel onboard the platform and as a worst outcome, 80 persons could lose their lives.

So for the further analysis regarding RAC, quantification and the cost-benefit analysis the consequence will be that 80 persons could lose their lives if the module would collapse into the ocean.

6.3 Risk acceptance criteria (RAC)

The risk acceptance criteria (RAC) are a way of ensuring a minimum level of safety (Aven, 2007) and this section will present a short background for RAC as well as presenting the RAC for the new module. The RAC will be a part of the total risk assessment.

6.3.1 Background

Norwegian authorities have required the use of risk acceptance criteria for the last 10 years but they were presented as early as in 1980. The acceptance criterion of $1*10^{-4}$ is the one used by the industry to protect people from hazards and it was estimated by calculating the impairment frequency for nine accident types that later on in the process could be disregarded. The regulations also state that an ALARP evaluation of the risks must be made in addition to the acceptance criteria (Aven & Vinnem, 2005). As with all risk assessments a certain amount of uncertainty is included because of among other things assumptions and different sources of information. To be able to fulfill the requirements and acceptance criteria the industry follows the NORSOK Z-013 standard and it states that the uncertainty will be reduced during the progression of the development process and to satisfy the requirements, either more conservatism must be applied in the risk analysis or the acceptance criteria must be fulfilled with some margin (NTS, 2001).

6.3.2 Risk acceptance criteria for new module

The acceptance criterion for the platform as well as the new module has been set to between 1 fatality per 100 years and 100 fatalities per 10000 years (NTS, 2001) and this is due to regulations made by Norsk Hydro (Scandpower Risk Management AS, 2006b).
This means that a risk level below these values should be acceptable and that no further reductions should be needed, which is also in line with the NORSOK Z-013 requirements mentioned above.

6.4 Summary

This chapter should function as the base for the risk estimation part in the risk management model, see chapter 4. The bigger part in this chapter has been handling the frequency analysis and how this has been done. The base in this frequency analysis will start with the event tree, see

Figure 6.1. To this base, fault trees and other values will be connected to be able to get an idea of the scenario outcomes for each leak size in each scenario type. Every value for the different steps in the event tree is explained and every value in the fault trees is also explained.

To be able to calculate the different leak sizes in each scenario type it is important to understand the distinction between distribution size and leak size. It is the leak size that will be calculated in each scenario types and thereby the risk that this leak size constitutes towards the module. This chapter along with Appendix 5 shows how the frequency analysis is meant to be calculated and will be used in the following chapter.

The conclusion in the consequence analysis is that the critical temperature for the steel is set to 450°C and if the temperature in the steel reaches this temperature the module will collapse. The consequence will differ from the different scenario types and also with the different leak sizes.

When the frequency analysis and consequence analysis has been made these two will be weighted together to see if the risk is acceptable on the basis of the risk acceptance criteria being used.

This far in the paper, explanations of the background for this modification and applicable laws and regulation as well as the theory behind the risk management model used in this paper have been presented. The whole risk management model will now be used in the following chapters to find out if an acceptable risk level can be sustained if no PFP is used on the structure of the module (chapter 7). Also a quantification will be made to se how much risk reduction the use of PFP is contributing with (chapter 8) and if it is cost efficient to use PFP as a barrier on the new module (chapter 9).

7 Scenario types

In this chapter the scenario types that constitute a direct relevant threat towards the module are presented. These scenario types are in fact different segments in the near soundings of the module and their exact location will be presented further in the scenario type sections. Every scenario type constitutes its own segment which means that the segment is a redundant part of the process system either on the module or Troll C. The whole process system on Troll C is connected, but if a part of the process system has to be separated, due to for instance a leak, the part that is separated is called a segment.

It is estimated that there are four different scenario types that can constitute a danger/hazard towards the module. Each scenario type can be divided into additional groups of scenarios depending on leak sizes. From these leak sizes five additional different scenarios, from each leak size, are being calculated using the event-tree in Figure 5 (see Chapter 6). This means that a scenario can for example be described as “scenario type 2, leak size medium”. The five different scenarios from the four different leak sizes are then summarized with its own category (1, 2, 3, 4 and 5) to be able to calculate the risk picture for each scenario type, see Figure 7.1 below.

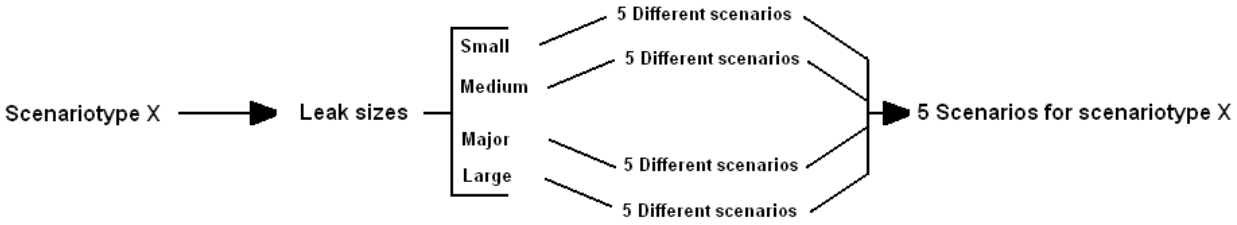

Figure 7.1 Procedure of how frequency rates are being calculated for each scenario type.

The procedure (Figure 7.1) is the same regardless of how many leak sizes that are present in each scenario type. If for example only two leak sizes can develop and are represent able in a scenario type, these two goes through the same procedure (Figure 7.1).

To reach any conclusions concerning how great a risk the module is exposed to if no PFP is used, an analysis of the different possible scenario types that can develop and constitute a threat towards the module has to be evaluated.

The first step in this process was to separate the scenario types roughly into two parts; scenario types that evaluate whether the activities on the module constitutes any threat to itself and if there are scenario types that can evolve on Troll C and possess a threat to the module. The relevant scenario types have been chosen with the following limitation in mind:

Scenario types that can develop and directly threaten the structural integrity of the module, if no other barriers, active or passive, (excluding the ones that are partakers in the process) would be present, shall be included in the risk analysis.

With this limitation it is estimated that four scenario types can constitute a direct threat to the module. These scenario types will be used when evaluating how much the use of PFP will contribute with to the total risk reduction in chapter 8

Every scenario type will be investigated and analysed on the basis of its own conditions which therefore will lead to a risk picture for every scenario type. These risk pictures will then result in a conclusion about if an acceptable risk level can be sustained, for both the module but also for Troll C, if no PFP is used on the module. It will also lead to a conclusion about how much PFP actually is contributing with as a risk reducing barrier, see chapter 8. Finally the use of PFP will be analysed in a cost benefit analysis to see if using PFP is a cost efficient measure, see chapter 9. All these questions will be answered on the basis of analysing each scenario type individually.

7.1 Scenario type 1

The purpose with this scenario type is to evaluate if the risk contribution that the module contributes with towards itself is acceptable. It will also determine with what frequency rate PFP will be needed i.e. with what frequency rate scenario outcome 2 will occur. The purpose is to evaluate whether the module constitutes any danger to itself. That is, how probable is it that a fire occurs on the module that generate more heat flux to the structural steel than it can tolerate before it starts to give in and as a worst consequence, collapses.

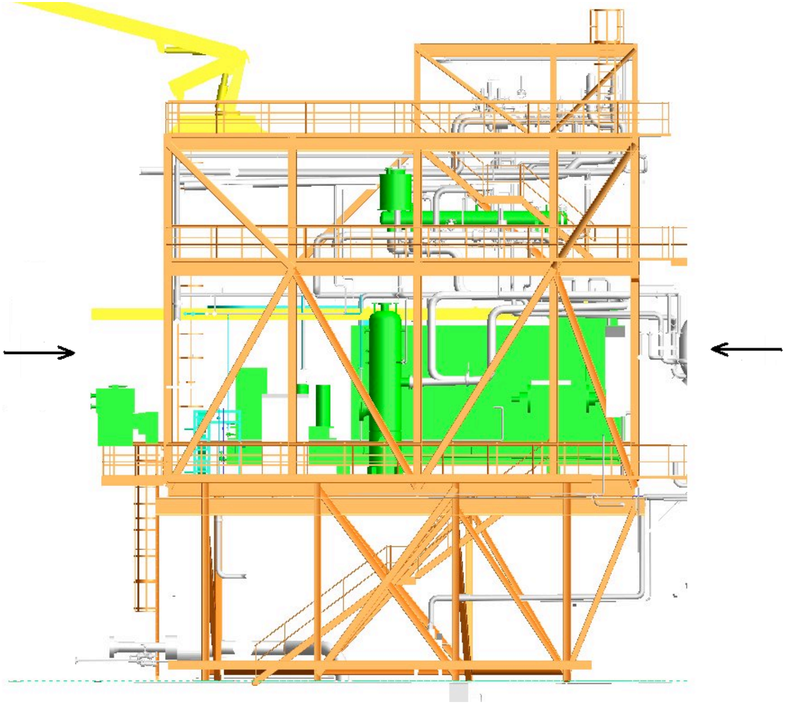

Figure 7.2 Picture of the module with arrows showing the main production area presented in this scenario type (Aker Solutions AS, 2008f)

7.1.1 Risk analysis

The following step constitutes a part of the overall risk analysis and will include the following:

- A system definition
- A hazard identification
- A risk estimation (including consequence analysis, frequency analysis and a risk picture for this scenario type)

The system definition and hazard identification will only include definitions valuable for the purpose of the quantification if any PFP is needed. Because of this only some of the steps required for the risk analysis mentioned in section 4.2.1 will be investigated. The system definition in this scenario type will include the structural system of the module, the ongoing process on the module (the segment) and the different barriers placed in this segment.

System definition - Structural

The module is separated into three different levels; the lower deck, the upper deck and the valve deck. The main structure of the module is built with different steel beams. If a fire occurs on the module due to process failure and ignition, only one type of beam can be exposed to the heat flux. The steel used is "standard steel", i.e. carbon steel (Aker Kværner AS, 2007a) and the beams used for load bearing have an I-profile and the beams are the standardised beams of type HE300A, see Figure 7.3 below. The number in the specification indicates the width of the beam (the width is set as "b" in the figure below). There are box beams present but their only task is stabilisation of the module structure, hence calculations are only performed regarding the load bearing I-beams.

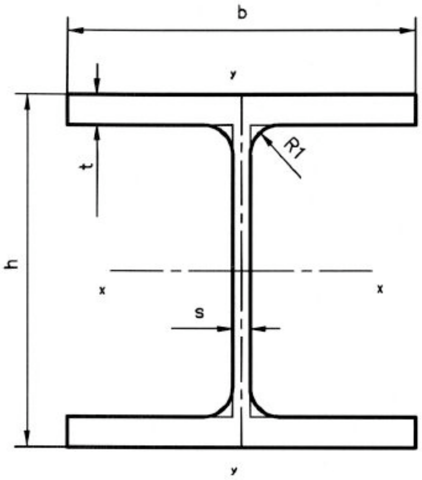

Figure 7.3 HE-Beam (SpontAB, 2008)

System definition - Process

From the test separator, which is located on the platform Troll C, the methane comes into the main process line of the module with a pressure of 6 bars and the main pipes have a dimension of about 12 inches. The mass flow rate is about 5.5 kg/s (Aker Solutions AS, 2008e). First the gas will be cooled of in the heat exchanger. After that it will go into a scrubber where the gas is separated from the oil and water. This follows by the gas going into a compressor where the main pipes dimension is getting smaller, 10 inches and the pressure is rising to about 21 bars (Aker Solutions AS, 2008e). After the pressure rise the gas will once again go to the platform Troll C and to the first stage export compressor. The main process line (segment) through the module consists of different components that all have some form of failure rate that can cause a gas leak and evolve into a jet fire. The numbers of components for the different sizes are listed in Table 7.1.

Table 7.1 Number of components of different sizes used in this scenarios segment

Components	**Size 10”**	**Size 12”**
Valves (number)	5	8
Flanges (number)	1	5
Pipings (meter)	15	20
Compressor (number)	1	
Heat ex (S&T)		1
Vessel		1

System definition - Barriers

The system consists of different barriers and these include, among other things, two pressure transmitters. One is located just before the compressor and the other one is located right after the compressor. This means that they are responding to different pressure drops caused by for instance a leak. There are also gas detectors and infrared flame detectors located in the modules process area (Grande, 2008).

The system consists of two emergency shutdown valves that constitute the boundaries for this segment. These emergency shutdown valves can be fully closed in about 20-24 seconds and thereby makes the segment redundant (Scandpower, 2006b). The flow in the system will have one direction and if a leak occurs there are check valves controlling that the flow does not swift direction.

Hazard identification

The substance that runs through the main pipe is methane gas, but there are also some amounts of water and oil. The presence of water is assumed to decrease the chance of the gas to ignite and at the same time, if ignited, to prevent developing as high a heat flux as ignited gas alone. This has not been taken into consideration in the calculations, because it is hard to estimate the proportions of the mixture of gas, oil and water. It is also a problem to estimate how much influence the water has in this scenario when considering the ignition probability as well as the expected heat flux if ignited. There is also not so much information on this subject available. By not including water in the calculations this will make the calculations a bit more conservative.

The scrubber on the module is the part of the module that contains the most oil but also with large quantities of water present. For the most part the volume of oil is 1 – 1,5 m^3 (Grande, 2008). This oil will not be considered to constitute any threat to the structure of the module if released and ignited. This is due to the low amount of oil and because there are drainage boxes located under the scrubber, which will take care of the oil if released that hinders any large pool build-ups.

7.1.2 Risk estimation

This part can be considered to constitute the core of the risk analysis, due to its importance when estimating the risk. It consists of a consequence analysis and a frequency analysis that will put together and form a risk picture for this scenario type.

Consequence analysis

Since gas is the main medium present through the piping on the new module some sort of jet-fire is assumed to be the only event that can happen. The heat radiation due to the jet-fires was calculated for methane gas and the jet-fires are expected to reach a total heat flux of 140 kW/m^2. The steel, if exposed to this heat flux, reaches the critical temperature of 450°C after approximately 7,5 minutes if only one side of the beam is exposed to the heat flux.

If a minor leak would occur the mass flow will be less than 0,05 kg/s and, because of the assumptions made earlier in section 6.1.1, these can be neglected. Because of the small volume of this segment, 5 m^3, every other type of leak, major or rupture, will only go on, if detected and if closed down, for a short period of time before the system is empty. The small amount of gas in the system also has an influence on the mass flow. If the leak is of such size that the initial mass flow is for instance of size major or large the initial release will deplete a large part of the gas in the system in just a couple of seconds at the most, reducing the mass flow as well as the pressure.

Since the theoretical mass flow for the larger leak sizes are larger than the incoming mass flow to the system, 5,5 kg/s, the result of the leak will almost instantly be reduced to a medium leak, 5,5 kg/s, even if the theoretical value should indicate a larger leak. Because of this the leak size frequencies will be regarded just as the theoretical figures suggest, however the consequence will be regarded as that of a medium leak, 5,5 kg/s. All large size leaks can be observed as one entity because the release will in a very short amount of time, independently of the piping size, be reduced to the mass flow that goes into the system due to the large initial release rate.

Since the possible leak sizes will release a very large amount of gas initially the detection will probably be fast and let the close down process begin at an early stage. This makes the total duration for the gas release to take approximately 1 minute or less. Since this short timeframe applies, none of the leak sizes in this scenario type constitute any danger towards the modules structure if the gas release from this segment is detected and the segment is closed down.

Tabel 7.2 Mass rates, radiation, depletion times and durations for different hole sizes

Hole size	**Mass rate (kg/s)**	**Radiation from flame front (kW/m^2)**	**Time to initial depletion of system (s)**	**DUR (min)**
Minor	0,046 (neglected)	140	-	-
Major 10-Inch	18,7 (initial)	140	3	~0,5
Major 12-Inch	9,1 (initial)	140	3	~1
Rupture 10-Inch	5,5	140	Instantly	~1
Rupture 12-Inch	5,5	140	Instantly	~1

Frequency analysis

The frequency analysis is based on fault-trees and an event-tree, see Figures 6.1-6.3. These aims to describe with what frequency rate leaks that ignite can occur and what the frequency rate becomes if leaks are detected and closure is initiated. The closing time has been estimated to take approximately 1,5 minutes, for calculations see the Appendix section. It has also been said in the consequence analysis that the steel beams can manage for 7,5 minutes (see Appendix section) before reaching the critical temperature. This means that a collapse is bound to happen with the frequency the duration has if the jet fire goes on for more than 7,5 minutes.

In this scenario, three different initial leak sizes are most likely to occur, namely medium, major and large leaks. The frequency rates for the different outcomes are presented in Table 7.3.

Table 7.3 Frequency rates for different outcomes in scenario 1

Leak size (leak frequency, per year)	**Duration (minutes)**	**Frequency rate (per year)**
Medium ($4,7*10^{-3}$)	0 – 7,5	$9,6*10^{-6}$
	7,5 - 20	$8,0*10^{-8}$
Major ($5.4*10^{-3}$)	0 – 7,5	$5,2*10^{-5}$
	7,5 - 20	$6,3*10^{-7}$
Large ($8.4*10^{-4}$)	0 – 7,5	$1,8*10^{-5}$
	7,5 - 20	$7,9*10^{-9}$

Risk picture for scenario type 1

The total risk picture for this scenario would evaluate whether it is acceptable or not to exclude PFP as a barrier by measuring the total frequency rate when PFP is needed. The total frequency rate for a possible collapse when not using PFP that could lead to a dangerous scenario for the whole platform Troll C is approximately $7,2*10^{-7}$ per year. This value will be used in the quantification part to see how much risk reduction implementation of PFP really gives.

This scenario could, if leading to a collapse mean that the 80 persons onboard lose their lives.

7.2 Scenario type 2

This scenario type is one of three scenario types intended to evaluate if an event of some sort can develop on the Troll C platform that can constitute any danger for the new module. This by showing how probable it is that a fire occurs that generates more heat flux to the structural steel than it can tolerate before it starts to give in and as a worst consequence, collapses. In this scenario type the investigation will be aimed at the 1st stage separator located on the upper deck on Troll C. This is to see if it constitutes any danger to the module if a leak occurs that ignites.

7.2.1 Risk analysis

The following step constitutes a part of the overall risk analysis and will include the following:

- A system definition
- A hazard identification
- A risk estimation (including consequence analysis, frequency analysis and a risk picture for this scenario type)

The system definition and hazard identification will only include definitions valuable for the purpose of the quantification if any PFP is needed. Because of this only some of the steps required for the risk analysis mentioned in section 4.2.1 will be investigated. The system definition in this scenario type will include the structural system of the module, the ongoing process on the module (the segment) and the different barriers placed in this segment.

System definition - Structural

The module will be located on the upper deck on the platform Troll C where it will be a part of the platform as a whole. The upper deck is where the main production on the platform takes place and it is also here the module foundation is located. The main foundation structure of the module is built with different steel beams and the total number of beams is eight, see Figure 10. The steel used is “standard steel”, i.e. carbon steel. The beams used have a box-profile (dimensions 300x300x10 or 300x300x16), and the beams closest to Troll C have the dimension 300x300x10 (Grande, 2008). According to Grande (2008) the two beams in the aft corners of the module have the larger dimension (300x300x16) but the other beams are located in such a way that the possible heat flux will affect these beams first and because they are thinner the critical temperature will be reached faster in these beams. This makes them more critical regarding collapse. The structure is said to be dependent of every single beam supporting the module hence no beam is allowed to give in. This has been said to simplify the calculations regarding structural collapse. Hence the calculations are based on the thinner steel beams managing time.

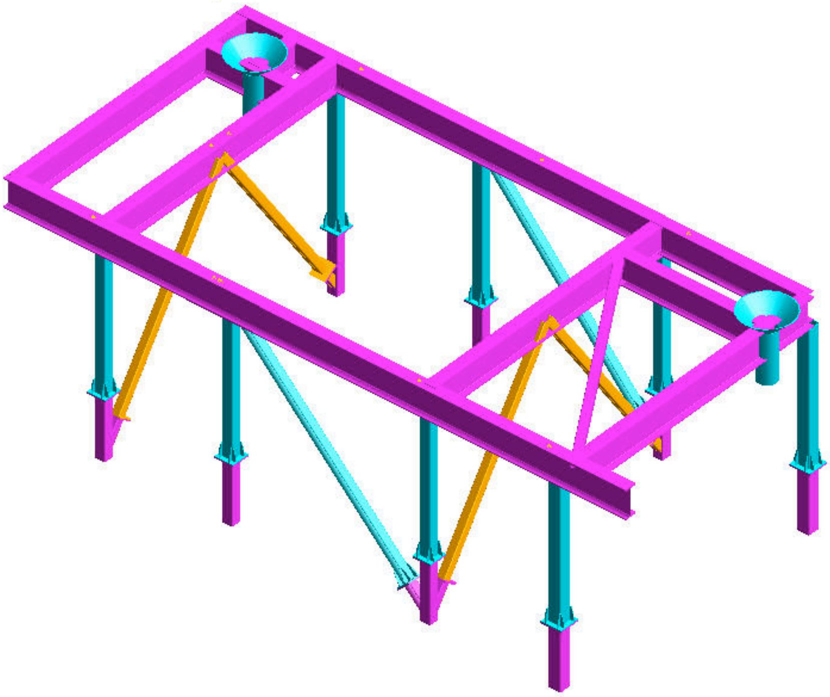

Figure 7.4 Picture of the support frame for the module showing the vertical beams of interest for the following scenario types (Aker Solutions AS, 2008f)

System definition - Process

Most of the substance in the 1st stage separator comes from the production and test manifolds on Troll C and for this reason the 1st stage separator consists of methane gas, crude oil and water. The pressure inside the system in this segment is 17 bars and the dimensions of the different components have been estimated to have a size distribution that varies between 0.6, 3, 8 and 16 inches. From the 1st stage separator the different mediums will as the name implies be separated from each other. The different mediums will then be transported into other locations on the platform. The values for the quantities of the components have been taken from Scandpower (2006b) and they are presented in Table 7.4 below.

Table 7.4 Number of components of different sizes used in this scenarios segment

Components	**Size 0,6”**	**Size 3”**	**Size 8”**	**Size 16”**
Valves (number)	27	34	8	20
Flanges (number)	2	69	16	38
Pipings (meter)	15	30	10	60
Vessel				1

System definition - Barriers

The segment consists of different barriers and these constitute, of among other things, of pressure transmitters. There are also gas detectors and infrared flame detectors located in the modules process area (Grande, 2008).

The system consists of two emergency shutdown valves that constitute the boundaries for this segment.

There are also drain boxes placed in the near surroundings of the 1st stage separator. These drain boxes can be seen as a passive protection system and the four drain boxes can together absorb 0,11 m^3/s fluid (Aker Maritime, 1998). This installation prevents a pool formation from a leak to expanding uncontrollably and thereby confines a pool-area to a maximum of approximately 100 m^2. The total pool area has been estimated on the basis of the area inside the drain boxes. Accordingly, in this scenario type it is assumed that these drain boxes constitute the limitation for how far the oil can reach in relation to the module and how big the pool area can be. To simplify the calculations the squared-shaped area has been translated into an equivalent circular one.

Hazard identification

The first stage separator is located fifteen meters from the modules front beams (closest to Troll C), see figure 7.5 below, and it contains crude oil, methane gas and water with the distribution of 1/3 of each. The segment including the separator has a total volume of 220 m^3 and contains approximately 173 000 kg of hydrocarbon and water according to the Scandpower (2006b) report.

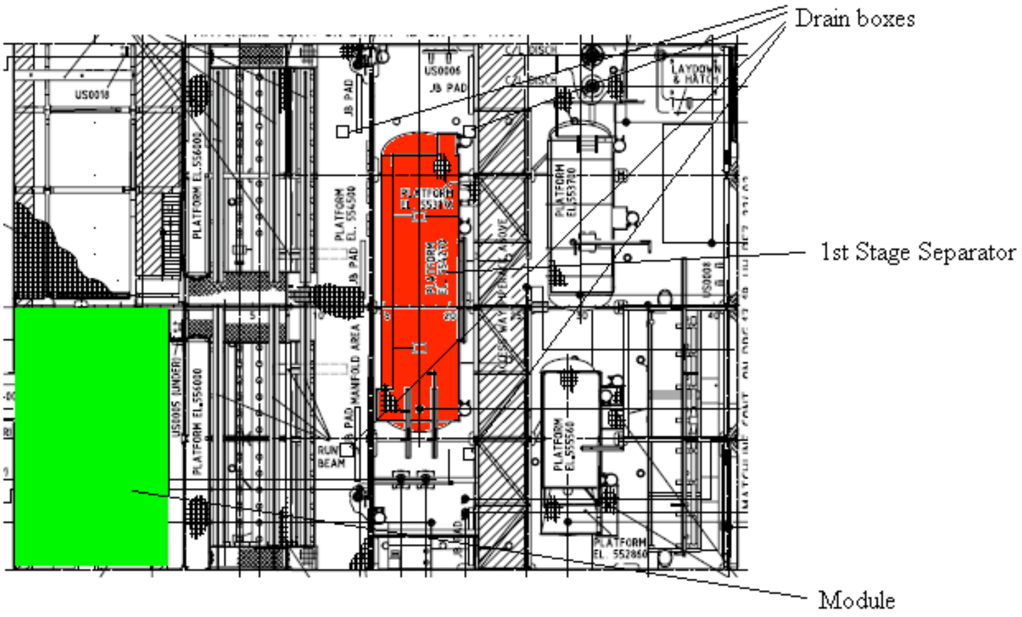

Figure 7.5 Upper deck seen from above. Green field shows area of the module and red indicates the danger (UMOE, 1997a)

The main hazard is assumed to be a pool with crude oil as a result of a leak. If the separator or components in this segment gets damaged in some way, with a resulting leak, the great volume can present a possible risk of a large pool build-up with the possibility of a pool fire if ignited.

It should also be noted that if a leak occurs and the segment is fully closed all the medium inside the closed segment will leak out, so in this scenario type approximately 58 000 kg of oil will come out of the segment and onto the platform even if fully closed.

7.2.3 Risk estimation

This part can be considered to constitute the core of the risk analysis, due to its importance when estimating the risk. It consists of a consequence analysis and a frequency analysis that will put together and form a risk picture for this scenario type.

Consequence analysis

Because of the great distance between the module and the separator approximately 15-20 meters, the possibility of a jet fire is ignored. This because there are many obstacles between the 1st stage separator and the module that inhibits free passage for the flame, like for instance the production manifold. Therefore it is not likely that a jet fire from the 1st stage separator may hit or come in contact with the module. For reasons like this, events that include jet fires are disregarded.

The different properties of the pool-fire were calculated, see Appendix 2, and the resulting radiation from the fire to the front row beams could be estimated to be approximately 16,1 kW/m^2. This is because the drain boxes are limiting the size of the pool. As described before the critical steel temperature for the steel beams is 450°C. Therefore calculations must be performed to see what time-frame that applies for the steel to reach this temperature due to a pool-fire with an area of 100 m^2. When exposed to this heat flux the steel can withstand the heat and will not rise to the critical temperature for approximately 66 minutes which is acceptable seeing to the required 60 minutes when exposed to a pool-fire (UMOE, 1999). No further calculations will therefore be performed for the different leak sizes concerning the duration and the burning time. This means that no dangerous consequence regarding the modules structure exist for scenario type 2.

Frequency analysis

The frequency analysis is based on fault-trees and an event-tree, see Figures 6.1-6.3, and aims to describe with what frequency rate leaks that ignite can occur and what the frequency will be if detected and a closure is initiated.

Due to the consequence and the fulfilment of the time limit that shows that the structural elements on the module can withstand the heat flux from a pool fire for more than 60 minutes, this scenario type, if doing just a risk analysis, would not need further evaluation about the frequency rates. But for the quantification about the risk reduction with PFP (chapter 8) this scenario type and the frequency rates it represents has to be presented.

In this scenario type, four different initial leak sizes are the most likely to occur and these are small, medium, major and large. The frequency rates for the different outcomes are presented in Table 7.5.

Table 7.5 Frequency rates for the different outcomes in this scenario

Leak size (leak frequency, per year)	**Duration (minutes)**	**Frequency rate (per year)**
Small	> 60	$4,8*10^{-6}$
Medium	> 60	$6,3*10^{-6}$
Major	> 60	$2,9*10^{-5}$
Large	> 60	$5,6*10^{-5}$

Risk picture for scenario type 2

The total risk picture for this scenario, for the purpose of a risk analysis, shows that it is acceptable to not include PFP as a barrier and this case has been evaluated to not constitute any risk to the module. For an overall quantification about risk reduction using PFP the values presented in this scenario type will be used.

7.3 Scenario type 3

This third scenario type will evaluate whether the production on Troll C, and more specifically the test and production manifold on Troll C, can constitute any danger to the module if a fire occurs. This will be evaluated by calculating the probability that a fire occurs and generates more heat flux to the structural steel than it is estimated that it can tolerate before it starts to give in and as a worst consequence collapses.

7.3.1 Risk analysis

The following step constitutes a part of the overall risk analysis and will include the following:

- A system definition
- A hazard identification
- A risk estimation (including consequence analysis, frequency analysis and a risk picture for this scenario type)

The system definition and hazard identification will only include definitions valuable for the purpose of the quantification if any PFP is needed. Because of this only some of the steps required for the risk analysis mentioned in section 4.2.1 will be investigated. The system definition in this scenario type will include the structural system of the module, the ongoing process on the module (the segment) and the different barriers placed in this segment.

System definition - Structural

The module is located on the upper deck of the Troll C platform in the aft section. This is also where the foundation of the module is located and it consists of eight box beams, six of them are RHS300x10 beams and the remaining two are RHS300x16 beams (Grande, 2008). The latter beams have their placement in the left and right corner of the module in the aft. The steel used is standard structural steel, i.e. carbon steel (Aker Kværner AS, 2007b), the first number in the specification name indicates the width of the beam (300 mm) where the last number in the specification name indicates the thickness of the steel (10 or 16 mm). The structure is dependent of every single beam supporting the module and hence no beam is allowed to give in. This has been said to simplify the calculations regarding structural collapse when this is considered. This makes the thinner of the beams the limiting ones because of their thickness.

System definition - Process

The production and test manifold is one of the most important components used in the oil recovery process. The test and production manifold is made up of a number of different stations that are used to control the flows from the individual wells from the bottom of the sea that goes into the production and test headers. The dry completion wells on the main field centre are fed directly into the production manifolds (Devold, 2006) and from there it goes on to the 1st stage separator, presented in scenario type 2.

The substance coming into the manifolds comes directly from the wells and consists of methane gas, crude oil and water. It is estimated that the distribution between the different mediums is 1/3 of each (Grande, 2008). The pressure inside the system in this segment is 20 bars and the dimensions between the different components have been estimated to have a size distribution that varies between 2, 6, 10 and 36 inches. The following values for the component quantities have been taken from Scandpower (2006b) and are presented in Table 7.6 below.

Table 7.6 Number of components of different sizes used in this scenarios segment

Components	Size 2”	Size 6”	Size 10”	Size 36”
Valve (number)	54	7	37	1
Flange (number)	43	9	77	2
Pipings (meter)	30	10	40	60

System definition - Barriers

The segment consists of different barriers and these constitute, of among other things, of pressure transmitters. There are also gas detectors and infrared flame detectors located in the modules process area (Grande, 2008).

The system consists of two emergency shutdown valves that constitute the boundaries for this segment and makes the segment redundant.

Next to and along the module there is a brink. This brink is approximately 10 centimetres high and can be said to function as a passive barrier between the manifold and the module. On the side where the manifold is placed there are drain boxes. It is assumed that this brink will hinder leaking oil from spreading out under the module and that the leaking oil will drain down in the drain boxes. In this scenario type there are only two drain boxes and these can together absorb 0,05 m^3/s (Aker Maritime, 1998).

Hazard identification

The test and production manifold is located just beside the module and the distance between them is approximately 5 meters. As mentioned in the system definition for process, this segment contains methane gas, crude oil and water, distributed 1/3 of each medium. The segment contains a total of 15 450 kg of hydrocarbon and water and has a total volume of 130 m^3 (Scandpower, 2006b).

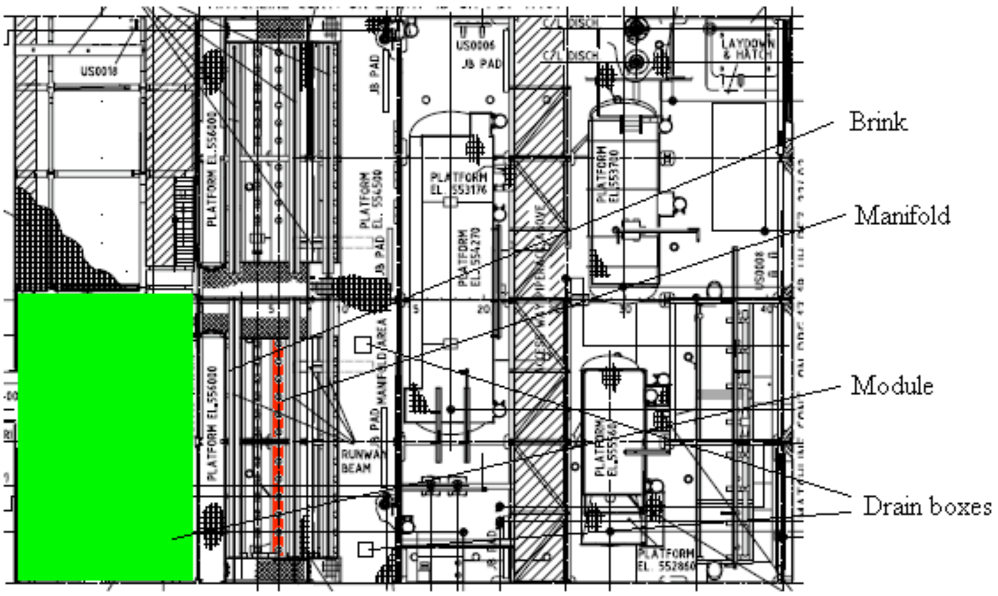

Figure 7.6 Upper deck seen from above. Green field shows area of module and red indicates danger (UMOE, 1997a)

It should also be noted in this scenario type that if a leak occurs and the segment is fully closed, all the medium inside the closed segment will leak out, so this will mean that approximately 5150 kg oil and the same amount of methane gas will come out.

7.3.2 Risk estimation

This part can be considered to constitute the core of the risk analysis, due to its importance when estimating the risk. It consists of a consequence analysis and a frequency analysis that will put together and form a risk picture for this scenario type.

Consequence analysis

The short distance between the manifold and the module, and the fact that this segment contains all three mediums makes it very possible that a jet fire and a pool fire can develop at the same time if a leak occurs and ignites. As in scenario 2 a full rupture will only go on for a couple of seconds and will release most of the pressure inside the system.

The proportions of the mixture of the two mediums (gas and crude oil) is quite hard to calculate, therefore calculations have been made for methane gas and crude oil separately. All large size leaks from the different component sizes will be observed as one entity. This is due to the large initial release of the systems medium. The release will in a very short amount of time be reduced to the mass flow that goes into the system independently of the piping size. For calculations, see Appendix 3.

Jet fire

The only chance for the module to collapse outwards is if the aft beams are affected first hand and this can only be achieved if some form of jet fire directly hits one of these beams. The calculations for jet fires show that the radiation from the flame will be approximately 140 kW/m^2, the same as in scenario type 1. However it is not likely that methane gas is the only medium that will burn. In a report from SINTEF, also mentioned in section 4.3.1, experiments show that the surface emissive power for jet flames with a gas oil mixture can reach between 203 and 409 kW/m^2. The emissive power depends on the distribution between gas and oil, but also on the release pressure (SINTEF NBL A/S, 2008b). For this reason the dimensioning accidental loads in the NORSOK S-001 standard (NTS, 2000) is used, see section 3.1.3. These calculations will be conservative and it should be noted that no account has been taken for the water that also is a part of the gas and oil mixture. If using the dimensioning accidental loads the steel beams can withstand the heat flux for approximately 3-4 minutes (the 10 mm beams) or 4-6,5 minutes (the 16 mm beams) before reaching the temperature of 450°C depending on whether the radiation is 350 or 250 kW/m^2. Leak sizes accounted for with this fire load will be small and medium.

For large hole sizes the pressure drop will be quick and this will reduce the mass rate significantly where the calculated mass flow is larger than the incoming mass flow in the system, 200 kg/s (UMOE, 2000). For the smaller calculated mass flows the hole will be the limiting factor for the mass flow. A large leak will go on for a maximum time of 1,5 minutes if detected and closed down and is estimated to not pose as a threat considering the steels managing time.

As described before the only sizes of holes that present leaks that can mean any danger towards the module are leaks from small, medium and major hole sizes. Calculations do show that a minor distribution size could result in a small leak with a mass flow of 0,054 kg/s which is just above 0,05 kg/s which is the limit for a neglected leaks. Considering that oil, water and gas are present at the same time with an even distribution of 1/3 of each, as all three mediums will be released through the hole at the same time which means that not all substances that are released through the opening is gas. This fact should make the mass rate of 0,054 kg/s be considered as equivalent to a mass rate below 0,05 kg/s and therefore be neglected.

Depending on the dimensions of the piping the mass flow varies. For 2 inch piping the result will be a small leak, 0,88 kg/s, that with the amount of gas present could go on for approximately 99 minutes if detected when not including the blow down function. If a jet fire should form this would result in a jet fire with the heat flux 250 kW/m^2 when using dimensioning accidental loads from NORSOK, (see section 3.1.3), which the steel can manage for approximately 4 or 6,5 minutes depending on the thickness of the beam. Detected or not this leak would still pose as a threat to the module because of the long duration with a possible structural collapse.

If the same should happen with 6 inch piping the resulting mass flow would be considered medium, 8 kg/s, and if ignited the heat flux will be 350 kW/m^2 when using the dimensioning accidental loads from NORSOK, see section 3.1.3. This jet fire would go on for approximately 11,5 minutes if detected where the steel only can manage approximately 3 or 4 minutes depending on the beam thickness, making structural collapse possible even if detected and closed down. A major distribution size for 10 inch piping would also result in a major leak with a mass flow of 22 kg/s. The resulting jet fire heat flux would be 350 kW/m^2 and it would go on for about

4,5 minutes if detected. The steel can manage approximately 3 or 4 minutes with this heat load before a possible structural collapse occurs, which also makes such a leak not acceptable. The possible leak from the 36 inch piping should only go on for approximately 2 minutes if detected.

Table 7.7 Summary of the gas leaks

Distribution size	Mass rate (kg/s)	Leak size	Radiation from flame front (kW/ m^2)	Duration if detected (min)
Minor	0,054 (neglected)	-	250	-
Major 2-Inch	0,88	Small	250	~99
Major 6-Inch	7,95	Medium	350	~11,5
Major 10-Inch	22,03	Major	350	~4,5
Major 36-Inch	285,6 (initial)	Large	350	~2

Pool fire

When it comes to pool fires the limitation for the area will be the drain boxes as in scenario type 2, however there are only two drain boxes functioning in this scenario. The other limitation for the pool area will be the brink that runs along the module. If the liquid medium reaches the brink and not past it, which has been assumed, the steel beams will be exposed to a heat flux of 70,2 kW/m^2 and it takes approximately 15 minutes until the steel beams reaches a temperature of 450°C with this heat load. According to NMD (Norwegian Maritime Directorate) requirements evacuation of a platform must be possible to perform within 15 minutes of the given alarm (HSE, 2008e) and this makes pool fires for this scenario type acceptable regarding the given requirements but then, no leaks can ever be considered acceptable. The two time-frames are admittedly the same but if some form of fire occurs due to ignition of the leaking manifold the beams closest to the manifold will be the first that gets affected. This fact makes a collapse inward, i.e. towards Troll C, the most probable. This is the same for all pool fires in the scenario type since the heat intensity is larger closer to the fire and decreases with the distance from it. From this statement conclusions can be made that pool fires originating from the manifold can make the module collapse but it will not collapse outwards and therefore not endangering the lives of all Troll C personnel. Even if this evaluation has been done the different times that apply for each leak size will still be presented since some form of collapse still is possible.

A minor distribution size can be neglected due to that its mass rate is below 0,05 kg/s. Calculations show that a leak with a rupture distribution size for 2 inch piping will go on for a maximum time of approximately 7 minutes including the burning time for the pool and for increased piping size this time frame changes to approximately 5 minutes.

If a leak with a major distribution size in a 10 inch piping occurs it leads to a major leak size, 11,8 kg/s, that can continue for approximately 15 minutes. Together with the burning time for the oil and the detection time this would equal approximately 19 minutes where the steel manages for 15 minutes which makes such a leak not acceptable and is estimated to constitute a threat to the module.

There are only 2 more leak sizes that at first can seem to be a danger to the module. These leaks will not reach the brink and the size of the pool is assumed to be limited by the burning rate. The first is a major distribution size that results in a small leak, 0,47 kg/s, which if ignited would go on for approximately 374 minutes with a heat flux of 4,2 kW/m^2. A heat flux of this size can go on for approximately 253 minutes before the steel gives in. But even if this time-frame is smaller than the leak time it is well above 60 minutes which is the required time-frame (NTS, 2006). The second distribution size is also a major that results in a medium leak size, 4,3 kg/s, and it continues for 45 minutes with the heat flux 29 kW/m^2. The steel can withstand this heat flux for approximately 37 minutes. This makes such a leak not acceptable regarding the time to reach the critical temperature and it is estimated to constitute a threat to the module.

Table 7.8 Summary for the oil leaks

Hole size	**Mass rate (kg/s)**	**Type of leak**	**Radiation from flame front (kW/ m^2)**	**DUR + oil burn time (min)**
Minor	0,03 (neglected)	Small	-	-
Major 2-Inch	0,47	Small	4,2	~374
Major 6-Inch	4,3	Medium	29	~45
Major 10-Inch	11,8	Major	70,2	~19
Major 36-Inch	153	Large	70,2	~6

Frequency analysis

The frequency analysis is based on fault-trees and an event-tree, see Figure 6.1-6.3, and it aims to describe the frequency rate of leaks that ignite. In three of the leak sizes (small, medium and major) it does not matter if the leak or fire is detected and an initiation of a closure of the segment starts. This is due to the large amount of hydrocarbons (gas and oil) in this segment. For a large leak size consideration has been taken for detection and closure of the segment.

In this scenario the frequency rates for leaks has only been done for gas as a medium. This is because the leak frequencies are the same for oil and gas but gas gives the worst consequence towards the object investigated. The ignition probability for gas is somewhat larger than the one for oil which will make the ignition probability more conservative. In Table 7.9 frequency rates for different gas leak sizes will be presented.

In the frequency rate presented (for leak size small, medium and major), it has only been calculated that a gas leak occurs and ignites.

If a gas leak ignites and forms a jet fire it is estimated that the probability that this jet fire will hit the module is 50 %. This estimation has been done on the basis of the location of the test and production manifolds versus the module. Instead of the jet fire pointing against the module, the jet fire can just as well be pointing into the already existing platform and thereby not constitute a threat to the module.

So in the frequency rates presented this 50 % possibility is included.

Table 7.9 Frequency rates for different gas leak sizes

Leak size (leak frequency, per year)	**Duration (minutes)**	**Frequency rate (per year)**
Small	> 4	$3{,}1*10^{-6}$
Medium	> 3	$1{,}5*10^{-5}$
Major	> 3	$5{,}5*10^{-6}$
Large	0 – 3	$9{,}1*10^{-5}$
	3 - 20	$1{,}8*10^{-8}$

Risk picture for scenario type 3

The total risk picture for this case evaluate whether it is acceptable or not to exclude PFP as a barrier by measuring the total frequency rate when needed. The total frequency rate for a possible collapse when not using PFP that can lead to a dangerous event for the whole platform Troll C is approximately $2{,}4*10^{-5}$ per year. This value will be used in the quantification part to see how much risk reduction the implementation of PFP really gives.

7.4 Scenario type 4

The fourth and final scenario type will evaluate if the oil export pipe located between the new module and Troll C constitutes any danger to the module if a leakage occurs that ignites. To estimate this danger the probability of a pool fire that develops under the module will be investigated as well as how hazardous an eventual pool fire might be. This in the essence of that the fire generated heat flux might exceed the steels tolerance and lead to a structural collapse.

7.4.1 Risk analysis

The following step constitutes a part of the overall risk analysis and will include the following:

- A system definition
- A hazard identification
- A risk estimation (including consequence analysis, frequency analysis and a risk picture for this scenario type)

The system definition and hazard identification will only include definitions valuable for the purpose of the quantification if any PFP is needed. Because of this only some of the steps required for the risk analysis mentioned in section 4.2.1 will be investigated. The system definition in this scenario type will include the structural system of the module, the ongoing process on the module (the segment) and the different barriers placed in this segment.

System definition - Structural

The module is located on the upper deck of the platform Troll C in its aft section. This is also where the foundation of the module is located and it consists of eight box-beams, six of them are RHS300x10 beams and the remaining two are RHS300x16 beams. The latter beams have their placement in the left and right corner of the module in the aft. The steel used is standard structural steel, i.e. carbon steel (Aker Kværner AS, 2007b), and the first number in the specification name indicates the width of the beam (300 mm) where the last number indicates the thickness of the steel (10 or 16 mm). The structure is said to be dependent of every single beam supporting the module as being said in the limitations section and hence no beam is allowed to give in. This makes the thinner of the beams the limiting ones.

System definition - Process

The oil that is separated in the first part (1^{st} stage separator) of the process is exported to the second stage (2^{nd} stage separator) of the process using the oil export pipe that is being investigated in this scenario type. The second part of the process is where the finer separation process takes place so the main medium transported in the piping is oil (Devold, 2006). This means that insignificantly small amounts of gas and water could be present which is why the calculations performed in this scenario will assume crude oil as the only present medium. The pressure inside the system is 2 bars and the section of piping that runs next to the module has the dimension 8 inches. The total length of the 8-inch piping is approximately 100 meters (Grande, 2008) and this dimension is the only one used in this scenario. The actual width of the module is approximately 20 meters but to provide conservative results the whole 8-inch piping length (100 m) is used.

System definition - Barriers

The segment consists of different barriers and these constitute, of among other things, of pressure transmitters. There are also gas detectors and infrared flame detectors located in the modules process area (Grande, 2008).

The system consists of two emergency shutdown valves that constitute the boundaries for this segment and makes the segment redundant.

The brink discussed in scenario type 3 is located below the oil export pipe and it is assumed that this brink will not work as a barrier in this scenario type. This because a leak above the brink might fill both sides of the by the brink separated upper deck. With the large amounts of hydrocarbons present in this segment this barrier will not make any difference. For conservative results for the calculations the total mass flow is assumed to only fill the area under the module. There are drain boxes on the upper deck but not in the exact vicinity of the module which makes it possible for the oil to spread onto the upper deck until any drain boxes appear. This means that there is a possibility of the whole area under the module getting filled with oil in case of a leak.

Hazard identification

The oil export piping belongs to the segment that contains most of the oil on Troll C. It contains a total of 639 119 kg crude oil with the total volume of 744 m^3 and only 116 kg gas (Scandpower, 2006b). The small amount of gas in comparison to the oil makes the gas insignificant compared to the oil and is therefore neglected in this scenario type. The segment is located both on the upper deck but also on the mezzanine deck (which is above upper deck). What this means is that if a leakage occurs on the upper deck and the segment gets fully closed all the oil will still eventually be released onto the deck (upper deck on Troll C) (Scandpower, 2006b). If a leakage of distribution size major or rupture will occur the oil can eventually cover the whole area under the module which if ignited can result in a pool fire affecting the foundation of the module.

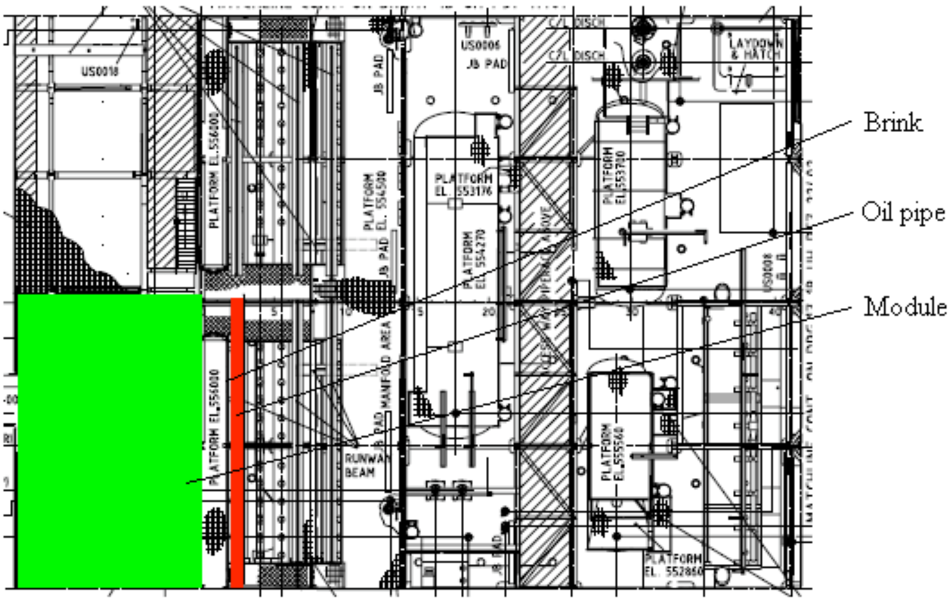

Figure 7.7 Upper deck seen from above. Green field shows area of module and red indicates danger (UMOE, 1997a)

7.4.2 Risk estimation

This part can be considered to constitute the core of the risk analysis, due to its importance when estimating the risk. It consists of a consequence analysis and a frequency analysis that will put together and form a risk picture for this scenario type.

Consequence analysis

As mentioned before the large quantity of oil compared to gas makes oil the only medium taken into consideration in the calculations for this scenario type. For the calculations, see Appendix 4.

If a pool fire should start under the module there will be no limitations for the pool to increase in size so that it eventually covers the whole module foundation. This of course depends on the size of the leak. A small leak size has a mass flow rate of 0,0065 kg/s, which can be neglected since all leakages below 0,05 kg/s can, given the assumptions in section 6.1.1, be neglected.

If the leak size should increase to either the size medium or large the time until the oil covers the whole module foundation is not very long. For a medium leak size this time frame is approximately 13 minutes and for a large leak size only 6 seconds. When engulfed in flames from a pool fire the heat flux will be approximately 109 kW/m^2. The absorption surface increases (four sides of the beam compared to only one in the other scenario types) which gives the steel beam only approximately 2,5 minutes before it reaches the critical temperature (450°C) and gives in.

Because of the large sizes of leaks the pool formation takes little time and given the large quantity of oil in the segment the oil will continue to fill up the pool and thereby maintaining the pool area for quite some time. Together with the oils burning time this time would equal approximately 6271 minutes for a major 8-inch distribution size and 55 minutes for a rupture 8-inch distribution size, making such leaking events not acceptable considering the time it takes for the steel to reach the critical temperature. The theoretical duration of 6271 minutes is of course not very likely since this equals about 5 days but since the pool build up is so fast for both medium and large leak sizes, whereas the steel only manages for the short time frame of 2,5 minutes, such big leaks will still be critical. These calculated leak durations do not consider the oil leaking further away from the area beneath the module (the foundation). Some of the oil will flow further out on upper deck as well as into the sea and not be contained in the area under the module as these calculated durations imply. How the actual oil flow will be in scenario type of a leak is very hard to predict due to the many factors that have an impact. Matters like for instance that the platform tilts due to weather conditions and where on the export pipe the damage is located. No further inquiries have been done regarding these durations since, regardless of how the oil flow will be, the duration in a scenario type such as this will most probably go on for longer than 2,5 minutes.

Table 7.10 Summary for the oil leaks in this scenario

Distribution size	**Mass rate (kg/s)**	**Leak size**	**Radiation from flame front (kW/ m^2)**	**DUR + oil burn time (min)**
Minor	0,0065 (neglected)	Small	-	-
Major 8-Inch	1,7	Medium	109	~6271
Rupture 8-Inch	212,3	Large	109	~55

Frequency analysis

The frequency analysis is based on fault trees and an event tree, see Figure 6.1-6.3, and aims to describe in what frequency rate leaks that ignite occurs. In this scenario type it does not matter if the leak is detected and an initiating closure of the segment starts and close down this segment. This is due to the large amount of hydrocarbons (oil) in this segment. Two leak sizes can develop in this scenario type, medium and large, and in Table 7.11 the frequency rates for the different oil leak sizes are presented. In the frequency rate presented, it has only been calculated that an oil leak occurs and ignites.

Table 7.11 Frequency rates for different gas leak sizes

Leak size (leak frequency, per year)	Duration (minutes)	Frequency rate (per year)
Medium	> 2,5	$7,8*10^{-7}$
Large	> 2,5	$9,4*10^{-7}$

Risk picture for scenario type 4

The total risk picture for this scenario type has evaluated whether it is acceptable or not to exclude PFP as a barrier by measuring the total frequency rate when needed. The total frequency rate for a possible collapse when not using PFP that can lead to a dangerous event for the whole platform Troll C is $1,7*10^{-6}$ per year. This value will be used in the quantification part to see how much risk reduction the implementation of PFP really gives.

This scenario type can lead to a collapse that could affect about 80 persons.

7.5 Scenario type summary

All scenario types above have been calculated using conservative figures for the fire calculations to provide passable results, all in accordance with the NORSOK standards. Together with the frequency analysis this gives the total risk picture for the module and a possible collapse of it.

The conclusions when summarizing the total frequency rates for all of the scenario types and their individually frequency rates that posses a threat, i.e. leading to a collapse of the module if no PFP is used, is that this can happen with a frequency rate of approximately $2,6*10^{-5}$ per year. This is approximately the same as once in every 40000 year. This frequency will be used in the quantification, see chapter 8.

7.6 Risk assessment

If the module should collapse into the ocean this would most probably result in rupturing the riser pipes as mentioned in section 6.2 with the result of 80 persons losing their lives. The total frequency rate for the module to collapse has been calculated to be approximately $2,6*10^{-5}$ per year. But the presumption that the module will tilt (collapse) into the ocean every time is not realistic according to the authors of this paper. A more realistic way to see it is that the probability that the module collapses into the ocean is lower than 50 %. This is because fires that can occur and threaten the module often starts on the platform Troll C and thereby threatens the steel beams closest to the platform first. This makes it more probable that the module will tilt (collapse), inwards, towards the module. But to make a conservative assumption about how the module will tilt (collapse) the probability has been set to 50 % that the module will collapse into the ocean. With this probability the frequency rate that a collapse of the module can threaten the whole platform and thereby 80 persons lives will be approximately $1,3*10^{-5}$ per year. This is well below the set RAC of $1*10^{-4}$ per year for a type of accidental load that can threaten the main safety function, meaning that the risk level can be seen as acceptable for this accidental load.

The frequency $1,3*10^{-5}$ is considering that 80 persons could lose their lives due to the implementation of the new module (if no PFP is used). Scandpower has in their report (2006d) presented the total frequency for all possible accidents for the whole platform Troll C. This frequency is $4*10^{-5}$ for more than 51 persons to lose their lives. If summarizing the two frequencies ($4*10^{-5}$ + $1,3*10^{-5}$) the result is the accumulated risk that more than 51 persons loses their life's if the module collapses into the ocean due to that no PFP is used. The accumulated risk is $5,3*10^{-5}$ (see picture 8.1 below) and this is still below the risk acceptance criteria (RAC) presented before.

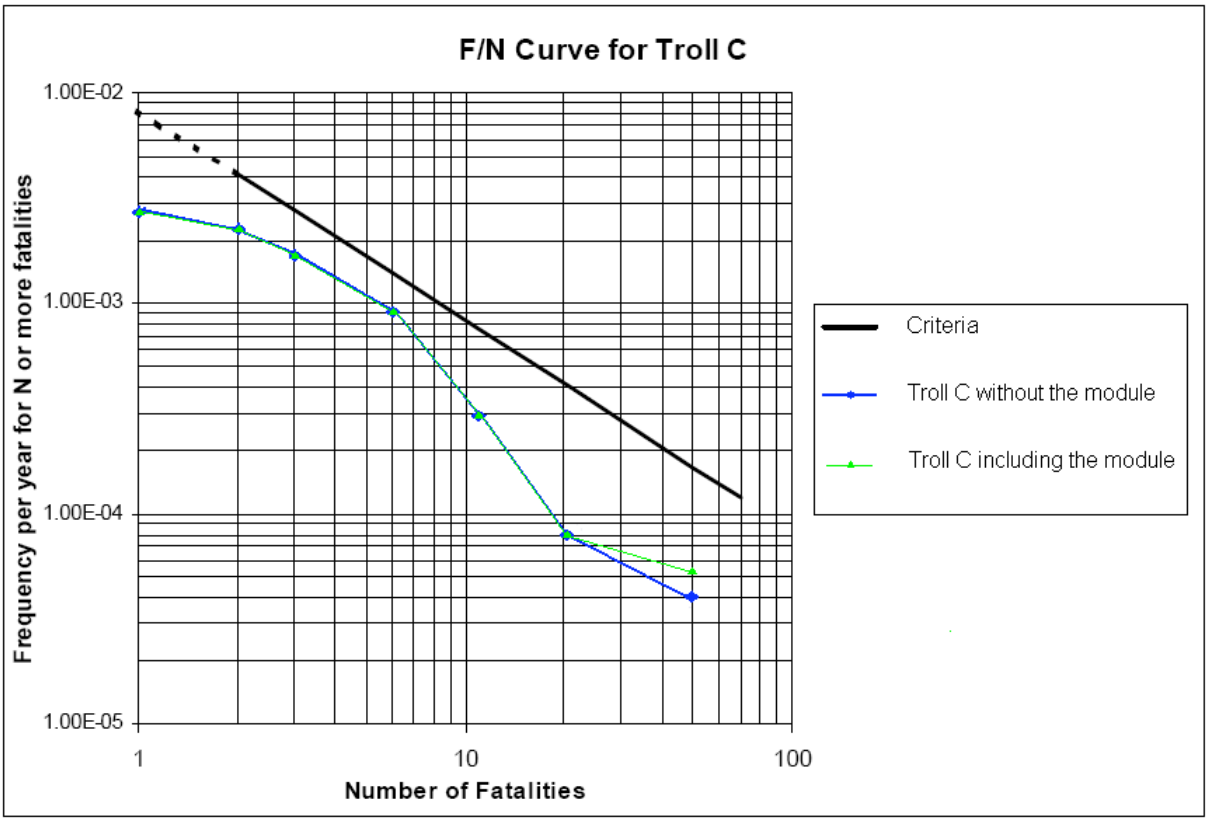

Figure 7.8 Frequency for number of fatalities

Table 7.12 Accumulated frequencies for fatalities and comparison with acceptance criteria

	Frequency for numbers of fatalities per 10^4 years						
	≥ 1	≥ 2	≥ 3	≥ 6	≥ 11	≥ 21	≥ 51
Totally Troll C including module	26,6	22,4	16,7	8,9	3,0	0,8	0,53
Criteria	83,7	41,8	27,9	13,9	7,6	4,0	1,7
Troll C without the module	26,6	22,4	16,7	8,9	3,0	0,8	0,4

8 Quantification

To be able to answer the question of how much risk reduction PFP contributes with as an individual barrier, i.e. with what frequency rate PFP really is needed, this has to be quantified. Two approaches, when quantifying the PFP´s contribution will be showed and used to evaluate the contribution PFP does in this paper. The quantification will be presented as a quotient for when PFP is needed versus not needed and this quotient will give the risk reduction that PFP contributes with in percent.

8.1 Background

When quantifying the risk reduction that PFP contributes with, this could in our opinion be measured in different ways. The writers of this paper have chosen to quantify this risk reduction in two different ways. These two approaches will be clarified here as well as the two different argument points that these approaches have.

Some limitations also have to be set to be able to quantify the risk reduction that PFP gives when applied onto the module (the structure). These limitations have to be done so that some form of quantification is possible to make about PFP and its risk reduction as well as simplifying this discussion. It is said that only scenario types that directly can threaten the module should be included in this quantification, if no other barriers, active or passive (whose main purpose is to act as a barrier),are present. This means that if no barriers had existed in the near surroundings of the module, these scenario types, if developed into a threatening event, could most likely have made the module collapse. It would mean that in these scenario types, PFP is not necessary because other barriers will help protect the module.

Barriers that partake in the process (whose main purpose is to be a part of the process but still can function as a form of passive barrier) are not included. This means that pipes or tanks among other things will not be accounted for as barriers despite their “stopping ability” of for instance jet fires.

When using the first quantifying approach it is assumed that the PFP is a part of all the barriers included on the Troll C platform (including the new module). This means that PFP should be included as a barrier as soon as a dangerous event occurs i.e. for the quantification in this paper, as soon as a leak occurs. It has been showed in many of the scenario types that when a leak occur that doesn’t ignite, emergency actions have still been taken, like for instance meeting at the muster area, either at a gathering station or the life boat area, to await further instructions (HSE, 2008d). Actions like this bear witness to that the personnel onboard the platform takes a leak seriously and apprehend a leak as a dangerous event. So for this reason a leak is treated as a dangerous event even if not ignited. When using this approach rewards are given to the platform-owner for risk reducing measures like for instance lowering the possibility of ignition.

In the second quantifying approach, PFP will only be regarded if a leak has ignited. This approach will only include PFP as a barrier for the purpose it is used for, a fire (this is where it is useful as a barrier). This approach will however not give a reward, in the quantification, to the platform-owner if the ignition probability has been lowered or for using barriers that indicates that a leak has occurred like for instance pressure transmitters or gas detection. It will only measure and account for developed fires and the risk reduction the PFP contributes with here as a barrier with its specified purpose.

8.2 Quantification steps

Each leak size in each scenario type has been analysed for the purpose of this quantification. In some scenario types it doesn't matter if the fire is detected. This is because the steel is going to reach the critical temperature and be affected anyway due to the time it takes for the medium to burn of.

In other scenario types the only circumstance causing the steel to be affected by the fire is if the barriers fail.

The first quantifying approach includes all the five scenario outcomes in the event-tree, see Figure 5. In the different scenario types in chapter 7 it is showed for each scenario type in what scenario outcome PFP is needed. The need for PFP is different in the different scenario types depending on for instance detection and closure matters. In scenario type 3 (except leak size large) and scenario type 4 it does not matter if the leak is detected if it has ignited. This is because the fire will go on for a longer time than the steel structure can manage anyway due to the large amount of hydrocarbon in the segment. So in these scenario types PFP is needed if a leak occurs and ignites versus not needed if the leak does not ignite. In scenario type 2 on the other hand it does not matter if the leak ignites due to the distance between the flame front and the steel structure, so in this scenario type PFP is not needed. This scenario type is however important to include in the quantification, because if no other barriers had been present this scenario type would have constituted a real threat to the module.

When using the second quantifying approach, scenario outcome 2, 3 and 5, in the event-tree, will only be used in scenario type 1. In scenario type 2, as mentioned before, it doesn't matter if the leak ignites or not because it doesn't affect the steel structure on the module anyway. In scenario type 3 (except leak size large, which will be used in the same way as scenario type 1) and scenario type 4, ignition of a leak will make the use of PFP necessary.

In the scenario types where detection does not matter, i.e. when the steel is going to be affected anyway, and in the scenario types when detection fails, PFP will be needed and thereby constitutes in what frequency rate PFP is needed per year.

On the other hand there are scenario types where PFP is not needed, in these scenario types the detection and closure work and the duration doesn't exceed the critical time for the condition of the steel. The time to reach critical conditions for the steel can also greatly exceed the duration. The different scenarios and the scenario types within them are presented in Table 8.1 below.

Table 8.1 Frequencies for the scenario types and their resulting leak size

Scenario types	**PFP is needed (frequency, per year)**	**PFP is not needed if leak is ignited (frequency, per year)**	**PFP is not needed if leak is not ignited (because a leak is always dangerous) (frequency, per year)**
Scenario type 1 Gas, 10” Major gives Medium leak	$8{,}0*10^{-8}$	$9{,}6*10^{-6}$	$6{,}7*10^{-3}$
Scenario type 1 Gas, 12” Major gives Major leak	$6{,}3*10^{-8}$	$5{,}2*10^{-5}$	$7{,}0*10^{-3}$
Scenario type 1 Gas, 10, 12” Rupture gives Large leaks	$7{,}9*10^{-9}$	$1{,}8*10^{-5}$	$9{,}9*10^{-4}$
Scenario type 2 Oil, 3” Major gives Small leak	-	$4{,}8*10^{-6}$	$1{,}5*10^{-2}$
Scenario type 2 Oil, 8” Major gives Medium leak	-	$6{,}3*10^{-6}$	$4{,}2*10^{-3}$
Scenario type 2 Oil, 16” Major gives Major leak	-	$2{,}9*10^{-5}$	$8{,}4*10^{-3}$
Scenario type 2 Oil, 16” Major gives Large leak	-	$5{,}6*10^{-5}$	$3{,}0*10^{-3}$
Scenario type 3 Gas, 2” Major gives Small leak	$3{,}1*10^{-6}$	$3{,}1*10^{-6}$	$1{,}9*10^{-2}$
Scenario type 3 Gas, 6” Major gives Medium leak	$1{,}5*10^{-5}$	$1{,}5*10^{-5}$	$1{,}9*10^{-2}$
Scenario type 3 Gas, 10” Major gives Major leak	$5{,}5*10^{-6}$	$5{,}5*10^{-6}$	$1{,}5*10^{-3}$
Scenario type 3 Gas, 2, 6, 10 and 36” Rupture gives Large leak	$1{,}8*10^{-8}$	$9{,}1*10^{-5}$	$2{,}8*10^{-3}$
Scenario type 4 Oil, 8” Major gives Medium leak	$7{,}8*10^{-7}$	-	$5{,}2*10^{-4}$
Scenario type 4 Oil, 8” Rupture gives Large leak	$9{,}4*10^{-7}$	-	$5{,}1*10^{-5}$
Total frequency, per year	$\mathbf{2{,}6*10^{-5}}$	$\mathbf{2{,}9*10^{-4}}$	$\mathbf{8{,}5*10^{-2}}$

The total frequency per year when PFP as a barrier matters and has to be used is $2{,}6*10^{-5}$ to not risk a collapse of the module. To quantify how much this is, in opposite to when PFP as a barrier does not matter, this frequency has to be compared to the frequency when PFP is not needed. For comparison, the first or the second approach can be used.

8.3 Conclusion

An evaluation of all the different scenarios shows that PFP is needed in a frequency rate of $2{,}6*10^{-5}$ per year, meaning that this is the frequency rate per year where an estimated relevant outcome can develop and constitute a threat to the module if no PFP is added onto the module. The same goes for development of outcomes where PFP is not needed.

Depending on which approach being used the total frequency rate when PFP is not needed will differ quite a lot. When including the possibility that the leak will not ignite (all the scenario outcomes in the event-tree) the total frequency rate will be approximately $8{,}5*10^{-2}$ per year. When only including the frequency rates for when a leak has been ignited (scenario outcomes 2, 3 and 5 in the event-tree) the total frequency rate will be approximately $2{,}9*10^{-4}$ per year.

By reasoning like this, quantification can be made of the impact by PFP on reduction of risk for the module. By dividing the two frequency rates, i.e. frequency rates for when PFP is needed in relation to the total frequency rate when PFP is both needed and not needed, for the different approaches. This forms a relation between these two outcomes that could describe how much risk reduction PFP contributes with as an individually (single) barrier on the new module.

$$\text{Risk reduction by use of PFP} = \frac{Total\ frequencyrate\ when\ PFP\ is\ needed}{Total\ frequencyrate\ when\ PFP\ is\ not\ needed + is\ needed}$$

Depending on which approach that is chosen the difference between the two frequency rates, on the basis of these scenario types, show that PFP causes a risk reduction. If we include the possibility that a leak will not ignite the risk reduction by use of PFP will be approximately 0,3 %.

If risk reduction by use of PFP are only measured if a leak ignites this will be approximately 8 %

When using these two approaches, so far, consideration has only been taken to the risk reduction that PFP gives the module at first hand. No consideration has been taken for the whole platform Troll C. To be able to do that the same arguments as used in risk assessment section 7.6 has to apply here.

The probability that the module could tilt into the existing platform instead of tilting towards the ocean and collapse into it, is not included see also section 7.6. With an estimated probability of 50 % that the module is going to collapse into the ocean and thereby constituting a threat to the whole platform Troll C, if the steel is effected, will lead to a final risk reduction of either 0,15 % or 4 % when using PFP, depending on which approach being used. This would also mean that the total frequency rate when PFP is needed is $1{,}3*10^{-5}$ to ensure that the module does not collapse into the ocean.

Two approaches have been presented in this chapter but the writers of this paper have chosen to use approach one when presenting the risk reduction that PFP gives. This decision has been based on the viewpoint that the present safety level onboard the platform Troll C already is high with the already existing barriers. To use approach two would not be fair because this approach does not consider the low probability that an ignition occurs or the work some of the barriers contributes with before an ignition occurs.

9 Safety and its costs

This chapter presents different ways of comparing safety and the costs that the safety enhancing solutions involve. Specifically, the PFP solution Chartek will be discussed from an economic point of view together with the quantification from chapter 8. The chapter will end up with a discussion of the estimated difference between having PFP or not as well as discussing the costs for an eventual implementation of the Chartek protection.

9.1 Different ways of evaluating safety and its costs

All offshore installations, both present and new ones, have to meet different criteria in order to be acceptable. Some of these criteria have been developed due to the findings after the Piper Alpha Disaster in 1988, where a total of 167 men lost their lives (Wang & Kieran, 2000). This has lead to the demand of specific acceptance criteria that have to be fulfilled, and presented to and thereafter accepted by the operational country's offshore safety division. All this before the owner of the platform is able to start operating the new installation. The presentation must present the different hazards that apply for the new installation and what potential serious accidents these can involve. All risks that in some way affect these hazards must be described as well as being shown that these risks have been reduced to an acceptable level. This level must also be as low as reasonably practicable (ALARP), writes Wang & Kieran (2000). What this means is that the final design must have been evaluated to such a degree that an acceptable risk level has been achieved where a further increase in safety would mean unreasonably large economic costs.

When performing safety analysis in the offshore industry, an early decision regarding all safety issues must be taken. This is to minimize time delays in an already tight time schedule as well as to minimize costs for last minute changes (Wang & Kieran, 2000). A time pressure as tight as this can affect the decision makers to go with a solution that could be "more safe" than it needs to be, according to the ALARP-principle. In a "perfect world" a design with minimum risk and at the same time minimum cost, seen to the installation's life cycle cost, would be optimal. As the diagram below shows a compromise between the highest possible safety and the best cost design must be met to find the best solution that at the same time is economically acceptable.

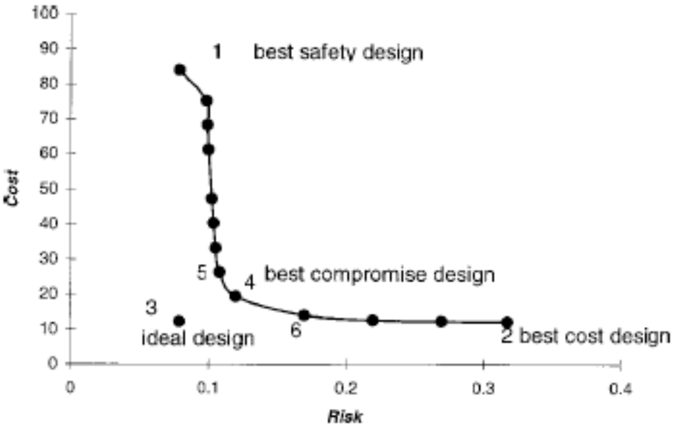

Figure 9.1 Cost-risk diagram (Wang & Kieran, 2000)

This means that some level of risk will be present for whatever design that is chosen but then absolute risk elimination is not practically, nor economically possible to accomplish. The design must reach a sustainable level regarding both safety and cost efficiency.

Safety and cost – The ISO 17776 standard

How does one determine the sustainability level of a design? In the ISO 17776 standard there is a presentation of a hierarchy for risk reducing measures which include; prevention, detection, control, mitigation and emergency response (ISO, 2002). This is also the chronologic order regarding the importance of the measures (the most important first) according to the ISO 17776 standard (2002). If everyone of the mentioned risk reducing measures are performed to their full, a sustainable level should be achieved but is it economically defendable? If the economic resources are managed in the same manner as the risk reducing measures chronology, i.e. so that the most money are spent on the first measure and thereafter descending in accordance with the hierarchy presented in the ISO-standard, a safe and sustainable design could also be achieved. Eliminating or reducing the probability that hazardous events occur constitutes the first measure, prevention (ISO, 2002). Actions like this should lower the number of hazardous events and thereby lowering the need of the next coming measure. Even if the risk reduction is performed following the above guideline the economic aspect must still be taken into consideration.

Value of a statistical life - VOSL

Every individual has his or hers different preferences when it comes to safety and costs which makes it hard to determine a common decision basis for what the actual cost for safety is. To be able to make comparisons between different solutions one way of attending to this problem could be to view the safety cost in measures of the value of a statistical life (VOSL) (Persson et al, 2001). This way of thinking presents, more or less, how much a single life is worth in monetary terms. If a solution or a specific design can prevent the loss of a statistic life this actually saves the society or a company a certain amount of money. For instance, if a middle aged man should lose his life in a car accident this will actually mean a resulting cost for the society. Money spent on ambulance, police and perhaps hospitalization presents a cost for this individual as well as the loss of tax income to the state during this person’s remaining lifetime if not he had died in the accident.

This might be a crude way of seeing things but many organizations have started to observe risk and risk reduction like this including for instance the National Road Administration in Sweden (Persson et al, 2001). To be able to present a more correct VOSL the willingness to pay for a risk reduction must be included in the estimation as well as an income-adjustment (when observing individuals) means Persson et al (2001). During their study the income-adjusted VOSL was estimated to be 22,33 million SEK and they also observed that the willingness to pay increased proportionally to the risk reduction size but they were not willing to pay for a total risk reduction. For companies a present risk with a high possibility of a loss of life with its following costs could better be taken care of by installing for instance some sort of safety system for a less amount of money than a greater amount of money spent if an accident should occur (Crawley & Ashton, 2002). In the offshore industry this “bought safety” could for instance be the installation of PFP. To be able to estimate how much safety an organization must invest in and at the same time be cost efficient the organization must present risk criteria for their activities. If the risk level is below the set criteria an acceptable risk level has been reached and no more risk reducing measures need to be applied to further lower the risk level. However, if the risk level is above the set criteria one or more measures must be applied to lower the risk level below the acceptance criteria. It is important to know that a risk reducing action increases in cost the more safe the environment where the application shall be installed is. An example of this is the Swedish National Road Administrations "Zero Vision" whose aim is to reduce the number of traffic accidents to zero (Persson et al, 2001). A reduction of some of the risks can be done with a fair amount of money and thereby decreasing the number of accidents and lost lives. But in order to reduce the remaining assumedly low number of accidents to zero would mean radical and expensive measures for a comparatively low outcome and this also applies for the offshore industry. A risk reducing measure that means a low benefit at a disproportionate high cost should mean that a risk level that is ALARP, as mentioned before, has been reached (Ersdal & Aven, 2007).

9.2 Chartek pricing

The chartek application could be considered to be an expensive form of protection. This is not due to the material costs but due to high application costs, especially if applied offshore (Grande, 2008). The application needs a perfectly clean surface to ensure that the protection is as specified and the protective layer must be evenly thick (Akzo Nobel, 2008b). This is a fairly advanced procedure onshore, not to mention the rise in difficulty level if applied offshore which automatically heightens the costs.

To apply 1 m^2 of Chartek with 10 mm thickness costs approximately 500 NOK per hour and the work time is considered to be around 6 hours. If the exact procedure is to be performed offshore the price per hour increases to 1000 NOK and due to the complexity considered with offshore application a complexity-factor of 1,5 can be assumed which equals a working time of 9 hours (Grande, 2008). The thickness, 10 mm, is the actual thickness considered for the application on the module, means Grande (2008).

To greatly lower the costs of the new module the main construction should be done onshore and later be transported to the platform where the remaining Chartek should be applied. If applied, almost all the Chartek application will be done onshore except for the parts of the module that are going to be welded when installed on the platform (Grande, 2008). A distribution of 95% onshore and 5% offshore application should present a realistic view of the application process, says Grande (2008), as well as give enough input to estimate the Chartek costs.

To cover the whole module with Chartek protection a total of 15 tonnes needs to be applied (Grande, 2008). With the onshore-offshore work distribution a total cost for the Chartek protection application can be approximated to 5 million NOK. A fair amount of money but this only constitutes one percent of the total module cost that according to Grande (2008), approximately is 500 million NOK.

9.3 Summary & cost-benefit discussion

Chapter 9 has discussed different ways of seeing risk and its costs as well as presenting a cost estimation for applying PFP in the form of Chartek compared to no protection at all. The estimation is done to be able to see the relationship between the costs for the application and the benefits gained from it. ALARP is a very important tool for the offshore industry and all installations or modifications must be valued through such a perspective (NTS, 2001). PFP like Chartek goes in under the *prevention* category in the risk reducing measures hierarchy presented in ISO 17776 and should therefore be considered as a reasonable protection system. But is it reasonable to protect the whole module even if not every part of it can be exposed to a possible fire hazard? The writers of this paper do not believe so, but instead protection of exposed parts could be an option if the total risk picture exceeds the set criteria for an observed part of a design.

The main purpose of this paper has been to investigate how much risk reduction that is obtained by implementing PFP compared to no implementation at all, and if an acceptable risk level can be maintained if no PFP is applied. As presented above in chapter 8.3 the actual increase in safety is approximately 0,15% for a price of 5 million NOK. Is an investment like this then worth doing? A risk reduction of 0,15% is a reasonably small risk reduction but it could definitely be of interest for the decision makers if considering the ALARP principle. However, the total risk level before implementing the PFP on the structure is well below the set acceptance criteria and the implementation of this protection will further lower the risk compared to these criteria. As mentioned before the ALARP principle must be followed when considering a new installation. As stated before the ALARP principle means that risk reducing measures should be performed to, but not beyond, a point where the cost greatly exceeds the benefit gained. To perform a risk reducing measure to a system that already is “safe” according to the set criteria does not necessarily have to be a bad investment but as described before the costs must be in proportion to the benefits gained. To see whether the implementation of Chartek is cost efficient a comparison between the benefits and the costs of the installation is presented below.

For the cost-benefit discussion the writers of this paper have chosen only to regard the cost for the loss of lives onboard the platform and compare this to a cost-benefit analysis where the approximate cost for the whole platform Troll C also is considered. Loss of goodwill and reputation as well as the experienced risk reduction by the personnel will not be regarded as this is both a too complex a task as well as not within the scope of this work. When including the costs for the whole Troll C platform it should be mentioned that the steel structure is able to withstand a fire much better than a human being. If the fire intensity is great for a short period of time this can still mean that a lot of people might lose their lives but however only parts of the platform might need to be exchanged. This equalling a smaller cost than the loss of lives would mean.

The number of persons onboard the platform is approximately 80 and the total life cycle length of the new module is assumed to be 10 years (Grande, 2008). If the VOSL value mentioned in section 9.1 is used (22,33 million SEK ~ 20 million NOK assumed) the total amount of money saved if implementing PFP will be approximately 1,6 billion NOK. The 0,15% total risk reduction can be translated into a frequency rate of approximately $1{,}3 \cdot 10^{-5}$ which together with the 1,6 billion NOK gives the value 20000 NOK. This figure is the expected benefit gained by implementing PFP on the module. The total cost for the implementation is also calculated and this equals approximately 550 000 NOK (including maintenance costs). The cost can be said to actually exceed the benefit by a factor of approximately 26.

Only personnel included:

- Benefit gained: 20000 NOK
- Cost for implementation: 550 000 NOK
- Cost-benefit relation: 26

Grande (2008) means that a realistic figure for the total cost of the whole Troll C platform should be around 5-10 billion NOK and the writers of this paper have chosen the figure 7,5 billion NOK, which is in between. When implementing this in the calculations for the cost-benefit figures above the result would instead be approximately 113750 NOK as benefit gained for the same cost as before, 550 000 NOK. Here the cost exceeds the benefit by a factor of approximately 5. For calculations see Appendix 7.

Personnel and cost for Troll C included:

- Benefit gained: 118300 NOK
- Cost for implementation: 550 000 NOK
- Cost-benefit relation: 5

Independently of each other the cost-benefit calculations show that the implementation is cost inefficient. The above information together with the unknown factor the loss of goodwill presents are inputs the decision makers must take into consideration with the help of for instance an ALARP objective before reaching a verdict regarding the implementation of PFP.

10 Discussion with conclusions and recommendations

The production on offshore facilities can mean risky activities, if the right security measures are not met and fulfilled. The work with this paper has shown that when unplanned events occur, as for instance a leak that ignites, the results can be very dangerous. However, parts of the scenario types investigated in this paper show that no considerable danger exists towards the structural parts of a new installation if no PFP is applied. It should however be noted that all unplanned events must be supervised in order to prevent an, at first "safe" event, to escalate to perhaps an uncontrollable and very dangerous event with possibly catastrophic consequences. The analysis made in this paper shows that the safety barriers onboard a platform work very well to keep a safe environment. With all the already existing barriers included, the overall risk picture onboard can be considered to be safe when considering the acceptance criteria.

Even if the barrier, PFP, is reduced or not even implemented the total risk picture is actually below the risk acceptance criteria which indicates that an implementation of extra risk reducing measures, like PFP, should not be necessary. If comparing the total life span of Troll C with the frequency of a dangerous event occurring that would present a need for PFP, this further augments the argument for not implementing extra risk reducing measures. However, all offshore installations must, when considered being installed, be evaluated considering the ALARP principle which actually indicates that PFP is a good way of decreasing the total risk onboard for a relatively small amount of money.

The offshore industry is accustomed to the use of conservative assumptions and they extensively use these, often without taking into consideration that not every part of the platform might need more protection than already exists. Mostly this is due to lack of project time but the result should still be acceptable when using conservative assumptions, however this also leads to inability to incorporate new and perhaps safer and more cost efficient ways of dealing with a dangerous event. A development like this actually could hinder continuous improvement and by this limit the total safety onboard. If excessively conservative assumptions are used the result is not always cost efficient. Even though oil and gas are lucrative resources it is not defendable to in a way disregard the costs for protection. Of course protection to increase safety is necessary but all parameters must be regarded in order to keep a realistic balance, much more so when one can see that these lucrative resources will not last forever. To use conservative assumptions is not wrong but sometimes this conservatism means a higher cost than the benefit that is gained.

There have been three questions at issue in this paper and these are to be answered below.

1. Can an acceptable risk level be maintained even if PFP is not applied onto the new installation (in this paper the module)?
2. How much risk reduction is PFP contributing with as an individual (single) barrier?
3. Is implementation of PFP cost efficient on new installations (in this paper the module)?

1. This question has been evaluated from a RAC (Risk acceptance Criteria) point of view and with the establishment regulation that states that for each type of accidental load with a yearly frequency rate of more or equal to $1*10^{-4}$ should not lead to loss of the main safety function. The

loss of main safety functions due to a collapse of the module has been calculated to be approximately $1,3*10^{-5}$. The accumulated frequency that more than 51 persons loses their lives if the new module is installed without PFP is $5,3*10^{-5}$, this includes other accidents that can lead to more than 51 persons loses their lives. Both frequencies have a value less than $1*10^{-4}$ and could be seen as acceptable.

2. The risk reduction that PFP contributes with as an individual barrier could be seen in two ways using different approaches (see chapter 8). The writers of this paper has chosen to only use one of these approaches and concludes that the contribution only is 0,15%, which is quite low.

3. To quantify the risk reduction in monetary terms a cost-benefit analysis has been done (see chapter 9) to be able to show how much benefit that is gained when implementing PFP on the new installation. This cost-benefit analysis shows that the cost is approximately 26 times higher than the benefit gained. However this calculation has only been done with the cost of human lives saved and what the death of these humans would cost. If including the cost for the whole platform Troll C in this cost-benefit analysis and assume that the whole platform is destroyed if the module collapses into the ocean the cost will be approximately 5 times higher than the benefit gained.

It should be noted that no account in the cost-benefit analysis has been taken for costs involving reputation or goodwill since this is not within the scope of the work. These are factors that also should be considered when doing a cost-benefit analysis.

The results that give these values have in many scenario types being based on conservative assumptions both in the risk estimation but also in the consequence analysis made in the risk analysis.

Some of the more conservative assumptions have been:

- The influence that the Deluge systems can have on a fire has been disregarded.
- Critical temperature for collapse of the module, 450°C.
- The high amount of water present in the process which could inhibit ignition and how this influences a fire scenario.
- The weight distribution for the load bearing beams is equal.

Even through these conservative assumptions have been used it can still be observed that the influence the PFP makes is rather low given the already high security level on Troll C. One can also see that the benefit gained is rather low compared to the cost for the implementation of PFP, even when regarding the total cost for both personnel and the Troll C platform.

One of the intentions with this paper was to present a methodology so that Aker Solutions could be able to do similar analyses with future installations. By following the different steps (chapters) in this paper we think it is possible to do just this. The first six chapters can be used as a guide on how to perform the analysis that later should make up the contents of chapter 7-9. The positive features with this methodology are that it follows the NORSOK standard on safety management and risk control and that it gives a good overview of the total risk picture for the project at hand.

It is also a way of giving a good understanding of the additional risk a new installation can mean, if no PFP is used, by showing this in numbers.

Negative aspects of the methodology are that not all possible scenario types can fit in a paper like this, neither for future projects, since it is very time consuming. Which scenario types to choose is also a judgement call which also results in some uncertainty in the results. More uncertainty is added due to the use of statistics. The statistics give a notion of how the future might look like but the accuracy of the statistics should always be questioned. Even if not everything can be foreseen the results of an analysis like this is still valuable, both by preparing for the future but also by optimizing a new installation economically.

The recommendation we can give based on the results of this paper is to further investigate the effects the implementation of PFP means if reducing the amount of PFP to only cover chosen parts. A reduction could actually be profitable and at the same time safe. A reduction could for instance be made on parts that do not have any load bearing function.

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Appendix

1 Calculations for the consequence analysis in scenario 1

The calculation steps for the risk estimation

First a conceivable leak rate from a defined leak size for the gas has to be calculated for different sizes of equipment on the platform. This is made with the formula for continuous gas release for steady state condition during critical current, see below. This is made under the assumption that when the leak has started the pressure inside the system will be constant, as long as the emergency shutdown valves are opened and the blow down valve is closed.

If the leak rate is smaller than 0.05 kg/s it will be neglected and are not considered to constitute any real danger to the module.

For a minor leak with a hole diameter of 1mm^2 the calculation will proceed like this:

$$Q = C_d \cdot A \cdot \frac{P_0}{\sqrt{R \cdot T_0}} \cdot \sqrt{\gamma} \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} = 0{,}667 \cdot C_d \cdot A \cdot \frac{P_0}{\sqrt{R \cdot T_0}}, \text{ when } \gamma\text{=1,3 [kg/s]}$$

γ=1,3 is assumed because it usually varies between 1,1 and 1,6 but the number has little influence on the release data

$$Q = 0{,}667 \cdot 0{,}5 \cdot 1 \cdot 10^{-6} \cdot \frac{21 \cdot 10^5}{\sqrt{0{,}518 \cdot 442{,}2}} = 4{,}6 \cdot 10^{-2} \text{ [kg/s]}$$

This leak rate will be neglected.

For a major leakage for 12-inch piping (hole area 5,91 cm^2), the leak rate will be:

$$Q = 0{,}667 \cdot 0{,}5 \cdot 5{,}91 \cdot 10^{-4} \cdot \frac{6 \cdot 10^5}{\sqrt{0{,}518 \cdot 328}} = 9{,}1 \text{ [kg/s]}$$

This leakage will be considered as medium.

For a major leakage in a 10-inch component (hole area 4,04 cm^2), the leak rate will be:

$$Q = 0{,}667 \cdot 0{,}5 \cdot 4{,}04 \cdot 10^{-4} \cdot \frac{21 \cdot 10^5}{\sqrt{0{,}518 \cdot 442{,}2}} = 18{,}7 \text{ [kg/s]}$$

This leakage will be considered as major initially and then as medium.

For a full rupture in a 10 and 12-inch component (hole area 498,51 and 729,29 cm^2), the leak rate will be dependent on the mass flow from the test separator and the compressor. These two components have a mass flow rate of 5.5 kg/s each, which means that this is the maximum mass flow the system can deliver without any pressure built up inside it.

For calculation purpose a 2 phase model can be used to evaluate what the leak rate will be in the first couple of seconds. The equation used for that purpose is:
Phase 1 of the mass flow:

This phase goes on during the time $0 < t < \Delta t$

$$\Delta t = \frac{L}{c_i} \text{ [s]}$$

$$c_i = \sqrt{\gamma R T_i} \text{ [m/s]}$$

$$Q_t = A\sqrt{\alpha} \cdot \frac{P_i}{\sqrt{RT_i}} \cdot \frac{1}{\sqrt{1 + \alpha \cdot \left(\frac{\lambda c_i t}{D} \right)}} \quad \text{[kg/s]}$$

$$\alpha = \gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} = 0{,}445 \qquad \text{If } \gamma = 1.3$$

Phase 2 of the mass flow:

This phase goes on during the time $t \geq \Delta t = L/c_i$

$$M_{\Delta t} = M_0 \left\{ 1 - \frac{2}{\sqrt{\gamma \alpha}} \cdot \left(\frac{D}{\lambda L} \right) \left[\sqrt{1 + \alpha \cdot \frac{\lambda L}{D}} - 1 \right] \right\}, \text{ where } M_0 = \frac{P_i A L}{R T_i}$$

$$Q_t = \frac{M_{\Delta t}}{\beta} \cdot e^{-\frac{t - \Delta t}{\beta}}, \text{ where } \beta = \sqrt{\frac{\lambda L}{D}} \cdot \frac{L}{\sqrt{RT_i}}$$

The criteria for the models validity is expressed as:

$$Q_t \geq A \cdot \frac{P_a}{\sqrt{RT_i}} \cdot \sqrt{\frac{\gamma(\gamma + 1)}{2}}$$

Where:

L = The total pipe length [m]
c_i = The speed of sound at temperature T_i in the pipe [m/s]
γ = Poisson's quotient [-]
R = Gas constant [J/kg K]
P_a = Atmospheric pressure [N/m^2]

P_i = Pressure in piping before rupture [N/m^2]
T_i = Temperature in piping before rupture [K]
Q_t = Mass flow as a function of time [kg/s]
λ = Pipe friction coefficient = 0.03
α = Constant depending on Poisson's quotient [-]
A = Cross sectional area of hole [m^2]
D = Piping diameter [m]
$M_{\Delta t}$ = Remaining amount of gas in piping when t = Δt [kg]
M_0 = Amount of gas before rupture [kg]

The high release rate just after the rupture will, if ignited, probably develop a flash fire that will go on for 10-20 seconds. During this short time of high radiation it is estimated that the structure doesn't suffer any severe harm. Because the system delivers a mass flow rate of 5.5 kg/s this value will be used when calculating the leak rate for a full rupture. These 2 leakages will be considered as medium.

Full rupture 10-inch component:

Validity calculation:

$$Q_t \geq 0{,}05 \cdot \frac{1 \cdot 10^5}{\sqrt{0{,}518 \cdot 442}} \cdot \sqrt{\frac{1{,}3(1{,}3+1)}{2}} \Rightarrow Q_t \geq 404 \text{ [kg/s]}$$

Phase 1 release:

$$c_i = \sqrt{1{,}3 \cdot 0{,}518 \cdot 442} = 17{,}25 \text{ [m/s]}$$

$$\Delta t = \frac{L}{c_i} = \frac{15}{17{,}25} = 0{,}87 \text{ [s]} \quad \text{, the time phase 1 is going on}$$

$$Q_t = 0{,}05 \cdot \sqrt{0{,}445} \cdot \frac{21 \cdot 10^5}{\sqrt{0{,}518 \cdot 442}} \cdot \frac{1}{\sqrt{1 + 0{,}445 \cdot \left(\frac{0{,}025 \cdot 17{,}25 \cdot 0{,}87}{0{,}252}\right)}} = 3590 \text{ [kg/s]}$$

Phase 2 release:

$$M_0 = \frac{21 \cdot 10^5 \cdot \pi \cdot 0{,}126^2 \cdot 15}{0{,}518 \cdot 442} = 6879 \text{ [kg]}$$

$$M_{\Delta t} = 6879 \cdot \left\{1 - \frac{2}{\sqrt{1{,}3 \cdot 0{,}445}} \cdot \left(\frac{0{,}252}{0{,}03 \cdot 15}\right)\left[\sqrt{1 + 0{,}445 \cdot \frac{0{,}03 \cdot 15}{0{,}252}} - 1\right]\right\} = 3439 \text{ [kg]}$$

$$\beta = \sqrt{\frac{0{,}03 \cdot 15}{0{,}252}} \cdot \frac{15}{\sqrt{0{,}518 \cdot 442}} = 1{,}325$$

$$404 = \frac{3439}{1{,}325} \cdot e^{-\frac{t-0{,}87}{1{,}325}} \Rightarrow t = 3{,}3 \ \text{[s]}$$

Full rupture 12-inch component:

Validity calculation:

$$Q_t \geq 0{,}073 \cdot \frac{1 \cdot 10^5}{\sqrt{0{,}518 \cdot 442}} \cdot \sqrt{\frac{1{,}3(1{,}3+1)}{2}} \Rightarrow Q_t \geq 589 \ \text{[kg/s]}$$

Phase 1 release:

$$c_i = \sqrt{1{,}3 \cdot 0{,}518 \cdot 328} = 14{,}86 \ \text{[m/s]}$$

$$\Delta t = \frac{L}{c_i} = \frac{15}{14{,}86} = 1{,}01 \, \text{[s]}$$, the time phase 1 is going on

$$Q_t = 0{,}05 \cdot \sqrt{0{,}445} \cdot \frac{6 \cdot 10^5}{\sqrt{0{,}518 \cdot 328}} \cdot \frac{1}{\sqrt{1 + 0{,}445 \cdot \left(\frac{0{,}025 \cdot 14{,}86 \cdot 0{,}87}{0{,}302}\right)}} = 1270 \ \text{[kg/s]}$$

Phase 2 release:

$$M_0 = \frac{6 \cdot 10^5 \cdot \pi \cdot 0{,}151^2 \cdot 15}{0{,}518 \cdot 328} = 3804 \, \text{[kg]}$$

$$M_{\Delta t} = 3804 \cdot \left\{ 1 - \frac{2}{\sqrt{1{,}3 \cdot 0{,}445}} \cdot \left(\frac{0{,}3024}{0{,}03 \cdot 15} \right) \left[\sqrt{1 + 0{,}445 \cdot \frac{0{,}03 \cdot 15}{0{,}3024}} - 1 \right] \right\} = 1860 \, \text{[kg]}$$

$$\beta = \sqrt{\frac{0{,}03 \cdot 15}{0{,}3024}} \cdot \frac{15}{\sqrt{0{,}518 \cdot 442}} = 1{,}21$$

$$589 = \frac{1860}{1{,}21} \cdot e^{-\frac{t-0{,}87}{1{,}21}} \Rightarrow t = 2{,}03 \, \text{[s]}$$

Equations for calculating jet-flames

$$Q = C_d \cdot A \cdot \frac{P_0}{\sqrt{R \cdot T_0}} \cdot \sqrt{\gamma} \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} = 0{,}667 \cdot C_d \cdot A \cdot \frac{P_0}{\sqrt{R \cdot T_0}}$$

$F = C_d A(1{,}26P_0 - P_a)$, if γ = 1,3

$Y = Stoichiometric.conc. \cdot \frac{relative.density.in.relation.to.air}{1 - stoichiometric.conc.}$, where the relative density is set to 0.544 according to Fischer et al (1998) table 11.4.

$$L_f = x_s = \frac{5{,}95 \cdot Q}{\sqrt{\rho_a \cdot F}} \cdot \frac{1}{Y}$$

$$d_f = 0{,}15 \cdot L_f$$

$$d_f = 0{,}15 \cdot L_f$$

$$P = \frac{0{,}35 \cdot b' \cdot h_c}{1 + 4h_f / d_f}$$

Where:
Q = Mass flow [kg/s]
C_d = coefficient of discharge, is set to 0.5 because the damage is assumed to happen due to outer influence, hence the 0.5-figure.
A = hole area [m^2]
P_0 = pressure inside piping [Pa]
P_a = pressure outside piping [Pa]
R = gas constant [J/ kg K]
T_0 = gas temperature [K]
γ = gas specific heat ratio, is assumed to be 1,3 (it usually varies between 1,1 and 1,6 but the number has little influence on the release data)
F = jet force [N]
Y = mass fraction [kg/kg]
L_f = flame length stoichometric mixture [m]
h_f = flame height [m]
d_f = flame diameter stoichometric mixture [m]
ρ_a = air density, is set to 1.3 [kg/m^3]
P = radiation per area unit [W/m^2]
b' = burning rate per area unit [kg/m^{2}s]

Stoichiometric value for methane: 0,095 volume units ((Fischer et al, 1998) Table 11.4).
h_c = energy value [J/kg]
h_c(methane) = 50,1 [MJ/kg] ((Fischer et al, 1998) Table 11.4).
According to Fischer et al (1998) the heat flux (P) for a jet-flame can be approximated to twice the heat flux for a none sooting pool fire.

Calculations for methane jet fires

$Density = \rho = 10{,}86 \Rightarrow v_f = \frac{1}{\rho} = \frac{1}{10{,}86} = 0{,}092$ [m^3/ kg] (Aker Solutions AS {4}, 2008)

$Temperature = T_0 = 169{,}2 + 273 = 442{,}2$ [K]

Pressure: $P_0 = 21 bar = 21 \cdot 10^5$ [Pa]

Universal gas constant: $R_* = 8{,}314$ [J/K mol]

$m(CH_4) = 12{,}01 + 4 \cdot 1{,}0079 = 16{,}042$ [kg/mol] (Ekholm et al, 2002)

Gas constant: $R = \frac{R_*}{m} = \frac{8{,}314}{16{,}042} = 0{,}518$ [J/ kg K]

Minor leakage (hole area 1 mm^2):

$$Q = 0{,}667 \cdot 0{,}5 \cdot 1 \cdot 10^{-6} \cdot \frac{21 \cdot 10^5}{\sqrt{0{,}518 \cdot 442{,}2}} = 4{,}6 \cdot 10^{-2} \text{ [kg/s]}$$

$$F = 0{,}5 \cdot 1 \cdot 10^{-6}(1{,}26 \cdot 21 \cdot 10^5 - 1 \cdot 10^5) = 1{,}27 \text{ [N]}$$

$$L_f = \frac{5{,}95 \cdot 4{,}6 \cdot 10^{-2}}{\sqrt{1{,}3 \cdot 1{,}27}} \cdot \frac{1}{0{,}057} = 3{,}7 \text{ [m]}$$

$$d_f = 0{,}15 \cdot 3{,}7 = 0{,}55 \text{ [m]}$$

$$P = \frac{0{,}35 \cdot 0{,}11 \cdot 50{,}1 \cdot 10^6}{1 + (4 \cdot 3{,}7 / 0{,}55)} = 69111 \Rightarrow 2 \cdot P = 138223 \approx 140 \text{ [kW/m}^2\text{]}$$

The radiation from the flame front will be the same despite the flame length or width. The radiation depends more on the type of fuel burning.

Major leakage for 10-inch piping (hole area 4,04 cm^2):

$$Q = 0{,}667 \cdot 0{,}5 \cdot 4{,}04 \cdot 10^{-4} \cdot \frac{21 \cdot 10^5}{\sqrt{0{,}518 \cdot 442{,}2}} = 18{,}7 \text{ [kg/s]}$$

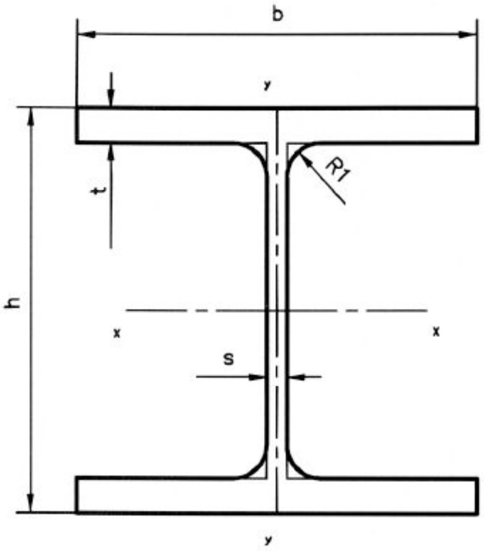
Rupture for 10-inch piping (hole area 498,51 cm^2) & 12-inch piping (hole area 729,29 cm^2):
The fast pressure drop, caused by the rupture will make the pressure inside the system almost equal to the pressure outside the system; therefore this will be treated as a non critical flow. The large amount of methane gas will come out during the first couple of seconds after that the mass rate will be controlled by the mass rate flowing into the system, 5,5 kg/s.

$Q = 5{,}5$ [kg/s]

Major leakage for 12-inch piping (hole area 5,91 cm^2):

$$Q = 0{,}667 \cdot 0{,}5 \cdot 5{,}91 \cdot 10^{-4} \cdot \frac{21 \cdot 10^5}{\sqrt{0{,}518 \cdot 442{,}2}} = 27{,}3 \text{ [kg/s]}$$

Heat transfer through steel



(SpontAB, 2008)

One type of I-beam is used; HE300A. The number in the specification indicates the width ("b" in the figure). The equations and tabular numbers are used in accordance with "Brandteknisk dimensionering av stålkonstruktioner" (Magnusson et al., 1974) apart from the weight per meter figures which were provided by SpontAB (2008).

Equations for heat transfer through steel

$$P = \frac{Q_{Jet}}{\Delta t \cdot w}$$

$$V_s = \frac{Weight/meter}{density}$$

$$Q = c_{ps} \cdot \Delta v_s \cdot V_s \cdot \gamma_s$$

Where:

P = Radiation [W/m^2]
V_s = Volume per length-unit [m^3/m]
Q = The needed energy to increase steel temperature by Δv_s °C [J/m]
Δv_s = Temperature increase for steel profile [°C]
c_{ps} = Specific heat capacity for steel [J/kg °C]
γ_s = Density [kg/m^3]
w = beam width [m]
Δt = length of time interval [s]
Q_{Jet} = Released energy from jet-flame [J/m]

HE300A-beam:

γ_s = 7850 [kg/m^3]
$Weight / meter$ = 88,3 [kg/m]
c_{ps} = 482 [J/kg °C]
$V_s = \frac{Weight / meter}{density} = \frac{88,3}{7850} = 0,0112$ [m^3/m]
Δv_s = 450-15 = 435 [°C]
$Q = 0,482 \cdot 10^3 \cdot 435 \cdot 0,0112 \cdot 7850 = 1,84 \cdot 10^7$ [J/m]
w = 0,3 [m]
P = 140 [kW/m^2] (according to calculations above)
$Q_{Jet} = P \cdot \Delta t \cdot w = 140 \cdot 10^3 \cdot 0,3 \cdot \Delta t$

$$Q_{Jet} = Q \Rightarrow 140 \cdot 10^3 \cdot 0,3 \cdot \Delta t = 1,84 \cdot 10^7 \Rightarrow \Delta t = \frac{1,84 \cdot 10^7}{140 \cdot 10^3 \cdot 0,3} = 438,10 sek \approx 7,5 \min$$

Estimated release times for the leaks

The total volume of gas in this segment is 5 m^3 and the approximate mass of this gas is 55 kg.

$$\text{DUR} = \frac{Mass}{Q_{initial}} + \text{Time to detection and full closure of section}$$

Mass = Total amount of mass in the sector (kg)
$Q_{initial}$ = Initial rate for gas (kg/s)

Leak sizes	Time to detection for gas release (seconds)
Small	60
Medium	30
Major	10
Large	5

Estimated total duration time for fire = DUR

Closing time is assumed to take approximately 2 seconds/inch (Scandpower, 2006a)

<u>10-inch gas leak</u>

Major: $$\text{DUR} = \frac{55}{18,7} + 10 + 20 \approx 0,5\,\text{min}$$

$\Rightarrow$ Total burning time = DUR = 0,5 min

Rupture: $$\text{DUR} = \frac{55}{5,5} + 5 + 20 \approx 1\,\text{min}$$

$\Rightarrow$ Total burning time = DUR = 1 min

<u>12-inch gas leak</u>

Major: $$\text{DUR} = \frac{55}{9,1} + 10 + 24 \approx 1\,\text{min}$$

$\Rightarrow$ Total burning time = DUR = 1 min

Rupture: $$\text{DUR} = \frac{55}{5,5} + 5 + 24 \approx 1\,\text{min}$$

$\Rightarrow$ Total burning time = DUR = 1 min

2 Calculations for the consequence analysis in scenario 2

Equations – Pool-fire and radiation

$$d_{eq} = 4 \cdot \left(\frac{poolarea}{poolcircumference} \right)$$

$$h_f = d_p \cdot 42 \cdot \left[\frac{b'}{\rho_a \cdot \sqrt{g \cdot d_p}} \right]^{0,61}$$

$$0,8 < h_f / d_f < 4$$

$$P = \frac{0,35 \cdot b' \cdot h_c}{1 + 4h_f / d_f}$$

$$P_S = \sigma \cdot T^4$$

$$P = \varepsilon \cdot P_S$$

$$P_{12} = P_1 \cdot \tau_a \cdot F_{12}$$

$$\tau_a = 1 - \alpha_W - \alpha_C$$

Where:
ε = emittance [-]
σ = Stefan-Boltzmann constant [W/m^{2}K^4]
ρ_a = air density, is set to 1.29 [kg/m^3]
τ_a = transmissive ability[-]
α_c = absorption factor for CO_2 [-]
α_w = absorption factor for water [-]
h_f = flame height [m]
d_{eq} = Equivalent diameter [m]
d_f = flame diameter [m]
d_p = pool diameter [m]
F_{12} = angle coefficient for A_1 to A_2 [-]
g = weight acceleration = 9,81 [m/s^2]
h_c = energy value [J/kg]
h_f = flame height [m]
P = radiation per area unit [W/m^2]
P_1 = radiation from A_1[W/m^2]
P_{12} = radiation from A_1 to A_2 [W/m^2]
P_S = radiation from a black body [W/m^2]
T = temperature [K]
b' = burning rate per area unit [kg/m^{2}s]

Calculations – Pool-fire and radiation

Measurements have been taken from Troll C blueprints.

Pool-area = (2,0 + 4,8 + 2,24) * (2,0 + 4,0 + 4,0 + (4,0 - 1,95)) = 108,932 [m^2]
Pool-circumference = (2*9,04) + (2*12,05) = 42,18 [m]

$$d_{eq} = 4 \cdot \left(\frac{108{,}932}{42{,}18} \right) = 10{,}33\,[\mathrm{m}]$$

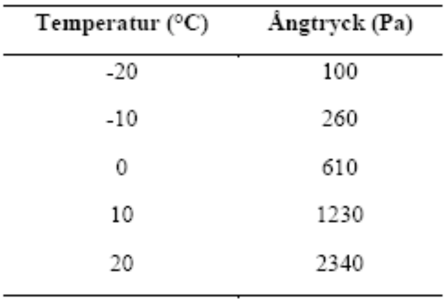
$$h_f = 10{,}33 \cdot 42 \cdot \left[\frac{0{,}045}{1{,}29 \cdot \sqrt{9{,}81 \cdot 10{,}33}} \right]^{0,61} = 13{,}7\,[\mathrm{m}]$$

$h_f / d_f = 13{,}7/10{,}33 = 1{,}33$ OK according to $0{,}8 < h_f / d_f < 4$

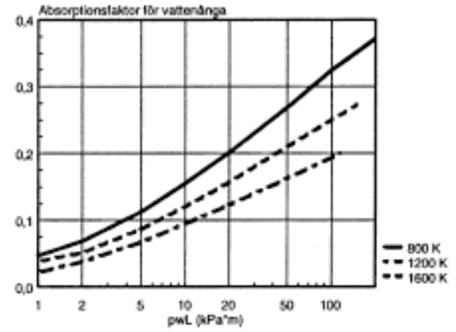
$$P = \frac{0{,}35 \cdot 0{,}045 \cdot 41{,}87 \cdot 10^6}{1 + 4 \cdot 13{,}7/10{,}33} = 104593 \approx 105 \quad [\mathrm{kW/m^2}]$$

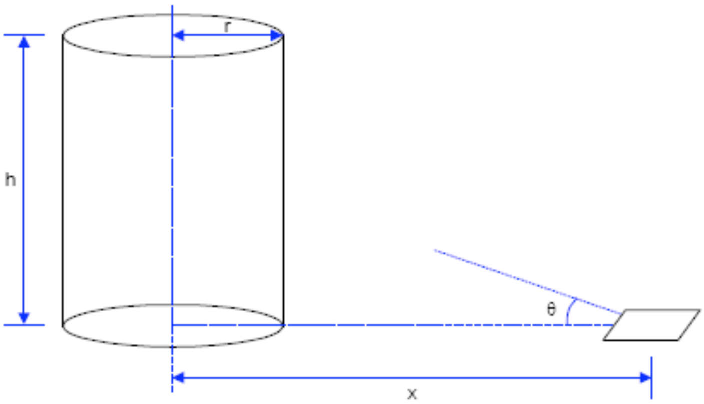
$P = \varepsilon \cdot P_S$, ε set to 1 due to black body assumption $\Rightarrow P = P_S$
$105000 = 5{,}67 \cdot 10^{-8} \cdot T^4 \Rightarrow T \approx 1167$ [K]
$\alpha_c = 0$, absorption factor for CO_2 can be neglected
Calculations for angular coefficient and absorption factor (using tables below) gives
$F_{max} = F_{12} = 0{,}18$ and $\alpha_w = 0{,}150$ (T = 15°C, 90% relative humidity assumed)
$\tau_a = 1 - 0{,}150 - 0 = 0{,}850$

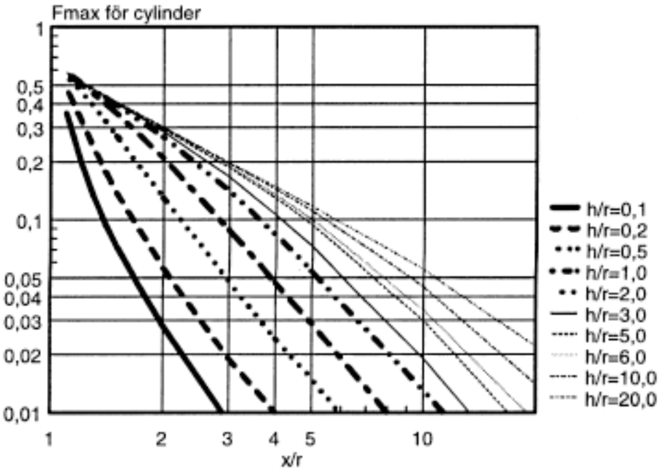
$P_{12} = 105000 \cdot 0{,}85 \cdot 0{,}18 = 16065 \approx 16{,}1\,[\mathrm{kW/m^2}]$



Temperatur (°C)	Ångtryck (Pa)
-20	100
-10	260
0	610
10	1230
20	2340







(Fischer et al, 1998)

Equations – Steel and critical temperature time

$$P = \frac{Q_{Jet}}{\Delta t \cdot w}$$

$$V_s = \frac{Weight / meter}{density}$$

$$Q = c_{ps} \cdot \Delta v_s \cdot V_s \cdot \gamma_s$$

Where:

P = Radiation [W/m^2]
V_s = Volume per length-unit [m^3/m]
Q = The energy needed to increase steel temperature by Δv_s °C [J/m]
Δv_s = Temperature increase for steel profile [°C]
c_{ps} = Specific heat capacity for steel [J/kg °C]
γ_s = Density [kg/m^3]
w = beam width [m]

Δt = length of time interval [s]
Q_{Jet} = Released energy from jet-flame [J/m]

Calculations – Steel and critical temperature time

$\gamma_s = 7850$ [kg/m^3]
$V_s = (l_2 \cdot w_2 \cdot h_2) - (l_1 \cdot w_1 \cdot h_1) = (0{,}30 \cdot 0{,}30 \cdot 1) - (0{,}28 \cdot 0{,}28 \cdot 1) = 1{,}19 \cdot 10^{-2}$ [m^3/m]
$c_{ps} = 482$ [J/kg °C]
$Q = 0{,}482 \cdot 10^3 \cdot 435 \cdot 1{,}19 \cdot 10^{-2} \cdot 7850 = 1{,}91 \cdot 10^7$ [J/m]
$\Delta v_s = 450\text{-}15 = 435$ [°C]
$w = 0{,}30$[m]
$Q_{pool} = P \cdot \Delta t \cdot w = 16{,}1 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t$

$$Q_{pool} = Q \Rightarrow 16{,}1 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{16{,}1 \cdot 10^3 \cdot 0{,}30} = 3954{,}5 sek \approx 66 \min$$

3 Calculations for the consequence analysis in scenario 3

All physical values have been taken from *"Scandpowers Technical Note No. 5"* and from *"Vådautsläpp av brandfarliga och giftiga gaser och vätskor. Metoder för bedömning av risker"* (Fischer et al, 1998) if nothing else is mentioned.

Equations mass flow (gas phase)

These equations apply for leakages Minor and Major.

$$Q = C_d \cdot A \cdot \frac{P_0}{\sqrt{R \cdot T_0}} \cdot \sqrt{\gamma} \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} = 0{,}667 \cdot C_d \cdot A \cdot \frac{P_0}{\sqrt{R \cdot T_0}}$$

$$F = C_d \cdot A \left[2\left(\frac{2}{1+\gamma}\right)^{\frac{1}{\gamma-1}} \cdot P_0 - P_a\right] = C_d A\left[1{,}26 P_0 - P_a\right]$$

$Y = Stoichiometric.conc. \cdot \frac{relative.density.in.relation.to.air}{1 - stoichiometric.conc.}$, where the relative density is set to 0.544 according to Fischer et al (1998) table 11.4.

$$L_f = x_s = \frac{5{,}95 \cdot Q}{\sqrt{\rho_a \cdot F}} \cdot \frac{1}{Y}$$

$$d_f = 0{,}15 \cdot L_f$$

$$P = \frac{0{,}35 \cdot b' \cdot h_c}{1 + 4h_f / d_f}$$

Where:

Q = Mass flow [kg/s]

C_d = coefficient of discharge, is set to 0.5 because the damage is assumed to happen due to outer influence, hence the 0.5-figure.

A = hole area [m^2]

P_0 = pressure inside piping [Pa]

R = gas constant [J/ kg K]

T_0 = gas temperature [K]

γ = gas specific heat ratio, is assumed to be 1,3 (it usually varies between 1,1 and 1,6 but the number has little influence on the release data)

F = jet force [N]

v_f = specific volume [m^3/ kg]

Y = mass fraction [kg/kg]

L_f = flame length [m]

h_f = flame height [m]

d_f = flame diameter [m]

ρ_a = air density, is set to 1.3 [kg/m^3]

P = radiation per area unit [W/m^2]

b’ = burning rate per area unit [kg/m^2s]

Stoichiometric value for methane: 0,095 volume units ((Fischer et al, 1998) table 11.4).
h_c = energy value [J/kg]
h_c(methane) = 50,1 MJ/kg ((Fischer et al, 1998) table 11.4)
According to Fischer et al (1998) the heat flux (P) for a jet-flame can be approximated to twice the heat flux for a none sooting pool fire.
b’ = 0,11 kg/m^2s ((Fischer et al, 1998) table 11.1)

For a full rupture leak the below equations apply

For calculation purposes a 2 phase model can be used to evaluate what the leak rate will be in the first couple of seconds. The equations used for that purpose is:

Phase 1 of the mass flow:

This phase goes on during the time 0 < t < Δt

$$\Delta t = \frac{L}{c_i} \text{ [s]}$$

$$c_i = \sqrt{\gamma R T_i} \text{ [m/s]}$$

$$Q_t = A\sqrt{\alpha} \cdot \frac{P_i}{\sqrt{RT_i}} \cdot \frac{1}{\sqrt{1 + \alpha \cdot \left(\frac{\lambda c_i t}{D} \right)}} \quad \text{[kg/s]}$$

$$\alpha = \gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} = 0{,}445 \qquad \text{If } \gamma = 1.3$$

Phase 2 of the mass flow:

This phase goes on during the time t ≥ Δt = L/c_i

$$M_{\Delta t} = M_0 \left\{ 1 - \frac{2}{\sqrt{\gamma\alpha}} \cdot \left(\frac{D}{\lambda L} \right) \left[\sqrt{1 + \alpha \cdot \frac{\lambda L}{D}} - 1 \right] \right\}, \text{ where } M_0 = \frac{P_i A L}{R T_i}$$

$$Q_t = \frac{M_{\Delta t}}{\beta} \cdot e^{-\frac{t - \Delta t}{\beta}}, \text{ where } \beta = \sqrt{\frac{\lambda L}{D}} \cdot \frac{L}{\sqrt{R T_i}}$$

The criteria for the models validity is expressed as:

$$Q_t \geq A \cdot \frac{P_a}{\sqrt{RT_i}} \cdot \sqrt{\frac{\gamma(\gamma+1)}{2}}$$

Where:

L = The total pipe length [m]
c_i = The speed of sound at temperature T_i in the pipe [m/s]
γ = Poisson's quotient [-]
R = Gas constant [J/kg K]
P_a = Atmospheric pressure [N/m^2]
P_i = Pressure in piping before rupture [N/m^2]
T_i = Temperature in piping before rupture [K]
Q_t = Mass flow as a function of time [kg/s]
λ = Pipe friction coefficient = 0.03
α = Constant depending on Poisson's quotient [-]
A = Cross sectional area of hole [m^2]
D = Piping diameter [m]
$M_{\Delta t}$ = Remaining amount of gas in piping when t = Δt [kg]
M_0 = Amount of gas before rupture [kg]

Calculations for jet-fires

$Density = \rho = 10{,}86 \Rightarrow v_f = \frac{1}{\rho} = \frac{1}{10{,}86} = 0{,}092$ (Aker Solutions AS [4], 2008) [m^3/ kg]

$Temperature = T_0 = 25 + 273 = 298$ [K]

Pressure: $P_0 = 20 bar = 20 \cdot 10^5 Pa$

Universal gas constant: $R_* = 8{,}314$ [J/K mol]

$m(CH_4) = 12{,}01 + 4 \cdot 1{,}0079 = 16{,}042$ [kg/mol] (Ekholm et al, 2002)

Gas constant: $R = \frac{R_*}{m} = \frac{8{,}314}{16{,}042} = 0{,}518$ [J/ kg K]

b' = 0,11 [kg/m^2 s]

Minor leakage (hole area 1 mm^2):

$Q = 0{,}667 \cdot 0{,}5 \cdot 1 \cdot 10^{-6} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} = 5{,}4 \cdot 10^{-2}$ [kg/s]

$F = 0{,}5 \cdot 1 \cdot 10^{-6} \left[1{,}26 \cdot 20 \cdot 10^5 - 1 \cdot 10^5\right] = 1{,}21$ [N]

$L_f = 5{,}95 \cdot 5{,}4 \cdot 10^{-2} /(0{,}0571 \cdot (1{,}3 \cdot 12{,}1)^{1/2}) = 1{,}42$ [m]

$d_f = 0{,}15 \cdot 1{,}42 = 0{,}213$ [m]

$$P = \frac{0{,}35 \cdot 0{,}11 \cdot 50{,}1 \cdot 10^6}{1 + (4 \cdot 1{,}42 / 0{,}213)} = 69717{,}47 \Rightarrow 2 \cdot P = 139629{,}52 \approx 140 \ \ [\text{kW/m}^2]$$

Major leakage for 2-inch piping (hole area 1,64*10^{-5} m^2):

$$Q = 0{,}667 \cdot 0{,}5 \cdot 1{,}64 \cdot 10^{-5} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} = 0{,}88 \ \ [\text{kg/s}]$$

$$P \approx 140 \, [\text{kW/m}^2]$$

Rupture for 2-inch piping (hole area 2,03*10^{-3} m^2):

Validity calculation:

$$Q_t \geq 0{,}00203 \cdot \frac{1 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \sqrt{\frac{1{,}3(1{,}3+1)}{2}} \Rightarrow Q_t \geq 19{,}95 \ \ [\text{kg/s}]$$

Phase 1 release:

$$c_i = \sqrt{1{,}3 \cdot 0{,}518 \cdot 298} = 12{,}47 \ \ [\text{m/s}]$$

$$\Delta t = \frac{L}{c_i} = \frac{30}{12{,}47} = 2{,}41 \, [\text{s}]$$, the time phase 1 is going on

$$Q_t = 0{,}00203 \cdot \sqrt{0{,}445} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \frac{1}{\sqrt{1 + 0{,}445 \cdot \left(\frac{0{,}03 \cdot 12{,}47 \cdot 2{,}41}{0{,}0508} \right)}} = 73{,}1 \, [\text{kg/s}]$$

Phase 2 release:

$$M_0 = \frac{20 \cdot 10^5 \cdot \pi \cdot 0{,}0254^2 \cdot 30}{0{,}518 \cdot 298} \cdot \frac{1}{3} = 263 \, [\text{kg}]$$

$$M_{\Delta t} = 263 \cdot \left\{ 1 - \frac{2}{\sqrt{1{,}3 \cdot 0{,}445}} \cdot \left(\frac{0{,}0508}{0{,}03 \cdot 30} \right) \left[\sqrt{1 + 0{,}445 \cdot \frac{0{,}03 \cdot 30}{0{,}0508}} - 1 \right] \right\} = 185{,}3 \, [\text{kg}]$$

$$\beta = \sqrt{\frac{0{,}03 \cdot 30}{0{,}0508}} \cdot \frac{30}{\sqrt{0{,}518 \cdot 298}} = 10{,}16$$

$$19{,}95 = \frac{185{,}3}{10{,}16} \cdot e^{-\frac{t-2{,}41}{10{,}16}} \Rightarrow t = 1{,}5 \, [\text{s}]$$

Major leakage for 6-inch piping (hole area 1,48*10^{-4} m^2):

$$Q = 0{,}667 \cdot 0{,}5 \cdot 1{,}48 \cdot 10^{-4} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} = 7{,}95\,[\text{kg/s}]$$

$$P \approx 140\,[\text{kW/m}^2]$$

Rupture for 6-inch piping (hole area 1,82*10^{-2} m^2):

Validity calculation:

$$Q_t \geq 0{,}018 \cdot \frac{1 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \sqrt{\frac{1{,}3(1{,}3+1)}{2}} \Rightarrow Q_t \geq 177\,[\text{kg/s}]$$

Phase 1 release:

$$c_i = \sqrt{1{,}3 \cdot 0{,}518 \cdot 298} = 12{,}47 \quad [\text{m/s}]$$

$$\Delta t = \frac{L}{c_i} = \frac{10}{12{,}47} = 0{,}80 \quad [\text{s}] \qquad \text{, the time phase 1 is going on}$$

$$Q_t = 0{,}018 \cdot \sqrt{0{,}445} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \frac{1}{\sqrt{1 + 0{,}445 \cdot \left(\frac{0{,}03 \cdot 12{,}47 \cdot 0{,}80}{0{,}1524}\right)}} = 1412 \quad [\text{kg/s}]$$

Phase 2 release:

$$M_0 = \frac{20 \cdot 10^5 \cdot \pi \cdot 0{,}0762^2 \cdot 10}{0{,}518 \cdot 298} \cdot \frac{1}{3} = 788\,[\text{kg}]$$

$$M_{\Delta t} = 788 \cdot \left\{1 - \frac{2}{\sqrt{1{,}3 \cdot 0{,}445}} \cdot \left(\frac{0{,}1524}{0{,}03 \cdot 10}\right)\left[\sqrt{1 + 0{,}445 \cdot \frac{0{,}03 \cdot 10}{0{,}1524}} - 1\right]\right\} = 399 \quad [\text{kg}]$$

$$\beta = \sqrt{\frac{0{,}03 \cdot 10}{0{,}1524}} \cdot \frac{10}{\sqrt{0{,}518 \cdot 298}} = 1{,}13$$

$$177 = \frac{399}{1{,}13} \cdot e^{-\frac{t-0{,}80}{1{,}13}} \Rightarrow t = 1{,}58\,[\text{s}]$$

Major leakage for 10-inch piping (hole area 4,104*10^{-4} m^2):

$$Q = 0{,}667 \cdot 0{,}5 \cdot 4{,}104 \cdot 10^{-4} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} = 22{,}03\,[\text{kg/s}]$$

$$P \approx 140\,[\text{kW/m}^2]$$

Rupture for 10-inch piping (hole area 5,067*10^{-2} m^2):

Validity calculation:

$$Q_t \geq 0{,}0507 \cdot \frac{1 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \sqrt{\frac{1{,}3(1{,}3+1)}{2}} \Rightarrow Q_t \geq 499\,[\text{kg/s}]$$

Phase 1 release:

$$c_i = \sqrt{1{,}3 \cdot 0{,}518 \cdot 298} = 12{,}47\ [\text{m/s}]$$

$$\Delta t = \frac{L}{c_i} = \frac{40}{12{,}47} = 3{,}21\,[\text{s}]$$, the time phase 1 is going on

$$Q_t = 0{,}0507 \cdot \sqrt{0{,}445} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \frac{1}{\sqrt{1 + 0{,}445 \cdot \left(\frac{0{,}03 \cdot 12{,}47 \cdot 3{,}21}{0{,}254}\right)}} = 3090\ [\text{kg/s}]$$

Phase 2 release:

$$M_0 = \frac{20 \cdot 10^5 \cdot \pi \cdot 0{,}127^2 \cdot 40}{0{,}518 \cdot 298} \cdot \frac{1}{3} = 8753{,}3\,[\text{kg}]$$

$$M_{\Delta t} = 8753{,}3 \cdot \left\{1 - \frac{2}{\sqrt{1{,}3 \cdot 0{,}445}} \cdot \left(\frac{0{,}254}{0{,}03 \cdot 40}\right)\left[\sqrt{1 + 0{,}445 \cdot \frac{0{,}03 \cdot 40}{0{,}254}} - 1\right]\right\} = 6528\,[\text{kg}]$$

$$\beta = \sqrt{\frac{0{,}03 \cdot 40}{0{,}254}} \cdot \frac{40}{\sqrt{0{,}518 \cdot 298}} = 7$$

$$499 = \frac{6528}{7} \cdot e^{-\frac{t-3{,}21}{7}} \Rightarrow t = 7{,}59\,[\text{s}]$$

Major leakage for 36-inch piping (hole area $5{,}32 \cdot 10^{-3}$ m^2):

$$Q = 0{,}667 \cdot 0{,}5 \cdot 5{,}32 \cdot 10^{-3} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} = 285{,}6\,[\text{kg/s}]$$

$$P \approx 140\,[\text{kW/m}^2]$$

Rupture for 36-inch piping (hole area 0,657 m^2):

Validity calculation:

$$Q_t \geq 0{,}657 \cdot \frac{1 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \sqrt{\frac{1{,}3(1{,}3+1)}{2}} \Rightarrow Q_t \geq 6466\,[\text{kg/s}]$$

Phase 1 release:

$$c_i = \sqrt{1{,}3 \cdot 0{,}518 \cdot 298} = 12{,}47\,[\text{m/s}]$$

$$\Delta t = \frac{L}{c_i} = \frac{60}{12{,}47} = 4{,}81\,[\text{s}]$$, the time phase 1 is going on

$$Q_t = 0{,}657 \cdot \sqrt{0{,}445} \cdot \frac{20 \cdot 10^5}{\sqrt{0{,}518 \cdot 298}} \cdot \frac{1}{\sqrt{1 + 0{,}445 \cdot \left(\frac{0{,}03 \cdot 12{,}47 \cdot 4{,}81}{0{,}914}\right)}} = 51508\,[\text{kg/s}]$$

Phase 2 release:

$$M_0 = \frac{20 \cdot 10^5 \cdot \pi \cdot 0{,}457^2 \cdot 60}{0{,}518 \cdot 298} \cdot \frac{1}{3} = 170019\,[\text{kg}]$$

$$M_{\Delta t} = 170019 \cdot \left\{1 - \frac{2}{\sqrt{1{,}3 \cdot 0{,}445}} \cdot \left(\frac{0{,}914}{0{,}03 \cdot 60}\right)\left[\sqrt{1 + 0{,}445 \cdot \frac{0{,}03 \cdot 60}{0{,}914}} - 1\right]\right\} = 86068{,}3\ [\text{kg}]$$

$$\beta = \sqrt{\frac{0{,}03 \cdot 60}{0{,}914}} \cdot \frac{60}{\sqrt{0{,}518 \cdot 298}} = 6{,}78$$

$$6466 = \frac{86068{,}3}{6{,}78} \cdot e^{-\frac{t-4{,}81}{6{,}78}} \Rightarrow t = 9{,}38\,[\text{s}]$$

Equation – Mass-flow (liquid-phase)

$$Q = C_d A \sqrt{\frac{2(P_0 - P_a)}{v_f}}$$

$\frac{Q}{\rho}$ mass flow expressed in [m^3/s]

Where:
Q = Mass flow [kg/s]
C_d = coefficient of discharge, is set to 0.5 because the damage is assumed to happen due to outer influence, hence the 0.5-figure.
A = hole area [m^2]
P_0 = pressure inside piping [Pa]
P_a = Air pressure [Pa]
v_f = specific volume [m^3/ kg]
ρ = oil density [kg/m^3]
1 inch = 2,54 cm is assumed

Calculations – Mass-flow

Minor (1 mm^2):

A = 1 mm^2 = 1*10^{-6} m^2
P_0 = 20*10^5 Pa
P_a = 1*10^5 Pa
ρ = 873 kg/m^3
v_f = 1/ρ = 1/873 m^3/ kg

$$Q = 0{,}5 \cdot 1 \cdot 10^{-6} \sqrt{\frac{2(20 \cdot 10^5 - 1 \cdot 10^5)}{\frac{1}{873}}} = 0{,}03 \text{ [kg/s]}$$

This leak can be neglected since $Q < 0{,}05 kg/s$

Major 2-inch (1,64*10^{-5} m^2):

$$A = \frac{\pi \cdot D^2}{4} \cdot 0{,}0081 = \frac{\pi \cdot 0{,}0508^2}{4} \cdot 0{,}0081 = 1{,}64 \cdot 10^{-5} \text{ [m}^2\text{]}$$

P_0 = 20*10^5 Pa
P_a = 1*10^5 Pa
ρ = 873 kg/m^3

$v_f = 1/\rho = 1/873\ \mathrm{m^3/kg}$

$$Q = 0{,}5 \cdot 1{,}64 \cdot 10^{-5} \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 0{,}47\ [\mathrm{kg/s}]$$

This qualifies as a medium leakage

Rupture 2-inch ($2{,}03 \cdot 10^{-3}\ \mathrm{m}^2$):

$$A = \frac{\pi \cdot D^2}{4} = \frac{\pi \cdot 0{,}0508^2}{4} = 2{,}03 \cdot 10^{-3}\ [\mathrm{m}^2]$$

$P_0 = 20 \cdot 10^5$ Pa
$P_a = 1 \cdot 10^5$ Pa
$\rho = 873\ \mathrm{kg/m^3}$
$v_f = 1/\rho = 1/873\ \mathrm{m^3/kg}$

$$Q = 0{,}5 \cdot 2{,}03 \cdot 10^{-3} \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 58{,}5 \qquad [\mathrm{kg/s}]$$

This qualifies as a large leakage

Major 6-inch ($1{,}5 \cdot 10^{-4}\ \mathrm{m}^2$):

$$A = \frac{\pi \cdot D^2}{4} \cdot 0{,}0081 = \frac{\pi \cdot 0{,}1524^2}{4} \cdot 0{,}0081 = 1{,}5 \cdot 10^{-4}\ [\mathrm{m}^2]$$

$P_0 = 20 \cdot 10^5$ Pa
$P_a = 1 \cdot 10^5$ Pa
$\rho = 873\ \mathrm{kg/m^3}$
$v_f = 1/\rho = 1/873\ \mathrm{m^3/kg}$

$$Q = 0{,}5 \cdot 1{,}5 \cdot 10^{-4} \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 4{,}3\ [\mathrm{kg/s}]$$

This qualifies as a medium leakage

Rupture 6-inch ($5{,}1 \cdot 10^{-2}$ m^2):

$$A = \frac{\pi \cdot D^2}{4} = \frac{\pi \cdot 0{,}1524^2}{4} = 1{,}8 \cdot 10^{-2}\,[\mathrm{m}^2]$$

$P_0 = 20 \cdot 10^5$ Pa
$P_a = 1 \cdot 10^5$ Pa
$\rho = 873$ kg/m^3
$v_f = 1/\rho = 1/873$ m^3/ kg

$$Q = 0{,}5 \cdot 1{,}8 \cdot 10^{-2} \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 524\,[\mathrm{kg/s}]$$

This qualifies as a large leakage

Major 10-inch ($4{,}1 \cdot 10^{-4}$ m^2):

$$A = \frac{\pi \cdot D^2}{4} \cdot 0{,}0081 = \frac{\pi \cdot 0{,}254^2}{4} \cdot 0{,}0081 = 4{,}1 \cdot 10^{-4}\,[\mathrm{m}^2]$$

$P_0 = 20 \cdot 10^5$ Pa
$P_a = 1 \cdot 10^5$ Pa
$\rho = 873$ kg/m^3
$v_f = 1/\rho = 1/873$ m^3/ kg

$$Q = 0{,}5 \cdot 4{,}1 \cdot 10^{-4} \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 11{,}8\,[\mathrm{kg/s}]$$

This qualifies as a major leakage

Rupture 10-inch ($5{,}1 \cdot 10^{-2}$ m^2):

$$A = \frac{\pi \cdot D^2}{4} = \frac{\pi \cdot 0{,}254^2}{4} = 5{,}1 \cdot 10^{-2}\,[\mathrm{m}^2]$$

$P_0 = 20 \cdot 10^5$ Pa
$P_a = 1 \cdot 10^5$ Pa
$\rho = 873$ kg/m^3
$v_f = 1/\rho = 1/873$ m^3/ kg

$$Q = 0{,}5 \cdot 5{,}1 \cdot 10^{-2} \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 1460\,[\text{kg/s}]$$

This qualifies as a large leakage

Major 36-inch ($5{,}3 * 10^{-3}$ m^2):

$$A = \frac{\pi \cdot D^2}{4} \cdot 0{,}0081 = \frac{\pi \cdot 0{,}9144^2}{4} \cdot 0{,}0081 = 5{,}3 \cdot 10^{-3}\,[\text{m}^2]$$

$P_0 = 20*10^5$ Pa
$P_a = 1*10^5$ Pa
$\rho = 873$ kg/m^3
$v_f = 1/\rho = 1/873$ m^3/ kg

$$Q = 0{,}5 \cdot 5{,}3 \cdot 10^{-3} \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 153\,[\text{kg/s}]$$

This qualifies as a major leakage

Rupture 36-inch ($5{,}1 * 10^{-2}$ m^2):

$$A = \frac{\pi \cdot D^2}{4} = \frac{\pi \cdot 0{,}9144^2}{4} = 0{,}66\,[\text{m}^2]$$

$P_0 = 20*10^5$ Pa
$P_a = 1*10^5$ Pa
$\rho = 873$ kg/m^3
$v_f = 1/\rho = 1/873$ m^3/ kg

$$Q = 0{,}5 \cdot 0{,}66 \cdot \sqrt{\frac{2\left(20 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{873}}} = 18920\ [\text{kg/s}]$$

This qualifies as a large leakage

Estimated release times for the leaks

The total mass of the segment is 15450 kg and with liquid components constituting 2/3 of this mass this equals to 10300 kg. Estimated total duration for the leak is given by the equation below:

$$\text{DUR}=\frac{Mass}{Q_{initial}}+\text{Time to detection and full closure of section}$$

Mass = Total amount of liquid mass in the sector (kg)
Q_{initial} = Initial rate for liquid (kg/s)

Leak sizes	**Time to detection (seconds)** **Gas**	 **Liquid**
Small	60	240
Medium	30	60
Major	10	20
Large	5	10

Estimated total duration for fire = DUR + Burning time of oil (when pool fire)

Closing time is assumed to take approximately 2 seconds/inch.

The burning time for oil is set to 3,5 minutes, see calculations below.

Burning time = Mass of oil per square meter / the burning rate for oil = $\frac{873 \cdot 0{,}01}{0{,}045} \approx 3{,}5\,\text{min}$

Mass of oil per square meter = Oil density * pool thickness [kg/m^2]
Burning rate for crude oil = 0,045 [kg/m^2 s]
Pool thickness assumed to be 1 cm

<u>2-inch oil leak</u>

Major: $\text{DUR} = \frac{10300}{0{,}47} + 240 + 4 \approx 370\,\text{min}$

$\Rightarrow$ Total burning time = $370 + 3{,}5 \approx 374\,\text{min}$

Rupture: $\text{DUR} = \frac{10300}{58{,}5} + 10 + 4 \approx 3{,}5\,\text{min}$

$\Rightarrow$ Total burning time = $3{,}5 + 3{,}5 = 7\,\text{min}$

6-inch oil leak

Major: $\text{DUR} = \frac{10300}{4,3} + 60 + 12 \approx 41\,\text{min}$

$\Rightarrow$ Total burning time $= 41 + 3,5 \approx 45\,\text{min}$

Rupture: $\text{DUR} = \frac{10300}{524} + 10 + 12 \approx 1\,\text{min}$

$\Rightarrow$ Total burning time $= 1 + 3,5 \approx 5\,\text{min}$

10-inch oil leak

Major: $\text{DUR} = \frac{10300}{11,8} + 20 + 20 \approx 15,5\,\text{min}$

$\Rightarrow$ Total burning time $= 15,5 + 3,5 = 19\,\text{min}$

Rupture: $\text{DUR} = \frac{10300}{1460} + 10 + 20 \approx 1\,\text{min}$

$\Rightarrow$ Total burning time $= 1 + 3,5 \approx 5\,\text{min}$

36-inch oil leak

Major: $\text{DUR} = \frac{10300}{153} + 10 + 72 \approx 2,5\,\text{min}$

$\Rightarrow$ Total burning time $= 2,5 + 3,5 = 6\,\text{min}$

Rupture: $\text{DUR} = \frac{10300}{18920} + 10 + 72 \approx 1,5\,\text{min}$

$\Rightarrow$ Total burning time $= 1,5 + 3,5 = 5\,\text{min}$

2-inch gas leak

Major: $\text{DUR} = \frac{5150}{0,88} + 60 + 4 \approx 99\,\text{min}$

$\Rightarrow$ Total burning time = DUR = 99 min

Rupture: $\text{DUR} = \frac{5150}{73,1} + 5 + 4 \approx 1,5\,\text{min}$

$\Rightarrow$ Total burning time = DUR = 1,5 min

6-inch gas leak

Major: $\text{DUR} = \frac{5150}{7,95} + 30 + 12 \approx 11,5\,\text{min}$

$\Rightarrow$ Total burning time = DUR = 11,5 min

Rupture: $\text{DUR} = \dfrac{5150}{177} + 5 + 12 \approx 1\,\text{min}$

$\Rightarrow$ Total burning time = DUR = 1 min

10-inch gas leak

Major: $\text{DUR} = \dfrac{5150}{22{,}03} + 10 + 20 \approx 4{,}5\,\text{min}$

$\Rightarrow$ Total burning time = DUR = 4,5 min

Rupture: $\text{DUR} = \dfrac{5150}{499} + 5 + 20 \approx 1\,\text{min}$

$\Rightarrow$ Total burning time = DUR = 1 min

36-inch gas leak

Major: $$\text{DUR} = \frac{5150}{285,6} + 5 + 72 \approx 2\,\text{min}$$

$\Rightarrow$ Total burning time = DUR = 2 min

Rupture: $$\text{DUR} = \frac{5150}{6466} + 5 + 72 \approx 1,5\,\text{min}$$

$\Rightarrow$ Total burning time = DUR = 1,5 min

Equations – Pool fire and radiation

$$d_{eq} = 4 \cdot \left(\frac{poolarea}{poolcircumference} \right)$$

$$h_f = d_p \cdot 42 \cdot \left[\frac{b'}{\rho_a \cdot \sqrt{g \cdot d_p}} \right]^{0,61}$$

$$0,8 < h_f / d_f < 4$$

$$P = \frac{0,35 \cdot b' \cdot h_c}{1 + 4h_f / d_f}$$

$$P_S = \sigma \cdot T^4$$

$$P = \varepsilon \cdot P_S$$

$$P_{12} = P_1 \cdot \tau_a \cdot F_{12}$$

$$\tau_a = 1 - \alpha_W - \alpha_C$$

Where:
ε = emittance [-]
σ = Stefan-Boltzmann constant [W/m^2K^4]
ρ_a = air density, is set to 1.29 [kg/m^3]
τ_a = transmissive ability [-]
α_c = absorption factor for CO_2 [-]
α_w = absorption factor for water [-]
h_f = flame height [m]
d_{eq} = Equivalent diameter [m]
d_f = flame diameter [m]
d_p = pool diameter [m]
F_{12} = angle coefficient for A_1 to A_2 [-]

g = weight acceleration = 9,81 [m/s^2]
h_c = energy value = 40 [MJ/kg] (Shitanda & Kenyatta, 2001)
h_f = flame height [m]
P = radiation per area unit [W/m^2]
P_1 = radiation from A_1[W/m^2]
P_{12} = radiation from A_1 to A_2 [W/m^2]
P_S = radiation from a black body [W/m^2]
T = temperature [K]
b' = burning rate per area unit [kg/m^{2}s]

Calculations – Pool-fire and radiation

Measurements have been taken from Troll C blueprints. The pool-area is assumed to be controlled by the drainage wells unless stated different. Due to the large mass flows in the large and major leakages the limiting factor for the pool-area is the brick on the deck, hence the pool-area for these leakage sizes are assumed to be equal.

Large and major:
Pool-area = $\pi * r^2 = \pi * 7^2 = 153$ [m^2]

$$d_{eq} = 2 \cdot 7 = 14\,[\text{m}]$$

$$h_f = 14 \cdot 42 \cdot \left[\frac{0{,}045}{1{,}29 \cdot \sqrt{9{,}81 \cdot 14}}\right]^{0{,}61} = 16{,}92\,[\text{m}]$$

$h_f / d_f = 16{,}92/14 = 1{,}21$ OK according to $0{,}8 < h_f / d_f < 4$

$$P = \frac{0{,}35 \cdot 0{,}045 \cdot 40 \cdot 10^6}{1 + 4 \cdot 16{,}92/14} = 107877 \approx 108\ [\text{kW/m}^2]$$

$P = \varepsilon \cdot P_S$, ε set to 1 due to black body assumption $\Rightarrow P = P_S$

$108000 = 5{,}67 \cdot 10^{-8} \cdot T^4 \Rightarrow T \approx 1175$ [K]

$\alpha_c = 0$, absorption factor for CO_2 can be neglected
Calculations for angular coefficient and absorption factor (using tables below) and assuming 15°C and 90% relative humidity gives
$F_{max} = F_{12} = 0{,}65$ and $\alpha_w = 0$, (radius and distance from pool centre to the beam are set as equal because pool is assumedly close to beam but not in contact with it)
$\tau_a = 1$
$P_{12} = 108000 \cdot 0{,}65 \cdot 1 = 70200 \approx 70{,}2$ [kW/m^2]

Medium:

Area is assumed to be controlled by burning rate, 0,045 kg/m^2 s. Medium mass flow is 4,3 kg/s.

This leads to an approximate pool-area of:

$$4{,}3 = 0{,}045 \cdot x \Rightarrow x \approx 95{,}6\,[\mathrm{m}^2]$$

$$\pi \cdot r^2 = 95{,}6 \Rightarrow r = 5{,}52\,[\mathrm{m}]$$

$$d_{eq} = 2 \cdot 5{,}52 = 11{,}04\,[\mathrm{m}]$$

$$h_f = 11{,}04 \cdot 42 \cdot \left[\frac{0{,}045}{1{,}29 \cdot \sqrt{9{,}81 \cdot 7{,}52}}\right]^{0{,}61} = 16{,}13\,[\mathrm{m}]$$

$h_f / d_f = 16{,}13/11{,}04 = 1{,}46$ OK according to $0{,}8 < h_f / d_f < 4$

$$P = \frac{0{,}35 \cdot 0{,}045 \cdot 40 \cdot 10^6}{1 + 4 \cdot 16{,}13/11{,}04} = 92099 \approx 92{,}1\,[\mathrm{kW/m^2}]$$

$P = \varepsilon \cdot P_S$, ε set to 1 due to black body assumption $\Rightarrow P = P_S$

$92100 = 5{,}67 \cdot 10^{-8} \cdot T^4 \Rightarrow T \approx 1129\,[\mathrm{K}]$

$\alpha_c = 0$, absorption factor for CO_2 can be neglected

Calculations for angular coefficient and absorption factor (using tables below) and assuming 15°C and 90% relative humidity gives

$F_{max} = F_{12} = 0{,}35$ and $\alpha_w = 0{,}1$

$\tau_a = 0{,}9$

$P_{12} = 92100 \cdot 0{,}35 \cdot 0{,}9 \approx 29\ [\mathrm{kW/m^2}]$

Small:

Area assumed to be controlled by burning rate, 0,045 kg/m^2 s. Small mass flow is 0,47 kg/s.

This leads to an approximate pool-area of:

$$0{,}47 = 0{,}045 \cdot x \Rightarrow x \approx 10{,}44\,[\mathrm{m}^2]$$

$$\pi \cdot r^2 = 10{,}44 \Rightarrow r = 1{,}82\,[\mathrm{m}]$$

$$d_{eq} = 2 \cdot 1{,}82 = 3{,}65\,[\mathrm{m}]$$

$$h_f = 3{,}65 \cdot 42 \cdot \left[\frac{0{,}045}{1{,}29 \cdot \sqrt{9{,}81 \cdot 2{,}38}}\right]^{0{,}61} = 5{,}33\,[\mathrm{m}]$$

$h_f / d_f = 5{,}33/3{,}65 = 1{,}46$ OK according to $0{,}8 < h_f / d_f < 4$

$$P = \frac{0{,}35 \cdot 0{,}045 \cdot 40 \cdot 10^6}{1 + 4 \cdot 4{,}94/2{,}38} \approx 92{,}2\,[\mathrm{kW/m^2}]$$

$P = \varepsilon \cdot P_S$, ε set to 1 due to black body assumption $\Rightarrow P = P_S$

$92200 = 5{,}67 \cdot 10^{-8} \cdot T^4 \Rightarrow T \approx 1129$ [K]

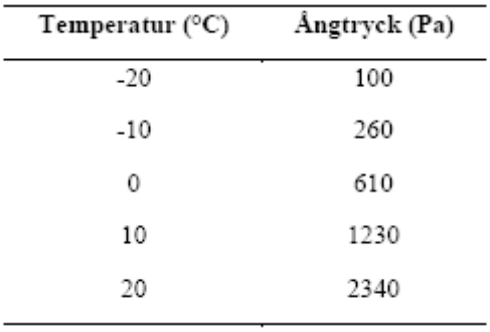
$\alpha_c = 0$, absorption factor for CO_2 can be neglected

Calculations for angular coefficient and absorption factor (using tables below) and assuming 15°C and 90% relative humidity gives

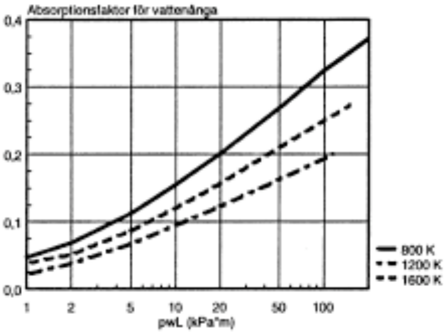
$F_{max} = F_{12} = 0{,}05$ and $\alpha_w = 0{,}1$

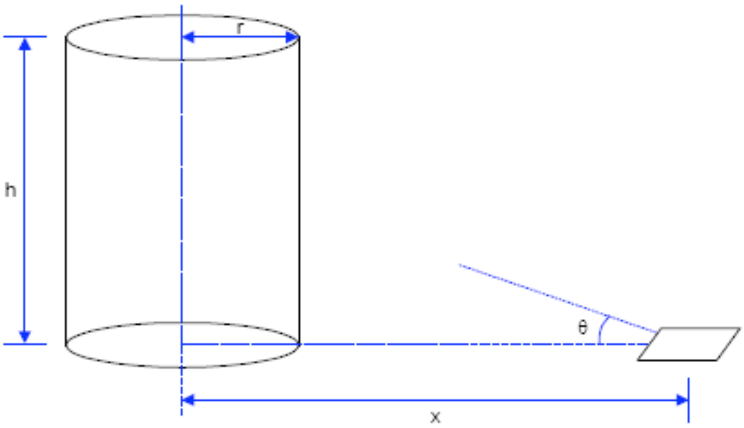
$\tau_a = 0{,}9$

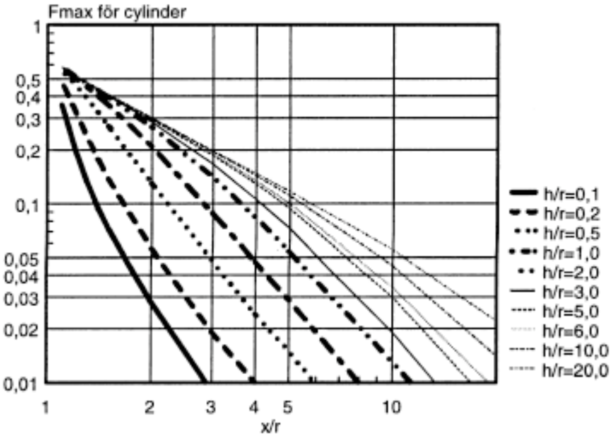
$$P_{12} = 92200 \cdot 0{,}05 \cdot 0{,}9 \approx 4{,}2 \text{ [kW/m}^2\text{]}$$



Temperatur (°C)	Ångtryck (Pa)
-20	100
-10	260
0	610
10	1230
20	2340







(Fischer et al, 1998)

Equations – Steel and critical temperature time

$$P = \frac{Q_{Jet}}{\Delta t \cdot w}$$

$$Q_{Jet/Pool} = Q \Leftrightarrow P \cdot \Delta t \cdot w = c_{ps} \cdot \Delta v_s \cdot V_s \cdot \gamma_s \Leftrightarrow \Delta t = \frac{c_{ps} \cdot \Delta v_s \cdot V_s \cdot \gamma_s}{P \cdot w}$$

$$V_s = \frac{Weight/meter}{density}$$

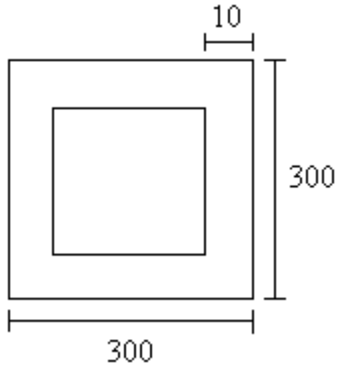
$$V_s = (l_2 \cdot w_2 \cdot h_2) - (l_1 \cdot w_1 \cdot h_1)$$

$$Q = c_{ps} \cdot \Delta v_s \cdot V_s \cdot \gamma_s$$

Where:

P = Radiation [W/m^2]
V_s = Volume per length-unit [m^3/m]
Q = The needed energy to increase steel temperature by Δv_s °C [J/m]
Δv_s = Temperature increase for steel profile [°C]
c_{ps} = Specific heat capacity for steel [J/kg °C]
γ_s = Density [kg/m^3]
w = beam width [m]
Δt = length of time interval [s]
Q_{Jet} = Released energy from jet-flame [J/m]
l_2 = outer length of beam [m]
l_1 = inner length of beam [m]
w_2 = outer width of beam [m]
w_1 = inner width of beam [m]
$h_2 = h_1$ = height of beam [m]

Calculations – Steel and critical temperature time



γ_s = 7850 [kg/m^3]

$V_s = (l_2 \cdot w_2 \cdot h_2) - (l_1 \cdot w_1 \cdot h_1) = (0{,}30 \cdot 0{,}30 \cdot 1) - (0{,}28 \cdot 0{,}28 \cdot 1) = 1{,}19 \cdot 10^{-2}$ [m^3/m]

c_{ps} = 482 [J/kg °C]

$Q = 0{,}482 \cdot 10^3 \cdot 435 \cdot 1{,}19 \cdot 10^{-2} \cdot 7850 = 1{,}91 \cdot 10^7$ [J/m]

Δv_s = 450-15 = 435 [°C]

w = 0,30 [m]

Large and major:

$Q_{pool} = P \cdot \Delta t \cdot w = 70{,}2 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t$

$$Q_{pool} = Q \Rightarrow 70{,}2 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{70{,}2 \cdot 10^3 \cdot 0{,}30} = 906{,}9 sek \approx 15 \min$$

Medium:

$Q_{pool} = P \cdot \Delta t \cdot w = 29 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t$

$$Q_{pool} = Q \Rightarrow 29 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{29 \cdot 10^3 \cdot 0{,}30} = 2195{,}4 sek \approx 37 \min$$

Small:

$Q_{pool} = P \cdot \Delta t \cdot w = 4{,}2 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t$

$$Q_{pool} = Q \Rightarrow 4{,}2 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{4{,}2 \cdot 10^3 \cdot 0{,}30} = 15158{,}7 sek \approx 253 \min$$

Jet-flame (250 kW/m2):

$Q_{Jet} = P \cdot \Delta t \cdot w = 250 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t$

$$Q_{Jet} = Q \Rightarrow 250 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{250 \cdot 10^3 \cdot 0{,}30} = 254{,}67 sek \approx 4{,}24 \min$$

Jet-flame (350 kW/m2):

$Q_{Jet} = P \cdot \Delta t \cdot w = 350 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t$

$$Q_{Jet} = Q \Rightarrow 350 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{350 \cdot 10^3 \cdot 0{,}30} = 181{,}9 sek \approx 3{,}03 \min$$

4 Calculations for the consequence analysis in scenario 4

Equations – Mass-flow

$$Q = C_d A \sqrt{\frac{2(P_0 - P_a)}{v_f}}$$

$\frac{Q}{\rho}$ mass flow expressed in [m^3/s]

Where:
Q = Mass flow [kg/s]
C_d = coefficient of discharge, is set to 0.5 because the damage is assumed to happen due to outer influence, hence the 0.5-figure.
A = hole area [m^2]
P_0 = pressure inside piping [Pa]
P_a = Air pressure [Pa]
v_f = specific volume [m^3/ kg]
ρ = oil density [kg/m^3]

Calculations – Mass-flow

These calculations consider the 8 inches piping that goes past the module which equals approximately a diameter of 20,32 cm.

Minor (1 mm^2):

A = 1 mm^2 = 1*10^{-6} m^2
P_0 = 2*10^5 Pa
P_a = 1*10^5 Pa
ρ = 859 kg/m^3
v_f = 1/ρ = 1/859 m^3/ kg

$$Q = 0{,}5 \cdot 1 \cdot 10^{-6} \sqrt{\frac{2(2 \cdot 10^5 - 1 \cdot 10^5)}{\frac{1}{859}}} = 0{,}0065 \text{ [kg/s]}$$

$$\frac{Q}{\rho} = \frac{0{,}0065}{859} = 7{,}45 \cdot 10^{-6} \text{ [m}^3\text{/s]}$$

This qualifies as a small leakage

Major ($2{,}6 \cdot 10^{-4}$ m^2):

$$A = \frac{\pi \cdot D^2}{4} \cdot 0{,}0081 = \frac{\pi \cdot 0{,}2032^2}{4} \cdot 0{,}0081 = 2{,}6 \cdot 10^{-4}\ [\mathrm{m}^2]$$

$P_0 = 2 \cdot 10^5$ Pa
$P_a = 1 \cdot 10^5$ Pa
$\rho = 859$ kg/m^3
$v_f = 1/\rho = 1/859$ m^3/ kg

$$Q = 0{,}5 \cdot 2{,}6 \cdot 10^{-4} \sqrt{\frac{2\left(2 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{859}}} = 1{,}7\ [\mathrm{kg/s}]$$

$$\frac{Q}{\rho} = \frac{1{,}7}{859} = 2 \cdot 10^{-3}\ [\mathrm{m^3/s}]$$

This qualifies as a medium leakage

Rupture ($3{,}24 \cdot 10^{-2}$ m^2):

$$A = \frac{\pi \cdot D^2}{4} = \frac{\pi \cdot 0{,}2032^2}{4} = 3{,}24 \cdot 10^{-2}\ [\mathrm{m}^2]$$

$P_0 = 2 \cdot 10^5$ Pa
$P_a = 1 \cdot 10^5$ Pa
$\rho = 859$ kg/m^3
$v_f = 1/\rho = 1/859$ m^3/ kg

$$Q = 0{,}5 \cdot 3{,}24 \cdot 10^{-2} \sqrt{\frac{2\left(2 \cdot 10^5 - 1 \cdot 10^5\right)}{\frac{1}{859}}} = 212{,}3\ [\mathrm{kg/s}]$$

$$\frac{Q}{\rho} = \frac{212{,}3}{859} = 0{,}25\ [\mathrm{m^3/s}]$$

This qualifies as a large leakage

Equations – Pool-fire and radiation

$$A = \frac{Q \cdot t}{h}$$

$$d_{eq} = 4 \cdot \left(\frac{poolarea}{poolcircumf\ erence} \right)$$

$$h_f = d_p \cdot 42 \cdot \left[\frac{b'}{\rho_a \cdot \sqrt{g \cdot d_p}} \right]^{0,61}$$

$$0,8 < h_f / d_f < 4$$

$$P = \frac{0,35 \cdot b' \cdot h_c}{1 + 4h_f / d_f}$$

$$P_S = \sigma \cdot T^4$$

$$P = \varepsilon \cdot P_S$$

$$P_{12} = P_1 \cdot \tau_a \cdot F_{12}$$

$$\tau_a = 1 - \alpha_W - \alpha_C$$

Where:
Q = mass flow [kg/s]
t = time [s]
h = thickness of oil in pool [m]
ε = emittance [-]
σ = Stefan-Boltzmann constant [W/m^2K^4]
ρ_a = air density, is set to 1.29 [kg/m^3]
τ_a = transmissive ability [-]
α_c = absorption factor for CO_2 [-]
α_w = absorption factor for water [-]
h_f = flame height [m]
d_{eq} = Equivalent diameter [m]
d_f = flame diameter [m]
d_p = pool diameter [m]
F_{12} = angle coefficient for A_1 to A_2 [-]
g = weight acceleration = 9,81[m/s^2]
h_c = energy value [J/kg]
h_f = flame height [m]
P = radiation per area unit [W/m^2]
P_1 = radiation from A_1 [W/m^2]
P_{12} = radiation from A_1 to A_2 [W/m^2]
P_S = radiation from a black body [W/m^2]
T = temperature [K]
b' = burning rate per area unit [kg/m^2s]

Calculations – Pool-fire and radiation

The thickness of the oil in the pool is assumed to be 0,01 m in all calculations.

Small:

Because of the small amount released the pool area is calculated using the time 60 minutes, which is the requirement for pool fires on the module, to see how large the pool can be in that time. This area is then used to calculate the radiation towards the steel and since ignition is assumed to take place as soon as the release of the oil takes place this makes the calculations conservative.

t = 60 min = 3600 s

$Q = 0{,}0065\,kg/s = (0{,}0065/859)\,m^3/s$, when $\rho = 859$ kg/m^3

$$A = \frac{Q\left[m^3/s\right]\cdot t}{thickness\,of\ pool}$$

$$A = \frac{7{,}57\cdot 10^{-6}\cdot 3600}{0{,}01} = 2{,}73\ [\text{m}^2]$$

Circular pool is assumed $\Rightarrow \pi\cdot r^2 = A \Leftrightarrow \pi\cdot r^2 = 2{,}73 \Rightarrow r = 0{,}932m \Rightarrow d = 1{,}86m$

$$h_f = 1{,}86\cdot 42\cdot\left[\frac{0{,}045}{1{,}29\cdot\sqrt{9{,}81\cdot 1{,}86}}\right]^{0{,}61} = 4{,}16\ [\text{m}]$$

$h_f/d_f = 4{,}16/1{,}86 = 2{,}24$ OK according to $0{,}8 < h_f/d_f < 4$

$$P = \frac{0{,}35\cdot 0{,}045\cdot 41{,}87\cdot 10^6}{1+4\cdot 4{,}16/1{,}86} = 66268 \approx 66{,}3\ [\text{kW/m}^2]$$

$P = \varepsilon\cdot P_S$, ε set to 1 due to black body assumption $\Rightarrow P = P_S$

$66300 = 5{,}67\cdot 10^{-8}\cdot T^4 \Rightarrow T \approx 1040\,[\text{K}]$

$\alpha_c = 0$, absorption factor for CO_2 can be neglected

Calculations for angular coefficient and absorption factor (using tables below) gives

$F_{max} = F_{12} = 0{,}65$ and $\alpha_w = 0$, (radius and distance from pool centre to the beam are set as equal because pool is assumedly close to beam but not in contact with it)

$\tau_a = 1$

$P_{12} = 66300\cdot 0{,}65\cdot 1 \approx 43{,}1\ [\text{kW/m}^2]$

Medium:
This size of leak makes the pool build up faster. Because of the somewhat higher mass flow one can expect the whole area under the module being filled with oil and thereby, if ignited, totally engulfing every supporting beam which is very ominous. The total area under the module is approximately 155,2 m^2 (9,7 x 16) the measurements have been taken from the Study report from Aker Solutions (Aker Kværner AS [2], 2007). The time it takes to fill this area with the actual mass flow is hence calculated.

$$Q = 1{,}7\,kg/s = (1{,}7/859)\,m^3/s = 2\cdot 10^{-3}\,m^3/s$$

$$155{,}2 = \frac{2\cdot 10^{-3}\cdot t}{0{,}01} \Rightarrow t \approx 13\,\text{min}$$

$$d_{eq} = 4\cdot\left(\frac{155{,}2}{9{,}7+9{,}7+16+16}\right) = 12{,}1\ \text{[m]}$$

$$h_f = 12{,}1\cdot 42\cdot\left[\frac{0{,}045}{1{,}29\cdot\sqrt{9{,}81\cdot 12{,}1}}\right]^{0{,}61} = 15{,}29\ \text{[m]}$$

$h_f/d_f = 15{,}29/12{,}1 = 1{,}26$ OK according to $0{,}8 < h_f/d_f < 4$

$$P = \frac{0{,}35\cdot 0{,}045\cdot 41{,}87\cdot 10^6}{1+4\cdot 15{,}29/12{,}1} = 108919 \approx 109\ \text{[kW/m}^2\text{]}$$

Large:
This size of leak makes the pool build up very fast. Because of the high mass flow one can expect the whole area under the module being filled with oil and thereby, if ignited, totally engulfing every supporting beam which is very ominous. The total area under the module is approximately 155,2 m^2 (9,7 x 16) the measurements have been taken from the Study report from Aker Solutions (Aker Kværner AS [2], 2007). The time it takes to fill this area with the actual mass flow is hence calculated.

$$Q = 212{,}3\,kg/s = (212{,}3/859)\,m^3/s = 0{,}25\,m^3/s$$

$$155{,}2 = \frac{0{,}25\cdot t}{0{,}01} \Rightarrow t \approx 6{,}2\,\text{sec}$$

$$d_{eq} = 4\cdot\left(\frac{155{,}2}{9{,}7+9{,}7+16+16}\right) = 12{,}1\ \text{[m]}$$

$$h_f = 12{,}1\cdot 42\cdot\left[\frac{0{,}045}{1{,}29\cdot\sqrt{9{,}81\cdot 12{,}1}}\right]^{0{,}61} = 15{,}29\ \text{[m]}$$

$h_f / d_f = 15{,}29 / 12{,}1 = 1{,}26$ OK according to $0{,}8 < h_f / d_f < 4$

$$P = \frac{0{,}35 \cdot 0{,}045 \cdot 41{,}87 \cdot 10^6}{1 + 4 \cdot 15{,}29 / 12{,}1} = 108919 \approx 109 \ \text{[kW/m}^2\text{]}$$

Calculations – Steel and critical temperature time

$$Q_{Pool} = Q \Leftrightarrow P \cdot \Delta t \cdot w = c_{ps} \cdot \Delta v_s \cdot V_s \cdot \gamma_s \Leftrightarrow \Delta t = \frac{c_{ps} \cdot \Delta v_s \cdot V_s \cdot \gamma_s}{P \cdot w}$$

Q_{Pool} = Heat flux from pool fire
Q = Heat flux needed to increase steel temperature by Δv_s °C.

See Appendix 3 for more information about the equations used for the steel.

Small:

$$Q_{pool} = P \cdot \Delta t \cdot w = 43{,}1 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t$$

$$Q_{pool} = Q \Rightarrow 43{,}1 \cdot 10^3 \cdot 0{,}30 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{43{,}1 \cdot 10^3 \cdot 0{,}30} = 1477{,}2 sek \approx 25 \min$$

Medium and large:

$$Q_{pool} = P \cdot \Delta t \cdot w = 109 \cdot 10^3 \cdot (0{,}30 \cdot 4) \cdot \Delta t$$

$$Q_{pool} = Q \Rightarrow 109 \cdot 10^3 \cdot 1{,}20 \cdot \Delta t = 1{,}91 \cdot 10^7 \Rightarrow \Delta t = \frac{1{,}91 \cdot 10^7}{109 \cdot 10^3 \cdot 1{,}20} = 146 sek \approx 2{,}5 \min$$

Estimated release times for the leaks

The total mass of the oil in the segment is 639 119 kg.

Estimated total duration = Time to empty segment + Detection time + Closing time + Burning time of oil

The time to empty the segment is calculated like the mass divided by the initial mass flow rate. Detection time and closing time is assumed to take 1 minute respectively and the burning time for oil is set to 3 minutes, see calculations below.

Burning time = Mass of oil per square meter / the burning rate for oil = $\frac{859 \cdot 0{,}01}{0{,}045} \approx 3{,}5 \min$

Mass of oil per square meter = Oil density * pool thickness [kg/m^2]

Burning rate for crude oil = 0,045 [kg/m^2 s]

8-inch oil leak

Major: $$\text{DUR} = \frac{639119}{1{,}7} + 60 + 16 \approx 6267{,}5\,\text{min}$$

$$\Rightarrow \text{Total burning time} = 6267{,}5 + 3{,}5 \approx 6271\,\text{min}$$

Rupture: $$\text{DUR} = \frac{639119}{212{,}3} + 10 + 16 \approx 51\,\text{min}$$

$$\Rightarrow \text{Total burning time} = 51 + 3{,}5 \approx 55\,\text{min}$$

5 Procedure of frequency analysis

To better understand how the method is used when doing the frequency analysis, the following example is shown to clarify the whole frequency analysis procedure. The procedure for one leak size is going to be showed and explanations will be given in each and every step why this is done. The input data that will be used in this example is for a medium leak size in scenario type 1. The procedure will follow the structure of the event-tree; see Figure 5 with the following points:

- Leak size and leak frequency, so that every relevant leak size in every scenario type gets a start leak frequency.
- Detection and closure failure, this will be made with the help of a fault-tree, see Figure 6 and the values presented in chapter 6.
- Ignition probability, what the probability is for a leak to ignite.
- Fire detection failure, this will be made with the help of a fault-tree, see Figure 7 and values presented in chapter 6. This detection will only make a difference if no other detection has been made earlier.

Leak sizes

In the example involving scenario type 1 there are two different component sizes in the segment, sizes 10 and 12 inch. When these sizes are known, calculations about the mass rates in each of the distribution sizes for each component size has to be done by using equation [1] or [2], see chapter 6. When the mass rates are calculated for each distribution size containing a component size, the mass rates are to be categorised into leak sizes using Table 3 in chapter 6. In scenario type 1 this would look like Table X below:

- First knowing the component sizes in the scenario type (segment).
- Second, calculating the mass rates for each distribution size using the hole size distribution and equation [1] or [2], chapter 6.
- And third, categorizing the distribution sizes after amount of medium (hydrocarbons) being released into the different leak sizes using Table 3, chapter 6.

Distribution sizes (inch")	**Q (kg/s)**	**Leak sizes**
Minor	0,04	Neglected
Major 10"	19	Major
Rupture 10"	> 30	Large
Major 12"	**9**	**Medium**
Rupture 12"	> 30	Large

- Distribution size minor when calculating with equation 1 (because the medium inside the segment is gas) will give a mass rate of 0,04 kg/s, this mass rate is neglected as one can see in Table 3 in section 6.1.1.

- Distribution size major 10” when calculating with equation 1 (because the medium inside the segment is gas) will give a mass rate of 19 kg/s. 10 inches is used because one of the pipes and component sizes are 10”. The mass rate 19 kg/s is a leak size major as one can see in Table 3 in section 6.1.1.
- Distribution size rupture 10” when calculating with equation 1 (because the medium inside the segment is gas) will give a mass rate larger than 30 kg/s. 10 inches is used because one of the pipes and component sizes are 10”. The mass rate larger than 30 kg/s is a leak size large as one can see in Table 3 in section 6.1.1.
- Distribution size major 12” when calculating with equation 1 (because the medium inside the segment is gas) will give a mass rate of 9 kg/s. 12 inches is used because one of the pipes and component sizes are 12”. The mass rate 9 kg/s is a leak size medium as one can see in Table 3 in section 6.1.1.
- Distribution size rupture 12” when calculating with equation 1 (because the medium inside the segment is gas) will give a mass rate larger than 30 kg/s. 12 inch is used because one of the pipe and component sizes is 12”. The mass rate larger than 30 kg/s is a leak size large as one can see in Table 3 in section 6.1.1.

The calculated mass rates are then used in the consequence analysis to see if a pool fire or a jet fire (in the example given here this will be a jet fire because the medium is gas) can cause any harm to the module that is associated with a collapse. In the scenario types where a collapse could be the result of a fire, further analysis about the frequency rate are being made to see how often this is bound to happen, beginning with the leak frequency per year.

Leak frequency per year

The leak frequency per year for different leak sizes and how this is calculated will be presented below. The example given is showing how a medium gas leak in scenario type 1 is to be calculated in the frequency analysis. A leak in a 12 inch component with a hole area major, will give the initial mass rate of 9 kg/s. This mass rate corresponds to the leak size category medium (1-10 kg/s), see Table 3 in section 6.1.1.

This means that when using different number of components and the failure rate per year for these components; see Table 4 in section 6.1.1, the failure rate for the distribution size major is being used. Below it is shown how the failure rate for different leak sizes in scenario 1 is calculated.

Medium size leak

Components	**Quantity of 12" components or pipes**	**Leak rate per year, major**
Valves	10	$1,7*10^{-4}$
Flanges	18	$1,3*10^{-4}$
Piping (10m)	2,0	$5,2*10^{-5}$
Compressor		$2,6*10^{-3}$
Heat ex (S&T)	1	$4,4*10^{-3}$
Vessel	1	

Calculation procedure:
SUM(($1,7*10^{-4}$*10)+($1,3*10^{-4}$*18)+($5,2*10^{-5}$*2)+ $4,4*10^{-3}$) = 0,0067 per year

This procedure is to be done for every relevant leak size in every relevant scenario type. However, calculations about frequency rates for major and large leak size in scenario type 1 has also been done.

Major size leak

Components	**Quantity of 10" components or pipes**	**Leak rate per year, major**
Valves	8	$1,7*10^{-4}$
Flanges	9	$1,3*10^{-4}$
Piping (10m)	1,5	$5,2*10^{-5}$
Compressor	1	$2,6*10^{-3}$
Heat ex (S&T)		$4,4*10^{-3}$
Vessel		

Calculation procedure:
SUM(($1,7*10^{-4}$*8)+($1,3*10^{-4}$*9)+($5,2*10^{-5}$*1,5)+ $2,6*10^{-3}$) = 0,007 per year

Large size leak

Components	Quantity of 10" components or pipes	Quantity of 12" components or pipes	Leak rate per year, rupture
Valves	8	10	$1,7*10^{-5}$
Flanges	9	18	$1,3*10^{-5}$
Piping (10m)	1,5	2,0	$5,2*10^{-6}$
Compressor	1		$5,1*10^{-5}$
Heat ex (S&T)		1	$4,4*10^{-4}$
Vessel		1	$4,2*10^{-5}$

SUM$((18*1,7*10^{-5})+(27*1,3*10^{-5})+(3,5*5,2*10^{-6})+ 5,1*10^{-5} +4,4*10^{-4}+4,2*10^{-5}) = 0,001$ per year

In the large size leak calculation the quantity of 10-inch and 12-inch components for full rupture has been added together. This is done because distribution size rupture 10" and rupture 12" both give large leak sizes.

The total frequency rate (failure rate) leading to different leak sizes in scenario type 1 is:

- medium leak is 0,0067 per year
- major leak is 0,007 per year
- large leak 0,001 per year

These three failure rate will be the start event in their different event-tree.

Detection and closure – phase 1

This section will handle the frequency rate for failure of the different barriers and closing devices. The outcome for the branches in the "detection and closure part" in the event-tree have been calculated using the fault-tree (Figure 6) presented in chapter 6. The values of the frequency rates and probability of failure for this fault-tree are also presented in chapter 6. The two different gates used in this fault-tree have been calculated using the following two equations:

OR gate = $Basic1 + Basic2 - (Basic1 * Basic2) = Or4$

AND gate = $Or1 * Or2 * Or3 = And1$

For the example with a medium gas leak in scenario type 1 when using the Tables in chapter 6, the medium probability is used.

The use of test intervals as mentioned in the beginning of section 6.1.3 is for example made like this for a pressure transmitter with a test interval of 24 hours.

$$PFD_{UK} = \lambda_{DU} * (t/2)$$

$$PFD_{UK}= 0.3*10^{-6} * (24/2)$$

$$PFD_{UK}= 3{,}6*10^{-6} \text{ per year}$$

The same goes for an IR point gas detector with a test interval of 6 month.

$$PFD_{UK} = \lambda_{DU} * (t/2)$$

$$PFD_{UK}= 0.7*10^{-6} * (24 * 30 * 6 / 2)$$

$$PFD_{UK}= 1{,}5*10^{-3} \text{ per year}$$

Ignition probability if a leak occurs
The ignition probability will then be multiplied, depending on the leak size and medium (gas or oil), with the two outcomes for the branches of detection and closure in the event-tree. For scenario type 1, medium size gas leak, the ignition probability of 0,15 % are being used, see Tabel 7.

Fire detection and closure – phase 2
The same procedure as described in "Detection and closure – phase 1" is used in this part except that fault trees (Figure 7) are being used, presented in chapter 6. The fire detection and closure is only used if no other detection has been made in the event-tree and of course if ignition has taken place. The "Or"-gate is calculated in the same way as in phase 1.

Also here for the example with a medium gas leak in scenario type 1 when using the Tables in chapter 6, medium probability is used.

The overall event tree

The event-tree as it should look like and the different frequency rates for the different scenario outcomes for a scenario type 1, leak size medium are presented below in the figure. By doing this procedure for every relevant leak size in every relevant scenario type the frequency values presented in the scenario outcome can be used both for the risk analysis and for the quantification.

The event-tree are put together to give a total risk picture for one scenario type.

To summarize the different scenario outcome in this scenario type this would be:

PFP is needed with a frequency rate of $8{,}0*10^{-7}$ (scenario outcome 2)

PFP is not needed for just leak with a frequency rate of $6{,}7*10^{-3}$ (scenario outcomes 1+3+4+5)

PFP is not needed if a fire develops with a frequency rate of $9,2*10^{-6}$ (scenario outcome 3+5)

These values only apply for this leak size in this scenario type. For a total value to use in the risk assessment, quantification or cost-benefit analysis one must summarize all the different frequency rates in every scenario type.

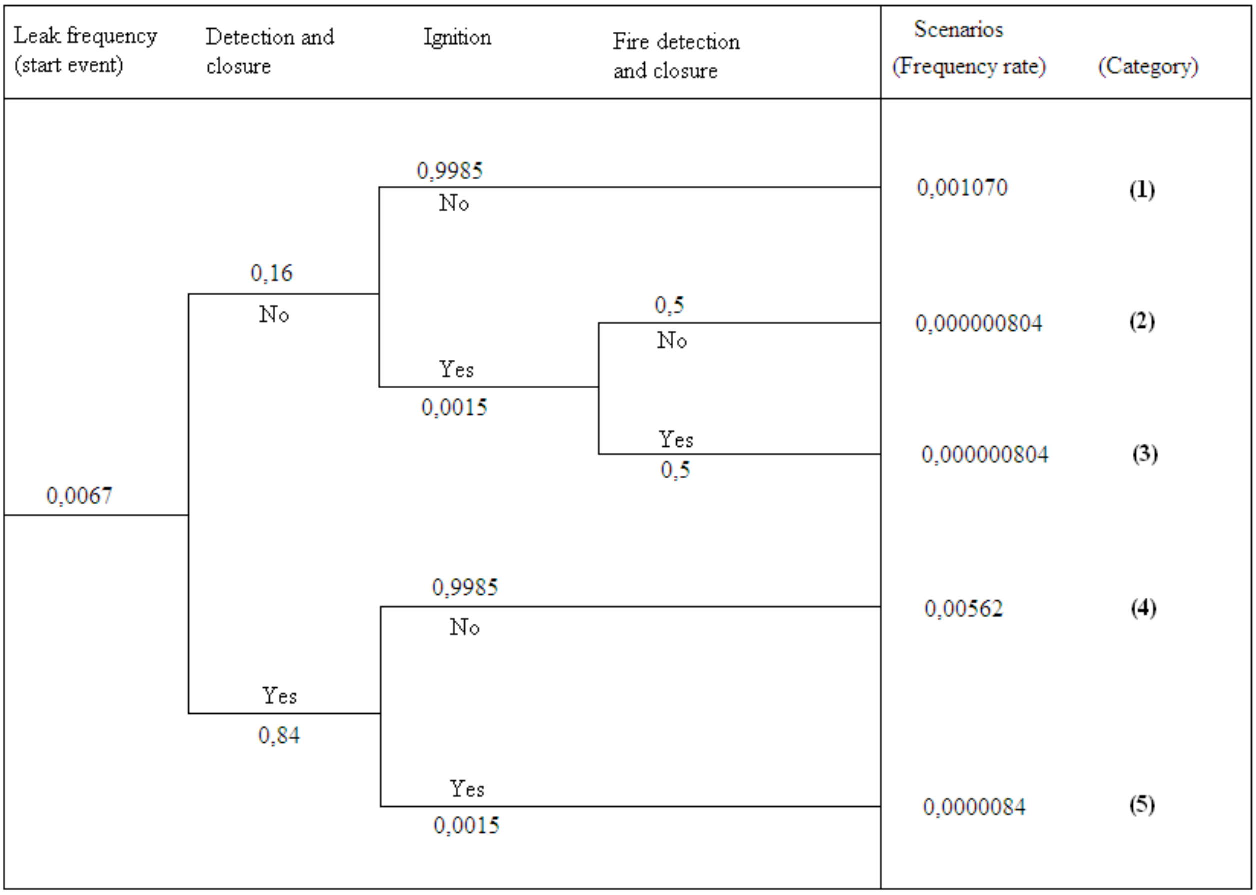


Figure showing different scenario outcomes, frequencies and probabilities for medium leak size in scenario type 1

6 Chartek pricing calculations

Chartek pricing

$$m = V \cdot \rho$$
$$V = A \cdot h$$

Where:

m	**mass**	**[kg]**
V	**volume**	**[m^3]**
ρ	**density**	**[kg/m^3]**
A	**area**	**[m^2]**
h	**thickness of chartek-layer**	**[m]**

$\rho = 1000$ kg/m^3
h = 10 mm = 0,01 m
m = 15000 kg

Calculations for total area estimation:

$$m = V \cdot \rho \Leftrightarrow 15000 = V \cdot 1000 \Rightarrow V = 15 \qquad \textbf{[m}^3\textbf{]}$$

$$V = A \cdot h \Leftrightarrow A = \frac{V}{h} \Rightarrow A = \frac{15}{0{,}01} = 1500 \qquad \textbf{[m}^2\textbf{]}$$

Work time and pricing:

Onshore work time: 6 hours/m^2
Offshore work time: 9 hours/m^2 (complexity factor of 1,5)

Onshore pricing including material costs: 500 NOK/hour
Offshore pricing including material costs: 1000 NOK/hour

A distribution of 95% onshore and 5% offshore work is assumed.

Costs = $A \cdot distribution \cdot time \cdot pricing$

Onshore costs:	$1500 \cdot 0{,}95 \cdot 6 \cdot 500 = 4275000$	**[NOK]**
Offshore costs:	$1500 \cdot 0{,}05 \cdot 9 \cdot 1000 = 675000$	**[NOK]**
Total cost:	$4275000 + 675000 = 4950000 \approx 5000000$	**[NOK]**

7 Cost-benefit calculations

Total expected cost for application of chartek:	5 million NOK
Annual maintenance cost:	50 000 NOK
Value of a statistical life (VOSL)(Persson et al, 2001)	22,33 million SEK ~ 20 million NOK
Expected life cycle for new module:	10 years
Personnel onboard:	80 persons
Total cost for Troll C platform:	7,5 billion NOK

Benefit gained by implementing PFP (only including human lives)
Frequency when PFP is needed where the result would be collapse into the ocean is calculated with the frequency for when PFP is needed multiplied with the 50% probability of the module falling into the ocean.

$$2{,}6 \cdot 10^{-5} \cdot 0{,}5 = 1{,}3 \cdot 10^{-5}$$

The total expected cost for a collapse that would result in the death of 80 persons is calculated with the number of persons onboard (80) multiplied with the VOSL value (20 million NOK):

$$80 \cdot 2 \cdot 10^{7} = 1{,}6 \cdot 10^{9}\ NOK$$

The benefit gained by implementing PFP is calculated by multiplying the frequency above with the total cost for a collapse meaning death for 80 human beings:

$$1{,}3 \cdot 10^{-5} \cdot 1{,}6 \cdot 10^{9} = 20800 NOK$$

Benefit gained by implementing PFP (Cost for platform Troll C included)
Same frequency as above applies but the total cost will instead be:

$$1{,}6 \cdot 10^{9} + 7{,}5 \cdot 10^{9} = 9{,}1 \cdot 10^{9}\ NOK$$

Benefit gained by implementing PFP:

$$1{,}3 \cdot 10^{-5} \cdot 9{,}1 \cdot 10^{9} = 118300 NOK$$

Costs for PFP implementation

Cost per year (just implementation of PFP):	5 million NOK / 10 years = 500 000 NOK
Annual maintenance cost:	50 000 NOK
Total annual cost:	500 000 + 50 000 = 550 000 NOK

Comparison between cost & benefit (only including human lives): $20800 \cdot x = 550000 \Rightarrow x \approx 26$

This means that the cost for implementing PFP is approximately 26 times larger than the benefit gained.

Comparison between cost & benefit (Troll C included): $118300 \cdot x = 550000 \Rightarrow x \approx 5$

This means that the cost for implementing PFP is approximately 5 times larger than the benefit gained.

Cost-benefit conclusion

The annual cost for the implementation and maintenance for PFP per year is 550 000 NOK. Compared to the benefit gained per person, 39 200 NOK. This means that the cost is approximately 26 times larger than the benefit gained. If the cost for the whole platform is included the cost will be 5 times larger than the benefit gained which makes the implementation cost disproportionate to the benefit gained. Through an ALARP point of view the cost must be grossly disproportional to the benefit gained to be unacceptable. How disproportional the calculated figures are, is up to the decision makers to decide.