How different safety barriers affect the margin between available and required evacuation time

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3 Summary

The main purpose of this thesis has been to document that people can evacuate to temporarily safe locations / safe distances during the defined escalating jet fire scenario. It has been important to document that available evacuation time is longer than the required evacuation time. The required evacuation time has been documented in evacuation exercise and by Simulex simulations. The choice of fire scenario is a jet fire on 0,3 kg/s. Jet fires are likely to occur in the processing area. It is assumed that this start fire after 2 minutes results in escalation, represented by a sudden increase to 10-30 kg/s.

Relevant theory has been used in this thesis. Standards in Statoil`s library for standards and requirement was used. Simulex simulation tool has been used for the evacuation simulations because it is suitable for simulations with a small amount of people, as in processing modules at Kårstø. Excel has been used in the insulation and the BLEVE calculations. Program uncertainties when doing the simulations might affect the result. There can also be uncertainties in the measured time from the evacuation exercise. Uncertainties from the insulation calculations when putting the parameters into the excel sheet must be mentioned.

The thesis includes detailed evaluations of how the safety barriers PS8 Blowdown, PS9 Active fire protection and PS10 Passive fire protection influence escalation risk. Safety barriers need to be seen in combination to achieve personnel safety. Safety barriers can increase the margin between required and available time for evacuation.

Unless hit by the start fire, the personnel will be able to escape a developing / escalating 0,3 kg/s jet fire, both with respect to escalated jet fire exposure and with respect to development towards BLEVE. It will be important to be aware of the consequences from a BLEVE in the congested processing area where there are a lot of people working.
Active and passive fire protection will increase time to rupture significantly and will thereby increase the margin between required and available evacuation time. Blow down may increase the margin by limiting the fire scenario. The positive effects of active fire protection and blow down are however dependent on early activation.

There might be a need for changing the methodology and a change in the mindset when setting up a barrier philosophy. A deeper understanding of the whole risk picture and knowledge of the technically safety systems can contribute to make the best solution in a risk assessment.

The uncertainties in the method will not affect the results appreciably. They will not affect the main conclusion.

4 Preface

This report is the result of my final thesis of the Master`s Degree Program, Safety technology – Technical safety. This master thesis has given me knowledge of how different safety barriers such as active, passive fire protection and blowdown work. It has given me a greater understanding of how safety barriers may affect safe evacuation. This thesis has given me time to consider the technically safety issues in a wider perspective.

One simulation tool has been used in order to conduct my thesis; Simulex. Excel calculations have been done for insulation and BLEVE calculations.

It has been an interesting and challenging process. In this occasion I would like to thank Statoil Kårstø by allowing me to perform the thesis and provided me with office space.

I would like to thank all of the people working in the technically safety department at Kårstø with their contribution during this process. I will like to thank them for inviting me to meetings regarding their work when making a timeline report. Special thanks to my supervisor; Prof. Torgrim Log who inspired me and gave me useful information during this thesis. Special thanks to my supervisor, Elin Kristin Dale for guidance and feedback during the process.

I will also like to thank Høgskolen Stord Haugesund who gave me answers when I contacted them regarding this thesis. Simulex support has also been helpful with answers regarding the simulation program.

5 Notes and abbreviations

ALARP:	As Low as Reasonably Practicable
BLEVE:	Boiling Liquid Expanding Vapor Explosion
CCR:	Central Control Room
CUI:	Corrosion under installation
EDP:	Emergency Depressurisation
ESD:	Emergency Shutdown
HC:	Hydrocarbon
HSE:	Health, safety and environment
KIP:	Kårstø Integrity Project
P&ID:	Process & Instrument Drawing
PA:	Public announcement
PFP:	Passive Fireprotection
PhD:	Doctor of Philosophy
PPE:	Personnel Protection Equipment
SJA:	Safe Job Analysis
TRA:	Total Risk Analysis

UTS: Ultimate Tensile Strength

1 Introduction

1.1 Purpose of the thesis

The purpose of this thesis is to look at the time for evacuation, and see if there is enough time to evacuate the plant. Different safety barriers such as passive, active fireprotection and blowdown will affect the escalation time, hence the available evacuation time. These will be investigated.
In the Total Risk Analysis (TRA) (Scandpower, E002-XX-S-RS9135 Total Risk Analysis Main report 2013) the available evacuation time is not documented. It is assumed that all of the people are out in safe area before the escalation starts. This needs to be documented. It might be a mis-match using the TRA to say something about the risk level when the question above has not been answered. The purpose of the thesis is to evaluate whether personnel not immediately exposed may evacuate during the succeeding fire development.

1.2 Problem description

The escalation shall not cause loss of life, environmental harm and economical consequenceses. The focus area in this thesis will be preventing loss of life.

This thesis investigates barrier philosophy to avoid / delay escalation with main focus on saving lives according to regulations and Statoil`s acceptance criteria and philosophy. The escalation risk must be controlled.
The focus area is to increase the margins between required and available time for evacuation and avoid loss of lives in the processing areas where the jet fire is a large contributor to escalation.

It has been focused on major accident risks associated to the storage vessel area. In this thesis risk in the processing vessel area has been chosen as the most relevant reference scenario.
Maybe there has not been enough focus on processing vessels and escalation risks in the processing areas?
This applies especially the potential for “Boiling liquid expanding vapor explosion” (BLEVE) in processing vessels.

Covering all the processing vessels with deluge / sprinkling will be expensive and not practicable. Processing areas are congested and this will increase the explosion risk.

What safety barriers can avoid or delay the escalation at a fire scenario?
First of all distance and layout can be planned to avoid escalation. This is easy when new plants are being built, but quite challenging for already existing plants. For older plants safety barriers need to be used rather than changing the layout barrier. Relevant safety barriers are passive and active fireprotection and blowdown. It is important to have a look at the barrier philosophy that has been applicable until today.

Question to be asked:

The main focus for existing plants will be saving lives, thus will it be necessary having all the safety barriers operating completely to achieve the personell safety needed?

Often, it may not be possible for all of the barriers being intact according to the newest regulations.
So; *how will it be possible to say something about the safety barriers beeing acceptable and to see if they are satisfying the government requirements and the company requirement?*
It needs to be investigated how these safety barriers are working together and how much each of them actually means for the available evacuation time.

Will some of them mainly have economical effect? How much can be taken credit for regarding escalation risk when evacuating? Which philosophy should the excisting plant have?

It can be questioned:
Will it be possible to get out to safe area with the time available?

There might be a need for changing the methodology and a change in the mindset when setting up a barrier philosophy.

The question will rather be: *What do we want to achieve?*
And from this question it can be possible finding a solution. This solution might be having diffent safety barriers together – not all of them fully operating, but the combination of barriers achieving the target. This will be a better solution rather than looking at the safety barriers seperatly.

When it comes to environment consequenses these are mainly assosiated with large leakages that will be covered by storage vessels and dikes.
When it comes to economical consequences from a leakage, these need to be considered in relation to investments.
These two consequences will not be relevant for this thesis.

2 Method

2.1 Research strategy

Relevant theory under chapter 3 has been used in this thesis. Douglas Drysdale`s “Fire Dynamics” (Dynamics u.d.) is relevant in this context.
Relevant research literature has been found through the University of Bergen`s library and Statoil`s search monitors. The science article database Science Direct has been used in this thesis. Relevant key words; such as BLEVE and radiation was used in order to find relevant articles. The references of the articles and its authors are listed in the reference list.

Standards in Statoil`s library for standards and requirement, Docmap was used, such as “Performance standards for safety systems and safety barriers – Onshore”. (TR2237) (Technology u.d.)Other standards can be seen in the reference list.

Meetings with the technically safety department in Statoil was conducted and this gave a better understanding of the work of the report; Risk evaluation of unacceptable ruptures - Kårstø (Engineering 2015). This work was completed April 2015.

Discussions with the technically safety department was carried out. Høgskolen Stord/Haugesund was contacted regarding theory in this thesis and regarding recommendation on which evacuation program to use.

Simulex simulation tool has been used for the evacuation simulations. Excel has been used in the insulation and the BLEVE calculations.

3 Theory

3.1 Heat transfer theory

There are 3 mechanisms in heat transfer:

- Heat conduction
- Convection
- Radiation

3.1.1 *Heat conduction*

(Dynamics u.d.)

Conduction is the mode of heat transfer associated with solids. Although it also occurs in fluids, it is normally masked by convective motion in which heat is dissipated by a mixing process driven by buoyancy. It is common experience that heat will flow from a region of high temperature to one of low temperature; this flow can be expressed as a heat flux, which in one direction is given by:

$$q^{*``} = -k \frac{\Delta T}{\Delta x} \qquad (3.1)$$

where ΔT is the temperature difference over a distance Δx.

In differential form:

$$q^{*``} = -k \frac{dT}{dx} \qquad (3.2)$$

where $$q^{*``} = \frac{\mathbf{(dqx\ /\ dt)}}{\mathbf{Ax}} \qquad (3.3)$$

A being the area through which heat is being transferred. This is known as Fourier`s law of heat conduction.

T is in °C (or K), and x in meter.

While many common problems involving heat conduction are essentially steady state, most of those releated to fire are transient and require solutions of time – dependent partial differential equations. Nevertheless, a system of this type will move towards an equilibrium that will be achieved provided there is no variation in the heat source or in the integrity of the materials involved. Indeed, as the steady state is the limiting condition, it can be used to solve a number of problems.

Thermal conductivity

The constant k is the thermal conductivity, and describes how well the material is conducting the heat and has unit of W/mK when q *`` is in W/m^2.

Air is a typical poor thermal conductor, (0,026 W/m K) compared to steel (45.8 W/m K).

The thermal conductivity is not always stable through a fire, but changes with temperature.

3.1.2 Heat convection

Convection is associated with the transfer of heat by the motion of a fluid. The motion may arise naturally as a consequence of temperature gradients in the fluid which generate buoyancy – driven flows. This is commonly referred to as “free” or “natural” convection to distinguish it from “forced” convection when external forces (such as those provided by a fan or blower) are involved.

The convection is expressed as:

$q^{*``}=h\ (\Delta T)\ (W/m^2)$ (3.4)

h = heat transfer coefficient (W/m k) – depending on the fluid properties (thermal conductivity, density and viscosity), the flow parameters (velocity and nature of the flow) and the geometry of the surface (dimensions and angle to the flow).

3.1.3 Heat radiation

According to Stefan – Bolzmann equation, the total energy emitted by a body is proportional to T^4, where T is the temperature in Kelvin. The total emissive power is expressed as:

$E=\varepsilon\sigma T^4\ (kW/m^2)$ (3.5)

where σ is the Stefan – Bolzmann constant ($5.67 \times 10^{-8}\ W/m^2K^4$) and ε is a measure of the efficiency of the surface as a radiator, known as the emissivity.

The perfect emitter – the “black body” has an emissivity of unity.

Thermal radiation involves transfer of heat by electromagnetic waves confined to a relatively narrow “window” in the electromagnetic spectrum. It incorporates visible light and extends towards the far infra-red. Depending on emissivity and the value of h (the convective heat transfer coefficient), convection predominates at low temperatures (150-200 °C), but above 400 °C, radiation becomes increasingly dominant.

A configuration factor, φ, is used in order to estimate the radiation intensity (q``) and it takes into account the geometrical relationship between the emitter and the receiver. The configuration factor is ranged from 0 to 1. φ increases with decreasing distance, width and height of the radiative object. The configuration factor in terms of this case depends on the distance between the radiative objects and the actual point where the radiation is estimated.

3.2 Principle scenario descriptions

(D. a. Safety 2014)
Hydrocarbon fires are usually divided into four main types: open pool fires, confined pool fires, small jet fires and large jet fires.

3.2.1 Definition jet fire

Jet fires will be the main focus area in this thesis. It has been focused on major accident risks associated to the storage vessel area. In this thesis risk in the processing vessel area has been chosen as the most relevant reference scenario. The scenarios will be based on pressurized liquid and gas in processing vessels and piping.

Jet fires may result from leakages of gas from pressurized process equipment, vessels or piping and are characterized by high momentum and highly turbulent jet flames. The flame is lifted above the leakage point (often called “lift – off” or “blow – off”) because combustion only takes place when the flow velocity and gas concentration allows for stable combustion. Due to the intense and efficient mixing of fuel and air in such fires, jet fires may exhibit higher flame temperatures than ordinary buoyancy controlled diffusion flames. Furthermore, jet fires may create high heat radiation zones inside the volume where combustion takes place. Outside the flame, however, the radiation decays rapidly with distance.

The thermal radiation fields from jet flames are quite limited in size. Unless hit directly by a jet fire flame personnel may therefore escape this radiation field following small size pipe rupture fire escalation. BLEVE scenarios are, however, different. Even a significant distance away from the vessel involved in the BLEVE, the thermal radiation is life threatning.

(D. a. Safety 2014)
The definition of a large jet fire is a combustion rate (leak rate feeding the fire) larger than 2 kg/s.

The main contributions to the personnel risk are (Scandpower, Total Risk Analysis TN-4 Assumptions 2014) delayed ignition of large combustible gas clouds that cause critical exposure to personnel locatd inside the combustible gas cloud at time of ignition (flas fire), and jet or spray fires exposing personnel located in the vicinity.

Jet fires are likely to occur and will be the main contributor to the escalation risk in the processing area.

Figure 1 0.3 kg/s jet fire. Propane vapour jet. Flame length is 6-7 m. Upstream pressure 11.5 barg and 16 mm nozzle. Picture is taken from PhD report by Leiv Anfin Drange

3.3 Time to escalation

Pressurized storage vessels will often be the main focus area regarding BLEVE, because the consequences are so severe. But this will be in the eye of major accidents. Pressurized storage vessels are typically placed with good distance from other equipment and it is not likely that personnel will be close to them. They are fire protected against rupture. A leakage will typically be from the piping / valve connected to the vessel. The dike will gather the leakage. If the leakage in the dike is being ignited, deluge system will extinguish the fire. This will avoid vessel rupture and avoid BLEVE resulting from high heat flux from the fire.

Whereas for the processing vessels, they are in most cases not equipped with dike and deluge system.
It will be important focusing on smaller vessels without deluge when it comes to BLEVE.

In the TRA, (Scandpower, E002-XX-S-RS9135 Total Risk Analysis Main report 2013), BLEVE is included in relation to the condensate buffer tanks and the steam boilers. Vessels discussed in this thesis are not included in the TRA.

The scope and main focus area in this thesis is looking at escalation risk related to processing equipment. Personnel are more often working in middle of processing trains, and it will therefor be important to look at the personnel safety in these areas.

The strength of steel pipes and equipment is weakened as the temperature increases. This is illustrated in Figure 2. When the temperature reaches 400 °C, the tensile strength reaches the point of rupture. After that the strength decreases significantly.

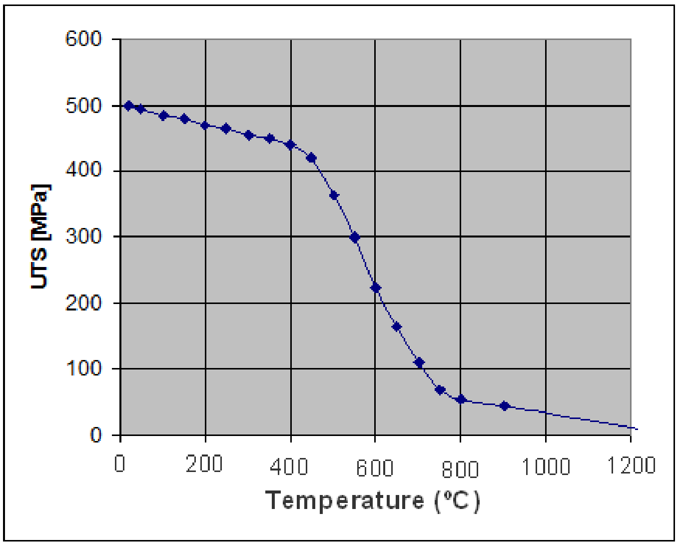

Figure 2 Tensile strength vs. temperature

(Engineering 2015)
The flame temperatures in hydrocarbon fires are typically in the range 1200-1350ºC, i.e. well above the temperature that weakens the pipe and equipment integrity. As the object is heated in a fire, the object may fail to carry the load it is designed for, that being containment, weight carrying capacity.

A jet fire of 0,3 kg/s will make a high noise level, as experienced by employees at Statoil Kårstø while previously doing research (PhD) on this type of jet fires at ResQ, Haugesund. The fire will therefore inform the people in the vicinity of its presence. It is assumed that even personnel working with heavy equipment and wearing Personnel Protection Equipment (PPE) will be quite “shaken up” when suddenly experiencing a jet fire in their neighborhood. It is therefore assumed that any personnel in the close vicinity of the fire, i.e. within the same part of Processing Train100, will hear, feel by body vibrations and maybe also see jet fire / feel heat radiation and thereby understand that this represents a life threatening danger. This understanding represents a solid motivation for escape actions, though there may be some uncertainties and need for orientation before efficient movement is started. Within the train, it is further assumed as a scenario that unless immediately close to a stairway, personnel will try to make a horizontal separation to the jet fire before moving vertically to ground level.

Assuming now that the 0,3 kg/s start fire after 2 minutes results in an escalation, represented by a sudden increase to 10-30 kg/s fire, i.e. a large release rate, due to a ruptured pipe, this new fire is unlikely to represent a threat to personnel at ground level 50 m from process train. Safety zone 1, temporarily safe distance, is therefor defined as 50 m.
This is based on an assumption of a flame length usually less than 50 m outside the process module, the flame direction may be in all principle directions where only a small sector is towads the person at risk, loss of momentum due to other pipe work, structures, etc. It is also based on the general knowledge that pipe work, flanges, etc. will fail after approximately 2 minutes exposure to the 0,3 kg/s initial jet fire, while process vessels have larger wall thickness and will

rupture later. This is illustrated in Figure 3. Rupture happens after 1,5 min with 2” pipe DC1 pipe spec (net wall thickness 7,14 mm). The peak load is 350 kW/m^2 background load is 100 KW/m^2.

(Engineering 2015)

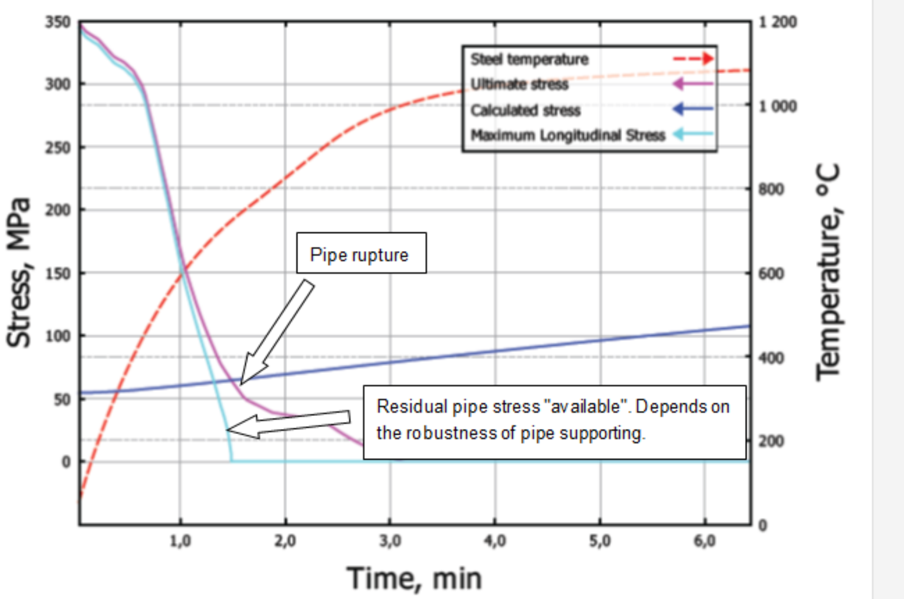

Figure 3 Pipe stress simulation with 2 “pipe

Safety zone 2 is scenario based. Due to the size of the 10-30 kg/s jet fire, it is expected to expose numerous pipes, vessels and structures. It is therefore likely that the fire scenario will further increase in severity. Exposed vessels, such as reflux drums, etc may burst in a BLEVE. Assuming now that the first vessel may go to BLEVE the temporarily safe distance may be several hundred meters away from the initial fire due to high thermal radiation levels from the vessel BLEVE.

The chosen start fire 0,3 kg/s jet fire, is a special case only. On the other hand, using this fairly frequent release rate as a reference will make it possible to establish reference evacuation distances, to temporarily safe areas during the fire development and evacuation process. There are smaller pipe dimensions than used as a reference for the vessel rupture time calcualtions, e.g. pipes and tubings. These will rupture faster, but will also result in a less severe escalation and limited flame lengths. It is therefor assumed that they do not represent a risk.

3.4 Introduction to evacuation

3.4.1 *Definitions in the evacuation theory*

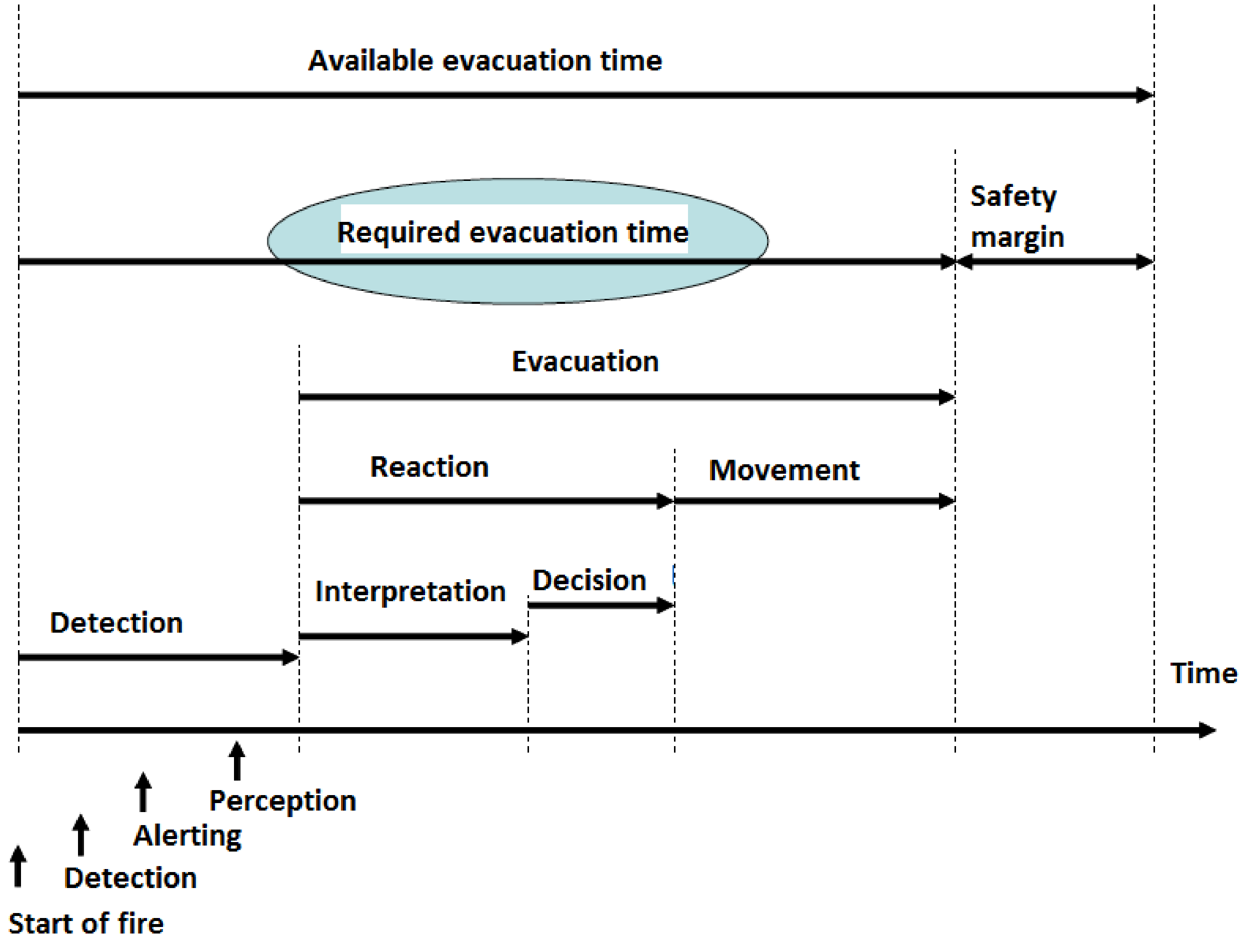

Figure 4 Definitions in evacuation theory

(Hagen u.d.)

The available evacuation time is defined as the time from the start of the fire/incident until the tolerance limit regarding visibility, warm and toxic gasses. The length of this periode is highly dependent on the actual conditions such as the ignition source, access to combustible material, ventilation conditions and so on. It will often be simulated by data models that are made from good understanding of fire – chemistry, fire dynamcis, spread of smoke, and toxicology.

It is important to mention that evacuation will not only occur when there is a fire. Evacuation can occur at different emergency situations, and it will be necessary at gas alarm, when the gas has not been ignited.

The required evacuation time will be divided into three parts:

1) Alert time:

Detection time + verification time

Detection time:

In the detection phase there are signals that imply there is an incident. The signals can be detected in two ways:

- A detector detects gas or a fire and a fire alarm system alerts the users of the building / plant
- A person gets signals that there is a fire – light, sound or the smell of a fire, and alerts others in the area

Verification time:

When the signals are detected, it will take some time verifying if it is a leakage or fire. At a fire alarm system there can be a delay before the firealarm is triggered. If there is a person detecting the leakage or fire this can take some time.

2) Assessment and decision time:

In this period it will be considered how dangerous the situation is. Based on this, the people in an area must decide which actions shall be taken, including escaping to a safer place.

3) Time for movement:

Time for movement is the time spent on moving from the incident through the evacuation route and to a safe place. Experiments have shown that the evacuation speed of those evacuating are dependent on the possibility on moving freely and unaffected of others.

***Safety margin**:*

This is the difference between the available evacuation time and the required evacuation time. It is an important principle that the available evacuation time shall be significantly larger than the required evacuation time.

3.4.2 Human behavior in emergency situations

When an emergency situation occurs, the individual must clarify the situation and decide which activities that must be implemented.
The signals need to be interpreted. This means the person will seek information to decide if the signals imply danger. This information can be physical signals, such as smoke or messages from other people nearby.

There are a lot of conditions affecting the human behavior:

- Detect signals (human or gas detection system)
- Interpret the signal – this is a process based on earlier experience and sufficient information. If the signals are weak or ambiguous, people will seek more information or they might ignore the signals. False alarms can lead to reduced reliability for the signals received. Good and clear alarming will give good information
- Define and consider the situation. In this phase the behavior pattern to other people will often affect the way a person behaves. The social setting is important for the human behavior.
- Decide solution. When the situation is considered as dangerous, the people in the area will decide different solutions to handle the situation. The choice of solution is depending on factors as; experience, training, social setting, responsibility for other people and gender.

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4 Information about Kårstø

4.1 Overall information about Kårstø

Kårstø processing plant receives gas and condensate from various fields offshore. The following pipelines deliver gas or condensate to Kårstø processing plant:

- Statpipe Rich Gas pipeline, rich gas from Statfjord, Gullfaks, Veslefrikk, Snorre and others
- Statpipe export pipeline may be used for import of rich gas from Draupner
- Sleipner, condensate (light oil after 2014 Gudrun Onshore Modification)
- Åsgard transport – rich gas from Åsgard / Haltenbanken

Kårstø plant can be seen in Figure 5 below.

Figure 5 Kårstø Plant

Kårstø started up as a gas processing plant in 1985, but has later undergone major modifications. Statpipe process, Train 100 and 200, were the only process modules at the plant start-up. Escape – routes and passive fire protection was not planned considering nearby processing trains because it was not necessary at that time. After this other modules were built nearby the Statpipe area. This makes the plant more complex including the technical safety system.

Each development of the Kårstø processing plant is related to requirements applied at the time. Laws, regulation and standards through these years have changed as knowledge has been developed. The Kårstø processing plant has been imposed to follow these regulations during the development of the facility. This means that the various part of the facility has different level of the technical safety systems. In addition, development of the plant has been performed as independent projects, which has led to different philosophy on use of safety systems.

Figure 6 Kårstø plant

4.2 Evacuation at Kårstø

At the Kårstø plant evacuation routes leads out of the plant area either towards East or West. Figure 7 shows the plant evacuation map displaying main roads and muster areas. These evacuation maps are placed at strategic locations throughout the plant.

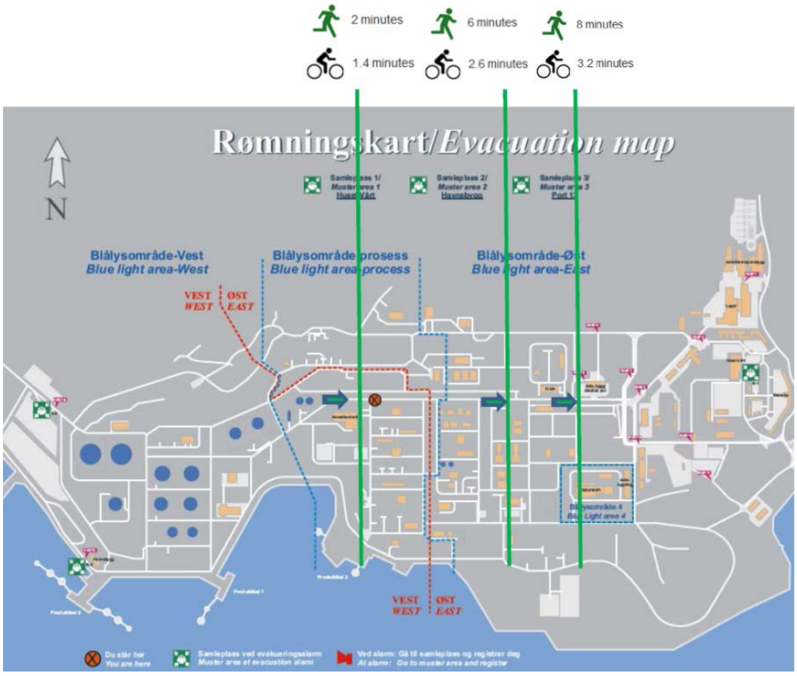


Figure 7 Kårstø evacuation map

Evacuation exercises are performed to make the workers more confident on what to do in emergency situations. Health, safety and environment (HSE)-24-course is being held, and this gives people information about the plant. It will be carried out Safe Job Analysis (SJA) before a job. All this will lead to more practice in what to do in evacuation situations. This is to avoid unwanted events as panicing in emergency situations. Workers at the Kårstø Plant have a good mobility.

(Scandpower, E002-XX-S-RS9135 Total Risk Analysis Main report 2013)
The evacuation alarm will be activated at confirmed gas detection and ignition sources will be shut down. Most leaks (90 % of all leaks) at Kårstø are detected within a short time period. For major / large leaks the time to detection is 45 seconds for ignited leaks and 180 seconds for unignited leaks.

The evacuation alarm is manually initited from the Central Control Room (CCR), meaning a delay of 2-5 minutes from the fire occur to the alarm is activated should be assumed. Based on this it is important that all personnel in the processing areas know that if a fire occurs within visual / audible distance, evacuation shall start immediately without waiting for evacuation alarm / Public announcement (PA) messages or any other delay.

4.3 Statpipe

(Engineering 2015)
The Statpipe Train 100 (T-100) is chosen as a reference process train for the initial evaluations as it has a high fire frequency and is representative and located close to the Central Control Room (CCR). Train 100 and train 200 were not originally designed with an emergency depressurization system since that was not a requirement when built. Vessels located in the Statpipe Train 100 are not designed for depressurization without previous liquid removal.
Statpipe has been used in the Simulex calculations.

At Statpipe the philosphy is to alert, inform and guide personnel as quick as possible at emergency and dangerous situations. PA shall be used to alarm personnel if the area needs to be evacuated. This needs to be considered by the area operator (områdeoperatør), based on the event. This verification time depends on how long the area operator spends on perceiving the incident, or how long it takes before someone informs about the incident.

Figure 8 Statpipe processing trains

4.4 Statoil`s overall requirements – relevant paragraphs regarding evacuation

4.4.1 TR2237 - Performance standard for safety systems and barriers – Onshore Kårstø

(Technology u.d.)
TR2237 describes the principles and corporate safety performance requirements to technical systems and barriers in order to manage safety risk.

The main objectives of this document are, in order of priority:

- *Safety personnel*
- *Protection of the environment*
- *Protection of assets and minimization of financial consequences of incidents, including fire and explosions*
- *Minimization of reputational consequences of incidents, including fire and explosions*

Escape and evacuation routes and exits
In the case of a hazardous incident, the purpose of escape and evacuation routes is to:

- *Ensure that personnel may leave the area(s) in question by at least one safe route*
- *Enable personnel to safely reach a temporary refuge from any position on the plant they are likely to occupy*
- *Enable personnel to safely evacuate the plant*
- *Enable rescue / medical teams to safely bring injured personnel to areas where medical treatment can be given*

Protection of escape routes from radiation heat should be considered where applicable.

Personnel shall be able to use the escape routes without being exposed to excessive toxic fumes, smoke nor unacceptable heat loads, hot liquids or falling objects.

4.4.2 Total Risk Analysis, (TRA)

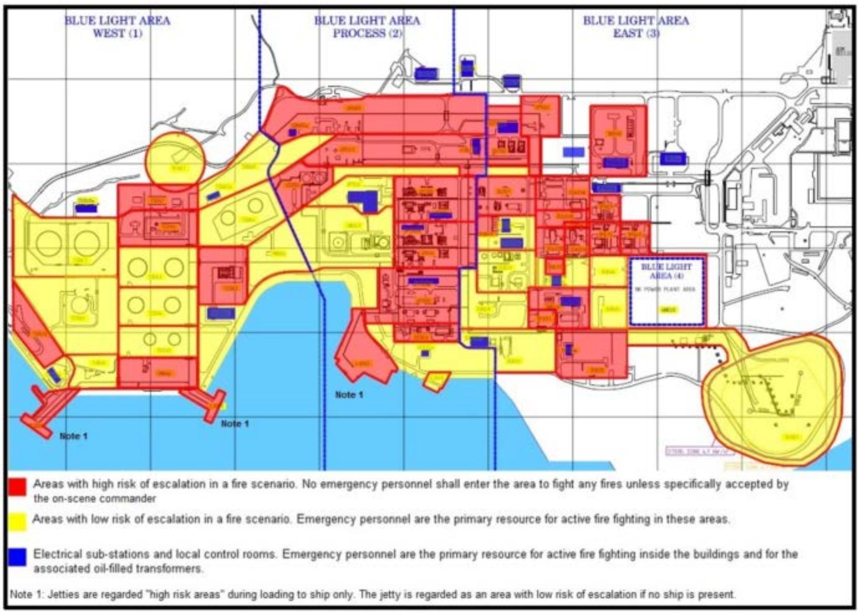
(Scandpower, E002-XX-S-RS9135 Total Risk Analysis Main report 2013)
In the TRA it is concluded that the personnel risk at the plant is low and well within the acceptance criteria which is 10^{-4}*. Personnel that are not affected by the initial fire will normally be able to escape in time to avoid any excess heat loads from the escalated event, i.e. only personnel exposed to the heat load of the initial fire are regarded to be at risk.*

The background for this assumption is the general idea that at an onshore facility, immediate escape to a safe area is possible in all directions with no dependences on structural integrity over time. As time to escalation may be very short (2 minutes for the smallest diameter piping) it is however critical that all personnel working at the plant is aware of the importance of immediate escape in a fire scenario.

As a general rule, personnel shall not be introduced to life threatening situations in order to carry out emergency response duties. This implies that emergency response personnel shall not enter areas where there may be explosive atmosphere due to release of flammable gas / liquid. Areas with high escalation risk are shown in Figure 9.

In areas with high escalation risk, fixed equipment that can be released and operated from a safe location (typical CCR) shall be the primary resource for fire fighting. Emergency response personnel may only enter such areas in a fire scenario if specifically approved by the on-scene commander.

Emergency response personnel shall be the primary resource for fire fighting in areas with low escalation risk, oil filled transformers and in buildings with no or very limited amount of hydrocarbons such as electrical substations and utility shelters.



🟥 Areas with high risk of escalation in a fire scenario. No emergency personnel shall enter the area to fight any fires unless specifically accepted by the on-scene commander

🟨 Areas with low risk of escalation in a fire scenario. Emergency personnel are the primary resource for active fire fighting in these areas.

🟦 Electrical sub-stations and local control rooms. Emergency personnel are the primary resource for active fire fighting inside the buildings and for the associated oil-filled transformers.

Note 1: Jetties are regarded "high risk areas" during loading to ship only. The jetty is regarded as an area with low risk of escalation if no ship is present.

Figure 9 High- and low risk areas with respect to escalation

4.4.3 GL4100 Personal HSE Handbook for Statoil Onshore Facilities

(Stokka u.d.)
The guideline is meant to help avoid incidents and ensure a safe workplace. It gives an overview of the most important HSE rules. It gives an overview over the local alarms, warning lights and muster areas. This is shown in Figure 10.

Alarm-signal with describtion	***Special for this alarm***	***Common for all alarms***
Evacuation alarm: For the evacuation alarm there will be an increasing and descending alarm. The "danger is over" will be given with continuous alarm.	Finish and secure workplace Go to gathering place and register through the card reader. (There are 3 muster areas at Kårstø. At a emergency situation a person will register at the card reader as soon as he or she arrives a muster area)	• Turn off any electrical equipment and disconnect it electronically • Stop engines and vehicles • Close any gas bottles • Work permittences becomes invalid and work shall not be resumed before a new permit will be given
Triggered fire, smoke or flame detector: The situation is announced over the speaker system and portable radio. Place and incident is announced.	Close and secure workplace Listen on portable radio or loudspeaker system for messages and relate to the message.	
High gas alarm in the area: Blue "rotating" light Red flashing lights and sound signal along highway	Close and secure workplace,in the current area	

Figure 10 Alarms and actions at Kårstø

5 Evacuation exercise

This chapter contains the findings from the evacuation exercise at the Kårstø plant, and will further be compared with evacuation simulations made in Simulex in the next chapter.

5.1 Description

(Engineering 2015)
An evacuation exercise was performed at Kårstø 22.05.2014. This exercise presented a good opportunity to observe and evaluate both time for esape and escape patterns. I got to be a part of this exercise as a first step in my thesis.

Figure 11 shows main areas, roads, and musters areas at Kårstø. During the evacuation exercise observers were placed at a module in T100 (Statpipe) and beside the Åsgard processing trains. This is marked with red circles on the map in the figure.

Figure 11 Main areas, roads and muster areas at Kårstø

4 people were working on the top level of the Statpipe module in Figure 12. One person was in a lift. After the alarm was initiated, with a following message, the personnel immediately secured the workplace and started lowering the lift. It only took about 3 seconds before all personnel started evacuating from the module.

Figure 12 Statpipe module 5 CA37

The personnel used the main escape stair on the west side of the module to get from the top level to ground level. Further, the personnel used bicycles placed at the ground level to continue evacuation away from the area. The escape pattern is shown in Figure 13.

Figure 13 Observed escape pattern from the module

The five persons all gathered at the main entrance at the main control room (145 meters from the module) before they started evacuating out of the plant together. The personnel did not evacuate through the process module area, but used the main road north of the process area to evacuate eastward to the administration area. This gives some distance to the potential hazardous area, however this escape pattern could expose personnel for heat loads given an early escalation of an initial event or if the personnel for some reason has a longer reaction time until they start evacuation. It was also observed that the personnel had a tendency to turn south at the Åsgard process train, which is downhill, compared to using the main road which has a slight upwards slope.

Table 1 Evacuation time from the exercise (Engineering 2015)

Time from the event occurs to the alarm is activated	**5 seconds**
Reaction time (from initiated evacuation alarm until personnel started evacuation)	**3 seconds**
Evacuation walking speed in stairs	**0,53 m/s**
Evacuation walking speed on platform / module deck	**1,74 m/s**
Evacuation walking speed on ground level	**2 m/s**
Evacuation speed by bicycle	**6,4 m/s**
Time for personnel to reach ground level from working at top level in a module	**60 seconds (first person used 34 seconds)**
Time for personnel to reach safe area (safe area is defined as 50 m from the module)	**1,2 minutes**
Time for personnel to exit the plant inner perimeter (“indre skallsikring”)	**13 minutes**
Escape route patterns	**Main escape stair – bicycle**
Information during the evacuation exercise.	**PA**

5.2 Discussion

The available evacuation time was described in chapter 3 as the fire scenario and in this thesis it will be used simulations from vessel ruptures. The different safety barriers will affect this time for rupture, as will be shown later in this thesis.

The required evacuation time is 1,2 minutes.

The safety margin will be the difference between available and required evacuation time. Long vessel rupture gives a longer safety margin.

Available time for evacuation out of zone 1: 120 sec (2 minutes) - Required time for evacuation zone 1: 90 sec, this includes evacuation down from module, 50 meters from module and 10 seconds time to assess and react =
Safety margin: 30 sec.

Available time for evacuation from zone 1 to zone 2: 120 or 240 sec (4 or 6 minutes) - Required time for evacuation zone 2 is scenario dependent.

Based on the assumptions that the time to assess and react is 10 seconds, and that no additional time delay will occur, all personnel will be at least 110 meters from the module after 2 minutes. This means that all personnel will be out of safety zone 1 with a margin of 60 meters for the first escalation period. After 4 minutes the personnel will be 350 meters from the module and after 6 minutes the personnel will be 590 meters from the module. Figure 14 illustrates the available time for evacuation versus required time for evacuation.

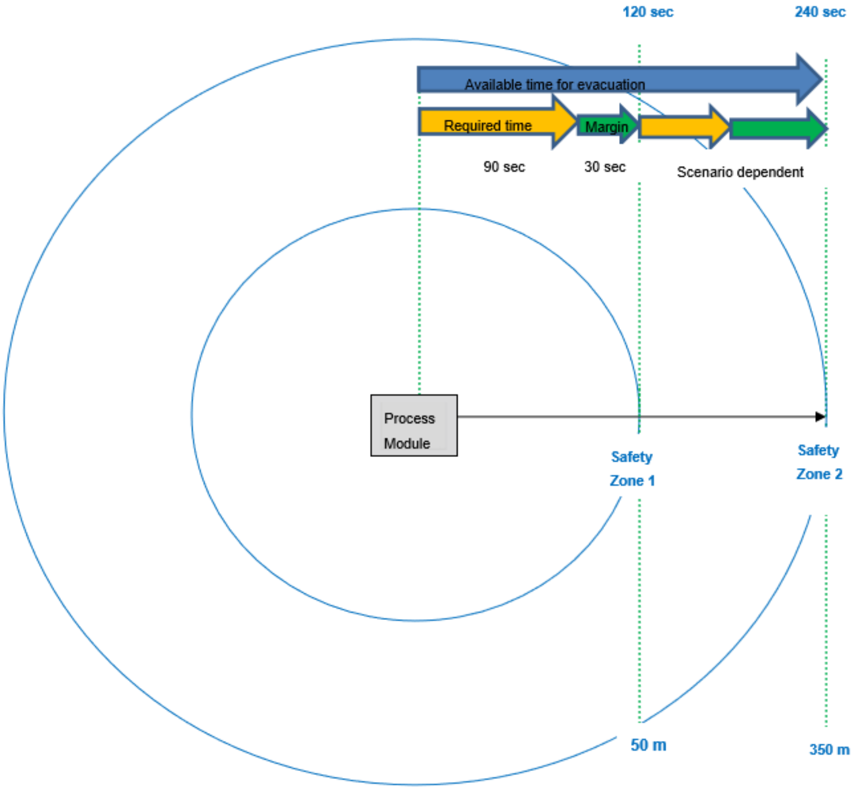


Figure 14 Illustration of Safety zone, available and required time for evacuation for defined scenario

The evacuation route illustrated in Figure 13 goes past the process utility area, K-lab and the main process areas Statpipe and Åsgard. Based on a person using 65 seconds to assess, react and evacuate down to ground level from a module, the personnel will be able to reach a safe area within the time available for evacuation. (After 2 minutes the person will be out of the fire area). If the person has a bicycle available the evacuation time will be significantly reduced. However, it must be made sure that the personnel at Kårstø are aware of the importance of immediate escape if a jet fire occurs in the process area.

The evacuation results will be discussed later in this thesis regarding BLEVE.

5.3 Improvements

In some areas the information was difficult to perceive due to echo effects and noise, hence the possibility to give relevant information and recommend escape routes can be limited in these areas.

As earlier mentioned, when interprenting the signal – this is a process based on earlier experience and sufficient information. If the signals are weak or ambiguous, people will seek more information or they might ignore the signals. As the information was difficult to perceive under the evacuation exercise, it is recommended to upgrade this.

In areas with a lot of noise the person that is wearing hearing protection with radio will get the information. People with hearing protection without radio might not get the message to evacuate. There are requirements for a person being fire guard incase there is a fire and people that are working needs to be be informed. This applies in different situations stated in the Statoil standards.

The information shall be short and concise. Familiar concepts and predefined concepts shall be used. It will be important to become familiar with this in the HSE 24 – course. If the information is very detailed, such as information about exactly where in the area the leakage is, this can be good in terms of people choosing evacuation routes away from the leakage. The negative effect of beeing very detailed is that a lot of information needs to be interpreted, and people might get confused.

At a processing plant, incidents rarely happen. Explosions and fires are something that people are not so familiar with. Because of this it will be important to remind people of the risk at a processing plant. Training is important and regulary courses to inform about the behavior in evacuation will be essential.

Another improvement is using the main roads away from the congested process train areas when evacuating.

5.4 Conlusion from Kårstø exercise

The exercise shows that peole have reached the temporarily safe area within the available evacuation time.

6 Simulex

The purpose of using evacuation modeling in this thesis was to compare the simulations with the evacuation exercise in Statpipe. The college Stord/Haugesund was contacted to discuss which kind of simulation program to use. Also, this was discussed with people in the technically safety department in Statoil. STEP simulation was considered, but the choice of Simulex was made based on being most userfriendly and suitable for the thesis. It is a good program to estimate the necessary evacuation time and look at how the evacuation conditions are at the Kårstø plant.
Since STEP had been used earlier it was also interesting to learn a new program. There are other evacuation programs to use for this purpose. (Pathfinder)

Later in this chapter the simulations have been compared with Åsgard processing train to see if the results from the Statpipe simulations can represent an evacuation in Åsgard.

6.1 Description

(Limited u.d.)
Simulex is a recognized program used worldwide to simulate evacuation conditions in different types of buildings and areas. The purpose of running simulation scenarios in Simulex is to assess the need for necessary moving time and to assess desired architectural conditions in a building or as in this thesis, at a plant. The program is developed by Integrated Environmental Solutions Ltd, a company in Glasgow specializing in computer technology based on the design and use of buildings. Scientists from different countries have analyzed human behavior at escape situations and used these data to program Simulex for the most accurate reproduction of such patterns.

The interface of Simulex is very simple. It can be used simple AutoCAD drawings of any construction as the basis for simulation. In the program, pre-defined staircases with desired length and width can connect different levels with links.

Floor:
The first activity to carry out is to create a «building». A building consists of floor pans, (imported from CAD files in DXF format) and staircases.

Defining links:
The staircase has to be connected to the floors with two links, one on each end of the stair.

Exits:
Exits can be placed in any plane at a given length. When exites and links are placed, the program can calculate distances to exits from different positions in the building so that "the people" escaping go to the nearest exit from their location.

The people are moving towards pre-defined exits with individual evavuation speed depending on individual characteristics. During a simulated evacuation, the program manufactures realistic flow rates with 1.1 to 1.4 people per meter exit width per second, representing a normal adult population under calm circumstances.
After everyone has moved through the exit one, total evacuation time is displayed on screen, and a data file of the results is saved.

Mesh:
Simulex is using a mesh consisting of squares of 0.2 x 0.2m to create a distance map. The various numeric values in the square correspond to the distance from this route to an exit. Using distance map Simulex can find the nearest exit for people in the building.

Defining the occupants:
People are placed in the building either individually or as a group. People who are placed can be given various personal characteristics in relation to the role they have in the current building. It is possible to specify the person’s physical and psychological characteristics. The physical characteristics affect people's size and distribution as well as maximum walking speed. The psychological characteristics are the choice of distance map (exit) and response time.

The typical person loads such as office workers, schoolchildren, elderly people, children and customers is given in the program. When selecting these properties the behavioral pattern of people in the building will change. This includes speed and how close people can come together before speed will be reduced. The default setting for Simulex makes people go slavishly to the nearest exit regardless of personal impact. One can however assign groups of persons other routes and exits than the shortest that is the standard one to use.

Calculation of distance maps:
Simulex will automatically calculate all "travel distances" and routes through the building. The user can look at an evacuation on the screen and zoom into an area of interest. It is also possible to record a simulation on a hard disk for later "realtime" playback.

The algorithm for the movements of individuals is based on data collected by using computer-based techniques for the analysis of human movement, observed in reality.
A great advantage when using Simulex instead of hand calculations is that building drawings are used and it will then be taken into account the obstacles in the escape routes. This can affect the escape time considerably in relation to real-life scenarios. Inventory, building parts that are sticking out, columns, etc, will in fact lead to the accumulation of people, and this is taken into account in the program.

One can also see how congestion of people will occur due to architectural design or constriction. Accumulations in Simulex can be a good basis for fire engineers working in companies; to argue against "dangerous" solutions given by the architect or builder.

Simulation
When all the people are defined and the project file is saved the simulation can begin. The simulation of large numbers of people can take a long time, depending on the speed of your computer. People are progressing towards exits.
In a processing module, however, there are not so many people working. In the evacuation exercise 5 people were in the Statpipe module.

When doing simulation it is possible to get information at any time about how many people are left in any plane or stairwells.

6.2 Principles and assumptions

The following basic principles and assumptions made in Simulex:

- *Each person is given a normal, unobstructed walking speed*
- *Walking speed is reduced when people come closer together*
- *People move to a second exit by moving into a direction which makes right angles to the mesh that is formed in the selected distance map*
- *Bypassing, bodily rotation, lateral movements and small movements backwards are included*

People walking speed:

- *The evacuation speed is dependent on the person density and on the design of the escape route: corridor, staircase, etc. The evacuation speed describes the average rate for a group of people in the actual escape item. The individual may move faster or slower than average. A consequence of variations in the evacuation velocity is that people who escape will be distributed in the escape road.*

- *Simulex randomly select individuals unhindered walking speeds in the range of 0.8 to 1.7 m/s. A person's evacuation speed will depend on the distance to the people in front of him. The velocity descending a stair will be 0.5 times the horizontal velocity. Ascending a stair will take place with a velocity of 0.35 times the horizontal velocity.* In the simulations in this thesis, only descending a stair will be relevant, since the workers are walking down the module from upper levels.

6.3 Simulation scenarios

8 simulation cases were performed. (Appendix 1). This was done so the results could be compared to the evacuation exercise. The simulations represented Statpipe where two of the observers where placed in the exercise, as described in chapter 5.

A module that represents the one in the exercise was made in AutoCad. The length and with on the module was measured and this was the input for Simulex. The obstructions in the module, such as vessels and pumps, were put into the AutoCad file. Then the 3 levels in the module were linked together.

The staircases were placed as in the module. Then the occupants were defined.

It was found interesting to simulate with different amount of people and placing them at different levels, having one or two exit`s. There will be different simulations showing different scenarios. Sometimes there will be more people working at the plant, when there is higher activity then in normal operation, but normally there are not so many people in one module.

All the cases were done with following:

- Characteristic people: It was chosen both "Office Staff" / All 1 m/s (there was no difference between the two options)
- Response time: It was chosen both "Random distribution" / "Normal distribution" (there was no difference between the two options)

6.4 Discussion

Tables with detailed results can be found under Appendix 2.

CASE 1
The first person uses 10 seconds down the first stair which is 8.5 m and this gives a walking speed of 0.85 m/s. Next person uses 5 seconds, and the last person uses 10 seconds.

In Simulex the walking speed for a person depends on the distance to the person in front. A person in front will reduce the speed. Speed in stairs is reduced compared with the speed at horizontal surfaces. The velocity descending a stair will be 0.5 times the horizontal velocity. In this case the speed down stairs is applicable when escaping from the top level down to the ground level.

The normal unobstructed walking speed for each person will be randomly selected in the intervals between 0.8-1.7 m/s. Based on real exercises at the plant at Statpipe the measured time of the speed in stairs will be 0.53 m/s. Expected time for evacuation in a staircase which is 8.5 m long is 16 sec. The simulations show a faster evacuation speed down stairs based on what is measured in the field.

Figure 15 Picture of the staircases in module 5 in Statpipe

Figure 16 shows 3 people that are placed at top level. The first person uses 20 seconds, i.e average vertical evacuation speed is 0.75 m/s, from where he is positioned to the first link. He is located approximately 15 m from the link. He must pass an obstruction.

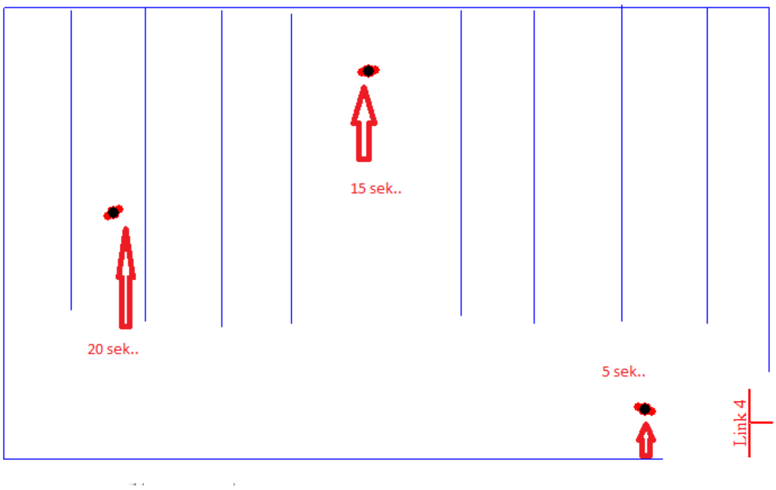


Figure 16 Picture taken from Simulex simulation

The next person uses 15 sec. He must pass an obstruction. He is positioned as shown in Figure 16.
The last person is standing very close to the link, 1 m from it, and then uses 5 seconds to get to the link.

Based on the results compared with the evacuation speed of 1.74 m/s, as measured in the exercise, the evacuation speed of 0.75 m/s is somewhat lower. It referres to what is previously written about the normal unobstructed walking speed for each person. In Simulex this will randomly be selected in intervals between 0.8-1.7 m/s. This represents the lower limit.

A bit surprising result is evacuation speed in stairs; 0.85 m/s. It was expected from the Simulex user manual; 75 m/s / 0.5 = 0.4 m/s. A possible explanation could be that the influence of other people. But this should not have any impact for the first one, which is also measured with a high walking speed down stairs.

CASE 5

In this case the people are evacuating from different levels. Evacuation time was approximately the same as for the three persons which was placed on the upper level in case 1; 38 seconds.
It was expected that it would be a bit longer when there are more people going down the stairs. But increasing from 3 to 7 people gives little variation. Having a closer look at this, a simulation with 30 people was made. After 100 sec 16 people is coming out. The effect of accumulation can be seen.

To see *when* the accumulation occurs, a simulation with 10 people is done. These are also getting out after 38 seconds, ie, no accumulation.
Then a simulation with 20 people is done. After 50 sec 16 people are out of the exit. After that it takes a long time before the rest is out.
According to the results it can be seen that with more than16 people accumulation occurs. This confirms a simulation with 15 people: all out after 39 sec. At 17 people; accumulation begins. This confirms that accumulation is not relevant in this thesis, as there are not more than 17 people in a module at normal operation.

CASE 7

All of the people in the program select the exit that is closest, regardless of other people choosing it. In this case everybody selects stepladder, which is also naturally considering the distance. To persuade them to escape towards a particular escape route, the people must be placed closest to the exit that is desirable for them to use, or the exit that is not desirable using, can be removed.

CASE 8

It can be seen that by choosing to put people close to the exit that is located at the safety zone, then people choose this exit. 3 people are located at a distance 20-30-50 m from this exit, and they choose this.

If the people are placed close to the safety zone, these people select to evacuate against this exit. Some people are placed in the long hallway toward the safety zone.
By simulation with 7 people versus simulation with 15 people it was only 1 second difference in the results.
Time is slightly larger, as expected, but not much, only 1 second.

In the simulation it can be seen clearly that the 3 persons that are placed closest to the exit 1 chooses this. The fourth person is placed closest to the second exit and therefore chooses this one.

It was tested whether obstructions do matter in the choice of exits. One person was located in between exit no.1 and no. 2 but closest to no. 2. In the escape route towards the exit no.2 an obstruction-wall was located. It turned out that people still chose exit nr. 2 despite that the person had to pass the obstruction. The distance is more important than the obstruction, when it comes to chosing the escape pattern.

General for all cases

The time it took to perform simulations proved to vary. The simulations were fast if accumulation didn`t occur and everything went "smooth", ie ca. 2 sec. If there were accumulation the simulation never stopped, when one or more people had jammed. Then the simulation had to be stopped and the link where accumulation occurred had to be localized. The link was moved and the simulation was “smooth”. It is important that an area around the link is defined.

It was not necessary to divide the simulations into smaller parts; the simulations were with a relatively low number of people.

Walking speed that was used in the simulations is arbitrarily chosen in the program based on speeds between 0.8 and 1.7 m/s. The program takes into account that the speed is reduced by increased personal density. It is also possible to select the speed of 1 m/s. This was done, and simulations were done with different response distributions "normal distribution", "random distribution" and "triangular distribution". It turned out that by the simulation that was done with 15 people there was not any difference in the results with the different response distributions or the different walking speed.

To see what differences that could occur, it was done a simulation with 100 people. It turned out that there were no differences in the stimulation times in choose of random, triangular or normal distribution with a larger amount of people. Results from simulations are not compared with another simulation program, but with a real exercise that was held at the facility. But it is read that different simulation programs give quite different results.

Simulation Software is a very good tool to illustrate an escape situation visually. They open to walking speeds and character types / shapes.

Known limitations
A general problem with the use of simulation programs is their inability to include a number of conditions that were presented in the literature. Another important factor is that people do not behave like robots. Sometimes people will make decisions that are not necessarily conducive to an effective escape. Such as going towards an exit and then changing mind and go against another. This is not considered in the program.

The distance is more important than the obstruction, when it comes to chosing the escape pattern. This is a limitation in the program.

6.5 Comparing the evacuation exercise with the Simulex simulations

Table 2 Evacuation time exercise vs. Simulex simulations

Activity	**Exercise time**	**Simulex simulations time**
1) Evacuation walking speed in stairs	**0,53 m/s**	**0,85 m/s** (measured in stairs)
2) Evacuation walking speed on platform / module deck	**1,74 m/s**	**0,75 m/s - **(measured in beginning of simulation) **0,8 – 1,7 m/s** (in general for Simulex)
3) Evacuation walking speed on ground level	**2 m/s**	**1,25 m/s** (Appendix 2)
4) Time for personnel to reach ground level from working at top level in a module	**60 seconds (first person used 34 seconds)**	**38 sec**
5) Time for personnel to reach safe area (safe area is defined as 50 m from the module)	**1,2 minutes**	**1,3 minutes** (Appendix 2)

1) Evacuation walking speed in stairs

The walking speed in stairs in the simulation is higher than in the exercise. This was an exercise but if this would be a real life **–** incident it can be expected that people are walking faster, because of the seriousness in the situation.

2) Evacuation walking speed on platform / module deck

The walking speed on platform / module deck compared with the speed measured in beginning of simulation is high. Compared to the general limit for Simulex, 0,8 – 1,7 m/s it is comparable with the upper limit. This value could represent the fact that people do have different physics.

The speed measured in the beginning of Simulex may not be constant under the whole simulation, as Simulex chooses values between two limits. As can be expected for walking speed in stairs, this speed could also be higher in a real life incident. People may also start running, which is easier than in stairs, so the speed her could become significantly higher. A possible explanation for a low speed in simulations with a lot of people can be accumulation with congestion.

3) Evacuation walking speed on ground level

As can be expected this evacuation speed is higher than the speed on platform /module deck. There are fewer obstructions (pumps and valves), more open area, and the probability of people starting running is higher then in the module, where there are physical obstacles to pass.

Another example of the speed beeing lower in simulations can be found also at ground level. But not of appreciable significance. It is not included the time used when people are changing their mind and choosing another direction that will make the required evacuation time longer. It might not be the first choise that is the right one.

4) Time for personnel to reach ground level from working at top level in a module

The simulations were done with 3 levels. This seems reasonable when comparing the 38 seconds that it took for all the 3 people to get out of the module with the exercise, were it took *60 seconds*.

It will be expected from the simulations, that with 4 levels, the time would be: 38 sec / 2 levels (first walk from top level to mid level, then walk from mid level til bottom level) = 19 sec * 3 levels = *57 seconds*

This agrees well with the exercise result.

5) Time for personnel to reach safe area (safe area is defined as 50 m from the module)

Here the values are quite the same for simulation and the exercise. The people seem to walk faster, no obstrucions, and easier to run.

6.6 Comparing simulations with Åsgard processing train

Figure 17 Åsgard processing trains

The purpose of this chapter is to se how the Simulex simulations in Statpipe can be compared to Åsgard processing trains. This will provide the simulations a wider range.

The equipment density is greater in Åsgard than Statpipe. This can make evacuation more complex as there are more obstacles to pass. But after having an inspection in the area it was observed that it was a larger number of evacuation exits from the modules than in Statpipe. This factor will compensate for the equipment density. At the most, one plane at Åsgard had 3 ladders and one staircase. This means that a person evacuating can choose the exit route with fewest obstacles to pass. If the person is standing inbetween two exits, the person can have a quick overwiew of the area, and choose the route with fewest obstacles. It is important with good exit signs that can be seen from all areas.

6.7 Conclusion from Simulex simulations

Simulex is suitable for the simulations required for a processing train. The program weaknesses such as accumulation do not affect results much in simulations with 5-8 people, which is representable for a module at Kårstø.
The simulations show results quite similar the results in the evacuation exercise performed at Kårstø.
The simulations are representable for Statpipe. The calculations will also be representable in Åsgard processing trains where the equipment density is greater, because there is a larger number of exit`s.

7 Hazard from thermal radiation from a fire to a standing person

The purpose of this chapter is to show how radiation from a fire will affect a person.
Regarding the evacuation at the Kårstø plant it is important to have an idea of how much the radiation will affect, and at which time it will affect the most. Radiation will in worst case harm people in a fire, and it is essential to prevent this. A lot of experiements on this has been done and articles in the litterature have been used to discuss this human impact. These articles have been considered as adequate for the purpose of the work.

Some of the questions that are important to answer are:

Which effects does the clothing have regarding radiation and how important is it where a person is placed from the fire?

How will the equipment density absorb the radiation?

Table 3 Effects of thermal radiation at different heat fluxes

Radiant heat flux (kW/m^2)	**Observed effect**
0.67	Summer sunshine in UK
1	Maximum for indefinite skin exposure
6.4	Pain after 8 sec skin exposure
10.4	Pain after 3 sec exposure
12.5	Volatiles from wood may be ignited by pilot after prolonged exposure
16	Blistering of skin after 5 sec

7.1 Clothing

(K.Raj u.d.)

Clothing normally worn by people can partly absorb, partly reflect and scatter incident thermal radiation and thus protect the covered skin from experience full intensity of the incident radiation.

For large radiant heat flux levels (30 kW/m^2, which levels would be experienced when the person or an object is very close to a fire) the researchers found that the absolute protection time provided by normal clothing (of 1-1,5 mm thickness) was short and that much thicker (and multi – layered) clothing, such as worn during winter months, was necessary to provide any burn protection.

The author demonstrated with the test data that a normal adult can easily withstand, without severe pain or injury, a radiant heat flux level of 5 kW/m^2 for much longer than current literature numbers (for unbearable pain) and up to almost 30 seconds without skin burns / blisters. At lower heat flux these “tolerance” times are significantly longer.

Table 4 Results from the test that was done by P.K Raj – when exposed to relatively prolonged durations

Heat flux – exposure level	**Experienced feeling**
5 kW/m^2	Feeling of standing close, 1 m in front of a well-establised fire in a home fireplace
6,5 kW/m^2 and higher	With duration of the order of 10 sec, feeling of pain on the unprotected skin
4 kW/m^2 and higher	With exposure to long durations (50 sec) feeling of heat was felt on the skin protected by clothing
5-7 kW/m^2	With durations slightly less then 30 sec no feeling of heat was felt on the skin protected by clothing – the body began to sweat resulting in the maintenance of the body temperature at the normal human temperature (37 °C)

7.2 TR3002 Flare, vent and drain

(G. D. Safety 2014)
The document is intended for use in the design of flare, vent and drain systems, both onshore and offshore.

Permissible design level: 6.3 kW/m^2
For colder environments, i.e. where people are wearing an overcoat: Maximum radiant heat intensity where escape to a shielded location takes less than 5 minutes or where emergency actions takes less than 5 minutes without the need to climb exposed ladders and stairs. Escape shall include required termination of ongoing work in the exposed area.

For warmer areas: Maximum radiant heat intensity where escape to a shielded location takes less than 30 seconds, or where emergency actions takes less than 30 seconds, without the need to climb exposed ladders and stairs. Escape shall include required termination of ongoing work in the exposed area.

Permissible design level: 4,7 kW/m^2
For colder environments, i.e. where people are wearing an overcoat: Maximum radiant heat intensity where escape to a shielded location takes less than 10 minutes or where emergency actions takes less than 10 minutes. Escape shall include required termination of ongoing work in the exposed area.

For warmer areas: Maximum radiant heat intensity where escape to a shielded location takes less than 5 minutes or where emergency actions takes less than 5 minutes. Escape shall include required termination of ongoing work in the exposed area.

7.3 Discussion of results

(K.Raj u.d.)
A person with ordinary civilian clothing can, relatively easily, withstand incident heat flux levels up to 5 kW/m^2 for at least 25-30 sec without experiencing unbearable pain, permanent injury/skin burns or skin blisters. The skin will feel a heat flux of only about 1.67 – 2.5 kW/m^2. At lower heat flux values these “tolerance” times are significantly longer.

From the test it can be concluded that ordinary civilian clothing, even single layer clothing, provides a factor of 2 – 3 reduction in the magnitude of radiant heat flux reaching a person`s skin for relatively long term exposures (on the order of minutes) at an exposure level of 5 kW/m^2 or close to it.
To compare this with the Kårstø protecting clothing it will be expected that the effect of these clothes are even better, as a factor of 2-3 reduction of radiant heat flux applies to ordinary civilian clothing. It is to be expected a factor of 3-4 reduction in the magnitude of radiant heat flux, this being conservative. With air gap between the clothing and the skin, the effect will be even better.

A person with personal protective clothing will have the face without protection. This area can be exposed to radiation. It is expected that a person will turn away from the fire, so the area that can be exposed for radiation will be the neck. The probability of the area on the body being exposed to radiation will be larger if the person is close to the fire, and will decrease with distance.

It has been shown that the first 5-10 seconds a person will turn away when feeling pain to the skin.
Considering this reaction the person will probably start running. The first 5-10 seconds the person will be exposed to the highest heat flux on a very little area, but after this the person will probably start running at 4 m/s and the distance from the heat flux wil rapidly start increasing and the radiation will be less intensive. After the next 10 seconds the person will be 40 m further away and after 30 seconds as much as 120 m away from the radiation source.

Any object that intervenes between the heat flux source and a person or an element receiving the heat flux results in a substantial decrease in the heat flux to the person or the element. Opaque objects, such as buildings and solid objects will provide a good protection.
This will be a positive effect at the Kårstø plant where the equipment density is high. It can be expected that some of the heat radiation from the fire will be absorbed from the equipment in the area and it will be assumed that less radiation will affect people nearby.

Another positive effect of the equipment at Kårstø is how people can use this as a shelter in a fire situation, hiding behind this equipment. .

7.4 Conclusion from thermal radiation

Thermal radiation implies a risk considering jet fires. There is a risk for people placed near the fire incident being exposed to radiation. This emphasizes the fact that there is a risk for people that are very close to the fire scenario, which is stated in the Total Risk Analysis. (Scandpower, E002-XX-S-RS9135 Total Risk Analysis Main report 2013). The possibility to evacuate early before the fire is fully developed is of great importance. Early evacuation alarm will lead to evacuation from the heat radiation source at early stage.

The protecting clothing used at winter time will protect better than thinner clothing at summer time. Using Personnel Protecting Clothing, (PPE) is of great importance avoiding radiation fluxes.

8 Definition of BLEVE

(Tasneem Abbasi u.d.)

BLEVE is defined as a sudden loss of containment of a pressure – liquefied gas existing above its normal atmospheric boiling point at the moment of its failure, which results in rapidly expanding vapor and flashing liquid.
BLEVE is a shortening for «Boiling liquid expanding vapor explosion».

A BLEVE can be the outcome of the fire scenarios listet under chapter 3.2.

Time to BLEVE

Once a vessel suffers from a minor or major failure, it can lead to a BLEVE even if pressure relief valves may be operating. During the accidents that have occurred in the past, some vessels have exploded within a few minutes of fire engulfment, some other has done so after several hours. In some cases vessels have suffered a BLEVE as many as 24 hours after being jeopardized. It is important to estimate the time that may elapse between the initial jeopardization of a vessel and its eventual BLEVE as this may help in devising damage – control strategies.

If a rupture takes place in a vessel holding a liquid at or near its atmospheric superheat limit, it may not always produce a BLEVE. The vessel must open completely for a BLEVE to occur. This will only happen if the vessel has been weakened sufficiently to initiate a rupture and if the pressure transient during failure is sufficient to drive the failure crack to fully open the vessel.

The time to initial failure depends on the first condition and on the design of the vessel and pressure relief system.

BLEVE prevention and control

There are some actions to make, preventing the causes which can make a vessel vulnerable to BLEVE:

- Preventing exposure to fire
- Preventing mechanical damage
- Preventing overfilling and overpressure
- Prevention of internal weakening of vessel structure due to fatigue, creep, corrosion, etc.
- Thermal insulation. Thermally protecting the vessel will reduce the rate of heating of the vessel when it receives heat load and delay the pressure increase inside
- Passive fireprotection
- Directed water deluge
- Rapid depressurization

Fireball - thermal hazard

(SINTEF u.d.)

If the vessel has a significant fill level with a combustible fluid when the BLEVE occurs, the resulting fireball can often impose damaging thermal loads at greater distances than the blast waves. For this reason, it is important to predict the size and duration of the fireball from a BLEVE where the vessel contents are combustible or flammable.

Fireball is a fire, burning sufficiently rapidly for the burning mass to rise into the air as a cloud or ball.

As the fireball grows, the turbulence of the fire entrains air into the fireball. Simultaneously the thermal radiation vaporizes the liquid droplets and heats the mixture. As a result of these processes, the whole mass turbulently increases in volume, evolving towards an approximately spherical shape that rises, leaving a wake of variable diameter. Such fireballs can be very large, causing a very strong thermal radiation.

Figure 18 BLEVE fireball; spherical when fully developed

Diameter and height of fireball

(SINTEF u.d.)

Numerous empirical models are available for calculating the fire characteristics of fireballs. Most of the models are based on the following basic assumptions:

- The fireball is homogeneous, isothermal and spherical
- All the fuel within the expanding vapour cloud is consumed
- The fireball radiates as a black body
- The wind has no effects on the fireball characteristics

The incident radiation to target at a distance x from the fireball is given by (SINTEF u.d.)

$$q''_r = \tau F E_p$$

The atmospheric transmissivity (τ) will range between 0.7 and 0.8. E_p is calculated from the fuel radiation temperature and Stefan Boltzmann constant, with the assumption of an emissivity of 1. F is the view factor, the fraction of radiation emitted from the fireball which would shine directly on a ground level target. The radial distance x from the radiating surface of the fireball to the object is found by equation (SINTEF u.d.)

$$F = \frac{\frac{H - Ds/2}{Ds} + 0.5}{4\left\{\left[\frac{H - Ds/2}{Ds} + 0.5\right]^2 + \left[\frac{x}{Ds}\right]^2\right\}^{3/2}} \qquad (0.1)$$

H is the height of the fireball and D_s is the diameter of the fire ball, and is calculated based on the amount of fuel [m] and molecular weight [Mf] (SINTEF u.d.)

$$H = 3.1\left[44.8\ \frac{m}{Mf}\right]^{1/3} \qquad (0.2)$$

Average diameter D_s of a fireball:

$$D_s = 3.44\left[44.8\ \frac{m}{Mf}\right]^{1/3} \qquad (0.3)$$

(where m is the total amount of fuel participating in the fireball, (in kg), and Mf is its molecular weight of the fuel (kmol / kg))

In different examples on determine the diameter of BLEVE fireball, it is assumed different percentages of fuel flashes off to vapor immediately at the time of tank rupture. A large percentage, as 80 % of the fuel that flashes, will give a larger fireball than if the percentage would be for example 30 %. This will be shown in chapter 8.2 ”BLEVE calculations”

$$t_d = 0.31\left[44.8\ \frac{m}{Mf}\right]^{1/3} \qquad (0.4)$$

Failure pressure

The pressure at failure is not always known. However, depending on the assumed cause of the failure, an estimate of pressure can be made.

If failure is initiated by an increase in internal pressure in combination with a malfunctioning of the pressure relief, the pressure at failure will equal the failure pressure of the vessel. This failure pressure is usually the maximum working pressure multiplied by a safety factor. More precise calculations are possible if the vessel`s dimensions and material parameters are known.

If failure is due to external heat applied to the vessel (e.g from fire), the vessel`s internal pressure rises, and at the same time its material strength drops. For initial calculations, it can be assumed that failure pressure equals relief pressure at rated flow.

If failure is initiated by corrosion or impact of a missile or fragment, it can be assumed that failure pressure will be the normal operating pressure.

Fragments and Debris Throw

A BLEVE can produce fragments that fly far from the explosion source. Primary fragments, which are part of the original vessel, can be highly hazardous and may result in damage to structures and injuries to people. Where the vessel breaks into large pieces, they may be thrown while carrying some of the flashing liquid with them. As the liquid flashes, it will expand and propel the pieces in a manner similar to that of a rocket. For this reason, these self-propelled fragments are called “rockets”. Primary fragment and rocket effects are determined by the number, shape, velocity, and trajectory of fragments; these fragments and rockets generally represent the farthest ranging hazard due to BLEVE`s.

The number of fragments will usually be high for a high rate of pressure rise, such as a runaway reaction. For situation in which failure occurs near working pressure, such as loss of mechanical integrity due to fire exposure and on the external agencies, the number of fragments from such events tend to be low, usually from 2 to 10 pieces.

8.1 BLEVE calculations

A BLEVE can be the outcome of a fire scenario described in chapter 3.2. As jet fires are assumed to be the worst case in fire scenarios, BLEVE calculations are based on vessels being hit by a jet.

Overview of vessel rupture at Kårstø as a result of a jet is listet in Appendix 3.
Time for rupture will decrease with increased wall thickness and will increase with thermal insulation. The rupture time calculations in Appendix 3 have been estimated without taking into account any insulation. The rupture time is based on a worst case scenario where the jet fire hits the upper part of the vessel (gas phase) and the vessel ruptures due to weakening of the steel wall. The rupture time would be longer if the liquid phase was subjected to the jet fire, as the liquid will cool the vessel wall and heat energy will evaporate the liquid. In this case the BLEVE scenario would be a rupture of the vessel based on internal pressure build-up.

It will be important to detail the fire scenarios for each vessel to get the results the most correct. It will be important to look at the flanges, the leakage points, if the heat loads are global or local. This working sheet does not include this, and it will be suggested as further work.

The excel – sheet that has been used in the BLEVE calculations (Appendix 4) have been performed by using the fireball radiation method from the Scandpower Handbook for Fire Calculations and Fire Risk Assessment in the Process Industry (SINTEF u.d.) Formulas that have been used in the excel calculations are those given in Chapter 8.1 Definition of BLEVE.

The calculations were done with two different radiation levels from chapter 7.2.

Calculations with 100 % flash off to vapour immediately at the time of vessel rupture was carried out. After that calculations with 80 % flash off were done for 4 of the vessels. The results from the BLEVE calculations can be found in Appendix 5.

8.2 Discussion

(Engineering 2015)
Based on calculations of BLEVE radiation zone from vessels located in processing areas at Kårstø a safety zone of approximately 200-300 meters will be representative. (Appendix 5) This distance is possible to achieve within 4 minutes after the initial event. The safety zone 2, as seen in chapter 5.2, and available time for evacuation from a BLEVE will however be scenario dependent and needs to be evaluated for the specific vessels.

When comparing the safe distance with the time for rupture, included 2 minutes delay until first escalation, the results shows that there will be time enough to get to the safe distance for all vessels. For the vessels with passive fire protection or thermal insulation the results will be conservative. The insulation will give credit in a fire scenario and in chapter 9.2.1 "Insulation cases", it can be seen how much credit this wil give.

There are also several factors that may reduce the risk picture, both with regards to probability and consequences. It is assumed that evacuation starts when a small or large jet fire occurs. However, in most scenarios there will be a time delay from a gas leak occurs until it is ignited, and detection of the gas leak will trigger an earlier start of evacuation and thereby a longer available time for evacuation. The radiation exposure assumes an open area, but in some cases the radiation could be blocked by obstructions, as shown earlier in chapter 7 "Radiation". The radiation exposure duration will be very short for the most time critical BLEVE scenario; ≤ 5 seconds. This can be shown in Appendix 5. The walking speed will probably be higher (jogging), especially in the first minutes after the incident occur. Personal Protection Equipment (PPE) is a necessary barrier to reduce thermal exposure until it is possible to get to a shielded area or the BLEVE fire ball has weakened sufficiently. (Engineering 2015)

The calculations show that small amount of liquid gives a smaller BLEVE. With 80 % flash off the liquid, the safe distance will become smaller than with 100 % flash off the liquid.

For situations in which failure occur near working pressure, such as loss of mechanical integrity due to fire exposure and other external agencies, the number of fragments from such events tend to be low, usually from 2 to 10 pieces.
The likelihood of personnel being hit by such fragments are therefore low, in the range of 1-2 * 10^{-3} per BLEVE. (This is based on the following conservative assumptions: two fragments per vessel, 30 % fraction of a fragment escaping the module, up to 1000 m travel distance, 100 escaping personnel within this radius at a given time and a 10 m^2 damage area when the fragment hit the ground level.)

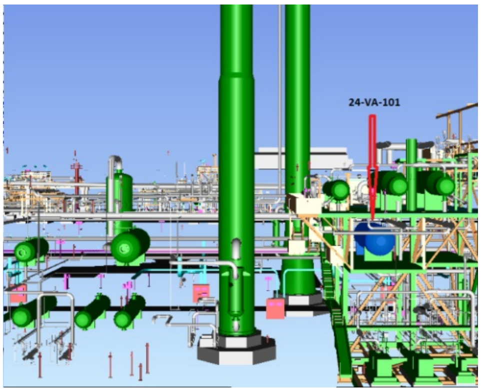


Figure 19 Vessel placed in the middle of a processing train

It is of importance where in the module the vessel is located considering the effect of the BLEVE. Most of the vessels that have been looked at in the BLEVE calculations are placed on the top of the module. It will not be obstructions preventing the fireball getting out completely. It can be assumed that with a vessel located in the middle of a processing train, as in Figure 19, the fireball will be hindered in getting out. Also it can be assumed that the obstruction will take some of the pressure, by bursting and cracking. It might be assumed that with a lot of obstructions the pressure will be less than with only a few. It can also be assumed that the vessels that are placed above the vessel that goes to BLEVE will be heated, meaning that some of the energy in BLEVE will be a part of heating other vessels.

The literature tells a lot about BLEVE experiments in open areas, and it has not been found articles regarding BLEVE in the middle of obstructions. There might be a need for increased understanding of BLEVE risk releated to smaller processing vessels in congested areas. This will be suggested as “Further Work”.

Actions taken for prolonging the available evacuation time must be considered and the negative effects must be included in the assessment. The economical issues must be included. “As low as Reasonably Practicable”(ALARP) must me carried out.

8.3 Conclusion from BLEVE

In the oil and gas industry the focus on BLEVE is mainly related to larger storage vessels. At Kårstø there are, however, several vessels located in different processing areas that require focus.

The 1/6 of the train containing the vessel of interest may have an instant large fire frequency a little less than $1 \cdot 10^{-3}$ per year. Given that the local fire frequency is expected to be lower than this due to low density of leakage sources and ignition sources, an instant large fire frequency of $5 \cdot 10^{-4}$ per year may be a sound estimate. The fraction of fires exposing the particular vessel of interest will be a fraction of this frequency, estimated to 1/10. Only a fraction (estimated to 1/5) of these fires will have an immediate heat load of 350 kW/m^2 hitting the gas phase of the vessel and thereby contribute to an early BLEVE scenario. As an estimate, the particular vessel is involved in an early BLEVE scenario at a frequency of $\leq 1 \cdot 10^{-5}$ per year.

Available time for evacuation in BLEVE scenarios needs to be evaluated for each specific vessel. The calculations show that there will be sufficient time to get to safe distance for all vessels evaluated with respect to radiation exposure. The likehood of personnel being hit by fragments are low, in the range of 1-2 * 10^{-3} per BLEVE.

This show that there is a low probability being hit by fragments from BLEVE and there is a low frequency of vessels being involved in early BLEVE scenario.

9 Passive fire protection (PFP) and how it affects evacuation time

PFP can prolong the escalation time. Important questions are:

For how long can the pfp prolong the evacuation time? If the equipment has got thermal insulation or other kind of insulation, can this give credit in a fire situation, even if it is not pfp?

First in this chapter Statoil`s requirements regarding passive fire protection are described. After this, calculations have been done showing how the heat loads gets through the different layers in different insulation materials. This is done to have an idea of how the escalation time prolongs, hence the available evacuation time.

9.1 Statoil`s overall requirements – relevant paragraphs regarding Passive Fire Protection

9.1.1 TR2237: PS 10 Passive Fire Protection

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

(PS 10.4.2.)
Where the need for protection has been determined, a minimum of 30 minutes protection against a hydrocarbon jet and/or pool fire shall be provided, however, the involved equipment and functions may need longer protection times.

It is assumed that during this period plant operating staff will have been evacuated. Where this is unlikely, increasing the fire resistance to a longer duration shall be considered.

PFP shall preferably be avoided on hydrocarbon (HC) piping, vessels and equipment due to increased risk of corrosion under installation (CUI). A total risk assessment shall be made.

9.2 Insulation calculations

9.2.1 Insulation cases

Insulation calculations were performed in excel to compare the calculations with simulations done by other people. They were based on a jet with the flame temperature of 1100 °C impinging the vessel. The heat load consists of Qrad = radiation and Qinn = conduction.
The calcualtions are based on radiation and conduction equations given in chapter 3; Theory.

It has first been used an excel sheet: excel calculation steel rupture without insulation. After that excel sheet with insulation was used (Appendix 6)

Table 5 Vessel rupture for 5 different cases

Case 1	Steel rupture without insulation (first 19 mm – then 7,14 mm)
Case 2	Steel rupture with thermal insulation in Åsgard
Case 3	Steel rupture with thermal insulation in Statpipe
Case 4	Insulation with personnel protection
Case 5	Passive fire protection

The results from the insulation cases can be found in Appendix 7.

9.2.2 Calculation input / limitations

Convergence:
When doing the calculations it was important to get the solution to converge.
After inserting the parameters the first time and doing the calculation, a problem occured. The solution gave results from the heatloads that were negative. To solve this problem, the «delta t», the time unit, was set to be lower. This made the solution converge.

Thermal conductivity:
The size of the thermal conductivity will affect the result. This will vary with the temperature. Therefor it was made a formula for this, so increased temperature gave increased thermal conductivity.

Thickness layer:
A thickness layer representative for vessels at Kårstø is used in the calculations. Thermal insulation will avoid the thermal conductivity from the vesselcontent. So it will also avoid heat from a fire getting into the vessel wall. Thicker layers will do this job better than thinner layers.

Flame temperature:
In the calculations the flame temperature is set to be 1100 ° C, and this temperature is in direct contact with the vessel wall. Based on (Engineering 2015), flame temperatures in hydrocarbon fires are typically in the area1200 - 1350 °C, substantially above the temperature at which the steel loses its strength. Since 1100 °C (that has been used in the calculations) is slightly below the area 1200 – 1350 °C. It was used different flame temperatures in the calculations to see the difference in the results. It turned out that the highest flame temperature gave the highest temperature in the layers, as expected.

Melting point and erosive effect from jetfires:
The melting and the compression is something that needs to be included. This is something that is difficult to insert into an excel calculation. So it is quite difficult to set a period of time for the melting and the mechanical impact. By knowing the melting point for the insulation it can be assumed when the insulation will loose its ability to prevent heat from entering the steel. To decide the exact moment when this starts to happen, can be challenging, and this might be

something that needs to be seen by a camera in an experiment. So it can roughly be assumed that when the insulation gets to its melting point the thermal conductivity gets even higher. And after this point it just increases. After this there will also be open areas where the melted insulation has run down, and the heat load is directly in contact with the steel in some areas.

The formula that has been inserted into the excel sheet is taking into account the increase of the thermal conduction, but not the fact that it will increase faster after the melting point than before. Melting points for materials are often high; as for cellular glass it is 732 °C. So this phenomen will often happen late in the process. This is also depending on the heat load the material is exposed to. All of the materials used in the calculations have a melting point above 700 °C. Therefor the melting point does not affect the results before after the rupture time has been reached.

When dealing with jet fires, the erosive effect of the flame has to be considered because it can cause significant damage to protective coatings particularly if the coating is not physically intact. This can not be included in the excel sheet formulas.

Liquid between insulation:
A phenomenon that can occur when using cell glass as insulation is liquid that gets in between the insulation and the steel. If this liquid starts boiling from heat loads heating it up to higher temperatures, the cell glass can burst and in this way the insulation looses its ability to prevent heat from entering the steel. This is also an important fact that needs to be considered.

Sintering:
The process occurs at approximately 2/3 of the material melting point.
Sintering is when loose particles in a granular material are bound together as large pieces of contiguous grains. The bonding can be done by melting the grain surface or by growing together by diffusion. Sintering usually takes place under pressure or using heat. This can not be included in the excel sheet formulas.

9.2.3 Comparing the calculations with simulations

Steel rupture without insulation

The first calculation showed a temperature of 646 °C after 7 minutes. (19 mm steel thickness)
Vessfire simulation for the vessel 46-VA-104 has been done by senior engineer Ingvald Bårdsen at Statoil Kårstø. This simulation gave rupture after 8,5 minutes with heat flux of 250 kW/m^2. The calculation agrees with the Vessfire simulation.

The second simulation showed a temperature of 744 °C after 3 minutes. (7,14 mm steel thickness)
To compare this result with the result in Figure 3, it can be seen from the figure that the pipe rupture occurs after 1,5 minutes. The calculation shows that wall rupture happens after ca. 2,5 minutes. This is not far from the result from the Figure 3. The difference in the result might come from the heat load that it is exposed to.

Steel rupture with thermal insulation in Åsgard

The calculation gives a temperature of 689 °C after 16 minutes and 726 °C after 17 minutes.
From the report (Danielsen 2014) this solution has a jet resistance of 15 minutes, according to ISO 22899 – 1 (typical 250 kW/m^2 – test). Comparing this with the 15 minutes from the test this seems very reasonable and only 1-2 minutes more than in the test.

Steel rupture with thermal insulation in Statpipe

In this case thermal insulation in Statpipe process area is calculated. The steel weakens at 729 °C after 18 minutes. Although this configuration is not tested, it is evaluated that it will at least have the same degree or better fire resistance as the one used in Åsgard. This means at least 15 minutes rupture time. Foamglas and mineral wool properties (e.g. thermal conductivity, thermal capacity, melting point, etc.) are almost identical. (Danielsen 2014).

Insulation with personnel protection

The steel loses its strengt (700 °C) after 15 minutes.

Passive fire protection

The steel loses its strenght (700 °C) after 28 minutes.
From the “Main summary” in the report it is given a fire protection solution for at least 30 minutes. (Danielsen 2014)
The calculation agrees well with this.

Steel with no insulation will rupture first in the 7,14 mm steel and then in the 19 mm steel. This can be shown in Figure 20. After that the steel with personnel protection will rupture, which makes sense, since this protection is not intended to protect the steel. But it can be made credit for in a fire. With the thermal insulation in Åsgard, the vessel fails at 15 minutes in a fire scenario. The result shows that passive fire protection is the best protection in a fire compared to the other insulation cases from Table 5.

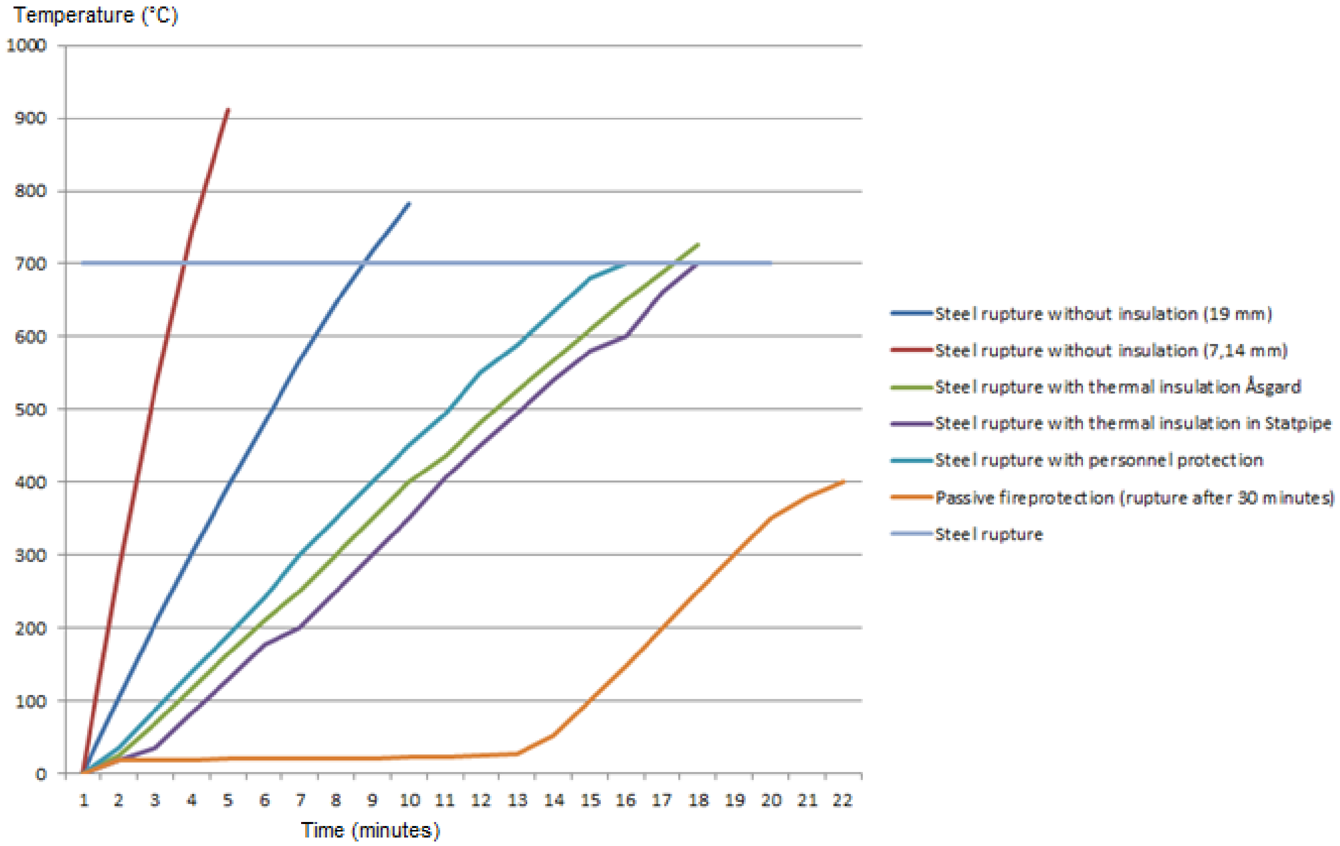


Figure 20 Different temperature increases for different materials

9.3 Discussion

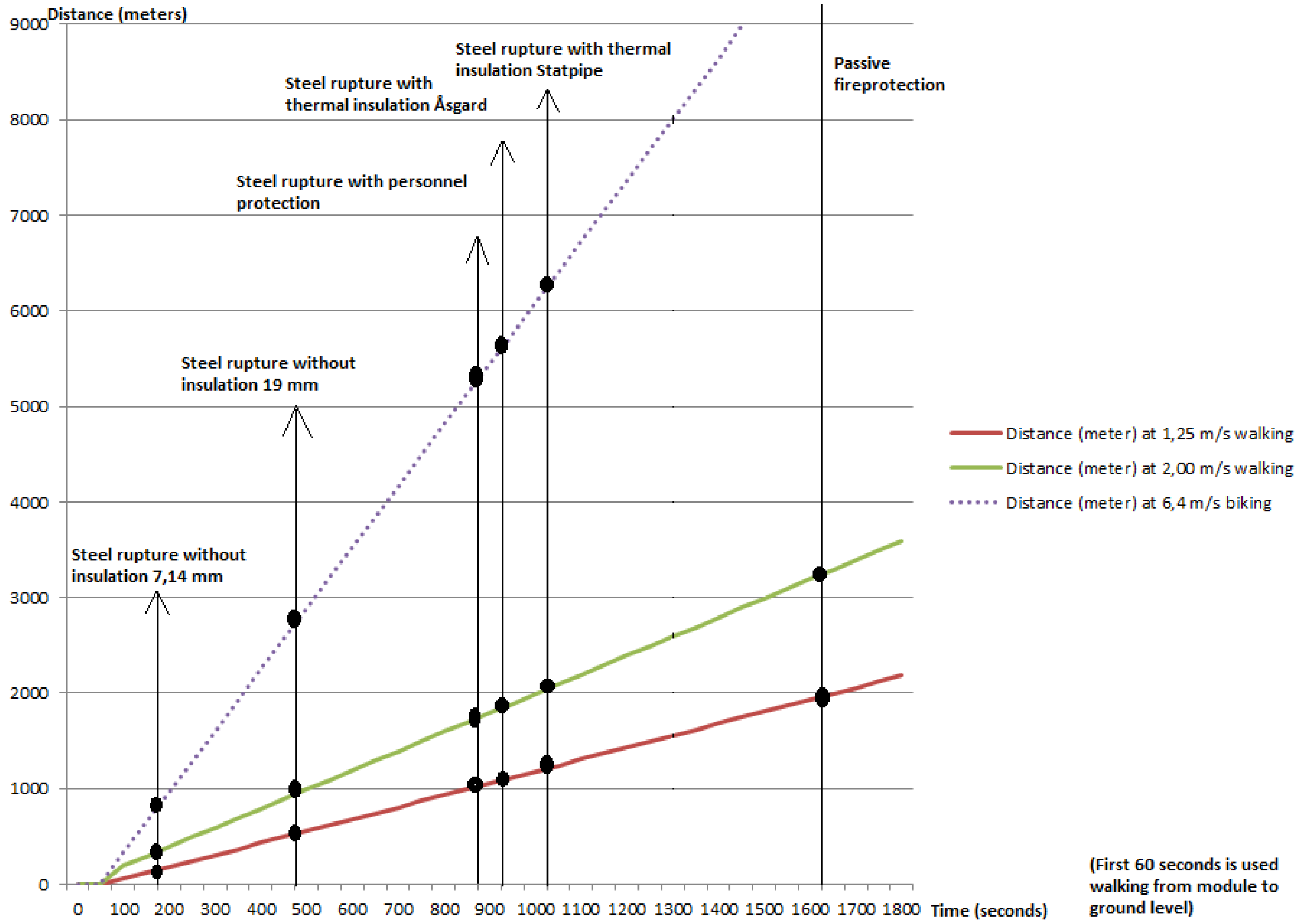


Figure 21 Escape time vs. rupture time in steel vessels

Figure 21 shows that with no insulation rupture happens after 3 and 7 minutes. With insulation the rupture happens from 15 minutes with the personnel protection and 28 minutes with passive fireprotection. Hence the insulation will prolong the time to escalation. The rupture time will give the available evacuation time. The available evacuation time will affect the safety margin that will become greater when the available evacuation time increases. This means the safety margin can cover the time that people spend on changing their mind and going towards another exit than their first choise, and other issues that can prolong the required evacuation time. The insulation will affect the safety margin in a positive direction.

It can be seen from Figure 21 that with the rupture time after 3 minutes, without insulation, the people are 144 m away from the leakage with 1,25 m/s walking speed when the rupture happens. (65 seconds down the processing train and they have walked144 m in 115 seconds). They have passed the first safety zone (50 m) by 94 m. With the walking speed of 2 m/s they have passed the first safety zone by 180 m. (And with bike 686 m).

With the rupture times with insulation people are out of the plant before the rupture happens. The insulation will delay the time to escalation, but will mainly affect economical consequences as the results in Figure 21 shows that people are out of the area with good margin. ALARP on these consequences should be carried out.

(Engineering 2015)
Kårstø gas terminal has extensive use of thermal insulation to prevent heat loss or heat gain and external ice formation. Thus one can argue that the challenges for PFP are not relevant since many pipes are already insulated. However it will be expensive to replace the existing thermal insulation with combined thermal and passive fire protection insulation. When replacing existing insulation it should be evaluated if new type can also be PFP. Space requirements and increased explosion risk should be assessed. Thermal insulation is not designed to withstand a HC-fire of piping and equipment. It may, however, have a positive effect regarding the fire escalation risk (prolong the time to rupture).

9.4 Conclusion

The calculations show that even without insulation the people have reached temporary safe area before vessel rupture time. All of the insulation cases in Chapter 9.2.1 will give credit to the safety margin between available and required evacuation time. Even personnel protection will give a rupture time of 14 minutes.

The negative effects such as corrosion, increased explosion pressure, reduced possibility for inspection, space requirements and increased maintenance must be evaluated. It may also be expensive to implement it, so ALARP needs to be carried out.

Use of passive fire protection increase the effect / importance of the blow down system in a fire scenario, i.e. gives more time available for reduction of the pressure before the temperature in the metal may reach critical temperature related to rupture.

10 Active fireprotection and how it affects evacuation time

10.1 Statoil`s overall requirements – relevant paragraphs regarding active fireprotection

10.1.1 TR2237

(Technology u.d.)
The main purpose of the active fire protection systems is to provide quick and reliable means for fighting fires and preventing/delaying escalation. In addition active fire protection systems may be used to mitigate explosion effects

PS. 9.4.1 Active fire protection strategy
Fire protection principles shall be detailed in the Safety Strategy.

Where the Safety Strategy requires fire water to mitigate explosion effects, the fire water shall be released automatically upon confirmed gas detection. Manual remote release of fire water should be implemented for other situations. Automatic release may be arranged for general active fire protection pruposes where the fire water reservoir and supply capacity is sufficient for such operation. It shall be automatically released where the main purpose of the firewater is to act as a substitute for passive fire protection

The plant shall not be dependent on manual active fire protection where this represents a significant risk to personnel.

The need for a fire brigade, active fire protection vehicles and mobile equipment shall be defined in the safety strategy.

10.1.2 Addendum to TR2237

(Gunnarshaug u.d.)
The active fire protection systems shall provide cooling of piping and equipment in a fire scenario to prevent escalation as well as extinguish small pool fires or fires in utility systems / equipment.

It should be noted that in several "high risk areas" any active fire fighting is dependent on personnel entering the area as there are no or few firewater systems with remote control capabilities installed. In a fire scenario in such areas, an assessment shall be made, and if it is considered safe for personnel to enter the area, firewater may be used to cool down equipment or extinguish pool fires. It should be emphasized that until all segments are pressure relieved, most HC-fires will have a significant escalation risk and normally no manual intervention in the area will be performed in this time period. This means that for most process related fires, no fire water will be available in these areas.

It should be noted that until all segments are pressure relieved, most HC-fires may have a significant escalation risk and normally no manual intervention in the area will be performed in this time period. This means that for most process related fires, no firewater will be available.

(Engineering 2015)
It is assumed that the effect of fire water is reduced with leak size. Since firewater is a consequence reducing safety barrier, one has to evaluate its risk reducing effect relative to the escalation frequency. The escalation frequency is a fraction of the fire frequency.

Table 6 Effect of firewater

Leak category	Risk reducing effect [RRE]	Description	Comments
Small (0,1 – 1 kg/s)	20 % (0,2)	It is assumed that rapid application of firewater will be able to reduce the escalation frequency (EF) by 20 %	Theoretical free field jet fire flame length off approximately 12 m@0,5 kg/s
Medium (1-10 kg/s)	10 % (0,1)	It is assumed that rapid application of firewater will be able to reduce the escalation frequency by 10 %	Theoretical free field jet fire flame length of.approximately 38 m@0,5 kg/s
Major (10-30 kg/s)	2 % (0,02)	It is assumed that rapid application of firewater will be able to reduce the escalation frequency by 2 %	Theoretical free field jet fire flame length of.approximately 66 m@0,5 kg/s
Large (30- >100 kg/s)	0,5 % (0,005)	It is assumed that rapid application of firewater will be able to reduce the escalation frequency by 0,5 %	Theoretical free field jet fire flame length off approximately 93 m@0,5 kg/s

$$\textit{Risk reducing effect} = \left(\frac{\sum_{small}^{large}(EFxRRE)}{\sum_{small}^{large} EF}\right) x\ 100$$

Applying water to the heated pipes may prevent the rapid heating towards rupture. It should, however, be noted that water must be applied very quickly to maximize cooling efficiency. If the metal object is heated to above the Leiderfrost temperature, (Engineering 2015) *the droplets do not wet the surface and the droplets are repelled. (This may be visualized by water droplets on a sufficiently hot traditional cooking plate where the droplet typically start dancing on the surface rather than evaporate quickly.) This critical temperature is around 190 °C for most metals, i.e. the cooling water must be applied quickly to give proper droplet wetting. Especially in a jet fire environment, wih a lot of strong turbulence, the nonwetting water droplets are just bouncing off any surfaces above this temperature.*

Water applied to the fire also cools the flames by its large heat of evaporation and dilutes the oxygen content by a 1700 fold expansion when evaporating at 100 °C. In addition, the water droplets also attenuate heat radiation from the flames. This means that even when pipes are above the Leiderfrost temperature, applying water to the fire may seriously delay any pipe or vessel ruptures and may indeed in some cases also completely prevent escalation.

It is today not recommended to manually combat jet fires due to escalation risk and risk to personnel.

10.2 Discussion

In accordance with (NORSOK S-001 Technical safety 2008) the effect of firewater has not been included in the risk picture assembly. This gives that active fireprotection as a safety barrier should not be given credit for in a risk assessment.

(Engineering 2015)
Thus, rapid application of firewater in the area may prolong time to escalation, and will have a positive effect on the time available for personnel to escape from the fire in the module. In order to achieve rapid application it should be evaluated to implement automatic release of firewater upon confirmed fire detection.
By manual release the firewater will be released 5 minutes later than with automatic release upon confirmed fire detection.

To have the active fireprotection working, factors as correct type of extinguishing system (deluge, sprinkler, foam, manual fire fighting; monitors), size of the leakage, correct droplet size, the water getting to the root of the fire, the application being appropriate and the effect of wind should be taken into consideration. The fire equipment needs to be maintained and fire protection strategy must be thoughtful and good enough at the entire facility.

Extinguishing a jet fire is not easy, because hydrocarbons are constantly beeing poured out and there will be a supply of hydrocarbons. As long as this supply is not stopped by Emergency Shutdown (ESD) and then blow down, hydrocarbons will get to the fire.

It should not compromise with personnel risk - going into the area releasing the fire water.

10.3 Conclusion

Automatic release of the firewater will have an effect on time for escalation.
Based on the exercise and the Simulex simulations it will be assumed that people have reached the first safe zone before the manual release of active fire protection. This will have an effect to avoid further escalation and give credit in relation to financial assets and loss of equipment, more than for the evacuation time. It will also give credit for the emergency team going into the area helping people.

11 Blow down and how it affects evacuation time

11.1 Statoil`s overall requirements – relevant paragraphs regarding blowdown

11.1.1 TR2237

(Technology u.d.)
The purpose of the Emergency Depressurisation system (EDP) is to:

Reduce the pressure and inventory in a process segment in case of a fire exposing the segment in question. A reduction in pressure implies reduced material stress and, hence, reduced risk of rupture due to heating caused by the fire
Reduce the leak rate and leak duration from a leaking process segment (and, hence, also reduce the associated fire in case the leak is ignited)
Avoid spread / escalation of fire between areas / units and during escape / rescue by reducing internal pressures, fire load and duration

The depressurization rates shall be maximized within the available total flare capacity to reduce risk further and minimize the need for passive fire protection.

The consequences of fire rupture (BLEVE, aerosol, size of fire ball), shall be considered when not having EDP.

EDP shall be activated in accordance with the Safety Strategy (manual or automatic). Automatic activation of EDP initiated upon confirmed fire detection as a mean to avoid passive fire protection in a production area shall be avaluated.

EDP initiation shall activate area sectionalisation by closure of ESD valves.

11.1.2 GL3003; Emergency Depressurisation

(D. a. Safety u.d.)
The main objectives of GL3003 are to:

- *achieve a safe and cost efficient design of EDP system,*
- *specify how process equipment and piping is protected against fire exposure while keeping the need for Passive Fire Protection (PFP) at a minimum,*
- *select correct materials with respect to low temperatures resulting from depressurisation*

The need for protection against fire is highly dependant on the plant specific criteria for unacceptable rupture based on location, escape possibilities and fire fighting equipment and strategy.

11.2 Discussion

With a blow down system the depressurization will happen after 5 minutes. The jet fire will be most extensive in the start, but will gradually start to weaken. When activated, the blow down system will reduce the pressure and time to rupture. This means that it is important regarding the escalation risk and the consequences of a fire. The blow down will remove the hydrocarbons in the area.

(Engineering 2015)
It should not be assumed that the blow down system is capable of preventing an ignited leakage to escalate within a process module. This is because time for depressurization is long (15 minutes to halve the operational pressure, 30-45 minutes for total depressurization.) Also the blow down is manually initiated, meaning response time may be a minute or two.
In areas with no blow down (Statpipe T100/T200) control valves towards flare may be used. Time for depressurization for these may however be long (more than 30 minutes), and the response time may be long due to the fact that the operator need to identify the correct valve from P&ID’s etc before it can be opened from the panel faceplate.

11.3 Conclusion

The time to escalation may be very short (about two minutes), meaning that blow down should not be assumed to have any risk reducing effect with respect to available time for personnel to evacuate the area. Ignited leakages may be assumed to escalate internally within the processing train before any effect of depressurization to flare can be expected. Blow down may however have a significant risk reducing effect with respect to not ignited leakages as depressurization will reduce the duration of the leak.

Blow down can contribute in avoiding further escalation / fires or new leakages that will harm the emergency personnel. It takes 5 minutes before blowdown is activated and 15-20 minutes before it gets its maximum effect. In insulation calculations, the pressure has not been considered. But with the blowdown effect it is to be expected even more delay in the rupture time than the calculations gave.

12 Discussion

The safety barriers active and passive fireprotection will prolong time for rupture but for the active firepretection it will be different when activated manually or automatic. Fire water activation may in several cases be a sound risk reducing measure, especially when initiated early, and it may increase the time to rupture significantly. Even when activated early there are limitations for active firewater, such as the water not hitting the vessel, wind affecting the deluge, etc. The manual release will have a 5 minutes delay, and will contribute after people have reached temporarily safe area.

With blow down being released manually, it will operate after 5 minutes. Passive fire protection will proplong the time to rupture. It can not be stated that passive fireprotection can avoid the heat fluxes completely in 5 minutes until EDP is activated, as passive fire protection has its best effect in the beginning and will gradually start to get weaker. But it will contribute in positive direction.
Blow down working after 5 minutes will not contribute in evacuation situation, but will be more important regarding the economical issues. Blow down activated immediately may increase the margins for evacuation, and in some situations eliminate a BLEVE scenario, or make the BLEVE less severe.

Rather than dealing with the safety barriers alone it is important to look at them in combination.
To show where the safety barriers have their effect, the timeline in Figure 22 is shown. It is important to mention that limitations of the barriers are not included, and the figure does not show where in the timeline the effect is best. This has been discussed earlier in the report. It can be seen from this timeline which of them can be compared, when it comes to where in the timeline they are placed, and which comes after another.

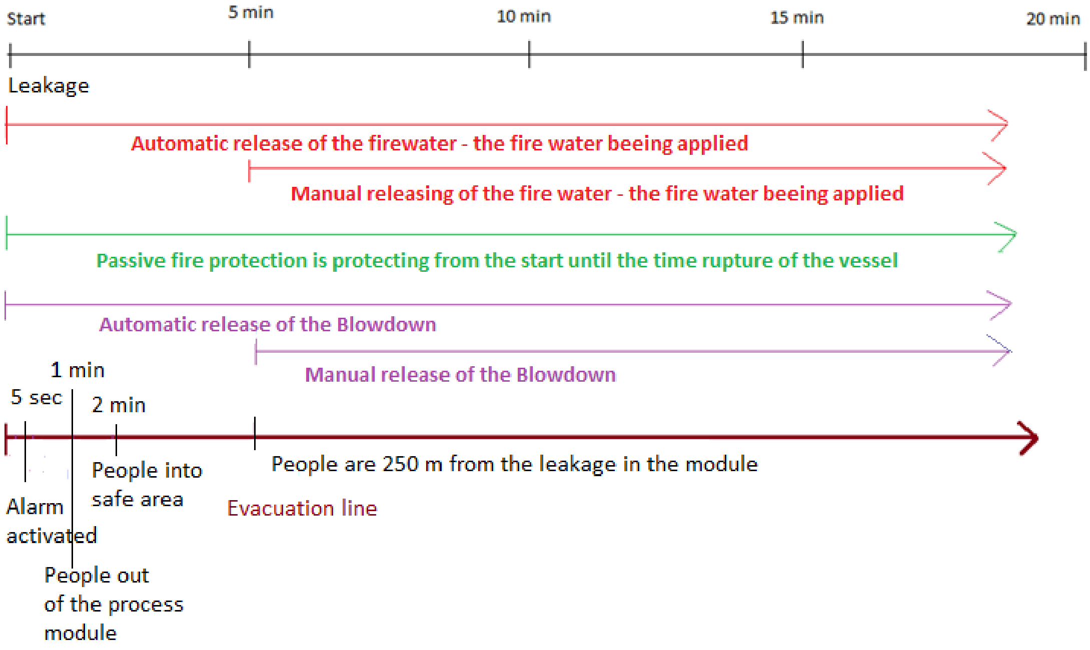


Figure 22 Where in the timeline different safety barriers operate

If the required evacuation time for a reason will take longer than the available there is a need of a safety margin. This margin can be achieved with the safety barriers. The combinations of safety barriers shall be considered and the negative effects shall be taken into consideration.

To achieve safe evacuation, exercise and Simulex simulations have shown that people will be in temporarily safe place within the available evacuation time. Uncertainties in the use of Simulex program when doing the simulations should be mentioned, such as measured evacuation times. It can also be uncertainties in the measured time from the evacuation exercise. When doing the insulation and BLEVE calculations there are uncertainties such as choise of thermal conductivity, melting point and flametemperature. These uncertainties will not affect the results appreciably.

Personal Protection Equipment (PPE) is a necessary barrier to reduce thermal exposure until it is possible to get to a shielded area or the BLEVE fire ball has weakened sufficiently.

In oil industry there has been been focused on major accident risks associated to incidents. The calculations have shown that the consequences for BLEVE in processing vessels can be large. This confirms that focusing on BLEVE in processing areas to a greater extend in the future will be necessary. BLEVE should not be identified only with huge explosions in open areas, but the consequences from even smaller vessels shall be widely understood. It has been shown that the frequency of vessels being involved in BLEVE in the processing area is low.

13 Conclusion

Processing plants, such as Kårstø, are quite complex and different parts have been built at different time periods. An overall safety barrier philosophy evaluation is necessary to evaluate personnel risk.
This thesis shows that personnel can evacuate to temporarily safe locations / safe distances during the defined escalating jet fire scenario. Short duration heat loads identified in the worst case scenarios are considered non-lethal for personnel and is within the acceptance level for heat load exposure. It is, however, of importance that personnel evacuate effectively and immediately after an evacuation alarm. Personal Protection Equipment (PPE) will effectively reduce thermal exposure until it is possible to get to a shielded area or the BLEVE fire ball has weakened sufficiently.

Safety barriers, such as active and passive fire protection, will increase the time to rupture significantly and will thereby increase the margin between required and available evacuation time. Blow down may increase the margin by limiting the fire scenario. The positive effects of active fire protection and blow down are however dependent on early activation. Risk reducing effect from a safety barrier is scenario depend and needs to be evaluated in each case.

14 Further work

Radiation:
As the focus area of the thesis was evacuation it is recommended as further work to have an experiment on the effect of radiation on a human being. For example a fiberglass mannequin can be dressed up with the protective clothing that is beeing used at Kårstø. This model can be exposed to different radiation fluxes, and the temperature in the model can be measured.
(Chapter 7)

Detail the fire scenario in each case for the vessels when finding vessel rupture time:
It will be important to detail the fire scenarios for each vessel. It will be important to look at the flanges, the leakage points, if the heat loads are global or local. This working sheet does not include this, and it will be suggested as further work.
(Chapter 8)

Focus area BLEVE:
The consequences for vessels in the calculations are not as big as for larger vessels. But the calculations have shown that there are consequences from a BLEVE from smaller vessels. This is shown in Appendix 5. It will be important to be aware of them. People are often working in the area where these vessels are placed. It is suggested as further work; focusing on these vessels. It is also suggested as further work focusing on BLEVE in middle of processing train.
(Chapter 8)

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16 Appendixes

16.1 Appendix 1

Simulex simulation cases

Case 1 – 4: Escaping from top level of the module

CASE 1 Number of people: 3 Number of levels: 3 Escaping from: top level Exit placed: Floor 0 Walking speed: 0,8-1,7 m/s *Runs first once with exit and then takes into acount safety zone (50m)*	**CASE 2** Number of people: 3 Number of levels: 3 Escaping from: top level Exit placed: Floor 0 + step ladder Walking speed: 0,8-1,7 m/s *(In relation to the case 1 it is here a stepladder as the second exit in addition to the main exit)*
CASE 3 Number of persons: 7 or 15 (as in a production stop) Number of levels: 3 Escaping from top level Exit placed: Floor 0 Walking speed: 0,8-1,7 m/s *Runs first once with the two exits and then takes into account safety zone (50 m)* *(In relation to the case 2 it is here 7 and 15 persons in addition to 3 persons)*	**CASE 4** Number of persons: 7 or 15 (as in a production stop) Number of levels: 3 Escaping from top level Exit placed: Floor 0 + step ladder Walking speed: 0,8-1,7 m/s *Runs first once with the exit`s and then takes into account the safety zone (50 m) – first with 7 people and then with 15 people* *(In relation to the case 3 there are 2 exit`s instead of 1 as in case 3)*

Case 5 – 8: Escaping from different levels

CASE 5 Number of people: 3 Number of levels: 3 People are spread at all levels Exit placed: Floor 0 Walking speed: 0,8-1,7 m/s	**CASE 6** Number of people: 3 Number of levels: 3 People are spread at all levels Exit placed: Floor 0 + step ladder Walking speed: 0,8-1,7 m/s *Runs first once with exit and then taken into account safety zone (50m)* *(In relation to the case 5 there are two exits instead of one)*
CASE 7 Number of people: 7 and 15 Number of levels: 3 People are spread at all levels Exit placed: Floor 0 Walking speed: 0.8-1.7 m/s *Runs first once with exit and then the safety zone is taken into account (50 m) – first with 7 people; then with 15 people* *(In relation to case 5 the number of people is 7 and 15)*	**CASE 8** Number of people: 7 or 15 Number of levels: 3 People are spread at all levels Exit placed: Floor 0 + step ladder Walking speed: 0.8-1.7 m/s *Runs first once with the two exits and than safety zone is taken into account (50 m)* *(In relation to case 7 there are two exits)* *Then a simulation was runned with an obstruction in the direction of exit – step ladder*

16.2 Appendix 2

Results Simulex simulations

CASE 1:

How people are placed	All 3 persons were places on upper level
Evacuation time	After 25 seconds the first person was out the exit located on the lower level After 30 seconds the second person, and after 38 seconds the last person

They passed the links as follows:

Link 4 – the first link to pass	link that goes from the top of the staircase 1 to toplevel (Floor 2)	5, 15, and 20 seconds
Link 3	link that goes from the bottom of the staircase 1 to mid level (Floor 1)	15, 20 and 30 seconds
Link 2	link that goes from the top of the staircase 0 to mid level (Floor 1)	15, 20 and 30 seconds
Link 1 – the last link to pass	link that goes from the bottom of the staircase 0 to the lower level (Floor 0)	25, 30 and 38 seconds

Then the exit was placed where the safety zone of 50 m ends, so that people were not getting before they were outside this

How people are placed	All 3 persons were places on upper level
Evacuation time	1 minute 18 seconds. The horizontal speed on the ground floor up to the safety zone is 1.25 m/s. (Uses 40 seconds on 50 m)

CASE 2:

How people are placed	All 3 persons were placed spread in all 3 planes (one on each plane)
Evacuation time	As expected the totally evacuation time was less when everyone should evacuate from upper level. It was 10 seconds less: 29 seconds

They passed the links as follows:

Link 4	First link to pass: link that goes from the top of the staircase 1 to peak level(Floor 2)	10 seconds
Link 3	Link that goes from the bottom of the staircase 1 to mid level (Floor 1)	20 seconds
Link 2	Link that goes from the top of the staircase 0 to mid level (Floor 1)	15, 20 seconds
Link 1 – last link to pass	Link that goes from the bottom of the staircase 0 to lower level (Floor 0)	25, 30 seconds

Then the exit was placed where the safety zone of 50 m ends, so people were not outside before they were outside this

How people are placed	All 3 persons were placed spread in all 3 planes (one on each plane)
Evacuation time	All persons reached exit that was located outside the safety zone after 1:22. (50, 70 and 85 seconds)

CASE 3:

How peole are placed	All three individuals were placed spread on the upper level
Evacuation time	0:32
Number of people through Exit 1	After 35 seconds: 2 people
Number of people through Exit 2	After 30 seconds: 1 person (Stepladder)

They passed the links as follows:

Link 6- First link to pass	link from the top of the ladder (Staircase 2) to top level (Floor 2)	10 seconds (1 person)
Link 5	link that goes from the bottom of the ladder to the lower level (Floor 0)	After 30 seconds; 1 person
Link 4	link that goes from the top of the staircase 1 to Floor 2	After 10 seconds; 2 persons
Link 3	link that goes from the bottom of the staircase 1 to Floor 1	After 20 seconds; 2 persons
Link 2	link that goes from stair 0 to Floor 1:	After 20 seconds; 2 persons

Link 1 – Last link to pass	link that goes from stair 0 to Floor 0	After 30 seconds; 2 persons

CASE 4:

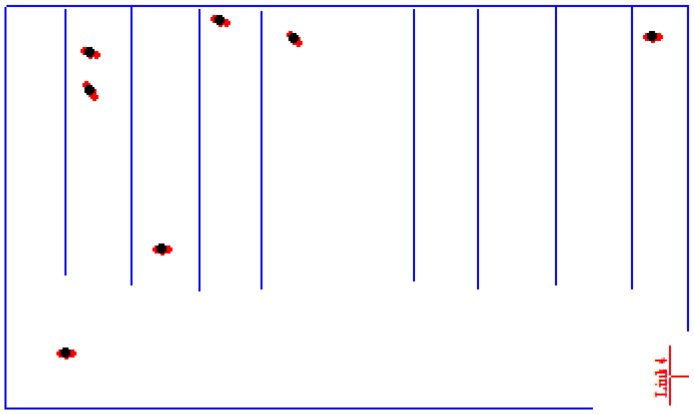
How people are placed	All three persons were placed spread at all levels
Evacuation time	0:33.7
Number of persons through Exit 1	After 20 seconds; 1 person
Number of persons through Exit 2	After 10 seconds; 1 person, after 35 seconds; 1 person

They passed the links as follows;

Link 6	the first link to pass; link from the top of the ladder (Staircase 2) to toplevel (Floor 2)	After 10 seconds; 1 person
Link 5	link that goes from the bottom of the ladder to the lower level (Floor 0)	After 35 seconds; 1 person
Link 4	link that goes from the top of the staircase 1 to Floor 2	Noone
Link 3	link that goes from the bottom of the staircase 1 to Floor 1	Noone
Link 2	link that goes from staircase 0 to Floor 1	After 10 seconds; 1 person
Link 1	Last link to pass: link that goes from staircase 0 to Floor 0	After 20 seconds; 1 person (a person on the lower plane does not pass any links)

CASE 5

How people are placed	7 persons, as expected at a larger operations was placed spred at upper level
Evacuation time	37 seconds



Then the ble exit was placed where the safety zone ends at 50 m, so that people were not out before they were outside this zone

At 7 people the times are as follows:

How people are placed	7 persons, as expected at a larger operatrion was placed spread at upper level
Evacuation time	1:35 (1 person after 65 seconds, 2 personer after 80 seconds, 2 persons after 85 seconds, 2 persons after 95 seconds)

At 15 people the times are as follows:

How people are placed	15 persons were placed spread at upper level
Evacuation time	1:40 (1 person after 75 seconds, 4 persons after 80 seconds, 3 persons after 95 seconds, 7 persons after 100 seconds)

CASE 6

How people are placed	7 persons were spread on all 3 levels (2-3 persons on each level)
Evacuation time	40 seconds

They passed the links as follows:

Link 4	link that goes from the top of the staircase 1 to Floor 2	5, 10,15 seconds (2)
Link 3	link that goes from the bottom of the staircase 1 to Floor 1	20 seconds (2), 25 seconds (2)
Link 2	link that goes from the top of the staircase 0 to mid level	15 seconds, 20 seconds (3), 25 seconds, 30 seconds (2)
Link 1 – last link to pass	link that goes from the bottom of the staircase 0 to Floor 0	30 seconds (2), 35 seconds (3), 40 seconds (2), a person at the bottom plane does not pass through any links

Then the exit was placed at the safety zone at 50 m, so the people were out when they had reached this exit
At 7 people the evacuation times were as follows:

How people were placed	7 persons spread on all 3 planes (2-3 persons at each level)
Evacuation time	1:30.6 (2 persons; 75 seconds, 2 pers; 85 seconds, 2 pers; 90 seconds, 1 pers; 95 seconds)

Then the exit was placed at the safety zone at 50 m, so the people were out when they had reached this exit
At 15 persons the evacuation times were as follows:

How people were placed	15 spread on all 3 planes (2-3 persons at each level)
Evacuation time	1:45 (2 persons; 50 seconds, 3 pers; 65 seconds, 3 pers; 75 seconds, 2 pers; 80 seconds, 3 pers; 90 seconds, 2 pers; 105 seconds)

CASE 7

How people are placed	7 persons were spread on all 3 levels (2-3 people at each level)
Evacuation time	40 seconds
Number of people over exit 1	2 persons after 35 seconds, 2 persons after 40 seconds, 1 person after 45 seconds
Number of people over exit 2	1 person after 30 seconds, 1 person after 40 seconds

They passed the links as follows:

Link 6	First link to pass. Link from the top of the ladder (staircase 2) to the top level (floor 2):	1 person after 10 seconds, 1 person after 15 seconds
Link 5	Link that goes from bottom of the ladder to the lower level (floor 0)	1 person after 30 seconds, 1 person after 35 seconds
Link 4	Link that goes from the top of the staircase 1 to floor 2	1 person after 5 seconds, 2 persons after 10 seconds, 2 persons after 15 seconds
Link 3	Link that goes from the bottom of the staircase 1 to floor 1	1 person after 15 seconds, 1 etter 20 seconds, 3 etter 25 seconds
Link 2	Link that goes from Staircase 0 to floor 1	1 person after 20 seconds, 3 after 25 seconds, 1 after 30 seconds
Link 1	Link that goes from staircase 0 to floor 0	1 person after 30 seconds, 2 after 35 seconds, 2 after 40 seconds

Then one of the exit`s was placed at the safety zone 50 m, so the people were not out before they reached this

With 7 people the evacuation time was as follows:

How people were placed	7 people were spread on all 3 planes (2-3 people at each plane)
Evacuation time	0:47 All people selected stepladder. This is natural as the exit in the safe zone is placed too far away relative to the other one, and naturally they choose the exit that is located closest

With 25 people the evacuation time was as follows:

How people were placed	15 persons were placed spread on all 3 levels
Evacuation time	1:44.7
Number of people over exit 1	1 person etter 30 sek, 2 personer etter 35 sek, 2 personer etter 40 sek og 6 personer etter 45 sek
Number of people over exit 2	1 person after 35 seconds, 3 persons after 40 seconds

They passed the links as follows:

Link 6	the first link to pass; link from the top of the ladder (staircase 2) to the top level	1 person after 10 seconds, 1 person after 15 seconds
Link 5	link that goes from the bottom of the ladder to the lower level (floor 0)	1 person after 30 seconds, 1 person after 35 seconds
Link 4	link that goes from the top of the staircase 1 to floor 2	1 person after 5 seconds, 5 persons after 10 seconds, 5 persons after 15 seconds
Link 3	link that goes from the bottom of the staircase 1 to floor 1	1 person after 15 seconds, 6 after 20 seconds, 4 after 25 seconds
Link 2	link that goes from staircase 0 to floor 1	1 after 20 seconds, 6 after 25 seconds, 3 after 30 seconds, 1 after 35 seconds
Link 1	link that goes from staircase 0 to floor 0	1 after 30 seconds, 4 after 35 seconds, 2 after 40 seconds og 4 after 45 seconds

CASE 8

How people are placed	7 persons were spread on all 3 planes (2-3 persons at each level)
Evacuation time	0:38
Number of people over exit 1	1 person after 10 seconds, 1 person after 20 seconds, 2 persons after 25 seconds og 1 person etter 40 seconds
Number of people over exit 2	1 person after 15 seconds, 1 person after 35 seconds

They passed the links as folloes:

Link 6	the first link to pass; link from the top of the ladder (staircase 2) to top level (floor 2)	1 person after 10 seconds
Link 5	link that goes from the bottom of the ladder to the lower level (floor 0)	1 person after 35 seconds
Link 4	link that goes from the top of the staircase 1 to floor 2	1 person after 15 seconds
Link 3	link that goes from the bottom of the staircase 1 to floor 1	1 person after 25 seconds
Link 2	link that goes from staircase 0 to floor 1	2 persons after 10 seconds, 1 after 15 seconds, 1 after 25 seconds
Link 1	link that goes from staircase 0 to floor 0	1 after 20 seconds, 2 after 25 seconds og 1 after 40 seconds

How people are placed	15 persons were spread on all 3 planes
Evacuation time	0:38
Number of people over exit 1	2 pers after 10 seconds, 1 after 15 seconds, 1 after 20 seconds, 3 after 25 seconds, 4 after 30 seconds, 1 after 35 seconds, 2 after 40 seconds
Number of people over exit 2	1 person after 30 seconds

They passed the links as follows:

Link 6	the first link to pass; link from the top of the ladder (staircase 2) to the top level (floor 2)	1 person after 10 seconds
Link 5	link that goes from the bottom of the ladder to the lower level (floor 0)	1 person after 30 seconds
Link 4	link that goes from the top of the staircase 1 to floor 2	2 persons after 5 seconds, 2 after 10 seconds, 1 after 15 seconds
Link 3	link that goes from the bottom of the staircase 1 to floor 1	2 after 15 seconds, 2 after 20 seconds, 1 after 25 seconds

Link 2	link that goes from staircase 0 to floor 1	1 after 5 seconds, 3 after 10 seconds, 3 after 15 seconds, 2 after 20 seconds, 2 after 25 seconds
Link 1	link that goes from staircase 0 to floor 0	2 after 20 seconds, 3 after 25 seconds, 3 after 30 seconds, 1 after 35 seconds, 2 after 40 seconds

Then, one of the exit`s was placed at the safety zone on 50 m, so that people were not out before they passed this

With 7 people the evacuation times were as follows:

How people are placed	7 people spread on all 3 levels (2-3 persons at each level)
Evacuation time	0:44.3 seconds
Number of people over exit 1	1 after 10 seconds, 1 after 25 seconds
Number of people over exit 2	1 after 15 seconds, 1 after 20 seconds, 1 after 35 seconds, 2 after 45 seconds

With 15 people evacuation times were as follows:

How people are placed	15 persons were spread on all 3 planes
Evacuation time	0:45.5
Number of people over exit 1	1 person after 10 seconds, 1 after 15 seconds, 1 after 25 seconds (3 persons evacuate towards the safetyzone)
Number of people over exit 2	1 person after 10 seconds, 1 after 15 seconds, 1 after 25 seconds, 3 after 35 seconds, 4 after 40 seconds, 1 after 45 seconds, 1 after 50 seconds

Then a simulation was done with obstruction in the direction exit – stepladder

How people were placed	15 persons were spread on all 3 levels
Evacuation time	0:53.5
	The person chooses the exit closest to him/her, despite the fact that the person in this direction as to pass an obstruction

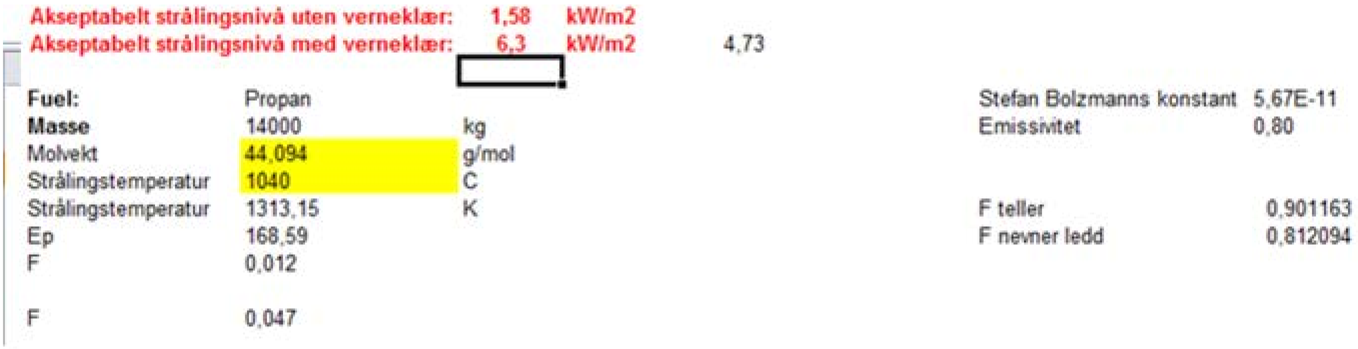
16.3 Appendix 3

Time to vessel rupture – overview

Tag number	Name of the vessel	Time to rupture / 350 kW/m^2
24-VA-102	Depropaniser Reflux Drum	2-6 min / 2,3 min
24-VA-103	Debutaniser Reflux Drum	1-3,3 min / 1, 3 min
24-VA-105	Butane Splitter Reflux Drum	2 – 4, 7 min / 2,5 min
24-VA-205	Butane Splitter Reflux Drum	2 – 4, 7 min / 2,5 min
25-VA-104	Propane Refrigerant	Not ok
24-VA-101	Ethane Reflux Drum	8 – 20 min / 8 min
20-VD-102	Regenerator gas KO drum	2 – 4, 7 min / 6 min
21-VA-102	Demethaniser feed separator	2 – 4,7 min / 6 min
21-VE-103	Demethaniser	2 - 4,7 min / 11 min
24-VA-101	Deethaniser drum	2 – 4, 7 min / 4 min
24-VE-110	Buthane splitter	2 – 4, 7 min / 4 min
25-VA-102	M.P Propane Drum	2 – 4, 7 min / 3 min
25-VA-103	H.P Propane Drum	? ok
25-VA-013	Propane accumulator	2 – 4, 7 min / 8 min
24-VE-403	Butane splitter	2 – 4, 7 min / 3 min
24-VE-401	Depropaniser	2 – 4, 7 min / 4 min

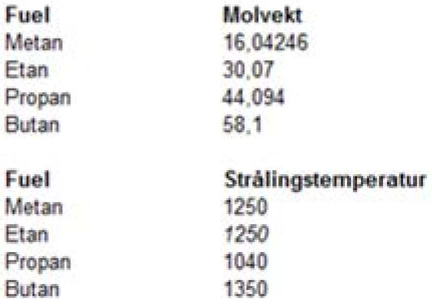
16.4 Appendix 4

View from Excel sheet calculation BLEVE



Akseptabelt strålingsnivå uten verneklær: 1,58 kW/m2
Akseptabelt strålingsnivå med verneklær: 6,3 kW/m2 4,73

Fuel:	Propan		Stefan Bolzmanns konstant	5,67E-11
Masse	14000	kg	Emissivitet	0,80
Molvekt	44,094	g/mol		
Strålingstemperatur	1040	C		
Strålingstemperatur	1313,15	K	F teller	0,901163
Ep	168,59		F nevner ledd	0,812094
F	0,012			
F	0,047			



Fuel	**Molvekt**
Metan	16,04246
Etan	30,07
Propan	44,094
Butan	58,1

Fuel	**Strålingstemperatur**
Metan	1250
Etan	1250
Propan	1040
Butan	1350

16.5 Appendix 5

BLEVE calculation results

Tag of vessel	Liquid/gas	Effective height fireball	Fireball duration	Effective diameter fireball	Maximum diameter Fireball	Amount of liquid	Safe distance in limited stay with protective clothing (Acceptable radiation level: 4,73 / 6,3 kW/m2) / without protective clothing (1,58 kW/m2)
24-VA-102	Propane	22 m	2, 2 sec	24,6 m	45, 2 m	359 kg	97 m / 77 m / 225 m
24-VA-103	Butane	44 m	4,4 sec	49 m	98 m	3669 kg	368 m / 295 m / 843 m
24-VA-105	Butane	42 m	4,2 sec	46 m	93 m	3136 kg	350 m / 280 m / 800 m
24-VA-205	Butane	52 m	5,2 sec	58 m	116 m	6136 kg	437 m / 351 m / 1000 m
25-VA-104	Propane	85 m	8,5 sec	94 m	173 m	20001 kg	293 m / 370 m / 858 m
24-VA-101	Etane	71 m	7 sec	79 m	128 m	8165 kg	395 m / 493 m / 1132 m
20-VD-102	*Propane*	15,4 m	1,5 sec	17 m	31 m	120 kg	53 m / 67 m / 166 m
21-VA-102	*Propane*	30 m	3 sec	34 m	62 m	930 kg	106 m / 133 m / 308 m
21-VE-103	Metane	61,4 m	6,1 sec	68 m	90 m	2778 kg	340 m / 424 m / 974 m
24-VA-101	Etane	71 m	7 sec	79 m	128 m	8165 kg	395 m / 493 m /1131 m
24-VE-110	Butane	50 m	5 sec	56 m	112 m	5500 kg	323 m / 421 m / 965 m

25-VA-102	Propane	100 m	10 sec	111 m	204 m	32853 kg	346 m / 436 m / 1012 m
25-VA-103	Propane	80 m	8 sek	90 m	164 m	17196 kg	280 m / 351 m / 816 m
25-VA-013	Propane	69 m	7 sek	76 m	140 m	10664 kg	238 m / 299 m / 696 m
24-VE-403	Butane	36 m	3, 6 sek	40 m	80 m	1990 kg	241 m / 300 m / 687 m
24-VE-401	Propane	63 m	6,3 sek	70 m	128 m	8200 kg	218 m / 274 m / 637 m

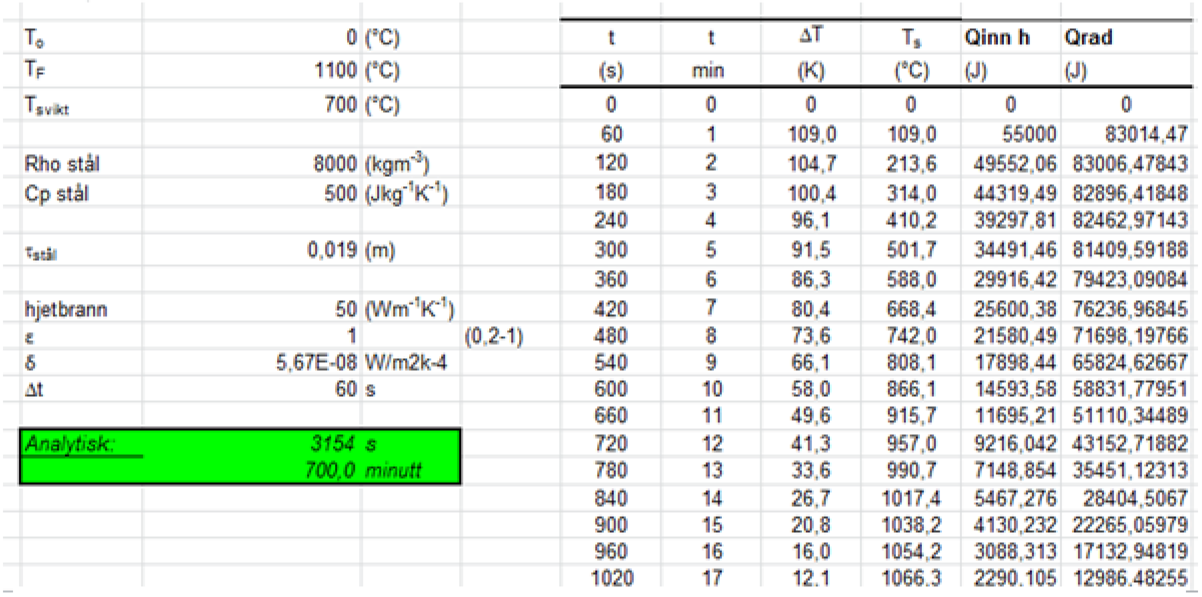
Safe distance in limited stay with protective clothing

Tag of vessel	**Liquid/ gas**	**Effective height fireball**	**Fireball duration**	**Effective diameter fireball**	**Maximum diameter Fireball**	**Amount of liquid after 80 % flash off**	**Safe distance in limited stay with protective clothing** **(Acceptable radiation level: 4,73 / 6,3 kW/m2) /** **without protective clothing (1,58 kW/m2)**
24-VA-102	Propan	20, 6 m	2, 1 sek	22,8 m	42 m	(359*80)/100= 287 kg	90 m / 71 m / 208 m
24-VA-103	Butan	40,7 m	4,1 sek	45, 2 m	91,1 m	(3669*80)/100= 2935 kg	341 m / 274 m / 782 m
24-VA-105	Butan	38,6 m	3,9 sek	43 m	86,4 m	(3136*80)/100= 2508 kg	324 m / 260 m / 742 m
24-VA-205	Butan	48, 3 m	4,8 sek	54 m	108 m	(6136*80)/100= 4908 kg	405 m / 326 m / 929 m

Safe distance in limited stay with protective clothing with 80 % flash off the liquid

16.6 Appendix 6

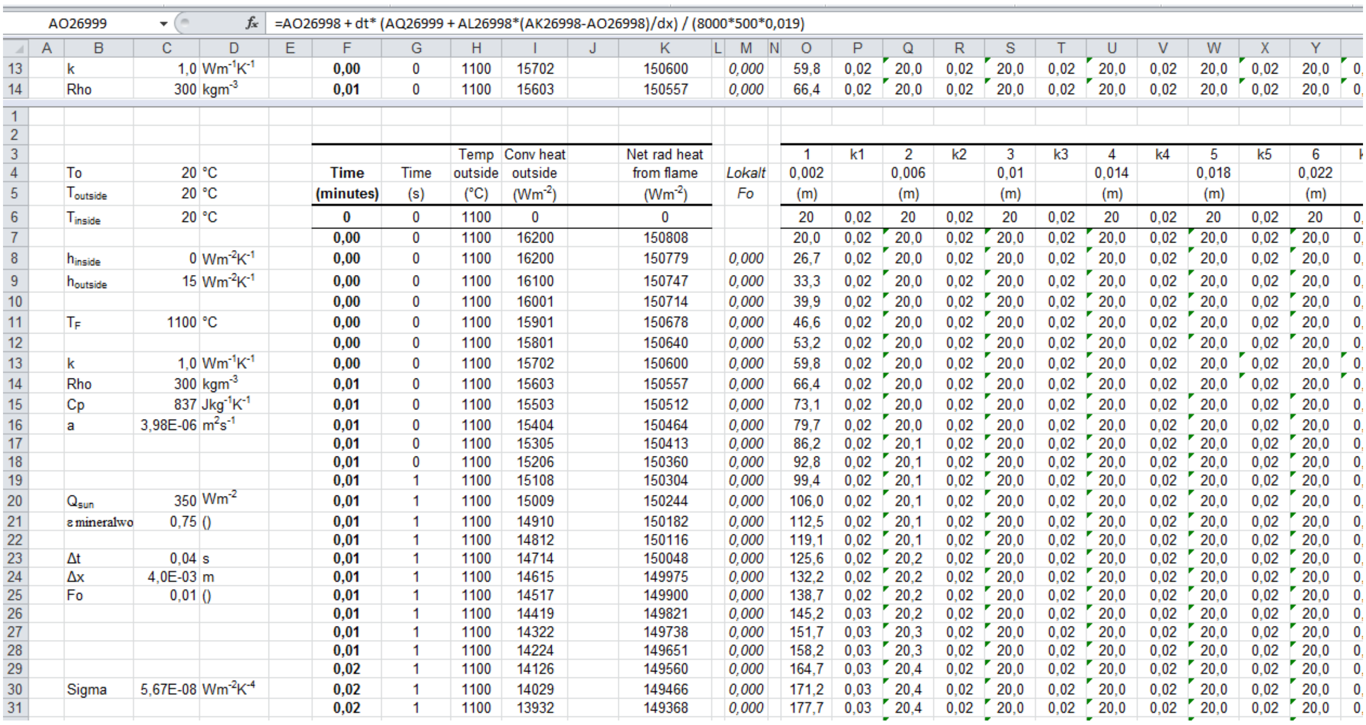
Snapshot from Excel sheet calculation – vessel rupture time without insulation



T_o	0	(°C)	
T_F	1100	(°C)	
T_{svikt}	700	(°C)	
Rho stål	8000	(kgm^{-3})	
Cp stål	500	($Jkg^{-1}K^{-1}$)	
$\tau_{stål}$	0,019	(m)	
hjetbrann	50	($Wm^{-1}K^{-1}$)	
ε	1		(0,2-1)
δ	5,67E-08	W/m2k-4	
Δt	60	s	
Analytisk:	*3154*	*s*	
	700,0	*minutt*	

t	t	ΔT	T_s	Qinn h	Qrad
(s)	min	(K)	(°C)	(J)	(J)
0	0	0	0	0	0
60	1	109,0	109,0	55000	83014,47
120	2	104,7	213,6	49552,06	83006,47843
180	3	100,4	314,0	44319,49	82896,41848
240	4	96,1	410,2	39297,81	82462,97143
300	5	91,5	501,7	34491,46	81409,59188
360	6	86,3	588,0	29916,42	79423,09084
420	7	80,4	668,4	25600,38	76236,96845
480	8	73,6	742,0	21580,49	71698,19766
540	9	66,1	808,1	17898,44	65824,62667
600	10	58,0	866,1	14593,58	58831,77951
660	11	49,6	915,7	11695,21	51110,34489
720	12	41,3	957,0	9216,042	43152,71882
780	13	33,6	990,7	7148,854	35451,12313
840	14	26,7	1017,4	5467,276	28404,5067
900	15	20,8	1038,2	4130,232	22265,05979
960	16	16,0	1054,2	3088,313	17132,94819
1020	17	12,1	1066,3	2290,105	12986,48255

Snapshot from Excel sheet calculation – vessel rupture time with insulation



AO26999

=AO26998 + dt* (AQ26999 + AL26998*(AK26998-AO26998)/dx) / (8000*500*0,019)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	
13		k	1,0	$Wm^{-1}K^{-1}$		**0,00**	0	1100	15702		150600		*0,000*		59,8	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
14		Rho	300	kgm^{-3}		**0,01**	0	1100	15603		150557		*0,000*		66,4	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
1																										
2																										
3								Temp	Conv heat		Net rad heat				1	k1	2	k2	3	k3	4	k4	5	k5	6	k
4		To	20	°C		**Time**	Time	outside	outside		from flame		*Lokalt*		0,002		0,006		0,01		0,014		0,018		0,022	
5		$T_{outside}$	20	°C		**(minutes)**	(s)	(°C)	(Wm^{-2})		(Wm^{-2})		*Fo*		(m)		(m)		(m)		(m)		(m)		(m)	
6		T_{inside}	20	°C		**0**	0	1100	0		0				20	0,02	20	0,02	20	0,02	20	0,02	20	0,02	20	0,
7						**0,00**	0	1100	16200		150808				20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
8		h_{inside}	0	$Wm^{-2}K^{-1}$		**0,00**	0	1100	16200		150779		*0,000*		26,7	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
9		$h_{outside}$	15	$Wm^{-2}K^{-1}$		**0,00**	0	1100	16100		150747		*0,000*		33,3	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
10						**0,00**	0	1100	16001		150714		*0,000*		39,9	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
11		T_F	1100	°C		**0,00**	0	1100	15901		150678		*0,000*		46,6	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
12						**0,00**	0	1100	15801		150640		*0,000*		53,2	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
13		k	1,0	$Wm^{-1}K^{-1}$		**0,00**	0	1100	15702		150600		*0,000*		59,8	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
14		Rho	300	kgm^{-3}		**0,01**	0	1100	15603		150557		*0,000*		66,4	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
15		Cp	837	$Jkg^{-1}K^{-1}$		**0,01**	0	1100	15503		150512		*0,000*		73,1	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
16		a	3,98E-06	m^2s^{-1}		**0,01**	0	1100	15404		150464		*0,000*		79,7	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
17						**0,01**	0	1100	15305		150413		*0,000*		86,2	0,02	20,1	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
18						**0,01**	0	1100	15206		150360		*0,000*		92,8	0,02	20,1	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
19						**0,01**	1	1100	15108		150304		*0,000*		99,4	0,02	20,1	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
20		Q_{sun}	350	Wm^{-2}		**0,01**	1	1100	15009		150244		*0,000*		106,0	0,02	20,1	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
21		ε mineralwo	0,75	()		**0,01**	1	1100	14910		150182		*0,000*		112,5	0,02	20,1	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
22						**0,01**	1	1100	14812		150116		*0,000*		119,1	0,02	20,1	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
23		Δt	0,04	s		**0,01**	1	1100	14714		150048		*0,000*		125,6	0,02	20,2	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
24		Δx	4,0E-03	m		**0,01**	1	1100	14615		149975		*0,000*		132,2	0,02	20,2	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
25		Fo	0,01	()		**0,01**	1	1100	14517		149900		*0,000*		138,7	0,02	20,2	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
26						**0,01**	1	1100	14419		149821		*0,000*		145,2	0,03	20,2	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
27						**0,01**	1	1100	14322		149738		*0,000*		151,7	0,03	20,3	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
28						**0,01**	1	1100	14224		149651		*0,000*		158,2	0,03	20,3	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
29						**0,02**	1	1100	14126		149560		*0,000*		164,7	0,03	20,4	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
30		Sigma	5,67E-08	$Wm^{-2}K^{-4}$		**0,02**	1	1100	14029		149466		*0,000*		171,2	0,03	20,4	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,
31						**0,02**	1	1100	13932		149368		*0,000*		177,7	0,03	20,4	0,02	20,0	0,02	20,0	0,02	20,0	0,02	20,0	0,

16.7 Appendix 7

Insulation calculations

Steel rupture without insulation (19 mm)

Time, minutes	Temperature, steel	Qinn, conduction	Qrad, radiation
0	0	0	0
1	105 °C	55000 J	78000 J
2	206 °C	49700 J	78027 J
3	303 °C	44700 J	77900 J
4	395 °C	39863 J	77600 J
5	483 °C	35300 J	76730 J
6	568 °C	30800 J	75100 J
7	646 °C	26600 J	72500 J
8	718 °C	22700 J	68800 J
9	783 °C	19102 J	63880 J

Steel rupture without insulation (7,14 mm)

Time, minutes	Temperature, steel	Qinn, conduction	Qrad, radiation
0	0	0	0
1	280 °C	55000 J	78000 J
2	529 °C	41026 J	77708 J
3	744 °C	28553 J	73862 J
4	911 °C	17795 J	61695 J

Steel rupture with thermal insulation in Åsgard

19 mm steel tank wall
50 mm cellular glass
0,5 mm SS316 cladding – will contribute quite substantially in expanding the pipe integrity time period in a fire

Cellular glass	
Density, ρ	300 kg/m^3
Heat capacity, C_p	880 J/kgK
Emsissivity, ε	0,80
Thermal conductivity	$0{,}08 + (T_s/500)^{\wedge 4}$

SS316 cladding is as stainless steel	
Density, ρ	7833 kg/m^3
Heat capacity, C_p	461 J/kgK
Emsissivity, ε	0,9

Time (min)	**Temperature, first insulation layer (0,002 m)**	**Temperature Steel layer**
1	947 °C	25 °C
2	956 °C	70 °C
3	957 °C	117 °C
4	957 °C	164 °C
5	958 °C	210 °C
10	964 °C	437 °C
11	966 °C	482 °C
12	968 °C	525 °C
13	971 °C	567 °C
14	974 °C	609 °C
15	978 °C	650 °C
16	982 °C	689 °C
17	987 °C	726 °C

Steel rupture with thermal insulation in Statpipe

19 mm steel tank wall
50 mm mineral wool
Spacers

Mineral wool	
Density, ρ	300 kg/m^3
Heat capacity, C_p	837 J/kgK
Emsissivity, ε	0,75
Thermal conductivity	0,02+(Ts/500)^4

Time (min)	Temperature, first insulation layer	Temperature Steel layer
1	885 °C	20 °C
2	939 °C	36,3 °C
3	943 °C	83 °C
4	944 °C	130 °C
5	945 °C	177°C
10	950 °C	406 °C
12	954 °C	495 °C
14	960 °C	580 °C
16	968 °C	661 °C

17	990 °C	700°C
18	1008 °C	729 °C

Insulation with personnel protection - Oseberg Feltsenter, (TN13-sluttrapport)

Silika (calcium silicate) – Thermo – 12 Gold (0,05 m)
SS 316 Mantling

Calcium silicate – Thermo	
Density, ρ	300 kg/m^3
Heat capacity, C_p	400 J/kgK
Emsissivity, ε	0,92
Thermal conductivity	0,05-0,123 W/mK

Time (min)	**Temperature, first insulation layer**	**Temperature Steel layer**
1	960 °C	35 °C
2	961 °C	87 °C
3	962 °C	139 °C
4	963 °C	191 °C
5	963 °C	243 °C
10	971 °C	494°C
12	977 °C	589 °C
12,24	978 °C	600 °C
13	980 °C	634 °C
14,49	988 °C	**700 °C**

Passive fire protection

40 mm celleglass
25 mm AES fiber
SS316 mantling

Cellular glass	
Density, ρ	300 kg/m^3
Heat capacity, C_p	880 J/kgK
Emsissivity, ε	0,80
Thermal conductivity	$0{,}08 + (T_s/500)^{\wedge 4}$

AES fiber – high temperature glass wool	
Density, ρ	400 kg/m^3
Heat capacity, C_p	1130 J/kgK
Emsissivity, ε	0,75
Thermal conductivity	0.05 – 0.48 W/mK

Products made from AES are generally used at application temperatures less than 900 °C and in continuously operating equipment and domestic appliances.

Time (min)	**Temperature, first insulation layer (Cellular glass)**	**Temperature, second insulation layer (AES Fiber)**	**Temperature (Steel layer)**
1	1085 °C	20°C	20 °C
2	1090 °C	22,4 °C	20 °C
3	1092 °C	32,3 °C	20 °C
4	1093 °C	50 °C	20,1 °C
5	1093 °C	71 °C	20,3 °C
10	1095 °C	168 °C	23,3 °C
12	1081 °C	454 °C	27,9 °C
13	972 °C	690 °C	51,8 °C
14	974 °C	700 °C	100 °C
15	975 °C	707 °C	148 °C
20	983 °C	755 °C	379 °C
23	990 °C	792 °C	509 °C
25,22	997 °C	823°C	600 °C
27,85	1007 °C	863 °C	700 °C