RISK ANALYSIS FOR E-FUEL PLANT AT HERØYA INDUSTRIAL PARK

NORDIC ELECTROFUEL AS

110.023_R1-B01

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Client	**Project No.**	**Document No.**	
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SUMMARY

In this report a Quantitative Risk Assessment (QRA) for the Nordic Electrofuel (NEF) E-Fuel facilities at Herøya Industrial Park (HIP) has been performed in accordance with “Direktoratet for Samfunnssikkerhet og Beredskab” DSB guidance for QRAs.

The amount of hazardous substance stored at the E-Fuel plant is limited and the plant does therefore not fall under the term “Storulykkeanlegg” as described by the DSB regulations. However, as the E-Fuel plant is located next to a number of “Storulykkeanlegg”, a QRA has been performed and domino effects between E-Fuel plant and the “Storulykkeanlegg” Yara, Air Liquide Skagerak and PVC plant and vice versa have been investigated.

The risk has been quantified as ISO-risk contours that describes the probability for a person to become a fatality in case the person is located permanently (24/7 – year-round) inside the ISO-risk contour.

The QRA results shows that the E-Fuel plant project will **NOT** impact the existing HIP ISO-risk contours, and will therefore not have any impact on 3rd parties outside HIP. This is a very strong conclusion, that is very robust to future changes, as potential consequences from E-Fuels plant will not have a reach where they can harm 3rd party.

In addition, it has been shown that it is not credible that accidents on the E-Fuel plant can impact neighbouring “Storulykkeanlegg” critically, causing a major escalation by domino effects. Furthermore is it not credible that E-Fuel plant can impact electrical substations in Building 95 and 162 and cause a power outage.

Domino effects from neighbouring “Storulykkeanlegg” can in no way impact the E-Fuel plant in a way where risk to 3rd party is increased. This is a very strong conclusion as no scenarios on the E-Fuel plant has been identified that could potentially expose 3rd parties. Domino effects from neighbours can in worst case cause local escalation at the E-Fuel plant, but this is not considered critical compared to the consequences of the initiating accident.

The risk of the Eramet discharge pipeline have been investigated in detail since the pipeline will be routed through large parts of the HIP. The E-Fuel project has therefore implemented a strict risk acceptance criterion of 10^{-6} per year, calculated the same way as for 3rd party, despite that 3rd party will not be exposed to the pipeline. The risk is found to be well within the risk acceptance criteria.

The main safety concern of the E-Fuel project is that the risk of toxic carbon monoxide (CO) releases increase in different local areas of HIP. The possibility of CO releases is not a new phenomenon on HIP since Eramet plant produces CO rich flue gas and CO gas is used in the production of Yara. For personnel risk due to E-Fuel project CO exposure is by far the highest risk, both based on potential extend of fatal consequences and frequency of occurrence. Toxic CO clouds can extend significantly outside the E-Fuel plant battery limits. The risk is however low and lower than risk levels normally considered acceptable to 1st and 2nd parties and CO toxic risk cannot expose 3rd parties.

It is important that it is ensured that the HIP emergency preparedness recognises the CO risk from the E-Fuel plant and that personnel working inside HIP is aware of the risk and trained to respond. The HIP requirement for gas masks is to use ABEK1 filter, which is not effective against CO. However, personnel will be required to carry CO detector at the E-Fuel plant and compressor station and will therefore be warned of CO releases. The CO risk from the Eramet pipeline is considered very low, and a leakage will occur in 5 m height and be diluted. Therefore is the risk of fatal exposure of personnel very remote. It has consequently not been considered necessary to change the overall requirement for gas mask filter specification in HIP.

A number of recommendations have been put forward in Section 18.1.

Prepared By	**Reviewed By**	**Approved By**	**Date**
Carsten Stegelmann	Einar Lunde	Per Ståle Larsen	2022.05.30

Rev.	**Description**
B01	Final revision

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1 ABBREVIATIONS

Abbreviation	Description
ABR	Area Blocking Ratio
AKSO	Aker Solutions
ALARP	As Low As Reasonably Possible
ATEX	Atmosphere Explosible
BLEVE	Boiling Liquid Vapour Explosion
BST	Baker-Strehlow-Tang
C	Concentration
CCR	Central Control Room
Cd	Discharge Coefficient
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Cr	Chromium
CRA	Concept Risk Assessment
D	Pasquil Stability Class: Neutral category
DDT	Deflagration to Detonation Transition
DeAL	Design Accidental Load
DNV	Det Norske Veritas
DSB	Direktoratet for Samfunnssikkerhet og Beredskap
E	East
EI	Energy Institute
EPC	Engineering, Procurement and Construction
ESD	Emergency Shutdown
EV	Emergency Shutdown Valve
EX	Explosion
F	Pasquill Stability Class: Moderately stable conditions
F&G	Fire and Gas
FAR	Fatality Accident Rate
FBR	Full Bore Rupture
FEED	Front End Engineering Design
FLACS	Flame Acceleration Simulator
FLAM	Flammable
FT	Fischer Tropsch

Abbreviation	Description
H_2	Hydrogen
HAC	Hazardous Area Classification
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HC	Hydrocarbon
HFTL	Heavy Fischer Tropsch Liquid
HIP	Herøya Industrial Park
HSE	Health, Safety, Environment
HV	High Voltage
HVAC	Heat, Ventilation Air Conditioning
HYEX	Hydrogen ignition model developed by HYEX
IBL	Inner Battery Limit
ID	Internal Diameter
IDLH	Immediately Dangerous to Life or Health
In:Flux	Commercial CFD software
IOGP	International Association of Oil and Gas Producers
KFX	Kameleon FireEx
LFL	Lower Flammability Limit
LFTL	Light Fischer Tropsch Liquid
LNF-region	Landbruks-, Natur- og Friluftsområde (Agricultural, Nature and Recreational area)
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
ln	Natural Logarithm
M	Molecular Weight
MAH	Major Accident Hazard
MIDEL	Synthetic ester-based dielectric transformer fluid
MSF	Main Safety Function
NAP	Normal Atmospheric Pressure
NBC	Nordic Blue Crude (now Nordic Electrofuel)
NCCS	Norwegian Centre for Climate Services
NDE	Non-Destructive Evaluation
NEF	Nordic Electro Fuel
NORSOK	Norwegian shelfs competitive position
NS	Norsk Standard
NW	North-West

Abbreviation	Description
NTNU	Norwegian University of Science and Technology
P&ID	Piping and Instrumentation Diagram
P1	Upstream pressure
PARLOC	Pipeline And Riser Loss of Containment
PFD	Process Flow Diagram
PFP	Passive Fire Protection
PHAST	Process Hazard Analysis Software Tools
PLL	Potential Loss of Lives
PLOFAM	Process Leak for Offshore installations Frequency Assessment Model
POX	Partial Oxidation Reactor
ppm	Parts per million
Probit	Unit of measurement of statistical probability based on deviation from the mean of a normal distribution
PSV	Process Safety Valve
PVC	Polyvinyl Chloride
Q	Mass flow
Q9	Equivalent stochiometric gas cloud used in FLACS
QRA	Quantitative Risk Assessment
R	Universal gas constant
RAC	Risk Acceptance Criteria
RRM	Risk Reducing Measurement
RWGS	Reverse Water Gas Shift
S	South
SCS	Schmidtsche Schack
SE	Southeast
SINTEF	Stiftelsen for Industriell og Teknisk forskning
SS	Stainless Steel
t	Time
T	Temperature
TNO	The Netherlands Organization for applied scientific research
TT	Tan line to tan line
VCE	Vapor Cloud Explosion
VCM	Vinyl Chloride Monomer
W	West
Z	Compressibility

2 DEFINITIONS

Definition	Description
Syngas	Syngas, or synthesis gas, is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide.
MIDEL	Synthetic ester-based dielectric transformer fluid
Q9	Equivalent stochiometric gas cloud used in FLACS
Probit	Unit of measurement of statistical probability based on deviation from the mean of a normal distribution
Domino effects	An event that causes a process or event with significant consequences i.e. more serious consequences than the immediate consequences of the first event.

3 REVISIONS

Revision	Description
A01	Update of FEED risk analysis to DSB comments
B01	Updated to NEF comments and comments from meeting with HIP and “Storulykkeanlegg” at HIP

4 INTRODUCTION

Aker Solution (AKSO) has previously prepared a Concept Risk Assessment (CRA) for the conceptual design of the E-fuel plant [1]. in 2021 AKSO carried out Front End Engineering Design (FEED) for the E-fuel plant where a new risk analysis based on the CRA, and FEED design was prepared [2].

ORS Consulting AS (ORS) has been engaged by Nordic Electrofuel AS (NEF) to update the FEED risk analysis of the E-fuel plant to be built in the Herøya Industrypark (HIP).

AKSO also prepared a concept risk assessment for the supply of carbon monoxide (CO) rich feed gas from Eramet plant flue gas to E-fuel plant involving a long pipeline passing through HIP [3].

In Conceptual Design and the FEED it was concluded that the E-fuel plant does not fall under the term “Storulykkeanlegg”, as described in Norwegian DSB regulations [1] [2] [4]. However, as the E-fuel plant will be established in the same area as a number of existing “storulykkeanlegg it has been evaluated by DSB that the E-fuel plant risk assessment shall follow:

- Risk assessment in accordance with DSB Guidance for Quantitative Risk Assessments (QRA) for risk to 3rd parties [5];
- Information on risk from E-fuel plant exposing neighboring plants shall be provided;
- Risk analysis shall investigate potential domino effects from E-fuel plant towards neighbors;
- Risk analysis shall investigate potential domino effects from neighbors towards E-fuel plant.

ORS will therefore update the previous risk assessments prepared by AKSO to include domino effects and update the risk analysis to a QRA that fulfill DSB guidance. As part of the update a single risk analysis that comprises all of the NEF’s activities in the HIP will be prepared i.e.:

- E-fuel plant;
- Pipeline with feed gas from Eramet to E-fuel plant;
- Compressor station for transporting the feed gas from Eramet to the E-fuel plant.

The update of the risk analysis will be based on the work previously performed by AKSO, supplemented with additional consequence modelling and quantitative risk modelling. The risk analysis has been completely re-structured compared to the FEED.

4.1 BACKGROUND

NEF will produce “e-fuels” which are high quality, carbon neutral, synthetic fuels, and other fossil replacement products, based on water, CO, carbon dioxide (CO_2) and renewable hydroelectric power. The first plant, named “E-Fuel 1”, will be located at HIP near the city of Porsgrunn in southern Norway, see Figure 4-1 and Figure 4-2.

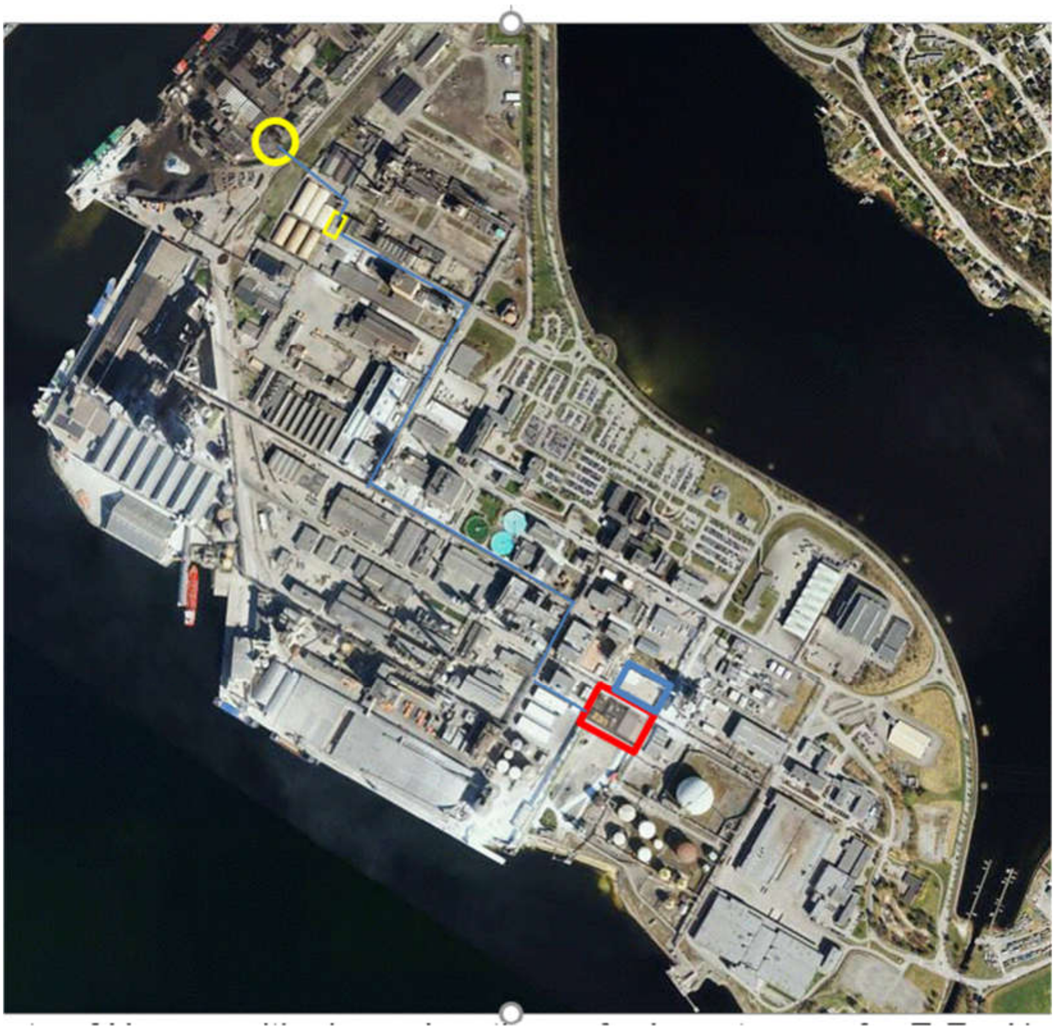

Figure 4-1 E-Fuel 1 in Herøya Industrial Park. Red square is the E-Fuel plant, yellow circle is the Erament factory supplying CO rich feed gas, yellow circle is compressor station, and the blue line is pipeline from Eramet to E-Fuel plant.

Figure 4-2 Close-up of E-Fuel plant

HIP is one of the largest industrial parks in Norway and is located in the municipality of Porsgrunn in Vestfold and Telemark County, 160 km south of Oslo.

The existing infrastructure at HIP provides utilities and feed stock necessary to operate the plant. The surroundings of the E Fuel 1 plant are illustrated in Figure 4-3.

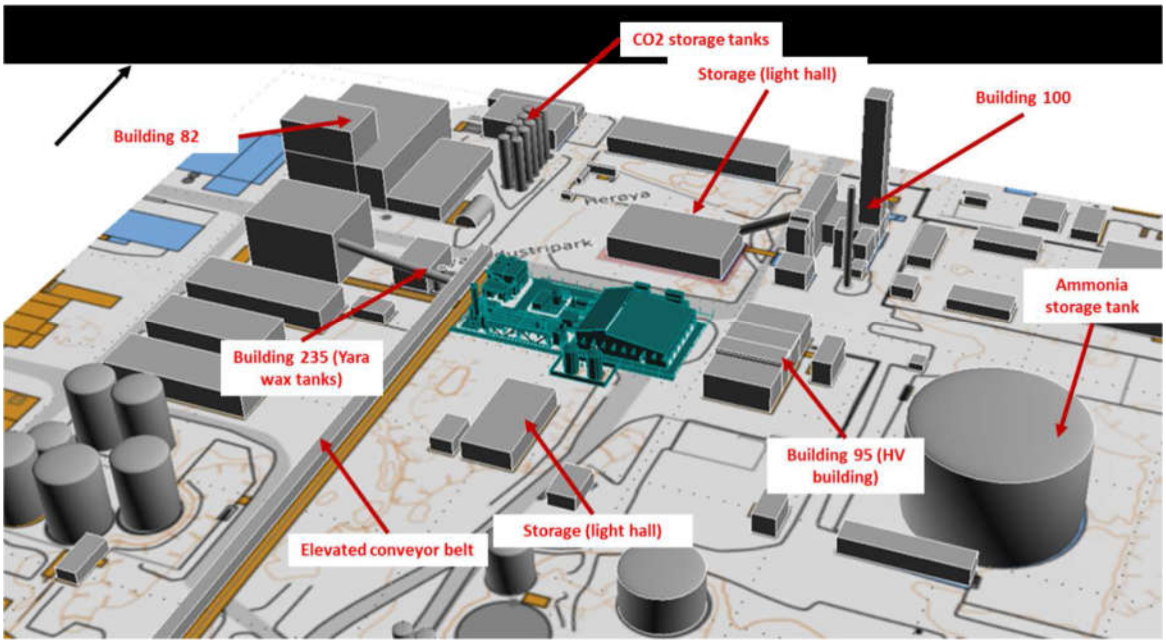

Figure 4-3 Surroundings of the E fuel 1 plant

The e-fuels are based on CO, derived from fume gas from the Eramet metal production factory at Herøya, and hydrogen (H_2), produced by electrolysis of water in a ~25 MW electrolysis facility. Water is supplied from the nearby lake Norsjø through the water pipeline to Herøya.

Fischer Tropsch Reactor (FT) and Partial Oxidation (POX) Reactor with reversed water gas shift (RWGS) functionalities are used to convert the gases to hydrocarbons. The FT reactor use catalysts which give different product mix depending on the supplier (licensor). NEF has chosen two Technology Partners for development and supply of these technologies. The Syngas module will be supplied by Schmidtsche Schack in Germany and the FT reactor process technology will be supplied by Emerging Fuels Technology in the USA.

The plant has two main functional areas; the electrolysis building including electrolysis system, major electrical equipment, control room and administration rooms, and the process area where the E-Fuel 1 products are made.

The main plot is ~4000 m^2, where the electrolysis building occupies about 40% of the area. Product storage tanks are allocated in the North-West corner of the plot. The remaining area is occupied by the FT and syngas process equipment, compressors, produced water treatment and steam system.

The plant shall produce 1000 kg/hr. of products (LFTL and HFTL, Light and Heavy Fischer-Tropsch Liquids) over 8000 operating hours per year, which amounts to 10 million litres with an average product density of 0.8 kg/l.

4.2 OBJECTIVE

The report shall establish E-Fuel plant's risk picture. The objectives of the analysis are:

- To identify and identify potential Major Accident Hazards (MAHs);
- Evaluate likelihood or probability of MAHs;
- Determine potential consequences of MAHs;
- Establish potential domino effects from E-fuel plant towards neighbours;
- Establish potential domino effects of neighbours impacting E-fuel plant;
- Calculate the risk from the MAHs in the form of ISO-risk contours of the plant ("hensynssoner");
- Establish impact of E-fuel plant on HIP overall ISO-risk contours ("hensynssoner");
- If relevant, make recommendations for implementation of additional risk reducing measures.

4.3 SCOPE

The risk analysis will include the following installations:

- E-Fuel plant;
- Pipeline for feed gas from Eramet metal production factory to E-Fuel plant;
- Compressor station for transporting Eramet feed gas;
- Exposure of neighbours from NEF installations in HIP (domino effects) e.g:
    - Yara ammonia storage tank
    - Yara wax tanks building 235
    - Building 95, High Voltage
    - PVC plant
- Exposure of E-Fuel plant from (domino effects):
    - Yara
    - PVC plant
    - Air Liquide Skagerak

5 METHODOLOGY

The risk assessment methodology used in this report is based on NS 5814 [6] and DSB guidance for QRA [5]. The risk analysis follows standard risk analysis methodology with the following activities:

- Information gathering;
- Hazard Identification (HAZID);
- Frequency analysis, e.g. establishing leak frequencies;
- Consequence analysis (gas dispersion, fire and explosion);
- Risk integration (combination of frequency and consequence analysis);
- Conclusion and recommendations.

The methodology has been illustrated in Figure 5-1.

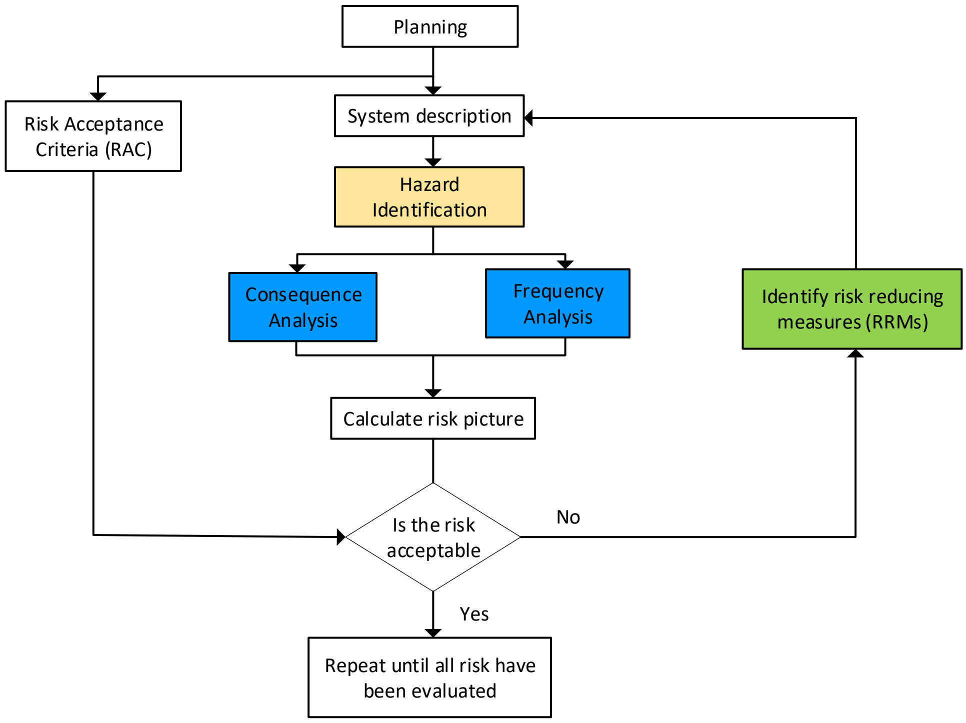

Figure 5-1 Illustration of the applied risk analysis methodology

The different steps in the methodology are described at a high level in the subsections below, i.e. section 5.1 - 5.7.

5.1 INFORMATION GATHERING

The information gathering is based on the FEED design [7], risk & safety analyses prepared previously by AKSO [1] [2] [3] [8],work meetings with NEF and QRA/Safety reports provided by neighbouring "storulykkeanlegg" [9] [10] [11] [12] [13].

5.2 HAZARD IDENTIFICATION

The identification of hazards of the present risk analysis is based on the HAZID carried out in the FEED project for the E-fuel plant [8]. In addition, have MAHs been identified in the previous risk analyses [1] [2] [3].

Furthermore, experience from previous conducted risk analyses for process plants by ORS and similar facilities and information from NEF and HIP "storulykkeanlegg" " [9] [10] [11] [12] [13] has been applied.

5.3 FREQUENCY ANALYSIS

Leak frequencies has primarily been based on the PLOFAM2 methodology [14] that has been referenced in the DSB QRA guideline [5]. The PLOFAM2 methodology has been developed for offshore QRA but has also been recommended for onshore process facilities.

For the pipeline, with feed gas from Eramet, leak frequencies determined by the PLOFAM(2) method has been adjusted to PARLOC data that is considered more realistic for pipelines [15] [16].

The leak frequencies calculated for different leak scenarios are based on component or parts count on the P&IDs of the E-fuel facility and the process conditions of different parts of the process.

For compressor station and electrolysis building P&IDs were not prepared in FEED. A conservative component count has therefore been performed based on P&IDs of similar process systems known to ORS from other projects. It is recommended to update the component count when detailed P&IDs becomes available, but such an update is not expected to impact the conclusions of the present analysis negatively.

Ignition probabilities are estimated based on the IOGP model [17] in order to establish the frequency of ignited releases. For hydrogen releases the HyEX ignition model has been applied instead [5].

The frequency analysis is further described in Section 10 and 11.

5.4 CONSEQUENCE ANALYSIS

Consequences of this risk analysis is calculated by PHAST version 8.4, as described in Section 12. PHAST has been developed by Det Norske Veritas (DNV) and is well recognized in Norway and internationally for onshore consequence modelling.

The modelled consequences includes:

- Flammable gas dispersion;
- Jet fire;
- Pool fire;
- Flash fire;
- Vapour Cloud Explosion (VCE).

Every simulated consequence is assigned a frequency based on scenario frequencies and weather data.

In the CRA some advanced CFD consequence modelling was performed [1]. These results will be maintained and discussed in the present risk analysis as they provide excellent visualisations. However, the quantitative part of the risk assessment will be based on the PHAST consequence modelling as it requires modelling of many different scenarios.

5.5 RISK PICTURE

The risk associated with activities on the plant is a combination of frequency and consequence. This combination results in hazard effect distances that are applied to construct ISO-risk contours ("hensynssoner"). The risk contours correspond to the fatality risk for individuals located at a certain location in the plant surroundings 24 hours per day year-round.

The calculated risk has been compared to risk acceptance criteria (RAC) for 3rd party personnel provided by DSB in "Tema 13, forskrift om sikkerheten rundt anlegg som håndterer farlig stoff" [4], which is governing for MAH or Seveso facilities ("Storulykkeforskriften") [18].

Domino effects due to E-Fuel plant incidents exposing neighbours will be evaluated based on simulated consequences, calculated event frequencies and vulnerability of targets. Hence it will be a risk-based or probabilistic quantitative assessment.

Domino effects due to incidents at neighbours exposing the E-fuel plant will be addressed based on the risk assessments of Yara [9] [10] [11], PVC plant [12] and Air Liquide Skagerak [13], which discusses such domino effects. A semi-quantitative argumentation will be presented for the impact on the E-Fuel plant specifically.

5.6 CONCLUSION AND RECOMMENDATIONS

Conclusions and recommendations are provided in dedicated sections of the report. This is primarily done in the form of the ISO-risk contour curves which limit what type of installations can be established inside different ISO-risk contours ("hensynssoner").

Furthermore, it is concluded whether E-Fuel plant can expose neighbours and causing domino effects and vice versa.

5.7 ASSUMPTIONS

Quantitative risk analysis will inevitable be based on a number of assumptions that will impact the risk results. A specific assumption register has not been prepared but it has been chosen to discuss the most critical assumptions directly in the report where relevant to the discussed modeling aspects.

6 FACILITY DESCRIPTION

The E-Fuel plant, the feed gas pipeline from Eramet and the feed gas compressor station will be discussed as separate facilities in the following due to their different locations inside the HIP.

6.1 E-FUEL PLANT

6.1.1 PROCESS DESCRIPTION

The facility converts water and Eramet furnace gas (mainly CO) into a hydrocarbon product. In this way carbon neutral fuel is generated. The process is very energy intensive and requires large amounts of electrical power.

The facility consists of:

- Hydrogen Production Alkaline Electrolyzer;
- Feed gas supply from industrial source (Eramet furnace flue gas);
- Partial Oxidation Reactor with Reverse Water Gas Shift functionalities and Syngas Cooler;
- Fischer Tropsch Reactor with associated Guard Beds;
- Fischer Tropsch Recycle Compressor System;
- Tail gas Recycle Compressor System;
- Product Separation and Stabilization System;
- Product Storage;
- Product Transfer;
- Produced Water Treatment;
- Steam System;
- Vent System;
- Utility systems as Cooling Water, Fresh Water, Potable Water, Air and Nitrogen.

The process design is developed based on earlier concept studies and a pre-FEED study with a revised concept. The first concept study was based on a description and simulation generated by The Norwegian University of Science and Technology (NTNU). The design has been further developed by Aker Solutions (AKSO), in the FEED phase also in close co-operation with technology suppliers Schmidtsche Schack and Emerging Fuels Technology [7].

A process overview has been provided in Figure 6-1.

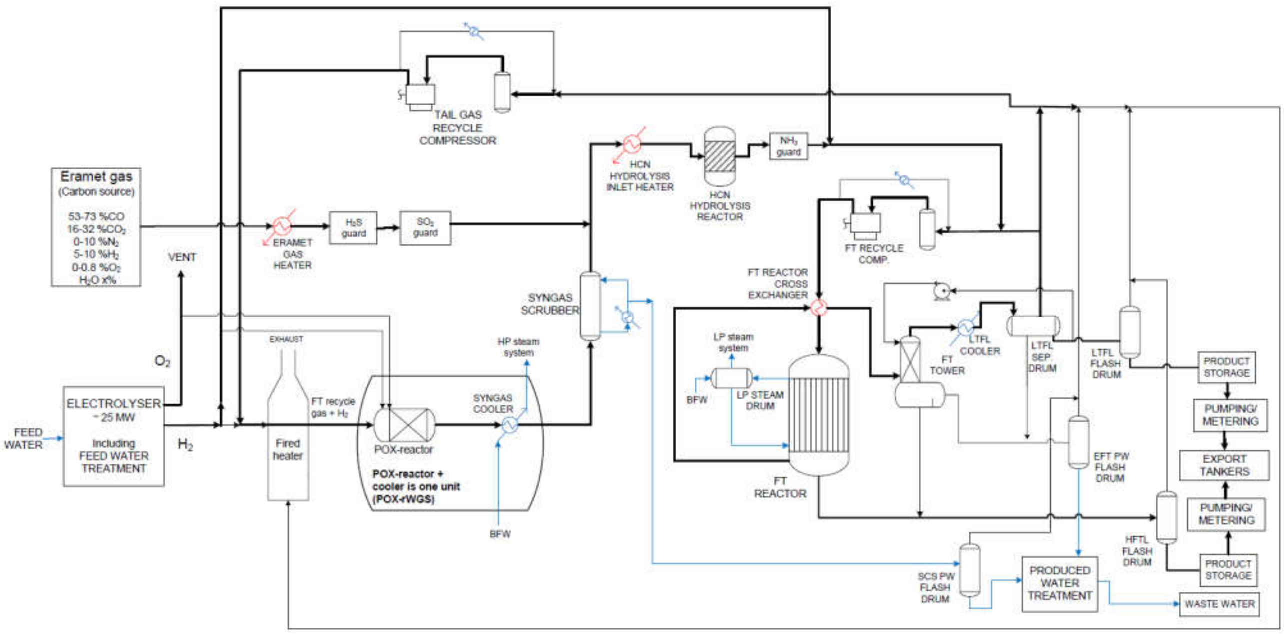

Figure 6-1 Process overview of e-fuel plant

The following utilities are supplied from Herøya Industripark (Outside Battery limits):

- Main electric power supply 12 kV (nominal) and 50 Hz;
- Essential power supply 10 kV (nominal) and 50 Hz;
- Fresh water (various use within plant; cooling water, fire water, service water);
- Potable water;
- Plant air (compressed air);
- Nitrogen;
- Interconnecting pipelines:
    - Pipeline from Eramet plant gas storage tanks to IBL by NBC.

6.1.1.1 PROCESS SECTIONALIZATION

The sectionalization philosophy is as follows:

- Isolate H_2 segment within the electrolyser building from segments outside to prevent backflow of syngas into the building (segment 1);
- Isolate feed gas system to prevent backflow of H_2 and syngas (segment 2);
- Isolate the high temperature part of the process with operational temperature above autoignition temperature for the syngas (segment 3);
- Isolate the assumed largest gas volume in the process (Fischer–Tropsch reactor) to limit the inventory taking part in a potential leak and to control runaway (segment 4);
- Isolate the product storage tanks from the rest of the process (segment 6);
- The remaining separation process section is separately isolated and preventing major HC leaks into produced water system (segment 5).

Figure 6-2 shows the sectionalization diagram. Note that the sectionalization diagram has been used as input to the process design and does not incorporate all changes made and reflected on P&IDs.

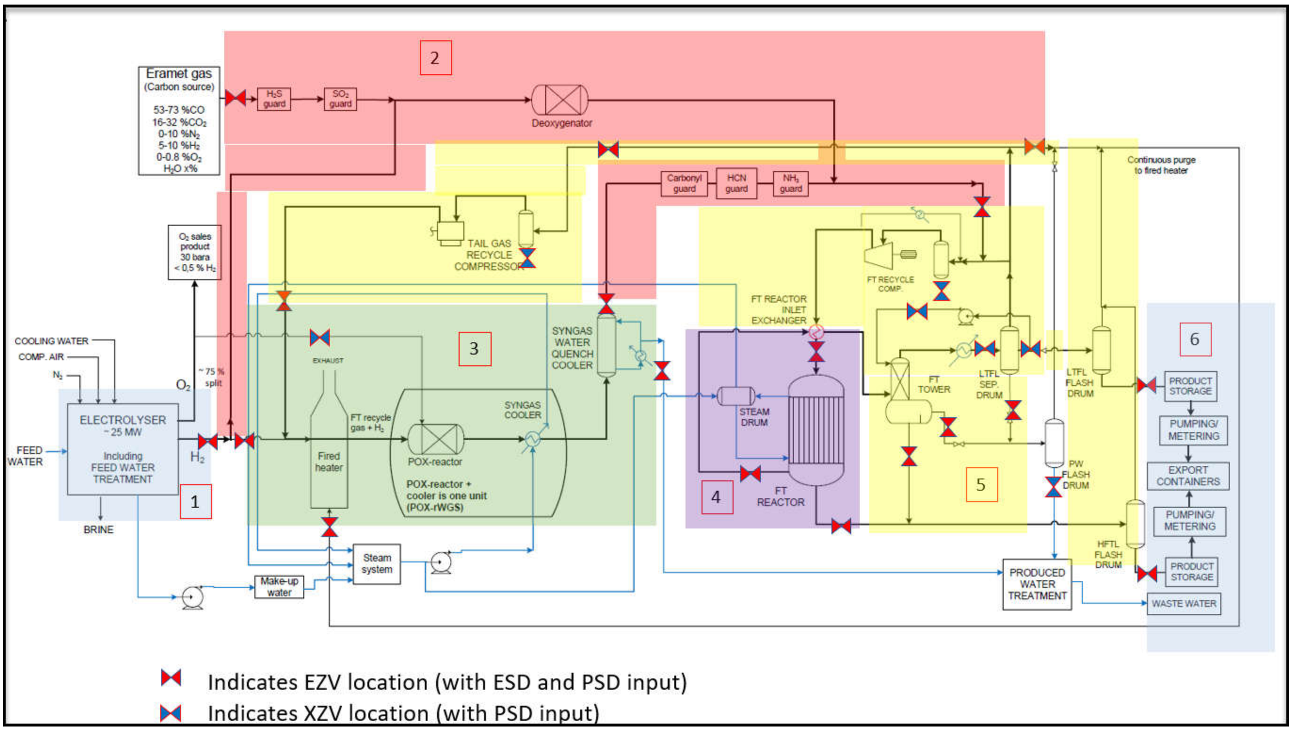

Figure 6-2 Sectionalization diagram

6.1.2 PLANT LAYOUT

The plant layout has been illustrated in Figure 6-3.

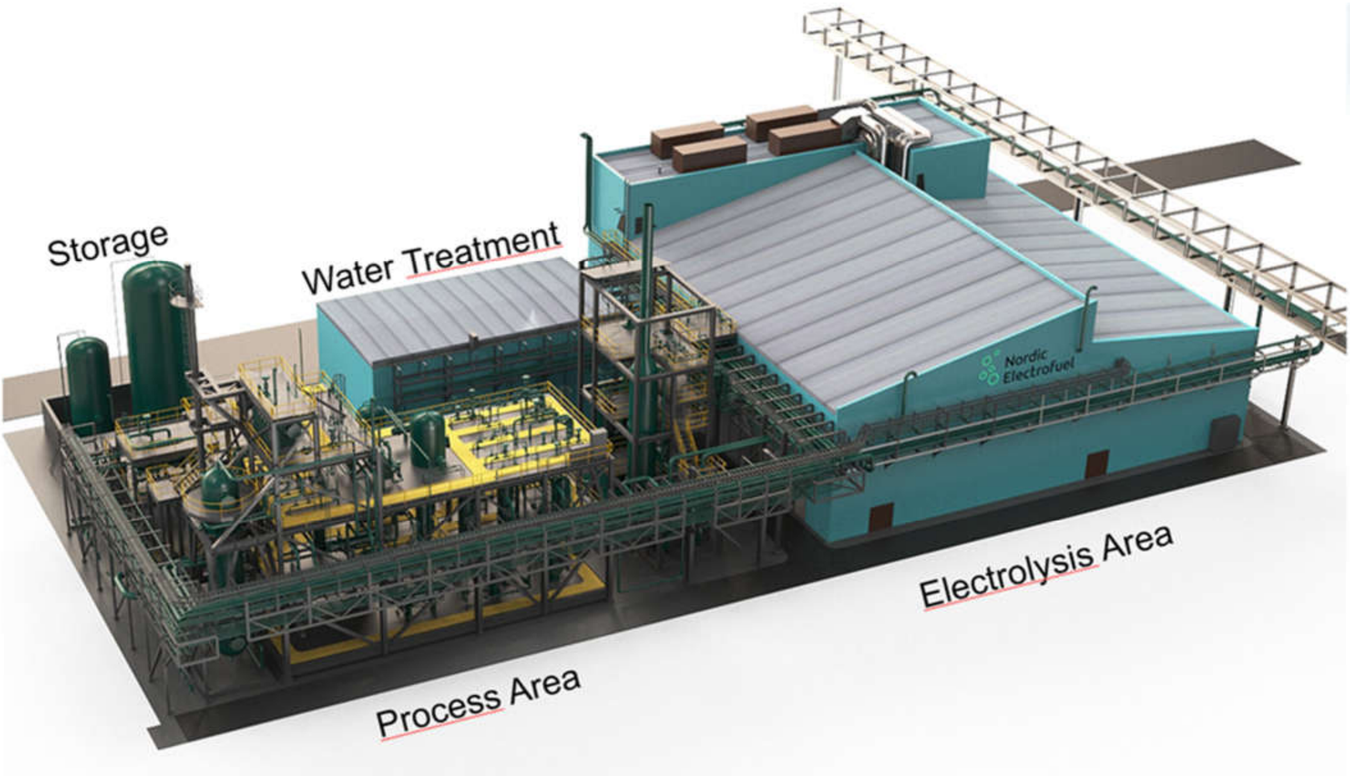

Figure 6-3 Plant overview

6.1.3 PLANT LOCATION

The E-fuel 1 plant location in the HIP has been illustrated in Figure 6-4.

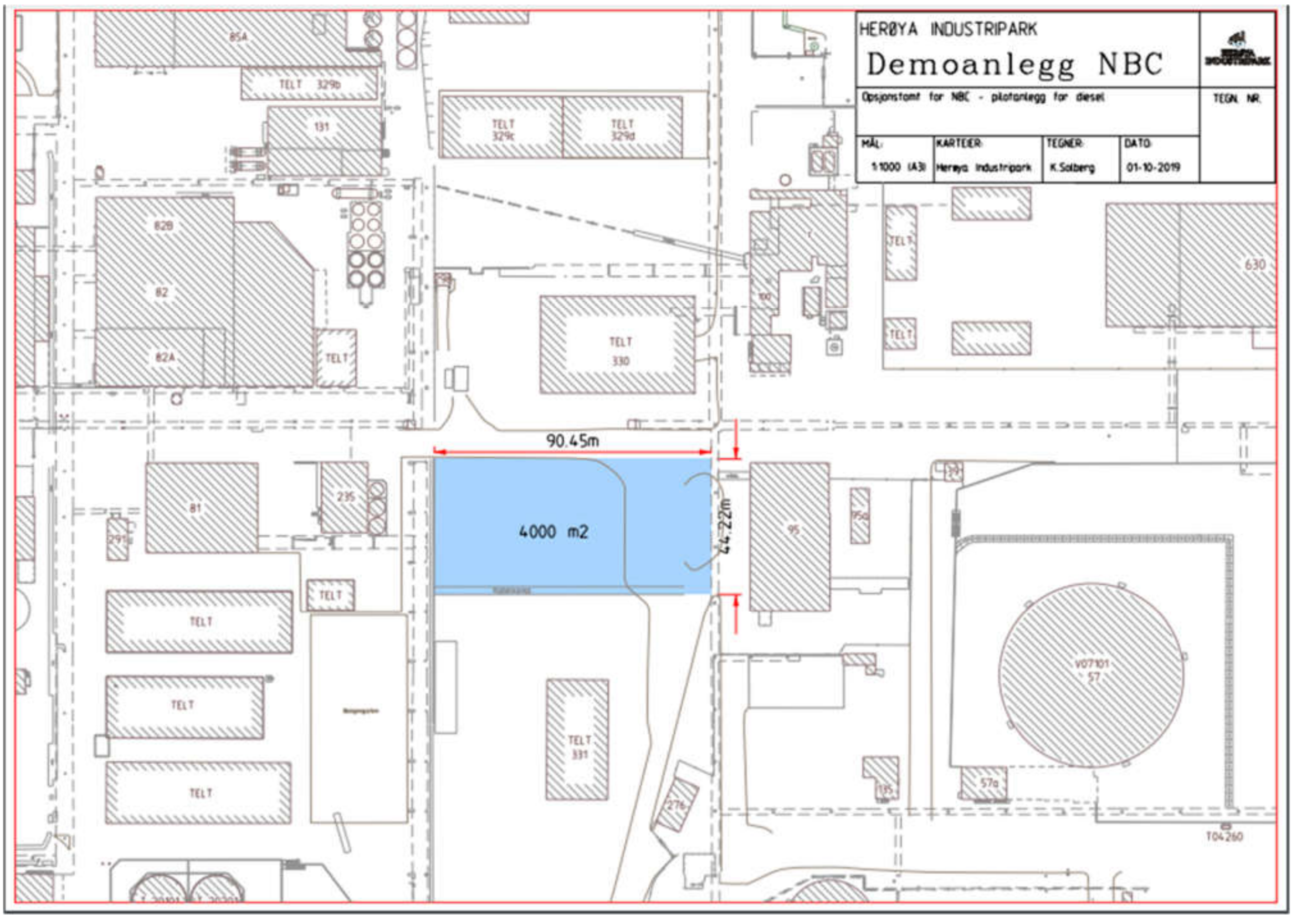

Figure 6-4 Plot location

Figure 6-5 and Figure 6-6 shows an overview of the buildings in the vicinity of the e-fuel plant, and the hazardous substances that have been reported to DSB:

- **Y37 and building 235:** contains wax used as coating on fertilizer;
- **Y52:** ammonia storage tank;
- **Y51:** spill oil tank;
- **Y54:** ethane storage tank;
- **I1:** VCM storage tanks (vinyl chloride monomer);
- **S1:** LNG storage tanks;
- **Building 95 (ignition source and critical infrastructure on HIP):**
  - Concrete building containing several transformers and other equipment related to the electrical power supply to HIP;
  - The building contains several pressure relief openings/panels, however, none of these are facing the e-fuel plant (pressure relief towards S, E and in the ceiling/roof);
  - The building has several ventilation openings and air intakes. Some of which are located on the W side of the building facing the e-fuel plant (see Figure 6-7). If gas is sucked in through the HVAC it could be ignited and cause loss of power. Even if ignition does not occur Building 95 may be shutdown manually again leading to loss of power.

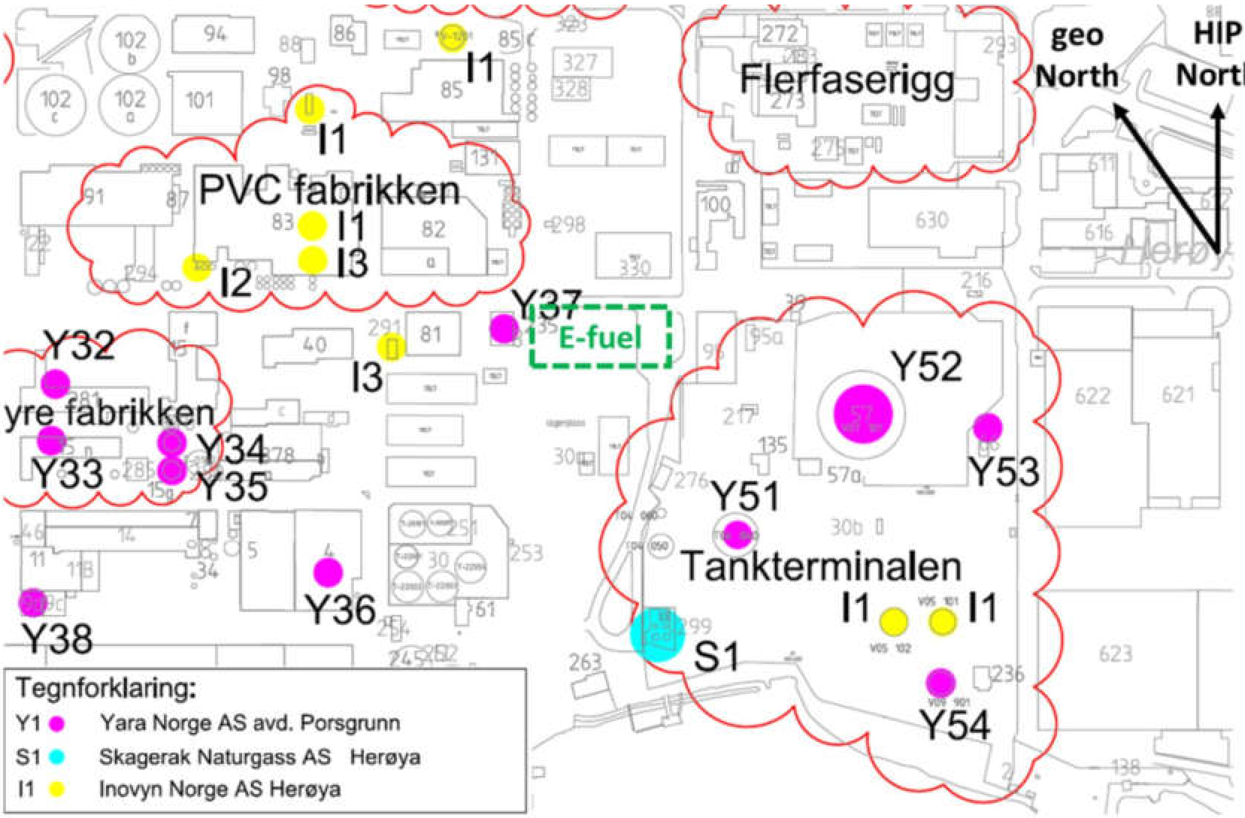

Figure 6-5 Overview of buildings and hazardous substances in the vicinity of the e-fuel plant

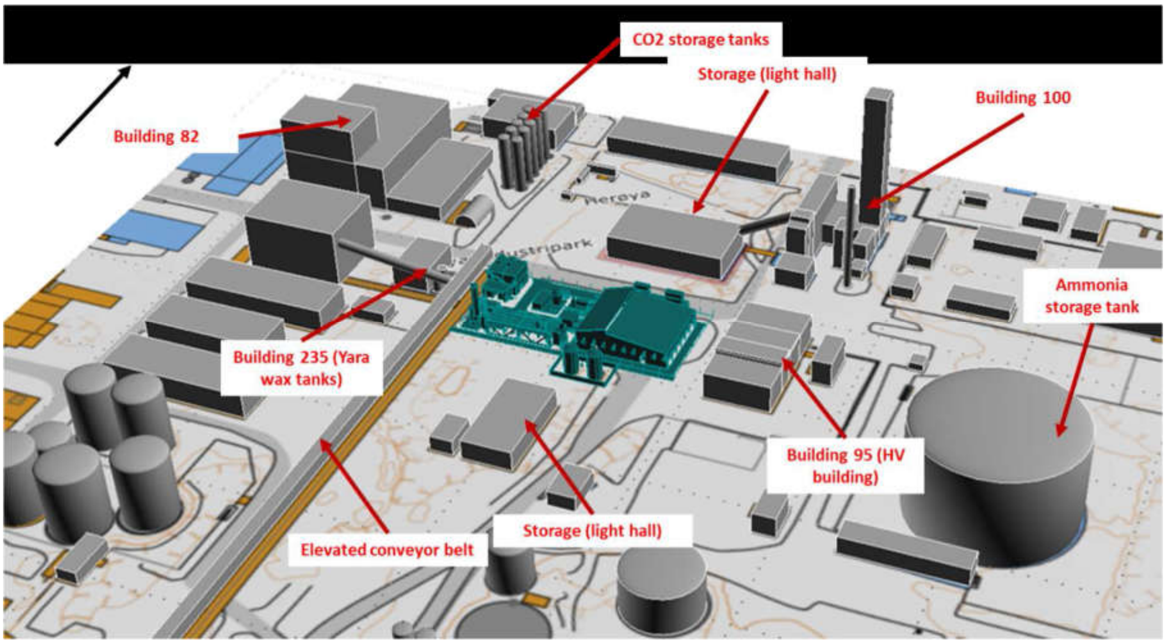

Figure 6-6 Surroundings of the E fuel 1 plant

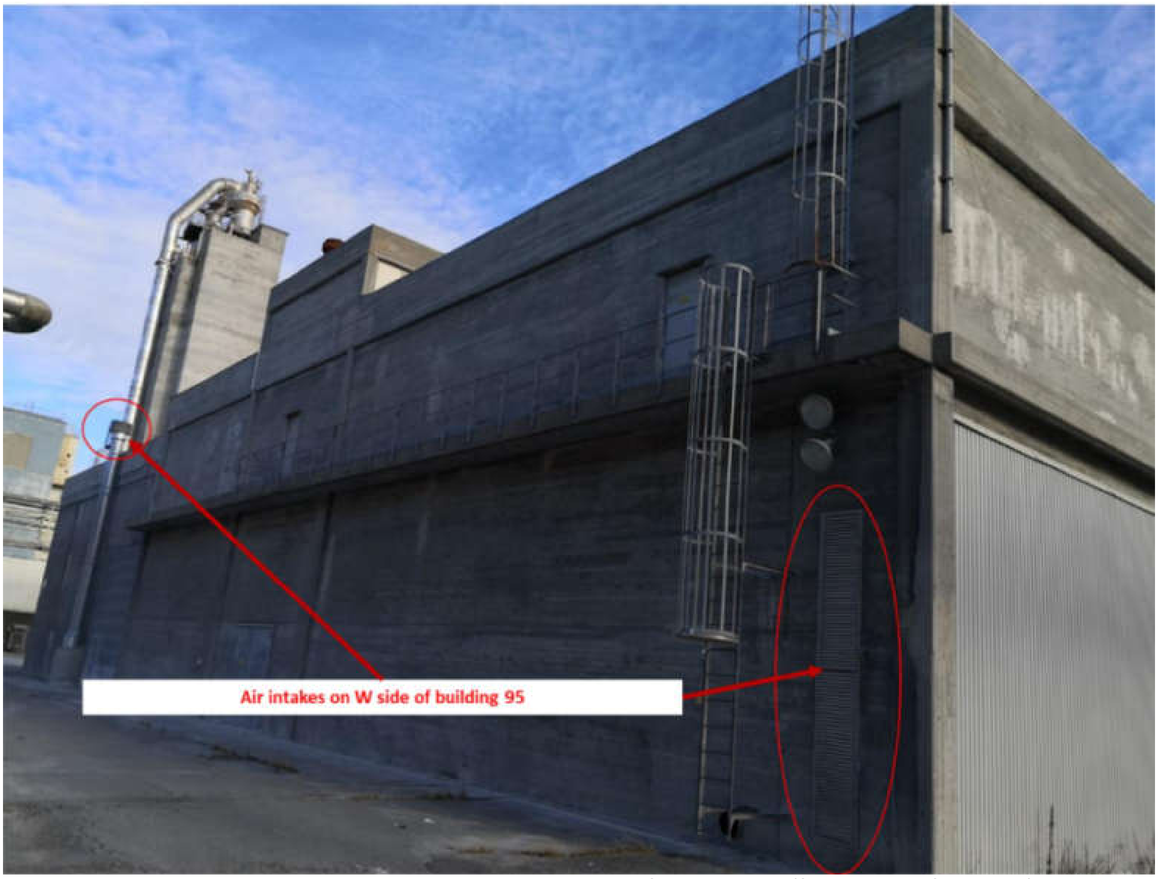

Figure 6-7 Air intakes to building 95, located on the W side of the building (facing the e-fuel plant)

The far field explosion pressures at the e-fuel plant from neighbouring facilities will be less than 0.05 barg side-on pressure, see Figure 6-8. This pressure can break windows and other fragile objects but will typically not result in significant damage on process equipment, module structures or buildings.

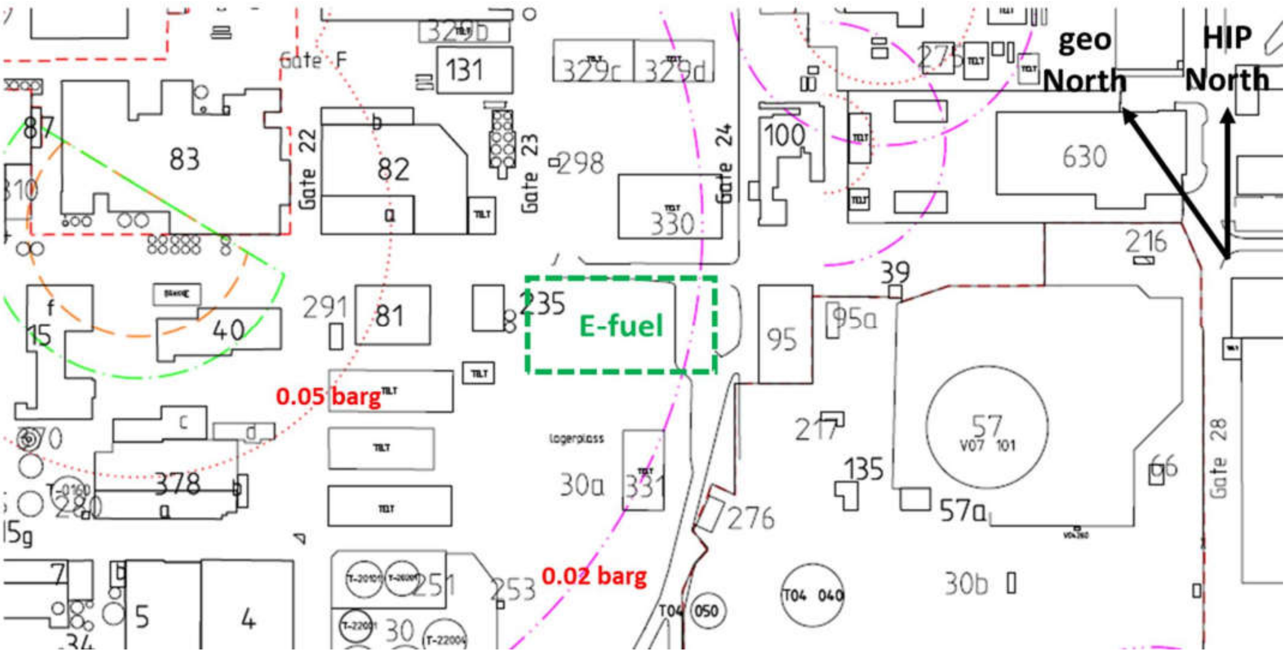

Figure 6-8 Far-field explosion loads [19]. Pressures are side-on pressures.

6.1.4 PLANT AREAS

The plant has been divided into separate areas that define the actual purpose for each area. The defining areas are as follows:

S00 – Overall Site;
S10 – Electrolyser / Office Building;
P20 – Syngas Module and Tail Gas Compressor;
P30 – FT & SCS Process area;
P40 – FT Recycle Compressor;
S50 – Product Storage / Tanker Offloading Area;
P60 – Steam Area and Spare Parts Storage;
S70 – Produced Water Treatment Area;
S80 – Compressed Air / Nitrogen Area:
R90 – Pipe racks

The separate areas can be seen in Figure 6-9.

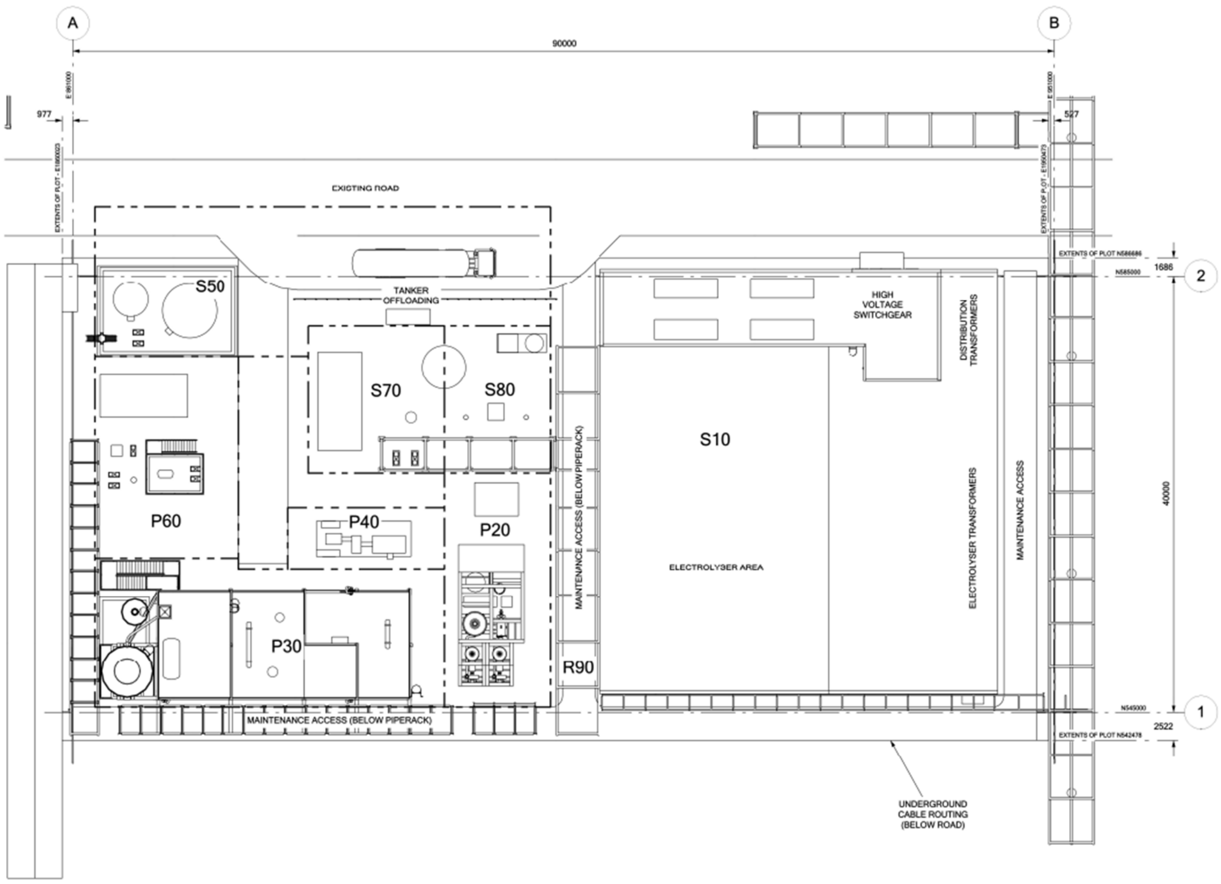

Figure 6-9 E-Fuel 1 - Defined Areas

The plant has been arranged to provide a safe and functional layout and takes into account the most logical installation requirements.

Most of the services required are located in the pipe rack to the east and north-west corner of the plant and have been identified in a separate report from Bilfinger.

A 3D sketch of the E-fuel 1 plant has been provided in Figure 6-10.

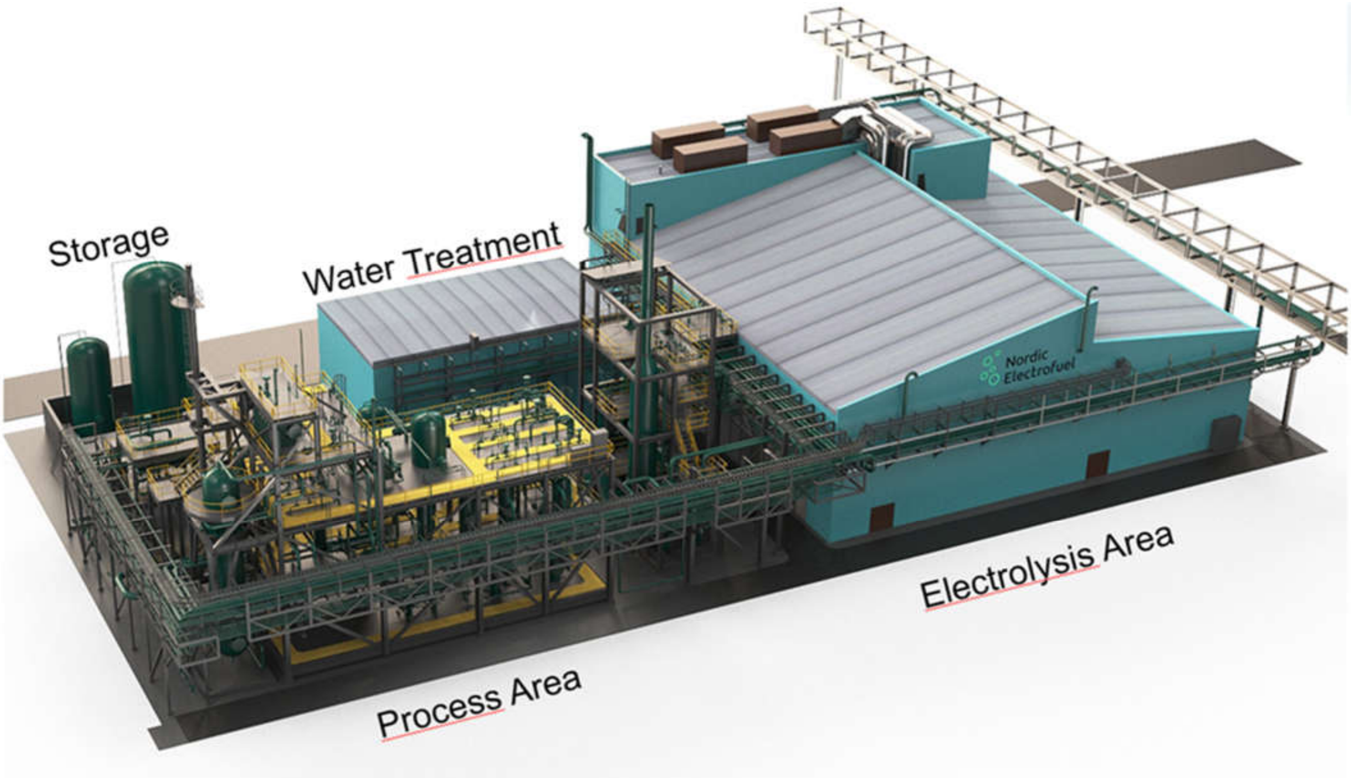

Figure 6-10 E-Fuel 1 - Overall 3D plot.

6.2 PIPELINE FROM ERAMET

An approximately 2 km 3” pipeline is planned to be routed from the Eramet plant to supply the E-Fuel plant with CO rich feed gas (dimension of pipeline may be decreased at a later stage). The planned pipeline routing through HIP is shown in Figure 6-11.

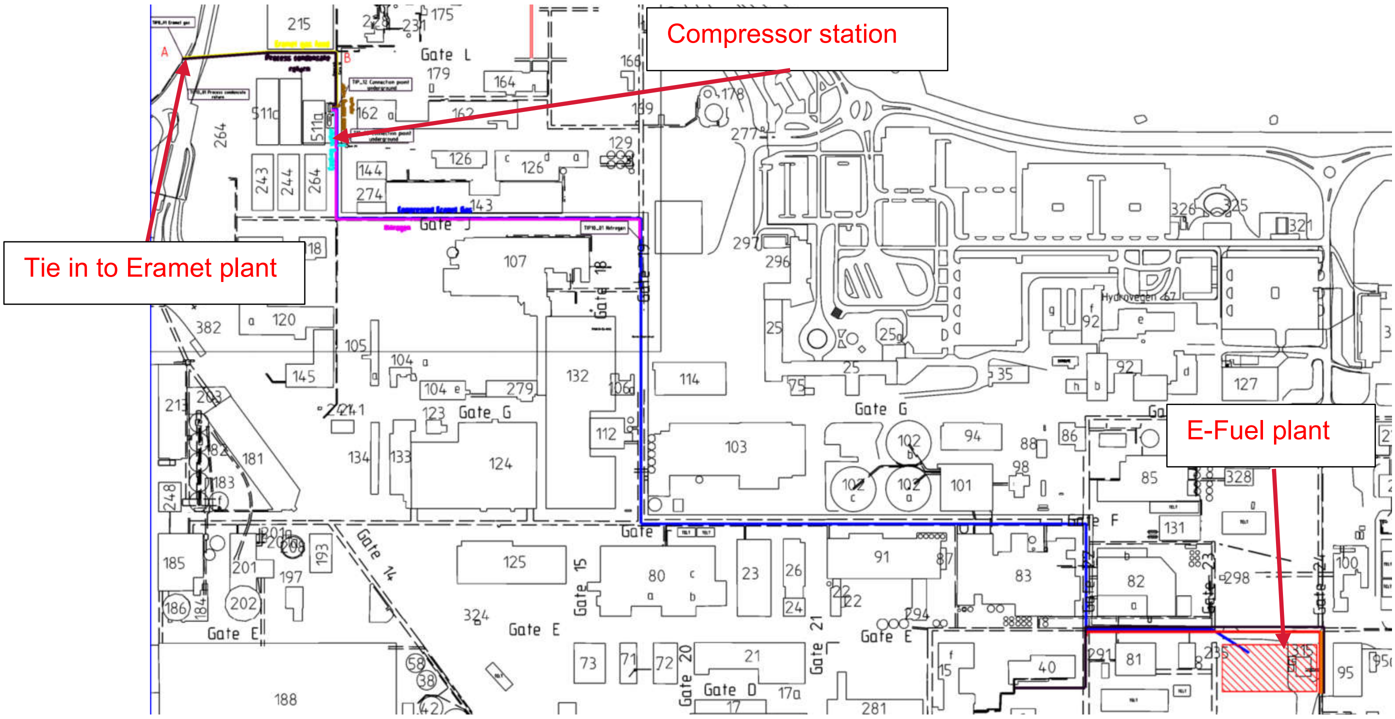

Figure 6-11 Pipeline routing between Eramet and E-Fuel plant

The pipeline consists of approximately 250 meters 10” suction pipeline from Eramet to the compressor station. The suction part of the pipeline will operate at close to atmospheric pressure or slight under pressure (vacuum).

From the compressor station a 1.7 km meters 3” discharge pipeline is routed to the E-Fuel plant. The operating pressure after the compressor station is up to 40 bar.

The discharge pipeline will be designed as a pipeline and not as ordinary process piping.

The pipeline is expected to be routed in minimum 5 meters height per HIP standard, in pipe racks or bridges, through HIP.

6.3 COMPRESSOR STATION

The compressor station is located next to Building 511a and will pressurize the CO rich gas from Eramet from atmospheric pressure to 40 bar.

The compressor is expected to be a 4 stage reciprocating compressor. The compressed gas is fed into a buffer tank with a capacity for one hour production of the E-Fuel plant.

6.4 SAFETY FUNCTIONS

As part of the FEED a large number of risk and safety studies have been performed to determine what safeguards or safety functions to include in the design [7]. The most important safety functions from a QRA perspective have been listed in Table 6-1.

Table 6-1 Main safety functions implemented in the design

Safety function	Remark
F&G detection	E Fuel plant and compressor station will be equipped with flammable gas detectors, CO detectors and flame detectors initiating automatic shutdown and alarm.
Emergency shutdown	On F&G detection will the process be shut down and isolated. E-Fuel plant outdoor process, electrolysis building and storage tanks will, as a minimum, be isolated by shutdown valves. The compressor station inlet and outlet will be isolated by shutdown valves. The Eramet pipeline will be isolated.
Emergency depressurisation	The E-Fuel plant will have emergency depressurisation to vent in case of F&G detection.
Ignition Source Control	Hazardous Area Classification and use of ATEX equipment. F&G and ESD system will isolate ignition sources, close fire dampers etc.
Process Safety	The process is equipped with instrumented trip function, Pressure Safety Valves (PSVs) etc. to follow best industry practice and as per HAZOP requirements.
Active fire fighting	The bund of the storage tank will be covered by deluge and foam system. Manual firefighting will cover all other areas.
Passive fire protection (PFP)	Requirement to be established in detailed design. Requirement for PFP not foreseen.
Gas shelter	The centra control room (CCR) located inside the electrolysis building shall be designed to be "gas safe" according to HIP FB-08.

6.5 WIND DATA

Figure 6-12 shows the wind rose for HIP showing the distribution of wind directions relative to the e-fuel plant. The predominant wind directions are wind from a northernly and easterly direction. The wind rose from HIP did not contain information on wind speed distribution.

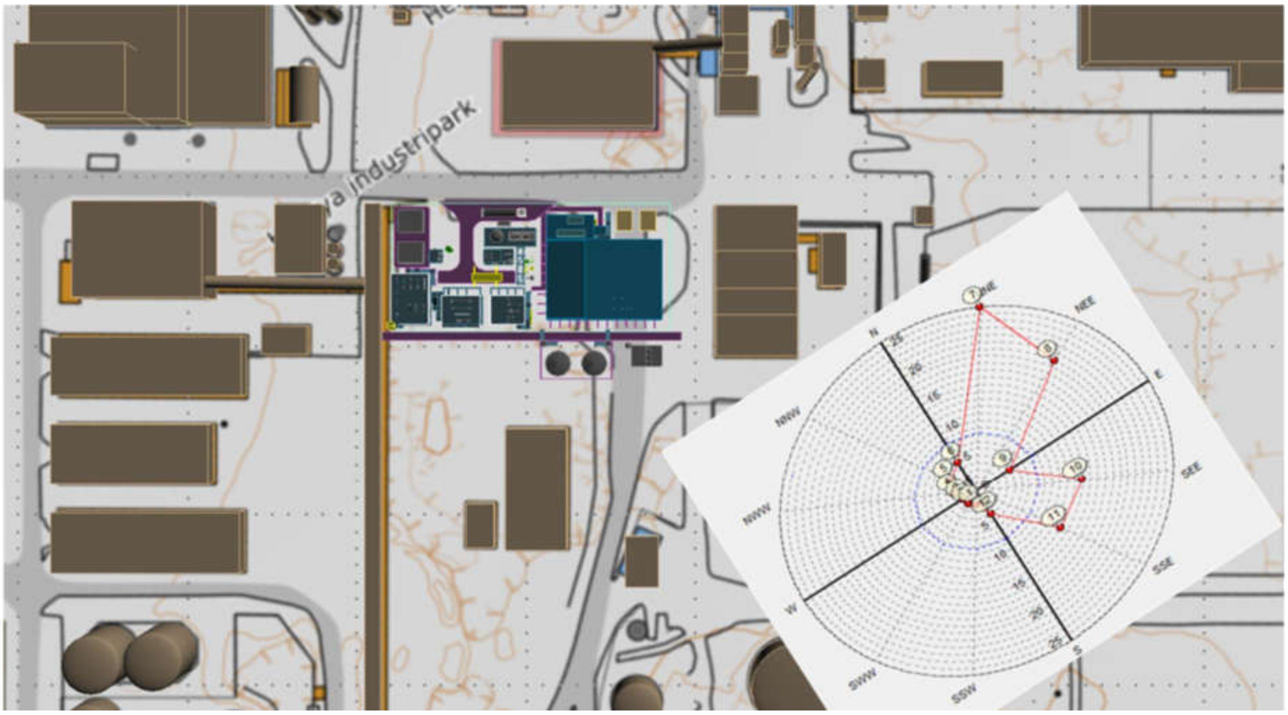

Figure 6-12 Wind rose relative to e-fuel plant [20].

For risk calculation purposes the wind speed distribution of Table 6-2 has been applied.

Table 6-2 Wind speed distribution for risk analysis

Wind speed interval	Rep. wind speed [m/s]	Beufort stability class	Probability [-]
0-3 m/s	1.5	F	72.45%
3-8 m/s	5	D	27.42%
>8 m/s	10	D	0.13%

For wind, data from the Norwegian Centre for Climate Services (NCCS) has been obtained for a 10-year period, with an hourly resolution. The data is not from Herøya itself, but from Ås, located 3.71 km south southeast of the plant, see Figure 6-13 , at a heigh of 100 m above sea level. Only the wind speed intervals are used, and only minor differences compared to Herøya is assumed. However, wind data from Herøya should be used at a later stage to qualify the results.

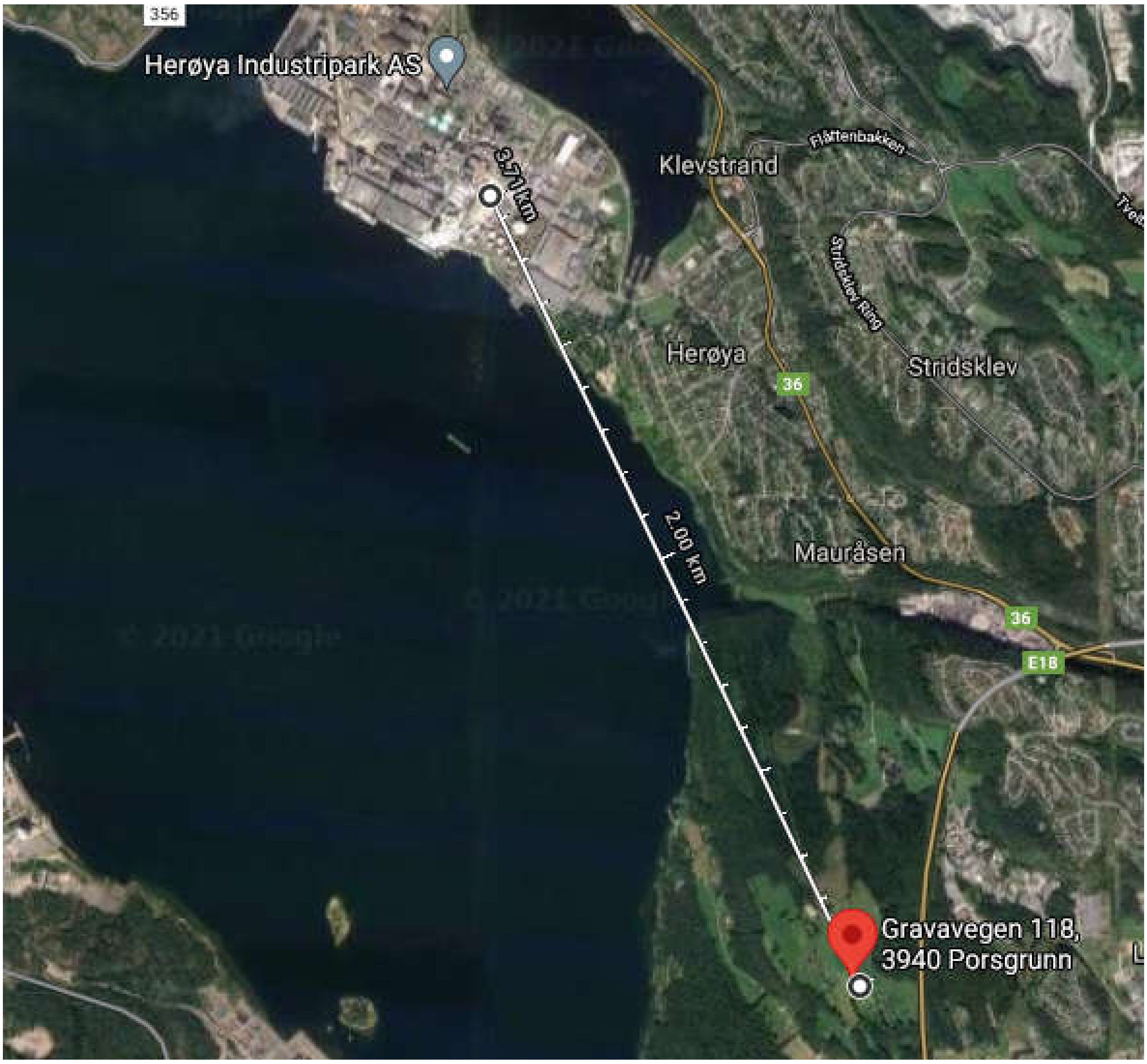

Figure 6-13 Distance from Herøya to point of wind measurements.

7 REGULATORY REQUIREMENTS

The amount of hazardous substance stored at the e-fuel plant is limited and the plant does therefore not fall under the term “Storulykkeanlegg”, as described by the DSB regulations. The background for this conclusion is documented in the FEED Report [7]. “Storulykkeforskriften” does therefore not apply.

The main regulations and guidelines applicable for the e-fuel plant is listed below:

- DSB, Forskrift om håndtering av farlig stoff [21];
- DSB, Temaveiledning om tilvirkning og behandling av farlig stoff [22];
- DSB, Sikkerheten rundt anlegg som håndterer brannfarlige, reaksjonsfarlige, trykksatte og eksplosjonsfarlige stoffer [4];
- DSB, Guidelines for quantitative risk analysis of facilities handling hazardous substances [5];
- Standard Norge, Krav til risikovurderinger, NS 5814:2008 [6].

7.1 RISK ACCEPTANCE CRITERIA

A set of risk acceptance criteria has been selected for the E-Fuel plant project.

7.1.1 RISK TO 3RD PARTY – OUTSIDE HIP

In order to limit the risk to 3rd party (persons outside the plant area), DSB has suggested restrictions in the type of buildings and activities around a plant handling hazardous substances, in the form of ISO-risk contours. Such ISO-risk contours have been developed for the entire HIP [10].

An ISO-risk contour is a line or plane where the frequency of fatal exposure is the same. The concept of ISO-risk contours are used for implementing sufficient safety distances between plants and other human activities.

According to DSB requirements [4], three ISO-risk contours shall be established around a facility that defined the following impact zones (“Hensynssoner”): Inner zone, Intermediate zone, Outer zone and outside outer zone. These zones are shown schematically in Figure 7-1. The definition of the zones is provided in Table 7-1.

Note that in addition to individual risk acceptance there is also a requirement for the risk to be ALARP, i.e. the risk needs to be reduced to lowest practical possible level.

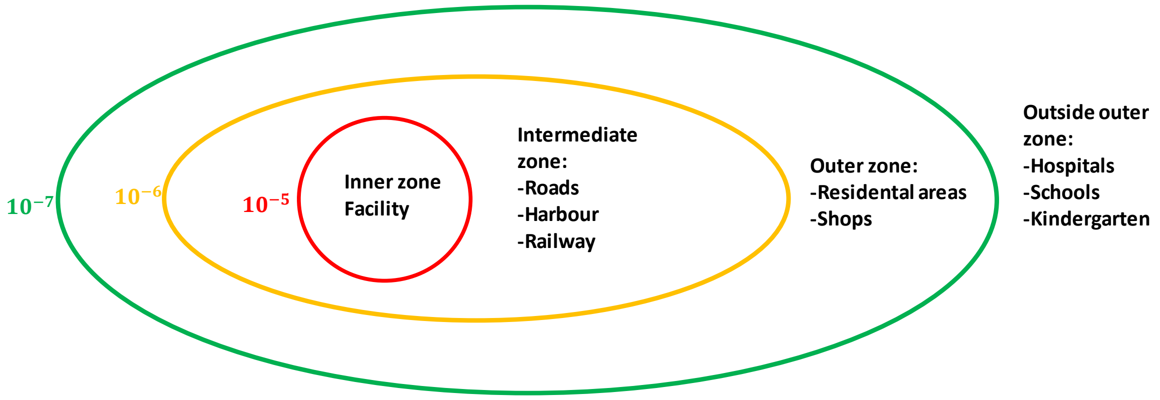

Figure 7-1: Illustration of DSB risk acceptance criteria for risk iso contours

Table 7-1 Description of impact zones [4]

Impact zones	Zone frequency boundaries [per year]	Requirements for impact zones
Inner zone	$\geq 10^{-5}$	This is basically the area of the plant itself. In addition, can for instance an LNF-region be part of the inner zone. Only short passage of 3rd party personnel.
Intermediate zone	10^{-6} - 10^{-5}	Public roads, rail, road, pier and similar. Fixed workplaces within industry- and offices can also be located here. In this zone there shall not be overnight stays or residential buildings. In special cases minor residential buildings can be allowed.
Outer zone	10^{-7} - 10^{-6}	Areas approved as residential areas or other uses by the general public can be part of the outer zone, including shops and smaller sleeping facilities.
Outside outer zone	$<10^{-7}$	Schools, kindergartens, hospitals, nursing homes and similar institutions, shopping malls, hotels or large crowd arenas shall be placed outside the outer zone.

In the industrial area surrounding a plant, the risk iso contour is not allowed to exceed 10^{-5} per year. In residential areas the ISO-risk contour is not allowed to equal or exceed 10^{-6} per year and for particular vulnerable areas such as, e.g. schools, the risk contour is not allowed to exceed or equal 10^{-7} per year.

It is important to note that 3rd party will not have access inside HIP and will therefore not be exposed inside the HIP boundaries.

1st and 2nd parties can be exposed inside the HIP boundaries. But 1st and 2nd parties are not as vulnerable as 3rd party personnel as they are trained and instructed on how to behave in case of an emergency.

Hence the “inner zone facility” should be considered as the HIP and not the E-Fuel plant itself i.e. the risk iso contour inside HIP is not limited to less than 10^{-5} per year.

Hence the following risk acceptance criteria (RAC) is suggested for 3rd party:

Inner zone: Businesses within HIP’s area including NEF e-fuel plant
RAC not applicable for 3rd party

Middle zone: Neighbouring businesses outside HIP
Suggested RAC: 10^{-6} per year

Outer zone: Residential areas, shops and other areas used by the general public outside HIP
Suggested RAC 10^{-7} per year

Outside outer zone: Vulnerable locations such as schools and kindergartens around HIP
Suggested RAC $<10^{-7}$ per year

7.1.2 RISK TO 1ST AND 2ND PARTY – INSIDE HIP

To provide decision support in the design process towards a safe plant, acceptance criteria internally in the E-Fuel plant are also suggested. The purpose of the criteria is to ensure that a small scenario does not escalate to a major accident and that personnel are protected during evacuation from accidents. Based on these points, the following RACs are suggested:

- Impairment of Main Safety Functions (MSF):
  - Control room inside electrolysis building;
  - Wall between hazardous and non-hazardous area in electrolysis building;
- Escalation (domino effects) causing significant worsening of initial event – e.g. to storage tanks.

The suggested RAC for the above is an upper frequency of occurrence of 10^{-4} per year. The 10^{-4} per year criteria matches criteria used inside HIP today for dimensioning accidental loads e.g. blast loads [11].

7.1.3 ERAMET PIPELINE

The Eramet pipeline will be routed inside the HIP and will therefore not cause exposure of 3rd party personnel. However, as the pipeline will pass through many different areas of HIP it will not be possible to provide local gas detection along the pipeline. Consequently it has it been decided to impose a stricter risk acceptance criterion of 10^{-6} per year fatality risk.

This based on that Figure 7-1 allow a risk to 3rd party of 10^{-5} per year outside the plant. Based on this it could be assumed that the risk from the Eramet pipeline will be acceptable if it does not exceed 10^{-5} per year. However, as there are other risks in the area of the Eramet pipeline, e.g. other pipelines in the pipe rack, the entire acceptance criteria cannot be used by the Eramet pipeline alone. A conservative assumption would be to assume that 10% of the total allowed risk can be taken up by the Eramet pipeline, corresponding to 10^{-6} per year.

The Eramet pipeline RAC is very conservative as it is based on requirements for 3rd party personnel.

8 HAZARD IDENTIFICATION

The identification of hazards of the present risk analysis is based on the HAZID carried out in the FEED project for the E-fuel plant [8]. Furthermore, have MAHs been identified in the previous risk analyses [1] [2] [3].

Furthermore, experience from previous conducted risk analyses for process plants by ORS and similar facilities and information from NEF and HIP “storulykkeanlegg” ” [9] [10] [11] [12] [13] has been applied.

In the present risk assessment focus is on MAHs in relation to loss of containment from E-Fuel plant, Eramet feed gas discharge pipeline and Eramet feed gas compressor station. Loss of containment from the Eramet feed gas suction pipeline is not considered a MAH as this part of the pipeline is operating below atmospheric pressure and can therefore not result in a significant release.

8.1 E-FUEL PLANT

8.1.1 HAZARDS AND POTENTIAL CONSEQUENCES OF OUTDOOR RELEASES

Loss of containment can occur for the outdoor process from a number of causes e.g.:

- Corrosion;
- Fatigue e.g. vibrations;
- External impact;
- Design failure;
- Maintenance failure;
- Operation failure;
- Human failure.

The outdoor E-Fuel plant is processing toxic and flammable gases e.g. syn gas and hydrogen. For part of the process the fluids are processed above their auto ignition temperature, meaning that in case of a leakage ignition will almost certainly occur.

Loss of containment of the outdoor process releases can therefore lead to toxic CO gas releases. If a syn gas or hydrogen release is ignited the outcome can be jet fires, flash fires or vapor cloud explosions (VCE). As the releases will be out in the open is VCE less likely to occur.

Pool fire can also occur in relation to loss of containment of the storage tanks with LFTL and HFTL or from other hydrocarbon liquid spills in the process.

Boiling liquid expanding vapour explosion (BLEVE) scenarios from E-Fuel plant is not considered a credible scenario. The only tanks with a large liquid content are the LFTL and HFTL storage tanks. It is very unlikely that a BLEVE can form with such relatively heavy components as it will require a long duration fire exposure of the storage tanks.

LFTL and HFTL spills can also occur due to hose operation in relation to filling operations where the storage tanks are offloaded to a tank wagon. Such spills will in worst case lead to local pool fire if ignition occur. The scenarios are not expected to develop into a MAH and will therefore not be modelled explicitly.

The tank wagon itself is not likely to cause a BLEVE in case it is engulfed in a fire. The wagon will be designed with overpressure relief and can most likely be moved away from any fire exposure. Considering the vessel is only present at the plant intermittently the risk of tank wagon fire is not modelled quantitatively. This is consistent with the normal approach of this kind of risk analyses.

8.1.2 HAZARDS AND POTENTIAL CONSEQUENCES OF INDOOR RELEASES

Hydrogen releases can occur inside the electrolysis building. If ignition take place fire and explosion can occur. As the release occurs inside a confined building the risk of an explosion causing significant blast loads are considered significantly higher than for outdoor releases.

8.1.3 DOMINO EFFECTS

For outdoor fires and explosions of E-fuel plant process releases there is a risk of escalation to the storage tanks causing a pool fire. A process release fire or explosion could also expose other parts of the process. It is however doubtful that this will lead to a major escalation compared to the initiating event due to the limited process inventories of the E-Fuel plant.

Outdoor process fires and explosions could also cause exposure of neighbours. Of especially concern is the Yara ammonia storage tank, Yara wax tanks at Building 235, and the PVC factory.

Flammable gas releases from E-Fuel plant outdoor process releases could perhaps also reach Building 95's HVAC air intakes. This may be able to cause a shutdown resulting in loss of Main Power for a large part of the HIP. This scenario will be investigated and discussed further.

PVC is stored in tents close to the E-Fuel plant. It can therefore not be ruled out that a fire on E-Fuel plant can escalated into a fire in the PVC storage. This will be analysed further later in the report.

A pool fire in the storage tanks bund could lead to critical exposure of the E-fuel process and/or Yara wax tanks causing escalation if the pool fire is not extinguished. Escalation to the E-Fuel process is probably not a major escalation compared to the initiating pool fire due to limited inventories of the process. However, an escalation to Yara wax tanks causing a fire in the wax tanks would be considered a major escalation.

Hydrogen explosions inside the electrolysis building would cause major escalations if the blast loads are able to cause structural failure of the building, impair the central control room (CCR) of the E-fuel plant, and/or expose personnel in the administration building. As discussed later the electrolysis building will be designed to survive dimensioning explosion load to avoid such escalation.

Domino effects could also occur from neighbouring plants with MAH potential e.g. Yara ammonia storage tank, Yara wax tanks, VCM storage at PVC plant, LPG storage etc. The exposure could be in the form of heat radiation from fires, blast loads or flying fragments from VCEs and BLEVEs.

The risk of domino effects has been analysed in Section 16.

8.2 ERAMET COMPRESSOR STATION

40 bar releases of toxic and flammable CO rich gas can occur from the compressor station. For an unignited release personnel could be exposed to toxic CO. For ignited releases personnel could be exposed to jet fire, flash fire or VCE.

This is similar to the situation for releases from the E-Fuel plants outdoor process.

It cannot be ruled out that fire and explosions may impact and damage neighbouring buildings, but none of the neighbours has a MAH potential. Hence a major escalation of the initial event is not possible (domino effect).

Flammable gas releases from the E-Fuel plant outdoor process could perhaps also reach Building 162 & 162a HVAC air intakes. This may be able to cause a shutdown, resulting in loss of Main Power for a large part of the HIP. This scenario will be investigated and discussed further.

8.3 ERAMET DISCHARGE PIPELINE

40 bar releases of toxic and flammable CO rich gas can occur from the Eramet discharge pipeline. For an unignited release personnel could be exposed to toxic CO. For ignited releases personnel could be exposed to jet fire, flash fire or VCE.

The pipeline runs through large parts of HIP and can therefore potentially lead to exposure of many different plants and buildings.

8.4 HIP PIPE BRIDGES

Pipe bridges are running along the boundaries of the E-Fuel plant and compressor station. Some of bridge piping may contain flammable and/or toxic material such as liquid ammonia or natural gas. Hence in case a fire or explosion of E-Fuel plant or compressor station causes rupture of such bridge piping an escalation or domino effect can occur.

An ignited loss of containment scenario of such bridge piping can also impact E-Fuel plant or compressor station leading to domino effects.

The Eramet pipeline will share pipe rack bridge with a number of different pipelines. In case of loss of containment and ignition, these different pipelines may effect each other leading to domino effects.

Domino effects of pipe bridges in HIP potentially impacted by the E-Fuel plant project will be investigated in the present risk analysis. Especially release of liquid ammonia is considered a concern in other risk analyses of HIP.

8.5 OTHER HAZARDS

8.5.1 AIR INGRESS INTO ERAMET SUCTION PIPELINE

The Eramet suction pipeline between Eramet and the compressor station will be running with a slight overpressure close to atmospheric pressure. However, it cannot be ruled out that part of the pipeline can run with underpressure. In case of a leakage, it is therefore a possibility that air is sucked into the pipeline and that an explosive mixture could form inside the pipeline. In case of ignition somewhere in the closed system this could cause an internal explosion.

In worst case the Eramet gas will consist of up to 10 mol% hydrogen and 73 mol% CO and the remaining being inert CO_2 and N_2. The resulting LFL is 11.7 vol%, and UFL 90.4 vol% in air. The pipeline flowrate is approximately 0.75 kg/s.

Conservatively assuming 0.9 bar inside the pipeline at location of a leakage, rough calculations indicate that a flammable mixture can occur for a leak size in the interval 26 to 222 mm. This means a significant leak size is required and that minor leaks will not be able to form a flammable mixture.

Furthermore, the explosive mixture will primarily consist of CO rather than H_2. CO is significantly less reactive than CO and is therefore likely to result in low blast loads. Whether internal explosions will be able to cause problems or just be contained by the system will depend on the design pressure of the Eramet suction pipeline. If the design pressure is 10 barg or higher an internal explosion is not likely to be able to damage the system.

In no event will the internal explosion be able to lead to a MAH that can threaten 3rd party or cause domini effects. The hazard is not considered a major issue at present but shall be re-visited in relation to the HAZOP of the Eramet pipeline and compressor station design.

8.5.2 CATALYST ACTIVATION AN REJEUVENATION

Emerging Fuels recommends performing so-called rejuvenation of catalyst regularly in addition to activation of the catalyst when it is replaced every 3 year.

On a yearly average the following activation and rejuvenation is expected:

1. 108 hours with 30 mol% H_2 and 70 mol% Argon at pressure of 25 bara and temperature of 168 ^oC takes place.
2. 81 hours with 50 mol% H_2 and 50 mol% Argon at pressure of 25 bara and temperature of 260 ^oC takes place.

Loss of containment from these operations will not be modelled explicitly for two reasons:

1. The activation and rejuvenation processes only take place for a small fraction of time and the likelihood of a release is therefore smaller than during normal operation.

2. The hydrogen content of the FT gas in normal operation has a hydrogen content of 50% or above and the gas is at a similar pressure, Hence the consequences of a release during activation and rejuvenation is implicitly addressed in the consequence modelling performed for normal operation.

8.5.3 TRANSFORMER FIRE AND EXPLOSION

Transformer tank burst scenarios can occur due to internal short circuit heating up the transformer oil generating pyrolysis gas that ignites. According to the CRA, transformer fires occur with a frequency of $4.6 \cdot 10^{-6}$ per transformer year [1]. Considering the number of transformers in the electrolysis building the frequency is still well below 10^{-4} per year normally used for probabilistic explosion DeALs.

Furthermore, is it planned to specify the transformers to apply MIDEL as coolant instead of traditional mineral oils, which has a flash point >260˚C. This will reduce both the probability and consequences of a transformer explosion.

With the low transformer explosion risk no transformer explosion DeAL will be applied for the building. There will be a large opening into the individual transformer in the buildings 4-5 m from a pipe rack to the west. Due the large opening in transformer building it is not considered necessary to install explosion relief panels in the roof as suggested in the CRA [1]. Such explosion relief would not prevent the explosion from exposing the pipe rack. Considering the low probability of explosion, the risk to pipe rack explosion exposure is considered acceptable. Furthermore, the pipe rack is well supported and will only be exposed to drag loads some distance from the transformer and it expected to survive most explosions.

8.5.4 EXTERNAL IMPACT

There is a risk of collision from vehicles colliding directly with personnel, or critical equipment resulting in loss of containment of flammable and toxic material. This risk will be managed in detailed design.

Dropped or swinging objects from lifting operations could also hit personnel or critical equipment. Again, these risks are not critical for the FEED project but should be investigated as part of detailed design. This also includes risk in relation to constructing and installing the E-Fuel plant.

8.5.5 OCCUPATIONAL RISKS

Occupational risk from everyday work activities cannot be avoided but can be reduced by effective HSE management on site. Occupational risk management will however not impact the FEED project design and has therefore not been considered at the present stage. Occupational risks need to be considered in the detailed design.

9 SELECTION OF SCENARIOS

In this section the scenarios to be modelled in this risk analysis has been identified.

9.1 E-FUEL PLANT

The following loss of containment scenarios has been considered for the E-Fuel plant:

- Outdoor release of Eramet feed gas;
- Outdoor release of hydrogen for the syn gas production;
- Release of hydrogen inside electrolysis building;
- Outdoor release of gas from Ammonia Removal unit;
- Outdoor release of gas from FT Process;
- Outdoor release of gas from FT Reactor;
- Outdoor release of gas from FT scrubber;
- Outdoor release of recycled tail gas to syn gas production;
- Outdoor release of syn gas;
- Release of LFTL/HFTL liquid from storage tanks.

Six different leak sizes are modelled for the outdoor release scenarios:

- 0.1 kg/s leakage rate;
- 0.5 kg/s leakage rate;
- 1 kg/s leakage rate;
- 5 kg/s leakage rate;
- 10 kg/s leakage rate;
- Full bore rupture leakage rate.

This gives a good resolution of the potential loss of containment scenarios.

The leak scenarios will be considered for three different wind conditions:

- Low wind: 1.5 m/s Pasquill Stability class for moderately stable conditions (1.5F);
- Medium wind: 5 m/s Pasquill Stability class for neutral conditions (5D);
- High wind: 10 m/s Pasquill Stability class for neutral conditions (10D).

For each of the above leakage scenarios both early and late ignition, as well as unignited releases, will be considered resulting in the below potential consequence outcomes:

- Flammable gas dispersion;
- Toxic CO dispersion;
- Jet fire;
- Flash fire;
- Vapour Cloud Explosion (VCE);
- Liquid pool fire (if liquid is part of the release).

All releases are assumed to be horizontal in 1 m height.

9.2 COMPRESSOR STATION

Loss of containment of Eramet feed gas can occur. Six different leak sizes are modelled for the outdoor release scenarios:

- 0.01 kg/s leakage rate;
- 0.05 kg/s leakage rate;
- 0.1 kg/s leakage rate;
- 0.5 kg/s leakage rate;
- 1 kg/s leakage rate;
- Full bore rupture leakage rate.

The leak scenarios will be considered for three different wind conditions:

- Low wind: 1.5 m/s Pasquill Stability class for moderately stable conditions (1.5F);
- Medium wind: 6 m/s Pasquill Stability class for neutral conditions (6D);
- High wind: 10 m/s Pasquill Stability class for neutral conditions (10D).

For each of the above leakage scenarios both early and late ignition, as well as unignited releases, will be considered resulting in the below potential consequence outcomes:

- Flammable gas dispersion;
- Toxic CO dispersion;
- Jet fire;
- Flash fire;
- Vapour Cloud Explosion (VCE);

All releases are assumed to be horizontal in 1 m height.

9.3 ERAMET DISCHARGE PIPELINE

Loss of containment of Eramet feed gas can occur. Six different leak sizes are modelled for the outdoor release scenarios:

- 0.01 kg/s leakage rate;
- 0.05 kg/s leakage rate;
- 0.1 kg/s leakage rate;
- 0.5 kg/s leakage rate;
- 1 kg/s leakage rate:
- Full bore rupture leakage rate.

Lower leakage rates have been considered for the Eramet pipeline compared to E-Fuel plant and compressor station since a small leakage can go unnoticed (no gas detection along pipeline) for a significant time but still potentially be toxic. The focus has therefore been on smaller leakages.

The leak scenarios will be considered for three different wind conditions:

- Low wind: 1.5 m/s Pasquill Stability class for moderately stable conditions (1.5F);
- Medium wind: 6 m/s Pasquill Stability class for neutral conditions (6D);
- High wind: 10 m/s Pasquill Stability class for neutral conditions (10D).

For each of the above leakage scenarios both early and late ignition, as well as unignited releases, will be considered resulting in the below potential consequence outcomes:

- Flammable gas dispersion;
- Toxic CO dispersion;
- Jet fire;
- Flash fire;
- Vapour Cloud Explosion (VCE);

The Eramet pipeline is expected to be routed in minimum 5 meters height, based on other pipe racks seen at the E-fuel plant. As personnel will normally be located below 2 m above ground, the toxic gas must reach such low levels to cause a risk. Consequence simulations will be performed for releases in 5 m height.

In reality, the pipeline will likely be routed at even higher heights for large part of the pipeline routing.

The releases from a pipeline can be in different directions along the cross sections as illustrated in Figure 9-1.

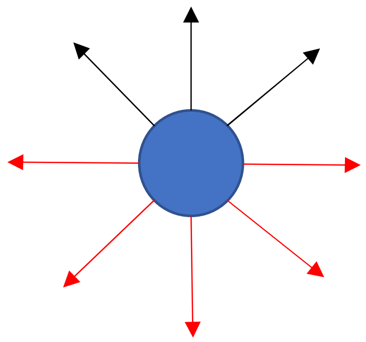

Figure 9-1 Different release directions for the pipeline relative the pipeline cross section

For the consequence analysis releases in eight different directions divided by 45 deg. angles will be considered. Only the red release directions are considered potential hazardous to personnel and needs to be considered. Hence consequences will be assessed for horizontal releases, 45˚ downward pointing releases and vertical downward pointing releases.

10 LEAK FREQUENCIES

Leak frequencies has primarily been based on the PLOFAM2 methodology [14] that has been referenced in the DSB QRA guideline [5]. The PLOFAM2 methodology has been developed for offshore QRA but has also been recommended for onshore process facilities.

Loss of containment (accidental releases) could be caused by various causes such as:
- External forces (e.g. collision, land slide);
- Overfilling, resulting in overflow or overpressure of tanks;
- Failing temperature control (overpressure);
- Breaking of piping;
- Design fault;
- Aging equipment;
- Corrosion;
- Vibrations/fatigue;
- Lack of maintenance;
- Failure to operate as intended (human error).

The release rate and duration depend on the hole size and where in the process the leak occurs (segment pressure, temperature, composition and inventory).

Leakage frequencies has been established based on a detailed component count on the FEED P&IDs. As the P&IDs are not complete a new count is recommended in detailed design.

For the electrolysis and associated equipment inside the electrolysis building detailed P&IDs have not been available in the FEED. Instead, a component count has been estimated based on P&IDs for similar projects and engineering judgment.

10.1 E-FUEL PLANT

Leak frequencies for loss of containment scenarios for the outdoor process area have been summarized in Table 10-1.

Table 10-1 Leak frequencies for outdoor process area

Leak frequencies [per year]							
Segment	Leak sizes						
	0.1 kg/s	**0.5 kg/s**	**1 kg/s**	**5 kg/s**	**10 kg/s**	**FBR**	**Sum**
1 - Erament Gas Feed	2.0E-03	7.0E-04	1.3E-03	8.6E-05	7.1E-05	1.9E-05	**4.1E-03**
2 - Hydrogen to syn gas production	2.1E-04	5.6E-05	4.0E-04	-	-	5.7E-06	**6.7E-04**
3 - Ammonia Removal Unit	5.1E-04	1.6E-04	1.2E-04	3.6E-05	1.4E-05	8.3E-06	**8.6E-04**
4 - Fischer Tropsch Process	5.7E-03	5.8E-03	5.8E-04	2.8E-04	3.4E-04	3.4E-05	**1.3E-02**
5 - Fischer Tropsch Reactor	8.0E-04	3.6E-05	2.1E-05	3.1E-05	1.5E-06	3.1E-06	**8.9E-04**
6 - Fischer Tropsch Scrubber	2.0E-03	7.0E-04	1.1E-03	2.5E-04	6.4E-05	6.5E-05	**4.2E-03**
7 - Recycled Tail Gas to Syn Gas Production	1.6E-04	5.0E-05	2.9E-05	1.4E-05	5.6E-06	1.5E-05	**2.7E-04**
8 - LFTL Storage and Offloading	1.2E-03	4.5E-04	8.5E-04	5.3E-05	2.1E-05	9.4E-05	**2.7E-03**
9 - HFTL Storage and Offloading	1.2E-03	4.7E-04	5.1E-05	5.3E-05	2.1E-05	9.4E-05	**1.9E-03**
10.1 - Syn Gas Production (H2+Recycle Gas)	1.1E-03	8.6E-04	1.2E-04	1.3E-04	6.7E-06	2.3E-05	**2.2E-03**
10.2 - Syn Gas Production (Dry Syngas	3.3E-04	2.2E-04	3.1E-05	1.5E-05	5.6E-06	9.3E-06	**6.0E-04**
Total	**1.5E-02**	**9.5E-03**	**4.7E-03**	**9.5E-04**	**5.5E-04**	**3.7E-04**	**3.1E-02**

For hydrogen releases inside the electrolysis building another leak size distribution has been applied than for outdoor releases as dispersion analysis in FLACS has been carried out rather than PHAST simulations. The investigated leak categories and release frequencies has been provided in Table 10-2.

Table 10-2 Leak size categories and associated release frequencies for hydrogen releases inside the electrolysis building

Leak category	Leak interval [kg/s]	Rep. leak size [kg/s]	Frequency [per year]
Small	0.1-0.3	0.2	1.36E-2
Medium	0.3-0.7	0.5	6.19E-3
Large	0.7-1.4	1.05	1.82E-4
Full bore rupture	Note 1	Note 1	1.14E-4

Note 1: Full bore rupture is assumed as 2" for determining the mass flow (a larger size is not expected to change the outcome as the entire inventory will be lost immediately followed by the hydrogen production rate until shutdown.

It is important to note that detailed P&IDs have not been available in FEED for the electrolysis equipment as several different vendors are still being evaluated. Hence the component count has been based on a typical PFD (McPhy proposal) and P&IDs for other projects of similar systems together with some safety factors. The release frequencies are therefore very uncertain but are believed to be to the conservative side.

10.2 COMPRESSOR STATION

Leak frequencies for loss of containment scenarios for the compressor station have been summarized in Table 10-3.

Table 10-3 Leak size categories and associated release frequencies for loss of containment for compressor station

Compressor station	
Leak scenario [kg/s]	Rel. freq [per year]
0.01	8.84E-03
0.05	2.91E-03
0.1	2.24E-03
0.5	8.30E-04
1	1.86E-04
40.54	2.57E-05

10.3 ERAMET DISCHARGE PIPELINE

The Eramet pipeline is assumed to be fully welded and is assumed not to have any leak sources such as flanges, valves or instruments.

Release frequencies of fully welded piping is in many respects considered negligible i.e. in ATEX/hazardous area classification (HAC) fully welded piping is normally ignored as a credible release source [23]. However, release accident statistics shows that fully welded piping can also leak, and therefore this scenario needs to be addressed in the present risk analysis.

PLOFAM(2) [14] and IOGP pipeline data [15] based on PARLOC 2012 [16] have been considered for determining release frequencies for the different leak sizes.

PLOFAM(2) release frequencies for the modelled leakage scenarios per meter piping has been established in Table 10-4.

Table 10-4 PLOFAM(2) leakage frequencies per meter discharge pipeline for different leak sizes

Discharge pipeline		
Leak scenario [kg/s]	**Rep. leak rate [kg/s]**	**Leak frequency [per meter per year]**
0 - 0.03	0.01	4.44E-06
0.03 - 0.075	0.05	1.79E-07
0.075 - 0.3	0.1	1.12E-07
0.3 - 0.75	0.5	2.86E-08
0.75 - 1.5	1	1.14E-08
Full bore rupture	40.54	1.60E-08

However, PLOFAM(2) is applicable for process piping and not pipelines. Pipelines have normally much less bending and welds and are typically designed to other design codes than process piping.

Hence it is expected to be very conservative to apply PLOFAM(2) data. This expectation has been confirmed by comparing with the IOGP data specifically for pipelines which indicates that the leak frequency of onshore pipelines is a factor 11-12 lower than that of PLOFAM(2). Unfortunately, the leak size distribution is not as well defined in the IOGP/PARLOC data as in PLOFAM(2) and it is therefore difficult to apply these data directly in the present analysis especially as very small leak sizes can be harmful due to the significant toxicity of CO.

It has therefore been decided to apply the PLOFAM(2) model with a **factor 10** reduction as the base case of the present risk analysis. Due to the uncertainty of this assumption a sensitivity of applying PLOFAM(2) without any reduction has also been considered, see Section 15.1.3.1.

Further justification for the factor 10 reduction in PLOFAM release frequencies for onshore pipelines have been provided below:

- The PLOFAM model has been developed for offshore piping systems and process equipment, based on extensive experience data from oil and gas facilities on the Norwegian Continental Shelf;
- The methodology may be used for less complex onshore pipelines providing that differences to offshore piping systems are properly addressed.;
- An offshore piping system is geometrically substantially more complex than a pipeline:
  - Risk for welding defects is higher;
  - Non-destructive evaluation (NDE) is more difficult to perform;
  - Coating is more difficult;
  - In-service inspection and maintenance are more complex;
- The weld density (number of welds per unit pipe length) is considerably smaller for a pipeline, tentatively by a factor 3;
- Fatigue is not a relevant cause of failure for a pipeline;
- Risk of corrosion is higher in an offshore environment than at a land-based, albeit coastally located plant.

Some expectations for the Eramet pipeline design justifying a low leak frequency are listed below:

- Selection of a material with higher strength and/or corrosion resistance than required for the actual service conditions (i.e. 22 Cr duplex SS in lieu of SS 316);
- Increase in wall thickness of pipes from the minimum wall thickness due to strictly following the design code;
- Use of seamless pipes to eliminate the risk of leakage in longitudinal weld seams;
- Increase the non-destructive evaluation (NDE) to 100% surface and 100% volumetric control.
- Avoid crevices.
- Apply coating, even if this is not strictly required by environmental conditions;

- Perform coating of spools in workshop under controlled conditions and only coat installation weld areas during installation.

11 IGNITION PROBABILITIES AND FIRE FREQUENCIES

In case of a gas or liquid leakage it is necessary to determine the ignition probability in order to predict the frequency of fires and explosions.

The Energy Institute (EI) developed an ignition model via an IP Research Project in 2006 and updated it in 2019 [24]. A full model was developed where the user could model scenarios in great detail. The full model is very complicated to apply in practice for QRA calculations. Therefore, a number of simple ignition probability look-up correlations have been developed based on the full model that covers a wide range of offshore and onshore applications. The correlations are very easy to apply and are popular for onshore and offshore QRA in many regions of the world. It is promoted by IOGP (therefore termed OGP model) [17]. The model is also referenced in DSB guidance [5].

The IOGP reports ignition probabilities for different types of releases. The relevant scenarios for the e-fuel plant are presented in Table 11-1 (scenario 8 and 11 for gas leaks and scenario 30 for storage tank pool fire).

Table 11-1 IOGP – Relevant scenarios for the e-fuel plant [17]

Scenario No.	Look-up Release Type	Application
8	Large Plant Gas LPG (Gas or LPG release from large onshore plant)	Releases of flammable gases, vapour or liquids significantly above their normal (NAP) boiling point from large onshore outdoor plants (plant area above 1200 m2, site area above 35,000 m2).
11	Large Plant Congested Gas LPG (Gas or LPG released from a large confined or congested onshore plant)	Releases of flammable gases, vapour or liquids significantly above their normal (NAP) boiling point from large onshore plants (plant area above 1200 m2, site area above 35,000 m2), where the plant is partially walled/roofed or within a shelter or very congested.
30	Tank Liquid – diesel fuel oil (Liquid Release from onshore tank farm of liquids below their flash point, e.g. diesel or fuel oil)	Releases of combustible liquids stored at ambient pressure and at temperatures below their flash point (e.g. most gas, oil, diesel and fuel oil storage tanks) from onshore outdoor storage area "tank farm". This look-up correlation can be applied to releases from tanks and low pressure transfer lines or pumps in the tank farm/ storage area. However, it should not be used for high-pressure systems (over a few barg): in these situations use curve No. 12 "Tank Liquid 300m x 300m Bund" or curve No. 13 "Tank Liquid 100 x 100m Bund"

The ignition correlations of Table 11-1 is illustrated graphically in Figure 11-1.

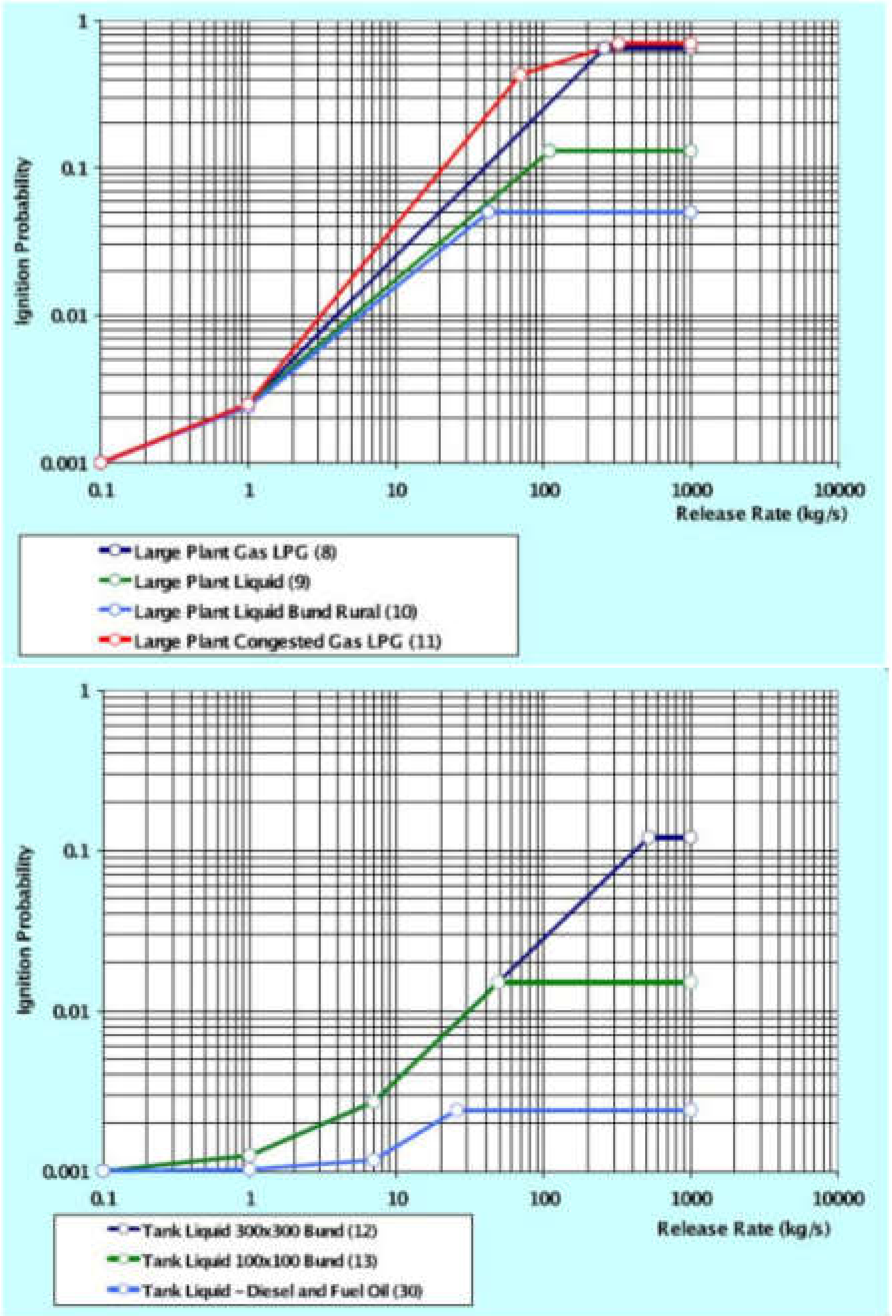

Figure 11-1 IOGP ignition correlations for scenarios relevant for e-fuel plant [17]

The IOGP ignition model is considered to be too optimistic for hydrogen releases. Hence for hydrogen releases the HYEX ignition model will be applied instead [5]. The HYEX ignition model has been illustrated in Figure 11-2.

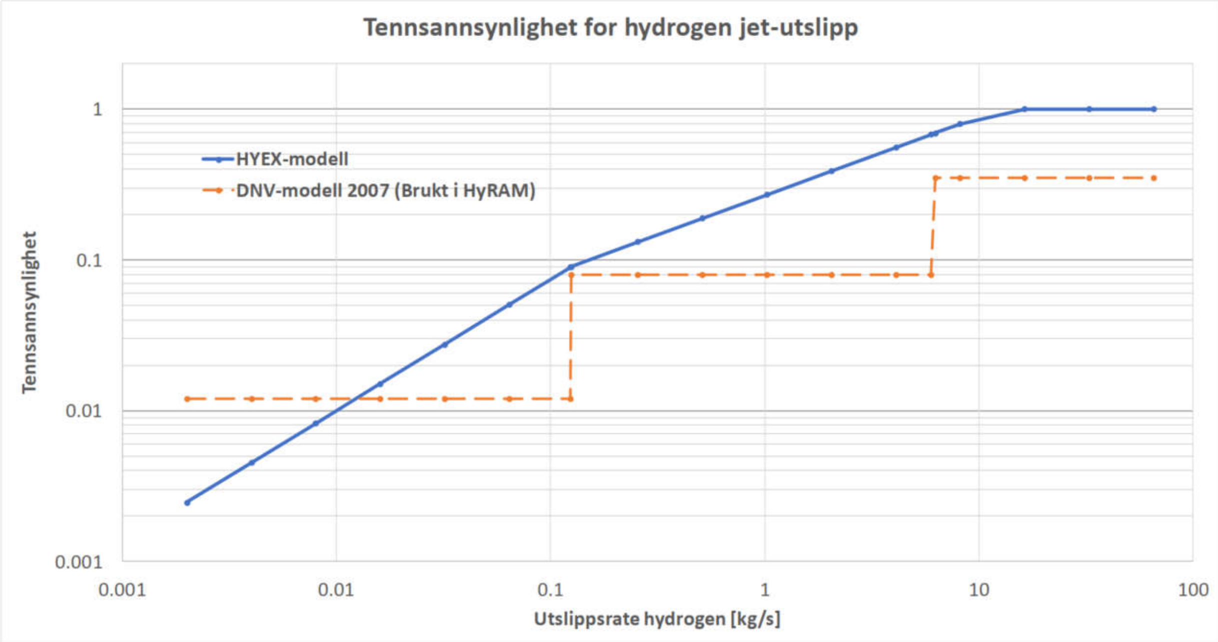

Figure 11-2 HYEX ignition probability model for hydrogen releases [5]

Flammable substances released above their auto-ignition temperature are likely to ignite on release and has been modelled as having an ignition probability of 1 (one).

11.1 E-FUEL PLANT

Ignition probabilities for outdoor process loss of containment scenarios have been summarized in Table 11-2.

Table 11-2 Ignition probabilities for outdoor process loss of containment scenarios

Ignition probabilities [--]						
Segment	**Leak sizes**					
	0.1 kg/s	**0.5 kg/s**	**1 kg/s**	**5 kg/s**	**10 kg/s**	**FBR**
1 - Erament Gas Feed	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	1.29E-01
2 - Hydrogen to syn gas production	7.42E-02	1.86E-01	2.67E-01	-	-	4.89E-01
3 - Ammonia Removal Unit	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	2.92E-01
4 - Fischer Tropsch Process	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	3.16E-01
5 - Fischer Tropsch Reactor	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	1.23E-01
6 - Fischer Tropsch Scrubber	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	7.77E-02
7 - Recycled Tail Gas to Syn Gas Production	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	7.77E-02
8- LFTL Storage and Offloading	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	4.69E-02
9- HFTL Storage and Offloading	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	4.87E-02
10.1 - Syn Gas Production (H2+Recycle Gas)	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
10.2 - Syn Gas Production (Dry Syngas	1.10E-03	1.95E-03	2.50E-03	1.25E-02	2.50E-02	2.01E-01

The fire frequencies (incl. explosions) for outdoor process loss of containment scenarios have been calculated based on Table 10-1 and Table 11-2. The fire frequencies have been summarized in Table 11-3.

Table 11-3 Fire frequencies incl. explosion for outdoor process loss of containment scenarios

Fire frequencies [per year]							
Segment	**Leak sizes**						
	0.1 kg/s	**0.5 kg/s**	**1 kg/s**	**5 kg/s**	**10 kg/s**	**FBR**	**Sum**
1 - Erament Gas Feed	2.17E-06	1.36E-06	3.25E-06	1.08E-06	1.77E-06	2.41E-06	**1.20E-05**
2 - Hydrogen to syn gas production	1.54E-05	1.04E-05	1.07E-04	-	-	2.80E-06	**1.36E-04**
3 - Ammonia Removal Unit	5.65E-07	3.14E-07	3.07E-07	4.49E-07	3.37E-07	2.41E-06	**4.39E-06**
4 - Fischer Tropsch Process	6.25E-06	1.13E-05	1.45E-06	3.50E-06	8.60E-06	1.06E-05	**4.17E-05**
5 - Fischer Tropsch Reactor	8.75E-07	7.09E-08	5.25E-08	3.81E-07	3.82E-08	3.81E-07	**1.80E-06**
6 - Fischer Tropsch Scrubber	2.16E-06	1.37E-06	2.85E-06	3.14E-06	1.59E-06	5.07E-06	**1.62E-05**
7 - Recycled Tail Gas to Syn Gas Production	1.76E-07	9.67E-08	7.32E-08	1.80E-07	1.39E-07	1.19E-06	**1.85E-06**
8- LFTL Storage and Offloading	1.31E-06	8.69E-07	2.14E-06	6.59E-07	5.23E-07	4.40E-06	**9.90E-06**
9- HFTL Storage and Offloading	1.37E-06	9.15E-07	1.26E-07	6.65E-07	5.37E-07	4.57E-06	**8.18E-06**
10.1 - Syn Gas Production (H2+Recycle Gas)	1.06E-03	8.58E-04	1.23E-04	1.28E-04	6.71E-06	2.33E-05	**2.20E-03**
10.2 - Syn Gas Production (Dry Syngas	3.58E-07	4.20E-07	7.82E-08	1.85E-07	1.39E-07	1.86E-06	**3.04E-06**
Total	**1.09E-03**	**8.85E-04**	**2.40E-04**	**1.38E-04**	**2.04E-05**	**5.90E-05**	**2.43E-03**

Ignition probability calculated with the HYEX model for releases inside the electrolysis building has been provided in Table 11-4.

Table 11-4 Ignition probabilities for hydrogen releases inside the electrolysis building

Leak category	**Release rate**	**Ign. Prob.**
	[kg/s]	**[-]**
Small	0.2	0.116
Medium	0.5	0.186
Large	1.05	0.274
Full bore rupture	3.2	0.489

11.2 COMPRESSOR STATION

Ignition probabilities for compressor station loss of containment scenarios have been summarized in Table 11-5.

Table 11-5 Ignition probabilities for gas releases from compressor station

Rep. leak rate [kg/s]	**Ign. Prob. [-]**
0.01	1.00E-03
0.05	1.00E-03
0.1	1.10E-03
0.5	1.95E-03
1	2.50E-03
40.54	1.01E-01

The fire frequencies (incl. explosions) for compressor station loss of containment scenarios have been calculated based on Table 10-3 and Table 11-5. The fire frequencies have been summarized in Table 11-6.

Table 11-6 Fire frequencies incl. explosion for compressor station loss of containment scenarios

Rep. leak rate [kg/s]	Ign. Prob. [-]
0.01	1.00E-03
0.05	1.00E-03
0.1	1.10E-03
0.5	1.95E-03
1	2.50E-03
40.54	1.01E-01

11.3 ERAMENT DISCHARGE PIPELINE

Ignition probabilities for Eramet discharge pipeline loss of containment scenarios have been summarized in Table 11-7.

Table 11-7 Ignition probabilities for gas releases from Eramet discharge pipeline

Rep. leak rate [kg/s]	Ign. Prob. [-]
0.01	1.00E-03
0.05	1.00E-03
0.1	1.10E-03
0.5	1.95E-03
1	2.50E-03
40.54	1.01E-01

The fire frequencies (incl. explosions) for Eramet pipeline loss of containment scenarios have been calculated based on Table 10-4 and Table 11-7. The fire frequencies have been summarized in Table 11-8.

Table 11-8 Fire frequencies incl. explosion for Eramet discharge pipeline loss of containment scenarios

Discharge pipeline	
Rep. leak rate [kg/s]	Leak frequency [per meter per year]
0.01	4.44E-09
0.05	1.79E-10
0.1	1.23E-10
0.5	5.58E-11
1	2.85E-11
40.54	1.62E-09

12 CONSEQUENCES

12.1 E-FUEL PLANT

In the consequence analysis is the different identified release scenarios simulated with PHAST. The simulated consequences are:

- Flammable gas dispersion (10%, 50% and 100% LFL);
- CO concentrations (6547 ppm, 11784 ppm and 11784 ppm)
- Jet fire (flame length, 5 kW/m^2, 8.5 kW/m^2 and 14.5 kW/m^2);
- Flash fire (100% LFL cloud);
- Vapour Cloud Explosion (VCE) (0.02 bar, 0.05 bar, 0.1 bar, 0.15 bar 0.2 bar, 0.5 bar, 0.75 bar and 1 bar);
- Liquid pool fire (if liquid is part of the release) (flame height, 5 kW/m^2, 8.5 kW/m^2 and 14.5 kW/m^2).

The consequence analysis results has been included in Appendix A and B.

The results of Appendix A are useful for investigating required evacuation distances, safety distance for installing new equipment, investigating potential consequences of near misses or just to get a general feel for the potential consequences of the facility.

In addition to the PHAST simulation results were a few CFD simulation performed as part of the CRA [1] that provides a good visual impression of potential consequences.

12.1.1 FLAMMABLE GAS CONSEQUENCES

In the CRA [1] flammable (20% LFL) was investigated by CFD for medium (4 kg/s) and large releases (21 kg/s) for different wind directions. Even though the plant layout has changed in the FEED the results are still considered relevant. The simulation results have been shown in Figure 12-1, Figure 12-2 and Figure 12-3 respectively.

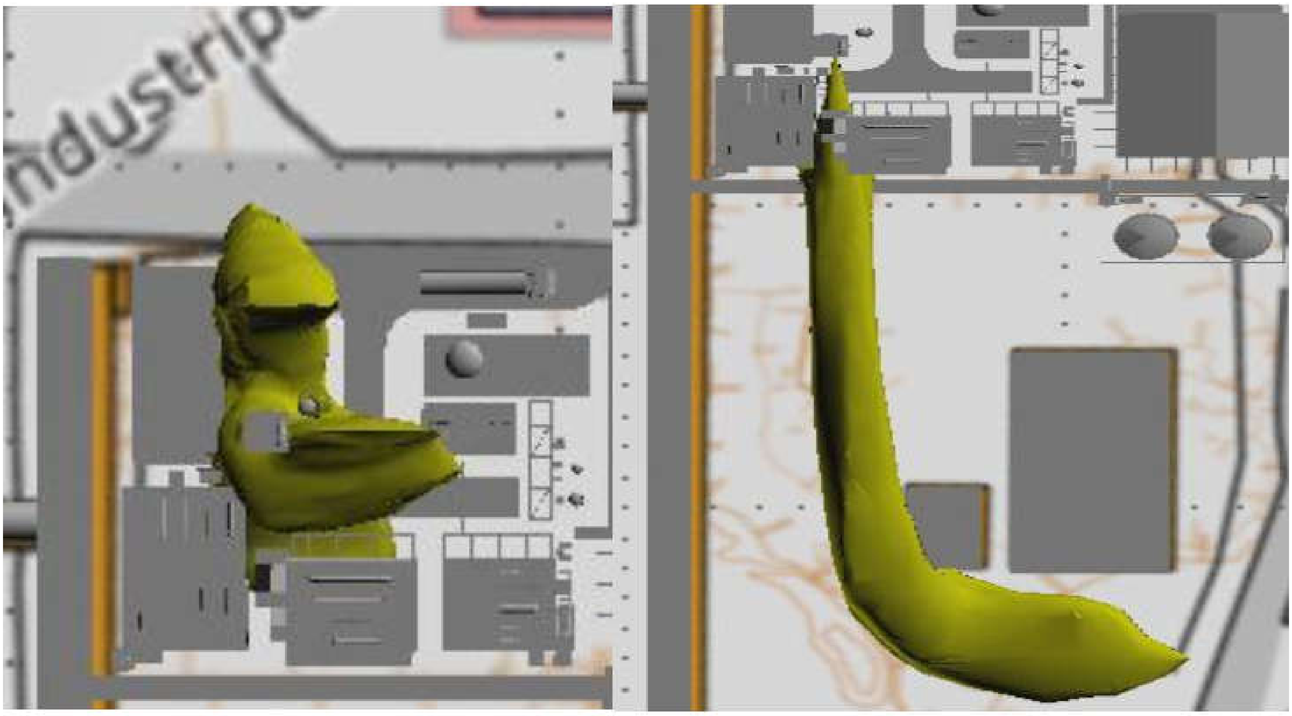

Figure 12-1 CFD simulation results of 20% LFL cloud. The left picture shows 4 kg/s leakage from FT reactor with 5 m/s wind blowing from W. The right picture shows 21 kg/s leakage from FT reactor with 5 m/s wind blowing from W [1].

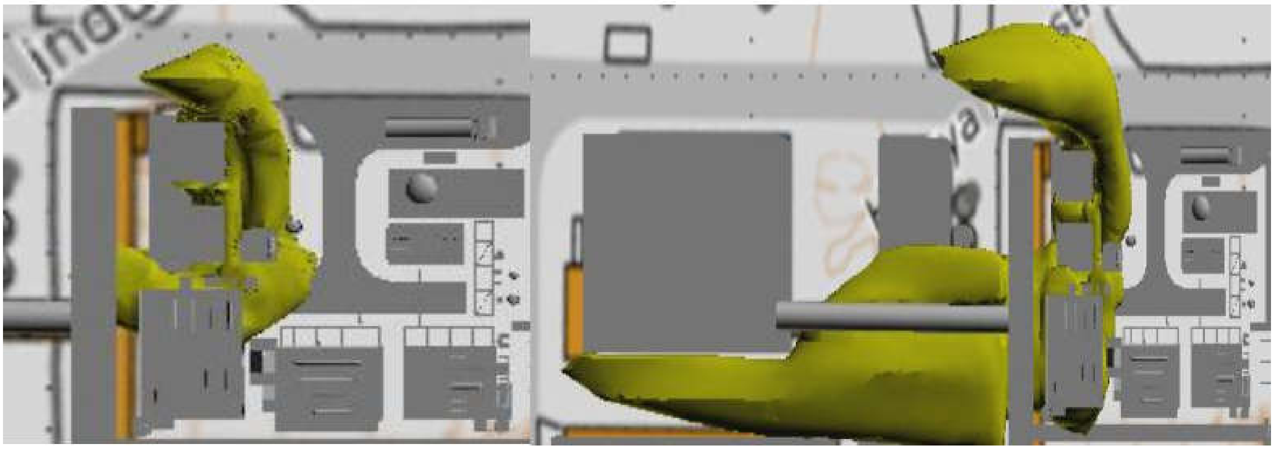

Figure 12-2 CFD simulation results of 20% LFL cloud. The left picture shows 4 kg/s leakage from FT reactor with 5 m/s wind blowing from E. The right picture shows 21 kg/s leakage from FT reactor with 5 m/s wind blowing from E [1].

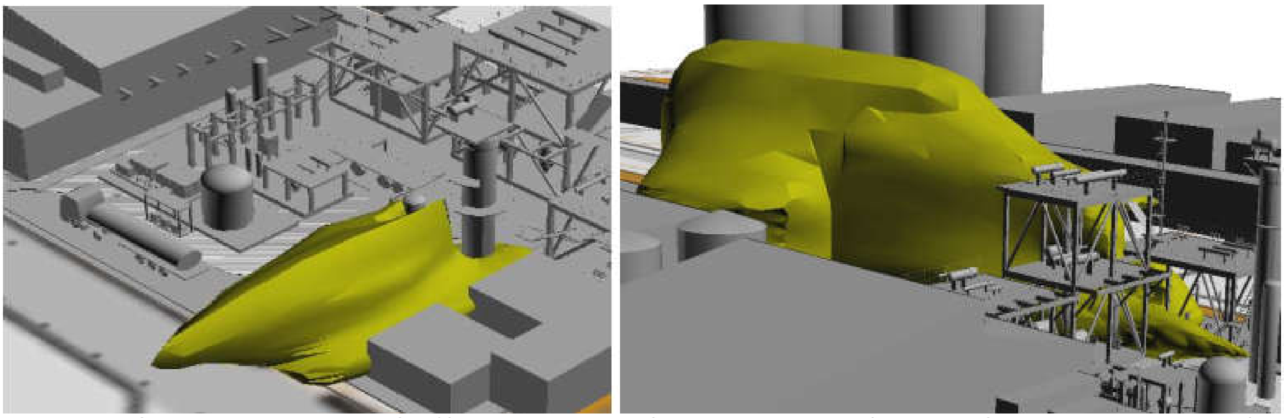

Figure 12-3 CFD simulation results of 20% LFL cloud. The left picture shows 4 kg/s leakage from FT reactor with 5 m/s wind blowing from S. The right picture shows 21 kg/s leakage from FT reactor with 5 m/s wind blowing from S [1].

It is apparent that flammable gas can have a significant reach for large releases. The results have been summarized in Figure 12-4.

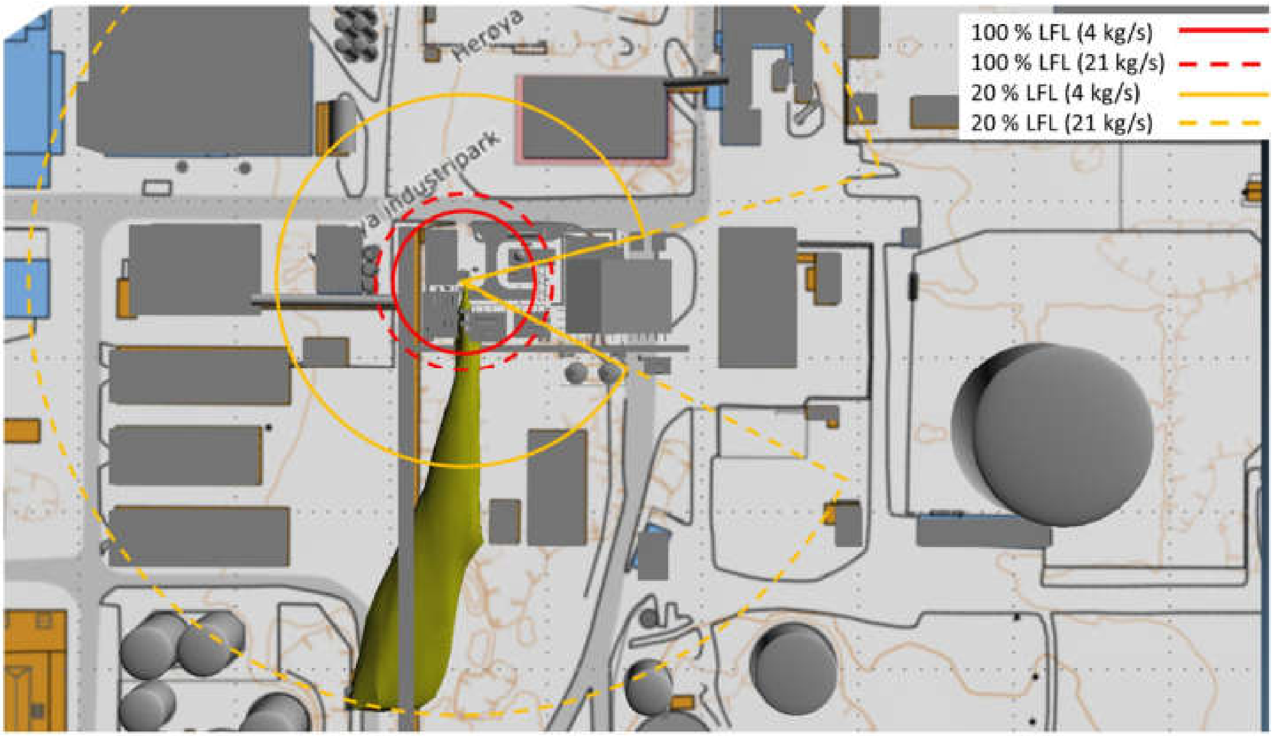

Figure 12-4 Summary of horizontal extend of 20% and 100% LFL cloud for different gas release rates from FT reactor (approximated and simplified). Contours can be moved around depending on leak location [1].

From Figure 12-4 it is apparent that:

- A release in one part of the E-Fuel plant will have the potential to expose other parts of the E-Fuel plant to above 100% LFL, including the non-hydrocarbon systems. There is simply not enough separation in-between the modules to avoid flammable gas exposure;
- The 100% LFL can also expose areas outside the E-Fuel plant, but it is only seen to extend a few meters outside the battery limits;
- The 100% LFL gas cloud is less affected by the wind and more affected by the release location and direction;
- The 20% LFL clouds extend further outside the e-fuel plant battery limits. Areas within a 150 m radius can be exposed (depending on leak location and direction, and wind speed and direction). The exception is areas East of the electrolysis building, like building 95 (HV building). These areas are less exposed as the electrolysis building acts as a barrier that limits the spread of gas in that direction. The air intakes for building 95 are not likely to become exposed to above 100% LFL gas. In most release scenarios the air intakes will not be exposed to 20% LFL. Figure 12-5 shows an example of the extent of the 20% LFL clouds in eastern direction;
- The HVAC air intakes for the electrolysis building can potentially become exposed to 20% LFL gas. F&G detection with shutdown of fire dampers should be implemented as the HVAC supplies the control room, which needs to stay operational in an emergency.

Flammable gas (100% LFL) will not be able to extend significantly outside the E-Fuel boundary. The 20% LFL cloud can however extend significantly beyond the site boundary and potentially impact neighbours.

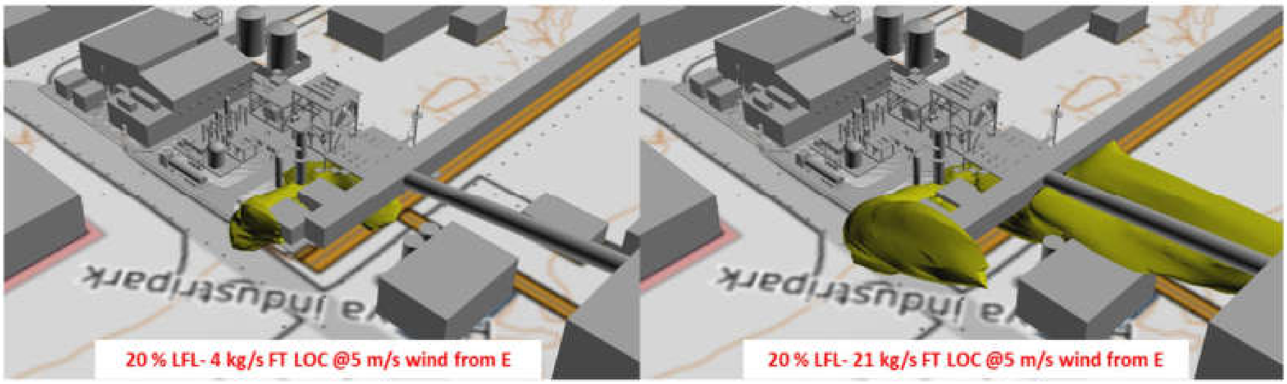

Figure 12-5 CFD simulation results of 20% LFL cloud. The left picture shows 4 kg/s leakage from FT reactor with 5 m/s wind blowing from E. The right picture shows 21 kg/s leakage from FT reactor with 5 m/s wind blowing from E [1].

The CFD study of flammable gas performed in the CRA forms a good basis for a qualitatively assessment of the potential risk. However, it only considers relatively larger leakages and only releases from the FT reactor. Hence, in order to span the full range of release scenarios flammable gas dispersion has also been modelled with PHAST. PHAST is not as accurate as CFD and does not include effects of building etc. But it is suitable for simulating many different release scenarios in order to get a proper resolution for a QRA.

Flammability has been investigated for 10% LFL, 50% LFL and 100% LFL in PHAST. In worst case rupture scenario 100% LFL cloud can reach 77m, 50% LFL cloud 200 m and 10% LFL cloud >1 km and therefore able to extend outside the boundary of the E-Fuel site. However, the reach of flammable gas is significantly less than that of CO toxicity. For most loss of containment scenarios, the reach of flammable gas is limited and will not extend significantly outside the E-Fuel site boundary.

The PHAST simulation results for flammable gas for the individual gas release scenarios have been included in Appendix A and B.

12.1.2 TOXIC CO CONSEQUENCES

In the CRA [1] toxic CO dispersion based on the Immediately Dangerous to Life or Health (IDLH) (1200 ppm) concentrations was investigated by CFD for medium (4 kg/s) and large releases (21 kg/s) for different wind directions. Even though the plant layout has changed in the FEED, the results are still considered relevant. The simulation results have been shown in Figure 12-6 and Figure 12-7 respectively.

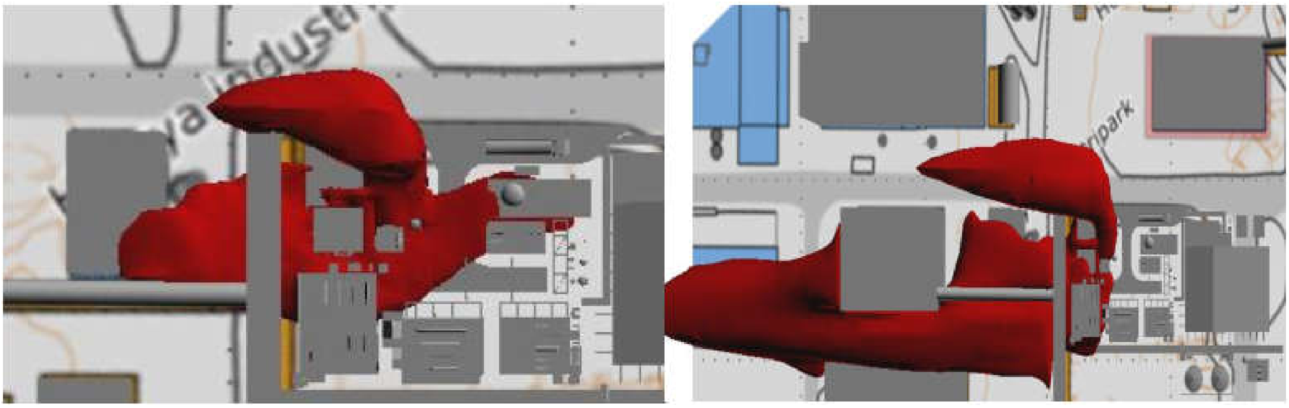
Figure 12-6 CFD simulation results of IDLH CO cloud. The left picture shows 4 kg/s leakage from FT reactor with 5 m/s wind blowing from E. The right picture shows 21 kg/s leakage from FT reactor with 5 m/s wind blowing from E [1].

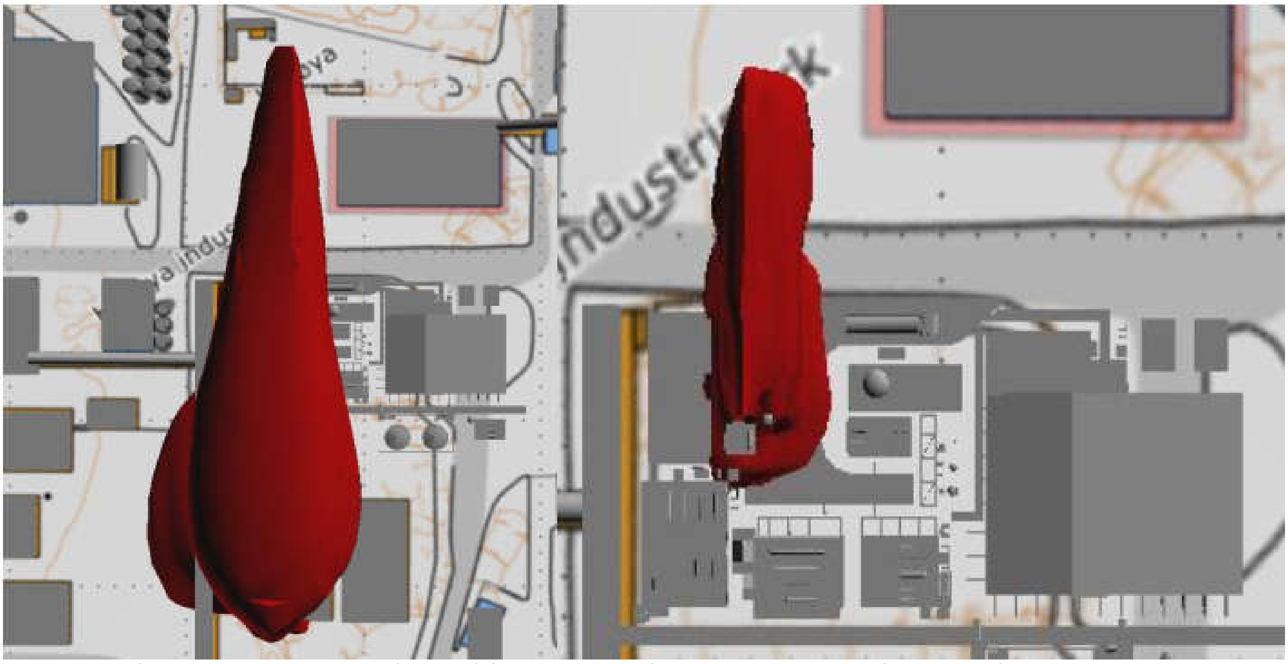

Figure 12-7 CFD simulation results of IDLH CO cloud. The left picture shows 21 kg/s leakage from FT reactor with 5 m/s wind blowing from S. The right picture shows 4 kg/s leakage from FT reactor with 5 m/s wind blowing from S [1].

It is apparent that potentially fatal CO clouds (IDLH level) can extend far away from the e-fuel plant. The potential extend of the CO IDLH cloud has been summarized in Figure 12-8.

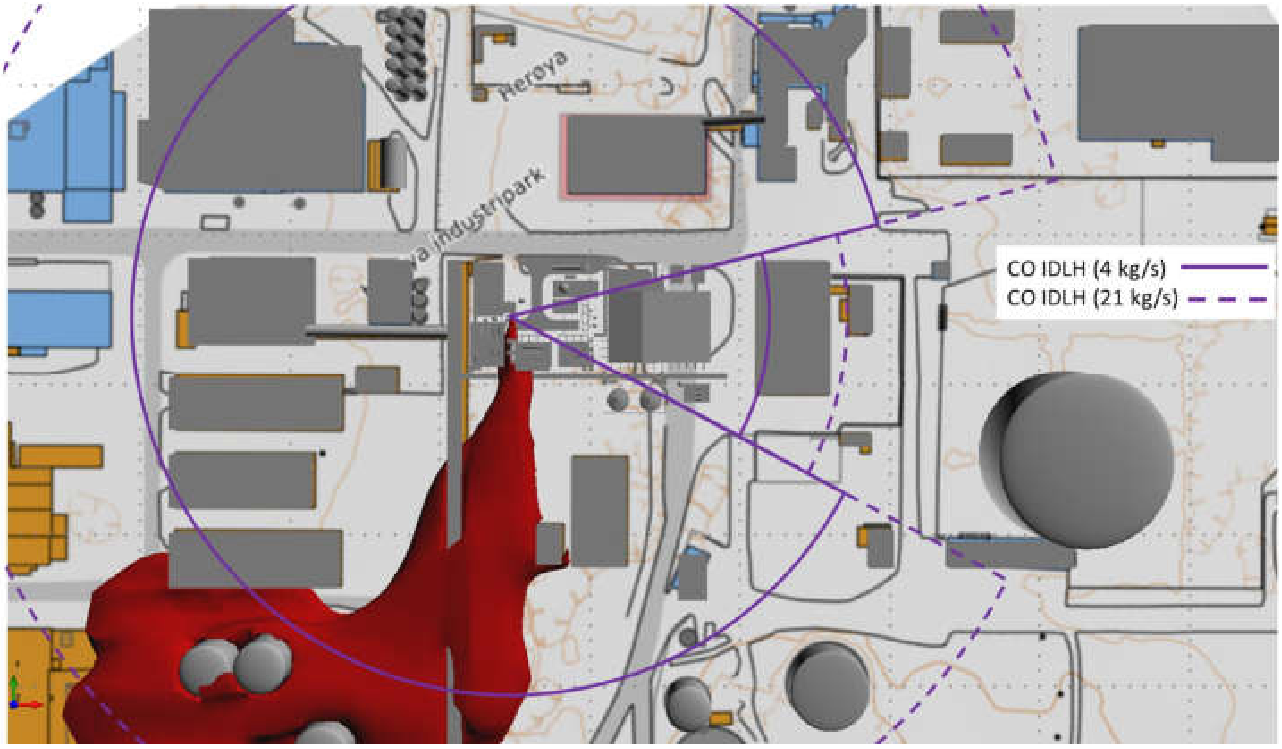

Figure 12-8 Summary of horizontal extend of CO IDLH cloud for different gas release rates from FT reactor (approximated and simplified). Contours can be moved around depending on leak location. The red iso contour show IDLH for a 21 kg/s unobstructed release wind from E [1].

From Figure 12-8 the following can be observed:

- Due to a high CO content in the FT gas and a low IDLH threshold value for CO, as low as 1200 ppm, the IDLH clouds are seen to extend far outside the e-fuel plant battery limits. The CO clouds extend further than flammable clouds. Areas within 150-200 m radius can become exposed (depending on leak location and direction, and wind speed and direction);

- Since the IDLH value is low, wind direction and speed will to a large extent determine what areas that become exposed;
- Like what is observed for flammable gas releases, the electrolysis building acts as a barrier that shield the areas east of the building. However, since the IDLH threshold value is so low, the gas is seen to have the potential to expose the HV building (building 95);
- The HVAC air intakes for the electrolysis building can become exposed to IDLH values of CO as illustrated in Figure 12-9.

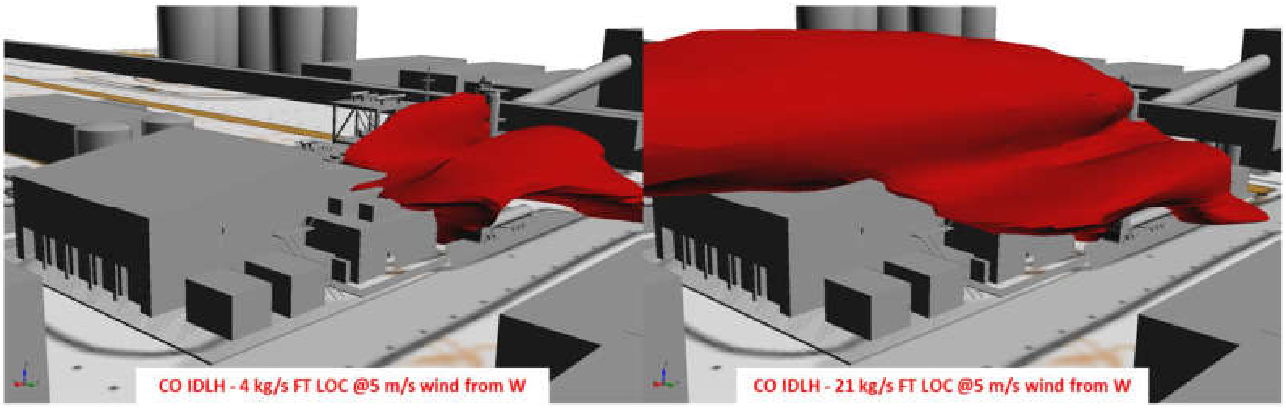

Figure 12-9 CFD simulation results of IDLH CO cloud. The left picture shows 4 kg/s leakage from FT reactor with 5 m/s wind blowing from W. The right picture shows 21 kg/s leakage from FT reactor with 5 m/s wind blowing from W [1].

The CFD study of flammable gas performed in the CRA forms a good basis for a qualitatively assessment of the potential risk. However, it only considers relatively larger leakages and only releases from the FT reactor. Furthermore, is only the IDLH concentration provided. Even though IDLH is a serious concentration it does not necessarily cause fatalities in case of exposure.

Hence, in order to span the full range of release scenarios, CO gas dispersion has also been modelled with PHAST. PHAST is not as accurate as CFD and does not include effects of building etc. But it is suitable for simulating many different release scenarios in order to get a proper resolution for a QRA.

CO toxicity has been investigated for three different concentration levels i.e. 6547 ppm, 11 784 ppm and 19 640 ppm (all significantly higher than the IDLH value of 1200 ppm) in PHAST for outdoor release scenarios. These concentration levels correspond to 50% probit concentrations for 15 minutes, 5 minutes and 2 minutes exposure time respectively. 15 minutes is considered the worst-case exposure time due to emergency shutdown and blowdown of the E-Fuel plant. In many cases 1st and 2nd party personnel can escape within 2 minutes and at least within 5 minutes.

Toxic CO consequences from Eramet, and syn. gas releases which has a high CO content, has a long reach and can for larger leakages extent several hundred meters out from the E-Fuel site. According to PHAST simulations, the worst-case reach (rupture) of 6 547 ppm level is 301 m, the worst-case reach of 11 784 ppm level is 157 m and the worst-case reach of 19 640 ppm level is 74 m.

It is important that an alarm is provided by the E-Fuel plant in such cases, and that HIP emergency preparedness is in place so 1st and 2nd party knows how to react and will seek refuge in a gas shelter.

The PHAST simulation results for CO dispersion for the individual gas release scenarios containing CO have been included in Appendix A and B.

12.1.3 JET FIRE CONSEQUENCES

In the CRA [1], jet fire consequences have been investigated by the state-of-the-art CFD software KFX for 4 kg/s and 1 kg/s jet fires. Both syngas jet fires and methane jet fires were modelled. The methane jet fire was applied as a reference for comparison. The jet fire simulations are still considered valid for the FEED.

Figure 12-10 to Figure 12-15 show a side-by-side comparison of methane jet fire and a syngas jet fire for 4 kg/s and 1 kg/s releases respectively. The following observations have been made from the figures:

- The syngas flame length is significantly shorter compared to methane jet fire with the same mass release rate. The approximate flame length is 7 m and 3 m (4 kg/s and 1 kg/s respectively) for syngas and 20m and 10m for methane (syngas jet fire length is around 1/3rd of the methane jet fire);
- The maximum flame temperatures are quite similar;
- The radiation footprint of a syngas jet fire is significantly smaller compared to a methane jet fire. This is partly because of the lower heat of combustion value and because the syngas jet fire produces very little soot. Less soot means that a smaller fraction of the combustion energy is emitted as radiation. The maximum radiation heat flux for a methane jet fire is in the range 250-350 kW/m^2, while it is 90-120 kW/m^2 for a syngas.

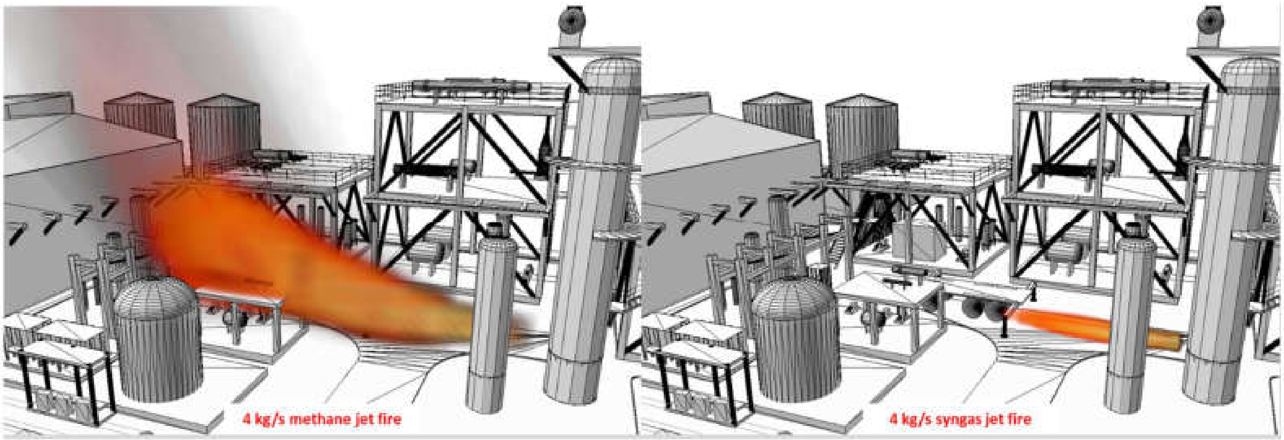

Figure 12-10 3D visualization of the 1 kg/s jet fire showing flames and smoke/soot. To the left a methane jet fire is shown whereas to the right a syngas jet fire is shown [1].

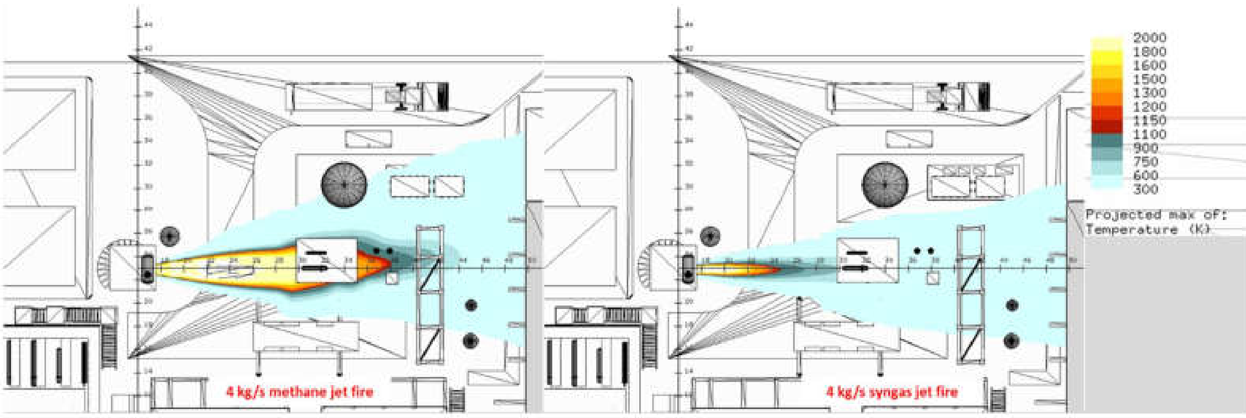

Figure 12-11 Projected maximum temperature flux for 4 kg/s jet fire. To the left a methane jet fire is shown whereas to the right a syngas jet fire is shown [1].

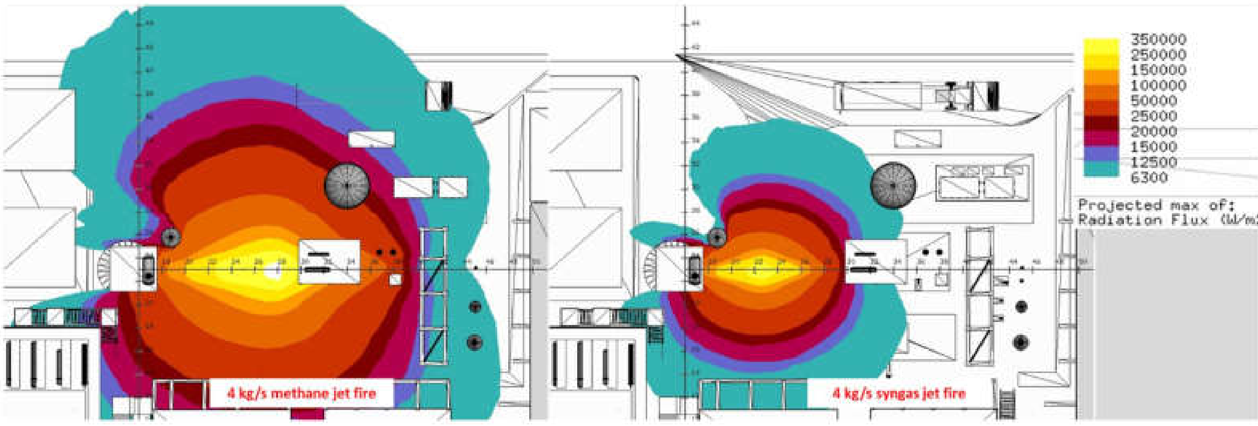

Figure 12-12 Projected maximum radiation flux for 4 kg/s jet fire. To the left a methane jet fire is shown whereas to the right a syngas jet fire is shown [1].

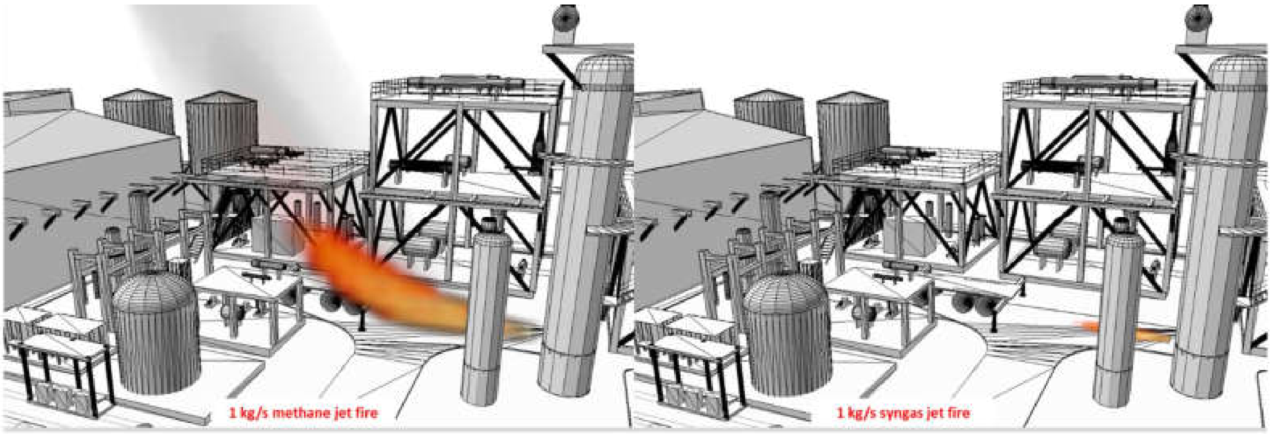

Figure 12-13 3D visualization of the 1 kg/s jet fire showing flames and smoke/soot. To the left a methane jet fire is shown whereas to the right a syngas jet fire is shown [1].

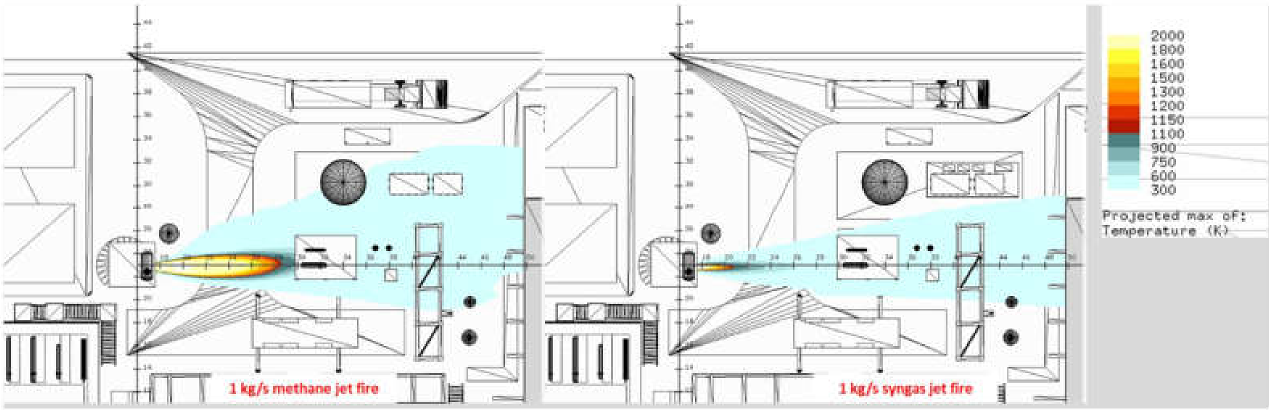

Figure 12-14 Projected maximum temperature flux for 1 kg/s jet fire. To the left a methane jet fire is shown whereas to the right a syngas jet fire is shown [1].

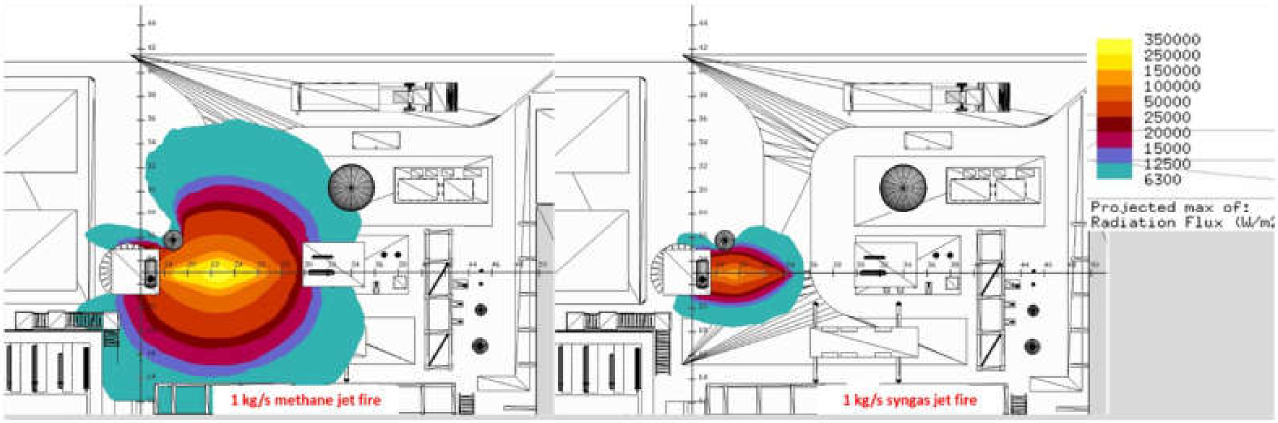

Figure 12-15 Projected maximum radiation flux for 1 kg/s jet fire. To the left a methane jet fire is shown whereas to the right a syngas jet fire is shown [1].

The CFD simulations showed that maximum radiation flux levels for syngas jet fires are about 1/3rd of a methane jet fire of the same size. But still these heat loads (90– 120 kW/m^2) are high enough to cause severe damage to exposed personnel, structures and equipment.

Jet fires will expose areas downstream the release if released unobstructed. This means that what areas exposed to the fire is mainly determined by leak rate and direction, and less affected by wind. If the jet fire is obstructed (released into the ground or it hits adjacent structures), the jet loses its momentum and will then be more affected by wind.

The extent of jet fires will be *approximately* the same as the extent of the 100 % LFL gas plumes. This means that jet fires in one part of the process will have the potential to expose other parts of the process, including the non-hydrocarbon systems. There is simply not enough separation in-between the modules to say that direct impingement is not possible. Jet fires can also expose areas a few meters outside the E-Fuel plant. This means that a jet fire could expose the wax storage tanks owned by Yara, just west of the E-Fuel plant.

Syngas jet fire are hydrogen rich jet fires. It shall be noted that experimental work is ongoing for pure hydrogen jet fires by SINTEF that may question the results from KFX above. But these data are not presently publicly available. Hence presently KFX is considered the best tool available for assessing the jet fire heat loads.

The CFD study of jet fires performed in the CRA forms a good basis for a qualitatively assessment of the potential risk and providing heat loads for DeAL purposes. However, it only considers relatively large leakages and only syngas releases. Hence, in order to span the full range of release scenarios, jet fire consequences have also been modelled with PHAST. PHAST is not as accurate as CFD and does not include effects of building etc. But it is suitable for simulating many different release scenarios in order to get a proper resolution for a QRA onshore.

Jet fire heat radiation levels has been investigated for heat fluxes of 5 kW/m^2, 8.5 kW/m^2 and 14.5 kW/m^2 corresponding to the 50% probit for exposure for 2 minutes, 1 minute and 30 seconds respectively. The exposure times are selected to reflect that everybody will be able to move away from an exposed area in 2 minutes time if they feel the heat radiation. The fastest escape time will be 30 seconds. It is assumed that nobody will just stand at their position and wait if the heat radiation starts to hurt.

For the worst-case rupture scenario, heat radiation levels can extend 130 m for 5 kW/m^2, 121 m for 8.5 kW/m^2 and 112 m for 14.5 kW/m^2 ,which is significantly outside the site boundary of the E-Fuel plant. However, this will be very unlikely scenarios. For more frequent jet fire scenarios fatal heat radiation levels will be inside the E-Fuel site boundary or only extend a relatively short distance beyond the site boundary.

The PHAST simulation results for heat radiation from jet fires for the individual gas release scenarios have been included in Appendix A and B.

12.1.4 BLAST LOAD CONSEQUENCES

The Baker-Strehlow-Tang (BST) methodology in PHAST is used to predict blast loads from outdoor process releases in case of delayed ignition. BST predicts the consequences of vapor cloud explosions (VCEs) in the form of peak overpressure, and impulse in the region around the explosion, using the flame speed table and the blast curves developed by Baker et al for an idealized Stoichiometric fuel-air charge. Distance from the explosion may be specified and then overpressure and impulse can be calculated using BST.

Using BST one obstructed volume can be given for each modelled case. This volume defines one confined explosion, with the explosion energy determined based on total flammable mass in the cloud, the given volume, and flame speed of the explosion. The flame speed can be given as an input or determined by BST using the flame speed table, based on the characteristics of the obstructed volume.

The flame speed is selected based on Table 12-1.

Table 12-1: The updated flame speed table for the BST model [25]

Degree of confinement	Material reactivity	Congestion		
		Low	Medium	High
2D	High	0.59	DDT[ii]	DDT
	Medium	0.47	0.66	1.6
	Low	0.079	0.47	0.66
2.5D	High	0.47	DDT	DDT
	Medium	0.29	0.55	1
	Low	0.053	0.35	0.5
3D	High	0.36	DDT	DDT
	Medium	0.11	0.44	0.5
	Low	0.026	0.23	0.34

The confinement of Table 12-1 may also be described as degree of expansion. An obstructed region is considered to be 3D if the flame is free to expand in all directions, 2D if the flame can only expand in two dimensions and is restricted in the third dimension and 2.5D where confinement is made of either frangible panels or by nearly confining planes.

For the PHAST simulations, the explosion is considered to be able to expand in all three directions, hence a 3D expansion has been selected.

The congestion of Table 12-1 is classified as “low”, “medium” and “high” depending on area blockage ratio (ABR) and pitch (i.e. the distance between successive rows or layers of obstacles) in the flame path as:

- Low congestion level: a few obstacles in the flame’s path or ABR less than 10% and a few layers of obstacles.
- Medium congestion level: anything falling between the low and high levels.
- High congestion level: closely spaced layers of obstacles with an ABR of 40% or higher.

In the PHAST simulations, a medium congestion has been chosen.

Material reactivity is rated as “low”, “medium” and “high” in Table 12-1. With respect to material reactivity, the reactivity varies from segment to segment, based on the substance, the material reactivity used in the PHAST simulation can be seen below in Table 12-2.

Table 12-2 Segment reactivity

Segment	Reactivity	Comment
Eramet Gas Feed	Low	
Hydrogen to Syngas Production	High	
Ammonia Removal Unit	Medium	
Fischer Tropsch Process	Medium	
Fischer Tropsch Reactor	Medium	
Tail Gas Scrubber	Low	set to low due to 8 % CO, 10 % H_2 and 80 % inert gas.
Recycled Tail Gas to Syngas Production	Low	
LFTL Storage and Offloading	-	Not considered to form vapor.
LFTL Storage and Offloading		Not considered to form vapor.
Syngas and H_2	High	
Dry Syngas	Medium	

The blast curves developed for the BST methodology were based on prediction of spherical free-air explosions. Corrections are required to account for the effect for explosions on or near to ground. The current approach is to apply a ground reflection factor to the explosion energy. A reflection factor of 1.5-2 has been recommended to take ground effects into account [25].

In the PHAST simulations, a ground correction factor of 1.7 has been chosen, as the ground correction factor.

Explosion blast load consequences have been investigated for 0.02 bar, 0.05 bar, 0.1 bar, 0.15 bar 0.2 bar, 0.5 bar, 0.75 bar and 1 bar. Explosion blast loads are significantly higher for hydrogen releases than for the other outdoor process releases. This is because hydrogen is much more reactive than syn gas and the Eramet gas. However, hydrogen releases only constitute 2-3% of the total outdoor estimated leakage frequency. For full bore rupture 0.2 barg blast load can reach 45 m, 0.5 barg blast load 21 m and 1 barg blast load 13 m, which is worst case outdoor explosion. The frequency of this event is however extremely low.

For syngas and Eramet gas releases the 0.2 barg blast load can reach less than 10 m, for FT releases the 0.2 barg blast load can reach up to 15 m for full bore rupture releases. Blast loads higher than 0.2 barg are relatively local phenomena inside the e-fuel site. Overall, the outdoor explosion consequences are considered to be low.

The PHAST simulation results for blast loads for the individual gas release scenarios in case of delayed ignition have been included in Appendix A and B.

12.1.5 POOL FIRE CONSEQUENCES FROM STORAGE TANKS

In the CRA pool fire consequences from the storage tanks were investigated with the CFD code KFX. In the FEED the storage capacity has been significantly reduced so the size of a pool fire will now be smaller, and the duration of the pool fire will be shorter than for the Concept Stage. Furthermore, has the storage tanks been moved to the northwest corner of the e-fuel plant site, further away from the electrolysis building.

Hence the consequences simulated in the conceptual stage will be conservative for the FEED stage. However, it has not been considered to create any significant value to update the pool fire simulations for the FEED. Hence the pool fire risk will be evaluated based on CRA consequences.

Figure 12-16, Figure 12-17 and Figure 12-18 shows the results of a pool fire filling the bunded area of the storage tanks.

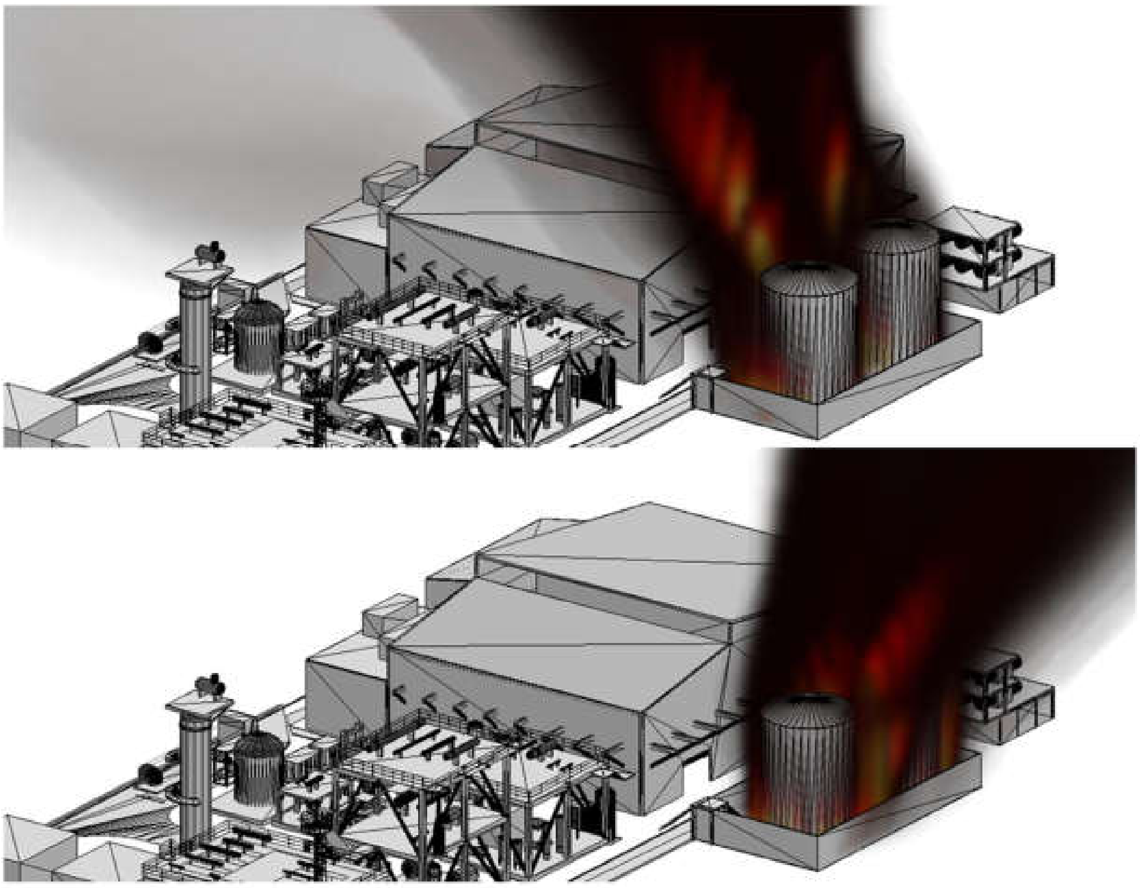

Figure 12-16 3D visualization of the pool fire showing flames and smoke/soot. Upper picture is for 2 m/s wind from S. Lower picture is for 2 m/s wind from W.

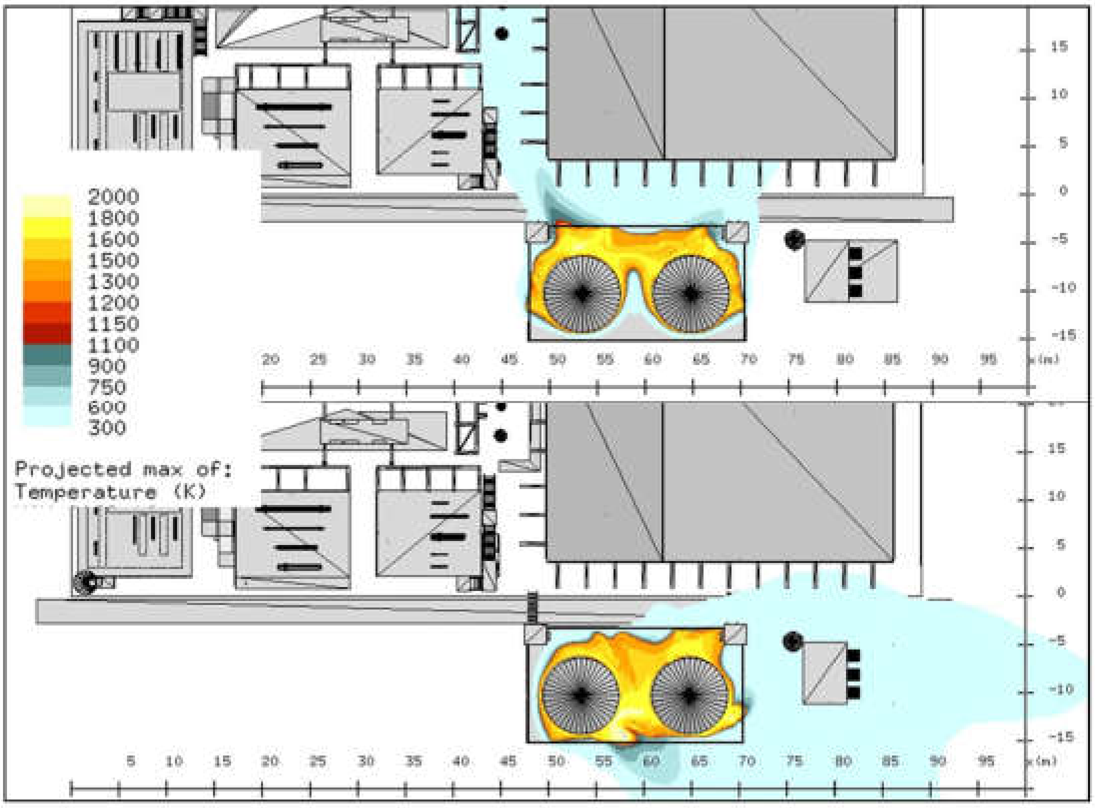

Figure 12-17 Projected maximum temperature (K). Upper picture is for 2 m/s wind from the South. Lower picture is for 2 m/s wind from W.

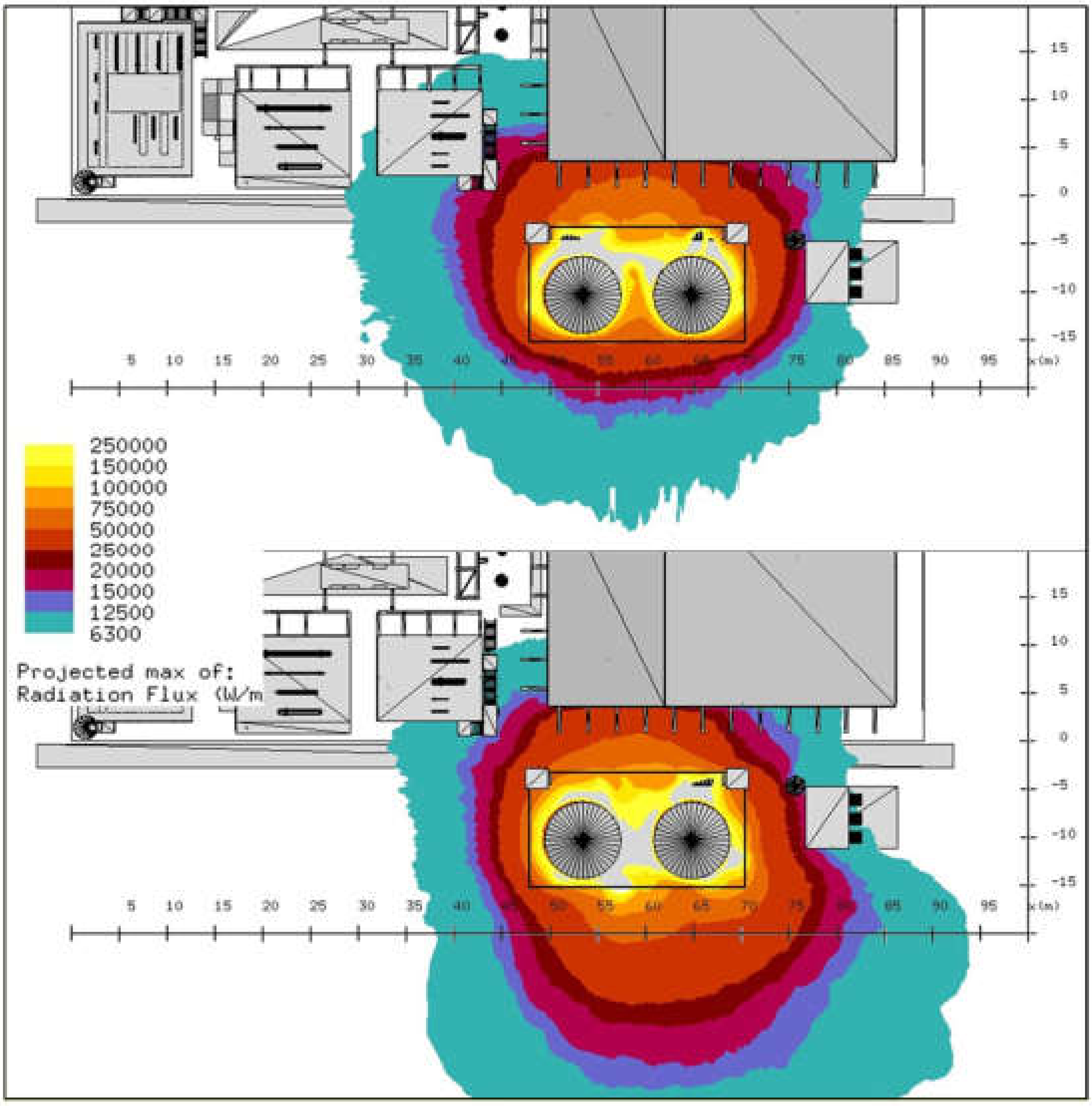

Figure 12-18 Projected maximum radiation flux (W/m2). Upper picture is for 2 m/s wind from S. Lower picture is for 2 m/s wind from W.

It is worth noting that the KFX simulations represent steady-state fires. But it takes time for a pool fire to develop into its full potential i.e. there is a feedback mechanism where heat from the fire increases the liquid evaporation and the burning rate. This means personnel in the area will most likely discover the fire before it is fully developed and escape while heat radiation levels are lower than presented here. Actually, in QRA it is often assumed that only personnel located directly inside the pool fire (area of the ignited liquid spill) will become fatalities [26].

The maximum radiation flux on the electrolysis building is in the simulations between 25 and 50 kW/m^2. It can be argued that a slightly higher wind speed would bend the flames more towards the building and hence increase the heat flux to about 100 kW/m^2. In FEED the product storage tanks have been moved a significantly longer distance away from the electrolysis building and heat radiation levels are expected to be significantly lower than 100 kW/m^2. On the other hand, the storage tanks are now relatively close to Building 235 (Yara wax tanks) and heat radiation levels in the order of 100 kW/m^2 could expose this building.

6.3 kW/m^2 is a typical value where, if exposed to this heat flux, escape is not considered possible (impairment of escape). The simulations in Concept Phase show that it will be difficult to escape out of, or via, the P20 module due high radiation levels (>6.3 kW/m^2). The stair tower currently located at the SE corner of P20 is highly exposed. The rest of the outdoor process and utility modules/areas are not exposed to >6.3 kW/m^2 radiation levels. In FEED escape routes may be impaired locally in the process areas and utility areas closest to the NW corner of the e-fuel plant site.

In case of a fire in the storage tanks it will be difficult to use the road north of the e-fuel plant, as escape route/access route are exposed to high radiation levels. However, the radiation levels are not likely to be high enough to hinder emergency response actions from the local emergency crew/fire department at HIP.

The impact of smoke has not been evaluated in detail. But in general, liquid hydrocarbon pool fires will produce a lot of thick black smoke. This smoke has the potential to impair escape due to low visibility and due to toxic substances found in the smoke. At low wind speeds the smoke will mainly disperse upwards and not impact the ground level in adjacent areas. But at higher winds the smoke will be pushed down and could expose areas downwind the fire. In areas affected by the smoke it will be difficult to escape and to perform emergency actions (firefighting, search and rescue) without proper protective gear and breathing apparatus.

The consequences of a pool fire in the storage tank area are mitigated by providing sufficient bunding to contain the inventory of the largest tank, plus 10%. Hence the pool fire itself will be contain to a local area. Furthermore, active fire-fighting system based on foam will be installed that can combat a fire or prevent ignition of a liquid spill.

Strict ignition source control (ATEX) will be exercised around the storage tanks and even though the products are not stabilized they are relatively heavy and not expected to ignite easily. Hence over all, the probability of a liquid spill and ignition is considered to be low and if ignition occurs systems are in place to combat the fire. The HIP fire brigade will serve as back-up.

Based on this the pool fire risk is considered to be managed and the risk is considered to be low. It is however important that Building 235 is made aware of the risk and it is ensured unacceptable escalation cannot occur.

Pool fire consequences has also been modelled with PHAST for LFTL fire in the bund of the storage tanks. The results are provided in Table 12-3.

Table 12-3 PHAST consequence results for LFTL pool fire in the bund of the storage tanks

Scenario	**Weather**	**Heat radiation distances [m]**		
		5 kW/m^2	**8.5 kW/m^2**	**14.5 kW/m^2**
Pool Fire storage tank bunding	1.5F	34.4	26.1	19.7
	5D	37.6	27.8	20.1
	10D	38.4	27.1	20.2

12.2 COMPRESSOR STATION

Consequences for release of Eramet feed gas is part of the consequences calculated for the E-Fuel plant discussed above. A consequence summary for releases from the compressor station has been provided in Table 12-4.

Table 12-4 Calculated consequences for releases from compressor station

Rep. leak rate [kg/s]	Wind speed [m/s]	Release direction [-]	CO 50% probit Reach [m]	8.5 kW/m^2 reach [m]	200 mbar reach [m]
0.01	1.5F	Horizontal	5.2	NR	NR
	6D	Horizontal	3.4	NR	NR
	10D	Horizontal	3.6	NR	NR
0.05	1.5F	Horizontal	14.8	NR	NR
	6D	Horizontal	6.7	NR	NR
	10D	Horizontal	7.2	NR	NR
0.1	1.5F	Horizontal	26.1	NR	NR
	6D	Horizontal	10.5	NR	NR
	10D	Horizontal	12.0	NR	NR
0.5	1.5F	Horizontal	79.9	7.93	NR
	6D	Horizontal	59.5	8.0	NR
	10D	Horizontal	65.2	8.0	NR
1	1.5F	Horizontal	123.3	11.1	NR
	6D	Horizontal	101.3	11.6	NR
	10D	Horizontal	108.2	11.5	NR
40.54	1.5F	Horizontal	111.5	59.1	27.3
	6D	Horizontal	118.1	65.5	26.9
	10D	Horizontal	115.5	63.2	27.0

It is apparent that toxic CO releases have a significantly longer reach than potentially fatal heat radiation loads from a jet fire or blast loads from a VCE.

The toxic CO releases (50% probit value) has a reach of almost 120 m for full bore rupture scenario. But also, for smaller leaks does the CO cloud have a significant reach and can expose personnel to toxic levels some distance away from the compressor station.

Jet fire can have fatal heat radiation reach (50% probit value) of 65 m for rupture scenarios. For smaller leaks the reach decreases significantly and will only cause local impact at the compressor station.

VCE has only been found to be possible for full bore ruptures and the 0.2 bar reach is just below 30 meters.

12.3 ERAMET DISCHARGE PIPELINE

Consequences for release of Eramet feed gas is part of the consequences calculated for the E-Fuel plant discussed above. A consequence summary for releases from the discharge pipeline has been provided in Table 12-4.

Table 12-5 Calculated consequences for releases from discharge pipeline

Rep. leak rate [kg/s]	Wind speed [m/s]	Release direction [-]	CO 50% probit Reach [m]	8.5 kW/m^2 reach [m]	200 mbar reach [m]
0.01	1.5F	Horizontal	NR	NR	NR
		45° downwards	NR	NR	NR
		Vertical downwards	NR	NR	NR
	6D	Horizontal	NR	NR	NR
		45° downwards	NR	NR	NR
		Vertical downwards	NR	NR	NR
	10D	Horizontal	NR	NR	NR
		45° downwards	NR	NR	NR
		Vertical downwards	NR	NR	NR
0.05	1.5F	Horizontal	NR	NR	NR
		45° downwards	4.0	NR	NR
		Vertical downwards	5.5	0.3	NR
	6D	Horizontal	NR	NR	NR
		45° downwards	NR	NR	NR
		Vertical downwards	NR	NR	NR
	10D	Horizontal	NR	NR	NR
		45° downwards	NR	NR	NR
		Vertical downwards	NR	NR	NR
0.1	1.5F	Horizontal	NR	NR	NR
		45° downwards	16.0	4.2	NR
		Vertical downwards	19.5	0.8	NR
	6D	Horizontal	NR	NR	NR
		45° downwards	NR	NR	NR
		Vertical downwards	1.6	NR	NR
	10D	Horizontal	NR	NR	NR
		45° downwards	NR	NR	NR
		Vertical downwards	2.0	0.4	NR
0.5	1.5F	Horizontal	NR	NR	NR
		45° downwards	17	10.2	NR
		Vertical downwards	28	2.9	NR
	6D	Horizontal	NR	NR	NR
		45° downwards	5.0	6.9	NR
		Vertical downwards	1.5	2.2	NR
	10D	Horizontal	NR	NR	NR
		45° downwards	5.0	7.0	NR
		Vertical downwards	1.2	2.2	NR
1	1.5F	Horizontal	NR	NR	NR
		45° downwards	32.0	14.3	NR
		Vertical downwards	49.0	4.9	NR
	6D	Horizontal	NR	NR	NR
		45° downwards	9.0	10.4	NR
		Vertical downwards	20.0	3.6	NR
	10D	Horizontal	NR	NR	NR
		45° downwards	13.0	10.8	NR
		Vertical downwards	27.0	3.7	NR
40.54	1.5F	Horizontal	NR	57.6	27.3
		45° downwards	58.0	72.5	37.9
		Vertical downwards	54.0	28.2	64.9
	6D	Horizontal	NR	62.8	26.9
		45° downwards	62.000	55.8	37.0
		Vertical downwards	114	23.6	84.2
	10D	Horizontal	NR	61.6	27.0
		45° downwards	63.0	57.4	37.1
		Vertical downwards	114.0	24.0	85.3

It is apparent that toxic CO releases have a significantly longer reach than potentially fatal heat radiation loads from a jet fire or blast loads from a VCE.

The toxic CO releases (50% probit value) has a reach of almost 114 m for full bore rupture scenario. But also, for smaller leaks does the CO cloud have a significant reach and can expose personnel to toxic levels some distance away from the pipeline.

Jet fire can have fatal heat radiation reach (50% probit value) of 73 m for rupture scenarios. For smaller leaks the reach decreases significantly and will only cause local impact close to the pipeline.

VCE has only been found to be possible for full bore ruptures and the 0.2 bar reach of 85 meters.

12.4 HYDROGEN RELEASES INSIDE ELECTROLYSIS BUILDING

The Concept Study [1] investigated some conservative hydrogen release scenarios inside the electrolysis hall indicating that significant flammable hydrogen clouds can build up, potentially leading to high blast loads if ignited.

In the FEED more realistic hydrogen release scenarios have been modelled with FLACS, which is a CFD tool validated for hydrogen dispersion and explosion [27]. This modelling initially confirmed the findings of the Concept Study, i.e. that significant flammable hydrogen clouds can build up inside the electrolysis hall. Despite of limited hydrogen volumes and effective F&G shutdown the hydrogen clouds can build up fast.

However, after dialogue with a potential electrolysis system vendor it has been concluded that the hydrogen inventories assumed in the CRA [1] was in the order of a factor 6 higher than expected. According to electrolysis vendor a worst-case scenario is release of up to 6 kg hydrogen.

Hence new hydrogen dispersion simulations were performed in the end of the FEED based on a significantly smaller hydrogen inventory [7] [27]. A summary of the results from the CFD study is provided in Table 12-6.

Table 12-6 Estimate of hydrogen cloud sizes and blast loads

Release rate	FLAM	Q9	Q9
0.2 kg/s	Up to 200 m^3	~3 m^3	Up to 0.05 barg
0.8 kg/s	400 m^3 to 700 m^3	10 m^3 to 30 m^3	Up to 0.1 barg
3.16 kg/s	700 m^3 to 1000 m^3	30 m^3 to 100 m^3	Up to 0.4-0.8 barg

* This is a best guess estimation based upon the previously simulated data for the vehicle tunnel and should be treated with caution.

It is very important to note that CFD evaluations has only been performed for estimating the flammable hydrogen cloud size and the Q9 cloud size in Table 12-6. The blast loads in Table 12-6 has not been calculated by CFD but has been guesstimated based on vehicle tunnel experiments.

For small leakages (0.2 kg/s) the flammable gas cloud can reach up to 200 m^3, for medium-large releases (0.8 kg/s) the flammable gas cloud reaches sizes in the region 400-700 m^3 and for rupture release (instantaneous release of the total hydrogen inventory) the flammable gas cloud reaches sizes in the region 700-1000 m^3.

Hydrogen is flammable in a wide range of mixtures with air, i.e. in the region 4 vol% to 74 vol%. For comparison natural gas is typically flammable in air in the region 5 vol% to 15 vol%.

The hydrogen accumulated within the hall is fairly dilute, i.e. 4-15 vol% for the bulk of the hydrogen cloud and significantly higher locally at the release location.

For explosion analysis it is normally not the flammable gas cloud that is considered but the equivalent stochiometric cloud volume, denoted the Q9 cloud. For 0.2 kg/s the Q9 cloud is typically in the range 3 m^3. For 0.8 kg/s release the Q9 cloud is in the region 10-30 m^3. For 3.2 kg/s leakage the Q9 cloud is typically in the range 30-100 m^3.

Corresponding blast loads has presently not been simulated in FLACS. But the expected range of blast loads has been guesstimated based on vehicle tunnel experiments [27]. Based on this, a blast load of small leakages of up to 0.05 barg has been guestimated. For medium leakages a blast load of 0.1 barg has been guestimated and for rupture releases blast loads in the region 0.4-0.8 barg has been guestimated. Depending on the frequency of occurrence for the different cloud sizes the blast loads may be acceptable or unacceptable. Blast loads of 0.2 barg and lower are expected to be manageable by building structure design in combination with relief panels. Blast loads in the range of 0.5 barg and above is however expected to cause total loss of building and impairment of the control room.

Hence whether the blast load is acceptable or not depend on cloud size for the 1 per 10 000-year re-occurrence. In principle, the Q9 cloud exceedance curve therefore should be constructed. However, it has not been considered possible to construct a reliable exceedance curve in FEED [7].

However, it is rupture or relatively large leakages that result in blast loads exceeding 0.2 barg. Such release scenarios are expected to be infrequent, and measures can be put in place to reduce the risk of such catastrophic releases. Hence for the FEED it seems reasonable to assume that it is small and medium leakages that will primarily determine the explosion DeAL.

Based on this it is expected that a 10^{-4} per year blast load will be in the region 0.2 barg. By including relief panels in the electrolysis building, it is considered feasible to limit the DeAL blast load to 0.2 barg. It is considered feasible to design the building for this explosion load.

However, since the blast loads have not been calculated but only guestimated based on literature data, the blast loads are very uncertain. Furthermore, recent research in relation to the Kjørbo hydrogen explosion in 2019 seems to indicate that hydrogen explosions can be subject to the phenomenon deflagration to detonation transition (DDT) significantly increasing potential blast loads.

Hence a more detailed blast load simulation needs to be performed in detailed design to validate the assumed DeAL. In addition, detailed exceedance curves based on actual design component count should be performed.

With the limited hydrogen inventory of 6 kg for the electrolysis stacks, a hydrogen release inside the electrolysis building cannot form a significant hydrogen cloud in the outdoor process area through ventilation louvres etc.

For the present risk assessment, it is assumed that dimensioning blast loads of electrolysis building can be managed by the design of the building in combination with relief panels in such a way the building maintain its integrity and there are no domino effects to the CCR or neighbouring buildings to E-Fuel plant. This assumption must be verified in detailed design.

13 LEAK DURATIONS

Leakage durations are very important as they determine for how long a jet fire can occur, or what kind of flammable or toxic gas cloud that can build-up.

It shall be noted that the PHAST simulations results of Appendix A and B ,discussed previously, have been based on unlimited inventory and therefore represent steady-state consequences of the initial leakage rate. This will be conservative in many cases. For evaluating escalation potential and hydrogen dispersion inside electrolysis building the actual transient release scenario and leakage duration is of interest.

The transient leakage scenarios will be calculated taking detection time, shutdown time, production rate and process inventory into account. Initial process conditions will be taken from the Heat & Mass balances [28].

The gas flow out of a gas release leak is calculated by:

$$Q = C_d \cdot A \cdot P_1 \cdot \sqrt{\frac{k \cdot M}{R \cdot T \cdot Z} \cdot \left[\frac{2}{k+1}\right]^{\frac{k+1}{k-1}}}$$

Where Q is the mass flow (kg/s), C_d is the discharge coefficient (--), A is the hole area (m^2), P_1 is the upstream pressure (Pa), k is ratio of specific heats at ideal gas conditions (--), M is molecular weight (kg/kmole), T is temperature upstream the leak (K), Z is the compressibility (--) and R is the universal gas constant (8314 J/kmole/K). The primary gas release drivers are the pressure, hole size and discharge coefficient. A discharge coefficient of 0.85 is assumed for gas releases.

The pressure, P, is calculated as:

$$P \cdot V = n \cdot Z \cdot R \cdot T$$

Assuming constant temperature of the inventory during the release (isothermal depressurization), which is a reasonable simplification. The initial compressibility is assumed to be valid throughout the depressurization.

By integrating the above equations over time steps the transient release scenario is simulated.

13.1 OUTDOOR PROCESS RELEASES

A detailed account of gas and liquid inventories have not been made during FEED, as design details are still missing. The process segment with the largest gas volume is the FT-reactor. The FT reactor has an ID of 2 290 mm and a length (TT) of 11 440 mm corresponding to a volume of 47.1 m^3. However, the fixed bed catalyst of the FT reactor will take up a large part of the volume. Hence it is assumed that 40% of the FT reactor volume is gas inventory, corresponding to 18.8 m^3 gas. To account for piping volume and uncertainties 25% gas volume has been added resulting in a total volume of 23.6 m^3. This is significantly less than estimated in the CRA where a volume of 39 m^3 syngas was assumed [1].

Durations will be calculated for gas releases from the FT reactor as worst case. Duration calculations have not been performed for the other process segments since the inventories are very uncertain at this stage and the FT reactor will be the worst case. A sensitivity will also be carried out based on the FT-reactor volume estimated in the CRA.

For outdoor releases it has been assumed it take 30 seconds to detect a gas release or fire and that it takes in addition 15 seconds to shut down the process, i.e. a total shutdown time of 45 seconds. Gas detection may take longer for small releases, but for releases with potential critical consequences to personnel detection is expected to be relatively fast. A F&G detector mapping should be carried out in detailed design to ensure this assumption is valid.

A conservative assumption is to assume that the production rate will maintain the pressure of the leaking inventory until shutdown occur. This basically mean the production will replace whatever is leaking out of the inventory. This is not realistic for large leak rates, especially not rupture. The production rate of the E-Fuel plant is normally only in the order of 1 kg/s.

For the base case FT reactor gas, inventory leakage rates as function of time for different initial leak rates has been calculated in Figure 13-1.

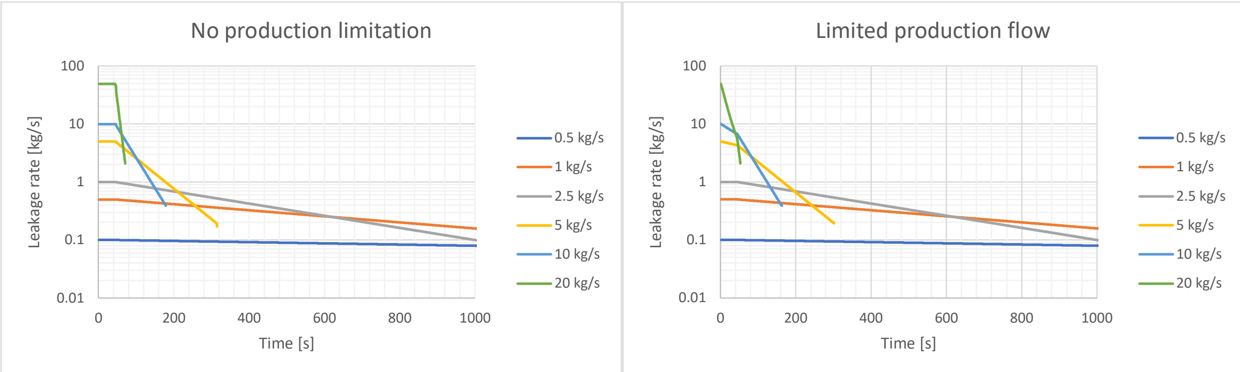

Figure 13-1 FT reactor gas inventory leakage rates as function of time for different initial leak rates based on base case gas inventory. In left figure unlimited production is assumed, meaning that the pressure is maintained in the system until shutdown, regardless of leakage rate. In right figure the production rate is limited to 2 kg/s, meaning that if the initial leakage rate is higher than 2 kg/s the inventory pressure will decrease prior to shutdown.

For the sensitivity case, FT reactor gas inventory leakage rates as function of time for different initial leak rates has been calculated in Figure 13-2.

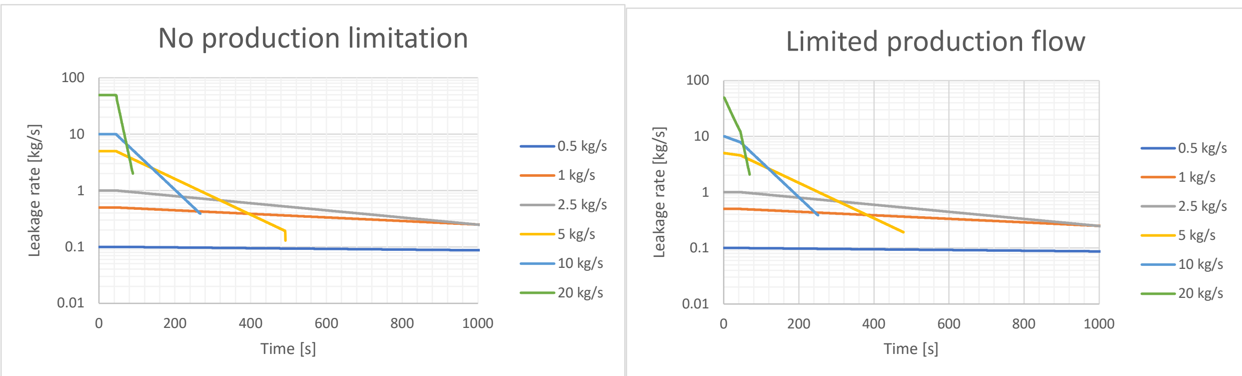

Figure 13-2 FT reactor gas inventory leakage rates as function of time for different initial leak rates based on sensitivity case gas inventory. In left figure unlimited production is assumed, meaning pressure is maintained in the system until shutdown, regardless of leakage rate. In right figure the production rate is limited to 2 kg/s, meaning that if the initial leakage rate is higher than 2 kg/s the inventory pressure will decrease prior to shutdown.

In NORSOK S-001 large and small jet fires are defined based on the mass flow of combustible material released. I.e. as long as the release is larger than 2 kg/s it can feed a large jet fire and as long as the release is larger than 0.1 kg/s it can feed a small jet fire. Flows below 0.1 kg/s is not considered a concern in relation to fire escalation. Hence the different duration of large and small jet fires in Figure 13-1 and Figure 13-2 have been tabulated in Table 13-1 and Table 13-2 for unlimited and limited production flow respectively.

Table 13-1 Duration of small and large jet fire for unlimited production flow until shutdown

Scenario	Initial leak sizes					
	0.1 kg/s	0.5 kg/s	1 kg/s	5 kg/s	10 kg/s	49.3 kg/s
Base case small jet fire duration	45 s	1379 s	999 s	315 s	180 s	73 s
Base case large jet fire duration	-	-	-	121 s	112 s	72 s
Sensitivity case small jet fire duration	45 s	2250 s	1622 s	493 s	269 s	91 s
Sensitivity case large jet fire duration	-	-	-	171 s	155 s	90 s

Table 13-2 Duration of small and large jet fire for limited production flow until shutdown

Scenario	Initial leak sizes					
	0.1 kg/s	0.5 kg/s	1 kg/s	5 kg/s	10 kg/s	49.3 kg/s
Base case small jet fire duration	45 s	1379 s	999 s	304 s	173 s	55 s
Base case large jet fire duration	-	-	-	109 s	96 s	54 s
Sensitivity case small jet fire duration	45 s	2250 s	1622 s	480 s	252 s	71 s
Sensitivity case large jet fire duration	-	-	-	158 s	139 s	70 s

The potential duration of small jet fires increases significantly (in the order of 15 minutes) if the inventory volume of the sensitivity case is assumed instead of the base case. The increase in duration of large jet fires is less severe, i.e. in the order of one minute.

Taking limited production flow into account will not impact the potential duration of small jet fires since it is the smaller leak sizes (0.5-1kg/s) that give rise to the longest small jet fires. The change in duration for large jet fires is also insignificant – limiting the production flow will decrease the duration of a large jet fire less than 15-20 seconds.

It is important to note that no credit has been taken for blowdown in the jet fire duration calculations. Blowdown is expected to have a significant impact on the duration of small jet fires but will have an insignificant impact on the duration of large jet fires.

13.2 RELEASES INSIDE ELECTROLYSIS HALL

A hydrogen release inside the electrolysis building will eventually be detected, and the electrolysis process shut down and segregated from the remaining process, after which the shut-in hydrogen inventory continues to release hydrogen until the inventory has been depleted.

The electrolysis building will be equipped with automatic hydrogen detectors that can detect the above leakage rates fast. FLACS simulations shows that a large thin cloud builds up fast, meaning that a detector will be exposed to hydrogen rapidly. The larger the release the faster detection is expected. The detector itself is expected to have a deadtime of 5 seconds. The assumed detection times including the dead time is provided in Table 13-3.

Table 13-3 Assumed hydrogen detection time inside electrolysis building for different leak sizes

Leak category	Detection time [s]
Small	90
Medium	35
Large	20
Full bore rupture	10

After hydrogen detection it will take some time to shut down the hydrogen production. This includes time to process signals from gas detection (few seconds), time to cut power (fast) and time to close EV towards outdoor process to avoid back flow (in case of failed non return valve).

Based on NORSOK S-001, the closing time of EVs (during the lifetime) shall not exceed two seconds per nominal inch. Assuming that the EV is 3”, the closing time is six seconds. Based on this a total shutdown time of ten seconds after detection will be assumed.

The hydrogen production rate is relatively low, i.e. up to 0.13 kg/s according to heat and mass balances [28]. It is therefore considered too pessimistic to assume that hydrogen production can maintain pressure in the leaking inventory until the shutdown. However, there is a risk of backflow from outdoor process if non return valve fails before the EV is closed. It could be considered to have two non-return valves in series of different make to reduce this risk. A continuous hydrogen production rate of 0.5 kg/s is conservatively assumed as an average.

The hydrogen inventory of the process inside electrolysis building will determine the how long a release can go on before the inventory is emptied. Based on the Concept Risk Assessment (CRA) [29] a hydrogen inventory of 11 m^3 is assumed. **Preliminary vendor information in FEED indicates that this is most likely a very conservative volume.** The volume should be validated in detailed design when electrolysis vendor has been selected. Note that only the volume of pressurized hydrogen is relevant and not volume of lye water etc.

Based on the above assumptions, the transient hydrogen release scenarios for different initial hydrogen leak sizes have been calculated and are presented in Figure 13-3.

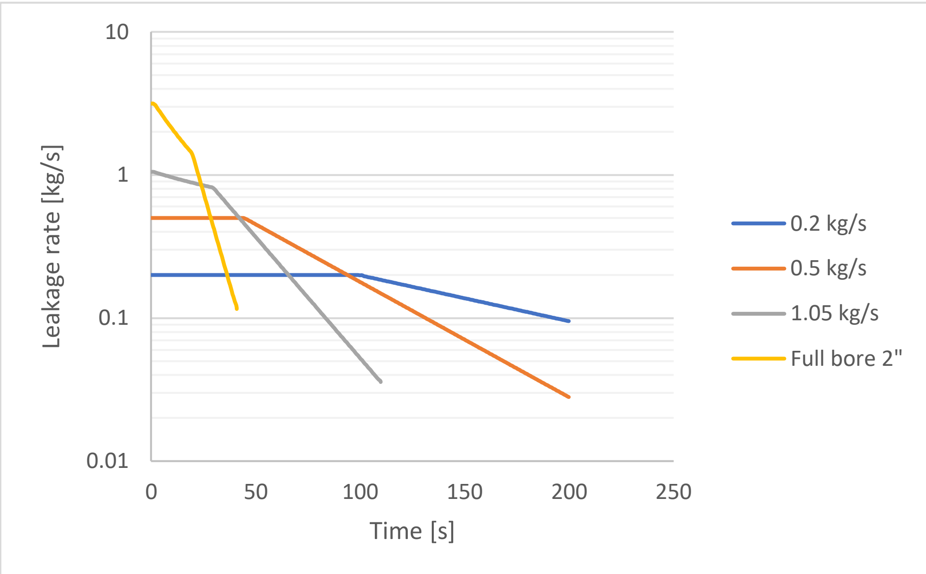

Figure 13-3 Hydrogen leak rate as function of time for different initial leak sizes inside electrolysis building

The hydrogen release durations inside the electrolysis building are relatively short lived. All releases have a leakage rate less than 0.1 kg/s after 200 seconds. This means that jet fires will be relatively short and have a limited escalation potential. Especially the larger leaks resulting in violent initial jet fire consequences will be over fast.

14 HUMAN VULNERABILITY

In order to calculate ISO-risk contours the vulnerability of humans in relation to different consequences needs to be established. DSB QRA guidance [5] recommends as a conservative simplified approach to apply 50% probits and assume 100% fatality inside the 50% probit reach and 0% fatalities outside the 50% probit reach. In reality, people can become fatalities outside the 50% probit range, but they can also survive inside the 50% probit.

Normally the ISO-risk contours are made for 3rd party, where it is assumed that a person is always present in the exposed area and will make no attempt to escape or protect themselves. This is very conservative, especially inside HIP, as 3rd party personnel will not be present here and 1st and 2nd party personnel will know how to react in an emergency.

14.1 CO TOXICITY

The CO IDLH value is 1 200 ppm. This does not mean that all personnel exposed to 1 200 ppm CO are killed immediately. CO's effect on humans is summarized in Table 14-1.

Table 14-1 Different CO concentrations effect on humans [26]

CO concentration	Effects
1 500 PPM	Headache after 15 minutes, collapse after 30 minutes, death after 1 hour
2 000 PPM	Headache after 10 minutes, collapse after 20 minutes, death after 45 minutes
3 000 PPM	Maximum "safe" exposure for 5 minutes. Danger of collapse in 10 minutes, danger of death in 15 to 45 minutes
6 000 PPM	Headache and dizziness in 1 to 2 minutes, danger of death in 10 to 15 minutes
12 800 PPM	Immediate effect, unconscious after 2 to 3 breaths, danger of death in 1 to 3 minutes

DSB recommends that TNO probit functions are applied for risk analyses [5]. To sets TNO probit functions, functions referred to as old and new have been considered [30]. The old and new TNO CO probit functions have been calculated in Figure 14-1.

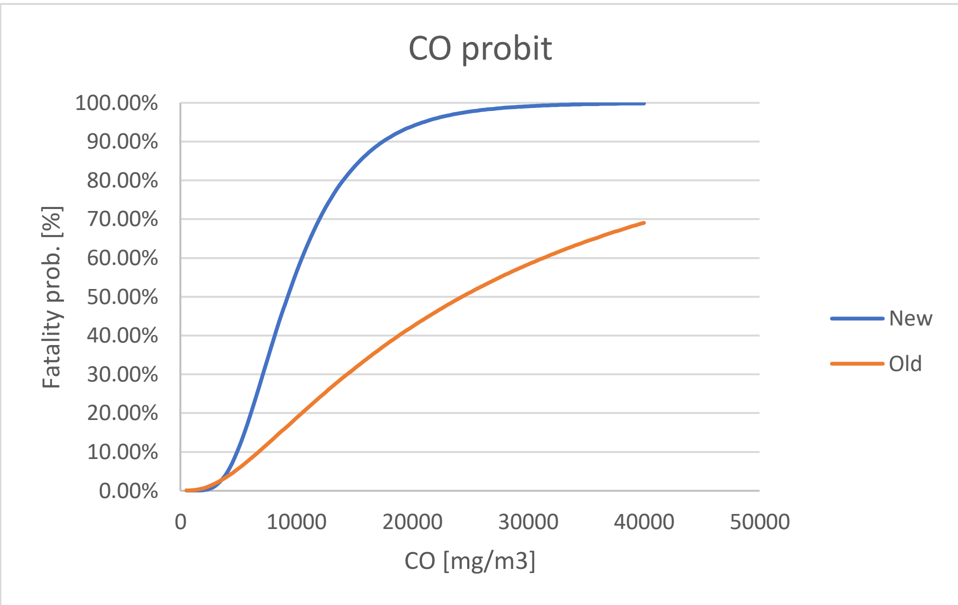

Figure 14-1 Old and new CO TNO probit functions for CO

As it will result in a higher risk to apply the new probit function compared to the old probit function it has been chosen to base the risk assessment on the new TNO CO probit function:

$$Pr = -15.9 + 1.11 \cdot ln(C \cdot t)$$

Where C is the CO concentration in mg/m^3, and t is the exposure time in minutes.

50% CO probit concentrations for different exposure times have been provided in Table 14-2.

Table 14-2: 50% CO probit concentrations for different exposure times

Exposure time	50% probit CO concentration
2 min	19 640 ppm
5 min	11 784 ppm
15 min	6 547 ppm

15 minutes is considered as the worst-case exposure time due to emergency shutdown and blowdown of the e-fuel plant. In many cases 1st and 2nd party personnel can escape within two minutes and at least within five minutes.

14.2 HEAT RADIATION (EARLY IGNITION)

In case of early ignition, jet fire will be the outcome and heat radiation can expose personnel. The TNO probit function [31] has been applied and results have been summarized in Table 14-3.

Table 14-3 50% probit heat fluxes for different exposure times

Exposure time	50% probit heat flux
30 sec	14.5 kW/m^2
1 min	8.5 kW/m^2
2 min	5.0 kW/m^2

The exposure times are selected to reflect that everybody will be able to move away from an exposed area in two minutes time if they feel the heat radiation. The fastest escape time will be 30 seconds. It is assumed that nobody will just stand at their position and wait if the heat radiation starts to hurt.

14.3 HEAT RADIATION/BLAST LOADS (DELAYED IGNITION)

In case of delayed ignition, the outcome will be either a flash fire (slow burning fire with no blast pressure) or an explosion (deflagration) with a blast load.

For flash fire, all personnel inside the flammable cloud are expected to become fatalities and all personnel outside the flammable cloud is assumed to survive.

The flash fire consequence will be the minimum consequence for explosion. In addition, the blast load may result in additional facilities outside the flammable cloud.

The flammable cloud volume has a longer reach than the 200 mbar blast pressure. In the open personnel are not likely to be killed by a 200 mbar blast unless they are hit by flying fragments or the head hits hard structures by being pushed by the blast [31]. Hence the flammable cloud envelope will determine the fatality risk to personnel from delayed ignition (flash fire or VCE).

15 RISK RESULTS

The risk results will be presented as ISO-risk contours ("Hensynssoner") by integrating frequencies and consequences of different hazard outcomes of the investigated release scenarios.

Furthermore, will dimensioning fire and blast loads be evaluated by a probabilistic approach to determine the 10^{-4} per year loads. This is important for the DeAL of the E-Fuel plant [32] as well as for evaluating credible domino effects.

Flammable and toxic gas impairment is also evaluated probabilistic.

15.1 ISO-RISK CONTOURS

ISO-risk contours will be evaluated for E-Fuel plant, Eramet compressor station and the Eramet discharge pipeline and be discussed in relation to the overall HIP ISO-risk contours.

The Individual risk as a function of distance from E-Fuel plant, compressor station and Eramet pipeline has been calculated based on the following main assumptions:

1) Only the outdoor process is expected to be able to significantly expose areas outside the E-Fuel plant, i.e. releases inside the electrolysis building has been ignored;

2) Only gas releases can significantly expose areas outside the E-Fuel plant boundary, i.e. pool fires from storage tanks has been ignored;

3) As a simplification all gas releases of the outdoor process at E-Fuel plant and compressor station is assumed to occur at the centre of the outdoor process areas and potentially point horizontally outwards in all directions (360 degrees);

4) For the Eramet pipeline releases can occur in all directions around the pipeline along the entire length of the pipeline;

5) A 50/50 distribution on early and late ignitions have been assumed. The assumption is not critical as unignited CO releases will dominate the risk.

The PHAST consequence envelope is conservatively based on the distance the 50% probit can reach and the maximum width of the consequence at any point along this reach.

15.1.1 E-FUEL PLANT

The Individual risk from E-Fuel plant has been calculated as function of distance from plant for different risk contributors in Figure 15-1.

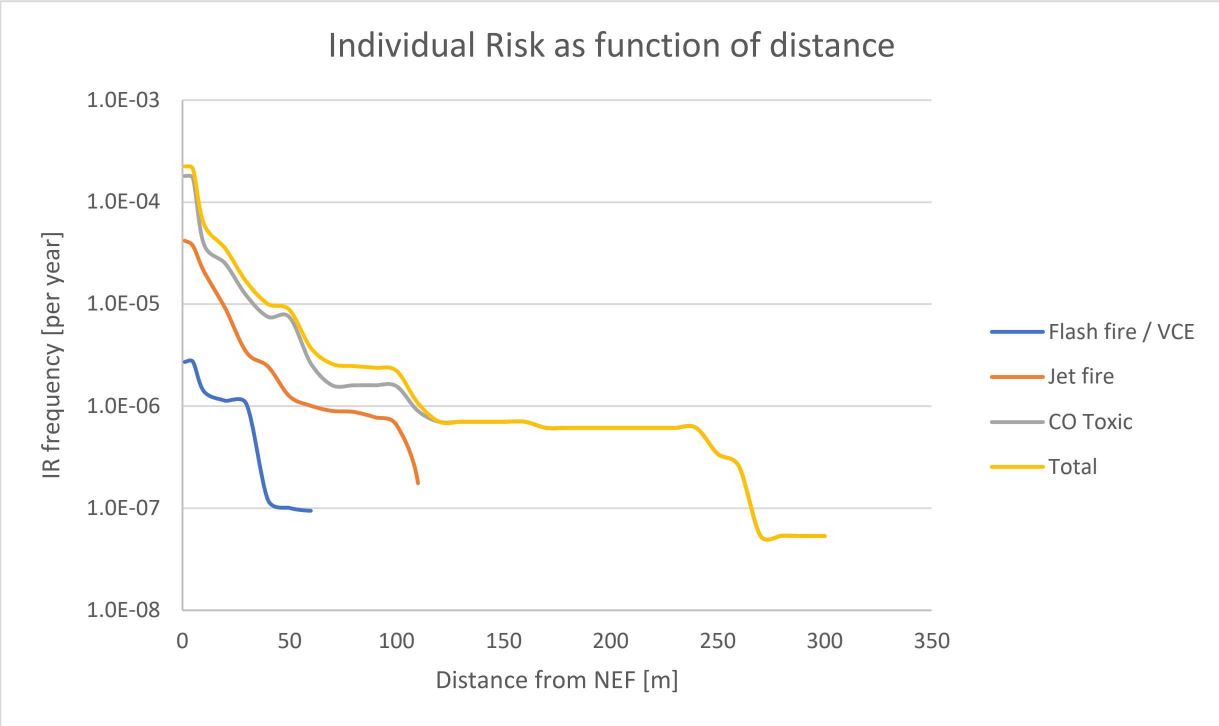

Figure 15-1 Individual risk from e-fuel plant calculated as function of distance from plant for different risk contributors

It is clear from Figure 15-1 that CO toxicity dominates the individual risk both in relation to frequency, but also the distance of exposure.

CO toxicity can reach as far as 300 m according the PHAST simulations. However, it is doubtful that such exposure can be sustained for 15 minutes so in particular the individual risk reaching distances longer than 100 m has been assessed very conservatively at present.

The 10^{-5} per year, 10^{-6} per year and 10^{-7} per year risk iso curves due to process releases on the E-Fuel plant has been plotted in Figure 15-2.

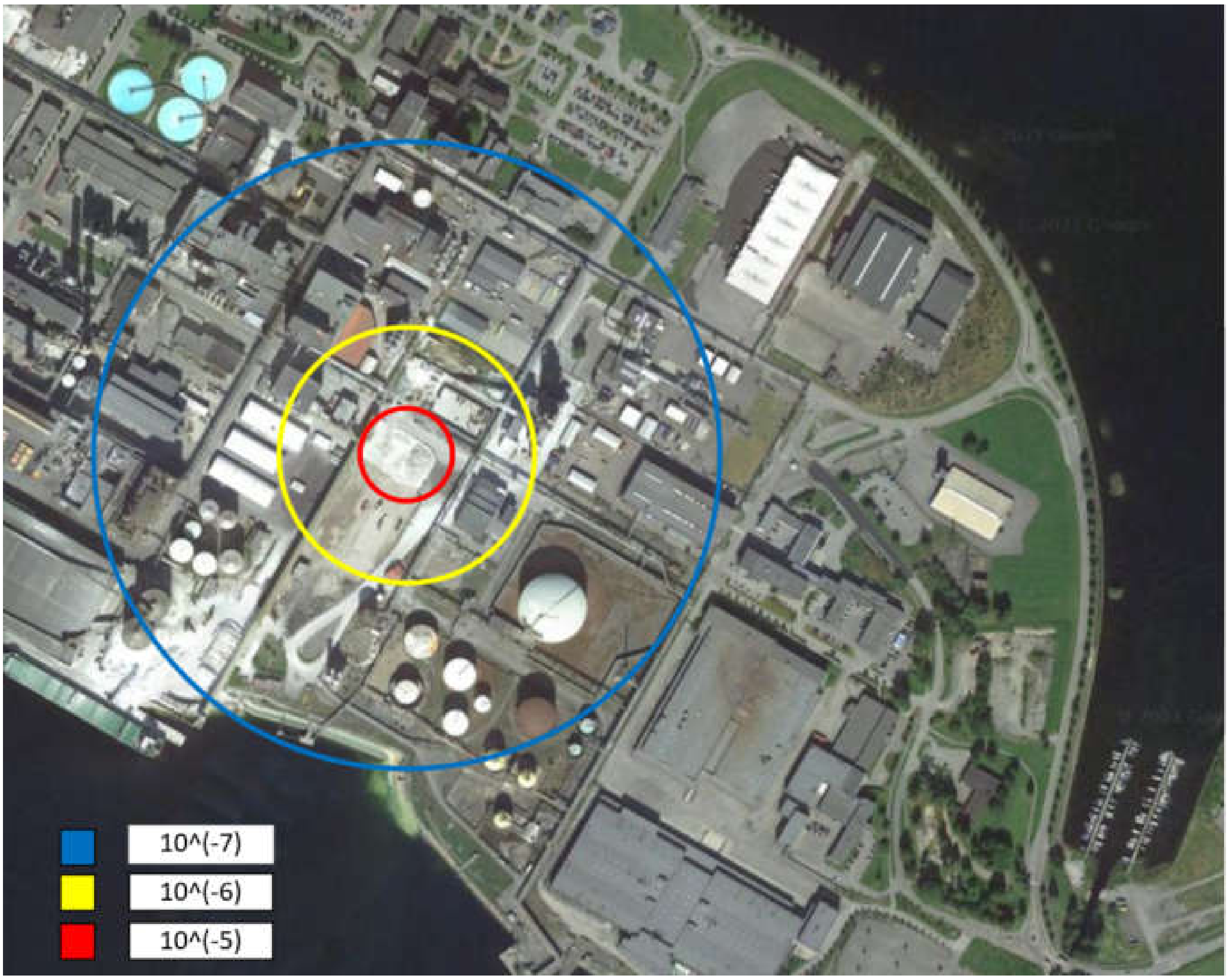

Figure 15-2 Iso risk contour curves from exposure from e-fuel plant

The 10^{-5} per year risk has a reach of 40 m, the 10^{-6} per year risk has a reach of 110m and the 10^{-7} per year risk has a reach of 270 m.

There is a relatively high risk (10^{-5} per year) locally around the E-Fuel plant but this is to be expected and is considered acceptable as it is inside HIP. The 10^{-6} per year risk contour does not extend outside the HIP. Even the 10^{-7} per year risk contour is limited to the HIP. This basically mean the E-Fuel plant will not impact the risk to 3rd parties in any way.

The overall ISO-risk contours for HIP are shown in Figure 15-3.

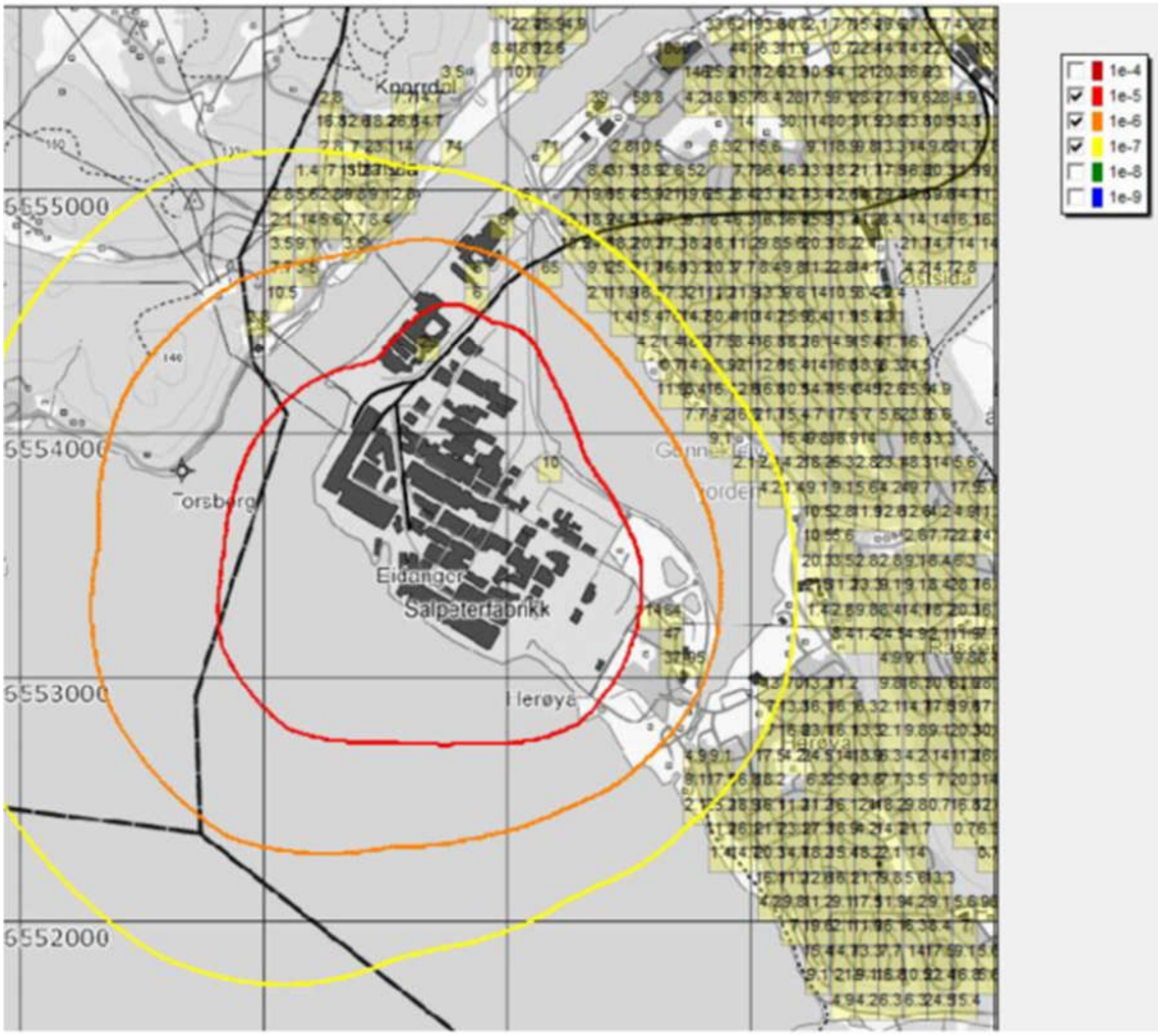

Figure 15-3 Overall ISO-risk contours for HIP before E-Fuel plant is built [10].

Comparing Figure 15-2 and Figure 15-3 it is clear that the HIP 10^{-5} per year risk contour lies outside the E-Fuel plants 10^{-7} per year risk contour. Based on this it is clear that E-Fuel plant will have negligible impact on the ISO-risk contours of HIP and this negligible impact will be inside the HIP boundary only. It will in no way change the risk to 3rd party. The effect of the E-Fuel plant is so minor it is not considered relevant to update Figure 15-3, any difference would not be detectable with the naked eye.

Considering the conservative approach taken, the risk exposure from the E-Fuel plant is considered to be acceptable.

However, it is important that it is ensured that the HIP emergency preparedness recognises the risk from the E-fuel plant and that personnel working inside HIP is aware of the risk and trained to respond. Especially the CO dispersion is considered critical as it has a long reach and can expose personnel without them being aware of it. The E-Fuel plant shall detect CO releases that can expose neighbouring areas and sound an alarm that can be heard in the surrounding areas of HIP. Personnel are then expected to escape to gas shelter distributed at strategic locations on HIP and wait for the alarm to be called off.

All personnel working outdoors in HIP shall carry a gas mask and all the companies at HIP shall provide gas tight shelters for their employees. The HIP requirement for gas masks is to use ABEK1 filter, which is not effective against CO. However, personnel will be required to carry CO detector at E-Fuel plant and will therefore be warned of CO releases. In addition will fixed CO detectors with alarm be installed at E-Fuel plant.

All HIP personnel working in HIP is trained to respond to alarms.

15.1.2 COMPRESSOR STATION

Detailed risk calculations for the compressor station have been included in Appendix D.

The Individual risk from Compressor Station has been calculated as function of distance from plant for different risk contributors in Figure 15-4.

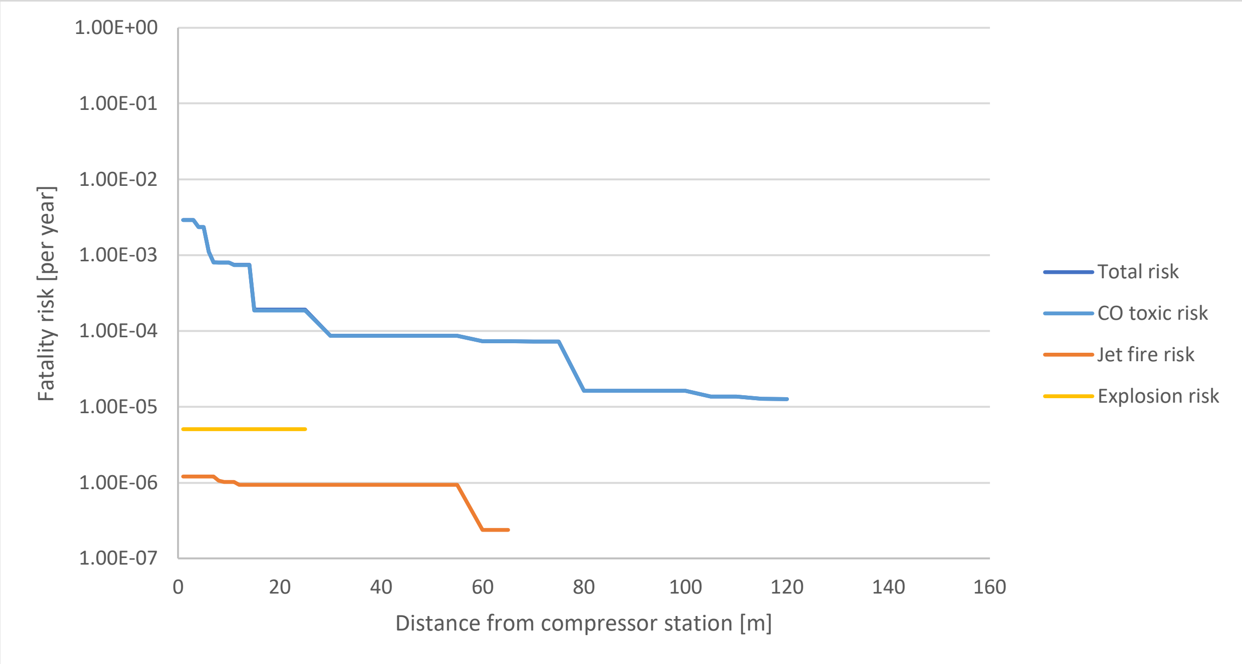

Figure 15-4 Individual risk from Compressor Station calculated as function of distance from plant for different risk contributors

It is clear from Figure 15-4 that CO toxicity dominates the individual risk both in relation to frequency but also the distance of exposure.

CO toxicity can reach as far as 120 m according to the PHAST simulations. However, it is doubtful that such exposure can be sustained for 15 minutes so in particular the individual risk reaching distances longer than 100 m has been assessed very conservatively at present.

The 10^{-5} per year, 10^{-6} per year and 10^{-7} per year risk iso curves due to process releases on the E-Fuel plant has been plotted in Figure 15-5.

Figure 15-5 Iso risk contour curves from exposure from Compressor Station

The 10^{-5} per year risk has a reach of 75 m, the 10^{-6} per year risk has a reach of 120m and the 10^{-7} per year risk has a reach of 125 m.

There is a relatively high risk (10^{-5} per year) locally around the E-Fuel plant, but this is to be expected and is considered acceptable as it is inside HIP. The 10^{-6} per year risk contour does not extend outside the HIP. Even the 10^{-7} per year risk contour is limited to the HIP. This basically means that the E-Fuel plant will not impact the risk to 3rd parties or the overall HIP risk contours of Figure 15-3 in any way.

The HIP requirement for gas masks is to use ABEK1 filter, which is not effective against CO. However, personnel will be required to carry CO detector at the compressor station and will therefore be warned of CO releases. In addition will fixed CO detectors with alarm be installed at the compressor station. All HIP personnel working in HIP is trained to respond to alarms.

15.1.3 ERAMET DISCHARGE PIPELINE

Detailed calculations for Eramet pipeline have been provided in Appendix C.

The Individual risk from Eramet pipeline has been calculated as function of distance from pipeline for different risk contributors in Figure 15-6.

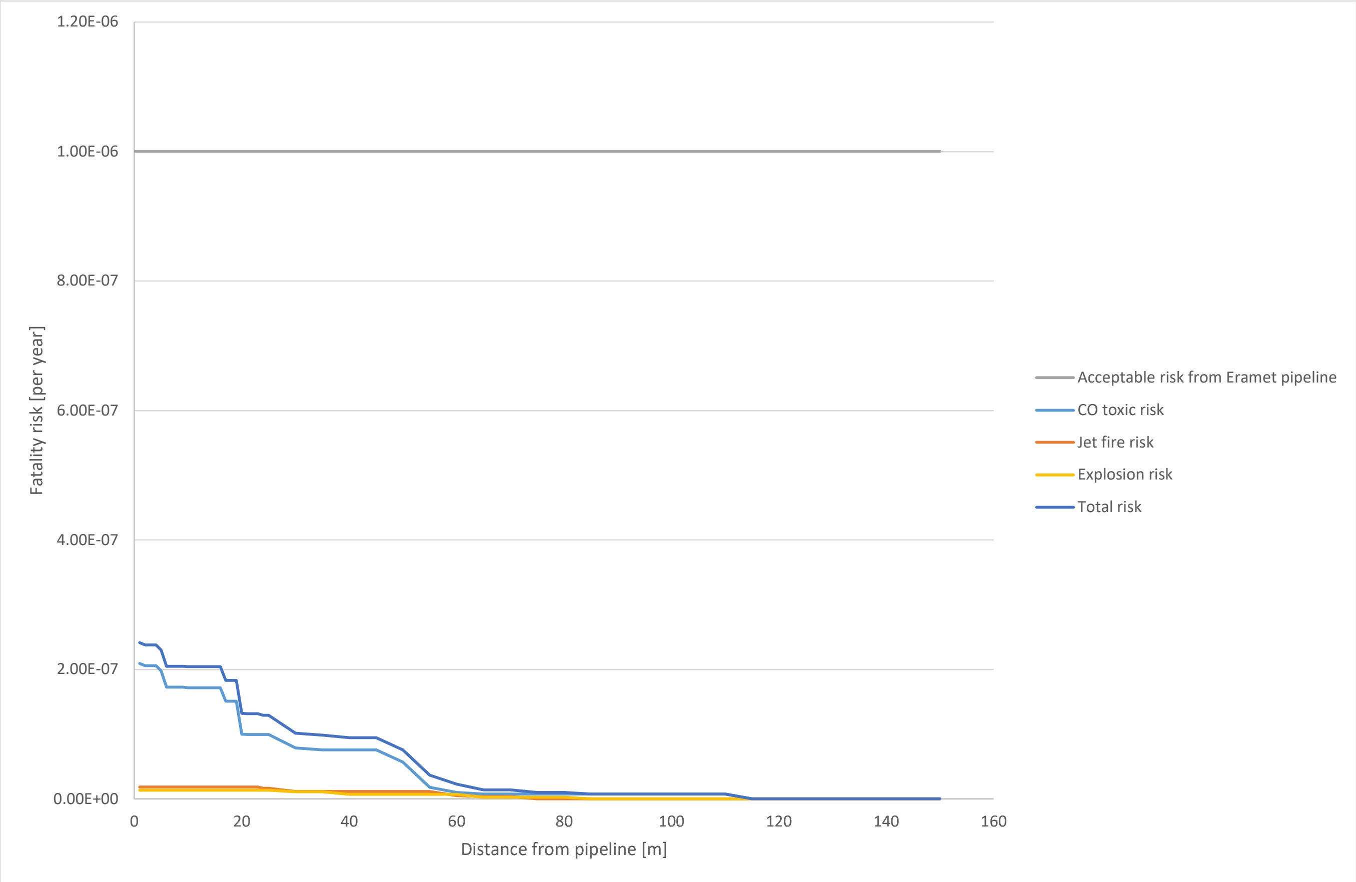

Figure 15-6 Individual risk from Eramet pipeline calculated as function of distance from plant for different risk contributors.

It is clear from Figure 15-6 that CO toxicity dominates the individual risk both in relation to frequency but also the distance of exposure.

CO toxicity can reach as far as 114 m according to the PHAST simulations. However, it is doubtful that such exposure can be sustained for 15 minutes so in particular the individual risk reaching distances longer than 100 m has been assessed very conservatively at present.

ISO-risk contours have not been drawn on HIP plot plan as the pipeline is routed through many different parts of HIP. But the pipeline has no 10^{-5} per year or 10^{-6} per year contours and the 10^{-7} per year contour is at 35 m, to both sides of the pipeline.

It is apparent from Figure 15-6 that the risk is significantly lower than the risk acceptance criteria determined by the project. As the risk acceptance criteria in itself is conservative, the risk is very low and considered acceptable.

The HIP requirement for gas masks is to use ABEK1 filter, which is not effective against CO. The CO risk from the Eramet pipeline is considered very low and a leakage will occur in 5 m height and be diluted and therefore is the risk of fatal exposure of personnel very remote. It has therefore not been considered necessary to change the overall requirement for gas mask filter specification in HIP. This is based on a dialogue between NEF and HIP.

Some sensitivities have been performed for the Eramet pipeline risk evaluation to test the robustness of the risk assessment since the pipeline will be routed through large parts of HIP.

15.1.3.1 SENSITIVITY I – PLOFAM(2) DATA

In this sensitivity the PLOFAM(2) release frequencies are used directly to investigate the uncertainty for combining the PLOFAM(2) model with PARLOC 2012 data as done for the base case. Hence in this sensitivity the leak frequencies correspond to what is expected from normal offshore pipework rather than an onshore pipeline. The sensitivity is believed to be very conservative.

The Individual risk from Eramet pipeline in Sensitivity I has been calculated as function of distance from pipeline for different risk contributors in Figure 15-7.

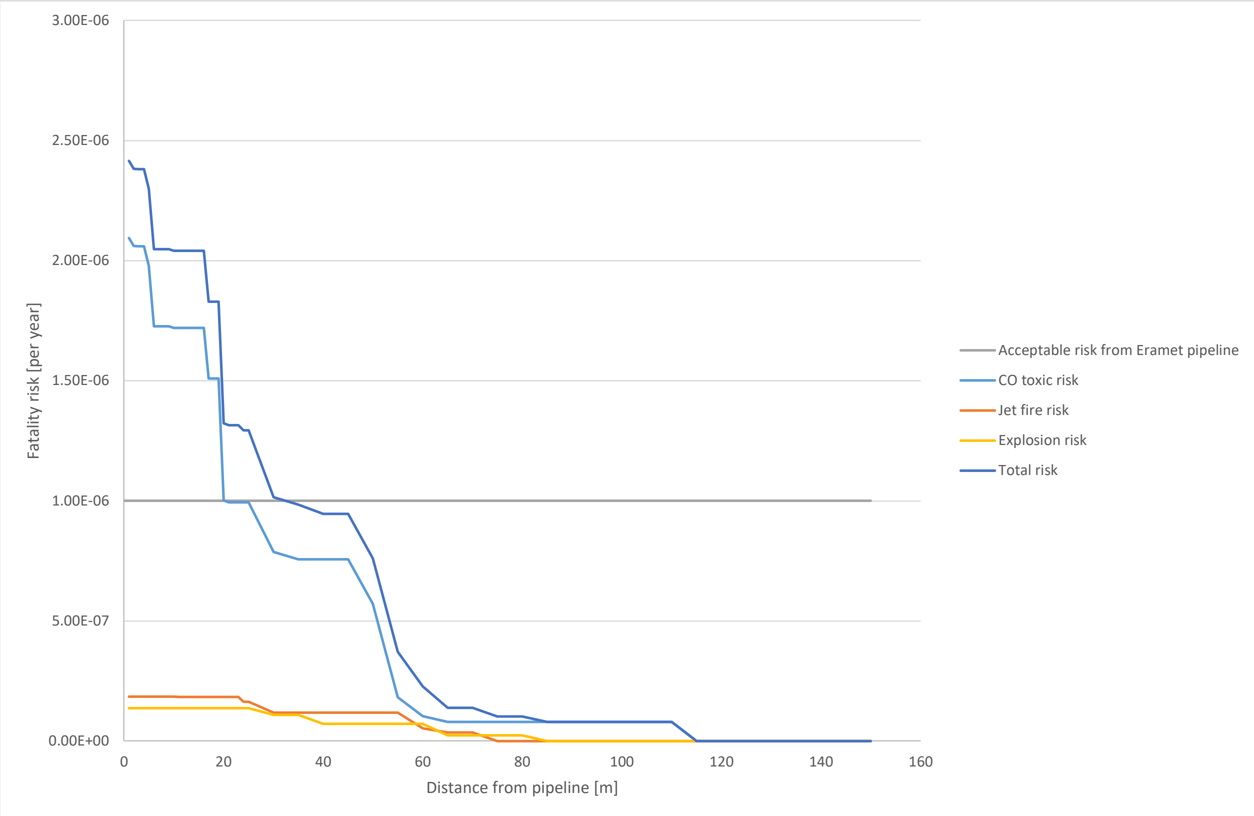

Figure 15-7 Individual risk from Eramet pipeline calculated as function of distance from plant for different risk contributors for Sensitivity I.

It is apparent from Figure 15-7 that the 10^{-6} per year ISO-risk occurs in approximately 35 m distance from the Eramet pipeline. The 10^{-7} per year iso contour risk curve is 85 m from the pipeline. Hence for Sensitivity 1 the RAC is exceeded up to 35 m from the pipeline, but the risk is still low.

Considering that Sensitivity 1 is very conservative, and it barely exceeds the target (only a factor 2.4), the sensitivity is not considered a concern. It is very important to note that DSB requires iso risk curves to be as realistic as possible. i.e. not overly conservative and not optimistic. But the ISO-risk curves should be “forventningsrett” [5].

15.1.3.2 SENSITIVITY II – LOW WIND

There is generally uncertainty about the wind data at HIP. Furthermore, as small leakages of the Eramet pipeline may go undetected for a relatively long time it is likely the release will not be detected before low wind conditions has occurred during the leakage. Hence a sensitivity is carried out assuming 1.5 m/s wind all the time.

The Individual risk from Eramet pipeline in Sensitivity II has been calculated as function of distance from pipeline for different risk contributors in Figure 15-8.

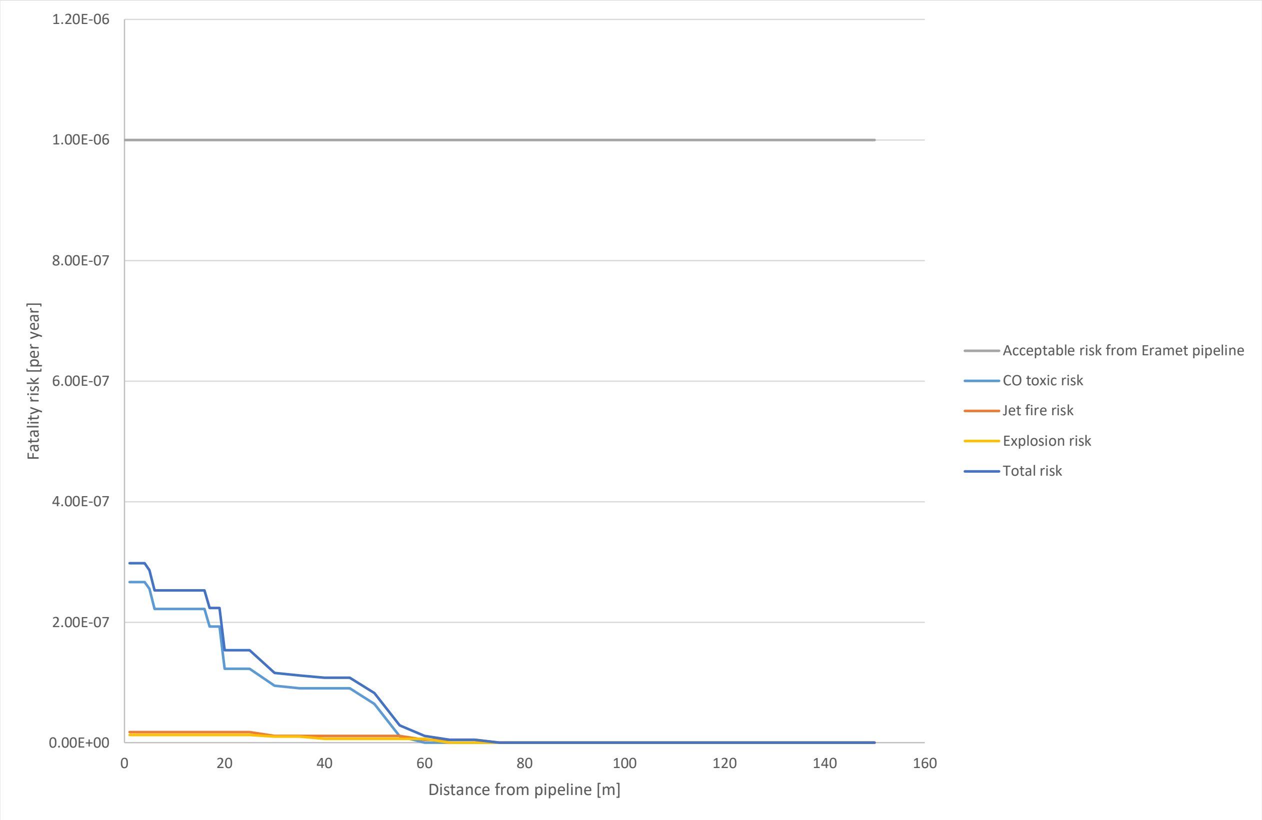

Figure 15-8 Individual risk from Eramet pipeline calculated as function of distance from plant for different risk contributors for Sensitivity II.

It is apparent from Figure 15-8 that Sensitivity II does not have a 10^{-6} per year iso curve due to the low predicted release frequencies. The 10^{-7} per year iso curve lies approximately 50 m from the pipeline.

Hence Sensitivity 2 is of no concern.

15.1.3.3 SENSITIVITY III – LOW PRESSURE OPERATION

It has been considered if it will be ALARP to operate the Eramet pipeline at a lower pressure. The pressure determines the potential leakage rate for a specific leak hole size which again impacts the extend of the consequences of a release.

An alternative could be to reduce the operating pressure to 9.1 bara, which requires a 4" pipeline, instead of a 3" pipeline used for the high pressure. This leads to a larger pipeline inventory.

The risk difference between operating the Eramet pipeline at high pressure (40 bar) or low pressure (9.1 bar) has been investigated previously be only considering the CO toxicity risk. As CO toxicity is clearly the dominating risk this simplification will not jeopardize any conclusions made.

In Figure 15-9 risk profiles of high and low pressure operation of Eramet pipeline has been compared.

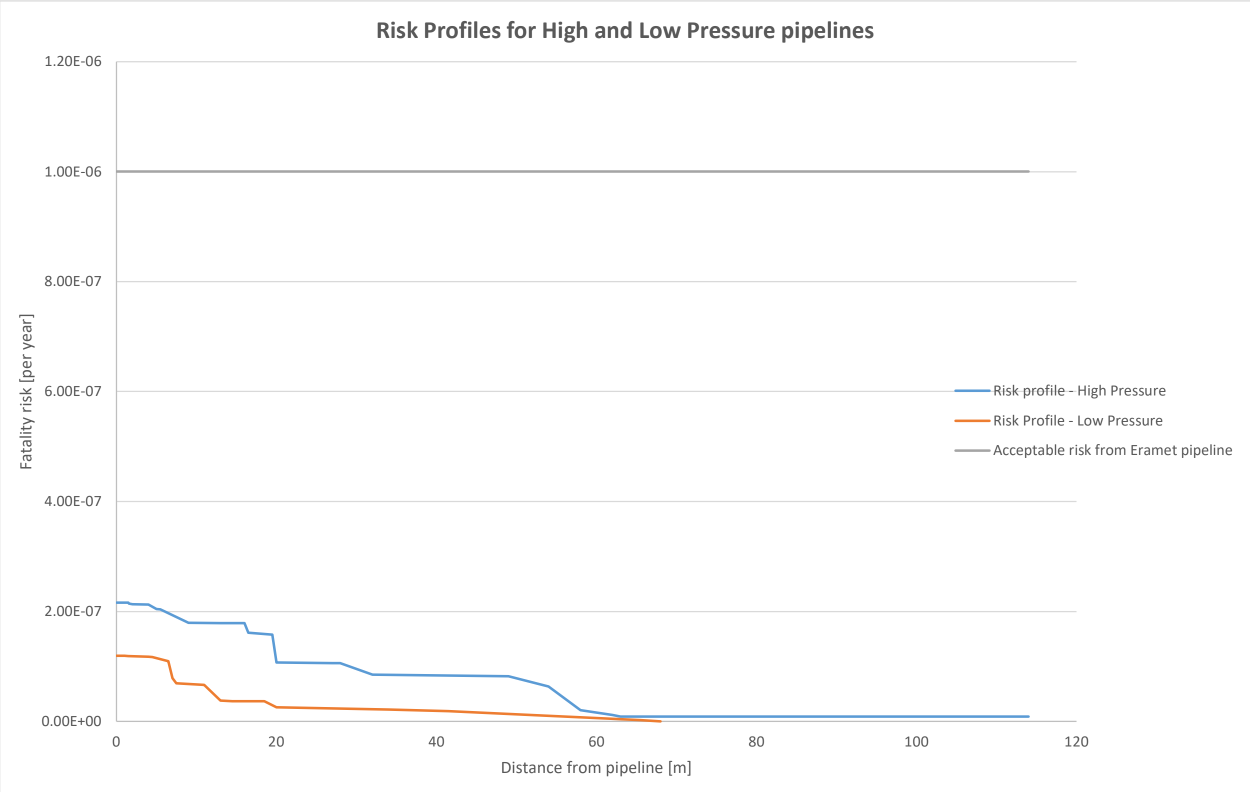

Figure 15-9 Comparison of high pressure and low pressure operation risk profiles in downwind distance from Eramet pipeline [3].

It is apparent from Figure 15-9 that the risk for low pressure operation is lower than that of high pressure operation, and that the fatal consequences cannot extend as far for low pressure operation as for high pressure operation. This is to be expected. However, the decrease in risk for low pressure operation compared to high pressure operation is relatively small compared to the risk acceptance criteria, and the high pressure case (base case) is already significantly below the risk acceptance criteria.

Based on this it is considered ALARP to operate the Eramet pipeline at approximately 40 barg as the risk benefit of lowering the pressure is low and the risk level of 40 barg operation is already very low.

Furthermore, lowering the operating pressure will have a knock-on effect on the E-Fuel plant where compression would have to be installed increasing the risk level locally at the E-Fuel plant.

15.2 DIMENSIONING BLAST LOADS

Dimensioning blast loads in HIP is defined as 10^{-4} per year blast loads [11]. Dimensioning blast load ISO-risk curves have been drawn for HIP in Figure 15-10.

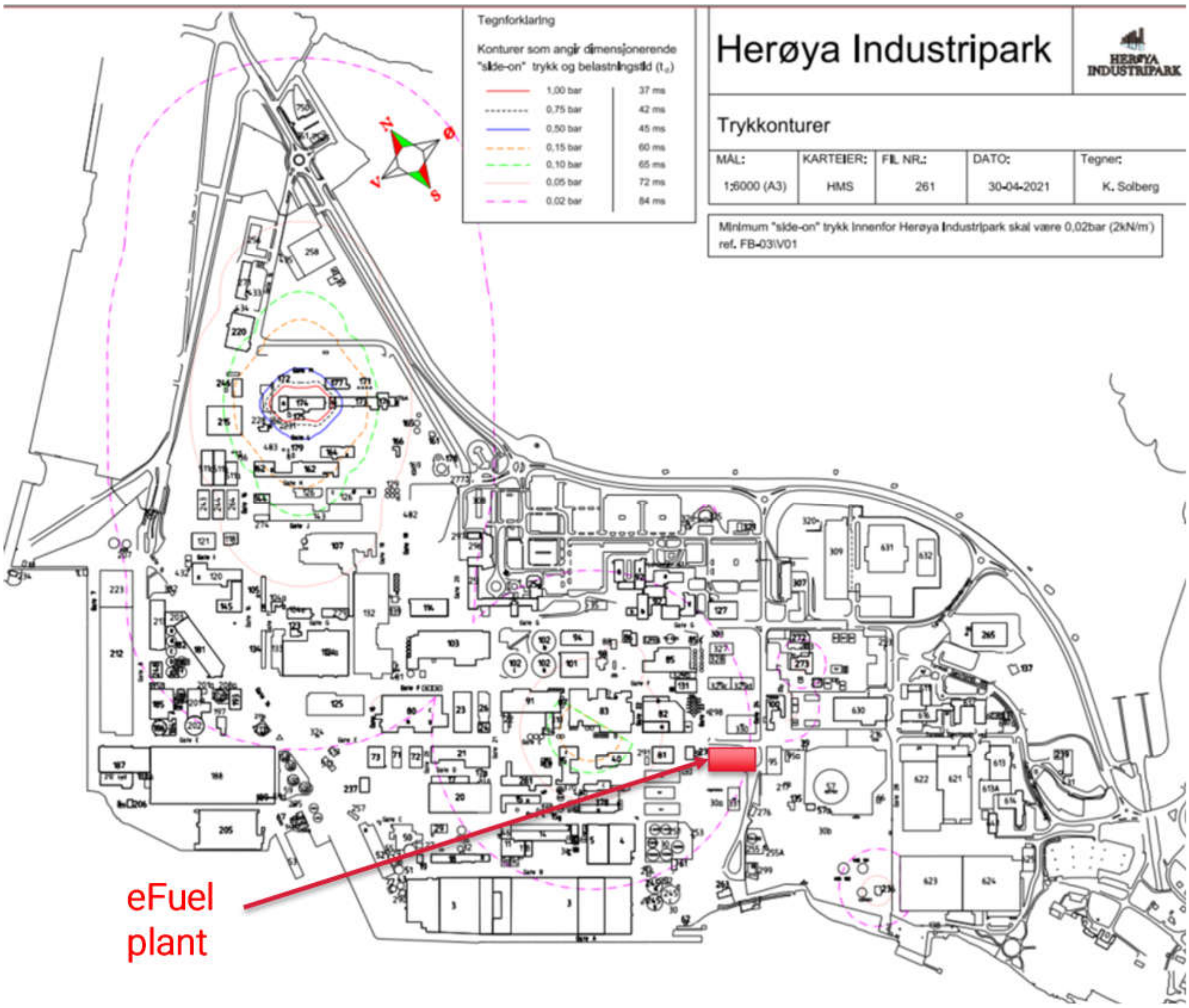

Figure 15-10 Dimensioning blast load iso curves for HIP

Blast loads at the E-Fuel site today is in between 0.02 bar to 0.05 bar and this blast loads stems primarily from the PVC plant.

Distance from the E-Fuel plant for dimensioning blast loads of different sizes has been calculated based on data presented in Section 11 and 12. The results have been presented in Table 15-1.

Table 15-1 Distances of dimensioning blast loads from E-Fuel plant

Dimensioning Blast load	Distance
[bar]	[m]
0.02	35
0.05	15
0.1	9
0.15	6
0.5	*3*
0.75	*2*
1	*2*

It is observed that E-Fuel plant dimensioning blast loads are unlikely to exceed 0.02-0.05 bar, which is considered low and manageable blast loads for the neighbours. Inside the E-Fuel plant, dimensioning blast load is in the range 0.05-0.15 bar. Dimensioning blast loads of 0.5 bar and higher has been calculated just where the ignition occurs. However, this is considered an artefact of the calculation method that is developed for far field blast loads investigations and not near field investigation. Hence blast loads above 0.15 bar can be disregarded.

The dimensioning blast loads from E-Fuel plant has been plotted on the HIP landscape in Figure 15-11. It is clear that the dimensioning blast loads from HIP are very local and will not expose any neighbours significantly. The E-Fuel Plant dimensioning blast loads has also been plotted on the HIP blast load card in Figure 15-12.

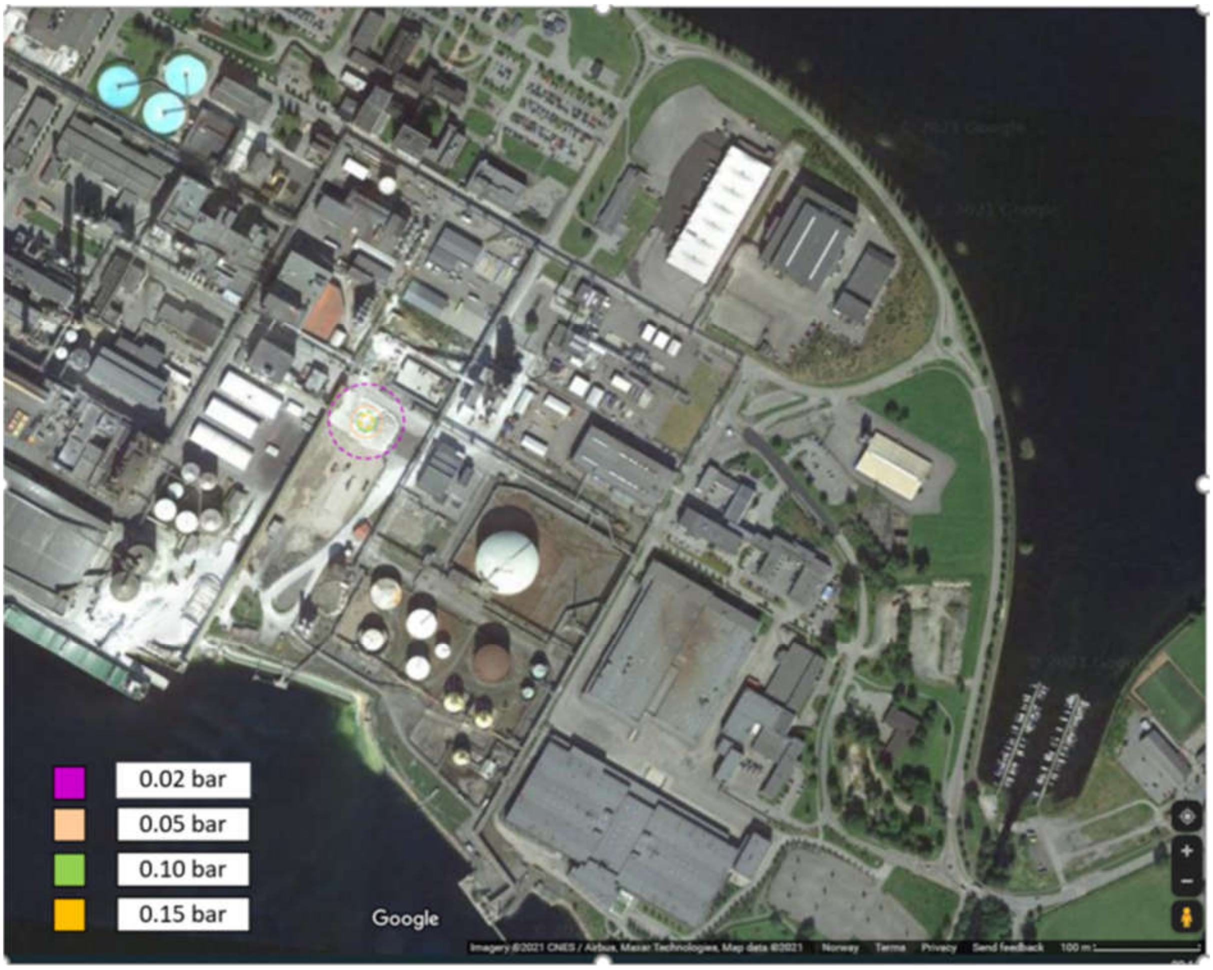

Figure 15-11 Dimensioning blast loads from E-Fuel plant plotted on HIP landscape.

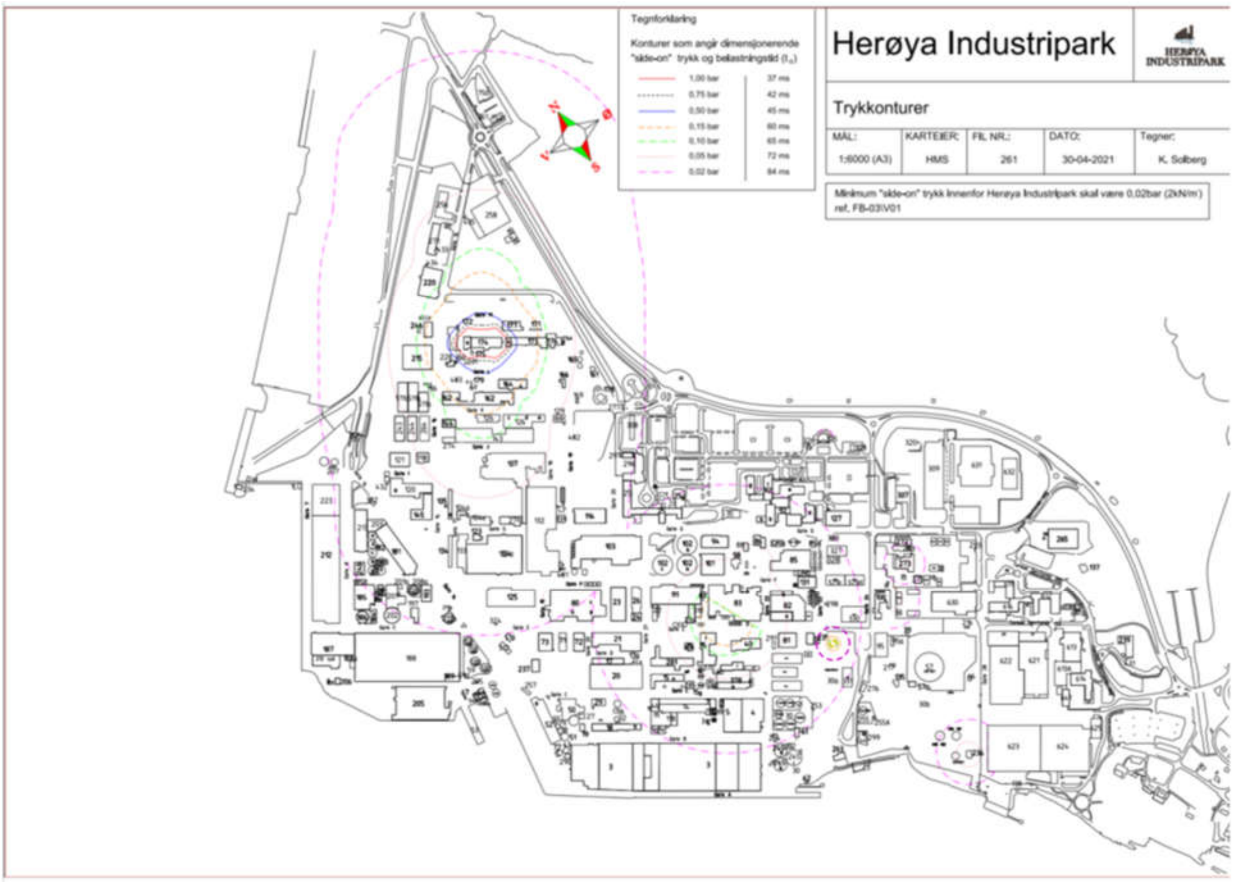

Figure 15-12 E-Fuel plant dimensioning blast loads plotted on the HIP blast load card.

Dimensioning blast load impact from Compressor Station and the Eramet pipeline will be even lower than for the E-Fuel plant and has therefore not been calculated.

15.3 DIMENSIONING JET FIRE LOAD

As for blast loads, the size of jet fire with a 10^{-4} per year re-occurrence has been calculated for the E-Fuel plant to see if it is credible that a jet fire can expose any neighbours critically. The jet fire reach from E-Fuel plant has been calculated in Table 15-2.

Table 15-2 Reach of dimensioning and worst-case jet fires from E-Fuel plant

Jet fire heat loads	$5\ kW/m^2$ [m]	$8.5\ kW/m^2$ [m]	$14.5\ kW/m^2$ [m]
Worst case	130	120	110
Dimensioning case	9	8	8

It is apparent from Table 15-2 that jet fires from E-Fuel plant in worst case can reach a long distance (>100 m). But such scenarios are both low frequency and short lived (will stop in less than 100 seconds) scenarios. The dimensioning jet fire of the E-Fuel plant is less than 10 m and can therefore only cause local exposure inside the E-Fuel plant site.

The duration of the dimensioning jet fire is in worst case approximately 10 minutes.

Dimensioning jet fire impact from Compressor Station and the Eramet pipeline will be even lower than for the E-Fuel plant and has therefore not been calculated.

15.4 DIMENSIONING POOL FIRE LOAD

The frequency of pool fire in E-Fuel plant storage tank bund has been calculated to be significantly less than 10^{-4} per year, meaning there is no dimensioning pool fire heat load when taking a probabilistic approach. In addition, if a pool fire should occur it is likely it would be extinguished by the foam firefighting system in place in the bund. Assuming the firefighting system will fail 5% of the time the storage tank pool fire will occur less than 10^{-6} per year.

Results of pool fire risk calculations have been provided in Table 15-3.

Table 15-3 E-Fuel storage tank pool fire risk calculations

Pool fire	Pool fire freq.	FF failure prob.	Uncontr. PF freq.	5 kW/m² distance	8.5 kW/m² distance	14.5 kW/m² distance	Worst heat at Yara wax tanks
	[per year]	[-]	[per year]	[m]	[m]	[m]	[kW/m²]
8- LFTL Storage and Offloading	8.58E-06	0.05	4.29E-07	38.4	27.8	20.2	13.7
9- HFTL Storage and Offloading	6.81E-06	0.05	3.41E-07	38.4	27.8	20.2	13.7
Sum	**1.54E-05**		**7.70E-07**				

In Table 15-3 worst case heat radiation level at Yara wax tanks has been calculated to 13.7 kW/m². It is expected to take a long time before this heat radiation level is able to expose the Yara wax tanks critically.

15.5 IMPAIRMENT BY FLAMMABLE GAS

Flammable gas may impair operations at neighbours, e.g. in case flammable gas is sucked into the HVAC air intake of Building 95 it is likely for a shutdown to occur, resulting in a large part of the HIP losing its main power. It has therefore been found of interest to determine the reach of flammable gas with a 10^{-4} per year re-occurrence.

The dimensioning flammable gas reach and worst-case flammable gas reach has been calculated in Table 15-4.

Table 15-4 Reach of flammable gas (100% LFL) for worst case and releases with a 10^{-4} per year re-occurrence.

Flammable gas reach	100% LFL
	[m]
Worst case	77
Dimensioning case	16

From Table 15-4 it is clear that it will be unlikely that flammable gas is formed outside the E-Fuel site boundary. Flammable gas releases that can expose outside the E-Fuel plant boundary will be short lived and low frequency events.

15.6 IMPAIRMENT OF CCR

It is important that the CCR on the E-Fuel plant can survive accidents on the plant so it remains functioning in an emergency.

Hydrogen jet fire in the electrolysis building is not considered critical for the building with the control room or the outdoor process. It is considered practical possible to design the wall for the control room building to withstand the jet fire DeALs. The last jet fires will be over in few minutes time and the long duration small jet fires are relatively small and it is considered possible to design a concrete wall to survive such fires.

As discussed in Section 12.4, dimensioning blast loads inside electrolysis building is expected to be in the region 0.2 bar. The electrolysis building shall be designed for the dimensioning blast load, so CCR is not impaired with a frequency exceeding 10^{-4} per year. The required design details shall be established in detailed design.

Outdoor blast loads will be low due to low confinement and relatively low reactivity of syngas. Outdoor blast loads are therefore not considered an issue for the electrolysis building and control room. The blast DeAL inside the building will be design governing.

15.7 INTERNAL ESCALATION ON E-FUEL PLANT

By internal escalation it is here meant that an initiating accident on the E-Fuel plant spreads or escalates to other part of the E-Fuel plant. This is important to consider to ensure that the design of the E-Fuel plant becomes sufficiently robust.

Fires inside the electrolysis hall is not considered a threat to the outdoor process, as their short duration prevents them from spreading outside. If a jet fire points towards a louvre, flames may disperse outside. But the flame would have lost its momentum and the heat load of the fire outside is expected to be very limited and not able to cause escalation.

The electrolysis building will be designed to manage hydrogen blast loads inside the building. Hence such explosion will not be a threat to the surroundings.

Due to the relatively open distance between process systems and product storage tanks, blast loads are not considered a problem for the product storage tanks. But the storage tanks should be design for a minimum nominal blast DeAL.

Drag loads from explosions in the outdoor process could impact the vent system which is an integrated part of the process system. Explosion escalation to the vent system is considered critical as an explosion will be followed by emergency blowdown of the entire process gas inventory through the vent. Hence any breach of the vent system could lead to an escalation. It is therefore recommended to design the vent system for a minimum nominal drag load.

Jet fire in the outdoor process is not expected to be a threat to storage tanks. Large jet fires will be relatively short-lived and the small jet fires are not expected to pose a threat. Most of the small jet fires will be located too far away to even reach the storage tanks. However, it needs to be confirmed in detailed design if any form of passive fire protection system is required for the storage tanks. It is however not expected that PFP will be required.

In detailed design it shall be ensured that the vent system including supports can survive fire and explosion DeALs. This is expected to be possible by applying appropriate material strengths and thickness for equipment, pipework and structures. As a last resort PFP may have to be applied locally for especially vulnerable parts, but this is not expected. The fire heat loads will be relatively low and of short duration.

Pool fire in the product storage tanks will be limited to bunded area of the storage tanks. The duration of such fires if not extinguished can be very long >1 hr. The fire will generate significant heat loads local at the fire, but the heat loads will decrease fast when moving horizontally away from the fire. The fire will also generate large amounts of black smoke that probably will require evacuation of the area.

Due to the large distance, pool fire in the product storage tanks is not considered a direct threat to the electrolysis hall and the control room. The largest threat is if smoke is sucked into the control room via HVAC air intakes. However, F&G system closing fire dampers should reduce this risk to an acceptable level.

Pool fires from storage tanks are not likely to escalate to the outdoor process area due to the distance between units. If escalation occurs it would most likely be after the process gas inventory has been blown down through the vent system. Furthermore, any escalation in the process system would be considered minor compared to the initial fire of the product storage tanks required to cause such escalation.

16 DOMINO EFFECTS

Domino effects (or chain reaction) is the description of an event that causes a process or event with significant consequences i.e. more serious consequences than the immediate consequences of the first event.

In the industry, the designation “domino effects” is used for hazardous events that occur as a result of an initiating accidental event.

For the E-Fuel project two types of Domino effects are of interest:

- Accident scenarios of E-Fuel plant, compressor station or Eramet discharge pipeline exposing neighbouring plants leading to a major escalation of the initial consequences;

- Accidental scenarios of neighbouring HIP plants with MAH potential exposing the E-Fuel plant, compressor station or Eramet discharge pipeline leading to a major escalation of the initial consequences.

The main concern is domino effects that can have serious consequences outside HIP and thereby a risk to 3rd party.

An overview of installations in HIP with MAH potential has been provided in Figure 16-1.

Vedlegg 1. Kart over HIP

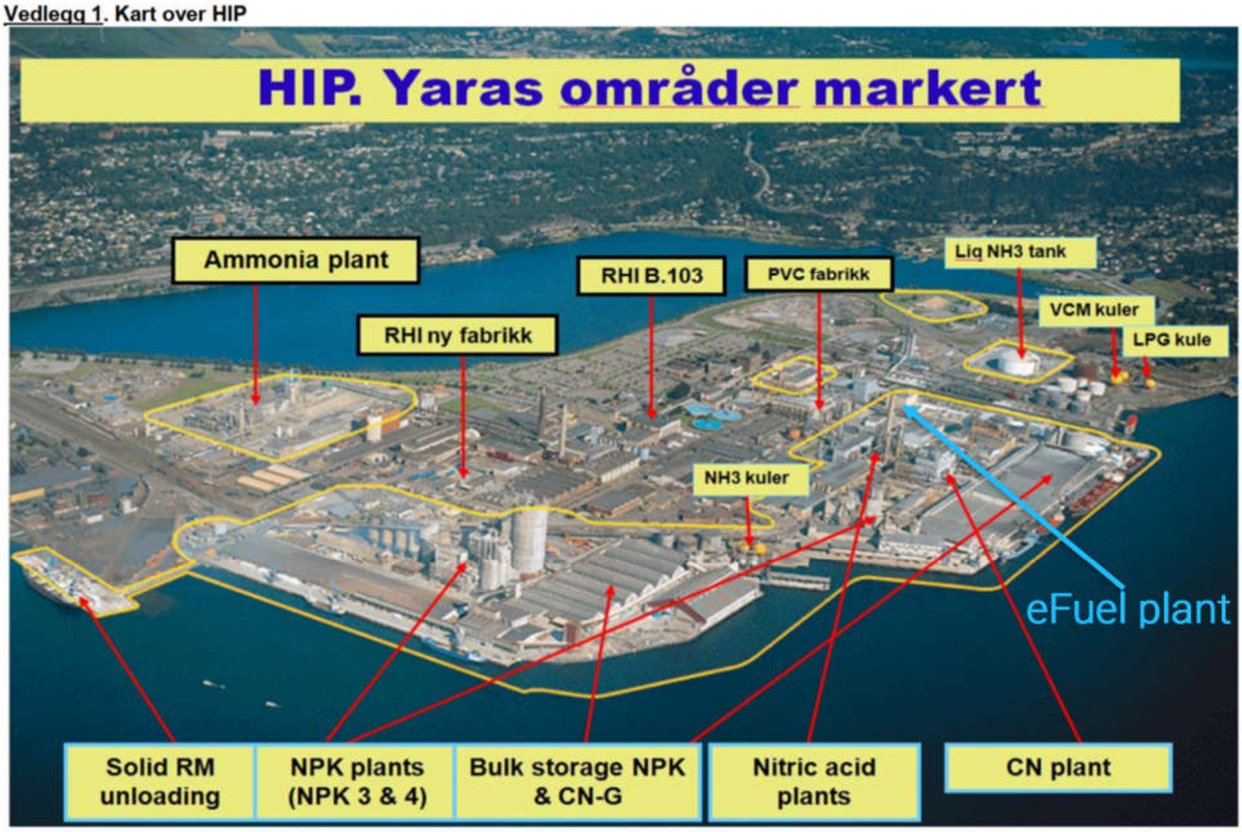

Figure 16-1 Map over HIP with installation with MAH potential [11].

The neighbouring plants of concern in relation to domino effects are:

- Yara
    - Ammonia storage tank (57)
    - Yara wax tanks at Building 235
    - Yara LPG storage tanks (236)

- PVC plant
    - VCM day tank at Building 83
    - VCM storage (236)
- Air Liquide Skagerak
    - LNG storage tanks (299)

In addition, impact from E-Fuel plant on high voltage Building 95 will be considered as shutdown or loss of Building 95 next to the E-Fuel plant will result in loss of main power supply to a large part of the HIP. This will not cause a major accident event but will cause production issues at HIP and has therefore also been considered.

The potential domino effects will be discussed with basis in the quantitative risk calculations of the present report (initiating events from E-Fuel project) and risk analyses provided for Yara [9] [10] [11], PVC plant [12] and Air Liquide Skagerak [13] (initiating events from neighbours exposing E-Fuel project).

16.1 DOMINO EFFECTS FROM INITIATING EVENTS FROM E-FUEL PROJECT

The E-Fuel plant, compressor station and Eramet discharge pipeline could potentially impact neighbours with:

- Blast loads from explosions (VCE);
- High heat radiation levels from jet fires;
- High heat radiation levels from pool fires;
- Exposure by flammable gas;
- Exposure by Toxic CO cloud.

BLEVE at E-FUEL plant of the LFTL and HFTL storage tanks is not considered a credible scenario due to the “heavy” hydrocarbon stored.

Exposure of flammable gas is not expected to cause any domino effects, but it could cause shutdown of Building 95 and thereby loss of main power for HIP.

Exposure by CO toxicity will not cause any domino effects and is therefore not considered further in the present section.

16.1.1 BLAST LOADS

Dimensioning blast loads at critical targets relatively close to E-Fuel plant has been calculated in Table 16-1.

Table 16-1 Dimensioning blast loads from E-Fuel plant at critical targets

Target	Distance from eFuel plant [m]	Dim. last load [bar]
Building 95 (HV)	58	<0.02 bar
Building 235 (Yara wax)	62	<0.02 bar
Yara ammonia storage tank	146	<0.02 bar
PVC plant	>100 m	<0.02 bar
Skagerak LNG storage	>170 m	<0.02 bar

Low dimensional blast loads cannot cause any significant damage or domino effects.

Worst case blast loads at critical targets with no regard to likelihood has also been considered in Table 16-2.

Table 16-2 Worst case blast loads at critical targets

Scenario	Target	Blast load [bar]	Remark
Full-bore rupture of Hydrogen to Syngas production - low wind (1.5F)	Building 95 (HV)	0.15	Shielded by electrolysis building
	Building 235 (Yara wax)	0.14	
	Yara ammonia storage tank	0.05	
	PVC plant	0.05	
	Skagerak LNG storage	<0.05	

The Yara ammonia storage tank, which has a large potential consequence and contribute significantly to the overall risk of HIP to 3rd parties, can in worst case be exposed to a blast load of 0.05 bar from the E-Fuel plant. As the storage tank is designed for more than 0.3 bar [11] domino effects from E-Fuel plant are not considered possible.

Domino effects towards the PVC plant (VCM day tank) is also not considered possible even in worst case.

Domino effects towards the Skagerak LNG storage is also not considered possible, even in worst case.

In worst case a blast load of 0.14 bar can expose the Yara wax tanks at Building 235. Depending on the specific design this may damage the wax tanks and cause a fire. However, such a wax fire will not lead to more domino effects and will in no way be able to expose 3rd parties outside HIP. As the frequency also will be less than 10^{-4} per year this is not considered an issue.

Building 95 could in worst case be exposed to a blast load of 0.15 bar which depending on the specific design of the building could damage the building and lead to loss of main power to HIP. However, the blast calculation does not take into account that the electrolysis building of the E-Fuel plant will shield Building 95, and therefore in reality cannot be exposed to this blast pressure. Furthermore, is the frequency also less than 10^{-4} per year and the outcome is not an escalation but production loss. Hence the risk of explosions for Building 95 is not considered an issue.

Hence in conclusion, blast loads from the E-Fuel plant cannot cause any domino effects that can expose 3rd parties. The blast load risk is even lower for the compressor station and Eramet discharge pipeline and therefore these cannot be the cause of any domino effects either.

16.1.2 JET FIRE LOADS

As discussed in Section 12.1.3 and 15.3 is it possible for jet fires to extent significantly outside the E-Fuel plant boundary, i.e. 110 m in worst case. However, such jet fires will be both low frequency (not dimensioning) and short lived (be over in a few minutes) and will therefore not be able to cause domino effects.

The dimensioning jet fires will not be able to expose areas outside the E-Fuel boundary.

Domino effects from jet fires on E-Fuel plant is therefore not considered a credible scenario.

The jet fire risk is even lower for the compressor station and Eramet discharge pipeline and therefore these cannot be the cause of any credible domino effects either.

16.1.2.1 PVC STORAGE

In relation to the PVC plant, PVC is stored in tents in relatively close proximity of the E-Fuel plant (2500-3000 tonne S-PVC). It is clear that the tents will not provide significant protection against a jet fire. The closest tent is 13 m away from E-Fuel plant (small tent) whereas the larger tents are at least 47 m away as illustrated in Figure 16-2.

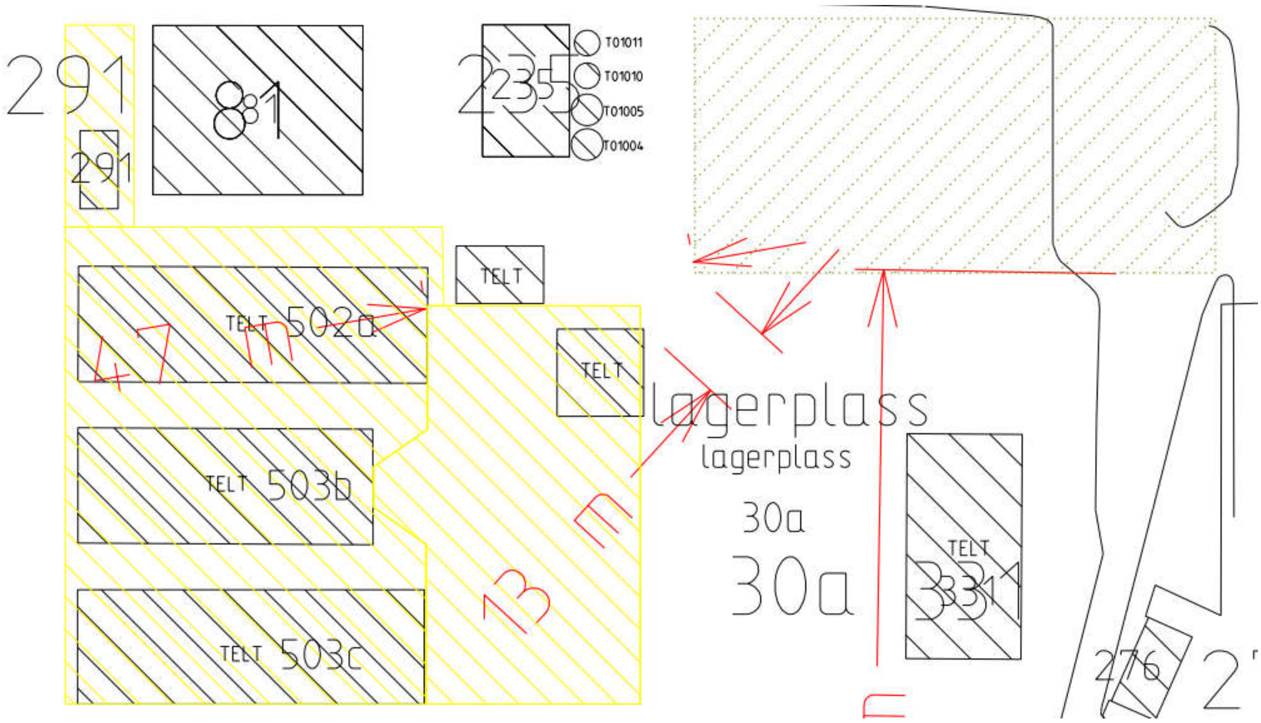

Figure 16-2 Distances between E-Fuel plant and PVC storage tents

If a jet fire reaches the PVC, the PVC can burn, but the fire is expected to die out when the jet fire stops This is due to the fire retardant characteristics of PVC. While a PVC fire is ongoing toxic HCL gas will form but personnel will be able to evacuate before this becomes a concern in relation to fatalities.

A fire in the PVC storage is not considered a MAH and will not expose 3rd parties to fatality risk. Furthermore, unlike other plastic storage fires that can burn for days a PVC fire is expected to be a controllable fire that either will extinguish itself or be extinguished by fire brigade as soon as the initial fire source is removes.

The frequency of a jet fire reaching the closest tent is less than 10^{-4} per year. The low frequency, and the consequences being loss of storage tents and PVC, means that the risk is considered low and acceptable.

16.1.3 POOL FIRE LOADS

As discussed in Section 15.4, pool fires in the E-Fuel plant storage tanks will be very low frequency events and not dimensioning for design. The frequency of an uncontrolled pool fire has been estimated to be less than 10^{-6} per year.

In worst case, the heat radiation levels at Yara wax tanks are 13.7 kW/m^2. This could potentially damage the wax tanks if long time exposure takes place, but it is not likely that a rupture will occur. Even if escalation should and a fire develop in the wax tanks this would not be a major escalation that would pose a threat to 3rd parties outside HIP.

Domino effects from fire in E-Fuel storage tanks is therefore not considered possible.

16.1.4 FLAMMABLE GAS IMPAIRMENT OF BUILDING 95

Flammable gas releases from E-Fuel plant could in worse case reach Building 95 and be sucked in through the HVAC air intakes on the west side of the building. This will not cause an automatic shutdown but will probably lead to a manual shutdown. In worst case the gas is ignited causing an explosion. The risk is however very remote and deemed acceptable.

The calculated frequency of flammable gas (100% LFL) reaching Building 95 has been calculated to $7 \cdot 10^{-6}$ per year, which is considered a very low likelihood.

Shutdown of Building 95 will not be a MAH, but production loss only and is therefore not considered a domino effect.

16.1.5 FLAMMABLE GAS IMPAIRMENT OF BUILDING 162 AND 162A

The high voltage buildings 162 and 162a are in relatively close proximity of the compressor station. However, the reach of flammable gas from releases from compressor station are not likely to reach HVAC air intakes of the buildings.

Furthermore, it is not considered credible (less than 1 per 10,000 year re-occurrence) that explosion can occur that will damage the buildings and cause loss of power.

16.2 DOMINO EFFECTS FROM NEIGHBORS EXPOSING E-FUEL PLANT

As discussed in Section 15.1, will none of the potential accident hazards on E-Fuel plant, compressor station or Eramet discharge pipeline have potential for exposing 3rd party outside HIP. Hence even if domino effects towards E-Fuel plant, compressor station or Eramet discharge pipeline were possible this would not lead to exposure of 3rd parties, with is the main concern when investigating domino effects.

In the following it will however be investigated if accidents on neighbouring plants can cause new accidents on the E-Fuel plant despite that these accidents will not be able to expose 3rd parties.

16.2.1 EXTERNAL BLAST LOAD EXPOSURE OF E-FUEL PROJECT

Existing dimensioning blast loads at HIP has been provided in Figure 16-3.

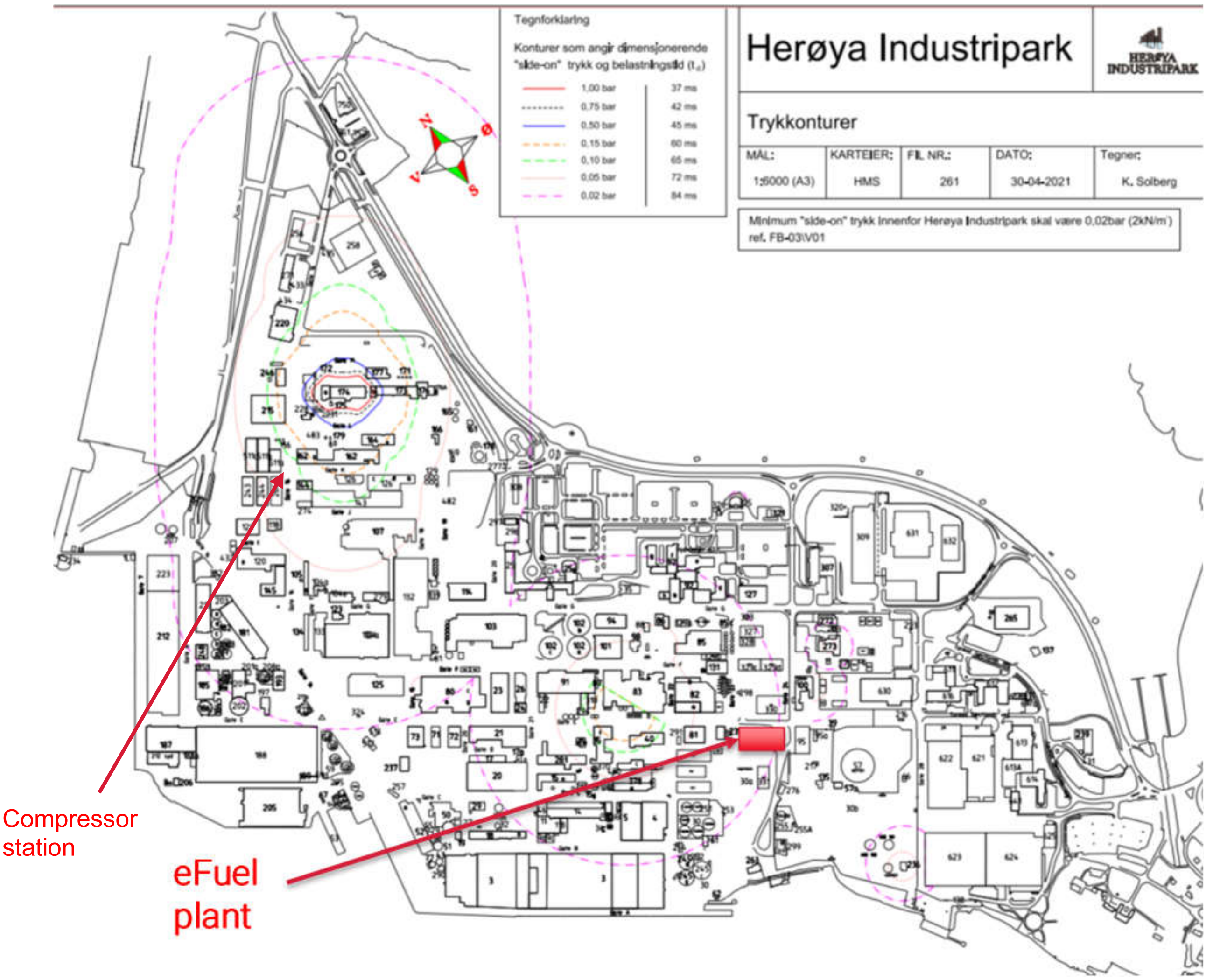

Figure 16-3 Blast loads at E-Fuel plant from existing installations [19]

It is clear from Figure 16-3 that blast loads at E-Fuel plant from neighbouring plants is in the range 0.02 bar to 0.05 bar. These low pressures are lower than the blast loads from incidents on the E-Fuel plant itself and the design will therefore be able to handle the external blast loads.

Hence explosions from neighbouring plants are not able to cause domino effects at the E-Fuel plant.

At the compressor station external blast loads in the range 0.05 bar to 0.1 bar can occur. The compressor station should be designed to handle such blast loads. If an explosion causes rupture of the compressor station this would lead to a release of flammable and toxic gas causing local escalation within HIP, but it cannot be a threat to 3rd parties.

External blast loads are not considered a threat to Eramet discharge pipeline due to its location and small dimensions. Even if an explosion were to cause rupture of the pipeline this would not be considered an escalation of the initial explosion.

16.2.2 EXTERNAL JET FIRE EXPOSURE OF E-FUEL PROJECT

Due to the distances between neighbouring plants with MAH potential and the E-Fuel plant and compressor station it is not considered credible that jet fires can cause domino effect and escalation. If such large jet fires were possible, they would be of low frequency and short duration.

Furthermore, would the immediate consequences of such jet fires be worse than any local escalation caused at E-Fuel plant or the compressor station.

16.2.3 EXTERNAL POOL FIRE EXPOSURE OF E-FUEL PROJECT

It is not considered credible that any pool fires at neighbouring plants can cause domino effects at the E-Fuel plant or compressor station. Potential pool fires will be a long distance from E-Fuel plant and compressor station and heat radiation levels of pool fires decreases fast with distance.

16.2.4 BLEVE FROM NEIGHBOURS

BLEVE has been identified as the events with the largest domino effect potential in the risk assessments/safety documents of Yara [9] [10] [11], PVC plant [12] and Air Liquide Skagerak [13].

BLEVEs can potentially impact E-Fuel plant but the BLEVEs will be of short duration and will most likely be fatal to any outdoor personnel exposed but are not likely to cause rupture of process system or storage tanks leading to an escalation. Flying fragments or missiles may be formed in the BLEVE that can reach the E-Fuel plant. Such fragments or missiles could cause loss of containment but are not likely to cause ruptures. These loss of containment scenarios are not considered an escalation of the initial consequences of the BLEVE and will in no way be able to impact 3rd party.

BLEVE can occur from the four LNG storage tanks of Skagerak at the tank terminal. The largest tank is 346 m^3 and can contain 121 tonne LNG. Consequence modelling shows that 300 mbar blast load has a reach of 110 m, 200 mbar blast load a reach of 140 m and 100 mbar blast load a reach of 250 m [11]. This means that the blast load at E-Fuel plant will be between 100 mbar and 200 mbar in a BLEVE. This may cause local loss of containment at E-Fuel plant, but this is not considered an escalation compared to the initial BLEVE scenario.

The VCM tank at the PVC plant is approximately 170 m away from the E-Fuel plant. A BLEVE has been estimated to create a fireball with radius of 120 m and duration of 15 seconds [12]. This will not cause domino effects on E-Fuel plant.

For the VCM storage tank at the tank terminal a BLEVE is estimated to form a fireball with radius 290m and burns for 30 seconds [12]. The tank is too far away to impact the E-Fuel plant.

BLEVE from Yara’s LPG storage at the terminal, e.g. ethane storage, is considered highly unlikely and the consequences of the BLEVE is not likely to cause loss of containment at E-Fuel plant. Even if it did it would not be considered an escalation of the initial BLEVE consequences.

16.3 DOMINO EFFECTS FOR PIPE BRIDGES

The Eramet pipeline will be running in a pipe bridge through various areas of HIP together with other pipelines supplying various parts of HIP with utilities and chemicals. Pipe bridges will also be located in the vicinity of the E-Fuel plant and the compressor station.

It is therefore necessary to evaluated if fire from explosion from E-Fuel plant or compressor station can cause a rupture of other bridge piping that will cause an escalation into a major accident hazard.

Fire or explosion from a release from the Eramet pipeline could also potentially cause rupture of neighbouring bridge piping leading to a major escalation.

Finally, there may be possibility of rupture of existing HIP bridge piping to cause escalation to E-Fuel plant, compressor station and Eramet pipeline that may escalate into a MAH.

This will be evaluated in the following.

16.3.1 ERAMET PIPELINE

Potential hazardous pipelines running in parallel with Eramet pipeline in pipe bridges have been identified in Table 16-3.

Table 16-3 Hazardous chemicals running along Eramet pipeline in pipe bridges

Pipeline(s)	Media	Pipe bridge section(s)
566	Propane/Ethane	16-07, 16-11
876, 742, 550	Fuel gas	16-07, 16-11, J-02, 19-01, F-14, F-29
975	Methane	16-07, 16-11, J-02, 19-01, 19-11, F-14, F29
67, 733, 512	Liquid ammonia	19-01, 19-11, 22-25, 22-29, F-14, F-29
99	Nafta	19-01, 19-11, F-14
933, 626	Propane	19-01, 19-11
711	Hydrogen	19-11
68	Nitric Acid	22-25, 22-29
513, 882, 912	Ammonia gas	22-25, 22-29
940	Hydrochloric Acid	22-25, 22-29, F-29
93	VCM (gas)	F-29
409	VCM (Liquid)	F-29

Of the above, only rupture of liquid ammonia pipeline and liquid VCM pipeline could potentially lead to a major escalation of an initial jet fire or explosion. For rupture of other pipelines in Table 16-3, the effects will be local and is not considered a significant escalation of the initial event.

The jet fire risk from release scenarios of the Eramet pipeline that can expose other pipelines will be significantly lower than 10^{-4} per year (for the entire pipeline). It has not been evaluated if such jet fires can cause rupture of the pipelines, which will depend on for how long the jet fire can be sustained. But the frequency is so low that the risk will not impact the risk analysis performed by the owners of the pipelines based on generic release frequencies [10] [11] [12] [13]. Even in worst case, where a rupture of liquid ammonia occurs, it does not impact the risk to 3rd parties as already investigated by Inovyn [12].

The risk of explosion due to ignited loss of containment from Eramet pipeline is at least an order of magnitude lower than that of jet fire risk. The risk can therefore be ignored.

Any fire and explosion from loss of containment of pipelines sharing pipe bridge sections with Eramet pipeline causing rupture of Eramet pipeline will not be considered a significant escalation of the initial event. This is due to the limited inventory of the Eramet pipeline. Personnel will be aware of the initial event and evacuate the area. Any CO toxicity from the escalation is not expected to lead to additional fatalities. The escalation can in no way lead to impact on 3rd parties outside HIP.

16.3.2 COMPRESSOR STATION

Potential hazardous pipelines running in parallel with compressor station in pipe bridges have been identified in Table 16-4.

Table 16-4 Hazardous chemicals running along compressor station in pipe bridges

Pipeline(s)	Media	Pipe bridge section(s)
566	Propane/Ethane	16-07, 16-11
876, 742	Fuel gas	16-07, 16-11, J-02
975	Methane	16-07, 16-11, J-02

In the highly unlikely event that fire and explosion from an ignited release from compressor station causes rupture of piping in pipe bridge this will not be considered a major escalation. There will be some local fires, but these cannot impact 3rd parties and will only cause local exposure, Hence the compressor station is not considered a concern for the bridge piping in the area.

16.3.3 E-FUEL PLANT

Liquid ammonia pipeline with an inventory of 55 m^3 runs in the pipe rack each of the E-Fuel plant. No other critical chemicals in pipe racks in the vicinity of the E-Fuel plant has been identified. The ammonia pipeline will be shielded from the E-Fuel plant outdoor process by the electrolysis building. Hence it is not considered credible the process can impact the ammonia pipeline. If it could the frequency would be significantly lower than 10^{-4} per year and the consequences would not impact risk to 3rd parties.

It is important that hydrogen explosions inside the electrolysis building is not vented in a way that can expose or damage the pipe rack.

Transformers on the east side of the electrolysis building is the only credible risk to the pipe rack. However, the frequency of such explosions is significantly lower than 10^{-4} per year and it is doubtful a transformer explosion can cause rupture of liquid ammonia pipeline in 5 m height, and again this would not increase risk to 3rd parties,

The domino risk in relation to pipe racks at E-Fuel plant is therefore considered low and acceptable.

16.4 IMPACT OF DOMINO EFFECTS ON HIP ISO-RISK CONTOURS

As discussed in Section 16.1 and 16.2, the E-Fuel project will not lead to any new domino effects on HIP that can impact risk to 3rd parties. This means that the ISO-risk contours reported for HIP in Figure 15-3 will not be impacted by any domino effects and is still considered valid for HIP.

The only close source of a potential pool fire is the Yara wax tanks at Building 95. However, it is not considered credible that a fire here will expose e.g. storage tanks of the E-Fuel plant critically. Pool fire in Yara wax tanks has not been identified as a critical scenario in the Yara risk assessments [9] [10] [11].

17 UNCERTAINTIES

Quantitative risk assessments (QRA) are applied to collect large amounts of data for a complex technical system in a format that is digestible and understandable to the reader of the QRA. The purpose is to aid the reader in making risk-based decisions. A QRA cannot predict exactly what will happen at a specific site in the near future but provides an estimate of what can be expected from a large group of such equivalent plants.

The most relevant uncertainties in the risk analysis concerns:

- Uncertainty in input parameters;
- Uncertainty in the applied model;
- Uncertainty in relation to completeness of the analysis.

When QRAs are applied for complex installations an extra applied conservatism result in requirement for expensive design measures to reduce risk can be applied. It is therefore important to balance uncertainty and the applied conservatism.

In the present QRA conservatism has been applied in estimating frequencies, consequences and human vulnerability. However, care has been taken not to be overly conservative and overestimating risks. As the main conclusions of the risk analysis (risk to 3rd parties) can be based on consequences alone and do not depend on a frequency analysis, the uncertainties of conclusions are low. It is a well known fact in QRA that there is a significant uncertainty in frequency analysis whereas consequences can be determined relatively precise.

17.1 UNCERTAINTY IN INPUT PARAMETERS

There will be a large uncertainty in especially leak frequencies and ignition probabilities applied in the analysis. To reduce the uncertainty recognised methods known to produce realistic results has been applied to predict release frequencies and ignition probabilities. In most respects the conclusion of the present study will not change even if the release frequencies or ignition probabilities increases significantly. Hence the analysis is largely robust towards the above uncertainties.

The component count is based on preliminary P&IDs and in some cases P&IDs for similar systems. The component count is therefore uncertain. However, contingencies have been included to handle this uncertainty and the conclusions of the present risk analysis are robust towards changes and not likely to change negatively for a more accurate component count. However, it is recommended to update the component count in detailed design.

17.2 UNCERTAINTY IN MODEL

Consequence modelling is performed with PHAST which is a recognised software for such purposes known to produce realistic results to the conservative side. Furthermore, has the PHAST simulations been supplemented with CFD simulations. In particular consequence modelling inside the electrolysis building has been based on state-of-the-art CFD modelling using FLACS. It should however be noted that FLACS explosion modelling for electrolysis building has not been performed at present but is recommended to be carried out in detailed design. However, this will not impact the conclusions of the present analysis as the electrolysis building shall be built to survive dimensioning explosion loads, so it is simply a matter of how to design the electrolysis building.

The uncertainties in the consequence modelling are much lower than that of the frequency modelling discussed above. It not considered realistic that the consequences can increase in such a way that conclusions of the present study can be compromised.

17.3 MODEL COMPLETENESS

Uncertainty in relation to completeness of the analysis includes risks not included in the analysis due to lack of knowledge e.g. important hazards not identified in HAZID etc. and therefore not included in the analysis.

It is not considered credible that hazard that can impact neighbours have been overlooked.

18 CONCLUSIONS AND RECOMMENDATIONS

In this report a QRA for the NEF E-Fuel facilities of HIP has been performed in accordance with DSB guidance for QRAs.

The amount of hazardous substance stored at the e-fuel plant is limited and the plant does therefore not fall under the term “Storulykkeanlegg” as described by the DSB regulations. However, as the E-Fuel plant is located next to a number of “Storulykkeanlegg” inside HIP, a QRA has been performed and domino effects between E-Fuel plant and the “Storulykkeanlegg” Yara, Air Liquide Skagerak and PVC plant and vice versa been investigated.

A large number of hazardous scenarios have been identified and the risk has been calculated by establishing frequencies and consequences of the scenarios.

The risk has been quantified as ISO-risk contours that describes the probability for a person to become a fatality in case the person is located permanently (24/7 – year-round) inside the ISO-risk contour.

The QRA results shows that the E-Fuel plant project will **NOT** impact the existing HIP ISO-risk contours, and therefore will the E-Fuel project not have any impact on 3rd parties outside HIP. This is a very strong conclusion that is very robust to future changes as potential consequences from E-Fuels plant will not have a reach where they can harm 3rd party.

In addition, it has been shown that it is not credible that accidents on the E-Fuel plant can impact neighbouring “Storulykkeanlegg” critically, causing a major escalation by domino effects. Also is it not credible that E-Fuel plant can impact electrical substations in Building 95 and 162 and cause a power outage.

Domino effects from neighbouring “Storulykkeanlegg” can in no way impact the E-Fuel plant in a way where risk to 3rd party is increased. This is a very strong conclusion as no scenarios on the E-Fuel plant has been identified that could potentially expose 3rd parties. Domino effects from neighbours can in worst case cause local escalation at the E-Fuel plant, but this is not considered critical compared to the consequences of the initiating accident.

The risk of the Eramet discharge pipeline have been investigated in detail since the pipeline will be routed through large parts of the HIP. The E-Fuel project has therefore implemented a strict risk acceptance criterion of 10^{-6} per year, calculated the same way as for 3rd party, despite that 3rd party will not be exposed to the pipeline.

The main safety concern of the E-Fuel project is that the risk of toxic carbon monoxide (CO) releases increases in different local areas of HIP. The possibility of CO releases is not a new phenomenon on HIP since Eramet plant produces CO rich flue gas and CO gas is used in the production of Yara. For personnel risk due to E-Fuel project CO exposure is by far the highest risk, both based on potential extent of fatal consequences and frequency of occurrence. Toxic CO clouds can extend significantly outside the E-Fuel plant battery limits. The risk is however low and lower than risk levels normally considered acceptable to 1st and 2nd parties and CO toxic risk cannot expose 3rd parties.

It is important that it is ensured that the HIP emergency preparedness recognises the CO risk from the E-Fuel plant and personnel working inside HIP is aware of the risk and trained to respond. The E-Fuel plant and compressor station shall detect CO releases that can expose neighbouring areas and sound an alarm that can be heard in the surrounding areas of HIP. Personnel are then expected to escape to gas shelter distributed at strategic locations on HIP and wait for the alarm to be called off.

All personnel working outdoors in HIP shall carry a gas mask and all the companies at HIP shall provide gas tight shelters for their employees. The HIP requirement for gas masks is to use ABEK1 filter, which is not effective against CO. However, personnel will be required to carry CO detector at the E-Fuel plant and the compressor station and will therefore be warned of CO releases. The CO risk from the Eramet pipeline is considered very low and a leakage will occur in 5 m height and be diluted and therefore is the risk of fatal exposure of personnel very remote. It has therefore not been considered necessary to change the overall requirement for gas mask filter specification in HIP. This is based on a dialogue between NEF and HIP. All HIP personnel working in HIP is trained to respond to alarms.

18.1 RECOMMENDATIONS

A number of recommendations has been put forward with the basis in this risk analysis as well as previous risk analyses:

- It is recommended that the equipment count for leak frequencies is updated at a later stage, when detailed P&IDs are available;
- Detailed explosion modelling for the electrolysis building has not been performed, but is recommended carried out in detail design. This is necessary to validate the assumed DeAL;
- It is recommended in detail design to establish exceedance curves based on the actual design equipment count;
- It is recommended to investigate possibilities in design and/or operation of the Eramet pipeline that can ensure that small leakages does not remain undetected for long periods. These measures should be investigated as a risk reducing measurement (RRM) within the ALARP principle despite that the risk is already below risk acceptance criteria;
- The HVAC air intakes for the electrolysis building can potentially become exposed to 20% LFL gas. F&G detection with shutdown of fire dampers should be implemented as the HVAC supplies the control room, which needs to stay operational in an emergency;
- The HVAC air intakes for the electrolysis building can become exposed to IDLH values of CO and should be shut down with fire dampers on CO detection;
- I needs to be confirmed that the gas mask carried by personnel at HIP can handle CO exposure;
- It is recommended that it is evaluated with Herøya Nett whether gas detection shall be installed in connection with HVAC air intakes of Building 95. The risk of gas ingress will be very low (less than 10-4 per year), but it cannot be ruled out at present that it will not be possible.;
- It needs to be confirmed in detailed design if any form of passive fire protection system is required for the storage tanks to protect against fire escalation from the process. It is however not expected that PFP will be required with the dimensioning fire load established in this analysis;
- In detailed design it shall be ensured that the vent system including supports can survive fire and explosion DeALs. This is expected to be possible by applying appropriate material strengths and thickness for equipment, pipework and structures. As a last resort PFP may have to be applied locally for especially vulnerable parts, but this is not expected. The dimensioning fire heat loads will be relatively low and of short duration;
- It is recommended to design the vent system for a minimum nominal drag load to cope with explosions in the process area.
- Pressure transmitters shall be installed at compressor station and E-Fuel plant to detect low pressure in Eramet pipeline caused by a large leakage.
- In relation with the design of Eramet pipeline and compressor station a HAZOP shall be conducted, that among other things evaluate the risk of air ingress into the Eramet suction pipeline and resulting risk of internal explosion.

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