Hydraulic Mist Hazards – A discussion of the practical implications for a nuclear project

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1. Summary

The purpose of this paper is to discuss the learning and implications for a nuclear high hazard reduction project from the application of the evolving understanding of hydraulic mist explosions. Mists have specific flammability properties which differ from gases and vapours, particularly that they may be ignited at temperatures below the flashpoint of the liquid.

The risk of generating mists has traditionally been regarded as low - negligible but there has been increased interest in the potential for mist formation in the past few years. Mists consist of a stable cloud or suspension of small, usually micron sized droplets, as distinct from sprays, which are typically mm sized droplets that fall quickly to ground.

2. Introduction

In 2013, HSE published their literature review on the generation of flammable mists from high flashpoint fluids. (Gant 2013). This highlighted the need for a consistent methodology for the Hazardous Area Classification for explosive mist systems. The work provided an update to a previous HSE literature survey undertaken in 1995. (Eckhoff 1995).

The 2013 survey concentrated on the fundamental questions:

1. when is a mist flammable?
2. how can a flammable mist be produced?

The review confined itself to mists, sprays and aerosols of liquids that are below their flashpoint at the ambient temperature. The fluids included:

- Lubricating oil;
- Vegetable oil;
- Hydraulic oil (both mineral & synthetic types);
- Light fuel oil;
- Heavy fuel oil (at operating temperature);
- Heat transfer fluid (at operating temperature);
- Jet fuel/kerosene;
- Transformer oils;
- Process fluids (e.g. Solvesso);
- Diesel;
- Bio-diesel;
- White spirit.

The 2013 work fed into the practical work undertaken in part one of the Joint Industry Project (JIP) on Area classification for oil mists (Bettis 2017). This work was an initial study and more work is planned, however, it does recommend that certain high flash point fluids including hydraulic fluids be treated as EI15 Cat C. (Energy Institute 2015).

3. The Nature of the High Hazard Reduction

As part of Sellafield Ltd.'s high hazard reduction mission, the contents of a legacy facility at Sellafield are to be retrieved and repackaged for long term, safe, secure and sustainable facility. One work stream to deliver the retrieval of the waste was the design, testing and deployment of the Silo Emptying Project Mobile Cave Facilities, known a SEP machines. There are three of these machines each subtly different. These machines are driven by hydraulic systems. The hydraulic systems and fluid were specified and designed long before the current evolution of knowledge about mist explosions and the guidance on high flashpoint fluid mists.

The machine designated SEP2 is to be installed and commissioned but first required permission from the Office of Nuclear Regulation (ONR). The challenge is, therefore, to apply the new knowledge to a machine that was designed and constructed before the new knowledge existed.

The aspects to the challenge include:

- The nature of the high hazard reduction project;

- The developments in the understanding of mist explosion;
- The demonstration that the hazard and risk from hydraulic mists were managed safely and proportionately.

The oldest section of the facility was built in the 1960s using a design based on grain storage silos; the facility now comprises four sections built at separate times. Each section reflects the standards applicable at the time of design and the evolving knowledge of operations. The facility stores radioactive contaminated materials from the reprocessing of Magnox Fuel, principally the fuel cladding material under water. The fuel cladding material is a magnesium and aluminium alloy known as Magnox (**Mag**nesium **N**o **Ox**idation; the no oxidation is in the carbon dioxide environment of the Magnox nuclear power reactors). The material is stored under water to eliminate a fire potential based on experience elsewhere and to encourage waste consolidation. The water provides an additional benefit of acting as shielding to protect against the radiation from the radioactive elements. The down side of underwater storage is its reaction with the Magnox alloy to produce hydrogen; under normal circumstances this is a slow reaction but nonetheless the hydrogen hazard must be managed, as must the possibility of increasing the reaction rate. This is not the subject of this paper but provides context on the range of hazards to be managed. It is a matter of public record that there have been "excursions" (effectively thermal runways reactions) in the past.

Any event involving loss of containment of the materials in this facility would have societally unacceptable consequences.

The building was not designed to retrieve the waste. The means and method to remove the waste had to be designed, developed, demonstrated, the machinery built and the building prepared. All of these, against the background of the high hazard environment and consequences, require meticulous care and time. The outcome of this being that the SEP machines were specified and designed many years before they needed to be tested and installed. The hydraulic systems were specified to use the proprietary, high flashpoint, alkylated aromatic amine, hydraulic fluid Renolin PG 32; the physical property data are from the Fuchs Safety Data Sheet (Pritchard 2019). The quoted flashpoint is 220°C and the systems operate at pressures of up to 207 barg.

The hydraulic fluid and hydrogen are but two of several hazards in the legacy facility that must be managed in compliance with the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR). It is the hydraulic fluid and the potential for flammable mist that is the focus of this discussion.

4. Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002

DSEAR requires that:

- All dangerous substances in the workplace are identified;
- A clear demonstration of how the hazards are managed to eliminate or minimise the risks to the workforce or any other persons who could be at risk from operations with the dangerous substances in the workplace.

The latter requirement must be recorded in a suitable and sufficient manner and all measures must be reasonable and practicable. The record, known as a DSEAR Risk Assessment, must take into consideration:

i) All dangerous substances, their properties and quantities;
ii) How the substances and risks are eliminated or minimised;
iii) Demonstrate how the hazards are managed that is the Basis of Safety;
iv) Classify the workplace into Hazardous and Non-Hazardous locations.
Any Hazardous locations must be further classified into Zones reflecting the frequency, extent, duration and consequences of the hazard.
Zoning defines the mandatory ignition source management measures required. All installed equipment in a Zoned location must comply with the Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres Regulations 1996.
v) Activities with the potential for an elevated level of risk, such as maintenance.

There are other provisions in DSEAR, but these are not germane to this discussion.

5. Developments in the understanding of mist explosion

The Dangerous Substances and Explosive Atmospheres Regulations 2002 makes it mandatory that the potential for mists and mist explosions must be identified and managed; mists are classified as "dangerous substances" under the regulations.

However, unlike our knowledge of vapour explosions there is little guidance on the management of flammable liquid mist explosions.

The DSEAR Approved Code of Practice L138 (HSE 2013) offers under Regulation 5 Guidance:

> *128 Additional information relating to the process rather than the substance should also be taken into account. Some substances do not form explosive atmospheres unless they are heated; some liquids if released under pressure will form a fine mist that can explode, eg hydraulic fluids in high-pressure lines as with gas turbines.*

Otherwise, it merely states that mists should be identified and accounted for in the Risk Assessment and Area Classification.

Prior to 2009, the British Standard on the Classification of Areas (BS EN 60079-10:2003) merely states: "….*the flammability characteristics of mists are not always predictabl*e." In the 2009 incarnation is the first version of the standard (BS EN 60079-10-1:2009) that includes specific advice, as an appendix, on explosion hazards from flammable mists generated by the release, under pressure, of high flash point liquids. (BS EN 60079-10-1:2009). This was not substantially changed in the 2015 evolution of the standard.

The BS EN 60079-10-1:2015 guidance includes a definition of a flammable mist:

> ***flammable mist*** *- droplets of liquid, dispersed in air so as to form an explosive atmosphere.*
>
> *G3 It has been proved that aerosol sized droplets are the most easily ignitable portion of the mist cloud, though generally these are only a small fraction of the total release. This fraction may increase if the release jet impacts on a nearby surface.*
>
> *NOTE 1 Aerosols are small (sub-micron to 50 microns) particles in suspension in the atmosphere.*
>
> *NOTE 2 Droplets in the aerosol range might be as low as 1 % of the total mass released, subject to release conditions.*
>
> *NOTE 3 Fuel droplet clouds have generally been found difficult to ignite, unless there is sufficient mass of vapour or very small droplets present.*

It also includes the guidance that:

> *G4 The likelihood that the release of liquid will generate a flammable mist during normal operation and/or expected malfunctions should be carefully assessed along with the likelihood of events that could lead to such a release. The assessment may indicate that the release of substance is of a very low probability or that the mist cloud could be generated only during rare malfunctions or catastrophic failures. Assessments should be backed up by references or operational experience with similar plants. However, due to thermodynamic complexity of mists and a large number of factors that influence formation and flammability of mists, the reference may not be available for every given situation. In such cases, a judgement based upon relevant data should be applied.*
>
> *G5 It is important to point out that not every leak will cause a mist formation, e.g. the leaks through broken flange gaskets or stuffing boxes/packing glands that are the most common secondary grades of release in case of gases or vapours, will usually be negligible in case of viscous liquids and in most cases will cause dripping rather than mist. That means that the likelihood of mists being generated through leaks at pipe joints, valves, etc. should not be overstated. Such considerations should take into account the physical properties of the liquid, the conditions at which it is being handled, mechanical details of the equipment through which it is being processed, quality of equipment and obstructions near source of release.*
>
> *NOTE 1 For liquids released well below their flash point, examples of mist explosions are rare in process industries. This is probably due to difficulty in generating sufficiently small droplet sizes from an accidental release and the associated difficulty of ignition.*
>
> *NOTE 2 Flammable mists may be ignited by sparks of similar energy as for vapour ignition but generally require very high surface temperatures for ignition. Ignition of mists by contact with hot surfaces generally requires temperatures higher than for vapour ignition.*
>
> *G6 If formation of a flammable mist is considered possible, then the source of release should preferably be contained or managed to reduce the hazard, e.g. by porous guards in order to promote the coalescing of the mist, mist detectors or suppression systems. Where containment or similar controls cannot be assured, then the potential for a hazardous area should be considered. However, because the dispersion mechanisms and the criteria of flammability for mists are different than those for gases and vapours, the methodology of classification presented in Annex B cannot be applied.*
>
> *NOTE 1 The conditions that are needed to form a flammable mist are so complex that only a qualitative approach may be appropriate. It might be useful to identify the factors related to the handled liquid which contribute to formation, and to the flammability of mist. These factors along with the probability of events that would lead to release of the liquid may be sufficient to evaluate the degree of the hazard and help to decide whether a hazardous area is required.*
>
> *NOTE 2 In general, the only element relevant to determining the type of zone is the grade of release. In most cases, it will be a secondary grade of release. Continuous or primary grades of release would typically be associated with equipment which is intended for spraying, e.g. spray painting.*
>
> *If a hazardous area for mist has been established, it shall be distinguished on the area drawing from other areas associated with gases and vapours, e.g. by appropriate marking.*
>
> *G7 Even the mists that are not ignitable according to the criteria of droplets size could eventually land on a hot surface, relative to the ignition temperature of the vapour, thus causing a fire hazard. Care should be taken to contain potential releases and prevent contact with hot surfaces.*

6. CLP Classification of Liquids

The European Directive on the Classification, Labelling and Packaging (CLP) provides a more specific definition of a flammable aerosol as one formed by flammable fluids with a flashpoint of less than or equal to (≤) 93°C. Admittedly, this is for aerosols deliberately produced from dispensing receptacles by a propellant and the decision logic associated with aerosols is more involved than implied here. On face value this would exclude high flashpoint hydraulic fluids.

The 4th Edition of the Energy Institute's Model code of safe practice Part 15 (EI15 2015) also includes a new section addressing the question of mists. It recognizes that flammable fluids handled below their flashpoint can form flammable atmospheres when released under pressure. It also requires that they should be regarded as a Category C fluid. It includes guidance that secondary grades of release can be addressed through a risk based approach detailed in *A risk-based approach to hazardous area classification, 2nd* edition, 2015.

This formal guidance is supported by a number of seminal studies including:

- Eckhoff's 1995 literature survey; (Eckhoff 1995);
- The HSE sponsored 2013 survey (Gant *et al* 2013);
- Final Report of Joint Industry Project (Mouzakitis *et al* 2017);
- Hazards 29 paper (Lees *et al* 2019).

7. Application

The current situation is that

- There is an increased awareness of the potential for flammable mists.
- The advice is to manage pressurized high flashpoint fluids as Category C.
- There is a lack of definitive guidance apart from use previous good practices.

The SEP facility was classified as Non-Hazardous when designed; this was on the understanding that the hydraulic fluid had a high flashpoint and was not a dangerous substance. This was reasonable at the time of design and construction. The challenge is to demonstrate that either: the facility is still non-hazardous or provide robust underpinning for any modifications required to ensure that it remains safe.

The prima facia case becomes: the hydraulic systems use a high flashpoint hydraulic fluid at high pressure; it is to be managed as a Category C fluid, therefore any leakage will attract at least Zone 2 area classification. Consequently, once the hazard radii are defined all equipment within the Zone must be assessed for acceptability and replaced with equipment certified as suitable for use in a Zone 2 location. This is potentially expensive in terms of:

- Programme time with the knock on to high hazard reduction schedules.
- Capital expenditure, whilst not an argument for not delivering a safe compliant system it does have site wide safety implications because it could restrict funding to other hazard reduction activities.

On face value, the simplest solution is to change the hydraulic fluid to one that is not flammable. This is not as simple as it first appears because of compatibility of an alternative fluid with materials of construction; flexible hoses seals and gaskets etc. This has the potential to require a full redesign of the hydraulic system and resultant back fitting of design changes. Any change with considerable time and cost implications requires robust underpinning because of the long term site safety implications.

The strategy adopted to resolve the challenge took a multi-pronged approach:

i) Undertake an analysis of the consequences of a mist initiated fire for personnel and on nuclear safety systems;
ii) Review of the available information of known hydraulic fluid incidents;
iii) Review the available date from the initial JIF report;
iv) Use the EI15 risk based approach to area classification
v) An assessment of the measures already included in the design.

These are discussed in turn below.

i. Consequence analysis

The two consequences of concern were:

1) Could an operator be hurt?

   There are areas of the facility that are not man accessible. Only the areas that are man accessible were addressed as part of the probabilistic risk analysis

2) Could any nuclear safety systems be compromised by a hydraulic fluid leak and explosion or fire?

   The study concluded that hydraulic mist events could not compromise any safety systems.

ii. Literature review of hydraulic oil mist fires & explosions

The first step was a review of the most recent literature surveys of Gant (Gant and Santon et al 2012, and 2013) and Lees is 2019 (Lees *et al* 2019). The aim was to provide an indication of the frequency of releases of high flashpoint hydraulic oil that led to an explosion or fire which caused significant damage or harm.

The Gant review (Gant 2012) identified 37 incidents which included 20 explosions over a period of approximately 130 years. Most of these incidents involve fluids with flashpoints significantly lower than Renolin PG32. Several incidents involved equipment with temperatures in excess of the flashpoint of the fluid involved. Some of the events considered could not be proven to have been an oil mist ignition. Only one incident is attributed to a hydraulic oil mist ignition which involved the atomization of the oil and sparks from a wire fed welding rig (high energy ignition source). This brief analysis indicates that:

- oil mist explosion incidents are rare;
- many incidents identified have flashpoints less than 220°C, suggesting they may be more susceptible to mist ignition than Renolin PG32;
- incidents involving high flashpoint hydraulic oils (greater than or equal to 220°) are even rarer.

Lee's 2019 paper (Lees *et al* 2019) includes an interrogation of the HSE's Hydrocarbon Release Database along with the

French ARIA (Analysis, Research and Information on Accidents) and the German ZEMA accident data base. What this does show is a greater incidence of hydraulic fluid leaks that previously identified but none of these resulted in a significant event with recorded injury.

iii. Flammable Oil Mist Formation Discussion

Renolin PG32 is a high flashpoint (220°C) hydraulic oil. It is a hydrocarbon and combustible (Pritchard 2019). A pressurized release of Renolin PG32 at a temperature below the flashpoint may form a mist cloud. The most ignitable portion of a mist cloud are the aerosol sized droplets, but these are only a small fraction of the total release. (BS EN 60079-10-1)

BS EN 60079-10-1 also states:

> *"it is important to point out that not every leak will cause a mist formation, e.g. the leaks through broken flange gaskets or stuffing boxes / packing glands that are the most common secondary grades of release in case of gases or vapours, will usually be negligible in case of viscous liquids and in most case will cause dripping rather than mist. This means that the likelihood of mists being generated through leaks at pipe joints, valves, etc should not be overstated."*

Leaks are far more likely to form drips rather than mists, this is explained by the properties of the fluid (high viscosity) and the physical aspects of a leak. The leak path is generally tortuous and causes the liquid to coalesce. The manufacturer of the hydraulic power packs supported the view that leaks from screwed connections form weeps and or drips because the pressure energy dissipates along the connection thread rather than producing a jet or mist.

The HSE (Gant *et al* 2016, Mouzakitis and Giles 2017) investigated mist formation and ignitability of a high flashpoint hydraulic oil. A general hazardous area classification system was developed that assigned a release class to the selected fluid based upon the Ohnesorge Ratio (a measure of ease of atomization and flashpoint of the fluid).

The Ohnesorge Ratio for Renolin PG32 at a pressure of 207 barg leads to a Release Class IV (less volatile fluid more prone to atomization). It also shows that Renolin PG32 mist behaviour is potentially similar to the hydraulic oil used within the HSE work.

The hydraulic oil mist generated in the test work did not ignite when released from a 1 mm diameter, smooth-bore orifice at pressures of up to 150 barg. This used a strong 1 joule ignition source. The result was no sustained combustion.

The detailed trial report (Mouzakitis and Giles 2017) includes the statement:

> *"Observations of the jet showed that there were comparatively few droplets formed at all the conditions tested, with a significant number of fine droplets only being observed once pressures approached 150barg. There was little evidence of any Primary / mechanical breakup occurring at release pressures less than 50 barg. Even at 150 barg the breakup observed consisted of fine droplets forming around the central dense core at a distance of approximately 200mm from the orifice, with the central core only showing signs of disintegrating at an axial distance of 600mm".*
>
> *"The limited droplet measurements that could be obtained due to the very poor nature of the spray agreed with observations made during ignition testing. Pressures of 150barg are insufficient to fully atomise the hydraulic oil resulting in an inadequate number of ignitable droplets being produced."*

The flashpoint and Ohnesorge ratio similarities between Renolin PG52 and the hydraulic oil used for the HSE work provide a strong indication that a release of Renolin PG32 at pressures of certainly up to 50 barg and even up to 150 barg are unlikely to produce a significant number of ignitable droplets.

The HSE advice, based on the Mouzakitis results, errs on the side of caution in recommending that hydraulic fluids be treated as Category C in the context of EI15 methodology. (Energy Institute 2015). This is in keeping with contemporary guidance.

What can be concluded is that:

- the probability of a leak is small;
- qualitatively the probability of generating a flammable mist is low.
  A quantitative value of 1 x 10^{-2}/year is used for the assessment and subject to a sensitivity analysis;
- the evidence is that hydraulic fluid mists are difficult to ignite.

iv. Risk Based Hazardous Area Classification

The overriding principle of a hazardous area classification is the protection of persons. Regulation 4 of the Dangerous Substances and Explosive Atmospheres Regulations 2002 is concerned with the duty of care of an employer to protect persons from harm whether they are at work or not.

The impact of an explosion within a nuclear plant may not result in a conventional safety consequence as covered under DSEAR but could result in release of nuclear material, which can cause long term harm or a significant economic risk which reduces the rate of waste retrieval and high hazard reduction. Containment of nuclear material is considered with the nuclear safety case which also addresses the requirements of Regulation 4.

The approach to Area Classification uses the methodology in: Energy Institute: A risk based approach to area classification 2016. This will be illustrated using extracts from the actual assessment undertaken. The hazardous area classification was carried out by dividing the plant up into areas as follows:

- In the vicinity of the hydraulic power packs and associated distribution lines where personnel access is possible. This is subdivided into five areas for assessment purposes;

- Inside the SEP Cave operating area where routine personnel access is not possible.
  The risk in this area to personnel is minimal therefore this will not be included in the case study.

The first step in the methodology is to assess the Grade of release.
The formation of a mist will be a fault; a leak from a pipes, fixtures, fittings or hoses.
It is therefore a Secondary Grade of Release. This guides the risk basis.

The methodology for Secondary Grades of Release from Energy Institute 2016 requires knowledge of:

a) Leak Frequency.
b) Frequency of a flammable release.
c) Occupancy probability.
d) Number of potential release sources.
e) Probability of ignition.

These factors are used to determine the risk to any individual in the workplace. If this is sufficiently low, then Area Classification and Zoning will not further enhance the safety to any significant extent. Sufficiently low is set as 1 x 10^{-5}/year for individual risk of fatality from an ignited flammable cloud or mist. Consequently, the workplace can be declared as Non Hazardous in DSEAR terms.

Taking in in turn:

a) Leak Frequency

The hydraulic power packs are not fully welded, hard piped systems; therefore, there are fixtures fittings and hoses that have the potential to leak. Frequencies were determined from literature reviews where possible; where this was not possible a judgement was made based upon the best available information. Overall there is a paucity of data on leak frequency form piping and hoses in hydraulic power packs. Table 1 is a summary of the values used.

One area worthy of discussion is the information on flexible hoses.

Sellafield Ltd has an internal Safety Reliability Database (SRD); this provided the failure rate of a lightly stressed flexible hose as 3.5 x 10^{-2}/year. as the flexible hoses are under static conditions; they are not moving or rubbing on other surfaces, therefore using the SRD information appears justified.

However, the underpinning requires caution; it appears drawn from a number of sources including:

- data published in 1972 by Green & Bourne of the UK Atomic Energy Authority
  (4 per million hours for lightly stressed hoses).
- the failure rate of washing machine hoses;
- other unknown nuclear sources.

Using the historical failure rate of 3.5 x 10^{-2} /year is judged pessimistic for a modern flexible hose because of better materials and construction techniques. Interrogating other sources revealed failures rates but many were tanker offloading hose failures often associated with the tanker not being secured effectively and are, therefore, nor applicable to this risk assessment.

Table 1 – Summary of Leak Frequency Data

Component	**Frequency yr^{-1}**	**Source**	**Comments**
Small bore connections (16mm NB)	$5x10^{-3}$	Cox *et al*	Most of the power lines on the Hydraulic Power Packs are 18mm. Value is for 16 mm; it is the best available in the absence of any specific information on 18mm connections.
Flexible hoses	3.5 x 10^{-2}	Sellafield Ltd Safety Reliability Database	
Quick release coupling	4 x 10^{-3}	Sellafield Ltd Safety Reliability Database	
Manifolds	$5x10^{-3}$		Data on small bore connections used in the absence of specific data on hydraulic manifolds. This is pessimistic; the manifolds are designed and installed to a high standard for use on very high-pressure system and feature screwed small-bore connections.
Valves	$1x10^{-3}$	Cox *et al*	
Pumps	$3x10^{-3}$	Cox et al	
These data are supported by Center for Chemical Process Safety (CPS 2015) information.			

b) Frequency of flammable release (F_{flam})

The frequency of a flammable release (F_{flam}) is the product of the leak frequency and the probability of forming a flammable mist.

$$F_{flam} = Leak\ frequency \times probability\ of\ formation\ of\ flamamble\ mist$$

The probability of the formation of a flammable oil mist if a leak was to occur is discussed above and judged to have a probability of 10^{-2}/year.

Table 2 illustrates the frequency of flammable release from typical potential leak locations.

Error! Not a valid bookmark self-reference.Table 2 – Calculation of Frequency of Flammable Release

Fixture / Fitting	**Leak Frequency (per year)**	**Probability of formation of a flammable mist if a leak occurred**	**F_{flam} (per year)**
Flexible hose	3.5×10^{-2}	0 Sleeves fitted see below	0
Screwed fittings Manifolds	5×10^{-3}	1×10^{-2}	5×10^{-5}
Valves	1×10^{-3}	1×10^{-2}	1×10^{-5}
Quick Release Coupling	4×10^{-3}	1×10^{-2}	4×10^{-5}
Pumps	3×10^{-3}	No info Therefore assume 1. This is conservative	3×10^{-3}

c) Probability of occupancy (P_{OCC})

The hydraulic systems have various modes of operation; sections of the systems only operate at the highest pressures for short durations and generally run in a recirculation mode at significantly lower pressures over a restricted length circuit. An understanding of the mode of operation and frequency of tool use enables a less conservative view of the probability that an individual would be present if a leak occurred.

EI15 defines the probability of occupancy (P_{occ}) as the proportion of time the most vulnerable individual spends on site exposed to at least one potential release source. It is calculated from the number of hours the individual spends in the hazardous area per year divided by the number of hours in a year.

Typical values of P_{occ} selected for Zone 2 within EI15 are:

- 100% of time on all shifts in a hazardous area $P_{occ} = 0.22$
- An average of approximately five hour/day in a hazardous area $P_{occ} = 0.13$
- An average of two hour/day in a hazardous area $P_{occ} = 0.055$
- An average of one hour/day in a hazardous area $P_{occ} = 0.028$

The application of this is illustrated by considering five areas of the machine.

Area 1 Access Platform and Gantries

Two Hydraulic Power Packs are in Area 1, which is not routinely accessed.

An individual operator is expected only to be in Area 1 of the order of a few minutes per day.

Operators and maintainers are expected to spend significantly less than 1 hour/day on average in Area 1. As such it is pessimistic to assume a probability of occupancy of 0.028 for use within the Individual Risk calculation.

Area 2 Main hydraulic power pack hydraulic lines beneath Area 1

Large sections of the hydraulic lines from the main hydraulic power pack sit within a channel beneath Area 1. These lines are routed to the Area 3, Area 4 and Area 5. These lines consist of hard piped sections with a small number of screwed joints. These lines are not accessible during routine operations and are effectively encased by Area 1 and the channel. A person can be located upon the floor plates above the pipelines for the order of a few minutes per day. There is equipment located within the vicinity of these pipelines, but maintenance and any other operations are expected to be infrequent.

Area 3 Main hydraulic valve manifolds

The hydraulic lines exit the channel beneath Area 1 and pass to the valve manifolds location.

Operators and maintainers are expected to spend significantly less than 1 hour/day, on average, in this location. Assume a pessimistic probability of occupancy of 0.028 for use within the IR calculation. This value is from EI15.

Area 4 Hydraulic Valve Manifolds to tools

A robust spray guard prevents access of the operator to the manifolds. Health Physics will access the radiometric equipment on an infrequent basis.

The platform, to enable access to lifting features, is above the manifolds and has no guarding. On average an individual operator will access this area twice per day.

Considering the individual roles of the different personnel (Operator, Health Physics and package lifting feature disconnector) it is estimated that an individual on average will spend significantly less than one hour per day in this area. As such it is pessimistic to assume a probability of occupancy of 0.028 for use within the IR calculation. (Energy Institute 2015)

Area 5 Drive Unit hydraulic lines

The Drive units are used infrequently during machine moves, this will be 2 to 4 times / year for approximately one hour per operation Operations estimate that an individual is standing next to the drive unit for approximately 50% of the operation. The average hours spent on plant by an operator per year is estimated as 1920 hours.

Overall probability

Taking all the areas together the probability, an individual operator is next to the drive unit when a leak occurs, is:

$$\frac{4\ occurances \times 1\ hour \times 50\%}{total\ hours\ per\ year} = 2.3 \times 10^{-4}$$

d) Number of potential release sources within range (N_{range})

The number of potential hydraulic oil release sources from various types of fixtures and fittings were estimated by undertaking walk downs and reviewing as built hydraulic system drawings. Table **3** is a summary of the results for the illustration areas.

Table 3 - Number of potential leak points on the hydraulic systems

Description	**$N_{(range)}$**				
	Flexible Hose	**Screwed Fittings and Manifolds**	**Valves**	**Quick Release Coupling**	**Pumps**
Area 1 & 2	Sleeves Fitted	60	13	3	2
Area 3a		37	33	11	0
Area 3b		6	4	2	0
Area 4		40	20	2	2

e) Probability of ignition (P_{ign})

The risk based approach is used to ascertain if the individual risk to the most exposed worker is sufficiently high that ignition source controls are warranted. In this case the probability of ignition is calculated based upon the strength of the ignition sources within a potential flammable zone and the strength of the ignition sources at the potential flammable zone boundary. There are items of unclassified electrical equipment in the vicinity of the hydraulic systems. There are no strong ignition sources such as fired heaters etc. in the vicinity of the hydraulic systems; there is, however, a heater within the operator bulge but there is no possibility of a leak of hydraulic oil mist reaching this heater.

This source of ignition would be classified as medium, the basis of which is that there is unclassified electrical equipment within the potential flammable zone and at the extent of the flammable zone. The probability of ignition is defined for a medium source of ignition as 0.1.

The JIF work used a strong ignition source of 1 Joule operating at 15Hz to attempt to ignite the high flashpoint hydraulic oil without success. Although there were limitations with the trial rig design and additional work needs to be undertaken it provides useful indication that a successful sustained ignition would require a strong ignition source. In relation to the indication that a strong ignition source is required to ignite a high flashpoint oil mist, it could be argued that the ignition probability is less than the 0.1 defined above due to the properties of the fluid released.

Therefore, the use of a P_{ign} for vapours and gases from EI15 is likely to be pessimistic.

v. Individual Risk (IR) Calculation

The Individual Risk (IR) from ignited secondary grade release sources is defined as:

$$IR_{ignited\ release} = F_{flam} \times P_{ign} \times P_{occ} \times N_{range} \times V$$

Where:

$IR_{ignited\ release}$	Maximum acceptable individual risk which is taken as 1 x 10^{-5}/year
F_{flam}	Frequency of formation of flammable atmosphere at Zone 2 boundary from each release source
P_{Ign}	Probability of ignition at Zone 2 outer boundary
P_{occ}	Occupancy: Probability that individual is within the effect distance
N_{range}	Number of release sources within the range of the individual
V	Vulnerability: Probability of fatality per exposure to ignited release (0.01 using EI15)

Table 4 provides an illustration of the summation of risks by fitting type for Area 1. The overall composite IR for an area is derived by summing the individual risks. A summary of the composite results for all areas are shown in Table ***5***.

Table 4 – Example of Individual risk calculation (Area 1 Hydraulic Power Packs)

Area 1	**F_{flam}**	**x P_{Ign}**	**x P_{occ}**	**N_{range}**	**V**	**$IR_{ignited\ release}$ / year**
Flexible hose	**Mist prevented from occurring due to safe sleeves**					
Screwed fittings	5 x 10^{-5}	0.1	0.028	60	0.01	8.4 x 10^{-8}
Valves	1 x 10^{-5}	0.1	0.028	13	0.01	3.6 x 10^{-9}
Quick Release Coupling	4 x 10^{-5}	0.1	0.028	3	0.01	3.4 x 10^{-9}
Pumps	3 x 10^{-3}	0.1	0.028	2	0.01	1.7 x 10^{-7}
					Sum	**2.6 x 10^{-7}**

Table 5 - Summary of all Areas

	$IR_{ignited\ release}$/year
Area 1	2.6 x 10^{-7}
Area 2	7.3 x 10^{-8}
Area 3	1.2 x 10^{-8}
Area 4	2.3 x 10^{-7}

The conclusion from the risk data ins Table 5 is that the risks to personnel from a flammable hydraulic fluid mist are significantly below the risk criterion for the application of Area Classification and Zoning.

8. Design Basis of Process Safety

The design included a series of good practice measures that include:

1) **Flexible hoses and guarding**

The flexible hoses are installed with 'Safe Sleeve' (or similar) guarding. The purpose of this guarding is to:

- to prevent hydraulic fluid sprays;
- eliminate hydraulic fluid mist potential;
- protect persons in the vicinity of a failed hose.

Generally, flexible hoses fail:

- as they age;
- when they are subjected to unusual operating conditions;
- abrasion of the outer cover;
- when under undue tensile forces on the end fittings;

  or
- machine accidents.

The flexible hoses located in personnel access areas on the SEP Cave and drive units are effectively static (not moved in operation). Hence, they are not subject to any undue forces, operating conditions or subject to excessive wear and tear.

Sheathing hoses is considered best practice and international standards are currently in development to ensure hoses exposed to the public are always subject to secondary protection to prevent injury to a third party.

Fitting all the flexible hoses with a 'Safe Sleeve' over-sheaths over the entire length of each hose prevents the formation of a potentially flammable hydraulic fluid spray and mist should a leak occur. Further assessment of flexible hoses is unnecessary.

Consequently, for this Basis of Safety to be adequate, a high degree of control is required to ensure that the 'Safe Sleeves' are always fitted when the system is operation. This results in the following recommendation:

An adequate system of inspection needs to be in place to ensure that flexible hoses over sheathing are subject to routine inspection and replaced / re-instated prior to re-energization post maintenance.

2) **Screwed Joints, pipes and fittings**
Screwed joints and fittings are potential leak points.

The original design considered sheathing all joints, however it was deemed not practical to do so.

However, the design addressed the potential for formation of leaks from the hydraulic system by:

- Minimising the number of joints by using manifolds.
  However, hydraulic systems require some joints to enable the system to flex during operation. This helps maintain system integrity.
- Components are adequately rated to the required pressure and flow.
- High integrity piping and components.
  Manufacturer uses proprietary technology compression fittings to ISO 8434-1 standard pipework is cold drawn seamless stainless steel tube which has been correctly sized for the flow and pressures required.

This type of fitting presents a tortuous path high pressure drop path for any leak that aims to reduce the energy of release and to encourage the hydraulic oil to coalesce so that the leak is as a weep or drip rather than a spray or mist.

9. Conclusion

1) Consequence analysis shows that safety systems are not compromised by any hydraulic fluid mist fire

2) Based on the available analyses:

   i) Reporting of hydraulic fluid leaks is improving;

   ii) Hydraulic fluid explosion incidents are rare and require high energy ignition sources;

3) The Joint Industry Project demonstrated within defined limitations that:

   i) Ignition of high flashpoint hydraulic fluid is exceedingly difficult;

   ii) The fluid used is similar in its mist formation potential to the material used in the SEP machines. Therefore, the probability of ignition is very small;

4) Applying the Energy Institute Methodology on Risk Based Hazardous Area Classification demonstrates that:

   i) the individual risk is negligible from an ignited hydraulic fluid mist;

   ii) the assessed risk is much lower than the criteria for applying Zone 2 Area Classification;

   iii) Area classification for hydraulic fluid is Non Hazardous.

5) The Basis of Safety applying best practice measures effectively minimises leaks and eliminate the possibility of creating a hydraulic fluid mist.

When these conclusions are collected into a Risk Assessment combining both the Qualitative and Probabilistic aspects, it demonstrates that whilst hydraulic mist events are possible they are managed in a proportionate and practicable manner.

Although there is work in progress to extend knowledge of hydraulic fluid mist behaviour, the approach can be adopted and adapted to many other hydraulic power systems.

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Figure 1: SEP Mobile Cave showing hydraulic systems