DSEAR and RGP in a novel nuclear application

Keith A Johnson, Design Capability Lead, Sellafield Ltd.
Hinton House, Birchwood Park Avenue, Birchwood
Warrington, WA3 6GR

Gareth Davies, Safety in Engineering Centre of Expertise, Sellafield Ltd.
Hinton House, Birchwood Park Avenue, Birchwood
Warrington, WA3 6GR

Matthew Webber, Senior Process Engineer, Sellafield Ltd.
Hinton House, Birchwood Park Avenue, Birchwood
Warrington, WA3 6GR

Jeff Tattersall, Responsible Process Engineer, Sellafield Ltd.
Hinton House, Birchwood Park Avenue, Birchwood
Warrington, WA3 6GR

Abstract

A feature of storing materials with a radioactive component is that over time chemical reactions initiated by the radiation – radiolysis – can produce hydrogen. These materials are often in sealed containers to maintain the containment of the radioactive component. As a result, the hydrogen accumulates. The explosive properties of hydrogen are then a hazard that needs to be managed.

These containers, although stored in controlled environments, do require routine inspection and maintenance, occasionally they need moving between facilities and over time there can be changes in the integrity of the container. The challenge is to manage the hydrogen hazard.

Chemical engineering judgement might tend to guide one to believing that the risk to workers from the hazard is low, but the real challenge is to underpin that judgement with sufficient evidence to meet the regulator's assessment criteria.

The tolerability of risk for the nuclear industry is lower by at least an order of magnitude than for other industries. This drives a greater degree of evidence to support a safety argument. This higher evidence bar is reinforced by the regulatory framework for the nuclear industry; it is a permissioning regime through the Office of Nuclear Regulation (ONR), which is different from the approach applied by the Health and Safety Executive (HSE) to non-nuclear industries in the UK.

The situation is novel. The question is what, if any, relevant good practices (RGP) from other industries could be applied to the circumstances to demonstrate adequately and robustly, in a suitable and sufficient manner, that the risk to workers is genuinely as low as reasonably practicable. Wider industry has a plethora of learning from experience that has contributed to the development of RGP; transfer of this knowledge into the novel application proved highly beneficial to resolve the challenge.

The purpose of this paper is to explore the challenges of applying established RGP from broader industry to a novel nuclear processing problem.

Two immediate questions to be addressed are:

a. how to manage the uncertainties in source terms due to a paucity of data.

b. how to develop robust but pragmatic solutions whilst managing both confirmation bias and solution bias in the justification of the methodology and resolution.

A prime example of the latter is that the simple application of BS EN 60079-10-1:2021 leads to the conclusion that the area must be classified as Hazardous and that ignition source management is a mandatory given. Use of alternative approaches such as the Energy Institute's risk based approach to hazardous area classification may lead to a different conclusion. The question is which is the appropriate conclusion?

The solution includes taking a holistic approach to the situation balancing both radiological and chemical consequence analysis with the relative reductions in individual risk from applying solutions.

1 Introduction

This paper addresses the approach taken to underpin the management of a hydrogen hazard on a nuclear facility and achieve compliance with the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002. The facility is to undergo discrete remediation operations to reduce long term risks.

Chemical engineering judgement might tend to guide one to believing that the risk to workers from the hydrogen hazard is low, but the real challenge is to underpin that judgement with sufficient evidence to meet the regulator's assessment criteria. The question is can this be done using common RGP methodologies and manage to avoid confirmation bias?

The nuclear industry in the UK is heavily regulated; to paraphrase Trevor Kletz (Kletz 2000) no other industry would neither tolerate nor survive the regulatory scrutiny to which the UK nuclear industry is subject. There are two aspects to this that are germane to any discussion of achieving DSEAR compliance and the use of RGP on a nuclear licensed site:

1. the first is the regulatory framework.
2. the second is the tolerability of risk within the nuclear industry.

1.1 Regulatory Framework

It is the HSE that regulates the majority of UK industry and ensures that the requirements of the Health and Safety at Work Act 1976 and its many secondary regulations are applied and complied with. This is largely on a notification basis.

Originally the regulator was the HSE through their Nuclear Installations Inspectorate (NII) but this morphed into the ONR as enacted in the 2013 Energy Act.

However, the nuclear industry must not only meet the Health and Safety at Work Act but also the requirements of the Nuclear Installations Act 1968. Under the Nuclear Installations Act a nuclear licensed site will have a set of site license conditions. These licence conditions confer specific powers to the ONR for the control of the licensee's activities. The conditions provide six powers:

- **Consent**
  A consent is required before the licensee can carry out certain activities identified in the licence or other activities which ONR has the power to specify. In order to secure a consent, the licensee must satisfy ONR that the proposed action is safe and that all procedures necessary for control are in place.
- **Approval**
  Approvals are used to 'freeze' a licensee's arrangements and other key elements of its safety management system. This may include the terms of reference of the nuclear safety committee, operating rules, maintenance schedule and the 'place and manner' in which radioactive waste can be stored or accumulated. If ONR so specifies, the licensee is required to submit the arrangements etc. <u>to ONR for approval</u>. Once approved, the arrangements cannot be changed without ONR's agreement, and the procedure itself must be carried out in accordance with the approved arrangements: failure to do so would infringe the licence condition and would be an offence.
- **Direction**
  A direction is issued by ONR when it requires the licensee to take a particular action. For example, licence condition 31(1) (Office for Nuclear Regulations, 2017) gives ONR the power to direct a licensee to shut down any facility, operation or process. Such a direction would relate to a matter of major or immediate safety importance.
- **Agreement**
  An Agreement issued by ONR allows a licensee to proceed with an agreed course of action.
- **Notification**
  The standard licence conditions give ONR powers to request the submission of information by notifying the licensee of the requirement. For example, in license condition 21(8) (Office for Nuclear Regulations, 2017) the licensee shall, if notified by ONR, submit a safety case and shall not commence operation of the relevant facility or process without <u>the consent of ONR</u>.
- **Specification**
  The standard licence gives ONR discretionary controls with regard to a licensee's arrangements and these are implemented through Specifications. For example, in license condition 23(2) (Office for Nuclear Regulations, 2017), if ONR specifies, the licensee is required to refer operating rules to his nuclear safety committee for consideration.

In addition, a number of licence conditions require the licensee to 'make and implement adequate arrangements…'. In many cases the licensees have drafted their arrangements in such a way as to provide mechanisms for <u>ONR to permission</u> activities via licence instruments issued under 'derived' powers. Since licensees' arrangements vary significantly the derived powers can be different from licensee to licensee.

Application of these license conditions and the powers means the nuclear industry has to seek permission from the regulator at some level for all activities.

Hence, the nuclear industry operates within a licensing regulatory framework as opposed to the largely notification regime for all other industries.

ONR, as the regulator, must be well informed by the licensee to be able to provide the necessary consents, approvals and permissions. Thus, the evidence and reasoning to gain permission inevitably has to be more robust than might be expected in broader industry.

The practical outcome is that it is necessary for the nuclear industry to approach DSEAR issues slightly differently to industries directly regulated by HSE. RGP from wider industry may require more explanation and justification as to the applicability to a facility on a nuclear licensed site.

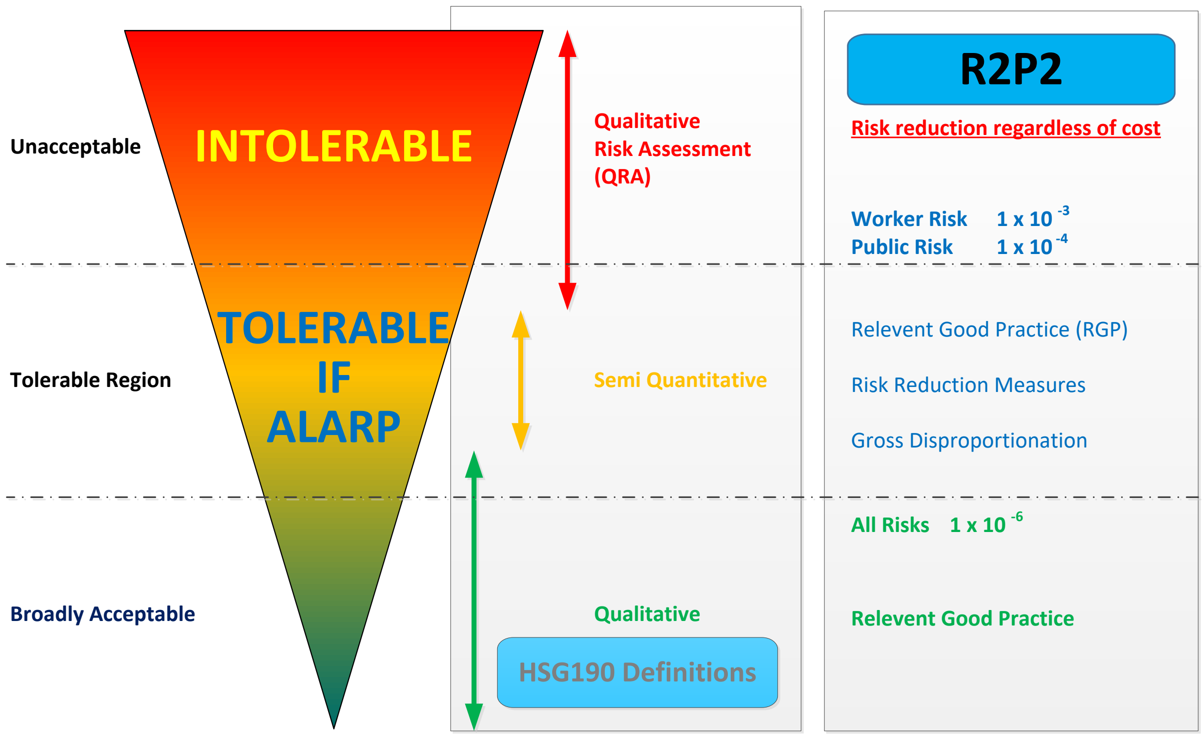
1.2 Tolerability of Risk

The HSE document "*Reducing Risks, Protecting People. HSE's decision-making process*" (HSE, 2001), commonly referred to as R2P2, discusses the question of managing risk to achieve "as low as is reasonably practicable" (ALARP). The principle is that risks must be reduced to a level which is ALARP based on the tolerability of risk as outlined in R2P2 (HSE, 2001). This is summarized in the "risk carrot" which is shown in Figure 1. The concept is applicable to both nuclear and non-nuclear hazards. Once there is a design for a facility, we assess the risks from the associated hazards.

Generally, risks may be designated as one of three levels, these being:

- Intolerable - denoted by a red zone on the risk carrot.
- Tolerable if ALARP – orange/yellow zone on the risk carrot.
- Broadly acceptable - green zone on the risk carrot.

Figure 1 – The "Risk Carrot"



If we demonstrate the frequencies are low enough when applying RGP (i.e. standards), then risks can be regarded as insignificant and adequately controlled. They are broadly acceptable. This does not usually warrant any further action to reduce risks unless reasonably practicable measures are available.

Risks classified as intolerable must be mitigated regardless of cost. Risks classified as tolerable if ALARP should be considered for further mitigation, although a cost-benefit analysis may be conducted as part of the argument for not carrying out specific improvements. Note that cost-benefit analysis is not the only criteria which should be used but is one of several potential approaches. There is also a specific requirement that even risks which are in the broadly acceptable region of the risk matrix must be considered for further mitigation if further reductions in either frequency or severity can be made.

The HSE's 1992 paper on the *Tolerability of Risk from Nuclear Power Stations* (HSE 1992) develops the arguments on risk tolerability concerning the nuclear industry. The philosophy developed in that paper can be summarized as:

- the risks to worker should be at least an order of magnitude less than the risks to workers in other industries. The suggested maximum tolerable risk to worker in any industry is 10^{-3}; therefore, the risk to the average radiation worker facility should be less than 10^{-4}.
- risks to average members of the public should be of the order of 10^{-6} or less, this is an order of magnitude less than other public risks.
- The overall risk to the average member of the UK public should be less than 10^{-7}, this is similar to the risk of being struck by lightning.

It is important to understand these two influences on the philosophy and approach to any safety related discussion in the nuclear industry.

- The regulatory framework means any safety case presented to the regulator for permission is subject to greater scrutiny than might be expected in broader industry and must be, potentially, more robust than the evidence and underpinning produced for other industries.
- Likewise, the residual risks limits and targets are lower than for other industries.

This is a fact of life. The question is: how it affects the application of RGP when assessing hazards and risks that fall under the umbrella of the DSEAR. Are RGP still effective and deliver an adequately robust case on the management of "dangerous substances."

1.3 Nature of the Problem

The problem being addressed in this paper is a hazard that is unique to the nuclear industry. It is the management of hydrogen hazards generated by radiolysis in materials in long term storage.

Radiolysis is the process by which ionizing radiation initiates chemical reactions causing compounds to degrade into smaller molecular compounds or constituent elements.

When moisture is present, hydrogen is formed. Theoretically, the process can produce a stoichiometric mixture of hydrogen and oxygen. However, the actual mechanisms are complex and dependent on circumstances which means that often the oxygen does not manifest as gaseous oxygen, but the hydrogen can be released as gaseous hydrogen but not necessarily. As stated, the chemistry is complex and rates vary with time.

Some polymeric materials, such as poly-vinyl chloride, will degrade releasing chorine as chloride that can produce hydrogen chloride, although in theory it could form vinyl chloride monomer.

These processes are slow; they are dependent on the energy of the ionizing radiation, the isotopic compositions of materials, the quantities of materials and the chemical and physical circumstances.

The result is that when materials that generate ionizing radiation are stored for long periods of time hydrogen can accumulate in the containment system.

The specific problem concerns containers of nuclear materials in long term storage. The current storage is in an array of horizontal concrete tubes. The tubes are sealed at one end and access at the other is restricted by a, non gas tight, cover. These containers are to be transferred from current facility to a newer facility designed to modern standards. The aggregated hydrogen is considerable and if all were to become involved in an incident would undoubtedly incur unacceptable consequences. The storage containers have an interstitial and ullage volume of about 1 litre each. These containers are essentially sealed. The accumulation of hydrogen will cause these containers to pressurize and, in some cases, has caused the end caps to bow. Basic engineering judgement says: the release of these quantities of hydrogen from a single container should not cause harm to workers. The challenge is how to underpin that judgement:

- without falling foul of confirmation and other inbuilt biases.
- with sufficient robustness to satisfy the scrutiny of the regulator, the ONR.
- whilst meeting the required residual risk targets and demonstrating they are ALARP.

The approach to avoiding confirmation bias is:

- to assume the opposite is true (that there is a problem and it has the potential to cause harm) and proceed to assess the situation.
- to use a variety of RGP techniques to address the question from different perspectives.
- use independent subject matter experts or peers to review, comment and provide challenge (in other words don't work in a silo).
- Seek out both internal and importantly external learning from experience.
- A positive but challenging environment created and behaviour demonstrated by leadership.
- To be aware of group think behaviours and provide measures to identify and avoid.

The downside to the approach is the potential to be accused of:

- making a mountain out of a molehill.
- The assessment detail is pointless and will delay progress.
- the nuclear safety case addresses the question rendering the need for the proposed work unnecessary.

The former two require explanation of confirmation bias.

The latter is discussed below.

1.4 Nuclear Safety Case and DSEAR

A useful way to examine the interactions between the nuclear and the DSEAR aspects of the non-nuclear (chemotoxic) safety case is to look at the six types of harm that can be incurred from an explosion. These are:

1) **Barometric** — the human body although can be quite tolerant to pressure it is not tolerant to rapid changes in pressure. Rapid pressure changes can damage to ears, eyes, lungs, gastrointestinal tract and certain extremities.

2) **Thermal** — this is the obvious burn potential.

3) **Missile** — shrapnel injuries from debris created by systems breaking due to the deflagration or detonation.

4) **Translational** — expanding pressure waves and the fast moving gas can propel people over and upon landing they incur broken bones, penetrating wounds and other blunt force traumas.

5) **Toxic** — explosions can create or release materials that can be cause acute and or chronic poisoning. This includes the release of radioactive materials with an associated radiation dose and contamination.

6) **Societal and Environmental Effects** — These are the wider consequences beyond the site boundary that have acute and or chronic effects for impact the general public and environment. This includes in both release of contaminants to environment, damage to water courses, water supplies, farmland etc.

The nuclear safety case, because it is looking at the specific consequences associated with dose uptake to worker and public, loss of containment and release of materials into the environment it only addresses Item 5) the toxic consequences and Item 6) societal and environmental. This it does very effectively. This is the limit of its applicability; consequently, it does not address items 1 to 4 which are the non-nuclear harm to workers or the public. Hence, this must be covered through a chemotoxic non-nuclear risk assessment and safety case.

Likewise, the fire risk Assessment addresses item 2) the thermal effects from any consequent fire but does not consider Items 1, 3 & 4. Again, not all aspects of harm from an explosion event are covered in the fire risk assessment.

DSEAR requires that the potential harm to workers is reduced to as low as is reasonably practicable, therefore, as a minimum: Items 1, 2, 3 and 4 must be addressed in terms of understanding potential consequences. As a corollary, Items 5 and 6 should be considered as part of DSEAR. The societal and environmental consequences of catastrophic events are often addressed under Control of Major Accident Hazards (COMAH) regulations 2017 however:

- this is outside the scope of this discussion.
- COMAH excludes the nuclear facets of facilities handling radioactive materials.

There is a mismatch between the defined scope of nuclear safety case and the non-nuclear consequences with respect to the management of "dangerous substances," this must be addressed through the DSEAR risk assessment process.

2 Source Term Data

Any analysis of consequences, area classification exercise and overall risk assessment all require a definition of the hazard and the quantities involved. There is a paucity of data and that which is available involves a degree of uncertainty.

The quantity of hydrogen that could theoretically be generated in any package is dependent upon multiple factors and subject to a degree of uncertainty. The rate and overall quantity of hydrogen within containers will be influenced by:

i) The quantity of moisture present.

ii) The quantity of any other hydrocarbon compounds.

iii) The radiation dose rate from the contained material and the proportion absorbed.

iv) Possible mass transfer effects.

These are parts of the complex chemistry present that have certain interdependencies and will see both rate and volume vary over time. Even if these factors are known, the outcomes will still be subject to empirical evaluation; the empirical data are often measured under specific experimental conditions and small changes (e.g. changes in chemistry) can result in different rates, this includes the potential for radiolytic back-reaction.

The conclusions to be drawn from this are:

- it is exceedingly difficult to predict the hydrogen content at any moment in time because of uncertainties in the information about the containers.
- Radiolysis will only generate hydrogen whilst there is moisture or organic contaminants present.
- The rate of evolution will decrease with time as the quantity of reactant is depleted and the concentration of product increases (which can result in back-reactions). The evolution rate is initially linear but changes with time.

The absorption of any oxygen that arises from either radiolysis or residual air by materials in the container does reduce the hazard. Over time, the container ullage and interstitial atmosphere becomes oxygen deficient to below the limiting oxygen concentration for hydrogen combustion.

The alternative is to estimate the quantities from inspection data. Initially, the containers were routinely inspected. After a period of operation, the inspection regime was rationalized which changed the data collected. This rationalization was to reduce the dose detriment to the operators by balancing the risks from the (radiation) dose to the operators with the value of the information collected and its perceived potential for risk reduction.

The inspection data revealed that only 2% to 3 % of the containers showed any visual indication of pressurization that is deformation in the flat ends. Plastic deformation occurs at about 0.7 barg, hence if the pressure is relieved through a fissure or other flow path the container will remain distorted and look as though it is still pressurized. Therefore, the 2% to 3% is likely to be an overestimate (i.e. conservative).

Analysis of pre-rationalization inspection radiography data suggests that 0.7 barg is the most probable bounding case, it may not be the actual maximum value but the probability is expected to be low. All deductions are tested for sensitivity to source term up to an upper bound value of 2 barg.

The data collected through the rationalized inspection regime does not allow pressurization analysis, therefore there is no definitive data on how many containers could have become pressurized in the past two decades.

However, one way to use the existing data (and deduce an upper bound value – for sensitivity analysis) is to apply Bayesian type logic. Applying this logic in a simple qualitative manner yields that if 2-3% of containers pressurized in the first half of their storage life (pre-rationalization); then there is a probability, with a 50% statistical significance, that:

- The original 2-3% could have pressurized beyond 0.7 barg
(although not expected due to the nonlinear nature of radiolysis).
- There could be 2-3% that are at 0.7 barg.
(these were pressurizing during the first period but did not show any sign of deformation and therefore were previously included).
- There could be an additional 2-3% that are between 0 and 0.7 barg.
- This gives a total of 6%-9% of all containers being pressurized.

This approach is purely statistical to provide an upper-bound value for sensitivity analysis.
It is not underpinned through technical knowledge of pressurization mechanisms and measurements.

This approach provides a basis for a reasoned sensitivity analysis in the consequence and risk assessments

3 Range of Approaches

The RGP approaches explored though our analysis were:

- The British standard BS EN 60079-10-1:2021
- The Energy Institute's (EI) *A Risk based approach to hazardous area classification*. (Energy Institute 1998 and Energy Institute 2015)
- Gas dispersion analysis to indicate the possible extent of any area classification
- An examination of harm to individuals using trinitrotoluene (TNT) equivalence method (Crowl, D. A., 2003 and Merrifield, R., 1993).

Each is discussed in turn.

3.1 BS EN IEC 60079-10-1:2021

BS EN 60079-10-1:2021 is the basic go to standard when first considering area classification.

The concrete storage tubes used to store the containers are not ventilated directly. There are variable induced chimney effects. Applying the methodology in BS EN 60079-10-1:2021 and summarized in Table 1 leads to the conclusions that:

- The effectiveness of the ventilation (dilution) is low.
- The release from any container is a secondary grade of release
  Any release is not intentional; it will arise as a fault not normal operation.
- Therefore, the area classification indicated in Table 1 is Zone 1 possibly Zone 0.

The room housing the storage tubes and allow access to the storage tubes can be treated in the same manner, but two situations have to be considered:

i) The situation when a cover is open.
   This is needed for operations to remove the containers from the storage tubes and prepare them for transport.
   - Any release will be a secondary grade
   - There is a mechanical ventilation capability to a nuclear standard and hence the availability is good.
   - The ventilation is a cascaded reduced pressure system with low local velocities (i.e. << 0.5 m/s) applying the detail of BS EN 60079-10-1:2021 leads to a low dilution
   - Conclusion is that the access area should be Zone 1 or even Zone 0.

ii) The situation when the covers are in place
   - The cover will restrict any release into the open room.
     It is a Type B opening.
   - the Release is defined as secondary as above.
   - There is a mechanical ventilation capability to a nuclear standard and hence the availability is good.
   - The ventilation is a cascaded reduced pressure system with low local velocities (i.e. << 0.5 m/s) applying the detail of BS EN 60079-10-1:2021 leads to a low dilution
   - Conclusion based on BS EN 60079-10-1:2021 Table B.2. is that the access area should be Zone 2.

Each conclusion requires mandatory ignition source management, and each conclusion suggests the original engineering judgment is erroneous.

The limitations of BS EN 60079-10-1:2021 include:

- heavily dependence upon the availability of ventilation.
- intended to cover a wide range of flammable gases predominantly dense gases and vapours.
  hydrogen is extremely buoyant and highly mobile.

These limitations make the BS EN methodology pessimistic.

However, both BS EN 60079-10-1:2021 and the DSEAR Approved Code of Practice L138 (HSE, 2013) indicate that any full risk assessment may modify the conclusions and application of mandatory ignition source management.

The engineering judgement took account of the potential volume of release and the coincident factors needed to get a release and achieve a flammable configuration.

Two further factors to consider:

- Area Classification is fundamentally a probabilistic methodology therefore our conclusions are tested against the Energy Institute's "Risk Based Approach to hazardous area classification"
- the BS EN methodology places great emphasis on the ventilation mixing and diluting releases. It is not good at accounting for the rapid buoyant mixing of hydrogen which is highly effective at dispersing hydrogen to below the lower flammable limit.

Each of these is considered.

Table 1 - Zones for grade of release and effectiveness of ventilation (Table D.1 in BS EN 60079-10-1:2015)

Grade of Release	**Effectiveness of Ventilation**						
	High Dilution			**Medium Dilution**			**Low Dilution**
	Availability of Ventilation						
	Good	**Fair**	**Poor**	**Good**	**Fair**	**Poor**	**Good, Fair or Poor**
Continuous	Non-hazardous (Zone 0 NE)[a]	Zone 2 (Zone 0 NE)[a]	Zone 1 (Zone 0 NE)[a]	Zone 0	Zone 0 + Zone 2	Zone 0 + Zone 1	Zone 0
Primary	Non-hazardous (Zone 1 NE)[a]	Zone 2 (Zone 1 NE)[a]	Zone 2 (Zone 1 NE)[a]	Zone 1	Zone 1 + Zone 2	Zone 1 + Zone 2	Zone 1 or Zone 0[c]
Secondary[b]	Non-hazardous (Zone 2 NE)[a]	Non-hazardous (Zone 2 NE)[a]	Zone 2	Zone 2	Zone 2	Zone 2	Zone 1 and even Zone 0[c]

[a] Zone 0 NE, 1 NE or 2 NE indicates a theoretical zone which would be of negligible extent under normal conditions.

[b] The Zone 2 area created by a secondary grade of release may exceed that attributable to a primary or continuous grade of release; in this case, the greater distance should be taken.

[c] Will be Zone 0 if the ventilation is so weak and the release is such that is practice an explosive gas atmosphere exists virtually continuously
(i.e. approaching a "no ventilation" condition)

3.2 Energy Institute Risk Based Approach to Area Classification

The Energy Institute Risk based classification methodology, although conceived for the petrochemical industry, provides a probabilistic risk-based approach to boundaries of Zone 2 area classification. This is more flexible and adaptable to batch operations required for remediation type tasks, such as that considered in this application.

The methodology provides good indication of the relative changes to risks for different operations rather than absolute values.

A summary of the Energy Institute's "*Risk Based Approach to hazardous area classification*" (Energy Institute,1998) is included in *Model code of safe practice Part 15 Area classification for installations handling flammable fluids* (Energy Institute, 2015). This probabilistic approach looks at the risk to an individual from a release of flammable gas.

The basic formula from Energy Institute 15 is (Energy Institute, 2015):

$$IR_{ignited\ release}(per\ year) = F_{flam}\ (per\ release\ source - year) \times P_{ign} \times P_{occ} \times V \times N_{range}$$

where
- $IR_{ignited\ release}$ — Maximum acceptable individual iisk due to ignited releases. Taken to be 1.0E-5/year
- F_{flam} — Frequency of a flammable atmosphere at the Zone 2 boundary from each release source
- P_{ign} — Probability of ignition at the Zone 2 outer boundary
- P_{occ} — Occupancy: probability that the individual is within the affected distance (hazardous area)
- V — Vulnerability: probability of fatality per exposure to an ignited release
- N_{range} — Number of release sources within range of the individual

One way to apply this methodology is to set an individual risk value (usually 10^{-5} as defined in Energy Institute 1998 and 2015) to be achieved at the boundary of a Zone 2 area and then back calculate the releases and levels etc to achieve that level of risk. We used it to determine individual risks and used the 10^{-5} as the target below which an area was classified as non-hazardous and not zoned but applied measures were reasonably practicable. At greater than 10^{-5} zoning was applied. The individual risk was also compared to the R2P2 (HSE, 2001) criteria to ensure regardless of zoning workers were not being subject to unnecessary risk.

Applying the method to each operation in the process because of the paucity of data will not give absolute answers but does give effective relative answers. Applying the ranges determined on source terms allows an individual risk range to be expressed for each operation. Ignition probabilities are determined through standard methodology within Energy Institute 2015 and 2006. The issue of occupancy is an area of confusion. It is easy to be seduced into believing that because each manual operation takes only a few minutes that the occupancy values are small, of the order 10^{-5} per year; in fact, the occupancy probability is 1 because a person has to be present for the manual operation to occur, hence it is not a truly independent variable.

The ranges developed using this methodology can be compared against the risk carrot tolerability (Figure 1) and identify what are the problematic operations. What this does show is that most operations involve individual risks of the order of 10^{-5}, which is in the tolerable if ALARP region some are more onerous and the risk traverse into the tolerable if ALARP region. This suggests that on a probabilistic basis the BS EN IEC 60079-10-1:2021 area zoning is extremely conservative but the conclusion is not definitive.

3.3 Extent Hazardous Zone

BS EN 60079-10-1:2015 generates an area classification but does not define the extent of any designated zone. Applying desktop analytical tools that solve the continuity equations in one geometric dimension based on the buoyant behaviour of hydrogen swiftly enables the conclusions:

- Slow chronic releases of hydrogen will disperse due to diffusion.
  These releases, whilst theoretically pass through the flammable envelope, involve quantities so small as not to be a hazard. These will be zone of negligible extent (represented by the abbreviation NE in Table 1). The definition of which is: (BS EN IEC 60079-10-1:2021)

  - In some cases, a zone of negligible extent may arise and may be treated as non-hazardous. A zone of negligible extent would also imply either a negligible release rate or a negligible release quantity and considering the volume for dispersion.

    Such a zone implies that an explosion, if it takes place, will have negligible consequences.

    The zone negligible extent concept can be applied irrespective of any other adjustments for risk assessment to determine equipment protection level.

- Acute releases in a storage rack will be as relatively short duration high momentum jets.
  They will encounter obstructions before the momentum is spent and the hydrogen is diluted to below the lower flammable limit, the hydrogen will rise under buoyancy and accumulate as a layer in the ceiling space of the storage rack. This will be dispersed by a combination of buoyancy and diffusion.

- Acute releases outside the storage rack will again be short duration high momentum jets.
  Should they encounter any obstruction and lose momentum they will rise due to buoyancy as a thermal and mix to less than the lower flammable limit.

3.4 Harm to Individuals

What is missing so far is an understanding of the potential harm to people from any event involving the quantities of hydrogen in the containers. This needs to be addressed

- The potential to directly injure people.
- The potential to cause indirect harm through asset damage that affects other safety significant systems.
  This is addressed in the nuclear safety case and did not form part of the DSEAR assessment.
- Potential to initiate any domino effects.

The methods to judge the degree of harm are limited. The common approach is to use TNT Energy Equivalency. This equates the energy released by the deflagration or detonation of a material to a mass of TNT that would release the same amount of energy. This method is a useful indicator of consequences of a hydrogen event because it enables a direct comparison with the TNT blast data.

The basic equation is: (Crowl, D. A., 2003)

$$\text{Equivalent mass of TNT } W = \frac{\eta m E_c}{E_{TNT}}$$

Where **η** empirical explosion efficiency, typically between 1 – 10%. (dimensionless)
in the absence of empirical data a value of 1 was assumed. This is conservative.

m Mass of flammable gas (hydrogen) (mass)

E_c heat of combustion of gas (energy/mass)

E_{TNT} TNT explosion energy (energy/mass) (typically 4602 kJ/kg)

This method does have limitations.

1. TNT detonates; using detonation energy and pressure distance decay curves to a deflagration will tend to overestimate close to the source and underestimate further afield.
2. TNT Equivalency is a point source methodology. Gas cloud burns are a distributed source.
   However when applied to the circumstances of small quantities of gas, in this case hydrogen, the burn approximates to a point source. Nonetheless it is a further conservatism.

There are alternatives to TNT equivalency such as Baker Strehlow or TNO MultiEnergy models. These are distributed source models; they are best applied to large (m^3) volumes of gas and require more detailed data on concentration distributions, geometry and geography. On face value, the refinement they offer is offset by the additional complexity and uncertainty.

The output from this can be used to either use simple indicative tables of effects for quantities of TNT such as illustrated in Table 2 below.

Table 2 - TNT Equivalent for Explosion Blast Damage (Merrifield, R.,1993)

TNT Equivalent	Consequences
1 g of Explosive	Any person holding the explosive could receive serious injury
10g of Explosive	Any person close to this quantity of explosive at the time of initiation would receive very serious injuries.1% of persons at a distance of 1.5 metres away are also liable to eardrum rupture.
100g of Explosive	50% of windows in a room likely to be blown out. 1% eardrum rupture at 3.5 m. 50% eardrum rupture at 1.5m. Persons in very close proximity (e.g. holding the explosive) almost certainly killed
500g of Explosive	Inside a 6m x 6m enclosed brick building structural collapse is most likely.; considerable damage to panels between steel or reinforced concrete frames in other structures Persons very close to blast will almost certainly be killed. Persons close to blast will be seriously injured by lung and hearing damage, fragmentation effects, and from being thrown bodily. Almost all persons within the room will sustain perforated eardrums

An alternative is to use the Merrifield's *Simplified Calculculations of Blast Induced Injuries and Damage* (Merrifield, R., 1993) to determine the standoff distance for a probability of eardrum rupture of less than 15% of persons.

Using these approaches led to TNT energy equivalences and standoff distances summarized in Table 2 below.

Table 3 - Summary of Standoff distances applied

	TNT Energy Equivalence (50% efficiency)	Standoff Distance
Best Estimate	~ 0.8 g	~ 46 cm
Upper bound sensitivity	~ 3.2 g	~ 74 cm

It is acknowledged in the calculation methodology that for 'energetic substances' where 'the rate of rise in pressure is slow and the duration of the explosion is relatively long' the method 'overestimates the close-in effects and underestimates the far-field effects. However, due to the calculation pessimisms discussed above and the small quantities of hydrogen involved, the method is judged to be an appropriate basis for this assessment.

Applying Merrifield's calculations (Merrifield, R., 1993) provides a simple methodology to determine potential injuries from a hydrogen event based on TNT equivalence. However, these predictions are conservative. Also, the buoyant nature of hydrogen means any burn will be rising away from an operator.

The practical conclusion taking all these factors into consideration is that anyone at arm's length from the container will have a low probability of sustaining any injury. This is the case for all six injury types.

i) Barometric injuries.
Short standoff distance and values are very conservative.
At arm's length 15% probability of eardrum injury. Mitigate with ear defenders or increase standoff distance or justify in Risk Assessment based on exceptionally low probability of hydrogen leakage and ignition. These distances are illustrated further in Table 4 below.

ii) Translational Injury
Applying the Merrifield *Simplified Calculculations of Blast Induced Injuries and Damage* (Merrifield, R., 1993) generates values but in reality, translation injuries are virtually impossible because

- not enough energy due to small masses of hydrogen.
- operations will not physically permit an operator close enough for translational effects.

Again, the results are illustrated in Table 4 below.

iii) Missile injury:
Using standard physics and methods these effects can be estimated leading to a conclusion that:

- Containers fail in a ductile manner so low probability of generating shrapnel
- The possibility of creating other missiles is small.
- The risk of injury is low.
- The risk of missile damage to other systems is low.

Therefore, the possibility of generating missiles that can cause injury or damaged is judged to be sufficiently low that more detailed analysis is not proportionate.

iv) Thermal Injury:
Hydrogen flames have a low thermal emissivity. An operator would have to be within a few millimetres to sustain any thermal injury however, even at this proximity, due to the short flame duration, it is unlikely that a thermal injury would result (Ingram et al, 2018). The practicalities of undertaking the work mean that there is a low probability of thermal injury to an operator.

v) Toxic Injury:
Hydrogen when burned forms water. Therefore, there is no potential for direct toxic injury.
The potential for breaching container integrity and losing containment of the contents is assessed in the nuclear safety case.

vi) Environmental Injury
This concerns the societal effects and does not fall within the realm of DSEAR. It is better addressed by the nuclear safety case or a COMAH case. COMAH is not applicable to facilities handling nuclear materials in this instance it is an exempt nuclear facility. COMAH would normally consider the catastrophic effects, assets damage and domino effects. These are issues with wider societal impacts are addressed within the through the nuclear safety case.

Table 4. Application of Merrifield's Simplified Calculculations of Blast Induced Injuries and Damage

Consequence:			**Distance from Source (m)**							
			Typical TNT Energy Equivalence (50% Efficiency) Values for Various Potential Releases							
Fatality Whole Body Translation	**Fatality Lung Damage:**	**Eardrum Rupture:**	**0.5 g**	**0.8 g**	**1.9g**	**2.3g**	**3.2g**	**4.7g**	**5 g**	**5.6 g**
100 % Probability Off-Chart (Bad)	100% Probability Off-Chart (Bad).	100% probability Off-Chart (Bad).	0.04	0.046	0.062	0.066	0.074	0.084	0.085	0.089
50 % Probability Off-Chart (Bad)	1 % Probability.	82 %	0.16	0.18	0.25	0.26	0.29	0.34	0.34	0.36
Mostly Safe.	Below Threshold Value.	15%	0.40	0.46	0.62	0.66	0.74	0.84	0.85	0.89
Mostly Safe.	Below Threshold Value.	1%	0.63	0.73	1.0	1.1	1.2	1.3	1.4	1.4

4 Risk Assessment and Conclusions

The question posed was whether the engineering judgement that the hydrogen hazard associated with a facility was very limited could be underpinned using common RGP methodologies. This had to meet the robustness required for the regulatory framework of the nuclear industry and meet tolerability of risk criteria. Overall, there was the need to avoid confirmation bias and address uncertainties in the source term information.

i) Employing a range of techniques has highlighted the conservative exigencies that arise from a simple application of BS EN 60079-10-1:2021.

ii) The use of the Energy Institute probabilistic area classification methodologies:

- Whilst not providing absolute answers is a good pointer of relative changes and provides risk ranges to indicate regions of tolerability of risk.
- Proved effective at looking at the series of discrete operations in the process
- The methodology addressed the questions of occupancy and pressurised releases well.
- Allowed sensitivity to be explored

iii) Assessing actual harm potential to operators whilst extremely conservative when put into the context of actual operations shows that the risk of harm from an explosion to individuals is low using TNT equivalency and the Merrifield 1993 methods.

The overall conclusion being that RGP methodologies did provide robust and pragmatic underpinning to an engineering judgement.

5 References

Kletz, 2000 — MOX Falsification Report

Office for Nuclear Regulations, 2017 — License condition handbook, February 2017

HSE, 2001 — Reducing risks, protecting people - HSE's decision-making process
ISBN 0 7176 2151 0

HSE, 1992 — Tolerability of Risk from Nuclear Power Stations

Crowl, D. A., 2003 — Understanding Explosions,
Department of Chemical Engineering, Michigan Technological University

Merrifield, R.,1993 — Specialist Inspector Reports Number 37
Simplified Calculculations of Blast Induced Injuries and Damage

BS EN IEC 60079-10-1:2021 — Explosive Atmospheres
Part 10-1: Classification of Areas – Explosive Gas Atmospheres

BS EN 60079-10-1:2015 — Explosive atmospheres
Part 10-1: Classification of Areas – Explosive Gas Atmospheres

HSE, 2013 — Dangerous Substances and Explosive Atmospheres Regulations 2002,
Approved Code of Practice and guidance, L138 (Second edition) Published 2013.

Energy Institute, 1998 — A risk-based approach to hazardous area classification
The Insitute of Petroleum, November 1998
ISBN0 85293 238 3

Energy Institute, 2015 — Model Code of Safe Practice Part 15
Area Classification for Instalations Handling Flammable Fluids
4th edition June 2015 Energy Institute
ISBN 978 0 85293 717 4

Energy Institute, 2006 — Ignition Probability review, model development and look-up correlations
January 2006 Energy Institute
ISBN 9780 85293 454 8

Ingram, J.M., Averill, A. F., Gomez-Agustina, L., Holborn, P. G., Battersby, P., Benson, C. M., 2018
Potential Hazard Consequences to Personnel Exposed to the Ignition of Small Volumes of Weakly Confined Stoichiometric Hydrogen/Air Mixture,
Hydrogen Hazards Unit, London South Bank University, November 2018