NUCLEAR ENABLED HYDROGEN CO-GENERATION: SAFETY AND REGULATORY INSIGHT

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ABSTRACT

National Nuclear Laboratory (NNL) is aiming to demonstrate through a research and development programme that nuclear enabled hydrogen can be used to support future clean energy systems. Demonstrating the safe operation of hydrogen facilities co-generating with a nuclear reactor will be key to enabling the deployment and success of nuclear enabled hydrogen technologies in the future. During the deployment, continuity of supply will be paramount and possibly requires inter-seasonal storage. Co-generation is a means of using a source of energy, in this case a nuclear reactor, to efficiently produce power and thermal energy. Since a great deal of the heat energy is lost to the environment in a power plant making use of wasted energy for other useful output like the production of hydrogen and direct heating would be advantageous to plant economics and energy system flexibility.

The civil nuclear industry is regulated around the world. This approach ensures that all the activities related to the production of power from nuclear and the hazards associated with ionising radiation are controlled in a manner which protects workers, members of the public, property and the environment. Nuclear safety assessments follow a rigorous process and are required as part of the Nuclear Site Licence. A fundamental requirement, which is cited in the UK legislation, is that the risks associated with all activities at the licensed site be reduced to As Low As Reasonably Practicable (ALARP). The principle places a requirement on duty holders to implement measures to reduce risk, where doing so is considered reasonable and proportionate. The inclusion of risks for hazardous materials associated with the hydrogen production facilities need to be considered and this requires harmonisation of two different safety and regulatory governance regimes, which have not previously interacted in this way. The safety demonstration for nuclear facilities is provided through the Safety Case.

1.0 INTRODUCTION

The civil nuclear industry is regulated around the world. This approach ensures that all the activities related to the production of power from a nuclear source and the hazards associated with ionising radiation are controlled in a manner which protects workers, members of the public, property and the environment. Within the UK nuclear instillations are licensed and regulated by Office for Nuclear Regulation (ONR), for England, Wales and Scotland. There are also environmental requirements placed upon nuclear facilities and these are regulated by regional authorities; namely the Environmental Agency (EA) in England, Natural Resources Wales (NRW) in Wales and the Scottish Environment Protection Agency (SEPA) in Scotland.

The legal framework for the nuclear industry in the UK is based around three pieces of legislation; the Health and Safety at Work etc. Act 1974 [1], the Energy Act 2013 [2] and the Nuclear Installations Act 1965 (as amended) [3]. The Health and Safety at Work Act is an encompassing piece of UK legislation which places responsibilities and obligations on all employers, including at a nuclear licensed site, for managing the health and safety of workers and members of the public. However, additional legislation is in place due to the unique nature of the hazards associated with the nuclear industry and the potential for accidents to cause widespread and long lasting harm. The Nuclear Installations Act requires the licensing of sites which are to be used for the installation and operation of nuclear reactors and obliges the license holder to comply with 36 Site Licence Conditions (SLCs) [4]. Provision for additional regulations at a nuclear site are also detailed in the Energy Act. In some cases specific regulations are also relevant, for example: the Ionising Radiations Regulations 2017 (IRR17) [5] and Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPIR) [6].

A fundamental principle which is cited in the UK's legislation is that risks be reduced to As Low As Reasonably Practicable (ALARP). The ALARP principle places a requirement on duty holders to implement measures to reduce risk, where doing so is considered reasonable and proportionate. The principle is often applied by observing recognised industry Relevant Good Practice (RGP), but in situations where this is absent, then it is demonstrated that sufficient measures have been put in place up to a point where the reduction in risk (i.e. benefit gained) compared to the additional cost of implementing more measures has become grossly disproportionate.

Radiological and nuclear safety assessments, used to evaluate risk, follow a robust process and are required to be carried out as part of the installation's SLCs. License holders typically have procedures, standards and guides which are based on their interpretation of the ONR Safety Assessment Principles (SAPs) [7]. Numerical risk assessment criteria will be contained in these guides for purposes of assessing radiological hazards to workers and members of the public. Defence in depth is also important in the design and operational of nuclear facilities to ensure nuclear safety. The aim of this approach is to prevent faults from occurring and mitigate the consequences of any accidents by implementing multiple layers of defence which provide diversity, independence and redundancy to different postulated fault scenarios.

The aspiration of using a nuclear reactor as the energy source to enable hydrogen production in a co-generation arrangement provides great opportunities to de-carbonise energy systems and improve energy efficiencies. But the introduction of significant quantities of flammable materials provides a hazard and therefore additional risk. Historically, experience has shown that explosion hazards will tend to dominate the risk associated with production and storage of large quantities of flammable gases (including hydrogen). This is due to the severe consequences if such a hazard did occur.

In theory, mitigation of hazards associated with hydrogen can be achieved by placing the hydrogen facilities at the greatest possible distance from the licenced site, to reduce the risk to ALARP. However, in practice when heat assisted technologies are placed closer to the heat source, they are expected to offer improved efficiency. Therefore, the preferred location of the hydrogen production plant will be based on a balance between the required efficiencies for the hydrogen production versus an acceptable increased level of risk. As such consideration of how to effectively manage this risk as part of the Safety Case for a co-generation site arrangement needs to be undertaken.

2.0 BACKGROUND AND CO-GENERATION SITE ARRANGEMENTS

Co-generation uses a single source of energy to produce power and useful thermal energy. The Carnot cycle (Figure 1) describes a reversable heat engine and gives an upper limit on the efficiency during conversion of heat energy into useful work [8].

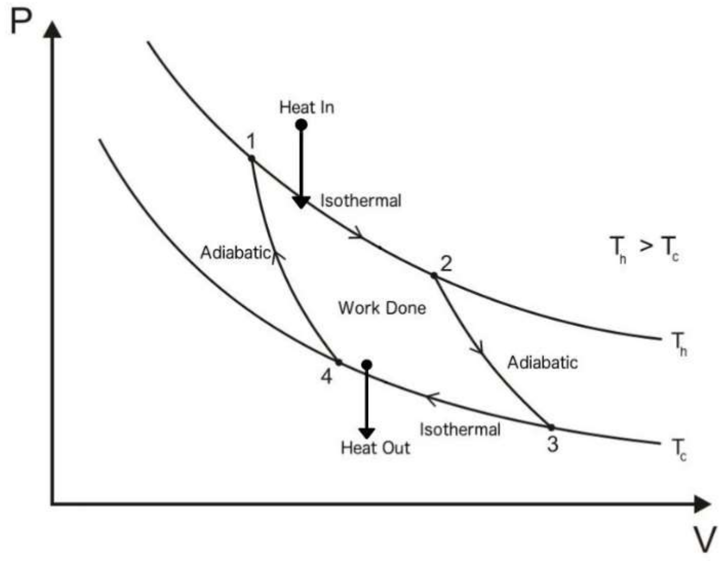

Figure 1: The Carnot Cycle

This cycle demonstrates that to produce a specific amount of power the ideal engine has to work between a hot source and a cold environment. Due to thermodynamic effects there will always a significant amount of heat energy which will be released into the cold source. This heat is in effect wasted energy and if it could be used for other application then it could significantly improve the efficiency of the heat engine.

The idea of co-generation is to use rejected heat in a secondary production plant which naturally increases the efficiency of the heat engine, in this case a nuclear reactor. Since a great deal of the heat energy is lost to the environment in a power plant making use of the wasted energy in another way (such as the production of hydrogen, process heat, chemical production or district heating) would be very advantageous. The production of hydrogen using nuclear derived heat requires additional plant and equipment to extract the heat energy from the nuclear reactor. Current interest for nuclear enabled hydrogen looks to take advantage of using high temperature steam, i.e. > 300 to 1000 °C [9], to drive efficiency and greater yields of hydrogen from the energy being inputted into the electrolysis facility. It is therefore assumed that there would be the addition of the following systems to extract heat form the reactor and generate hydrogen gas:

- Heat Extraction System (HES),
- Steam Electrolysis Facility (SEF).

The HES (including heat exchangers and any safety related isolation equipment) is required to be located within the nuclear site boundary as there will be the need for isolation in an accident scenario; which should be under the control of the licensee / reactor duty holder. This control for stopping and isolating the heat extraction would be considered a requirement for the control and safe operation of reactor transients, and likely be treated like other steam by-pass systems, such as that used in the turbine on the conventional island. The SEF, which takes the steam energy for use in the electrolysis processes, is not required to be located on the licensed site. It is essentially a chemical processing plant which once being provided with high temperature steam can be operated independently of the reactor site. Figure 2 provides an overview of the main systems and the nuclear site boundary:

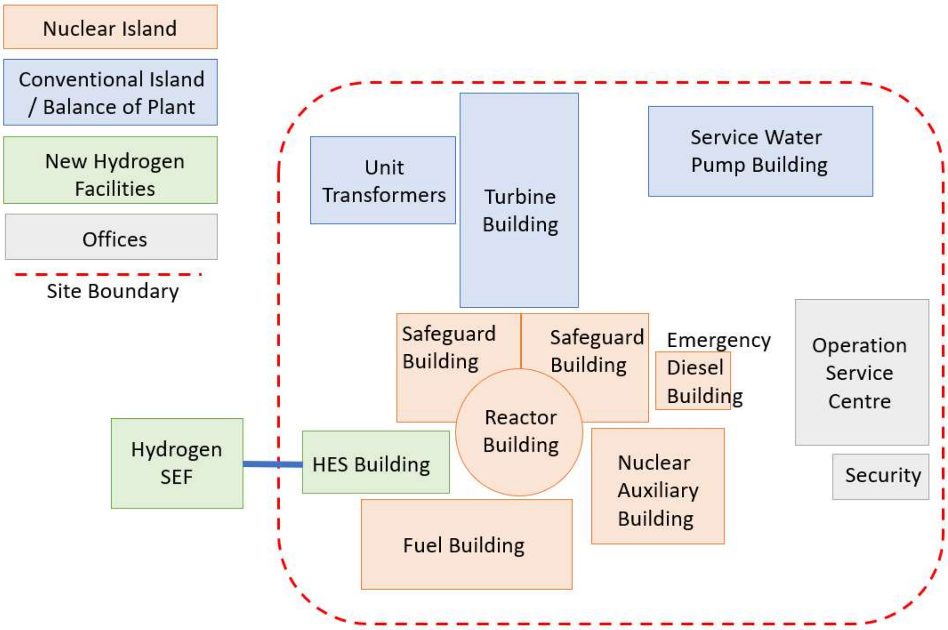

Figure 2: Hypothetical layout of a reactor site with typical Nuclear Island / Balance of Nuclear Island and Conventional Island Balance of Plant buildings, including HES (on-site) and SEF (off-site) for hydrogen production (N.B. the buildings are just those expected on a typical Giga Watt reactor site, a high temperature reactor may have different requirements necessitating a different layout).

Early engagement with the UK nuclear regulator, ONR, regarding a nuclear reactor being deployed in a co-generation arrangement has helped NNL to conclude that deployment of the SEF off the licensed site has significant advantages. It allows for modification and experimentation with the hydrogen SEF, which is currently based on technology yet to be proven. During initial demonstration the SEF design it is highly likely that changes and adaptions will be made as operational experience is gained. Being located off the nuclear licensed site is expected to reduce deployment costs of the SEF during the construction phase and running cost in the operational and decommissioning phases; but also allow for simpler modifications to the plant as it will not be regulated under the nuclear site license. Modifications within the context of radiological safety undergo significant scrutiny by the regulator. This approach ensures that sufficient time is given to consider the proposals and assessment of risk associated with a modification, but it adds time and costs, which can be considered appropriate due to the potentially long lasting consequences of a radiological accident. However, for conventional non-nuclear industries this approach would add considerable time in the approvals and permissioning which simply would not be in line with the expectations of other industries.

Management arrangements and understanding any changes in the operations downstream of the heat exchangers and off-site will need to be understood by the reactor site and a mechanism identified to share information. Part of this would require the site to be informed of operational and system changes which could impact the safety of the reactor and/or its protection systems. It is noted that a chemical processing plant can make many changes over just a few years. This is in total contrast to a nuclear site where changes take longer to approve and implement. As such, the existing arrangements already in the site license, such as the 10 yearly Periodic Safety Review, would have too long a periodicity. Something more frequent will be required going forward. To improve the safety of the reactor site the licensee needs to be aware of changes to external plants and facilities which could directly impact their sites, but also understand any dynamic changes in hazards or something further down the production process which may not be visible to the site but could impact radiological safety.

3.0 SAFETY CASE CONSIDERATIONS

The principle safety requirement of a nuclear plant is that radioactivity is completely retained inside the plant, even during extreme accidents, with no severe consequences outside the site fence. The nuclear industry already has a wealth of knowledge of managing the hazards associated with using and storing hydrogen gas at a nuclear site. Although the management of hazards at a nuclear licenced site can vary between different sites the general safety management strategies are usually the same. This is because they are required to satisfy the expectations of the regulator, ONR, by their assessment of the Safety Case. Which also provides the duty holder with the necessary information for safe management of the facility and to reduce risks to ALARP.

The fundamental requirement of any radiological Safety Case is to demonstrate that hazards presenting radiological exposure or harm can be safely managed and the risks are reduced to ALARP. Within the Safety Case there needs to be a clear link between the hazards, assessments and how safety measures are implemented within the facility, this has become known as the *'Golden Thread'*. The safety demonstration can be effectively illustrated through a Claims Arguments Evidence (CAE) approach, which has been described below.

However, it is worth noting that "*the Safety Case*" is not typically a single document, it is the totality of documented information and arguments developed by the licensee which substantiate the safety of the plant activity, operation or modification in question. It provides evidence to demonstrate adequate protection of workers and members of the public during both normal operations and during any fault conditions (when these cannot be prevented) and ensures that risk have been reduced to ALARP. For large and/or complex Safety Cases it is generally suggested by the regulator that licensees produce a top tier document, which is generally referred to as the Safety Report. The licensee is ultimately responsible for the Safety Case, as part of SLC 14 [4].

4.0 CLAIMS, ARGUMENTS AND EVIDENCE STRUCTURE

Using the CAE approach to Safety Case allows the key safety claim(s) to be clearly defined at the start and enables early engagement with regulatory bodies. The high level safety claim can be supported by additional sub-claims, arguments and evidence in order to provide the overall safety argument, as illustrated in Figure 3.

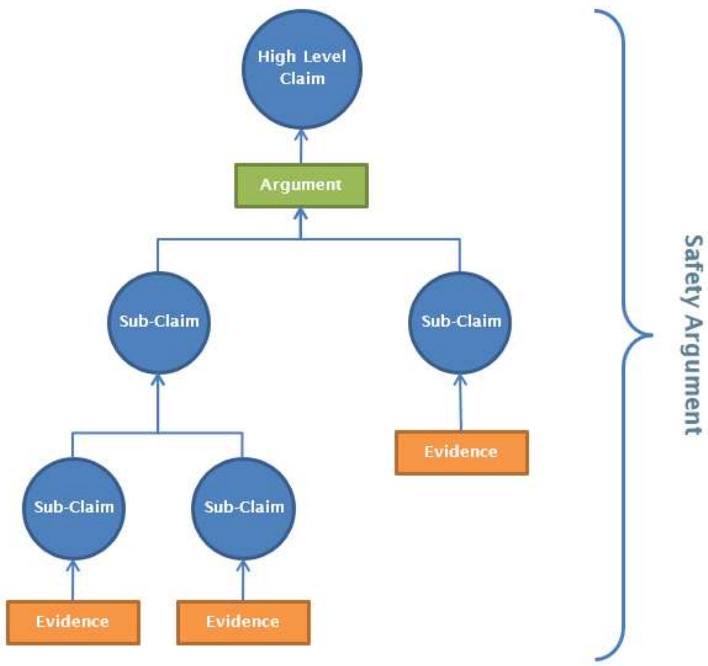

Figure 3: Overview of the CAE Argument Structure

A *claim* provides a statement which can be assessed within an argument and shown to be true or false. Each claim can be supported by sub-claims, arguments or evidence. Claims can also be used to explain additional information such as defining terms or providing a scope where the overriding claim is valid.

Arguments are used to support claims by explaining how the available evidence can be used to indicate that the operations and/or activities in question are safe. All arguments have to be supported with evidence otherwise the argument is unfounded. This is often demonstrated by but not limited to:

- Compliance with requirements, standards and RGP;
- Reference to operating processes and procedures;
- Hazard identification and assessments;
- Engineering Substantiation;
- Identification of adequate safeguards / safety measures to prevent, protect and mitigate during fault conditions;
- Safety measures to control impact from hazards.

Evidence is used to support claims and arguments and provides the principle source of information from which the safety claim can be inferred. Evidence is usually provided by assessments, testing, simulations or estimations. All the evidence referred to should be supporting an argument which explains what safety claim is being inferred.

From a radiological Safety Case CAE perspective, there is a top-level claim for introduction of a hydrogen production system, which is to ensure all hazards introduced by the new system can be safely managed and that the risks have been reduced to ALARP. The CAE approach can provide a simple and effective method to communicate the overall safety argument within the Safety Case.

5.0 IDENTIFICATION OF HAZARDS

An important part of the Safety Case is the identification of hazards, which supports the demonstration of safety and production of the ultimate case. The identification process covers both the formal method adopted for HAZard IDentification (HAZID) (e.g. through a Hazard and Operability (HAZOP) study) but should take account of experiences or lessons learnt from other similar plants or processes.

The HAZOP study examines the proposals at the relevant stage in the design and are conducted with a quorate group of suitably qualified technical experts familiar with the plant and processes being considered. HAZOP provides a structured and systematic approach to identify; potential fault conditions along with available barriers to prevent the fault conditions developing to consequences to the public, workforce or environment, damage to equipment, or issues which prevent efficient operation. The output of the HAZOP process is used by a project to manage the risks present, where possible the design will endeavour to remove hazards by implementing changes to the design, where this is not possible the HAZOP output is used to underpin the development of a Hazard Management Strategy (HMS) and safety assessments. These documents will inform the engineering teams of the Safety Case claims placed upon any safety related Structures, Systems and Components (SSCs) used to underpin safety.

6.0 HAZARD MANAGEMENT STRATEGY PRINCIPLES

The principals of Process Safety are highlighted under the acronym ERICPD, which are: Eliminate, Reduce, Isolate, Control, Personal Protective Equipment (PPE) and Discipline (Training). In each case it is preferable to eliminate or reduce a hazard rather than using control systems or mitigation measures. The following details each part:

- **Eliminate** Can something be altered or substituted so that it no longer presents a hazard (this is not possible in the case of generating hydrogen as it is the objective, but it may be possible to limit the stored inventory);
- **Reduce** Can reducing the frequency or inventory be undertaken so that the risks are also reduced. This could include reducing the concentration of materials to minimise associated hazards;
- **Isolate** Can the hazard be separated from individuals through physical barriers or zoning. Examples of this are containment structures and/or shielding;
- **Control** Managing the hazard though the use of engineered or managerial controls/arrangements to prevent exposure;
- **PPE** Allow exposure but protect the individual with PPE;
- **Discipline** Reliance on operator training to minimise the risks.

7.0 ASSESSMENT OF FAULT CONDITIONS

Different licenced sites can use differing nomenclature for engineered and administrative safety features; however all nuclear licenced sites are regulated by ONR inspectors who are guided by the same SAPs [7]. This means that all license holders aspire to the same safety principles and numerical targets and legal limits which define the Basic Safety Objective (BSO) and the Basic Safety Limit (BSL) respectively. As such, the details discussed below have to be applied to any situation where there are hazards and associated risk which needs to be managed.

The individual hazards are identified by an appropriate and suitability robust HAZID process and presented in a Fault Schedule with a number of grouped fault sequences. Each fault sequence which could lead to unwanted effects has an appropriate initiating event and unmitigated consequence calculated which suitably bounds the sequence.

Radiological safety assessments then specify safety measures which can be engineered or administrative in nature. The designated safety measures need to reduce the consequence and/or initiating frequency to an appropriate level. The concept of defence in depth is also important to ensure nuclear safety. The purpose of this is to prevent faults from occurring and mitigate the consequences of any accidents by implementing multiple layers of defence. Typically the following safety measures are required based on the dose consequence, i.e.:

- For significant faults (i.e. > 20 mSv dose to an operator), Design Basis Analysis (DBA) requires a passive safety measure or two independent engineered safety measures. In some instances it is possible for operational measures to be claimed. But this type of safety measures is lower in the hierarchy of safety controls and should therefore be justified.
- For less significant faults (i.e. > 2 mSv dose to an operator), DBA requires the designation of a single suitability robust engineered safety measure. In some instances it is possible for operational measures to be claimed. But this type of safety measures is lower in the hierarchy of safety controls and should therefore be justified.
- For faults which are below the lower threshold of the DBA region (i.e. < 2 mSv dose to an operator) there is no requirement to formally identify a safety measure in the Safety Case. However, engineering RGP may expect the inclusion of measures when they are simple and straight forward to implement. These are not formally claimed in the DBA but will act to reduce risks to ALARP.

The various engineered safety measures are identified as safety related SSCs in the Engineering Schedule, which also includes the safety function and any performance requirements. SSCs are substantiated against their safety function(s) and performance requirements to ensure they will fulfil their safety role when required. The operational safety measures and compliance arrangements are ultimately defined within a Clearance Certificate.

8.0 SAFETY CASE DEVELOPMENT STRATEGY

The approach to the development of a safety case will typically be in tandem with the design process through the various stages from concept to detailed design and construction. This includes the production of a number of expected outputs detailed for each design stage:

Concept / Preliminary Design:
- Optioneering studies,
- HAZOP 0 (early stage / concept design) / HAZOP 1 (preliminary / scheme design),
- Initial Fault Schedule,
- Preliminary Safety Report (PSR),
- Initial HMS.

Detailed Design:
- HAZOP 2 (detailed design),
- Fault Schedule,
- Hazard Assessments (including any Specialist Assessments),
- Engineering Schedule,
- Engineering Substantiation,
- Safety Case Summary Report / Pre-Construction Safety Report (PCSR).

Installation / Commissioning:
- Fault Identification,
- Safety assessment as required,
- Safety Commissioning Schedule,
- Pre-Commissioning Safety Report (PCmSR) / Pre-Operational Safety Report (POSR).

The incorporation of Safety Case development within the design process helps to ensure that the design develops with normal and fault condition safety in mind with the aim of minimising the hazards present and reducing the residual risks present and ultimately the overall cost at the final design stage.

9.0 ALARP DISCUSSION

The concept of ALARP is used in the nuclear industry worldwide, but in the UK this principle is enshrined in law. The Health and Safety at Work Act [1] places a duty on all employers to conduct their operations and activities in such way that risks to their workers and members of the public is reduced So Far As Is Reasonably Practicable (SFAIRP). SFAIRP has essentially the same meaning as ALARP. At their core is the concept of "*reasonably practicable*". Essentially both terms involve weighing up a risk against the cost (i.e. trouble, time and/or money) required to manage it. In the context of a nuclear power plant this duty requires that all measures are taken during design, construction, operation and decommissioning to minimise radiation doses to workers and members of the public; provided the cost of such measures is not grossly disproportionate compared to the benefits achieved. The Health and Safety Executive (HSE) / ONR has proposed thresholds of risk due to radiation exposure from operation of a nuclear power station, shown in Figure 4 which often referred to as the carrot diagram:

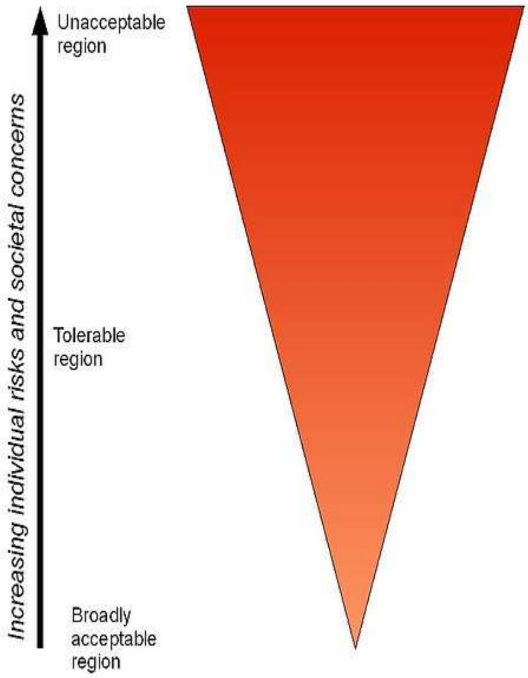

Figure 4: HSE The Tolerability of Risk from Nuclear Power Stations, 1988 [10]

- Lower threshold (Broadly Acceptable Region) provides an area which further measures to reduce risk would not normally be expected. However, there remains as legal requirement for the duty holder to reduce risk if it is considered reasonably practicable. The risk level in this region corresponds to a risk of an individual fatality due to radiation exposure of 1 x 10^{-6} per year [7].
- Intermediate region (Tolerable, if ALARP Region) provides an area where the plant operation can be justified if the level of risk can be clearly outweighed by the benefits, such that no further measures to reduce risk were reasonably practicable.
- Upper threshold (Unacceptable Region) provides an area where the operation is not acceptable. The risk level in this region corresponds to a risk of individual fatality due to radiation exposure of 1 x 10^{-4} per year [7].

Fundamentally, ALARP is the demonstration to a decision-making process, making it possible to justify that the risks have been reduced as far as practicable and identify the design option(s) that have been selected to resolve a safety issue. Noting that design solutions should also be fit for purpose and formally documented. The ALARP argument can also be suitably demonstrated by clear discussion and demonstration that a potential option is too costly and does provide significant reduction to risk. The ALARP process can be summarised as follows in Figure 5:

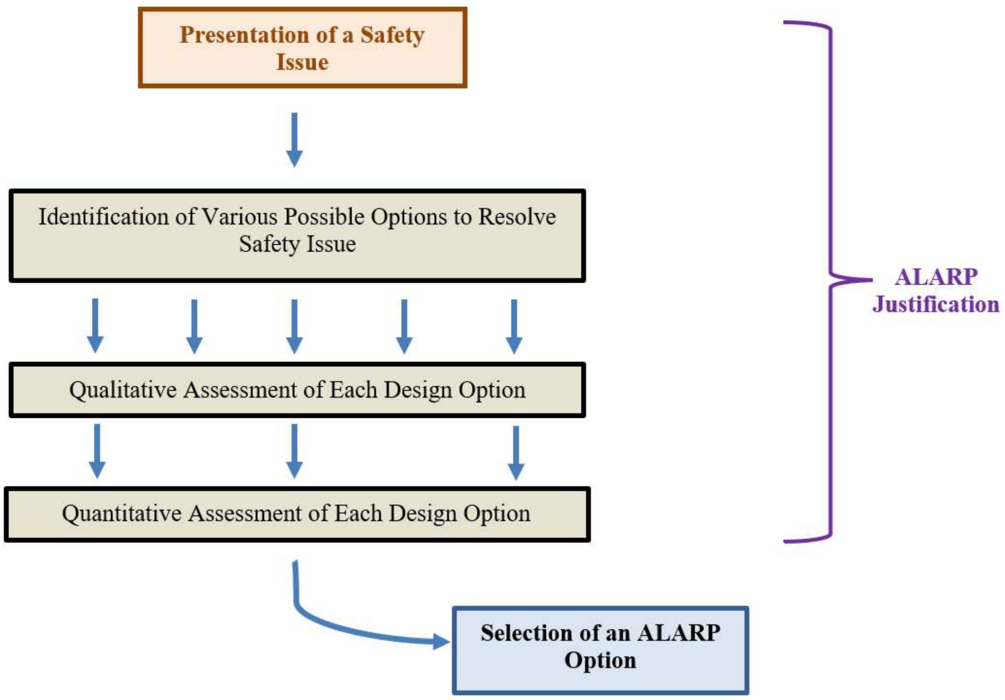

Figure 5: Summary of the ALARP Process

The following are typically presented to demonstrate that the ALARP principle has been met:

- Demonstration of RGP, which may include a review of plant design against applicable international / national standards and ONR Safety Assessment Principles;
- Optioneering studies, showing the justification for the design and demonstrating any improvements made to safety and explaining why the chosen design options were selected;
- Presentation of specific assessments, such as Probabilistic Safety Assessment (PSA), which show that radiological risk levels from operation of the facilities or introduction of new activities will be in the "*Broadly Acceptable Region*" in the tolerability of risk [10]. Where it is not, then further explanation and demonstration of why risk cannot be reduced further would be expected;
- Arguments and justifications that no further improvements could be practicably implemented to improve the design, and the risk is therefore considered to be ALARP.

It could be argued that so long as the risk for a nuclear accident is maintained at the same level as before the addition of the hydrogen production system then the Safety Case would remain valid. This should be taken in context with the need to re-assess the associated risks and include any equipment required to manage the risk. This is likely to include both radiological safety assessment and specialist fire / explosion assessments in order to provide a clear understanding of the consequences and any safety measures required.

10.0 POTENTIAL DESIGN STRATEGIES TO REDUCE RISK FROM SEF TO REACTOR AND NUCLEAR ISLAND BUILDINGS

In order to reduce the risk from faults involving the SEF there are a number of potential arrangements which could be considered when siting and constructing the facilities. Safety against the consequences from an explosion and chemical release hazard can generally be reduced with increasing separation distance or by the use of physical barriers to protect the nuclear facilities from the hazards associated with the SEF. There are numerous deployment scenarios which could be used to reduce or remove the risk on the reactor and its safeguard buildings. Some considerations to reduce risk are detailed as:

- Separation Distance,
- Raised Land Barrier (i.e. a berm) between the Facilities,
- Blast panels near the SEF,
- Move the reactor Central Control Room (CCR) off-site,
- Construct the nuclear reactor underground,
- Construct SEF underground.

The list above is not intended to be exhaustive but provides some ideas of methods which could be used to reduce the risk from explosion or chemical release from the SEF. These potential strategies take no account of the cost (i.e. time, trouble and money) required to implement or the impact they would have on the operations of the respective facilities. And some of the strategies suggested would likely cost a significant amount of effort to implement, i.e. placing facilities underground is both expensive and complicated depending on ground conditions.

An appropriate solution to reduce the risk in deployment of the co-generating facilities could look something like Figure 6; where separation distances are used to reduce consequences experienced by sensitive buildings and structures. And to support the security of the nuclear plant the SEF could be located off the licensed site, but within a security boundary to account for the potential for malicious activity towards the chemical plants, which could impact the nuclear plant.

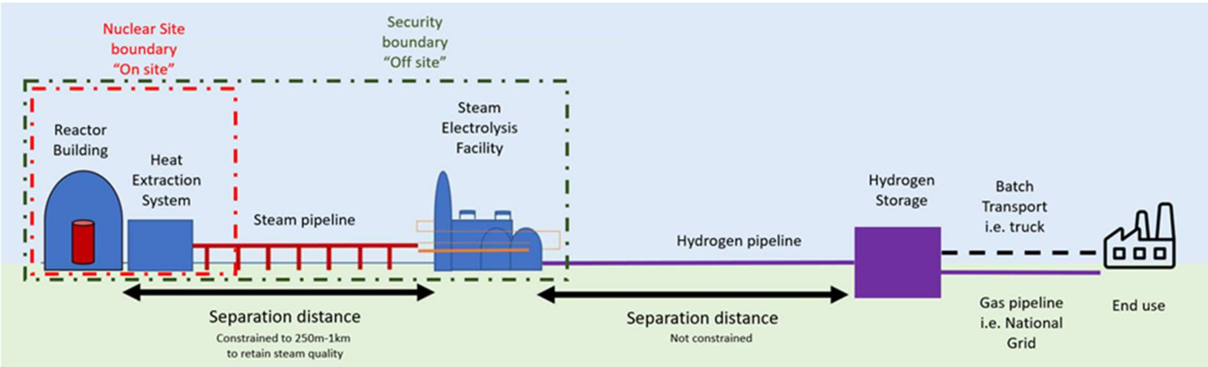

Figure 6: Potential arrangement for a co-generation facility

11.0 CONCLUSIONS

Generation of hydrogen from a nuclear energy source is not in itself novel or likely to introduce a disproportionate level of risk to the nuclear site, so long as the hazards are managed in line with the current expectations for safety.

Considerations for storage of chemicals and keeping the licensed site informed of changes to the surrounding facilities in an intelligent way will be important to support robust safety management of the reactor and its safeguard buildings. Extending this approach to other high hazard industries would help to improve site safety and the management of risk at other facilities co-located next to potential major accident hazard sites. In this respect it could, or perhaps should, become RGP and this approach should be adopted for similar high hazard applications, including smaller reactors.

Demonstrating the safe operation of hydrogen production technologies at a nuclear licensed site will be key to enabling the deployment and successful deployment of nuclear enabled hydrogen.

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