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Initial accident scenario analysis in support of a preliminary DEMO tritium plant design

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ABSTRACT

An initial safety analysis of a preliminary DEMO tritium fuel cycle has been undertaken using functional failure mode and effects analysis (FFMEA) to create accident scenarios for evaluation. A total of ten scenarios were developed and analysed based upon the current technology planned for the tritium fuel cycle. The findings indicate that the potential radioactive hazards from accident scenarios would result in increased dose rates to workers but that these rates can be kept within manageable levels through proper ventilation, backup systems, and engineered safety. The individual hazards found within the tritium fuel cycle are echoed in other processing industries, and knowledge transfer from well-established industries will enhance the safety procedures. The methodology for identifying and evaluating accident scenarios put forth in this paper can be used as the design of the fuel cycle progresses to maturity.

1. Introduction

Inherent safety is a fundamental part of plant design. Consideration of processes, technologies, and layout to eliminate or minimize risk from the initiation of a project can minimize reliance on administrative and equipment safety controls, leading to fewer safety accidents and a robustness to future modifications.

The tritium plant at planned EU DEMOnstration fusion power plant (DEMO) is at the pre-conceptual design stage. Accident scenario analyses highlight areas where further investigation or decision making is needed; they also identify areas and conditions which will need to be considered as part of future design. In the analyses and future design suggestions, parallels between other industries and experiences is drawn where practicable. The DEMO fuel cycle is unique in its combination of materials processing and technologies, but many of the types of technologies (such as gas separation or use of radioactive material) have been matured in other industries.

At conceptual and pre-conceptual design stages, intrinsic safety, followed by engineered safety, must be the focus of design efforts. It is recognised that many systems required for the DEMO fuel cycle require processes which cannot be made intrinsically safe (*e.g.* cryogenic separation process or high concentrations of flammable gases); by analysing the areas in which the most hazardous accidents can occur, efforts can be focussed on undertaking fundamental design decisions which will minimise hazards as detailed design continues.

2. The demo tritium plant

The DEMO tritium plant considered in this analysis comprises the direct internal recycle loop (DIRL), the inner tritium plant loop (INTL), and the outer tritium plant loop (OUTL) as specified in Fig. 1.

The individual components in Fig. 1 are detailed by Day et al. [1]. A summary of the items and their groupings for the scenario analysis in this paper is given briefly as follows:

- Gas Distribution Control and Monitoring (GDCM): this is represented by the associated block in Fig. 1. GDCM takes gas from direct internal recycling or gas storage or INTL and sends it to the torus fuelling systems.
- Torus Pumping: this system block considers 'Fuel Separation,' 'DIRL Vacuum Pumping, and 'INTL Vacuum Pumping'' blocks in Fig. 1. The pumping system block includes pumping for direct recycling, initial fuel separation, and pumping a fraction of the exhaust stream to further exhaust processing.
- Exhaust Processing System (EPS): this group includes the 'Exhaust Processing' and 'PEG Storage' in Fig. 1. This system block liberates any hydrogen isotopes (Q_2) bound in impurities, separates Q_2 from plasma enhancement gases (PEGs). The PEGs are sent for storage,

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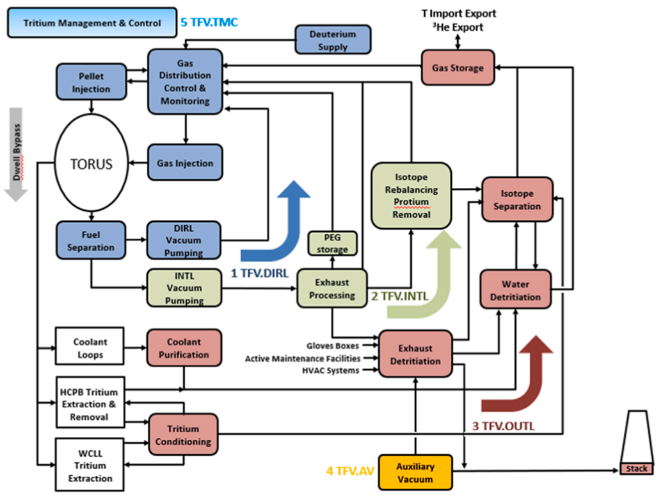

Fig. 1. DEMO tritium fuel cycle and associated system blocks, from [1].

and the Q_2 stream is sent either for separate storage, back to the GDCM, or for further processing in the inner fuel loop.

- Isotope Rebalancing and Protium Removal (IRPR): This system block removes unwanted protium and rebalances the ratio of tritium to deuterium in the inner fuel loop. The unwanted protium stream is sent to the outer fuel loop, whilst the rebalanced tritium and deuterium streams are sent for storage or reuse in the fuel cycle.
- Fuel Storage System: This group includes the system blocks 'Deuterium Supply' and 'Hydrogen Storage.' The system blocks in this group all provide long or short-term storage of fuel. Short term storage may include storage vessels (isotopes stored as gas).
- Exhaust Detritiation System (EDS): This system removes any remaining tritium from matter that will be released beyond the fuel cycle.
- Water Detritiation Systems (WDS): This block removes tritium from various water and gas sources.
- Coolant Purification System (CPS): This system removes the migrated tritium from the breeder coolant system and sends it to the outer fuel cycle. The technology used for this system will depend upon the breeder blanket technology chosen.
- Isotope Separation System (ISS): Numerous outer loop fuel cycle systems will create mixed Q_2 streams; the ISS system block will create purified isotope outlet streams; some of these will be through stack release.

The torus, individual torus injection systems, and the tritium conditioning system are not included in this analysis. The torus bypass is included in the pumping group for PIE consideration only. The bypass is required because the DEMO plant will operate in two modes: generation mode and dwell mode. Dwell mode occurs when fusion is paused for a short period but auxiliary systems must keep running to avoid shutdown procedures. Such systems include the pumping systems and the tritium fuel cycle.

2.1. Direct internal recycle loop and inner fuel cycle loop

This section comprises the DIRL and INTL shown in Fig. 1. Tritium and deuterium are the predominate hydrogen isotopes in these system blocks. The following list shows the technologies considered for each system block.

- The GDCM system block will comprise a series of pipes, small holding vessels, and connecting valves.
- The torus pumping system block will contain different types of pumps. It is expected that initial pumping will occur using metal foil pumps, backed by vapour diffusion pumps, and mercury ring pumps. The torus bypass line, likely comprising valves and pipework, is also included in this system block.
- The EPS block is expected to use palladium (Pd) membranes to separate plasma exhaust gases (PEGs) from Q_2. Pd membrane technology has been used in an industrial context, so basic estimates of operating conditions can be approximated.
- The technology to be used for the IRPR system block is Membrane-Coupled Temperature Swing Absorption (MC-TSA) (based upon the thermal cycling adsorption process (TCAP)), which uses temperature cycling to concentrate heavier isotopes on one side of a dual plug flow device system (with valve in between) and lighter ones in the latter [2,3]. MC-TSA works above ambient temperature and uses operating pressures fluctuating above and below atmospheric pressure. MC-TSA (as TCAP) devices have limited scalability (capacity increases through increased number of units) and operate in a semi-batch mode; as such, if this technology is chosen for the IRPR system block, then a method of buffering from continuous operation in the EP system is required.

2.2. Outer tritium plant loop

The outer tritium plant loop (OUTL) comprises the fuel storage system blocks, the EDS, WDS, Coolant Purification System (CPS), Isotope Separation System (ISS), and ISS Feed vessel. The tritium conditioning system is also part of this fuel cycle but not considered as part of the tritium plant in this analysis. The functional breakdown structure will require updating as the system blocks and connections become more definite. The technologies being considered for the outer fuel cycle system blocks are as follows:

- Fuel storage system blocks will comprise of either gaseous storage vessels for short-term storage or solid storage technology for longer term storage. The accident scenarios assume that hydrogen isotopes will bind to the medium at room temperatures and will be released when the medium is heated.
- The exhaust detritiation system (EDS) has been considered in a recent report [1]; a normal EDS and a safety EDS, the latter of which will be used for process upsets and accident conditions, are at the pre-conceptual design stage. The functional breakdown structure will include the process functions for the safety EDS in this system block.
- The water detritiation system (WDS) removes tritium from tritiated water; the tritium is sent back into the inner fuel cycle, whilst the waste components from the WDS are exhausted to the stack via EDS. This system will use a filtration system followed by an electrolyser and palladium (Pd) permeator membrane. The electrolyser will split the water into hydrogen and oxygen, whilst the Pd permeator will separate the two gases. The outputs of the system will be a tritiated Q_2 stream and detritiated hydrogen and oxygen.
- The isotope separation system (ISS) is a system block being designed to take a variety of Q_2 streams and create separate concentrated streams of tritium, deuterium, and protium. The technology chosen is cryogenic distillation. (CD). The ISS will require an input storage tank to buffer the various input streams and create a homogeneous input to the system.
- The CPS removes tritium which has migrated into the breeder blanket cooling system; this tritium is then sent to the ISS for further processing and movement into the inner fuel cycle. The technology chosen for the CPS will depend upon the breeder blanket (and associated) cooling technology chosen [1].

3. Functional breakdown structure and postulated initiating events

3.1. Plant functional breakdown structure

The development of the accident scenarios for consideration started with a functional breakdown structure (FBS) of the tritium plant. The goal of the FBS is to decouple the purpose of a system block from the type of technology that is being considered. The FBS starts with separating the individual sections of the tritium plant, and then considers the purpose of each section. At this pre-conceptual design stage, the FBS is used to ensure that the chosen technologies and designs meet all functions. From a safety perspective, these functions are used to identify methods in which each section of the plant may malfunction.

The tritium plant FBS starts with the blocks in the DIRL and INTL (combined) and OUTL. An example FBS, for the fuel storage system block, is shown in Table 1, whilst the entire FBS is shown in Appendix A. It should be noted that this FBS will need re-evaluation as the tritium fuel cycle develops and/or functions of the individual blocks change; this FBS acts as a starting point for accident analysis but should not be considered to be unchangeable.

Table 1 shows how only the purposes of the system block are discussed rather than any suppositions about how those purposes will be met. By focussing on the purposes, the methods of failure can be identified separately from the technology. A functional failure mode and effects analysis (FFMEA) links the purposes with the technology to create Postulated Initiating Events (PIEs).

3.2. Postulated initiating events

The FBS for the DEMO fuel cycle was used as a basis for the FFMEA, along with the safety breakdown structure outlined by Pinna et al. [4]. For each system block, the part of the FBS applicable to that group was isolated and the relevant parts of a safety breakdown structure were considered. Table 2 gives an example of how a PIE is created for function P2-5-1-1 (release of long-term storage isotopes for fuelling).

Table 2 shows that two potential failure modes were considered for function P2-5-1-1, one of which could create a PIE for an accident scenario; another results in a safe state. For each function in the FBS, each possible failure mode for each technology was considered; if a PIE was possible, then it was created. However, if two modes, causes, and effects were the same across different functions in the FBS, then the PIE was not replicated. Instead, a single initiating event (IE) which combines the similar PIEs was created by considering the similarities of the individual PIEs in question..

Some PIEs for the fuel cycle were already identified by Pinna et al. [4] as part of a wider DEMO plant accident scenario investigation; these have been added to the PIEs identified in this work for the subsequent accident scenario analysis.

3.2.1. Existing PIEs

Pinna et al. [4] identified a total of thirty three PIEs for DEMO; seven of these were considered relevant to the tritium plant:

- AOP1: Loss of off-site power for long duration ($1\ h < t < 32$ h).
- AOP2: Loss of off-site power for short duration ($t < 1$ h).
- TGG1: Break of tritium gas process line within secondary enclosure (*e.g.* glovebox (GB)): cryogenic fluid and fuel gas released into pellet injector guard vacuum volume.
- TGO1: Out-vessel release of tritium gas due to guillotine rupture in the process line of the Isotopic Separation System (tritium release inside the building).
- TGO3: Release of tritiated effluents to environment due to maloperation in the tritium process systems.
- THO1: Guillotine break of the hydrogen gas pipe at the outlet of the electrolyser. Direct tritium release into the WDS room.
- TWO1: Rupture of a high activity level holding tank in WDS.

The shorthand descriptors are taken from Pinna et al.

Table 1
Functional breakdown structure for fuel (or product) storage system block.

Number	Function description
P2–5	To store fuel gas
P2–5–1	To provide long-term storage of hydrogen isotopes
P2–5–1–1	To release long-term storage isotopes for fuelling
P2–5–1–1–1	To provide necessary state parameters (T,P)
P2–5–1–1–2	To maintain necessary state parameters (T,P)
P2–5–1–2	To contain long-term isotopes and storage medium indefinitely
P2–5–2	To provide short-term storage of hydrogen isotopes
P2–5–2–1	To release short-term isotopes for fuelling
P2–5–2–1–1	To provide necessary state parameters (T,P)
P2–5–2–2	To contain short-term isotopes and storage medium for a fixed time.

Table 2
Section of FFMEA analysis for part of the product storage system block.

Technology	Failure mode	Effects	Cause	PIE(s)
Heater and solid storage	Heating element fails off	Isotopes are not released	Loss of power, electrical fault, burnt filament	None – storage method is fail-safe
Solid storage	Storage material is lost	Isotopes cannot be released as desired	Break in containment, chemical change in material	PS-1 - Breach of storage medium

3.2.2. Tritium plant specific PIEs

Following on from the FFMEA analysis, fifty new PIEs and IEs were created for consideration for the tritium plant by looking at the FFMEA for each system block after looking at the FBS. In many cases, PIEs from different system blocks are similar (both in cause of PIE and associated effect); as such, these PIEs are grouped together into a single scenario for accident analysis. Appendix B shows the total list of PIEs created from the analysis shown in Table 2. Appendix C shows the details of how the PIEs were analysed and linked to create the scenarios analysed in this paper.

4. Accident scenario outlines

The tritium plant specific PIEs and the relevant DEMO PIEs were combined to create a shortlist of nine potential accident scenarios; a tenth design extension condition scenario was included to analyse the worst possible occurrence that could happen to the plant regardless of likelihood or plausibility. Table 3 shows the ten scenarios as well as the PIEs on which they are based.

The UK legal dose guidelines from IRR17 have been used as a baseline against which the severity of an accident scenario can be compared. The UK legal dose limit is 50mSv/yr if individual dose incidents are concerned [5]; this dose limit is used as an illustrative target only to understand the quantities to which an individual could legally be exposed.

4.1. Scenario LOOP-1: power loss to fuel cycle

This accident scenario considers the possibility of either a short-term or long-term loss of power to the fuel cycle. For a short-term loss of power, identified as being less than one hour, uninterruptible power supplies (UPSs) need to be available. Disregarding planned outages, all loss of power scenarios will start with a short-term loss of power. There are two initial design choices in relation to the fuel cycle: the system blocks in the fuel cycle can either be put into dwell mode, or they can be

Table 3
Accident scenarios identified from PIEs.

Scenario	Description	Associated PIEs
LOOP-1	Long-term loss of offsite (or total) power	AOP-1, AOP-2
INTL-1	Inner fuel cycle: break or leak of processing line or system block	GDCM-2, TP-2, PS-1, EP-3, IRPR-1, IRPR-2, TGG-1
INTL-2	Inner fuel cycle: release of tritiated solid storage material	PS-3
OUTL-1	Outer fuel cycle: break or leak of processing line or system block	ISS-2, ISS-3, EDS-1, WDS-3, WDS-6, CPS-4, TGO-1, THO-1
OUTL-2	Release of stored tritiated water	WDS-4, WDS-5, TWO-1
OUTL-3	EDS failure	EDS-2, EDS-3, EDS-4, TGO-3
PEG-1	Plasma enhancement gas release to inner fuel cycle	EP-1
CRYO-1	Loss of cryogens	IRPR-3, ISS-4
ACC-1	Tritium management and control failure	GDCM-3, TP-4, PS-5, EP-5, IRPR-7, ISS-7, EDS-5, CPS-6, WDS-7
CE-1	Design extension condition scenario of worst-case possible accident	N/A

set to move towards a shutdown state. Dwell mode is a fixed and temporary pause in fusion operations during which auxiliary systems continue working, whilst shutdown occurs when these systems are shut down. An important consideration in the tritium plant design will be how the system transitions to longer-term power outage.

A key consideration for power loss is the secure storage of the tritium inventory in the fuel cycle. Cryogens cannot last indefinitely; system blocks which rely on them for normal operation must have a method of containment for the tritium when it eventually heats to ambient temperature. The method of containment must not require power to contain the inventory safely, which indicates that spare storage beds, similar to those used for long-term storage, will need to be available for gaseous Q_2 held in the fuel cycle.

One solution is to use emergency storage beds; these would be behind bursting discs around or near each system block.

The number of emergency storage beds per system block must be refined as the detailed design of the technologies and their connections interact. Some considerations to keep in mind include:

- For certain fuel system blocks, unexpected storage of Q_2 may include PEGs or contaminants which can have an irreversible effect on processing or hydrogen storage media.
- The outer fuel cycle loop has more options for possible storage as it can run quasi-independently of the inner fuel cycle loops. The EDS will not require backup storage, and nor will the WDS. The use of WDS in process upset scenarios will need to be considered at the detailed design stage.
- Unlike a loss of cooling due to a break or leak in the cooling system, power loss will result in cryogens heating slowly; this time will allow the fuel cycle system blocks to be shut down to a safe condition.

This scenario highlights a consideration required for the detailed design of the plant; the hazard from the scenario – release of radioactive material - can be mediated through backup storage facilities.

4.2. *Scenario INTL-1: gas release from inner tritium plant loops*

This scenario considers the possibility of direct release of gas from the inner fuel cycle; such a scenario requires both a break of the primary loop containment and the secondary containment. The most at-risk group will be the tritium plant workers; different orders of magnitude are considered for this scenario, but detailed plume effects of gas releases are not considered at this stage.

Table 4 shows that the maximum inventory in the inner fuel cycle is in the IRPR system block. To give an estimation of the radiation, two potential rooms into which a release could occur are considered: one of 100 m^3 and one of 10,000 m^3.

Table 4
System block tritium inventories, from [6].

System	Mass T_2 (g)
Matter Injection	421
Torus Vacuum	78
Exhaust Purification (EP)	6.1
IR/PR	556
Exhaust Detritiation	11
Water Detritiation (WCLL)	35
Coolant Purification (HCPB)	2.8
Isotope Separation System (ISS) (WCLL scenario)	613
Isotope Separation System (ISS) (HCPB Scenario)	592
Tritium Conditioning (HCPB)	< 1
Tritium Removal (WCLL)	67

It cannot be assumed that all of the tritium will be bound as T_2; IRPR will have significant amounts of DT and HT. For a conservative estimate of the calculation, it will be assumed that the tritium will be dispersed as QT, thereby making the molar amount dispersed 92.7 mols QT. Assuming full mixing of dispersed gas within a room, Table 5 shows the concentration of tritium in each size room as well as the time in which an average worker would need to spend to reach the maximum legal dose rate of 50 mSv.

The time to reach a dose limit in a small room, assuming rapid mixing, is less than a minute. Considering dose exposure in isolation, Table 5 indicates that storing a system block with a large tritium holdup in a small room can be dangerous. However, other factors relating to frequency of room occupation and co-hazards will need to be considered as well. Such other hazards will include explosive hazards from a localized release of hydrogen.

The analysis shows that a robust ventilation system is essential to minimise unsafe conditions in the result of a severe break or leak in the IRPR system block. Beyond the usual secondary containments for all system blocks and alarms, a robust EDS is critical to minimizing the hazard from this scenario.

4.3. *Scenario INTL-2: tritium release from a solid storage bed*

Scenario INTL-2 investigates the possibility of a release of tritium on a solid storage bed of depleted uranium (DU). These beds will be designed to keep tritium bound to the solid material at room temperature. In the event of a break or leak resulting in the storage medium being released into the tritium plant, the associated bound tritium will also be released. This scenario considers the amount of tritium that could be stored on a single storage bed; multiple bed failures will not be considered in this scenario, as best practice will be to keep each bed in a separate containment. Taking the Active Gas Handling System (AGHS) at JET as a representative example, a single storage bed contains approximately 1 kg of depleted uranium (DU) and can store up to 27 mols of hydrogen, or an equivalent of 81 g tritium [7].

From a radiation hazard perspective, the amount of hydrogen released can be estimated:

$$\ln(P) = \frac{\Delta H}{RT} + \frac{\Delta S}{R}$$

Heung gives the enthalpy and entropy changes for DU loaded with tritium [8]; using these numbers and assuming an average room temperature of 298 K and a total of 13.5 mols of tritium, (T_2) the total partial pressure of gas released into the room will be approximately 4 Pa. The

Table 5
INTL-1 release times.

Room size	QT concentration (Bq/m^3)	Time to dose limit
100 m^3	1.98×10^{15}	34 s
10,000 m^3	1.98×10^{16}	5.6 min

value logically makes sense, as DU must be heated over 300 °C to release gaseous hydrogen. This value represents a negligible amount of tritium released for potential inhalation.

However, if it is assumed that, due to its high pyrophoricity, the DU ignites upon contact with air, then the amount of tritium released increases. Le Guyadec et al. [9] showed that uranium hydride can react spontaneously with air, resulting in powder temperatures up to 850 K. At 850 K, the partial pressure of tritium is 21.3 atm, indicating a rapid but localised release of tritium into the atmosphere. The actual amount of bound hydrogen isotopes that could be released will depend upon the combustion time and the surface area available for combustion; not all hydrogen on the bed will be released initially. Based upon this analysis, it would be suggested that any uranium hydrides are kept in areas where the environment of a potential spill is without oxygen.

In the event of a spillage of DU powder to an inhabited room, it is possible that the powder itself can spread through contact with people, liquid, or chemicals. DU beds are frequently referred to as having DU 'powder,' but the particle size range of the powder is not well documented. Sandia give an estimated average particle diameter of 0.5 μm and unit surface area of ~1m^2/g [10]. This diameter is of the same order of magnitude of the average grain of talc particle, such as may be found in medical talcum powder [11]. Fine grained particles easily stick to surfaces, especially in the presence of humidity, due to capillary forces between the particles.

Using talcum powder as an analogy, it is highly likely that DU powder would stick to and be transferred between surfaces, including human skin. Skin pore sizes vary depending upon body and skin types, but they range between 5 and 500 μm in diameter. Therefore, tritiated DU will stick in skin pores and be transferred between individuals and other surfaces easily. Estimates of how quickly the contamination could spread, and how it would affect individuals, is strongly dependent upon operational factors including room occupancy and staff training. Trained health physics technicians should be consulted in best practices for handling contaminated spilled items. As the design and training for the tritium plant continues, procedures for dealing with mobile contamination sources must be developed and tested. These procedures must also consider how to dispose of such a material, as it will not be suitable for further hydrogen storage once being in contact with oxygen.

4.4. Scenario OUTL-1: gas release from outer tritium plant loops

Scenario OUTL-1 considers the possible release of a tritiated stream of gas from the outer fuel cycle. Although the inner fuel cycle will have higher concentrations of tritium, the outer fuel cycle is likely to have higher flowrates and more potential for non-radiation hazards including asphyxiation and explosion.

Table 4 indicates that the highest tritium inventory in the OUTL is within the ISS. However, this scenario focuses on the WDS for two reasons. Firstly, a rupture in the outlet stream of the WDS electrolyser would result in a stream with higher tritium concentrations than other areas of the outer fuel cycle. Secondly, radiation is not the only hazard which needs to be considered in a break or leak scenario in the OUTL. Whilst the scenario has been identified by investigating radiation PIEs, by investigating the WDS, a holistic view of the potential effects of a break in the outer fuel cycle can be found.

When the design of the electrolyser system is more detailed, a safety analysis would need to be undertaken; such a safety analysis could be similar to those undertaken in related industries, such as for fuel cells or other industries which use electrolysers.

4.5. Scenario OUTL-2: release of tritiated water

Tritiated water will be held on site prior to processing in the WDS; Scenario OUTL-2 considers a potential release of this water. In order to consider the consequences of this event, the estimated size and activity of a holding tank is needed. At JET the expected initial concentration of stored water at the JET WDS is several GBq/litre, with a maximum of 185 GBq/litre. At ITER, the WDS initial water storage facility comprises two 90m^3 tanks [1].

In an accident scenario, a worker could inhale the water vapour, accidentally drink the water, or have it in contact with his or her skin to receive a radioactive dose. Some indicative quantitative assumptions are made for this scenario to evaluate its potential severity.

For ingestion, two possibilities are considered: one in which the water concentration is 10 GBq/litre and another in which it is 100 GBq/litre. For inhalation, a conservative assumption is taken in which a worker is in a 100% humidity room at 25 °C with all of the vapour being HTO. Estimates for inhalation and ingestion are based upon average adult size and breathing rate [12]. The average adult breathing rate varies considerably between 10 and 60 L/min based upon size and exertion; an order of magnitude estimate will assume a breathing rate of 25 L/min. Table 6 shows the amount of volume and time (for ingestion and inhalation, respectively) available until a maximum dose limit is reached.

Doses from skin contact also need to be considered; estimates are done using the little experimental evidence available on doses due to skin contact with liquid HTO (vapourised tritium is slightly better understood). The Canadian Nuclear Organisation gives an overview of some experimental work done on tritium uptake due to skin contact [13]; adsorption rates of HTO from measured experiments ranged between 0.018 and 0.065 mg/cm^2/min. However, accurate quantitative estimates are difficult due to mitigating factors. Instead, based upon [14], a general estimate of the skin dose rate is taken to behalf the inhalation dose. That dose rate is:

- 62.3 μSv/min for an initial concentration of 10 GBq/litre.
- 623 μSv/min for an initial concentration of 100 GBq/litre.

This information, combined with that shown in Table 6, gives an indication of the effects of each dose pathway in isolation. In the event of an accident, a worker will likely have some combination of all three dose pathways. Should a spill occur with a water concentration between 10 and 100 GBq/m^3, an individual would need to consume a small but noticeable amount of water (through inhalation, ingestion, and skin contact) before reaching a limit of 50 mSv. However, the risk to workers can and should be mitigated by the following measures:

- Minimising the amount of pre-concentrated tritiated water for storage (ahead of WDS processing).
- Locate water holding tanks below ground level, such as in a dedicated basement so that any spilled water is contained within that area. The tanks should be bunded to avoid any accidental contamination or possible contact with human skin.
- The bund should have a water level alarm to warn of any tank leaks.
- The basement should also be designed to have a slightly angled floor which directs water spilled out of the bund to a sump. A sump pump will allow the water to be recovered with minimal operator intervention.
- Radiation and oxygen sensors should be located above the tanks (but below the next floor level) to warn of leaks.
- The holding tanks should have a lid on them that is either flexible or can be vented.

Table 6
Values for ingestion and inhalation to reach 50mSv dose limit.

Required ingestion and inhalation	Initial water activity	
	10 GBq/l	100 GBq/l
Ingestion (mL)	277.78	27.78
Inhalation (hr)	10.70	1.07

4.6. Scenario OUTL-3: loss of EDS function

This scenario considers the possibility of either both the normal and safety EDS systems not working, or of a break or leak in one EDS system. This scenario does not consider the likelihood of such an event, but rather its potential consequences. Such an event could occur by the EDSs failing to capture any released tritium, but continuing to pump the fuel system, or by the blowers on the EDSs failing, stopping, or slowing ventilation. These options will be investigated by considering the consequences of loss of detritiation followed by loss of ventilation.

4.6.1. No EDS detritiation

The assumed detritiation factor of the DEMO EDSs is 1000 [1]. To consider the consequences of a full loss of detritiation, let it be assumed that the normal amount of activity released from the fuel cycle is the regulatory allowable limit; as shown in Table 7, this is 3666 TBq/yr, which equates roughly to 418 GBq/hr [1]. There will be variations in the amount released based upon operating conditions, but these cannot be quantified at this pre-conceptual design stage. If EDS releases a constant stream of 418 GBq/hr when a detritiation factor of 1000 is applied, then it would release 418 TBq/hr without detritiation.

The DEMO plant will not run indefinitely without detritiation; the tritium management and control regulations require that stack release points are monitored. Therefore, the amount released can be estimated by considering the amount of time taken to stop or decrease flow into the EDS. Investigation into tritium management and control technologies are ongoing, but tritium stack monitoring systems are well-established. At JET, the EDS is passively monitored and feeds a signal into a monitoring system. This scenario will assume that manual intervention is required to stop the plant or that an automatic intervention would be based upon a fixed time.

Table 8 shows releases of HT and HTO based upon different intervention times.

A release of between one and ten grams of tritiated material would breach regulatory limits but, given atmospheric dispersion and water dilution factors, be unlikely to cause any health problems to the local inhabitants of the power plant. For reference, the amount of radiation released from Chernobyl is estimated to be approximately 1.1×10^7 TBq, or over three orders of magnitude more than the worst possible case scenario [15]. The damage from such a scenario would be reputational and regulatory rather than pose significant risk or harm to health.

4.6.2. No EDS ventilation

EDS may fail by having ventilation stop due to a blower fault or similar. The two input systems to EDS are the EPS and the auxiliary vacuum systems. If the EDS were to stop pulling air from these systems, the following would occur:

- The EP system would have an outlet pressure rise. This pressure rise would minimise the efficiency of the Pd permeator. If an automatic system did not shut off the inner fuel cycle, subsequent pressure rises would be seen in the torus pumping subsystem, causing the pumps to trip and the system either to stop or have a break or leak. The latter is considered in Scenario INTL-1.
- Room and glovebox ventilation would cease; negative pressures in containments could not be sustained. Any gases naturally leaking from tritium processes (such as gloveboxes, waste characterisation, etc. would not be removed from working areas.
- If the tritium plant is normally held at negative pressure, then the pressure would rise to atmospheric.

Table 7
Expected maximum allowable release limits from DEMO [1].

Release source term	Demo release design objective (g/year)	Demo release design objective (TBq/year)
Tritium as HT	9	3333
Tritium as HTO	0.9	333
Total	9.9	3666

Table 8
Potential tritium releases based upon EDS detritiation failure.

	Time 1 min	1 h	8 h	Unit
HT	6.34	380.45	3043.59	TBq
	0.02	1.03	8.22	g
HTO	0.63	38.04	304.36	TBq
	0.00	0.10	0.82	g

The scenario of a break or leak in the inner fuel cycle due to a pressure increase is considered in Scenario INTL-1. The possibility of a loss of negative pressure and no room ventilation needs to be considered in this section. EDS will have the auxiliary vacuum system feed into it; this system will include, among other things [1]:

- Glove boxes and hot cell atmospheres.
- Heating, venting, and air-conditioning systems.
- Service vacuum systems.
- Safety systems.

Under normal operations, gloveboxes, buildings, and purge gas streams will have minimal tritium concentrations; tritium will enter the streams through outgassing of components. Under normal operating conditions, lack of EDS ventilation within the secondary containments will not cause a risk to people in the area.

The purpose of EDS during normal operating conditions is to stop a build-up of potentially hazards items in the local atmosphere; it is critical for ensuring that the plant reaches As Low As Reasonably Practicable (ALARP) standards. Furthermore, EDS is vital for process upset conditions, where hazardous conditions have a high impact on health. If EDS did not function, ambient tritium levels would increase and the plant would not operate under ALARP standards. Beyond immediate safety risks, this scenario would contravene regulatory requirements.

Therefore, quantitative analysis of the importance of the EDS system must be undertaken through a risk analysis process such as fault tree analysis. The factor of safety given to each EDS input system can only be calculated when information such as room sizes and potentially hazardous concentrations are known. This safety factor can be added into fault tree analysis scenarios to understand where it is most critical. Until this safety factor can be defined for these secondary containments, it is not possible to do a quantifiable analysis for this sub-scenario.

4.7. Scenario PEG-1: PEG contamination

This scenario considers the possibility that PEGs are not fully removed by the EP system block, as indicated in PIE EP-1, resulting in non-hydrogen elements contaminating the rest of the fuel system. This scenario would arise if there were a break or leak in the EP Pd membrane. Fig. 2 shows a qualitative representative of flows of tritium following a leak.

Green represents either a flow that is expected or an unexpected flow that will not have long-term effects on the destination fuel cycle system block. Yellow represents a flow which has the potential to cause significant long-term damage to a system block based upon the technology chosen. Red represents definite and significant long-term damage to system blocks as a result of an unintended flow.

Fig. 2 shows that the most significant and immediate effect of a Pd membrane break or similar in the EP system would be on the ISS system block. The technologies being considered for this system block use low temperatures to separate hydrogen isotopes. Any PEG which could be

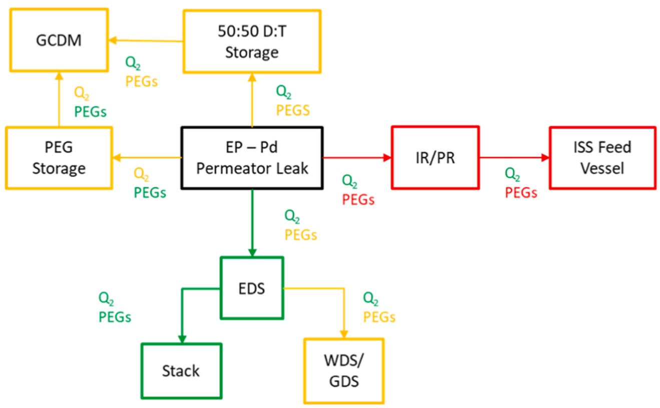

Fig. 2. Traffic light representation of flows following a Pd membrane break.

used would have a higher freezing temperature than hydrogen isotopes. As a result, the units would quickly accumulate ice, leading to a loss of functionality and increased thermomechanical stresses on the system. At best, the system block would require replacement and/or significant flushing to be useable again. At worst, the system blocks could rupture, resulting in a break or leak scenario.

Some design suggestions can be given based upon the considerations of the scenario:

- Sensors for PEG contamination in unwanted streams should be linked to interlock systems preventing flow to PEG-sensitive system blocks.
  - An alternative flow path may need to be provided.
- If the likelihood of this scenario is high, then a holding tank with PEG sensors prior to the IRPR system block could be inserted to give a time delay in the event of PEG contamination to minimise its effect on the system and the potential for the PEGs to move into the ISS, which could cause PEG freezing within the ISS cryogenic temperatures.

A holding tank would result in a tritium inventory increase. The associated benefits and drawbacks will need to be considered through quantitative risk analysis in the future.

4.8. Scenario CRYO-1: loss of cryogens

The quantities and types of cryogens are not yet quantified; this scenario will give a qualitative analysis about the potential effects of loss of cryogens in the fuel cycle systems. The possibility of having a dedicated cryogenic plant at DEMO is considered; if many cryogens are used, a separate plant will minimise risks and result in cost savings.

Cryogen loss covers the following possibilities:

- No power to the cryogenic plant, resulting in system blocks losing cooling but no cryogenic release.
- Break or leak at the cryogenic plant, resulting in all system blocks losing cooling and cryogens being released remotely from the system blocks.
- Break or leak at a system block, resulting in system block heating up and cryogens being released to the local area.

If the failure were not due to a break or leak, this scenario would become similar to the loss of power scenario; the systems blocks which use cryogens would heat up slowly and shutdown measures would need to be initiated as discussed in that scenario. If the loss of cryogens were due to a break or leak in the main plant, then the scenario discussed in the loss of power scenario would occur, but there also would be an immediate hazard within the cryogen plant.

Asphyxiation and cold burns would be two immediate concerns in the event of a break or leak in the cryogen plant. Any released cryogens would expand rapidly, lowering temperatures and pushing out ambient oxygen. Individuals in the area would be at immediate asphyxiation risk due to the likely flows, although quantitative analysis will be required once quantities are known.

This cryogen release scenario is not unique to the DEMO plant or the fusion industry. Gas purification plants have relied upon large scale cryogen use for decades; the best practices and lessons learned from this industry should be used as a guide for any future DEMO cryogen plant.

4.9. Scenario ACC-1: tritium management and control failure

Every system block had a PIE associated with a loss of tritium management and control; these have been grouped into this general tritium management and control failure scenario. The challenges and goals of this scenario include:

- Estimating the uncertainty around process flows as a result of the tritium management and control failure.
- Estimating potential harm to health in the event of tritium management and control failure.
- Estimating if a reportable incident of loss of control of dangerous materials has occurred, and if so, what remedial actions to take.
- Understanding the effect of concentration and flow uncertainty on the performance of the DEMO power plant as a whole, including fusion performance.

Legal requirements from the area in which DEMO is built and recommended best practices from international bodies, such as the International Atomic Energy Agency (IAEA) or the Nuclear Energy Agency (NEA), will also need to be used as guides for quantifying levels of acceptability for potential tritium management and control losses. At this stage of pre-conceptual development, the following qualitative recommendations can be given to minimise the overall risk (through likelihood and hazard minimisation) from a loss of tritium management and control:

- Sensor redundancy must form a fundamental part of the tritium management and control system design. As with many other parts of the tritium plant, backups for critical system components must be included in the design and quantitative fault analysis associated with a more detailed design.
- In alignment with the ALARP principle, the total flow of radioactive material through any one monitored point must be minimised. If the tritium management and control at that point fails, then the total possible amount of unaccounted for tritium can be bounded.
  - The application of this principle to the entire fuel cycle indicates that accident hazards are decreased by minimising the total amount of tritium stored and used in the plant.

Sensor error and uncertainty, both in terms of absolute amounts and uncertainty curves, must be considered when considering quantitatively a loss of tritium management and control.

4.10. Scenario CE-1: worst possible occurrence

This section considers briefly what would happen should the entire DEMO tritium inventory enter a local water system; it is not based upon the PIEs for the system blocks, but rather potential catastrophe scenario. This scenario is considered the worst case due to the potential high concentration of tritiated water in a small water source, such as a local aquifer, and the different methods of contamination. Contamination can enter through drinking water as well as water used for hygiene purposes; contamination can rest for generations if it is used to water crops and sustain livestock.

Given that this design extension condition scenario analysis is meant to push the bounds of expected analysis, this section considers the maximum amount of tritium which could be held in the fuel cycle. This amount includes the tritium associated with the torus and that being removed from the breeder blanket and coolant purification system (CPS).

Once a maximum total tritium inventory of the DEMO system has been finalized, the development of this design extension condition scenario can be quantified to give an estimate of the worst-case tritium release scenario.

This scenario allows some boundaries and generalisations to be made:

- The total amount of tritium held in the DEMO fuel cycle could contaminate the water supply of a town if it were concentrated but would be quickly diluted if added to large bodies of water. An issue would arise if the inventory were released into a small or medium sized aquifer which was the single source of water to a population. As such, if possible, DEMO should be:
  - Situated away from any **single** water source which would sustain a large population **or**
  - Be situated near a large waterway or body of water which would allow for sufficient dilution of any tritiated water spill to minimise harm to the overall population.
- The amount of tritium that could be released varies by order of magnitude based upon the outer fuel cycle system blocks; these system blocks will have a significant effect on the severity of a future analysis of this design extension condition scenario.
  - The concentration of tritium in the outer fuel cycle has not been considered in this scenario. For example, the HTO from the outer fuel cycle is already diluted with H_2O. Dilute system blocks will lessen the severity of this scenario by giving an overall dilution to the releasable contaminated water.
  - Future analysis will need to consider the concentration of each system block as well as the overall inventory.

This scenario also enforces the suggestion that concentrated active water should not be stored.

5. Discussion

In the previous sections, scenarios highlight risks associated with the DEMO tritium plant. Some areas of risk mitigation can be considered during the pre-conceptual and conceptual design stages. As with all good engineering design, methods for mitigating the risks need to be considered in the following order:

- Inherent safety: removing or minimising the risk by choosing a process which causes no or negligible danger.
- Engineered safety: minimising risk by applying robust safety design principles to a process.
- Administrative safety: decreasing risk by putting procedures in place for operators to follow.
- Protective safety: decreasing harm to operators or the environment by using protective equipment to guard against harm.

5.1. Ergonomic design and human factors in safety

Literature indicates that there is an increased focus on minimising human risk factors; inherent safety design has been developed since the 1960′s, but a 'plateau' in the number of accidents reduced has indicated that most accidents are now caused by human error [16]. Intuitive plant management and design is critical when considering accident scenario analysis. There is a growing field of research into human factors engineering (HFE); procedures and heuristics are being developed by various research groups to assist in ensuring that plant and product design is guided by human factors [17,18].

The references show a host of different methodologies for quantifying and formalising the consideration of human factors and ergonomics. At this point in the DEMO design, it is not feasible to recommend a particular methodology; indeed, Shorrock and Williams [19] advocate involving multiple stakeholders in choosing an HFE methodology. This methodology can also be combined with others; a too-prescriptive formula can be costly and time consuming.

Ergonomic factors in engineering include how the operators physically interact with the plant. In many cases, ergonomic design can seem obvious but is overlooked in the melee of overall plant design. As plant design progresses, consideration of human factors must be included in both safety analysis and in best working practice.

5.2. DIRL and INTL recommendations

Two main hazards within the DIRL and INTL are gas explosions, especially oxygen-hydrogen reactions and the release of hazardous material through leaks or breaks. These considerations are not unique to the DEMO fuel cycle; lessons can be taken from the (existing) nuclear power industry, which has pioneered techniques of engineered safety for high-risk processing systems. The IAEA has worked closely with the nuclear power industry to establish best practice, give guidance, and hold international conferences on nuclear safety [20].

Some engineering design principles which should be adopted include:

- Minimising process line connections through careful plant layout, including ancillary plant equipment. Leaks and breaks occur at structural weak spots.
- Connecting processing equipment through welding (such as orbital welding) and doing radiography on critical welds.
- Optimising pipe sizing.

One unique challenge of the inner fuel cycle is the requirement for long-term storage of tritium and deuterium in the PS system block. Depleted uranium (DU) is both pyrophoric and can combust readily in the presence of oxygen. A fundamental design consideration for this system block must be to ensure that the storage material does not mix with oxygen. Methods of minimising hazards include:

- Ensuring that the storage beds are kept in, as a minimum, double containment.
- Keeping the entire system block in an inert environment, such that if a spill were to occur, the storage material would not combust. As with gas explosions, the benefits and risks of having an inert storage area need to be balanced.
- Continuing research to find a non-pyrophoric storage material. The outlay of cost for research and development would need to be balanced against the likelihood of a potential spill and associated accident effects.

DU beds are effective at storing hydrogen, but one obstacle of using DU is public perception of its associated hazards. Medley et al. investigated the public perceptions of DU and the perceived acceptability of DU use in fusion power [21]. Although perceptions of DU were not found to be positive, information was well received; this indicated that public engagement could prove to be useful in changing perceptions.

Another unique hazard is the gas pumping train used in the torus pumping system block. The direct internal recycling loop will rely on the metal foil pump efficiency; as more information is available on the technology behind a metal foil pump, specific considerations will need to be given to its hazards. The use of mercury pumps will also introduce the unique hazard to the fuel cycle of working with mercury but will also give the opportunity to minimise the tritium inventory within the DIRL.

Pumps will require maintenance, which will require plant workers potentially to come in contact with mercury. Guidance and regulations for working with mercury can be found for different countries; for example, the UK Health and Safety Executive (HSE) gives guidance about working with mercury [22,23]. These documents and regulations will need to be consulted as design and operation details are considered at a detailed stage. Parallels with other industries using such pumps will also need to be investigated.

5.3. OUTL recommendations

The OUTL is a vital part of continued operation, but many parts of it will be able to run independently or semi-independently of the main energy generation part of DEMO. This level of removal poses some unique considerations. For example, the outer fuel cycle will be the only place where tritiated water is held indefinitely.

Scenario OUTL-2 investigates the effects of a potential water spill and remediating actions. Some mitigating design suggestions for minimising both the likelihood and hazard associated with storing tritiated water include:

- Ensure all water is held in a bunded area which can hold the entire volume of potential water released in a spill. This bund should also have a sump with slanted floor and associated pump so that spilled water can be removed to another container without direct operator intervention.
- Allow for controlled venting due to a potential build-up of helium due to tritium decay.
- Ensure the water storage tanks are made from suitable non-corrosive materials. The tanks will also need to be inspected for cracks and have a smooth surface finish. Tritium-based materials attack materials more readily than protium and deuterium-based ones.

Scenario OUTL-3 investigates the potential loss of EDS, resulting in increased radioactivity release from the tritium plant. Some important points bear extra focus:

- Both the normal and safety EDSs require redundancy. A quantitative analysis in terms of likelihood of failure of each part of the system (such as through fault tree analysis) will be needed to develop maintenance schedules and the level of required redundancy.
- Redundancy in tritium management and control sensors at stack release points. Scenario ACC-1 stresses that in the event of a radioactivity management and control failure, it must be assumed that the radioactivity has been released into the environment unless it can be proved otherwise. Accumulated released amounts of radioactivity will be limited by governmental regulations, and the tritium plant is more likely to continue running in the event of a sensor failure if it can be proved that the radioactivity is still bound within the fuel cycle.

The normal and safety EDSs require some special safety considerations that may not fit into one specific scenario. For example, it's indicated that a significant amount of the EDS input comes from environmental surroundings; this increases the size of EDS, thereby increasing inventory. It is suggested that the environmental input to EDS is optimised through consideration of what areas require regular access, minimising the size and air turnover of the areas that do, and implementing a dehumidifying system on incoming air streams rather than outgoing ones. Therefore, overall plant design needs to consider minimising the total amount of hydrogen isotopes that can enter the system, as this will result in lower overall flows and lower energy requirements.

6. Conclusions

A basic FFMEA has been undertaken using the information available on the fuel cycle system blocks to identify a range of PIEs. These PIES have been combined to create potential accident scenarios, which have then been analysed to identify important safety points and design considerations. Table 9 shows a summary of the main conclusions from each analysed scenario.

Table 9
Summary findings from scenario analysis.

Scenario	Key findings and design suggestions
LOOP-1	Define switch time between long-term and short-term loss of power Backup Q_2 storage system required for system blocks which require cryogens Backup storage must consider physical distances and Q_2 quantities
INTL-1	Release from the IRPR system block has more serious consequences than a break from the torus exhaust Gaseous release will result in elevated dose rates, although not fatal ones Q_2 release alone will only cause hotspot explosive hazards Asphyxiation hazards need to be considered from cryogen release (not Q_2 release)
INTL-2	Storage material pyrophoricity is the main hazard Spontaneous combustion of storage material would not immediately release the full Q_2 inventory Storage material must have an inert secondary containment Any released powder would cause contamination issues
OUTL-1	Better definition of flows is required to quantify hazard Current estimates show radiation hazard less than that of INTL-1 Main hazard is explosive hazard at WDS electroylser outlet
OUTL-2	Tritiated water should not be stored after concentration All storage areas must be bunded with level, oxygen, and radiation alarms
OUTL-3	Environmental impact of a loss of EDS does not pose immediate health hazard The safety EDS is critical to the safe running of other fuel system blocks The tritium plant should not run if there is not a working safety EDS
ACC-1	Sensor redundancy must be built into each system block Tritium management and control methods should be checked and balanced throughout the fuel cycle
PEG-1	PEGs sent through isotope separation systems could create irreversible damage.
CRYO-1	Cryogen plant failure creates similar circumstances to the LOOP-1 scenario. Cryogen plan design must draw on parallel industry experience (*i.e.* gas separation)

The DEMO tritium plant presents a unique challenge in terms of plant safety. However, there are numerous industries which have similar systems and risks; these industries need be scrutinised in the future to compare their safety systems to the ones required for DEMO. For example, gas purification industries use cryogenic distillation to produce their products, have similar sorts of hazards as the DEMO fuel system, including loss of cooling and production of explosive gases. Similarly, there are other industries which create gaseous and toxic products that cannot be released into the general atmosphere; their containment methods need to be investigated to see if any are applicable for DEMO. Fuel cells pose similar hazards as those found in the electrolysis system of the WDS.

Accident analysis and safety engineering are iterative and ongoing processes which become more detailed as design progresses. When technologies have definitively been chosen for each fuel system block, this document will need to be updated and revised to both find new PIEs and give more detailed analysis of existing scenarios. When a more detailed design has been agreed upon, Hazard Identification Studies (HAZIDs) and Hazard and Operability Studies (HAZOPs) will become a fundamental part of the design process.

CRediT authorship contribution statement

R. Shaw: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Data curation, Visualization, Writing – review & editing. **B. Butler:** Resources, Writing – review & editing, Project administration, Funding acquisition, Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Functional breakdown structure

Number	Associated system block	Function description
P2	**The DEMO Tritium Plant**	**To Supply Fuel and Provide Radiation Protection**
P2-1	Gas Distribution, Control, and Monitoring (GDCM)	**To supply fuel to fuel injection systems in plasma**
P2-1-1		To supply fuel pellets into the plasma
P2-1-2		To supply gas puffing into the plasma
P2-1-3		To perform tritium management and control on isotopes sent to the plasma
P2-1-4		To mix different gases in defined quantities
P2-1-4-1		To vary the quantities of feed gases
P2-1-4-2		To monitor the quantities of feed gases
P2-1-5		To keep separate the different fuel injection feeds
P2-2	Torus Pumping	**To recover unspent D-T from the tokamak exhaust through exhaust pumping and compress to ambient pressure conditions**
P2-2-1		To pump exhaust from the plasma vessel
P2-2-1-1		To provide initial separation of hydrogen gases from PEGs
P2-2-1-2		To ensure exhaust is pumped to direct internal recycling and exhaust processing
P2-2-2		Maintain high vacuum to the plasma vessel
P2-2–2-1		To provide primary pumping capabilities for high vacuum
P2-2-2-2		To provide backing pumps for the primary pumps
P2-2-3		To supply the tritium plant with steady inputs
P2-2-4		To allow for plasma vessel bypass during dwell periods
P2-2-5		To manage changes in flow amount between dwell and fusion periods
P2-2-6		To manage changes in flow composition between dwell and fusion periods
P2-2-7		To pump down the plasma vessel from non-vacuum pressure
P2-2-7-1		To pump down the plasma vessel in a specified time
P2-3	Exhaust Processing System	**To separate PEGs from hydrogen isotopes in exhaust processing**
P2-3-1		To move PEGs to separate storage systems from hydrogen isotopes
P2-3-2		To move PEGs to separate injection systems from hydrogen isotopes
P2-3-2-1		To store PEGs temporarily prior to induction in the GDCM
P2-3-3		To send a waste stream to the EDS
P2-3-4		To send separated hydrogen isotopes to hydrogen isotope rebalancing systems
P2-3-4-1		To minimise PEGs in the hydrogen isotope streams
P2-3-5		To produce a 50:50 mixed deuterium and tritium stream for the inner fuel cycle
P2-3-5-1		To minimise PEGs in the hydrogen isotope streams
P2-3-6		To perform tritium management and control on the system block
P2-4	Isotope Rebalancing / Protium Removal (IRPR)	**To rebalance hydrogen isotope fractions in streams destined for fuel injection or storage**
P2-4-1		To remove protium from streams destined for fuel injection or storage
P2-4-1-1		To minimise tritium in protium release stream
P2-4-1-2		To send the removed protium to further isotope separate, exhaust detritiation, and/or stack disposal
P2-4-2		To create a defined ratio of tritium to deuterium in fuel streams destined for fuel injection or storage
P2-4-2-1		To minimise the protium held in the tritium and deuterium stream
P2-4-2-2		To send the mixed tritium and deuterium stream to temporary storage prior to GDCM
P2-4-2-3		To send the mixed tritium and deuterium stream to long term storage
P2-4-3		To control the temperature swings within the system block
P2-4-4		To allow for a bypass or recycle stream around the system block
P2-5	Product Storage (PS)	**To store fuel gas**
P2-5-1		To provide long-term storage of hydrogen isotopes
P2–5-1-1		To release long-term storage isotopes for fuelling
P2-5-1-1-1		To provide information for controlled and measured release of these isotopes
P2-5-1-2		To contain long-term isotopes and storage medium indefinitely
P2-5-1-1-2		To maintain information on the stored isotopes indefinitely
P2-5-2		To provide short-term storage of hydrogen isotopes
P2-5-2-1		To release short-term isotopes for fuelling
P2-5-2-1–1		To provide information for controlled and measured release of these isotopes
P2-5-2-2		To contain short-term isotopes and storage medium for a fixed time
P2-5-2-1-2		To maintain information on stored the stored isotopes indefinitely
P2-5-3		To ensure management and control of the stored isotopes
P2-5-4		To receive fuel from external supplies
P2-5-4-1		To receive deuterium from external gas supplies

(*continued on next page*)

(*continued*)

Number	Associated system block	Function description
P2-5-4-2		To receive PEGs from external gas supplies
P2-5-5		To provide short-term storage of PEGs
P2-5-6		To maintain storage medium capabilities
P2-6	Isotope Separation System (ISS)	**To provide further isotope separation from initial processing system blocks.**
P2-6-1		To separate protium from deuterium and tritium
P2-6-1-1		To manage the required state parameters (T,P) in the separation system
P2-6-2		To create deuterium and tritium streams suitable for getter bed storage
P2-6-2-1		To minimise the amount of protium in the deuterium and tritium streams
P2-6-2-2		To create deuterium and tritium streams of the required purity for getter bed storage
P2-6-3		To manage variations in flow into the separation system
P2-6-4		To manage variations in composition into the separation system
P2-6-5		To perform management and control over the fuel system block
P2-7	Tritium Conditioning System (TCS)	**To recover tritium from breeding and multiplier materials**
P2-7-1		To separate tritium from carrier gas
P2-7-1-1		To maximise the amount of tritium removed from the carrier gas
P2-7-2		To minimise carrier gas removed from breeder system
P2-7-3		To return carrier gas to the breeding blanket
P2-7-6		To send any impurities to the exhaust detritiation system
P2-7-6-1		To maximise the amount of impurities removed from the tritium extraction system
P2-7-7		To perform tritium management and control over the system block
P2-8	Coolant Purification System (CPS)	**To maintain the breeder blanket coolant system balance**
P2-8-1		To remove tritium from the coolant system
P2-8-1-1		To send the tritium to a tritium recovery system
P2-8-2		To return the maximum amount of coolant back to the breeder blanket system
P2-8-3		To minimise the coolant sent to the detritiation system
P2-8-4		To remove any other impurities from the coolant system
P2-8-5		To perform tritium management and control on the system block
P2-9	Water Detritiation System (WDS)	**To detritiate water from process systems or secondary containment using a water detritiation system (WDS)**
P2-9-1		To split water into hydrogen isotopes and oxygen
P2-9-1-1		To create a non-radioactive water stream for release, if required
P2-9-2		To recover tritium and send it back into the fuel cycle
P2-9-2-1		To separate tritium from other hydrogen isotopes
P2-9-3		To exhaust non-radioactive hydrogen and oxygen to stack
P2-9-3-1		To ensure the gases do not react
P2-9-4		To store radioactive water indefinitely
P2-9-5		To perform tritium management and control on the system block
P2-10	Exhaust Detritiation System (EDS)	**To ensure gas discharges to the environment are within regulatory limits through an exhaust detritiation system (EDS)**
P2-10-1		To release non-tritiated gas into the environment
P2-10-2		To ensure no radioactive gases are released to the environment, accidentally or otherwise
P2-10-2-1		To allow sufficient time for short-lived radionuclides to decay
P2-10-2-2		To monitor the gas that is released into the environment
P2-10-2-3		To minimise the amount of tritium released to the environment
P2-10-3		To recover tritium and send it back into the fuel cycle
P2-10-4		To perform tritium management and control on the system block
P2-10-5		To provide room ventilation and detritiation for working areas of the tritium plant
P2-10-5-1		To provide extra ventilation in the event of an accident or unusual operating condition

Appendix B. Full list of tritium plant PIEs

PIE	Description	Related PIEs	Further analysis	Associated scenarios
GDCM-1	Valve Failure in GDCM System	–	No	–
GDCM-2	Break or Leak in Supply Line	TP-2, PS-1, EP-3, IRPR-1, IRPR-2	Yes	INTL-1: Inner Fuel Cycle Release
GDCM-3	Tritium Management and Control Failure	TP-4, PS-6, EP-5, IRPR-7, ISS-7, EDS-5, WDS-7, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
TP-1	Pump Failure	–	No	–
TP-2	Break in Pumping Line	GDCM-2, PS-1, EP-3, IRPR-1, IRPR-2	Yes	INTL-1: Inner Fuel Cycle Release
TP-3	Mercury Ring Pump Failure	–	No	–
TP-4	Tritium Management and Control Failure	GDCM-3, PS-6, EP-5, IRPR-7, ISS-7, EDS-5, WDS-7, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
PS-1	Break or Leak in Supply Line	GDCM-2, TP-2, EP-3, IRPR-1, IRPR-2	Yes	INTL-1: Inner Fuel Cycle Release
PS-2	Short-Term Lack of Storage Capability	–	No	–
PS-3	Breach of Storage Medium	–	Yes	INTL-2: Release of Solid Storage Material
PS-4	Loss of Non-Tritiated Material	EP-4	No	–
PS-5	Storage Material is Lost or Poisoned	–	No	–
PS-6	Tritium Management and Control Failure	GDCM-3, TP-4, PS-6, EP-5, IRPR-7, ISS-7, EDS-5, WDS-7, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
EP-1	Loss of Separation Capability	–	Yes	PEG-1: PEG Contamination
EP-2	Q_2 isotopes sent to PEG storage or EDS	ISS-6	No	–
EP-3	Break or Leak in Pd Membrane Supply Line	GDCM-2, TP-2, PS-1, IRPR-1, IRPR-2	Yes	INTL-1: Inner Fuel Cycle Release

(continued on next page)

(*continued*)

PIE	Description	Related PIEs	Further analysis	Associated scenarios
EP-4	Release of PEGs due to break or leak in storage area	PS-4	No	–
EP-5	Tritium Management and Control Failure	GDCM-3, TP-4, PS-6, EP-5, IRPR-7, ISS-7, EDS-5, WDS-7, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
IRPR-1	Break or Leak in System Block	GDCM-2, TP-2, PS-1, EP-3, IRPR-2	Yes	INTL-1: Inner Fuel Cycle Release
IRPR-2	MC-TSA Heating Element Failure	IRPR-1, GDCM-2, TP-2, PS-1, EP-3	Yes	INTL-1: Inner Fuel Cycle Release
IRPR-3	Loss of PSA Differential Pressure	ISS-1	No	–
IRPR-5	Solid Formation in PSA or CD	–	No	-
IRPR-6	Loss of Modular TCAP Switch-Over	–	No	-
IRPR-7	Tritium Management and Control Failure	GDCM-3, TP-4, PS-6, EP-5, ISS-7, EDS-5, WDS-7, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
ISS-1	PSA Loss of Differential Pressure	IRPR-4	No	–
ISS-2	TCAP Heating Element Failure	IRPR-2, ISS-3, ISS-5, EDS-1, WDS-3, WDS-6, CPS-4	Yes	OUTL-1: Outer Fuel Cycle Release
ISS-3	Excessive Gas Pressure	IRPR-2, ISS-2, ISS-5, EDS-1, WDS-3, WDS-6, CPS-4	Yes	OUTL-1: Outer Fuel Cycle Release
ISS-4	Loss of Cryogenic Cooling		Yes	CRYO-1: Loss of Cryogens
ISS-5	Break or Leak in System Block	IRPR-2, ISS-2, ISS-3, EDS-1, WDS-3, WDS-6, CPS-4	Yes	OUTL-1: Outer Fuel Cycle Release
ISS-6	Unexpected Flood or Variation of Q_2 Isotopologues	EP-2	No	–
ISS-7	Tritium Management and Control Failure	GDCM-3, TP-4, PS-6, EP-5, IRPR-7, EDS-5, WDS-7, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
EDS-1	Loss of EDS Input	IRPR-2, ISS-2, ISS-3, ISS-5, WDS-3, WDS-6, CPS-4	Yes	OUTL-1: Outer Fuel Cycle Release
EDS-2	Loss of EDS Detritiation	EDS-3, EDS-2	Yes	OUTL-3:
EDS-3	Loss of Safety EDS	EDS-2, EDS-3	Yes	OUTL-3:
EDS-4	Increased Environmental Release	EDS-2, EDS-3	Yes	OUTL-3:
EDS-5	Tritium Management and Control Failure	GDCM-3, TP-4, PS-6, EP-5, IRPR-7, ISS-7 WDS-7, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
WDS-1	Electrolyser Failure	–	No	–
WDS-2	LPCE Column Failure	–	No	–
WDS-3	Vapour Line Break	IRPR-2, ISS-2, ISS-3, ISS-5, EDS-1, WDS-6, CPS-4	Yes	OUTL-1: Outer Fuel Cycle Release
WDS-4	Tritiated Water Spill from Holding Tank	WDS-5	Yes	OUTL-2: Release of Tritiated Water
WDS-5	Tritiated Water Release into Environment	WDS-4	Yes	OUTL-2: Release of Tritiated Water
WDS-6	Potential O_2 and Q_2 Explosion	IRPR-2, ISS-2, ISS-3, ISS-5, EDS-1, WDS-3, CPS-4	Yes	OUTL-1: Outer Fuel Cycle Release
WDS-7	Tritium Management and Control Failure	GDCM-3, TP-4, PS-6, EP-5, IRPR-7, ISS-7, EDS-5, CPS-6	Yes	ACC-1: Tritium Management and Control Failure
CPS-1	Getter Switch Fails to Occur	CPS-2	No	–
CPS-2	Getter Material Poisoned or Not Regenerated	CPS-1	No	–
CPS-3	Getter Regenerators Stuck On	–	No	–
CPS-4	Break or Leak in System Block	IRPR-2, ISS-2, ISS-3, ISS-5, EDS-1, WDS-3, WDS-6	Yes	OUTL-1: Outer Fuel Cycle Release
CPS-5	Water Distillation Filter Failure	–	No	–
CPS-6	Tritium Management and Control Failure	GDCM-3, TP-4, PS-6, EP-5, IRPR-7, ISS-7, EDS-5, WDS-7	Yes	ACC-1: Tritium Management and Control Failure

Appendix C. Detailed PIE analysis

Appendix B shows the summary of the PIEs that were developed for this work and how they link together. This appendix gives the details of the individual PIEs and their analysis as grouped by the system blocks detailed for the DIRL, INTL, and OUTL.

1. Gas distribution, control, and monitoring (GDCM) PIEs

The GDCM PIEs have been developed by considering the causes and effects of failures associated with valve boxes, pipework, and small gas holding vessels.

1.1. PIE GDCM-1: valve failure in gas GDCM system

This PIE postulates that one or more valves within the GDCM system ceases to operate due to mechanical or electrical faults. The possible consequences of valve failure include:

- Unintentional mixing of fuelling due to lines being connected, resulting in contamination.
- Inability to stop sending fuel to the fuel injection areas, resulting in contamination.
- Increase in pressure in a fuelling line, resulting in a leak or break of equipment.

This initiating event can be considered more thoroughly from a few different angles. In terms of the worst-case scenario, in which the pressure in the fuelling line is increased and a break or leak occurs, this PIE will be wrapped with others to create a scenario in which there is a break or leak in the inner fuel cycle.

The issues associated with contamination will not be considered further in this document as a more detailed design is necessary for further analysis. For example, knowledge of the safety interlock system which will be used will give likelihoods of failure, and information on the tritium management and control system will give the levels of detection. This information will be available at a detailed design stage and must be considered as such.

1.2. PIE GDCM-2: break or leak in supply line

It is possible that, due to corrosion, vibrations, or external influences, one or more of the supply lines in the GDCM system fails. This PIE overlaps with PIE GDCM-1, as one of the possible reasons for supply line failure would be an increase in gas pressure due to a faulty valve. A general summary PIE for a break or leak in a tritium supply line in the inner fuel cycle is used for further analysis.

1.3. PIE GDCM-3: tritium management and control failure

The tritium management and control sensors determine how much radioactive material is being moved around the fuel cycle, and where that material is at a particular time. This PIE considers the consequences of tritium management and control failure in GDCM. These include:

- Incorrect fuelling mixtures for plasma
- Contamination of fuelling lines
- Loss of control of radioactive material

The first two consequences influence the DEMO plant running and efficiency, but do not result in serious harm to individuals or the environment. These consequences need to be considered as part of a detailed design but will not be considered further in this initial accident scenario analysis, although it is noted that the methodologies and implementation for tritium management and control have yet to be fully defined.

Loss of control of radioactive material may be an important accident scenario. As such, this PIE is combined with similar PIEs from other system blocks to create a general loss of tritium management and control scenario.

2. Torus pumping (TP) PIEs

The TP PIEs have been developed by focussing on the possible failures (and associated effects) of a metal foil pump backed by two separate pumping trains. No redundancy is assumed in the pumping trains and metal foil pumps for this analysis; redundancy will be considered in future accident analysis and detailed design.

2.1. PIE TP-1: pump failure

This PIE covers a generic pump or multiple pump failure within the system block. This PIE could be broken down into sub-PIEs considering the effects of the metal foil pump (MFP) failure or failure in one or more of the pumping trains.

The different possibilities have been amalgamated into one PIE for simplification. If a primary or roughing pump were to fail in one of the two trains (and no suitable bypass or backup were available), then the following consequences would occur:

- The line pressure would increase as either the failure would block or reduce fluid flow.
- The increased backing pressure could result in upstream pump trips or failures.
- The resulting pressure increase in one or both pumping trains would lead to a pressure imbalance or increase at the MFP.

If the MFP were to fail then the effect on the two pumping trains would be the same. Therefore, the main point of failure considered by this PIE is the MFP. A scenario based on this PIE would consider the results of a loss of efficacy of an MFP. Information about how an MFP will work and its possible failure mechanisms is not available due to ongoing research. As more information about MFPs becomes available, this PIE will need to be revisited.

2.2. PIE TP-2: break in pumping line

The exhaust line from the torus into the fuel cycle (and associated tritium plant) could leak or break due to corrosion, vibration stress, or external influences (such as a missile strike, etc.). The exhaust line could break anywhere within the torus pumping system block, but the most serious accident initiating event would occur if the break occurred before the metal foil pump.

The consequences of a line break will be considered further in a more general scenario of a leak in the INTL. However, this PIE will also include activated PEGs being released along with tritium.

2.3. PIE TP-3: mercury ring pump failure

It is currently assumed that the pumping trains for the direct recycle stream and the IRPR stream will use pumps with mercury as operating fluid. This PIE considers the effects of a potential mercury spill from one of the pumps following a failure.

Mercury does not carry any risk from ionising radiation as tritium does, but is, mainly due to its use in uncontrolled artisanal applications, considered one of the top ten chemicals of major health concern by the World Health Organisation (WHO). A spill of mercury could result in liquid and vapour mercury potentially being released to secondary containment or the local environment. The severity of the health problems associated with mercury varies depending upon the method, quantity, and length of exposure as well as the chemical composition of the mercury compound.

There is not enough information on the amount of mercury that will be used in the torus pumping system block to do any more detailed analysis on any future accident scenarios. Once information such as the amount of mercury to be used, the method of containment, and maintenance schedules exists, then a further accident scenario analysis can be used to evaluate the risk associated with this PIE.

2.4. PIE TP-4: tritium management and control failure

This PIE is nearly identical to other tritium management and control failure PIEs found for each system block. In this case, tritium management and control failure may occur on the DIRL or on the INTL (the link between the pumping system and the IRPR system block). If a single failure point were to occur, balances from other system blocks would likely mitigate any loss of control. However, this PIE is linked with the other PIEs to create a general tritium management and control failure scenario.

3. Product storage (PS) PIEs

The PS system block is assumed to comprise supply lines, solid storage material (depleted uranium), some gas holding tanks, and potentially an external supply.

3.1. PIE PS-1: break or leak in supply line

This PIE is very similar to PIE GDCM-3, given that the PS and GDCM systems are directly linked and the consequences of each PIE are the same. This PIE will be combined with PIE GDCM-3 and other PIEs to create a general summary PIE of a leak.

3.2. PIE PS-2: short-term lack of storage capability

DU storage mediums require heat to release stored hydrogen isotopes. If a heater on one or more of the storage mediums is stuck on, or if the ambient temperature of the storage area is high, then hydrogen isotopes may be released and/or unable to be stored on the medium. Mitigating factors which could be included in a detailed design would be backup storage beds or expansion volumes. If the worst were to occur and a pressure increase resulted in a break or leak in the line, then this PIE would link directly to PIE PS-1 and line breaks. Therefore, this will not be considered for detailed scenario analysis.

3.3. PIE PS-3: breach of storage medium

This PIE considers the possibility that a break occurs in the PS containment, resulting in the release of the hydrogen storage medium. This medium may have stored hydrogen isotopes or it may be empty. As a result:

- Solid contaminated DU could be released into the environment.
- The DU may interact with the environment and cause hazardous conditions (for example, DU is pyrophoric).
- A change in temperature and/or pressure could result in stored isotopes being released from the storage material into the environment.

The scenario analysis is required for this PIE.

3.4. PIE PS-4: loss of non-tritiated material

If supply of non-tritiated material is interrupted, such as bottled deuterium, it may not be possible to continue fuelling. Supply interruption may arise from:

- A break in the feed line from the source.
- An external (such as global or local supply) interruption resulting in no material being available on site.

This PIE leads to a disruption scenario which will need to be considered in the more detailed design of the fuel cycle; in particular, the possibility of an explosion (especially if a large deuterium supply is kept). Information about the amount of non-tritiated material, and how it will be stored, is not available, and this fact makes it difficult to undertake a full analysis. It is acknowledged that a release of PEG gases could result in asphyxiation and explosion hazards, but these will depend upon the amount of gas released and the environs. Future analysis will need to consider these explosion and asphyxiation risks.

3.5. PIE PS-5: storage material is lost or poisoned

This PIE considers the possibility that the effectiveness of a long-term storage material is degraded or lost, thereby leaving hydrogen isotopes without storage. This PIE has similarities to PIEs PS-2, in which the hydrogen isotopes cannot be stored in their usual area, and PIE PS-3, in which the storage material may have reacted with something to create a hazardous condition.

This PIE may be developed into its own scenario once a more detailed design of the fuel system is given; however, its similarity to PIE PS-2 and PS-3 means that with the current available information, not much extra knowledge could be gained through independent scenario analysis. As such, this PIE will be amalgamated with PIE PS-3.

3.6. PIE PS-6: tritium management and control failure

This PIE is nearly identical to that of PIE GDCM-2, TP-4, and others for each system block; it will be amalgamated into a general tritium management and control failure accident scenario.

4. Exhaust processing system (EPS) PIEs

The EPS block PIEs were developed by considering the EPS FBS and the main technologies. The EPS system technologies focus around using a Pd membrane to separate hydrogen isotopes and PEGs; the maturity of the technology means that the PIEs are easier to identify than in other system blocks.

4.1. PIE EP-1: loss of separation capability

The EPS block relies on the functionality of the Pd membrane to separate PEGs from Q_2. If the membrane were to lose efficiency, such as through a tear in the membrane or poisoning of the material, the following consequences could occur:

- PEGs are sent through to tritium processing blocks. Some of the technologies being considered for these blocks rely on cryogenic operation; the presence of PEGs could cause process and structural failures due to, for example, freezing PEGs in cryogenic conditions.
- Q_2 gas is sent through to PEG storage and inappropriate fuelling.
- The pressure differential across the Pd membrane is lost, creating flow issues.

The consideration of process upsets is beyond the scope of this investigation; however, the possibility of PEGs contaminating the rest of the fuel system poses a safety hazard which is investigated through qualitative analysis of Scenario PEG-1.

4.2. PIE EP-2: increase in Q_2 in PEG storage or EDS

A loss of functionality of the Pd membrane may also result in an increase of Q_2 in PEG storage or in the stream sent from the EP system block to the normal EDS. As with PIE PS-4, this PIE will cause process upsets, but will need to be considered in relation to more detailed plant design rather than accident scenario analysis.

4.3. PIE EP-3: break or leak in Pd membrane supply line

The supply line to the Pd membrane will be at high pressure; a break in this supply line would lead to:

- Q_2 and potentially activated PEGs being released to secondary containment or the local environment.
- Potential back-mixing, resulting in oxygen poisoning the Pd membrane.

This PIE will be combined with other PIEs relating to a break or leak in the inner fuel cycle to be analysed more thoroughly as Scenario IFC-1. Back-mixing and poisoning of the Pd membrane will need to be considered in future design analysis.

4.4. PIE EP-4: release of PEGs due to break or leak in PEG storage

This PIE considers the possibility that the temporary storage vessel for the separated PEGs leaks or breaks. Activated PEGs may be released into secondary containment or the local environment. Depending upon the average residence time of the PEGs, some may be temporarily activated; this activation can result in significant dose rates if the PEGs have not been stored for long enough to allow them to decay. The average residence time (and therefore decay time) of the PEGs depends upon the size of the temporary storage vessel. Without detailed information, this PIE assumes that the average residence time will be significantly large when compared with the PEG half-lives, thereby resulting in small amounts of residual activation. As such, the radiation due to the activation levels of the PEGs is assumed to be short-lived when compared to tritium activation. In this work, this PIE will not be considered as a primary safety issue in this document. However, this PIE will need to be revisited when quantitative information is available on average PEG activation and temporary storage vessel residence time; if the PEGs are found to have potentially high radiation levels, then an accident scenario needs to be analysed.

4.5. PIE EP-5: tritium management and control failure

As with the other tritium management and control failure PIEs found for each system block, this PIE will be amalgamated into a general tritium management and control scenario.

5. Isotope rebalancing and protium removal (IRPR) PIEs

The PIEs for this system block are more generic than those for the other inner fuel cycle system blocks due to the lack of knowledge of the system block technologies and fluid parameters. The technology which will be used for this system block is MC-TSA, which is based upon TCAP technologies. These PIEs will need to be revisited, along with the scenario analysis, when the MC-TSA information for the system becomes more detailed.

5.1. PIE IRPR-1: break or leak in system

This PIE covers the break or leak of either a line entering or exiting the IRPR system, or a potential break in the IRPR system block. Such a PIE could occur due to an unexpected mechanical impact (such as a missile or seismic impact), or due to corrosion or fretting wear of one of the components. This PIE is linked with other similar PIEs in the INTL to create a generic scenario for analysis.

5.2. PIE IRPR-2: MC-TSA heating element failure

This PIE considers the possibility a heating element could fail on in the MC-TSA technology. Unexpected increased temperatures can lead to material stresses and breaks as well as the uncontrolled release of gases. This PIE will be considered in the overall INTL gas release scenario, as both potential causes would result in a gas release to the environment. This PIE is combined with similar gas release PIEs, such as IRPR-1, to create a release scenario.

5.3. PIE IRPR-4: loss of PSA differential pressure

MC-TSA requires a pressure differential between the different columns in order to achieve suitable Q_2 separation. If equipment maintaining the pressure differential were to fail, the column pressures would equilibrate. The final resting pressure would depend upon the overall volume, temperature, and amount of gas in the two columns. This event will need to be considered at the detailed design stage when quantitative information is given; however, that design can consider the required containments for this event. This PIE does not, given the current knowledge of the fuel cycle, constitute a significant accident scenario and will not be considered further in this document.

5.4. PIE IRPR-5: solid formation from gases

This PIE considers the possibility that a heater in a unit breaks and, combined with a drop in pressure, this results in a significant drop in temperature. If heat is continually removed from one of these systems, it becomes possible that the overall temperature drops and liquid or solid forms within the system; this could also occur if impurities with higher freezing temperatures were to enter a unit. As a result, the units would have unexpected thermodynamic stresses due to the change of state. It may be possible for a unit to crack, releasing its contents.

This PIE is considered unlikely, but the possibility of a gas release from one of the units due to freezing can be wrapped into the general scenario of a break or leak in the INTL.

5.5. PIE IRPR-6: loss of modular switch-over

MC-TSAs are semi-continuous, as the unit must undergo a temperature cycle between gas inlet and gas outlet. Therefore, it is required to switch over to other units if there is a continuous input flow. If this switchover fails to occur:

- Pressure will build either in one of the units (provided a valve is kept open) or at the system block inlet.
- The increase of pressure could lead to a break or leak at a weak point in the piping system or in the unit.
- Isotope separation could not occur.

If a unit broke, the gas inside it would be released This PIE then becomes similar to PIEs relating to a break or leak in a system block and is combined with others to consider a break or leak in the INTL.

5.6. PIE IRPR-7: tritium management and control failure

The IRPR system block requires tritium management and control for ensuring that the correct mixtures of deuterium and tritium are sent for storage and/or fuelling. A failure of tritium management and control in this system block would result in incorrect fuelling and a loss of tritium management and control. This PIE will be combined with other similar PIEs to create a general loss of tritium management and control scenario.

6. Isotope separation system (ISS) PIEs

6.1. PIE ISS-1: loss of differential pressure

If a column lost its pressure differential (such as due to an equipment fault), resulting in incomplete separation and isotope migration; this PIE is very similar to PIE IRPR-3. This PIE will not be considered further in this document.

6.2. PIE ISS-2: ISS heating element failure on

This PIE is analogous to PIE IRPR-1; if the heating element were to fail on, the following actions could occur:

- All isotopes would be released, resulting in no isotope separation. Pressure inside the vessel may increase.
- Increased temperatures, potentially combined with increased pressures, could result in thermomechanical stresses causing a break or leak in ISS unit.
- Isotope separation would not occur.

A break or leak in the ISS will be covered under a general break or leak scenario in the OUTL.

6.3. PIE ISS-3: excessive gas pressure

This PIE considers the possibility that a failure in the separation system technology results in a significant increase in gas pressure within the system block.

An increase in pressure will have different effects on the different technologies; however, a worst-case scenario could consider the possibility of a containment rupture, leading to gas release. This PIE will consider a release of process gas in the same way that PIE ISS-2 does so; it will be combined with similar OUTL PIEs resulting in process gas release for further scenario analysis.

6.4. PIE ISS-4: loss of cryogenic cooling

A loss of cryogenic cooling could result in an increase of pressure in the system and, potentially, a release from the system block. This PIE is considered as part of the scenario CRYO-1.

6.5. PIE ISS-5: break or leak in system block

This PIE is similar to others considering a mechanical failure of a process line, resulting in release of process gas (for example, PIEs EDS-1, WDS-3, and CPS-4, among others). The ISS technology is independent of this PIE. Its origin is the same as the other mechanical failure PIEs (corrosion, large mechanical impact, etc.) and will be considered for further analysis as part of an outer fuel cycle process gas leak scenario (OUTL-1).

6.6. PIE ISS-6: unexpected flood or variation of Q_2 isotopologues

This PIE is unique to the ISS in that the ISS will be required to process a wide range of flowrates and compositions regardless of the technology chosen. For example, it is possible that the WDS system does not run continuously, or that a process upset results in an increase of flow in and out of the EDS. Especially in terms of a process upset in another system, it can be possible not to consider the downstream effects of the associated remedial actions. As the fuel system design continues, this PIE will need to be considered to inform not only the ISS, but the associated system blocks and their operation. However, the technology and flows in this system block are not sufficiently defined to allow this PIE to be considered further in the current document.

6.7. PIE ISS-7: tritium management and control failure

Tritium management and control will be particularly important on the outlet of the ISS to the environment to ensure that tritium release does not exceed regulatory or safety requirements. However, there is not sufficient information available for this document to discriminate between tritium management and control at a stack release point with tritium management and control failures elsewhere in the fuel cycle. Therefore, this PIE will be linked with the similar ones from other system blocks for the loss of tritium management and control failure.

7. Exhaust detritiation system (EDS) PIEs

At this level of accident scenario analysis, the normal EDS and the safety EDS are considered with the same methodology and therefore are not considered separately in the development of PIEs. Redundancy of components in each system is not taken as a reason to discount a PIE.

7.1. EDS-1: loss of EDS input

A blockage in the inlet of the EDS or a lack of input, such as through a physical barrier (solid build-up) or through a pumping failure (blower electrical fault), would result EDS not working. Two possible consequences are identified for this PIE:

- In the event of a physical barrier, the resulting effects could include an increase in pressure followed by a break or leak of the line.
- In the case of a pumping failure, ventilation within the tritium plant would stop and there could be an increase in pressure at the back end of the system blocks feeding the EDS.

No layout or ventilation information or requirements are available at the current stage of design for the physical aspects of the tritium plant building; therefore it is not feasible to do an initial investigation into the consequences of a loss of ventilation. However, the potential break or leak of the EDS input can be linked with similar PIEs relating to a leak or break of a line in the outer fuel cycle. Therefore, part of this PIE will be linked with the other PIEs used to create an OUTL release scenario.

7.2. PIE EDS-2: loss of EDS detritiation

The EDS system relies on removing tritiated materials through binding tritium into water and removing that tritiated water prior to stack release. It is possible that one or more of the elements of the EDS train fail, resulting in more gaseous tritium passing through the EDS and out of the stack. As a result:

- The system will continue to run normally if the increase of released tritium does not reach alarm limits on the stack monitors.
- Daily or yearly discharge limits could be reached whilst the system appears to work.

This PIE comprises one the accident scenarios considered.

7.3. PIE EDS-3: loss of safety EDS (s-EDS)

This PIE considers the possibility that the normal EDS continues to function, but that the safety EDS is not available when it is required. The results of this failure would mean that the normal EDS would be required to be used in the event of a process upset. Therefore:

- The fan speed would not be able to increase as much as expected, making detritiation of the internal plant take longer.
- The detritiation factor would be lower than designed as part of the safety EDS.

These possibilities need to be considered when designing the normal and safety EDSs, respectively. This PIE is combined with other EDS PIEs to create an accident scenario for analysis.

7.4. PIE EDS-4: increased environmental release

Increased environmental release could occur for a variety of reasons. The inputs into EDS could change due to processing upsets or faults, or part of the EDS system could cease to function as required. This PIE overlaps closely with PIE EDS-2 and PIE EDS-3, and will be combined with them to create an accident scenario for analysis.

7.5. PIE EDS-5: tritium management and control failure

Tritium management and control failure at the stack release would result in an unknown amount of radiation potentially being released into the environment. This PIE will still be wrapped with other similar tritium management and control failure PIEs for further analysis as in Scenario ACC-1.

8. Water detritiation system (WDS) PIEs

This section focusses on the water detritiation PIEs that could result from the technologies used in the WDS.

8.1. PIE WDS-1: electrolyser failure

The WDS requires tritiated water to be split into its constituent elemental gases (Q_2 and O_2) in order to exhaust the oxygen and send the tritiated hydrogen gas back to the ISS. Electrolysers will be used to split the water; if one or more electrolysers were to fail, then the system would cease functioning. Electrolyser failure can occur due to power failure, mechanical faults, or incorrect inputs (for example, poorly filtered water), and the design of the WDS must minimise the external influences on electrolyser failure. However, electrolyser failure is likely to result in the WDS system shutting down. These systems can be operated separately from the main tritium fuel cycle, and they do not need to be running in order for the fuel cycle to continue. Therefore, this PIE will not be considered as a critical accident scenario; rather, electrolyser failure will need to be considered in the system design phase. A break or leak in the electrolyser gas output lines is considered, however, as part of PIE WDS-3 and Scenario OUTL-1.

8.2. PIE WDS-2: LPCE column failure

The WDS uses a liquid phase catalytic exchanger (LPCE) to separate Q_2 isotopologues into tritiated and non-tritiated molecular hydrogen. This PIE considers the consequences of the LPCE column failure, either through structural failure or through an inability to separate the isotopologues. Structural failure will be considered in a separate PIE, in combination with a break or leak of a process line.

If the isotopologues are not separated due to other mechanical failures within the column, there is a possibility of QT being sent through the LPCE top product to stack exhaust. However, the most likely reason for loss of separation efficiency of any vapour-liquid exchange column is poor operating conditions; too much vapour will result in excess liquid holdup, and too much liquid will result in column flooding. These are issues which need to be addressed at the design phase of the system block; if a large variation in water or vapour flow is expected, then multiple columns may be required. If there is a possibility of QT being exhausted through to stack from the system block, then monitors, alarms, or interlocks will need to be fitted. The accident scenario of an accidental excess tritium stack release from this system block will not be considered further at this pre-conceptual design stage.

8.3. PIE WDS-3: break or leak in GDS/WDS vapour-phase process line

As with each system block, a leak or guillotine break in a process line is possible from a wide variety of scenarios, including corrosion, overpressure, or significant mechanical impact. Such a break may result in a release of tritiated gases into the tritium plant or local environment. Given the similarities in flow compositions between the WDS vapour flows and those in other outer fuel system blocks, this PIE is combined with others to create a general scenario for a break or leak of radioactive gas from the OUTL.

8.4. PIE WDS-4: tritiated water spill from water holding tank

The WDS will be the only part of the fuel cycle where tritiated water will be held. It is a system requirement that the system block can store tritiated water indefinitely as it awaits processing. A leak from a water holding facility can occur from overfilling or by a break or leak in the storage tank. Storage and subsequent potential clean-up of tritiated water poses unique challenges to the fuel cycle. This PIE is considered for further analysis in its own accident scenario OUTL-2 and is linked to Pinna's PIEs OFC-2, TGO-3, and TWO-1 [4].

8.5. PIE WDS-5: tritiated water release into environment

Most release PIEs in this document consider the possibility of Q_2 gas release. It is also possible for water vapour to be released into the environment, such as through a water spill. Tritiated water has a dose conversion factor four orders of magnitude higher than that of tritiated gas [12]; therefore smaller quantities of tritiated water vapour can pose significant hazards. Although this PIE is separate from PIE WDS-4, the two share similar scenario origins. Further analysis of this PIE is necessary; Scenario OUTL-2 gives consideration to release of HTO into the plant environment, and the beyond normal boundary scenario considers the possibility of a significant amount of tritiated water being released from the DEMO plant.

8.6. PIE WDS-6: potential O_2 and Q_2 explosion

An electrolyser will be used to separate water into Q_2 and O_2. It is possible that, due to a fault in the electrolyser or subsequent downstream failure, the two gases could meet and combust. This scenario will be part of a subsection of analysis for Scenario OUTL-1 which considers a possible break or leak in the electrolyser outlet link.

8.7. PIE WDS-7: tritium management and control failure

Tritium management and control in stack releases is important from a regulatory as well as safety perspective for the WDS. The modes and challenges of tritium management and control failure are not unique to the WDS, and this PIE will be combined with the other general tritium management and control failure PIEs to create the accident scenario.

9. Coolant purification system (CPS) PIEs

This analysis focuses on the possibility that either water or helium will be used as a coolant for the breeder blanket technology; tritium will migrate into this coolant and will need to be removed. The PIEs in this section consider potential events which could occur if a hydrogen getter were used (for a helium-based coolant) or if water distillation were to be used.

9.1. PIE CPS-1: getter switch fails to occur

Once an individual getter bed has adsorbed as much hydrogen as possible, the system must detect that no more adsorption can occur and switch to a fresh bed. If the detection system or the valve system fails, the switch will not occur and no more hydrogen isotopes would be adsorbed from the helium flow. This could cause a build-up of tritium within the helium. In this, the build-up would be slow; design considerations are needed to mitigate this risk, but the timescales involved indicate that this would not create an immediate accident scenario.

The helium system will be contained and not pose an immediate hazard to people in the local area. This PIE indicates that the CPS fails to fulfil its function; the breeder system would need to be stopped whilst the fault was rectified. Such an action does not create a significant hazard or immediate accident scenario; it will not be considered further in this document.

9.2. PIE CPS-2: getter material poisoned or not regenerated

Getter beds must be regenerated through heating to release the attached hydrogen and allow them to be reused. If one or more regenerator heaters were to fail, the beds would not regenerate and the system would not be able to adsorb hydrogen isotopes from the helium flow. As a result, tritium would accumulate in the helium system. Similarly, getters can be poisoned by contaminants in a system; the poisoning would result in a getter not being able to adsorb hydrogen.

This PIE links with PIE CPS-1; these do not form the basis for an accident scenario and will not be considered further in this document. However, along with PIE CPS-1, it must be considered in future design considerations such that engineered safety can mitigate the possibility of this event occurring, such as through redundant getter systems and beds.

9.3. PIE CPS-3: getter regenerators stuck on

Getter beds are regenerated through heating the material to drive off the hydrogen isotopes; once the hydrogen is gone, the heaters are turned off and the beds return to their normal temperature. It is possible that a heating element may fail on, causing the getter bed to continue heating. The consequences of an overheated getter bed will depend upon the technology used for the getter and the surrounding environment. There is little information on any potential getters in the CPS and less information on the effects of getter bed overheating. As such, this PIE will not be considered further in this analysis.

9.4. PIE CPS-4: break or leak in system block

This PIE encapsulates a variety of different parts of the system block which could be subject to a break or leak in the processing line. This break or leak could occur, as with similar PIEs for other system blocks, due to increased pressure, a physical strike, or corrosion at a critical weld or join. Such a break may result in a release of tritiated gases into the tritium plant or local environment. This PIE will be combined with others to create a general scenario for a break or leak of radioactive gas from the OUTL.

9.5. PIE CPS-5: water distillation filter failure

Water distillation columns rely on pure inputs; any accumulation of impurities will clog the system and result in an unworkable distillation column (such as through changing boiling and condensing points or poisoning packing material). Pre-column filtration systems ensure that the input water has the correct conditions; if these filtration systems were to fail, the performance of the distillation columns will decrease.

This PIE has similarities to PIE CPS-1 and CPS-2; a filter failure would result in the water distillation system being unable fulfil its function. If water distillation is the chosen technology, this PIE will need to be considered in the future. No further analysis on this PIE will occur at the current stage of design.

9.6. PIE CPS-6: tritium management and control failure

This PIE is nearly identical to the other PIEs relating to tritium management and control failure. It is possible that significant amounts of tritium are held up in the coolant system; if the amount were to be unknown, this could cause a breach in regulatory requirements. This PIE will be combined with the other tritium management and control PIEs to create a Scenario ACC-1.

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