Tritium release scenarios in the IRPR system of DEMO: Safety assessment and mitigation strategies

Fusion Engineering and Design 222 (2026) 115477

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Tritium release scenarios in the IRPR system of DEMO: Safety assessment and mitigation strategies

Samuele Meschini, Raffaella Testoni *

Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, Italy

ARTICLE INFO

Keywords:
DEMO
Fuel cycle
IRPR
Tritium
Safety
TSA
MELCOR

ABSTRACT

This study investigates potential tritium release scenarios in the Isotope Rebalancing and Protium Removal (IRPR) system of DEMO fuel cycle, focusing on failures in the Temperature Swing Absorption (TSA) unit, including its feed tank. Two accident cases are considered, based on the postulated initiating events identified by the FFMEA: (1) a guillotine break in the pipeline supplying the IRPR system and (2) a pipe rupture in the TSA unit. MELCOR 1.8.6 for fusion is used to simulate the dynamics of the gases (hydrogen, air, inert gases), the resulting pressurization of the enclosure volumes, and the accumulation of hydrogen isotopes. A parametric study evaluates the impact of design choices like feed tank configuration and glovebox volume, informing the design of the system to enhance safety. The analysis includes cases where safety systems such as detritiation or isolation fail to operate correctly. The findings support ongoing safety assessments for DEMO and inform strategies to improve safety in fusion power plants.

1. Introduction

The safe operations of DEMO require a clear understanding of potential tritium release scenarios in the fuel cycle [1,2]. Over the past few years, significant effort has been dedicated to quantify the mobilizable source terms in DEMO [3]. This included evaluating the amount of tritium among various components, systems, and buildings under different operating conditions. A detailed functional breakdown structure of the fuel cycle was developed to support a Functional Failure Modes and Effects Analysis (FFMEA) [4]. This analysis identified approximately 40 postulated initiating events (PIEs) that could lead to accidents.

This paper focuses on one of the accidents identified by the FFMEA, namely a break or leak in the Isotope Rebalancing and Protium Removal (IRPR) system (PIE IRPR-1: break or leak in system). The IRPR system employs Temperature Swing Absorption (TSA) technology to restore the appropriate deuterium–tritium (D–T) ratio in the inner fuel loop and to remove excess protium generated by outgassing and isotope exchange reactions. Two accident cases are examined: (1) a guillotine break in the pipeline that supplies the IRPR system, and (2) a rupture of a pipe within the TSA unit.

To analyze these scenarios, we simulated the transient thermo-hydraulic behavior of the escaping flow using MELCOR1.8.6 for fusion. The simulations assess the buildup of hydrogen isotopes in the glovebox and tritium building, and the potential leak to the environment. We conducted a parametric analysis to examine the impact of key parameters, such as feed tank configuration and the glovebox volume, as well as investigating additional safety barriers, such as a detection system coupled with an isolation valve, and a detritiation system. Additional goals of the safety analysis were the sizing of the glovebox to avoid reaching the lower flammability limit in the largest credible release of hydrogen (additionally, the glovebox atmosphere is maintained inert under nominal circumstances to prevent any hydrogen explosion), and the assessment of hydrogen stratification in the tritium building.

The paper is organized as follows. Section 2 describes the IRPR system, the TSA technology, and the accident analysis specification. Section 3 details the nodalization and modeling assumptions. Section 4 presents the preliminary results and parametric analysis. Section 5 discusses the primary safety outcomes and provides closing remarks.

2. IRPR system and accident analysis specification

This section describes the IRPR system. The IRPR unit is essential for tuning the D-T ratio (over a long timescale) and to remove protium from the fuel cycle [2]. A promising technology for the IRPR system is the TSA process.

The TSA process uses two columns filled with different bulk materials. The material in the first column preferentially absorbs the lighter isotopes, while the second column retains the heavier isotopes. The

* Corresponding author.
E-mail address: raffaella.testoni@polito.it (R. Testoni).

https://doi.org/10.1016/j.fusengdes.2025.115477
Received 2 May 2025; Received in revised form 15 September 2025; Accepted 2 October 2025
Available online 11 October 2025

columns operate in an alternating cycle, where the same gas mixture is transferred back and forth to achieve the desired separation. The process can be summarized by the following steps [5]:

- The gas mixture is introduced into the first column. The temperature in the first column is lowered to promote absorption, while the second column is simultaneously heated to trigger desorption. The heating and cooling is provided by oil flowing in a double-wall tube.
- The temperatures in the columns are swapped. The first column is heated and second column is cooled;
- A valve connecting the two columns is opened to create a pressure difference, causing the gas to flow from one column to the other;
- These steps are repeated several times, with the gas continually cycled between the columns, gradually increasing its isotopic enrichment;
- Once sufficient enrichment is achieved, the gas is extracted from the enriched ends of the first column. The process is semicontinuous (i.e. the gas is replenished after each extraction to maintain efficiency).

The accidental scenario evolution is the following. First, the break of a pipe is assumed, either in the connecting line between the tank and columns, or in the piping connecting the two columns. A fraction of the Q_2 (hydrogenic species in any molecular form) is released into the surrounding environment. For the first case, a tritium detector eventually detects the failure, closing the valve that allows the gas flow to enter the IRPR system. The amount of Q_2 released is therefore dependent on the detection time, for which a sensitivity analysis was carried out. The Q_2 mixes with the gas present in the enclosure. At that point, the gas inside the enclosure slowly permeates through the enclosure walls and contaminates the tritium building. The detritiation system (DS) constantly purifies the atmosphere both in the enclosure and in the tritium building. Lastly, the tritium that is not captured by the detritiation system eventually leaks out the building. For the second case, no isolation valves and detection systems are considered. As a matter of fact, isolating a TSA column from the other with an isolation valve does not seem feasible due to the layout of the TSA. Therefore, the tritium is released to the TSA glovebox, whose volume is continuously processed by the DS during an accidental scenario.

The sensitivity analysis was carried out on the following parameters:

- A single feed tank and multiple feed tanks. Increasing the number of tanks decreases the maximum releasable inventory in case of failure of one tank.
- Glovebox size for the feed tank. The nominal size $1\,m^3$ and an increased size of $30\,m^3$ were considered. Increasing the size of the glovebox prevents a potential hydrogen explosion even if air replaces the inert gas in the glovebox. The glovebox (or more in general, the enclosure) volume for the TSA is instead kept fixed in the second scenario because the nominal value is large enough to prevent hydrogen from reaching the lower flammability limit, as verified *a posteriori* by the analysis. We highlight that the feed tank and the TSA are enclosed in two separate glovebox, as specified by [6].
- Detection system threshold. Lower detection thresholds allow for a quicker detection of the tritium release. Values ranging from $0.001\,\mu Ci\,m^{-3}$ ($37\,Bq\,m^{-3}$) to $1\,\mu Ci\,m^{-3}$ ($3.7 \times 10^4\,Bq\,m^{-3}$) were considered.
- Valve response time. This includes not only the time needed by the valve to open, but also possible delays from the control system. Similarly to the detection threshold, the quicker the response time, the lower the release, thanks to the prompt isolation of the faulty line. Values ranging from $1\,s$ to $2400\,s$ were considered.

Table 1
Feed tank and feed line specifications.

Parameter	Value	Units
Tank volume	0.15	m^3
Tank maximum pressure	4×10^5	Pa
Tank temperature	300	K
Tritium mol fraction	0.495	–
Pipe diameter	10	mm
Pipe length	10	m
Max flow rate	0.2	mol/s

Table 2
TSA design and operating parameters [6].

Parameter	Columns 1	Columns 2
Total number of columns per unit	220–10	220-10
Length of 1 column (mm)	6000	6000
Diameter of 1 column (mm)	10	10
Diameter of connection tubes (mm)	10	–
Total length of connection tubes (mm)	10 000	–
Superficial average T2 mol fraction	0.55	0.45
Edge case 1: Pressure peak in Columns 1		
Maximum Pressure (Pa)	1×10^6	5×10^3
Temperature (K)	433	263
Edge case 2: Pressure peak in Columns 2		
Maximum Pressure (Pa)	5.5×10^3	7.5×10^5
Temperature (K)	293	323

- Detritiation system process volume. For rooms served by HVAC, the volumetric flow rate is 1–2 $vol\,h^{-1}$. For rooms served by DS, the volumetric flow rate is $0.1\,vol\,h^{-1}$. Therefore, the nominal flow rate in case of tritium release was considered equal to $0.1\,vol\,h^{-1}$ for a conservative analysis. Two additional flow rates were investigated. A null flow rate (faulty detritiation system), and $0.01\,vol\,h^{-1}$.

3. Methodology and nodalization

The nodalization used in MELCOR is schematically shown in Fig. 1.

The TSA is fed by gaseous Q_2 in a representative fuel composition of (49.5/49.5/1; D/T/H) periodically from a feed tank. During the feed phase, a valve opens and 0.2 mol/s flow through piping (L1) into the TSA unit for 60 s. The tank and feed line specification are given in Table 1. The initial tritium inventory in the feed tank is 72 g (2.57×10^{16} Bq). The tank is housed in a glove box/secondary confinement. A TSA unit consists of two arrangements of tubular columns connected to each other via a valve (V2) and piping (L2). The specifications of both arrangements are given in Table 2. During operations, pressure and temperature oscillate in a counter phase manner in both column arrangements. Table 2 also gives the peak pressure and temperature values for each column arrangement (during which the other is at a minimum). The most critical conditions are assumed for the TSA, namely when T_2 molar fraction is maximum, at 92.5% [5]. The remaining fraction (7.5%) is D_2, with H_2 present only in trace. The volume of one arrangement is computed from the data in Table 2. For an arrangement with 220 columns, which are 6 m long and have a diameter of 10 mm, the total volume is $0.104\,m^3$ (the contribution from the connection tubes is negligible). Hence, the initial tritium inventory (assuming thermodynamic equilibrium) is 161 g (5.75×10^{16} Bq) during the pressure peak in arrangement 1.

3.1. MELCOR nodalisation

To consider tritium in the analysis, a user-defined Non-Condensable Gas (NCG) has been defined in MELCOR input. This approach allows H2, D2 and T2 to be treated separately. No water, steam or fog is present in the Control Volume Hydrodynamics (CVH). The nodalisation

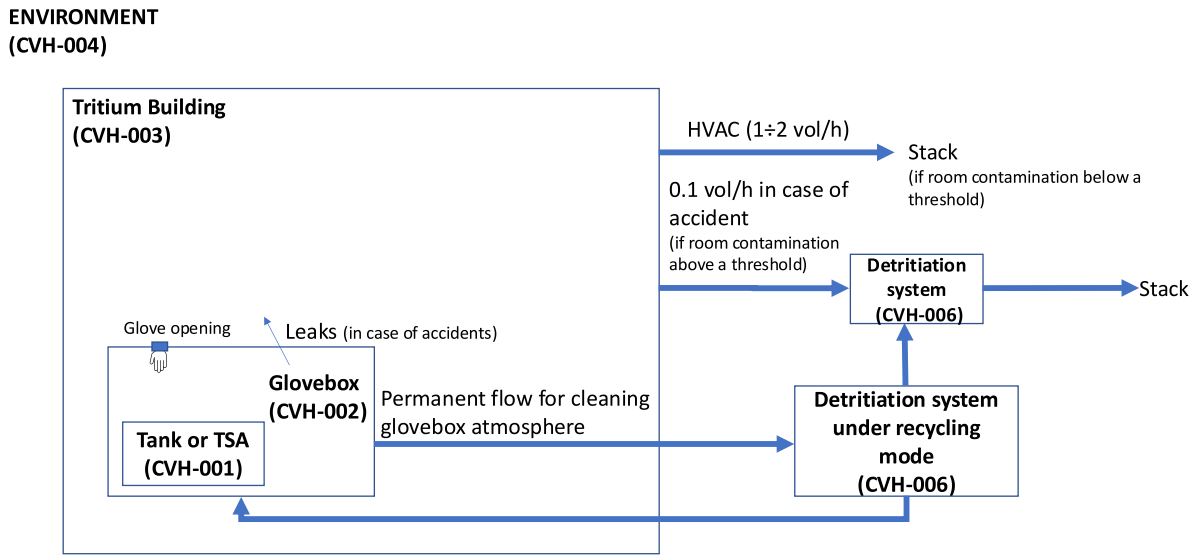


Fig. 1. MELCOR nodalization. The control volume for each component is depicted.

for the guillottine break in the feed line and in the TSA piping is summarized in the Appendix for readers' convenience. The leak rate is derived from ISO 11933-4, which specifies a nominal leak rate of $\dot{V}_{\text{nom}} = 2.5 \times 10^{-3}$ h^{-1} for class 2 containments at $\Delta p_{\text{nom}} = 250$ Pa. Since the pressure difference between the glovebox and the tritium building is not constant during the release, the leak rate is defined as a function of pressure difference:

$$\dot{V}(\Delta p) = \dot{V}_{\text{nom}} \times \sqrt{\frac{\Delta p}{\Delta p_{\text{nom}}}}. \tag{1}$$

The flow path area corresponds to the glovebox surface to simulate leakage through the surface.

Two additional modeling assumptions were made:

- No gas flow input is assumed for the feed tank, meaning that when the accident occurs, part of the gas mixture in the tank is released into the glovebox, but no additional gas enters from the tank inlet pipe (i.e. an isolation valve is assumed to be present upstream of the feed tank). Consequently, the maximum amount of tritium released is limited to the amount initially present in the feed tank.
- A detection system monitors the tritium content inside the glovebox and triggers an isolation valve downstream of the feed tank, with a delay determined by the detector response time and valve actuation time (Sections 4.1.3 and 4.1.4).

3.2. Hydrogen stratification model

An additional analysis based on MELCOR results involved the calculation of hydrogen concentration in the tritium building considering potential stratification. While the hydrogen concentration might be below the flammability limit when homogeneous dilution is considered, the limit could be exceeded locally due to stratification. The case under consideration is essentially an isothermal system at rest, where buoyancy effects arise due to molecular weight differences in the species mixture. For simplicity, the mixture is assumed to consist of hydrogen (subscript H) and air, with $x_{\text{air}} \gg x_H$, where x_i denotes the mole fraction of species i.

An exact solution to this problem can be obtained by solving the momentum equation for a binary mixture under an external gravitational force:

$$\rho \frac{Dv}{Dt} = -\nabla p - \bar{\rho} g - \nabla \cdot \tau - \bar{\rho} g \bar{\xi} (\omega_a - \bar{\omega}_a), \tag{2}$$

where ρ is the mixture density, $\bar{\rho}$ is the reference density at which the coefficient $\bar{\xi}$ is computed, $\bar{\xi}$ is the mass transport analog of the $\bar{\beta}$ coefficient in the Boussinesq approximation for buoyancy forces driven by temperature gradients, τ is the stress tensor, and ω_a is the mass fraction of species A.

The momentum balance equation, coupled with the mass balance equation for each species, provides the exact profile of the hydrogen concentration, $C_H(z)$, from which stratification can be evaluated. However, $\bar{\xi}$ is a complicated parameter that is not readily available, requiring some additional simplifications. The system can be approximated by recalling the momentum balance equation for a stationary fluid in a 1D system:

$$\frac{dp}{dz} = -\rho g. \tag{3}$$

Since, at steady state, there are no net mass fluxes, the molar fraction of species i can be obtained by solving:

$$\frac{dx_i}{dz} + \frac{M_i x_i}{RT} \left(\frac{\bar{V}_i}{M_i} - \frac{1}{\rho} \right) \frac{dp}{dz} = 0, \tag{4}$$

where M_i is the molecular weight and $\bar{V}_i$ is the partial molar volume of species i. Writing Eq. (3) separately for hydrogen and air, taking their difference, and integrating along the z-axis yields the solution for x_H:

$$\left(\frac{x_H(z)}{x_H(0)} \right)^{\bar{V}_{\text{air}}} = \exp\left(\frac{(M_{\text{air}} \bar{V}_H - M_H \bar{V}_{\text{air}}) g z}{RT} \right) \left(\frac{x_{\text{air}}(z)}{x_{\text{air}}(0)} \right)^{-\bar{V}_H}. \tag{5}$$

Since $x_{\text{air}} \gg x_H$, we approximate $x_{\text{air}}(z)/x_{\text{air}}(0) \approx 1$. Thus, Eq. (4) provides the molar (and thus volume) fraction as a function of the tritium building height. The initial value $x_H(0)$ can be determined by noting that once tritium is fully released from the TSA,

$$\int_0^{H_{\text{hall}}} n_H(z)\, dz = n_{\text{tot},H} \tag{6}$$

which yields the value for $x_H(0)$.

4. Results

In this section we present first the results for the guillotine break in the supply pipeline of the TSA (Section 4.1), including all the different cases to mitigate the release. Then, we show the results for the break of a pipe within the TSA unit (Section 4.2). Lastly, we present the results from the hydrogen stratification model following the tritium release from the TSA (Section 4.3), which leads to a larger hydrogen release compared to the guillotine break in the supply line of the TSA.

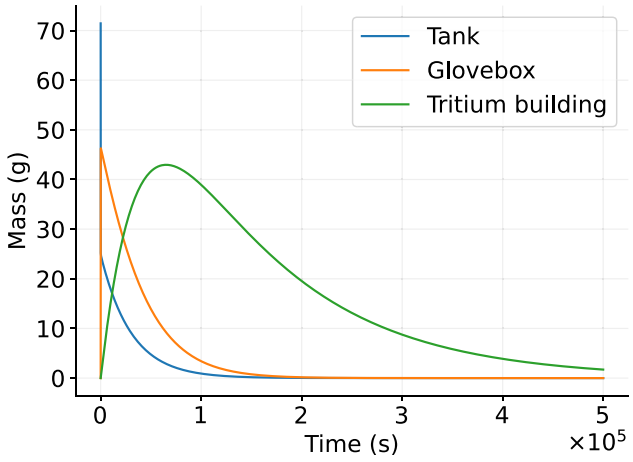


Fig. 2. Transient release of the tritium mass from the tank to the glovebox and the tritium building. The DS is assumed not to operate, and tritium leaks at constant rate from the tritium building.

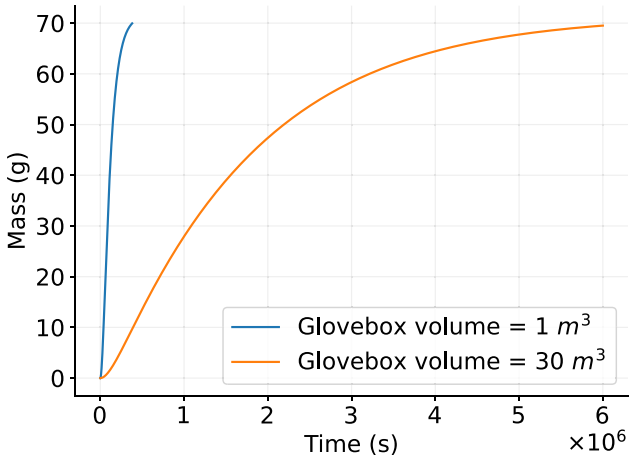


Fig. 3. Tritium release from the containment building assuming the DS system malfunctions. A larger glovebox volume leads to a slower transient and prevents hydrogen to reach the flammability limit in the glovebox.

4.1. Guillotine break in the supply pipeline of the TSA

4.1.1. Number of feed tanks

The T_2 mass transients is shown in Fig. 2. The initial inventory in the tank is 72 g (2.57×10^{16} Bq). The initial transient is rapid, and an equilibrium between the tank and the glovebox is almost reached in approximately 500 s. Specifically, the pressure in the tank and in the glovebox equalizes after 30 s from the beginning of the transient, reaching an equilibrium pressure of 1.4×10^5 Pa. The temperature transient lasts longer, approximately 400 s, with an equilibrium temperature of 300 K. A fraction of the T_2 mass originally present in the tank flows into the glovebox, leading to approximately 46 g (1.64×10^{16} Bq) of T_2 in the glovebox at the end of the first transient. However, the constant leak rate from the glovebox results in a second, much longer transient (Fig. 2).

The volumetric concentration of tritium in the glovebox is 13.4% vol, and the volumetric concentration of deuterium is the same, resulting in a total hydrogenic species concentration of 26.8% vol. Best practices to prevent hydrogen explosions include maintaining an inert atmosphere in the glovebox under normal circumstances. The results demonstrate that this is required also in this scenario, as the hydrogen concentration exceeds the lower flammability limit of hydrogen (4%).

It is important to note that the DS is assumed to be not working, and tritium leaks outside the glovebox at a rate of 2.5×10^{-3} h^{-1}. Consequently, the estimated T_2 concentration is conservative, as it will gradually decrease as tritium leaks outside the glovebox. Larger volumes could reduce T_2 concentrations below the lower flammability limit (Section 4.1.2), but the presence of an inert gas may be sufficient to prevent fire and explosion hazards.

After 5.0×10^5 s (~5 days), all the tritium initially contained in the tank has leaked into the tritium building. Increasing the number of tanks decreases proportionally the total tritium released and the hydrogen concentration in the glovebox. At least six tanks are needed to limit hydrogen concentration below 4% (assuming that only one tank at a time fails). The use of an inert gas in the glovebox containing the tank(s) appears as a more efficient safety measure.

4.1.2. Glovebox size

Similarly to the number of feed tanks, the glovebox size was increased from the nominal value of 1 m^3 up to 30 m^3. The released mass of tritium is shown in Fig. 3. The larger volume slows down the transient, and prevents the hydrogen concentration from reaching 4%. Specifically, the maximum hydrogen concentration, reached at the end of the transient, is 0.9%.

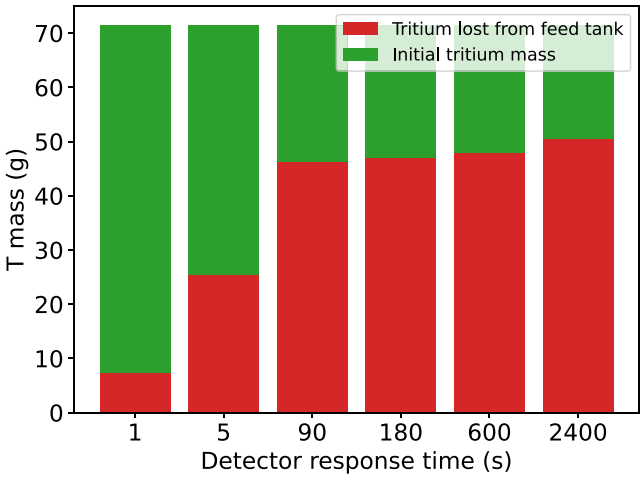
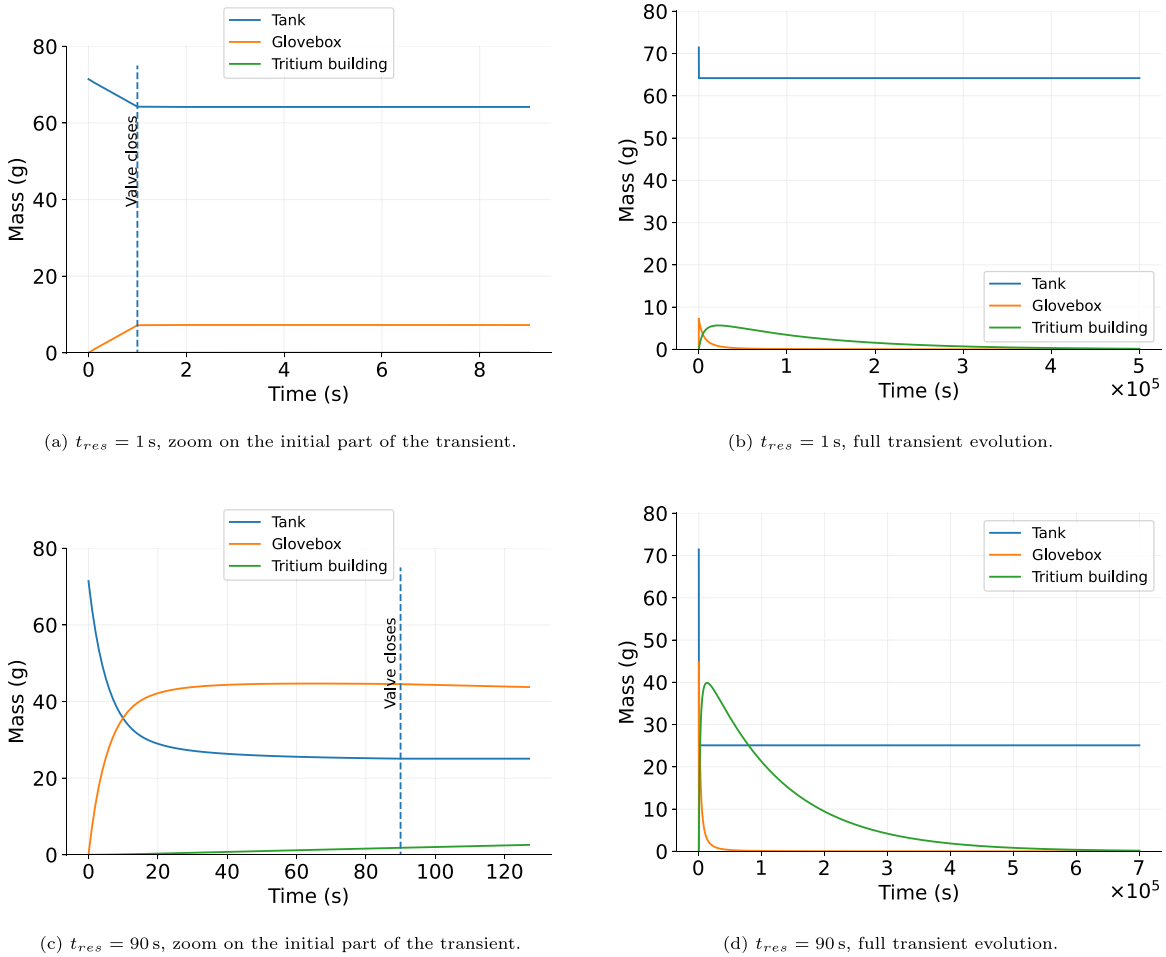


Fig. 4. Tritium released from the feed tank before the valve isolates the fault line.

4.1.3. Valve isolation time

The valve response times considered in this sensitivity analysis are 1 s, 5 s, 90 s, 180 s, 600 s, and 2400 s, with a detection threshold of 0.001 μCi m^{-3} (37 Bq m^{-3}), which is slightly lower than the detection threshold of state-of-the-art detectors (100 Bq m^{-3}). From a practical perspective, a detection threshold of 0.001 μCi m^{-3} corresponds to an instantaneous detection of the tritium release. Nevertheless, as shown in Section 4.1.4, there is no difference even if using higher detection thresholds. The response time of 1 s and 5 s can be considered representative of a fast isolation valve, potentially coupled with a control system with redundant logic to avoid spurious activations. The response time > 600 s is instead representative of a manual action that could be needed if the automatic isolation fails. Once the isolation valve downstream of the feed tank closes, no additional tritium is released from the break. The amount of tritium released for different response times is shown in Fig. 4. For t_{res} = 1 s, the released tritium is 7.2 g (2.57×10^{15} Bq), quickly rising up to 25.2 g (9×10^{15} Bq) for a response time of 5 s, and then slowly increasing above 46.1 g (1.65×10^{16} Bq) for $t_{res} \geq 90$.

Since the detection is practically instantaneous, the response time is due to the valve actuators only. For fast-acting isolation valves this can be less than (or comparable to) 1 s. Therefore, the combination of a tritium detector and an isolation valve downstream of the tank allows to prevent most of the release. If, instead, either the detection system or



(a) $t_{res} = 1\,\text{s}$, zoom on the initial part of the transient.

(b) $t_{res} = 1\,\text{s}$, full transient evolution.

(c) $t_{res} = 90\,\text{s}$, zoom on the initial part of the transient.

(d) $t_{res} = 90\,\text{s}$, full transient evolution.

Fig. 5. Comparison of transient release between $t_{res} = 1\,\text{s}$ and $t_{res} = 90\,\text{s}$ valve response times. Scenario: Guillotine break in the supply pipeline of the TSA.

the valve experience a malfunctioning or a delay, then 90 s are enough to release most of the tritium in the glovebox (Fig. 5).

4.1.4. Detection threshold

The detection threshold has been varied from $0.001\,\mu\text{Ci}\,\text{m}^{-3}$ ($37\,\text{Bq}\,\text{m}^{-3}$) to $1\,\mu\text{Ci}\,\text{m}^{-3}$ ($3.7 \times 10^4\,\text{Bq}\,\text{m}^{-3}$) to assess if higher detection thresholds could lead to a longer response time of the valve. Nevertheless, due to the high pressure in the feed tank, the release occurs so rapidly that the detected concentration is reached in less than 1 s for any chosen detection threshold.

The tritium mass transient in all relevant volumes remains identical to that shown in Fig. 5. The detection threshold was varied over four orders of magnitude, selecting values within the sensitivity range of current instrumentation. Since no differences were observed in the results, it can be concluded that the detection threshold does not impact this safety application.

4.1.5. Detritiation system process volume

All the previous results were obtained by assuming the DS malfunctions. Here, we assess the transient release for two different DS processing rates: $\dot{V} = 0.1\,\text{vol}\,\text{h}^{-1}$, which can be considered the nominal value, and $\dot{V} = 0.01\,\text{vol}\,\text{h}^{-1}$, which can be considered a pejorative case.

The DS purifies the gas stream from the glovebox and the tritium building and provides a flow of 100% N_2 for the glovebox (glovebox atmosphere is inert by N_2 filling) and air for the tritium building. No isolation valves and tritium detection systems are assumed in this analysis.

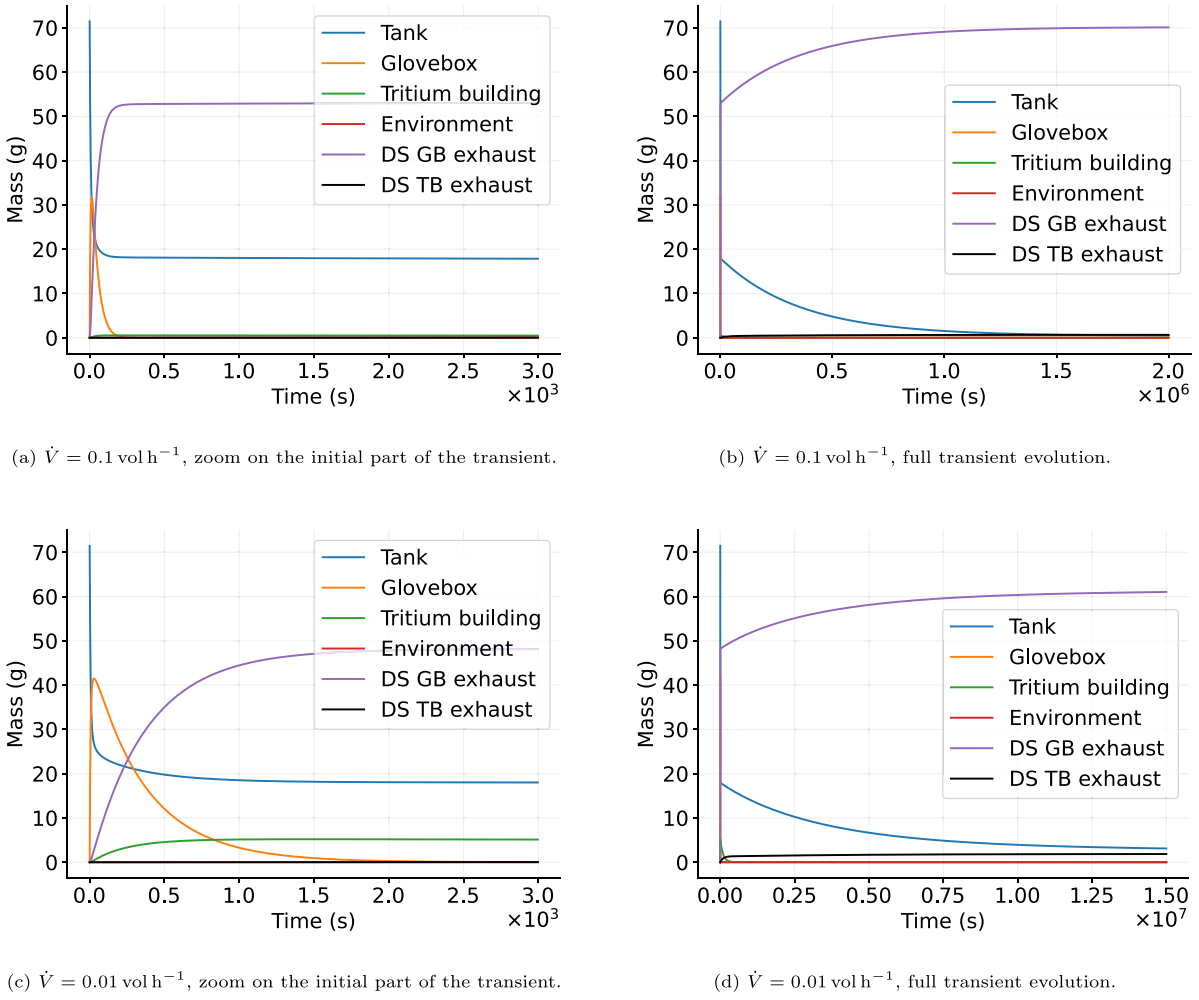
A detritiation system processing rate of $\dot{V} = 0.1\,\text{vol}\,\text{h}^{-1}$ ensures that the majority of the tritium released from the tank is captured by the DS units in the glovebox (GB DS), effectively preventing its release into the environment (Fig. 6(a-b)). Approximately 50 g (1.78×10^{16} Bq) of tritium is released within the first 60 s following the pipe break. A significant portion of the released mass is rapidly exhausted by the glovebox DS within 200 s, while the contribution of the DS in the tritium building (TB DS) is comparatively minor (Fig. 6(a-c)).

At the end of the long transient (Fig. 6(b)), which lasts for 23 days, the glovebox DS has processed 70.9 g (2.53×10^{16} Bq) of tritium, while the tritium building DS has processed only 0.65 g (2.32×10^{14} Bq).

For the second case postulated ($\dot{V} = 0.1\,\text{vol}\,\text{h}^{-1}$), 50 g ($1.78\times10^{16}$ Bq) of tritium is released within the first 500 s following the pipe break for $\dot{V} = 0.01\,\text{vol}\,\text{h}^{-1}$ (Fig. 6(c)). A large fraction of this released mass is gradually exhausted by the glovebox DS, but the process takes significantly longer (~2000 s) compared to the $\dot{V} = 0.1\,\text{vol}\,\text{h}^{-1}$. The contribution of the DS in the tritium building remains minor. As the transient progresses, the release rate slows considerably after ~20 days due to pressure equalization across all volumes and the low DS processing rate in both the glovebox and tritium building. After 170 days, the glovebox DS has processed 61.3 g (2.18×10^{16} Bq) of tritium, while the tritium building DS has processed 1.85 g (6.60×10^{14} Bq) (Fig. 6(d)). The tritium leaked to the environment amounts to 0.2 mg (7.14×10^{10} Bq) for a DS process flow rate of $\dot{V} = 0.1\,\text{vol}\,\text{h}^{-1}$, and to 5 mg ($1.79 \times 10^{12}$ Bq) for $\dot{V} = 0.01\,\text{vol}\,\text{h}^{-1}$.

4.2. Rupture of a pipe within the TSA unit

We recall that for the TSA release scenario less cases were analyzed due to the TSA configuration (Section 3). Since the break takes place at



(a) $\dot{V} = 0.1\,\mathrm{vol\,h^{-1}}$, zoom on the initial part of the transient.

(b) $\dot{V} = 0.1\,\mathrm{vol\,h^{-1}}$, full transient evolution.

(c) $\dot{V} = 0.01\,\mathrm{vol\,h^{-1}}$, zoom on the initial part of the transient.

(d) $\dot{V} = 0.01\,\mathrm{vol\,h^{-1}}$, full transient evolution.

Fig. 6. Comparison of transient release between $\dot{V} = 0.1\,\mathrm{vol\,h^{-1}}$ and $\dot{V} = 0.01\,\mathrm{vol\,h^{-1}}$ detritiation system process flow rates. DS GB and DS TB refer to the glovebox detritiation system and tritium building detritiation system, respectively. Scenario: Guillotine break in the supply pipeline of the TSA.

the connection line between the two columns, no isolation of the fault column is possible, therefore releasing all the gas in the column. The transient for two detritiation system flow rates is shown in Fig. 7.

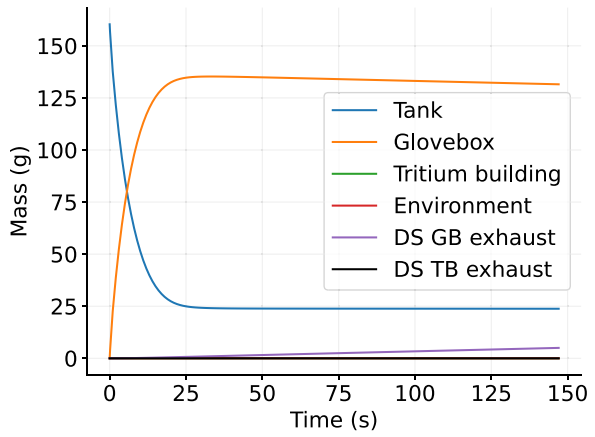
Approximately 140 g (5×10^{16} Bq) of tritium are released in the first 30 s following the pipe break. The maximum tritium concentration reached in the glovebox during the transient is 0.5%. A large fraction of the released mass is readily exhausted by the DS of the glovebox within 2×10^4 s (5.5 h). The contribution of the DS in the tritium building is much less relevant. At the end of the long transient that lasts for 11.5 days, the GB DS has processed 159.6 g (5.70×10^{16} Bq) of tritium, while the TB DS has processed 0.04 g (1.43×10^{13} Bq) of tritium. A slower DS process flow rate leads to a slightly different result, with the transient lasting for 15 days. In that case, the GB DS processes 159.5 g (5.70×10^{16} Bq) of tritium, while the TB DS processes 0.12 g (4.28×10^{13} Bq) of tritium. The tritium leaked to the environment amounts to 12 mg (4.28×10^{12} Bq) for a DS process flow rate of $\dot{V} = 0.1\,\mathrm{vol\,h^{-1}}$, and to 0.38 g ($1.35 \times 10^{14}$ Bq) for $\dot{V} = 0.01\,\mathrm{vol\,h^{-1}}$.

4.3. Hydrogen stratification

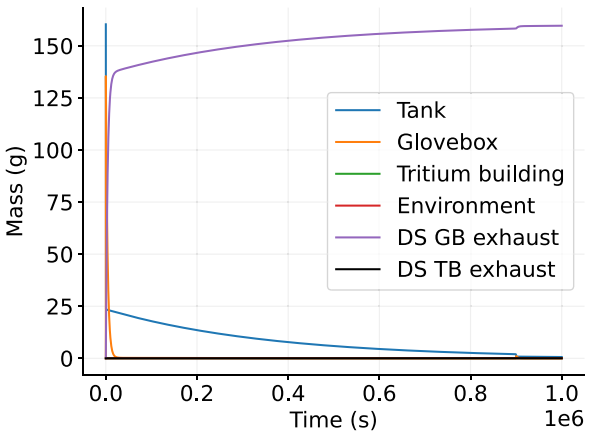
Release of hydrogen isotopes inside the glovebox or in the tritium building can lead to fire and explosions. In Section 4.1.2 we showed how the hydrogen concentration can be kept below the flammability limit by increasing the size of the glovebox, even in the pejorative scenario in which the inert gas is displaced by air. While hydrogen concentration in the tritium building is well below the flammability limit if an homogeneous distribution is considered, stratification may increase its concentration locally. During the initial transient the large pressure difference between the feed tank or TSA unit and the glovebox atmosphere would provide gas mixing such that stratification would not take place. However, once the pressures equalize and the tritium leaks from the glovebox, the system reaches an equilibrium where stratification may take place. The concentration as a function of the building height is shown in Fig. 8. The maximum volume fraction is reached at the top of the hall (1.2×10^{-4} vol%), but the value is well below the lower flammability limit. Therefore, we can conclude that even if stratification effects are included, there is no risk of fires and explosion in the tritium building.

5. Discussion and conclusions

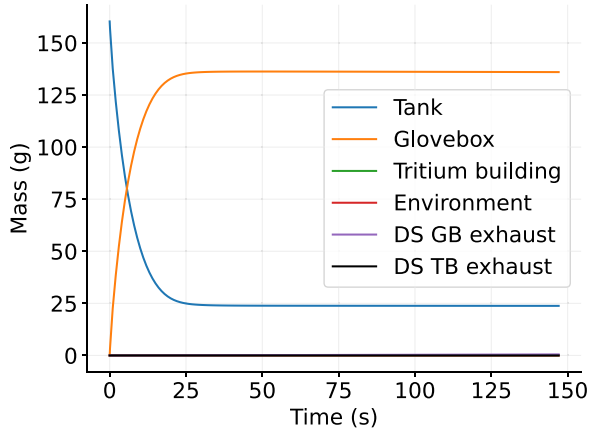
In this work, two accidental scenarios in DEMO IRPR system were analyzed. The model was developed in MELCOR 1.8.6 for fusion, and included the feed tank, the piping and the TSA. A detritiation system that processes the atmosphere inside the gloveboxes (both for the feed tank and the TSA unit) and inside the tritium building was considered. Additionally, a tritium detection system and an isolation valve were considered as an additional safety measure. The detection system was placed in the feed tank glovebox, and the isolation valve was located downstream of the tank to minimize the amount of tritium released in



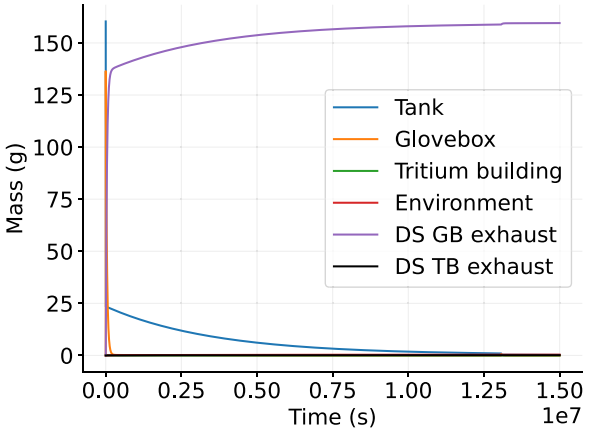
(a) $\dot{V} = 0.1\,\mathrm{vol\,h^{-1}}$, zoom on the initial part of the transient.



(b) $\dot{V} = 0.1\,\mathrm{vol\,h^{-1}}$, full transient evolution.



(c) $\dot{V} = 0.01\,\mathrm{vol\,h^{-1}}$, zoom on the initial part of the transient.



(d) $\dot{V} = 0.01\,\mathrm{vol\,h^{-1}}$, full transient evolution.

Fig. 7. Comparison of transient release between $\dot{V} = 0.1\,\mathrm{vol\,h^{-1}}$ and $\dot{V} = 0.01\,\mathrm{vol\,h^{-1}}$ detritiation system process flow rates. Scenario: Rupture of a pipe within the TSA unit.

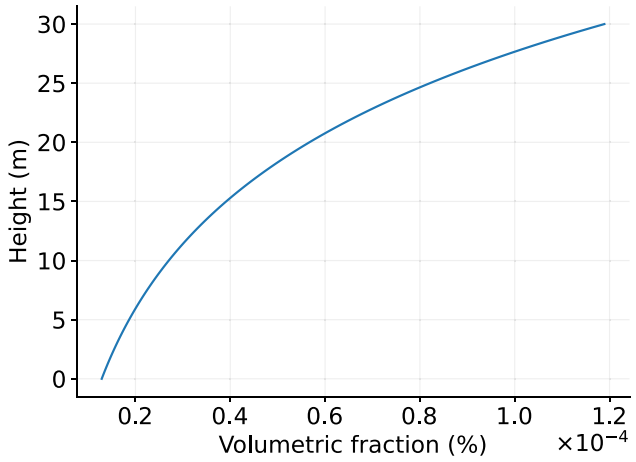


Fig. 8. Hydrogen concentration as a function of the tritium building height.

case of a guillotine break in the pipeline that connects the tank with the TSA unit. Pressure-dependent leak rates were also modeled to simulate the tritium leak from the glovebox to the tritium building. We found that the amount of tritium released is strongly reduced by the presence of the detection and isolation system and by the detritiation system, which, together, can prevent tritium release from the tritium building. The main results of this analysis can be summarized as follows:

- The response time of the detection and isolation system strongly affects the tritium released to the environment. The optimal response time is around 1 s. Fast-acting isolation valves are thus recommended to ensure rapid system isolation. Since most of the tritium is released from the feed tank and the TSA in short times (i.e., on the order of tens of seconds), the effectiveness of this safety system rapidly decreases as the response time increases from seconds to tens of seconds (Fig. 4). Provided that the response time is short, the detection and isolation system alone may provide a suitable safety barrier to face radiological releases, even in case of detritiation system malfunctions.
- The detection threshold does not affect the performance of the detection and isolation system. In fact, during an accident, the release of tritium is so fast that the detection threshold is reached in less than a second, even considering poor performances (high detection thresholds) of the detector.
- Maintaining an inert atmosphere in the glovebox is mandatory, as the hydrogen concentration can exceed the lower flammability limit in the accidental scenarios considered in this analysis.
- A detritiation system working at nominal flow rate (0.1 vol/h) can limit the tritium release for both cases below 1 g (3.57×10^{14} Bq),

in a release time of 23 days, without any isolation of the fault line. Therefore, the combination of the DS system and an isolation valve can prevent significant tritium releases. The release from the tritium building increases to 5.44 g (1.94×10^{15} Bq) if the DS flow rate is reduced by a factor of 10 (i.e., 0.01 vol/h). In both cases, a detection and isolation system may be envisioned as an additional safety barrier.
- Stratification of hydrogen may occur, but the maximum value of the volume fraction reached in the tritium building is 1.2×10^{-4}, well below the flammability limit of hydrogen.
- The IRPR could be located in a dedicated, smaller room to provide an additional enclosure volume and to allow extraction to a DS without affecting the rest of the plant.

CRediT authorship contribution statement

Samuele Meschini: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Raffaella Testoni:** Writing – original draft, Resources, Methodology, Formal analysis, Conceptualization.

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.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Appendix

- CVH-001, CVH-002, CVH-003, and CVH-004 model the feed tank, the glovebox, the tritium building, and the external environment, respectively. CVH-005 serves as a reservoir of air at ambient pressure and temperature to model the inflow of air into the tritium building via the HVAC system. CVH-006 represents the downstream section of the glovebox detritiation system, while CVH-007 acts as a sink for the tritiated stream from the glovebox detritiation system.
- CVH-001 initially contains a mixture of D_2, T_2, and H_2 (49.5/49.5/1; D/T/H) under the corresponding thermodynamic conditions, $p = 4 \times 10^5$ Pa, $T = 300$ K. CVH-002 contains an inert gas (N_2) at room pressure (10^5 Pa) and temperature (298.15 K). CVH-003, CVH-004, and CVH-005 contain air at room pressure (10^5 Pa) and temperature (298.15 K). CVH-006 contains N_2 at room pressure (10^5 Pa) and temperature (298.15 K). CVH-007, acting as a sink for the tritiated flow from the detritiation system, is initially filled with N_2 at room pressure (10^5 Pa) and temperature (298.15 K). The molar fraction input for CVH defines the correct mixture in the corresponding volumes. A volume of 1 m^3 is assumed for the glovebox, with a height of 1.3 m to accommodate the tank. The tritium building volume is estimated at about 140000 m^3.
- The height (H) and diameter (D) of the feed tank are assumed to be $H = 120$ cm and $D = 40$ cm. The height is a required input for defining CVH-001, while the diameter is needed to properly define the Heat Structure (HS), as described below.
- HS-001 models heat transfer between CVH-001 and CVH-002, while HS-002 models heat transfer between CVH-002 and CVH-003. The HS is essential to establish thermodynamic equilibrium between the two volumes following the accident. A vertical, rectangular heat structure made of stainless steel is assumed, with HS-001 and HS-002 having a thickness of 0.3 cm, one internal node, and two boundary nodes, spaced at 0.15 cm. A convective boundary condition is set on both the internal and external surfaces. The initial temperatures of HS-001 and HS-002 are 300 K and 298.15 K, respectively. HS-003 and HS-004 model heat transfer between the tritium building and the external environment. The heat transfer surface is 13160 m^2 (i.e., the total building surface minus the floor surface). HS-005 and HS-006 connect the glovebox to the DS to maintain thermal equilibrium. A convective boundary condition is applied on both the internal and external surfaces.
- FL-001 models the hydrodynamic connection between CVH-001 and CVH-002. The pipe linking the feed tank to the TSA unit is assumed to break at 5 m from the tank connection. FL-001 is thus a Flow Path (FL) with a length of 5 m and a diameter of 1 cm (Table 1).
- FL-002 models the constant leak rate from CVH-002 (glovebox) to CVH-003 (tritium building). The leak rate is derived from ISO 11933-4, which specifies a nominal leak rate of $\dot{V}_{\mathrm{nom}} = 2.5 \times 10^{-3}$ h^{-1} for class 2 containments at $\Delta p_{\mathrm{nom}} = 250$ Pa. Since the pressure difference between the glovebox and the tritium building is not constant during the release, the leak rate is defined as a function of pressure difference:

$$\dot{V}(\Delta p) = \dot{V}_{\mathrm{nom}} \times \sqrt{\frac{\Delta p}{\Delta p_{\mathrm{nom}}}}. \tag{7}$$

  The flow path area corresponds to the glovebox surface to simulate leakage through the surface.
- FL-003 models the leak rate from CVH-003 (tritium building) to CVH-004 (environment). A constant leak rate of 100% volume/day is used [7]. The flow path area is set equal to the HS-003 surface to simulate leakage through the surface.
- FL-004 models the air intake from the HVAC system, which connects CVH-005 to CVH-003 (tritium building). The flow rate is balanced to match the leak rate of FL-003.
- FL-005 and FL-006 represent the inflow and outflow through the glovebox. FL-005 connects CVH-006 (DS downstream) to CVH-002 (glovebox), while FL-006 connects CVH-002 (glovebox) to CVH-007 (DS stream sink). The nominal flow rate in FL-005 and FL-006 is set at 0.1 vol/h, corresponding to 2.7×10^{-2} m/s.

The nodalization for the break in the TSA piping followed a similar approach. We report here the main differences in the nodalization, the remaining part being the same as described previously.

- CVH-001 models all the 220 columns in a single volume. CVH-002 models the glovebox. CVH-003 models the tritium building. CVH-004 models the external environment. The most critical conditions have been assumed for CVH-001, according to the values reported in Table 2, i.e., $p = 10^6$ Pa and $T = 433$ K. The volume of CVH-001 is the sum of all the column volumes. The gas mixture in CVH-001 is taken from [5]. The most critical condition (from a safety perspective) is reached when the T_2 molar fraction is maximum, at 92.5%. The remaining fraction (7.5%) is D_2, with H_2 present only in trace. CVH-002 contains an inert gas (N_2) at room pressure (10^5 Pa) and temperature (298.15 K). The glovebox volume for the TSA unit is assumed to be 105 m^3 to accommodate the TSA arrangement ($1.5 \times 12 \times 5$ m). As mentioned in Section 2, this value accounts for the TSA glovebox only, while the tank is placed in its own glovebox. CVH-003, CVH-004, and CVH-005 contain air at room pressure (10^5 Pa) and temperature (298.15 K).

CVH-006 contains N_2 at room pressure (10^5 Pa) and temperature (298.15 K). CVH-007 acts as a sink for the tritiated flow from the DS and is initially filled with N_2 at room pressure (10^5 Pa) and temperature (298.15 K).

- HS-001 models the heat transfer between CVH-001 and CVH-002, while HS-002 models the heat transfer between CVH-002 and CVH-003. The heat structures (HS) are essential to achieve thermodynamic equilibrium between these volumes following an accident. A vertical, rectangular heat structure made of stainless steel is assumed. The thickness of both HS-001 and HS-002 is set to 2×10^{-5} m, with three equally spaced nodes (one in the middle and two at the boundaries). This small thickness prevents the thermal energy stored in the HS from significantly influencing the accident scenario evolution. Convective boundary conditions are imposed on both the internal and external surfaces of the HS. Finally, HS-003 models the heat transfer between CVH-003 and CVH-004.

Data availability

Data will be made available on request.

References

[1] C. Day, B. Butler, T. Giegerich, B. Ploeckl, S. Varoutis, A smart three-loop fuel cycle architecture for DEMO, Fusion Eng. Des. 146 (2019) 2462–2468.
[2] C. Day, K. Battes, B. Butler, S. Davies, L. Farina, A. Frattolillo, R. George, T. Giegerich, S. Hanke, T. Härtl, et al., The pre-concept design of the DEMO tritium, matter injection and vacuum systems, Fusion Eng. Des. 179 (2022) 113139.
[3] J. Schwenzer, C. Day, T. Giegerich, A. Santucci, Operational tritium inventories in the EU-DEMO fuel cycle, Fusion Sci. Technol. 78 (8) (2022) 664–675.
[4] R. Shaw, B. Butler, Initial accident scenario analysis in support of a preliminary DEMO tritium plant design, Fusion Eng. Des. 189 (2023) 113482.
[5] C. Neugebauer, Y. Hörstensmeyer, C. Day, Technology development for isotope rebalancing and protium removal in the EU-DEMO fuel cycle, Fusion Sci. Technol. 76 (3) (2020) 215–220.
[6] J. Schwenzer, TFV Technical Note, Tech. Rep., 2021.
[7] M. Povilaitis, Safety Data List, Tech. Rep., 2021.