Tritium Inventories and Tritium Safety Design Principles for the Fuel cycle of ITER

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ABSTRACT

Within the Tritium Plant of ITER a total inventory of about 2 to 3 kg will be necessary to operate the machine in the DT phase at a throughput of about 1 kg tritium per hour. During plasma operation, tritium will be distributed in the different subsystems of the fuel cycle. A tool for tritium inventory evaluation the dynamic model (TRIMO) of the tritium content in each sub-system of the Fuel Cycle of ITER was developed. The code reflects the design of each system; both the physical processes characteristics of each system and the associated control systems are modeled in TRIMO. The confinement of tritium within the respective systems of the Fuel Cycle is one of the most important safety objectives. The design of the deuterium / tritium fuel cycle of ITER includes a multiple barrier concept for the confinement of tritium and has two major features, namely a two (primary and secondary) barrier design and secondary containment atmosphere and gaseous waste treatment systems. Ultimately the building is equipped with a vent detritiation system and re-circulation type room atmosphere detritiation systems, required as an emergency tritium confinement barrier during possible accidental events. In order to assure a high integrity of the tritium bearing systems within the ITER Tritium Plant the design considers largely protection measures (mainly overpressure and overtemperatue protection).

1. Introduction

Within the Tritium Plant of ITER a total inventory of about 2 to 3 kg will be necessary to operate the machine in the DT phase at a throughput of about 1 kg tritium per hour. During plasma operation, tritium will be distributed in the different subsystems of the fuel cycle. About 1 kg tritium will be located in the Long Term storage; a significant amount of tritium will also be in the vacuum vessel and in the Hot Cells.

2. Fuel Cycle of ITER

In Figure 1 the block diagram of the Fuel Cycle for ITER is presented. D₂, DT and T₂ fuel is withdrawn from the Storage and Delivery System (SDS) which is composed of several storage beds and buffer vessels. Gas is injected in the Torus through the gas and pellet injection systems. The pressure in the Torus is kept by the Vacuum pumping system (consisting of cryopumps) and the exhausted gas is directed to the Tritium Plant for purification and re-injection. In the Tritium Exhaust Processing impurities are separated from hydrogenic isotopes and these eventually are separated in the Isotope Separation System being sent back in the SDS. In the Water Detritiation System tritiated water (mainly produced in the atmosphere detritiation systems) is converted to gaseous form and tritium is recovered using the Isotope Separation System.
3. Effluents and releases

An assessment of the potential effluents and emissions from ITER has been carried out [3]. Both airborne emission and waterborne effluent releases have been considered with estimates being made for both normal plasma operation and maintenance. As a result project release guidelines have been established, below possible national requirements together with implementation of the “as low as reasonably achievable” (ALARA) principle. As a following a detailed release assessment has been performed for each element in the ITER WBS to ensure that no significant release pathway was missed. As a result the release estimate in comparison with the project guideline is presented in Table 1.

<table>
<thead>
<tr>
<th>Species</th>
<th>Release estimate</th>
<th>Project Guideline</th>
<th>% of Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium – as HTO in air</td>
<td>0.05 g/a (18.07 TBq/a)</td>
<td>0.1 g tritium/a</td>
<td>50</td>
</tr>
<tr>
<td>Tritium in water</td>
<td>0.0004 g/a (0.14 TB/a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tritium – as HT in air</td>
<td>0.18 g/a (67 TBq/a)</td>
<td>1 g tritium/a</td>
<td>18</td>
</tr>
</tbody>
</table>

4. Tritium inventory modeling for the Fuel Cycle of ITER

A tool for tritium inventory evaluation within each sub-system of the Fuel Cycle of ITER is vital, with respect to both the process of licensing ITER and also for operation. It is very likely that measurements of total tritium inventories may not be possible for all sub-systems, however tritium accounting may be achieved by modeling its hold-up within each sub-system and by validating these models in real-time against the monitored flows and tritium streams between the systems. A dynamic model (TRIMO) of the tritium content in each sub-system of
the Fuel Cycle of ITER was developed [1]. The code operates by solving the mass balance around each sub-system, progressing in each time step through fueling, Torus, Vacuum pumping, Tokamak Exhaust Processing (TEP), Water Detritiation System, Isotope Separation System and finally Storage and Delivery System. The code reflects the design of each system; the physical processes characteristics to each system are modeled (non-steady, 1-dimensional for most of the systems) and additionally the associated control systems are modeled in TRIMO. TRIMO provides information related to the tritium inventories within each Fuel Cycle system during burn-dwell functioning but also during other operational scenarios of ITER (e.g. during tritium inventory procedures). Graphical outputs are available for time variation of flow rates and composition in the streams between Fuel cycle subsystems. Composition variations along the CD columns from the ISS and LPCE column from WDS are also computed in TRIMO. Tritium inventories as trapped in Torus or as build-up in impurities as CQ4, Q2O in the vacuum pumping system is computed in TRIMO.

In Figure 2 the tritium inventories in the Fuel Cycle of ITER is plotted for 1 day of operation considering the Long pulse scenario (3000s burn, 9000s dwell time). It can be seen that the highest values of tritium inventories are in the SDS, ISS and in the Cryopumps. For the moment the inventory in the Pellet Injection System was considered constant, but on-going R&D will have to validate this assumption.

Presently a draft documentation of TRIMO was issued and work on validation by comparison with experimental results on various subsystems (cryogenic distillation column, water detritiation system, storage beds) is on-going.

Figure 2 Time variation of the tritium inventories in the Fuel cycle of ITER

5. Tritium confinement

The confinement of tritium within the systems of Fuel Cycle is one of the most important safety objectives. The design of the Fuel Cycle of ITER includes a multiple barrier concept for the confinement of tritium. The concept follows the experience and practice of tritium facilities and has two major features, namely a two (primary and secondary) barrier design and secondary containment atmosphere and gaseous waste treatment systems. As the final barrier for tritium confinement, buildings and/or rooms which contain tritium processing systems are equipped with emergency isolation dampers in the ducts of heating, ventilation and air conditioning system (HVAC).
5.1. Primary barrier

In order to assure a high integrity of the primary (tritium bearing) systems within the ITER Tritium Plant they are designed to high standards using tritium compatible materials. Austenitic stainless steel is used for vessels and piping of the tritium subsystems unless use of other material is an essential requirement (for example the electrolytic cells for highly enriched tritiated water, catalysts in the WDS). When this is the case an extensive R&D program has been carried out to investigate the limitations and lifetime of these materials [2]. The design target for the overall helium leak rate of the primary systems is generally $10^{-9}$ mbar l/s. The primary systems and its parts are to be protected against over-pressure, over-temperature, tritium permeation through structural materials and tritium spill to secondary containments system. Heated components above 150°C are equipped with an outer jacket. The evacuated interspace serves for thermal insulation and allows recovering permeated tritium, the pressure in the interspaces being monitored. Purging (helium, nitrogen) and evacuation for maintenance or removal of components is always foreseen in the design. While for heated components in general the jacket volume can be kept under vacuum, padding of the jacket volume with helium is important in case of a tritium storage bed to avoid any temperature rise above ambient.

5.2. Secondary containments

Depending on the tritium amount and concentration the secondary containments in the tritium handling facilities can be glove-boxes, hard shell boxes and in some cases the building itself. The atmosphere of secondary containments is provided with detritiation systems and on a case by case basis an atmosphere cooling system can also be provided. The glove-boxes are operated in under pressure conditions (typically 4-7 mbar). To avoid build-up of tritiated water in the primary system in case of an inleakage, the atmosphere of the secondary containment is nitrogen with very little oxygen. A certain partial pressure of oxygen (0.5-1%) is needed to convert leaked isotopic hydrogen and hydrocarbons into water and carbon dioxide. The secondary containment system is connected to a tritium retention system. Typically the tritium retention systems of a glove-box comprise a catalytic oxidation step for the conversion of hydrogen isotopes and impurities into water and carbon dioxide, followed by an adsorption step where water is retained on molecular sieves. The secondary containment system is equipped with sensors to measure tritium level (typically limited to $4 \times 10^6$ Bq/m$^3$) and as requested humidity, temperature, pressure and composition.

5.3. Safety relevant design features of the ITER Fuel cycle

The most important features implemented in the design of the tritium containing systems are over-pressure protection, over-temperature protection and avoiding cross-contamination. The principal sources for an over-pressure in tritium processing systems can be external, such as (bottled) gas supplies, or internal, such as pumps, evaporation of liquids or desorption of gases from getter beds or molecular sieves. While the limitation of pressure from external gas supplies by burst disks or relief valves discharging into conventional ventilation systems is straightforward, the measures against over-pressure by internal sources is more demanding. As the ISS has the highest tritium inventory (and which is in liquid form) for exemplification the overpressure protection philosophy for cryogenic distillation of hydrogen isotopes (Figure 3) is given as an example in the following.
Since most of the CD column content is in a liquid form, once evaporated, the pressure in the process will be substantially higher. As it can be seen from Figure 3, the process relief devices would be discharging into an expansion vessel. The primary envelope has an automatic valve, which directly connects the envelope with the expansion vessel and would release pressure from the primary envelope into the expansion vessel before the rupture disc is activated. The expansion vessel is sized to contain all CD content including a safety margin. The coldbox is a pressurized vessel provided with a relief valve which discharges into the atmosphere de-tritiation system. Since the coldbox may be contaminated with tritium, a rupture disk is provided upstream of the relief valve to minimize its contamination.

Figure 3 Over-pressure protection strategy for CD columns

Several issues have been considered such as avoiding contamination of the refrigerant with tritium, by providing an intermediate hydrogen cooling pool to separate the refrigerant cooling stream by the process gas, hardware pressure limitations (depending on the pump types) and recovery of process gas after expansion following warm shutdown.

Related to the over-temperature protection, generally two redundant temperature sensors are employed with one sensor being connected to the Automated Control System and the other to the Safety System.

In addition to the design philosophy exposed above, several measures are taken into the design of both the primary and secondary containment systems (and the automated control system and safety system correspondingly) such as installation of redundant or diverse components if the failure of the component is a significant safety concern, monitoring of the system through the computer control system and vacuum leak testing as part of the operating routine.
6. Detritiation systems

6.1. Atmosphere Detritiation Systems

Tritium Detritiation subsystems for the tokamak building, tritium building, hot cell and radwaste buildings are operated on various modes depending on the plant operation states such as normal operation, maintenance and off-normal events.

The integrated atmosphere detritiation system configuration for the Tokamak and tritium buildings is presented in Figure 4. As it can be seen, during normal operation a Normal Vent Detritiation system (700 Nm$^3$/h) processes tritiated streams from many sources (effluents from tritium plant, vacuum pumping, glovebox atmosphere detritiation systems and purge gases) and operates in semi once-through.

In the case of an off-normal event the HVAC systems branch ducts in each room/area are isolated and the recirculation type room atmosphere detritiation systems (standby atmosphere detritiation system, S-ADS 4500m$^3$/h) is put into operation. In this case the N-VDS is backed up by the once-through standby vent detritiation system SVDS 3000m$^3$/h). The S-ADS and S-VDS ensure that in case of an accidental tritium release into rooms negative pressure is maintained, the extracted air is detritiated to the required low level before release into the environment and the tritium concentration in the affected room(s) is rapidly decreased.

Figure 4 Integrated Atmosphere Detritiation System Configuration

A typical atmosphere detritiation system general consists of three stages:
a. recombiner stage, where elemental tritium in the source air is catalytically converted into tritiated water molecules and tritiated organic species are oxidized to tritiated water molecules and CO2.
b. molecular sieve bed dryer regeneration loop, where tritiated water produced in the recombiner is adsorbed on the dryer bed. The necessary components for bed regeneration (heater, condenser, mist separator) are also part of this stage.
c. Direct condensing stage (condenser and mist separator) for the case when the air humidity is very high. In this case the recombiner loop is bypassed until the moisture level is reduced.

6.2. Water Detritiation System

During ITER operation tritiated water will be generated by various sources, which lead to accumulated amounts that are by much in excess of the amounts that can be periodically discharged as effluent. In the Water Detritiation System tritium is recovered from tritiated water and the remaining tritium concentration in the effluent streams has to be within the discharge limits. The employed method is Combined Electrolysis Catalytic Exchange having as major components an electrolyser unit where tritiated water is converted to gaseous form (part of this stream is furthered process in the ISS for tritium recovery) and a Liquid Phase Catalytic Exchange column. In the LPCE column tritiated hydrogen from the electrolyser is processed in counter-current with pure water and decontaminated to the extent that it can be released into the environment. Currently R&D is carried out to assess the consequences of returning the top stream release from the ISS to the WDS for final detritiation. In this manner the only stream that will discharge directly to the environment without additional detritiation system would be the WDS.

7. Closing remarks

The concept and design of the Fuel cycle and Tritium Plant for ITER ensure that confinement and minimization of the tritium releases during ITER normal operation and in any accidental state is assured together with maximum availability for ITER normal operation. The safety measures appropriate to protect the tritium processing systems against the risks identified in safety considerations are well known; practical experience is available from experiments in tritium laboratories or tritium facilities serving fusion machines like Joint European Torus.

Acknowledgement

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References:

3. ITER Generic Site Safety Report, vol IV