Multiscale integral analysis of tritium leakages in fusion nuclear power plants

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Abstract— Current conceptual design efforts regarding tritium (T) recovery from breeders focus on the Internal Regenerator Cycle (IRC). Tritium could be recovered either from He flowing gas, or directly from solid or liquid breeders. Tritium environmental release rate limit are assumed to be ~ 1 g-T/y (~20 Ci/y) (without species distinction). This limit determines the key parameters for the T in IRC. The mechanism of transfer to the environment is assumed to be through leakages or permeation at the exchange system of the power plant (primary to secondary loop). Hence, chemical process optimization of the primary system is a key factor that needs to be reanalyzed in terms of radiological impact. Transfer from the IRC to the environment is conservatively assumed to be operating with a single enclosure scheme. Tritium loss is mainly caused by elementary tritium (HT) and tritiated water vapour (HTO) permeation and simultaneous primary coolant leakage through steam generators. Primary coolant chemistry appears to be the most effective way to control T permeation from the breeder into primary coolant and from primary coolant through Steam Generators (SG) by H2 flux isotopic exchange or steel.

Keywords—tritium; leakages; atmospheric transport; CFD, system codes, coupling)

1. Introduction

It is foreseen that tritium (T) will be responsible for a large fraction of the environmental impact of the first generation of DT fusion reactors. The EU Fusion Program is currently developing two breeding blanket conceptual designs, both using He as coolant. One is a solid breeder that uses Li-ceramic material (HCPB, Helium-Cooled Pebble Bed) and the other is a liquid breeder that uses a liquid metal eutectic alloy (Pb15.7Li) (HCLL, Helium-Cooled Lithium Lead). Both are based on Li-6 enriched materials. Demonstration scale designs will be tested as Test Blanket Modules (TBM) in the ITER experimental fusion reactor. The tritium cycles linked to both blanket concepts are similar, with some different characteristics. Tritium is recovered from the He purge gas in the case of HCPB, and directly from the breeding alloy through a carrier gas for the HCLL.

A future 2.5GWth self-sufficient fusion reactor will need a few hundred grams of T per day. Safety and environmental impact are today the top priority design criteria. Dose impact limits should determine the design margins and parameters. Transfer from the IRC to the environment is conservatively assumed to be operating with a single enclosure scheme through the T plant power conversion system (intermediate heat exchangers and helium blowers). Tritium loss is mainly caused by HT and T2 permeation and simultaneous primary coolant leakage through steam generators. Primary coolant chemistry appears to be the most

effective way to control tritium permeation from the breeder into primary coolant and from primary coolant through Steam Generators (SG) by H2 flux isotopic exchange or steel (EUROFER/INCOLOY) oxidation.

In a generic CANDU, the water detritiation system capacity is around 360 L/h while ITER capacity is of 20 L/h. Note that he NRC inspection reports [1] list of reactor sites that experienced a leak or spill to the environment show that tritium release was larger than 20.000 pCi/L (740 Bq). The present work exposes an integral methodology that pretends to be a decided step towards a standard for safety analysis regarding tritium leakages to the environment. An example of a multiscale integral analysis of a tritium leakage at a fusion power plant is presented, illustrating when, where and how different scale analysis interface with each other, in order to provide accurate and reliable results and give valuable insights from the design, operation and safety point of view. The methodology is based on a multiscale analysis covering the whole tritium cycle within a nuclear power plant, from a micro scale, analyzing key components where tritium is leaked through permeation, to a macro scale, considering its atmospheric transport. The mechanism of transfer to the environment is assumed to be through leakages or permeation at the exchange system of the power plant (primary to secondary loop). Hence, chemical process optimization of the primary system is a key factor that needs to be reanalyzed in terms of radiological impact. It is necessary to consider all the pathways of tritium from the reactor to the atmosphere and to model al transport phenomena adequately. Early and chronic doses, which have been evaluated for the Most Exposed Individual (MEI), has been calculated at particular distance bands from the release point.

2. Integral multiscale analysis methodology

2.1. Tritium micro scale analysis

Tritium is a lightweight species capable of permeating through structural materials of a fusion reactor. As a results special care must be taken when calculating tritium inventory as time and spatial scales must be resolved with the necessary resolution to take into account all phenomena that may take place. Micro scale analysis can be achieved by using highly complex codes that take into account most of the tritium related transport phenomena. However, most of these codes have not been validated. As a result a thorough assessment of these codes have to be done before using them. Once a code has been selected as suitable boundary and initial conditions (BC & IC) have to be determined as well as the output or coupling to other codes. Time and spatial scales for this type of calculations is small and, therefore, coupling becomes difficult.

System Codes (SC) can be easily coupled to Computational Fluid Dynamic (CFD) codes. However, spatial discretization must be handled with care. Most of the cases only require a so called soft coupling, i.e. SC results are set as a transient BC or IC in the CFD codes. Some special cases will need a hard coupling due to the interaction between calculation domains.

2.2. Tritium macro scale analysis

Macro scale analysis can also be achieved by using SC and CFD depending on the computational resources available. In this case, the same coupling problems arise for SC-CFD coupling and at the same time for micro to macros scale coupling. Note that soft coupling is here also the preferred method as small time scale phenomena may not impact the behavior of the macro scale calculations. Multiscale integral analysis must be carried out from the conservative point of view. Hence, coupling has to be performed so that the simulated phenomena overestimates the tritium transport rather than underestimating it. As a result

special consideration must be taken regarding numerical tolerances, boundary and initial conditions settings and phenomena impact on the overall behavior of the system.

2.3. Tritium atmospheric analysis

For selecting the boundary conditions in the Tritium atmospheric dispersion at the macro scale, conservative parameters are used to define the input of the coupling. With the data calculated at macro scale, a suitable input can be established for the coupling of the atmospheric dispersion required for the primary phase. First of all, the initial deterministic calculations are considered and in a second step they are corrected with probabilistic techniques. In this way, an output can be obtained for the secondary phase of the tritium released to the atmosphere, leading to a more realistic data approximation.

2.4. Tritium dosimetric analysis

The methodology used for the calculation of the doses is considered probabilistically. The secondary phase in the tritium dispersion requires a coupling in the dispersion outputs and the tritium transport in all the body intake enclosures. In this phase, all mechanisms should be established where the deposition and incorporation in the environment can result in absorbed dose, including the oxidation of tritium in the case of HT.

3. RESULTS

In the present work a leakage from a steam generator (SG) is taken as an example to expose the integral and multiscale methodology. As an example a 2.5 GWth fusion power plant with three power loops is simulated at system level with MELCOR [3], coupled to ANSYS® Fluent® CFD code for site analysis and atmospheric transport up to 1 km. The postulated accident assumes that the SG breaks and HTO leaks through a hole in its shell. Note that this is a worst case scenario design to clearly show how different codes can be coupled to achieve an integral and multiscale analysis.

3.1. SG MELCOR results

MELCOR have been used as system code simplified example in order to analyze the behavior of a leakage at a SG and to expose its coupling to ANSYS® Fluent®. A small leakage, which is a hole in the shell, at the top of the SG with a section of 7.5 x 10-5 m2 is set to happen 1000 s after the system reaches the steady state. Leakage is located at the external shell of the steam generator so that water vapor together with tritium, permeated from the primary He coolant loop, are leaked to a room inside an auxiliary building (see Fig. 1). Steam generator as simulated with MELCOR

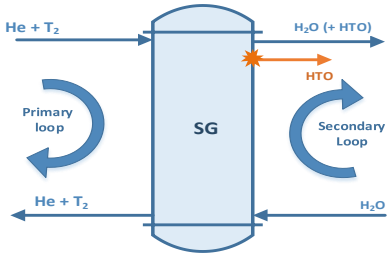

Fig. 1. Steam generator as simulated with MELCOR.

A safety measure is tripped 1800 s after the accident, isolating the SG's secondary loop. MELCOR nodalization is shown in Fig. 2.

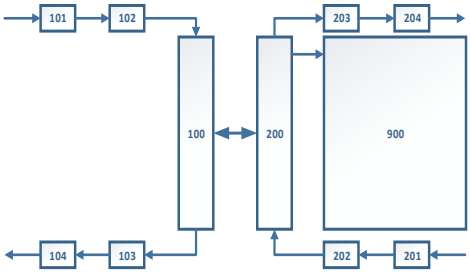

Fig. 2. MELCOR nodalisation for the SG.

Results, shown in 0, present a maximum mass flow rate of 0.82 kg/s and rapidly decreases when the secondary loop is isolated. The tritium leakage is assumed to be only in form of HTO and with a mass fraction of a 0.001 for a conservative calculation. Leakage mass flow rate evolution. The resulting MELCOR data is set as a time dependent boundary condition in ANSYS® Fluent® through a User Defined Function (UDF) as detailed in the following section.

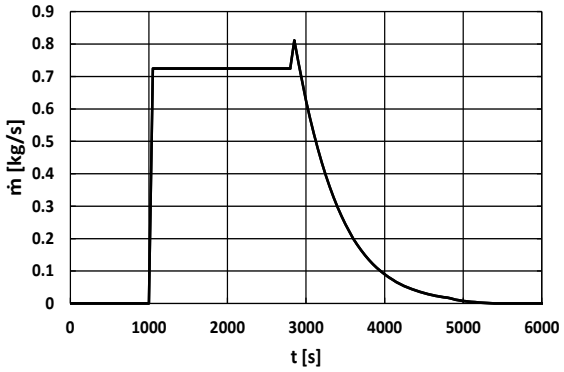

Fig. 3. Leakage mass flow rate evolution.

3.2. CFD room and site results

MELCOR mass flow rate with a HTO mass fraction of 0.001 is set as a time dependent BC at the surface corresponding to the SG leakage. A UDF has been coded in order to couple the MELCOR results to ANSYS® Fluent®. It must be noted that the current coupling, which is a simplified example to show how this calculation can be run, is a soft-coupling, but both codes can be hard coupled. This way, ANSYS® Fluent® will read the MELCOR results for each time step and the other way round. A simplified generic geometry for a fusion reactor site has been meshed, using polyhedral cells for a better convergence. In addition, a room within an auxiliary building with a simple HVAC system have also been modelled. Leakage effects at the room and at site scale have been analyzed from a qualitative point of view in order to assess the exposed methodology.

A case without the leakage has been run until convergence is achieved in order to have a steady state solution as an initial condition for the transient leakage case. The transient case is run until the plume

reaches its maximum. Distribution of HTO in the auxiliary room is shown in Fig. 5. Note that concentrations are 3 to 4 orders of magnitude larger than those in the plume (see Fig. 4). Wind velocity streamlines over the plant are shown in Fig. 4 together with the plume surface evolution. Note that that an isosurface for 1.0 x 10-9 kgHTO/kgtot is shown and that the plume impacts the ground as shown in Fig. 7 the ground mass fraction distribution in Transient case results show how the leakage is diluted due to the HVAC system and the time necessary for the HTO leakage to exit through the exhaust. HTO mass fraction is shown for a slice through the emission point in Fig. 6. Note that HTO is dispersed and diluted rapidly.

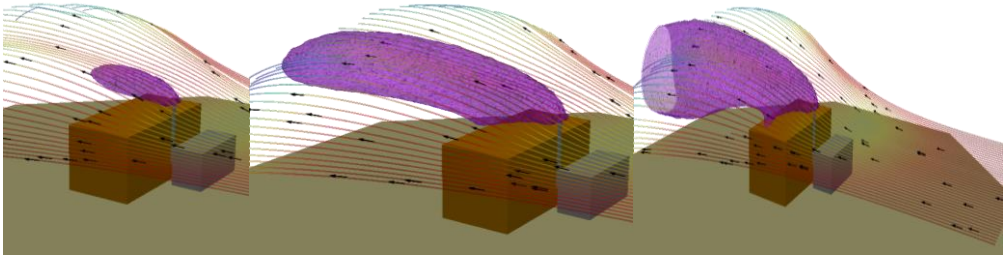

Fig. 4. Velocity streamlines over the simulated plant. Plume isosurface for 1.0 x 10-9 kgHTO/kgtot.

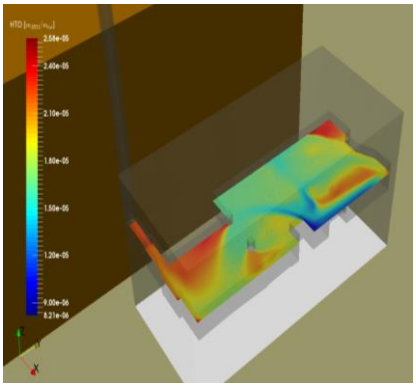

Fig. 5. HTO mass fraction inside the auixiliary building.

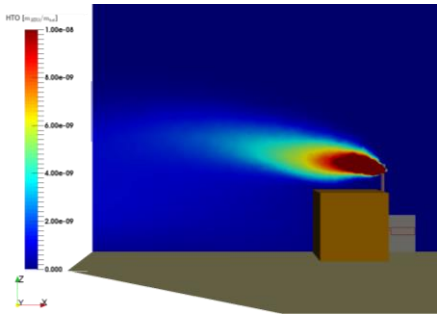

Fig. 6. HTO mass fraction at a slice centered in the emission point.

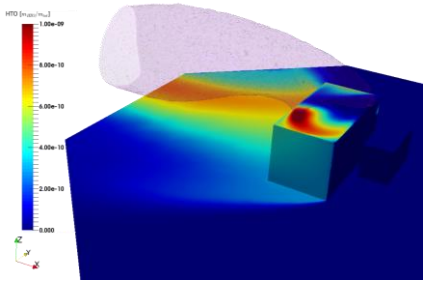

Fig. 7. HTO mass fraction on the site ground surface. Plume is shown with transparency as a reference.

HTO mass fraction on the site surface due to the plume dispersion, (as shown in Figures 6 and 7) which has been conservatively assumed to be at the atmosphere's temperature and, therefore, impact on site surface has been maximized.

3.3. Atmospheric analysis

The environmental conditions of the primary and secondary phases of tritium emission are factors that determine the intake concentrations into the biological agents. Atmospheric processes have an important role mainly in the primary phase where tritium is (still) not deposited in soil and plants in the environment. The height of building 10 m and other 10 m out of the stack, whereas the HTO emitted to the atmosphere deposition speed on the soil is low. The input of the UFOTRI code is the wind velocities, at the first 145 meters of distance output, assumed as spatial conditions. The rate of emission into the atmosphere was of 1 gram every 30 minutes in the worst case. We have considered different releases, HT and HTO, for comparison the different chemical forms of tritium. Weather data taken every 10 minutes (including humidity, precipitation, wind speed and wind direction) were used as decisive parameters for quantifying tritium in the proximity of the reactor, see Figure 8.

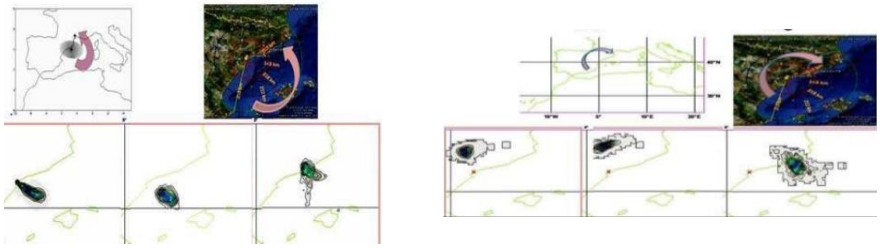

Fig. 8. Real time forecast of tritium transport in air from off-site the fusion reactor towards far downwind distance.

The major chemical forms of tritium, HT and HTO, are strongly dependent on their velocity of deposition. HTO is a factor 10 higher than the elemental tritium. This parameter determines the concentration of tritium released to the atmosphere as HTO and the amount of tritium that penetrates into the lower layers of the soil below 5 cm from the surface. Measures were evaluated with emissions to the atmosphere of each of the tritiated species in a worse case of accident with 1 gram of release (3.57 x 1014 Bq) at 10 m of height. Dispersion parameters are based on the distance from the point of emission. The mixed layer varies according to the atmospheric stability. The angular resolution was established with a 20 radii and with 72 sectors by throwing an azimuthally angle of 50 degrees according UFOTRI code [5] . The downwind distance ranges between 145 m up to 10 km. This stage of the route of tritium in the environment was established within a maximum of 7 days after the accident. We used the Spanish Regulation (PENTA-CSN regulation remains under the defined values into the protocol PENTA), [6]. The time-integrated air concentration close to the soil is provided by the dispersion model, [7].

3.4. Dosimetric analysis

The doses resulting from inhalation are considered from two different perspectives: on one hand tritium enters the body from direct inhalation of the plume passage, and, on the other hand from (the plume) re-emission [8]. For calculating the intake doses, the assumption made is that all of food consumed is produced locally and it is considered a compartment which is divided into an organic part and an inorganic part [9].

The absorption of β-particles in the body material within about 0.9 μm limits and assuming that all tritium is reabsorbed in the body. The processes of water loss from the top layer (up to 5 cm) are divided into two separate processes: water evaporation from soil on the one way and transpiration of plants on the other way. In this second way, the amount of water which must be transported from the root system to the plant in order to balance the loss of water, is assumed to be transported into deeper soil layers at diffusion rate of 0,4% per hour. The bacteriological oxidize called Hydrogenase is the catalyst of the re-emission in the HTO chemical form. The re-emission rate decreases with the time after the release. All intake pathways [10] are taken into account: inhalation and skin absorption, re-emission and ingestion. This form of tritium is similar to those of free HTO. In this work, Organically Bound Tritium is also considered. OBT is classified into exchangeable tritium and non-exchangeable tritium and has a retention time from 21 days up to 580 days. TABLE I. Contribution at Total doses by Direct Inhalation (IH), Inhalation by Re-emision (IHR) and Ingestion (IG) of HTO release up to 1 km of distance, only in Chronic time.

TABLE II. Pecentile of HTO release up to 1 km of distance

Distance (m)	% IH	%IHR	% IG
145	42.73	0.41	56.86
180	40.84	1.58	57.58
320	40.06	2.32	57.62
500	39.13	3.01	57.85
680	38.18	3.70	58.12
1000	37.56	4.18	58.26

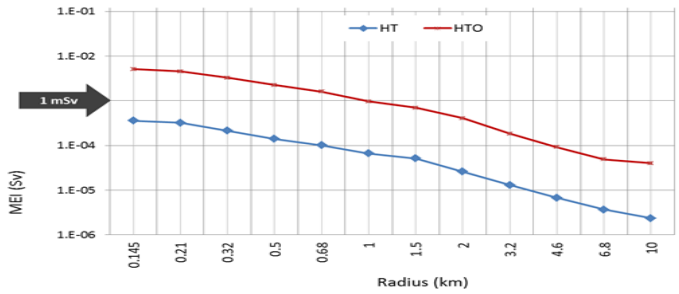

Fig. 9. Ufotri code Most Exposed Individual (Sv) values with downwind distance.

The contribution to dose by ingestion of food contaminated by tritium is the largest contributor to the total dose (see Table I). The HT contribution to MEI in the worst case is one order of magnitude lower than the correspondent HTO contribution. The doses by elemental tritium are never above 1 mSv. See Figure 9. The behavior of HTO is different. The doses near the release point up to 1 km are higher than the doses indicated in the recommendation of ICRP-60, 0, see Table II.

TABLE II. Pecentile of HTO release up to 1 km of distance

Downwind distance (km)	0.145	0.21	0.32	0.5	0.68	1
FRACTILE 99	4.68E-03	4.27E-03	4.68E-03	4.27E-03	4.27E-03	4.27E-03
FRACTILE 95	4.67E-03	4.26E-03	3.09E-03	2.09E-03	1.48E-03	8.91E-04
FRACTILE 90	4.27E-03	3.98E-03	2.82E-03	1.91E-03	1.35E-03	8.13E-04
FRACTILE 50	1.45E-03	1.29E-03	8.32E-04	4.68E-04	2.95E-04	1.78E-04

CONCLUSIONS

A first step towards an integral and multiscale methodology for Tritium leakages calculation has been exposed, showing that different techniques can be coupled to determine Tritium transport at different time and space scales. All Tritium transport phenomena have been assessed from a conservative point of view. A CFD analysis has been used to show how a detailed scale simulation can be coupled to atmospheric transport calculations. Plume and site concentrations can be analyzed at a micro scale giving valuable insight on the behavior of HTO leakages. Calculated doses are different according to the distance from the emission point, but only the HTO chemical form is higher than 1 mSv value set by the ICRP-60 regulation guide for the worst case of accidental event. The difference of doses for HT and HTO emission is due to the contribution to total doses by re-emission, which is important at short distance but not at large distances, because 95% of the HT deposited on the surface is returned to the air as HTO, increasing the atmospheric levels of this species.

ACKNOWLEDGMENT

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