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The safety features of the future nuclear fusion reactors are one the key issue for their attractiveness if compared with the fission plants. In fusion devices accidents with high release of radioactive materials have low probabilities because the most part of abnormal transients lead to passive plasma shutdown. It does not mean that radiological source terms such tritium and dust are not generated and released, but their inventory does not increase during abnormal events. Therefore, the source terms inventory has to be assessed during normal operation and traced when accidents occur. For this reason, a study for qualification and quantification of the tritium and dust source terms was established with the aim to understand their production, deposition, penetration in the vacuum vessel and in the breeding blanket and their release during the main accident scenarios to comply with a future licensing process. In case of abnormal event scenarios, the source term inventory involved in the release changes and requires a different confinement approach and mitigation.

For the estimation of the source terms in the DEMOnstration Fusion Power Station (DEMO), a methodology was developed. First time it was presented in 2016 SOFT conference. The methodology scales the tritium and dust source terms inside the vacuum vessel from the International Thermonuclear Experimental Reactor, the European Power Plant Conceptual Study and reports the tritium generated inside the breeder blanket from data quantified in other studies for DEMO. In this article the methodology was updated and tritium and dust source term for DEMO 2016 design were estimated. Moreover, the tritium and dust release pathways were highlighted according to different accidental scenarios. These results were obtained for all blanket concepts under investigation in the ongoing DEMO EUROFusion project.

Keywords: *EUROFusion, DEMO, tritium, source term, vacuum vessel, breeding blanket, safety*

1. Introduction

The Tritium Source Term (TST) and the Dust Source Term (DST) estimation in the Vacuum Vessel (VV) and Breeding Blanket (BB) [1] for next generation of fusion device is an important and complex issue, which involves neutronics, chemistry, material science and physics together. In particular, the DST and the TST in the VV are linked to each other due to the presence of the tritium inside the dust particle eroded by the plasma from the Plasma Facing Components (PFCs). In particular, unlikely event such as disruption and runaway electrons can lead to a significant increase of the dust, as well as for the total source term. Such scenarios are considered as accident in DEMO reactor.

In the frame of the EUROfusion DEMO project a methodology [1] was developed and assessed in order to estimate the TST and DST [2]. The methodology was created [1] to be flexible in recalculating the TST and DST in the case of changes of the VV, the Divertor (DV) and the First

Wall (FW) dimensions and characteristics and reactor fusion power. The references used for the study are ITER [3], Power Plant Conceptual Study (PPCS) [4] and the analyses performed for the DEMO Breeding Blanket [5], [6], [7], [8], [9].

The aim of this paper is to update the methodology and to estimate TST and DST for DEMO 2016 design [10]. A particular attention is given to identify and describe the physical state of tritium in VV and its components. In addition, the results are properly linked to the Functional Failure Mode and Effects Analysis (FFMEA) [11] to trace the TST and DST release pathways in case of accident.

2. EU DEMO 2016 Design Evolution

The latest conceptual design of DEMO was modified from 2014. The fusion power increased significantly and the dimension of the tokamak became bigger, as a consequence. The main DEMO

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parameters, basic for the radiological source terms evaluation are summarized in Table 1.

Table 1 DEMO 2016 [10] versus DEMO 2014 concept [5]

Variable	DEMO 2014	DEMO 2016
Fusion power (MW)	1572	2037
VV Plasma volume (m^3)	1453	2502
Average Neutron Wall Load (MW/m^2)	1.067	1.06

3. Methodology

The proposed methodology adopts ITER as reference for the tritium and dust inventory assessment in DEMO. ITER is an experimental machine mainly devoted to test the technological solutions in fusion while DEMO is a reactor to demonstrate the fuel breeding capacity and the competitive electricity production with the other energy resources. The DEMO fusion power and plasma volumes are 4 times the ITER ones (Table 2). In ITER the plasma facing components materials are Be for the FW and W for the DV, while FW and DV in DEMO are in W. The pulse length is 400 s in ITER followed by 30 min. of dwell time. DEMO pulse length is 2 hours and the dwell time 10 min. The frequency of unmitigated disruptions leading to significant dust production in ITER has been assumed to be several per year [3], while in DEMO is expected to be once in the life of the plant (40 years).

The approach to evaluate the source term inventories in DEMO comes from the ITER dust and tritium inventories, which are evaluated and estimated as an administrative limit [4]. When these quantities are exceeded the VV has to be cleaned to operate in safe conditions. ITER accident analyses confirmed that the design release limits in the environment are never overtaken. In DEMO the in-VV source term inventory limits are not available currently. The methodology tries to overcome the lack of reference data applying the scaling factors to the ITER limits.

The methodology is based on the experience gained in the past starting from the models used in the analyses of the mass inventory and the source term for Gen II and III reactors. In particular, the methodology is inspired similar to semi-empirical approach used in model introduced in the system

codes such as CORSOR in MELCOR [12] [13] in order to be simple and flexible. It is a combination of several steps starting from the identification of the reference data to be scaled and the main assumptions [1].

The process is shown in Figure 1, where each block represents the necessary step to calculate and to link the TST and DST to the reference accident scenarios.

The assumptions adopted for the methodology are:

1. All calculations are based on the most pessimistic radiological conditions, i.e. the end of operational life or that of its components.
2. Any detritiation technique is considered to be used in order to reduce the quantity of dust and the tritium.
3. The most pessimistic fluence rate value is taken into account. It is estimated as 6.4 $MW.y/m^2$ at the end of DEMO operational life [2].
4. The plasma-facing surfaces has radiotoxic tungsten activation products. The Be dust (particulates) is foreseen in HCPB concept in the pebble bed.
5. All tritium released is assumed to be in the form of tritiated water in order to maximize the doses.
6. The maximum penetration layer of the tritium in PFC's tungsten is 7 μm according to [14].
7. The uncertainty is estimated 25% for tritium and 30% for dust in agreement to the methodology adopted in ITER [15].

The predicted source term inventories are scaled with the factor "f" as a function of fusion power (Φ), plasma volume (V), plasma facing components (PFC) surface area (A), number of disruptions (Dis), material diffusivity (D), tritium extraction pumping (P), number of pulses (NP, length of pulses (LP) and material hardness (H).

The heart of the VV mass estimations for tritium is characterized by the formula (1):

$$m_l^i = f(\Phi, M, V, A) \cdot m_{i,or} \qquad (1)$$

where: m_i the newly estimated mass of material i; $m_{i,or}$ is the original mass of material i, derived from literature and prior studies related to ITER [3] [1]; f is a scaling factor described in Table 2. The decision to use ITER as source term reference is based on two main criteria:
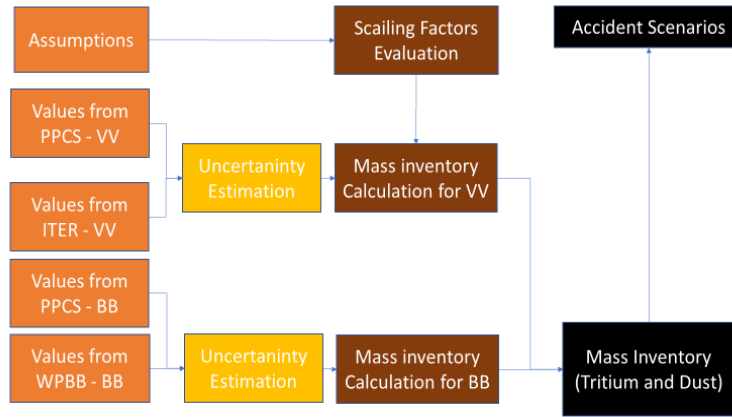
Figure 1 Schematic of the developed methodology

1. ITER will be the closer fusion reactor to DEMO for dimension, geometry, power;
2. The use of these values represents a conservative compromise in the frame of the frequent changes in the DEMO design and due to the approximation adopted to consider the phenomenology.

The results of the methodology will be used in the safety analyses and in the limit imposed by the requirements.

Indeed, at the present stage of the methodology the main coefficients and factors that can influence the order of magnitude of the inventory are considered. This is due to the lack in the physics correlations that have to be tuned on DEMO and on the experiments necessary to understand the phenomenology in details.

Table 2 Scaling factors for tritium (*T*) and dust (*D*) mass estimation starting from ITER [3] [1] in comparison to DEMO 2016 [2]

Variable	Source term	ITER	DEMO 2016	Factor *f*
Fusion power [MW]	T, D	500	2037	4.07 (Φ)
VV plasma volume [m^3]	T	837	2502	2.99 (V)
FW Material Diffusivity [m^2/s] (Material)	T	(Be) 1.03E-12 (Abramov Ex.) 1.47E-13 (Abramov H.)	(W) 1.00E-13 (Garcia-Rosales	0.0978 (D) 0.682 (D)
Brinell Hardness [MPa]	T, D	590 (Be)	2000 (W)	0.295 (H)
N. of disruptions	D	> 1 event/year	≥ 1 event/life of FPP	0.025 (Dis)
PFC surface [m^2]	T, D	893	1711	1.6 (A)
Tritium extraction pumping	T	Cryogenic	Turbo-molecular	0.8 (P)
Number of pulses/y	D	3500	4040	1.15 (NP)
Length of pulses [s]	D	450	7200	16 (LP)

3.1 Tritium Phenomenology

The biggest amount of tritium in the VV is deposited from the plasma to the FW and the DV surfaces and into the dust. The tritium distribution in the tungsten is within the first 7 μm facing the plasma according to the experiments conducted with deuterium high energy ions beam simulating the plasma condition [14]. Although in the experimental campaign, the deuterium distribution has a peak in the 0.2 – 0.5 μm layer due to the high energy ions [16] [14], in the current version of the methodology the concentration is assumed to be constant [1]. The tritium deposition on the FW and in the DV are scaled by ITER [3] using different diffusivity at the operational temperature. In the case of ITER, with a

beryllium plasma-facing surface, the diffusivity is calculated for a temperature of 110 °C, while for DEMO, with tungsten, the working temperature is 550 °C.

The correlations adopted for beryllium are Abramow's and Garcia-Rosales for pure tungsten [14] because this study has several common references with [3]. The beryllium correlations depend on the purity grade of the material used for the first wall. In the case of ITER as described in [14] and in [3], the correlations used represent both 99.8% and 99% of pure Beryllium. The presence of beryllium oxide changes drastically the diffusivity of the tritium. The correlations are (in m^2/s):

Abramov 99.8% Be Purity

$$D = 8.0 \cdot 10^{-9} \cdot e^{\left(\frac{-0.29\,eV}{kT}\right)} \tag{2}$$

Abramov 99.0% Be Purity

$$D = 8.0 \cdot 10^{-9} \cdot e^{\left(\frac{-0.36\,eV}{kT}\right)} \tag{3}$$

Garcia-Rosales W

$$D = 3.5 \cdot 10^{-11} \cdot e^{\left(\frac{-0.39\,eV}{kT}\right)} \tag{4}$$

Where:
- k is the Boltzmann constant in *eV/K*.
- T is the operational temperature of the FW material in *K*.

To scale ITER in DEMO 2016, it is necessary to introduce opportune factors. The final step is to calculate the mass inventory of the dust contaminated by the tritium as part of the total dust eroded from the PFCs. It is estimated considering that the FW surface is 1556 m^2 and the divertor surface is 155 m^2 [10] with the maximum tritium penetration layer of 7 μm [14].

Another source of the tritium infers from the BB. In DEMO the whole tritium is generated by the reaction with Li in form of Li$_{17}$Pb$_{83}$ or Li$_4$SO$_4$. The tritium during the normal operation diffuses into the structural material of the BB modules, such as EUROFER. The T mass inventory in BB is calculated considering the operational regime.

3.2 Dust Phenomenology and Erosion Phenomena

In tokamaks, several transient plasma events carry the potential for first wall and DV erosion. Among them there are Edge Localized Modes (ELMs) and disruptions. Physical sputtering is the erosion mechanism, at the DV targets. ELM plasma energy losses have been evaluated between 3% and 8% of the total stored energy (~350 MJ) [17]. A portion of the eroded material does not adhere to

surfaces and dust is generated by these mechanisms. It can arise from plasma vaporized material produced in a disruption (only vaporized material is considered to have the potential to produce dust), accumulated over time from disruptions and sputtering (plasma erosion), or produced by mechanical operations such as cutting during in-vessel maintenance.

During normal operation, the dust formation is closely linked to the erosion of the PFC materials. The eroded materials tend to redeposit and to form layers in areas not in direct contact with the plasma (Figure 2). The W erosion rates in DEMO are estimated to cause a lower net dust inventory compared to ITER.

In fact, the erosion of FW material as a result of unmitigated major disruptions will account only for a negligible number over the life of the reactor, since the disruption occurrence is expected to be low [18]. Regarding runaways and Vertical Displacement Events several systems are planned to mitigate such phenomena [18] in DEMO2016. In the actual methodology, the dust is estimated in the upper band due to these events.
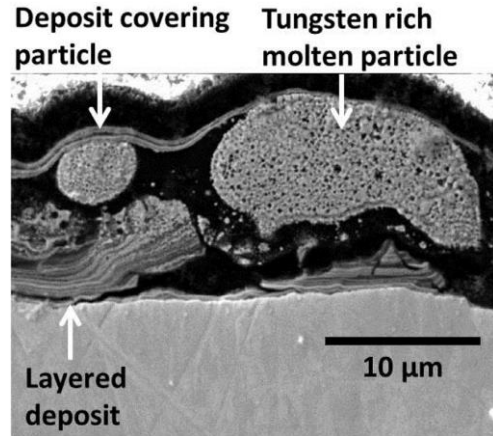

Figure 2 SEM image showing layered deposit and metallic droplet encapsulated with over laying deposit [20].

4. Results

4.1 Tritium and Dust Mass Inventory Estimation

As assumed in the methodology, a possible strategy is to evaluate the tritium inventory in the VV scaling the limit of ITER. The amount of the dust is strongly influenced by the flux, so it directly depends on the power. Also, the material of the FW and DV with different diffusion coefficient as function of the operational temperature has an important role. These factors are common in each concept. In agreement with the methodology, the tritium estimation is based on three main contributions: 1) the dust presented in VV and deposited in the DV 2) tritium

diffused into the FW and DV and 3) tritium in the BB.

The eroded layer is significantly thinner (§3.1) than the tritium permeation layer, then the whole tritium amount is located into the dust. DEMO 2016 dust inventories are scaled with the factor "f" (Table 2) as a function of fusion power, PFC surface, Brinell Hardness due to different materials, the number of disruptions foreseen in the plant, the number of pulses in a year and the length of any pulse.

According to the equation (1) and considering that the yearly dust mass limit ($m_{i,or}$) for ITER is 500 kg [3], the dust mass limit for DEMO 2016 design would result in 689 kg/year, including a safety factor 1.3, to account 30% of uncertainties [15]

In order to calculate the tritium mass in the FW and DV walls it was assumed that tritium has an uniform concentration between the DV and FW. This assumption is necessary in order to achieve a preliminary data set. With this hypothesis, the mass will be allocated in repartition of the surface areas. The DV has a surface area of 155 m^2, while the FW has 1556 m^2. The amount of tritium is fractioned in the following way: approximately 20% for the DV and 80% in the FW, consequently. According to the equation (1), considering that the ITER tritium limit is 1000 g ($m_{i,or}$), applying the scaling factor for T shown in Table 2 and 25% of uncertainties the tritium mass limit for DEMO 2016 is estimated between 671 g and 4676 g if Abramov Ex or Abramov H correlation is applied, respectively.

To calculate the tungsten dust containing T, some tentative assumptions also have to be done: a) maximum penetration layer of the tritium in PFC's tungsten is 7 μm according to [14]; b) total PFC surface area is 1710 m^2 according to [2]; c) tritium distribution in the first tungsten layer is uniform; d) dust and the tritium considered in the VV corresponds to the mass at the end of DEMO life. The total tungsten mass containing tritium is calculated multiplying the PFCs surface for the penetration layer and the tungsten density. The corresponding value of the activated dust will be 210 kg contaminated by tritium. Summarized calculation results are presented in Table 3.

Table 3 Tritium mass distribution in the VV

	Abramov Ex.	Abramov H.
Tritium in the W dust, g	671	4676
Dust activated by Tritium [kg]	210	

Tritium is produced by neutron irradiation in the BB modules containing normally Lithium compounds, Beryllium and Lead (depending on the concept). It could diffuse into the water or helium cooling system needed for the breeding blankets. Thus, the third tritium mass inventory component is in BB. Four blanket concepts are being developed during the conceptual phase of the DEMO design: a) Helium-Cooled Pebble Bed concept (HCPB); b) Helium-Cooled Lithium Lead concept (HCLL); c) Water-Cooled Lithium Lead concept (WCLL); d) Dual-Coolant Lithium Lead concept (DCLL).

Table 4 summarizes the tritium inventory for all DEMO breeding blanket concepts. The presented data are theoretically estimated or numerical calculated for HCPB [5]; HCLL [5], [6]; WCLL [6], [7], [8]; [20], DCLL [9]. Because at this moment, there is lack of the experimental data to cover the uncertainties, the 25% of bound was applied for the referred values [15].

From the safety aspect the highest (conservative) value of tritium inventory must be selected in order to have the most conservative scenario for the accident analysis.

Table 4 Tritium inventory in the cooling loops of the breeding blanket concepts which could be released during an accident

Tritium inventory	HCPB	HCLL	WCLL	DCLL
Breeder	40.1 g	32 g	32 g	0.713 g
Coolant	1.6 g	1.6 g	160 g [20]	under evaluation
BB structure	1.9	1.9	1.7	0.059
Total:	44.5 g	35.5 g	192 g	0.772 g
With 25%	55.63 g	44.38 g	243 g	1.05 g

4.2 Evaluation of possible pathways of releases

The most relevant postulated initiating events recognized by the FFMEA on DEMO Heat Transfer Systems [11] are related to the cooling loops of the FW/BB circuits, to the DV cooling loops and to the general loss of power supply. For any of these accident scenarios the pathways for controlled and uncontrolled release of the radiological source terms (tritium and dust) can be followed during the evolution of the event.

Several postulated accidents confine the tritium and dust in volumes such as the Vacuum Vessel Suppression System, Expansion Volume and VV from which the releases are controlled (typically 1%

of the volume per day). On the contrary for some of them the tritium and dust release occurs towards uncontrolled volumes and can contaminate zones in which hands-on work is performed engendering potential doses for the workers and the public. Table 5 shows the critical accident scenarios for tritium and dust uncontrolled releases in DEMO HCLL concept [11].

Table 5 Critical accident scenarios for tritium and dust releases

Accident	Release pathway
Loss of coolant accident (LOCA) in-vessel because large rupture of the DV cassette	VV to port interspace
LOCA Out-VV because large rupture of the FW primary cooling loop in the helium manifold feeder inside PHTS Vault	ex-VV to in-VV bypass if failure of plasma shutdown occurs
LOCA Out-VV caused by large rupture of the liquid metal loop	ex-VV to in-VV bypass if failure of plasma shutdown occurs
Rupture of the steam generator tubes of the liquid metal loop	ex-VV to in-VV bypass if failure of plasma shutdown occurs
Loss of heat sink in all FW, breeding zone and DV primary cooling circuits caused by trip of both high and low pressure turbines due to loss of condenser vacuum	Towards tokamak building
Loss of heat sink in one cooling train of the blanket module (either breeding zone structure or FW)	Towards tokamak building

The most significant tritium mobilization and releases occur when the VV is involved in the event characterized by high energy release such as LOCA and dust explosion, containing the maximum tritium inventory (Table 3). The BB cooling loop and/or the breeder loop (HCLL, DCLL, WCLL) failure lead to lower amount of tritium release if an out-of-vessel LOCA occurs (Table 4). The ex-VV followed by an in-VV LOCA is the potentially worst scenario for tritium mobilization.

5. Summary and conclusions

The updated methodology is used for the new estimation of the TST and DST inventories in VV DEMO 2016 design applying the scaling from ITER limits. Such values have the double interpretation as limit and mass inventory, due to the problem to collect concrete data in order to estimate directly the source term. This interpretation is postulated as a conservative assumption that can be reduced with future analytic investigation of the phenomenology.

The estimated TST values for DEMO 2016 design are between 671 g and 4676 g in the VV depending on the different diffusivity correlations adopted and 1-240 g for BB coolant depending on the concept. The DST inventory limit for DEMO 2016 has been quantified in 689 kg/year.

The screening of the abnormal events, in which the source term inventory is involved, highlights the importance of controlling the plasma shutdown triggered by a malfunction detection in order to avoid a plasma disruption that can cause additional failures and the risk to connect in-VV with ex-VV zones.

The tritium and dust inventories should be considered as operational limits. The tritium and dust inventories need to be revised in the future to follow the design changes that will occur. In addition, the methodology has to be assessed versus experimental data or results supplied by simulated plasma transients. Furthermore, the reference data could be supplied by the existing fusion experiments such as the Joint European Torus (JET)[20] and/or the future COMPASS-U under designing in the Institute of Plasma Physic in the Czech Republic.

Acknowledgments

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