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Tritium and Dust Source Term Inventory Evaluation Issues in the European DEMO reactor concepts

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Fusion reactors represent a future evolution of the nuclear technology improving the world-wide energy portfolio. The experimental fusion reactor under construction (ITER) and the planned industrial fusion reactors (DEMO) are large and complex facilities. For their operation it is necessary to ensure safety limiting the radiological and mobilizable source terms inventory such as tritium and radioactive dust.

The source term inventories shall be assumed in the establishment of the operational and safety requirements for DEMO, as well as performing the safety analyses for the commercial fusion devices. In the last few years a methodology for the evaluation of tritium and dust source term inventory has been proposed in the framework of the EUROFusion project. The basis of the methodology is a semi-empirical approach to scale the radioactive inventory limits implemented in ITER. The source term amounts derived for DEMO will supply a guidance for the safe operation of the future fusion reactors. The development of the methodology has to be completed and refined because of the lack of a validation versus adequate experimental data and rules for the extension to different scenarios.

The aim of this work is the assessment of the developed methodology for the evaluation of the source terms inventory versus JET operating limits for tritium and versus the dust control strategy adopted in ITER for the dust.

Keywords: DEMO, Tritium, Dust, Source Term, Methodology

1. Introduction

The source terms in a nuclear facility are the key point for the risk evaluation in case of accident and then it is necessary to quantify them for a correct safety assessment. In European DEMOnstration Power Station (DEMO) **Error! Reference source not found.**, among the most critical are the radiological source terms enclosed in the Vacuum Vessel (VV) such dust and tritium (T). The quantification of their inventories is the topic of this paper.

In addition to the inventory in the VV, the T in the cooling loops has to be included in this evaluation. The assessment was done in the frame of the Breeder Blanket and Tritium DEMO Work Packages (WP) that estimated provisionally an amount of 100 g **Error! Reference source not found.**.

The experimental data available for the in-VV source terms in a tokamak, mostly collected at the Joint European Torus (JET) [2], resulted in fragmented information and not directly scalable to DEMO. For this reason, a different approach has been followed in this study in which a scaling is proposed versus ITER T and dust inventory limits [3]. After that the methodology proposed was assessed versus the JET limit for T and versus the control strategy adopted in ITER for the dust.

2. Methodology for source terms estimate

The methodology is based on the experience involved in the research starting from the models used in the analyses of the mass inventory and the source terms for Gen II and Gen III reactors [4] [5]. It is a combination of several steps. The first ones are the identification of the reference data to be scaled and the main assumptions [6]. Then it follows the physical interpretation of the main phenomena and its correlations involved in the generation and mobilization of the source terms.

Due to the lack of experimental data for DEMO source terms, the safety approach starts from the previous state of the art referring to ITER source term inventory [3] and scales it on the base of the main parameters, phenomena and correlations affecting the Tritium Source Term (TST) and Dust Source Term (DST) production (Table 1).

The outcomes obtained represent the maximized limits of the quantity of T and dust products for the 2016 design of the EU DEMO concept. The expression that represents such methodology is described by the formula:

$$m_i = f(\Phi, V, A, D, NP, LP, H, Dis, P) \cdot m_{i,or} \quad (1)$$

where:

- m_i is the newly estimated mass of material i;
- $m_{i,or}$ is the original mass of material *i*, derived from literature and prior studies [3];
- $\Phi, V, A, D, NP, LP, H, Dis, P$ are the variables listed in Table 1.

The aim is to obtain these inventories with a sufficient safety margin waiting for improving of the neutronic and the plasma transients and plasma-wall interactions analyses in the other DEMO WPs.

The initial mass inventory obtained from the reference data [3] has to be revaluated based on the uncertainties

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[7]. These values, which represent TST and DST values are scaled using the formula (1).

Table 1 Factors and data affecting source term production in ITER [3] [8] and DEMO2016 [1] [8]

Variable	ITER	DEMO 2016	Factor f
Φ – Fusion power [MW] (TD)	500	2037	4.07
V - Plasma volume [m^3] (T)	837	2502	2.99
D - 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 0.682
H - Brinell Hardness [MPa] (TD)	590 (Be)	2000 (W)	0.295
Dis - N. of disruptions (D)	> 1 event/year	≥ 1 event/life of FPP	0.025
A - PFC surface [m^2] (TD)	893	1711	1.91
P - Tritium extraction pumping (T)	Cryogenic	Turbo-molecular	0.8
NP - Number of pulses/y (D)	3500	4040	1.15
LP - Length of pulses [s] (D)	450	7200	16

(T) is for tritium, (D) for dust and (TD) for tritium and dust

2.1 Dust source term

The dust production in the VV is caused by the plasma burning and/or by its abnormal behaviour. It is generated mainly by stationary shots, unmitigated edge localized modes (ELMs), unmitigated major disruptions, unmitigated runaway electrons and unmitigated vertical displacements (VDEs). Each of these causes depends on several parameters, among them to the fusion power, the Brinell Hardness and the Plasma Facing Components (PFCs) surface.

The methodology applied in the past [1] was based on unmitigated disruption events supposed to occur only once in 100 years. Currently the hypothesis is corrected in once in 40 years of machine operation. In addition, the number of the pulses per year and their duration are accounted in the revised approach.

Studies dedicated to the behavior of the typical ITER PFC materials (W, Be) have been performed recently in JET [9] with the ITER-like wall. Analysis of the transient impurity events associated with dust shows that W dominates, but only qualitative information are available for that.

According to the factors *f* presented in Table 1, the dust mass for the DEMO2016 design would result:

$$m_i^{W,DEMO16} = f \cdot m_0^{dust,ITER} = (f\emptyset) * (fNP) * (fPL) * (fA) * (fH) * (fDis) * m_0^{dust,ITER} = 530\,kg/year$$

considering 500 kg as the ITER safety limit for the mass inventory in one year of operation [3]. Including the uncertainties (30%) the inventory would reach 689 kg/year.

2.2 Tritium source term

As assumed in the methodology, the T inventory is scaled using the ITER limit. The T is estimated as mainly located inside the dust presented in VV/deposited at the divertor (DV). The procedure is the following:

- the ITER T mass (in plasma facing components, dust, co-deposited etc.) is assumed to be 1 kg [3]. Such precautionary value considers the high permeability of the Beryllium of the first wall and the immobilization due to the low operational temperature (approximately 100 °C).
- The factors described in the general approach of the methodology are combined in order to estimate the T mass inventory (Table 1).

The T mass is between 671 g and 4676 g including 25% of uncertainty [7]. A small variation of the purity rate in the beryllium leads to a significant reduction of the diffusion constant becoming close to the value of the W at the temperature of 500 °C. Such a difference results in a significant difference in the estimated mass inventory.

During normal operation every year about 689 kg of dust is generated in the whole VV according to the eroded layer. In similar condition, the whole W mass is not fully contaminated by the T due to the low permeability. In order to calculate the T in the W dust, some literature references have to be used: a) the maximum penetration layer of the T in PFC's W is 7 μm [8]; b) the erosion rate is around 0.3 mm/year [9]; c) the total FW surface area is 1556 m^2; d) as stated for the methodology, the T distribution in the first W layer is supposed uniform; e) the dust and the T considered in the VV corresponds to the safety limit allowable before to clean the vacuum chamber. The total W mass containing T is calculated by multiplying the FW surface for the penetration layer and the W density (around 210 kg). This means that all the T (between 671 g and 4676 g) is assumed to be trapped in the dust.

3. Dust assessment

The origin of the dust inventory limits in ITER derives from DST control strategy [3], in which the amount of dust generated was quantified on the basis of theoretical studies on the plasma-wall interactions in both normal and

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abnormal events. A typical ITER experimental campaign was taken as reference lasting around 2 years, during which 5000–7000 discharges are planned. The ITER approach for DST control strategy has been used for DEMO to assess the results obtained by the DST methodology (§2.1).

The stationary shots will be the cause of the major amount of dust production. According to [9] the erosion rate of the DEMO wall armor of W due to stationary shots will be of the order of 0.3 mm per full power year. These data agree well with the 0.2 mm calculated in [6]. The expected dust inventory in such conditions are 1 ton/year of DEMO full operation. The other abnormal transients (disruptions, VDEs and ELMs) should have very low probability in DEMO and they would contribute marginally, to the total W dust inventory. As for ITER [3], hypothesizing that the W melted layer depth in DEMO was 0.4 mm for unmitigated ELMs, 0.6 for unmitigated disruptions, 2.5-7.5 mm for unmitigated runaway electrons events and 0.6 for VDEs the expected dust production in one year of operation, considering that any abnormal event could occur once every 40 years is of the order of 1015 kg of W (Table 2).

Comparing the results obtained applying both the ITER strategy for the dust control and the results available from the plasma-walls interaction calculations (Table 2) it is possible to state that the methodology supplies a dust inventory insufficiently conservative (689 kg versus 1015 kg) if the abnormal events are supposed to be rare (once every 40 years), and conservative (1389 kg versus 1031 kg) if the abnormal events increase their frequency (once every 20 years).The results can be considered suitable with some limitations, waiting for additional simulations of plasma-wall interaction and ad hoc experiments, if possible.

Table 2 Expected dust production in one year of DEMO full operation

Events	# of events/year	dust /event	dust/year (kg)	Melted layer depth (mm)
Stationary shots	4040		1000 kg W	
Unmitigated ELMs	0.025	4 kg W	0.1 kg W	0.4 mm
Unmitigated major disruptions	0.025	≤20 kg W	≤3 kg W	0.6 mm
Unmitigated runaway electron events	0.025	~4 kg W	~(0.1-0.2) kg W	2.5-7.5 mm
Unmitigated VDEs	0.025	~462 kg W	~12 kg W	0.6 mm (as for disruptions)
Total			**~1015 kg W**	

4. Tritium Assessment

The methodology proposed for DEMO and described in[1] has been built in analogy with the extrapolation and the considerations adopted in [7] and [3]. To demonstrate its congruency with the previous estimated correlations it has been applied in scaling the ITER T limit starting from the JET parameters and limit

However, the main difference with DEMO remains in the materials used for in the FW in both JET and ITER reactor [10]. Those differences in the materials have been considered for the FW (built in pure beryllium) and for the DV in W.

The range of ITER T inventory scaling the operational limit from the JET limit is between 728 g and 1458 g for the beryllium and 540 g for the W. Such T amount has to be considered divided in two parts: the T trapped in the beryllium FW corresponding to the majority of the T mass inventory in the VV and the T trapped inside the beryllium and W dust and mobilized when the dust is heated up.

The ITER administrative limit is set up to 1000 kg of dust [3], deposited on the DV, but generated in the whole VV. This value can be considered as the maximum dust amount generated without using any removal techniques. In order to calculate the T in the dusts, some tentative assumptions have to be done:

a) the maximum penetration layer of the T in FW Be is around 1 mm [3];

b) the maximum penetration layer of the T in the DV is around 7 μm [8];

c) the total FW surface area is 680 m^2 according to [11];

d) *Be dust % = Be dust /(Be dust + W dust)= 45.8%* scaling the 1000 kg of dust (ITER safety limit) results in 458kg of Be dust;

e) the methodology assumes that the T distribution in the first Be and W layer is uniform;

f) in agreement with the methodology, the dust and the T considered in the VV corresponds to the mass at the end of ITER life or when it approaches the administrative limits.

The total beryllium mass contaminated by the T is calculated multiplying the FW surface for the penetration layer and the beryllium density (1850 kg/m^3), that is:

*SurfaceFW * p. layer T in Be * Be density = 1258 kg*

The contaminated dust value is the wall amount estimated using [3] and it corresponds to 458 kg. The rest of the contaminated beryllium is located in the FW (780 kg). The T in Be is shared between Be dust (36.4%) and Be PFC (63.6%) proportionally to the masses. As final step, considering that the whole W mass containing T will be eroded, the T in the W dust will be 540 g (Table 3).

In particular focusing on the T amount mobilized into the dust, the estimated discrepancy from the limit of 1000 g is in a range of -195 g / + 71g. Such values agree with the assumption adopted in [7] and [3] as shown in the correlations used in [8].

Table 3 T mass distribution in the ITER VV

Variable	Abramov Ex.	Abramov H.
T in the Be dust [g]	531.1	265.1
T in the Be FW [g]	926.7	462.5
T in the W dust [g]	540	
T in dust (W+Be) [g]	**1071.3**	**805.2**
Sum of T in the VV [g]	**1997.9**	**1267.7**

In addition, the assessment indicates that the closest value is the one calculated with Abramov Extra purity rate. As final remark, the methodology considers some non-linear effects such as the material properties depending on the temperatures.

5. Summary and conclusions

The methodology applied is an attempt to overcome the lack of data that a first of a kind machine like DEMO presents. In the future it will be fundamental in this approach separate the real estimation from the limit, considering the 2nd order phenomena, not included in the current expression of the methodology. In addition, ad hoc campaigns could be planned at JET, tuned on the DEMO needs to get all the boundary conditions specific for dust and T production investigation.

Other peculiar factors can be considered such as the plasma distance between the FW and the DV, the phenomenology of the T permeating inside the eroded dust to take the real T distribution and considering the experimental pulse number and duration also for the T, in particular following the relation from pulse/plasma before going into maintenance

An updating of a methodology for the dust and T inventory evaluation in DEMO has been presented. The new values of the in-VV source terms (689-1389 kg for DST and 671-4676 g for TST) to be used for the safety assessment of the fusion reactor are the outcomes. These values show a reasonable agreement with the DST and TST inventories if scaled versus ITER or assessed versus JET limit.

The constant updating of the DEMO design leads to a large uncertainty to the initial values to be applied in the methodology. Improvements are expected from future plasma transient calculations in which the TST and DST mobilizable inside the VV can be defined with a more accurate approximation.

Forecasts about the probability of disruptions events are expected to be improved in the plasma-wall interaction studies. The disruptions affect significantly both T and dust inventory in the VV that can be released in case of accident.

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