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Methodology of the Source Term Estimation for DEMO Rector

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Abstract

The problem of Source Term qualification is one of the most important topics in order to predict possible releases of the Activation Products (APs) and Tritium from the DEMO Fusion reactor. The prevention of any possible consequence, which can affect the environment and the population, is the mission of Fusion technology. In the frame of the EUROfusion Work Package of Safety and Environment (WPSAE) a methodology to scale and evaluate the source terms assessed for ITER and the Fusion Power Plant Conceptual Study (PPCS) has been studied.

This paper refers to the activity currently conducted for the DEMO source terms assessment and the preliminary results obtained. During activities in the task, the methodology was developed for the evaluation of Tritium and APs concentration inventory. The methodology is explained in detail for the prediction of the Tritium and APs concentration in Vacuum Vessel (VV) and in the Breeding Blanket (BB) starting from the DEMO current design data and the inventories assumed in ITER, PPCS and SEAFP programs. These results refer to the Helium Cooled Lead Liquid (HCLL) and the Helium Cooled Pebble Bed (HCPB) concepts. The approach is based on the foundations, set in the fission technology safety analysis of the Design Basis Accidents (DBA), Design Extension Conditions (DEC) and Beyond Design Basis Accident (BDBA).

Key words: DEMO, Safety, Source Term, Tritium, Activation Products

1. Introduction

The source terms qualification is an important issue in order to set up the codes and models in predicting the releases during the evolution of scenarios under operational and accidental conditions. The source term is characterized by mainly two different groups: the Tritium retained in the vacuum vessel and the Activation Products (AP) generated by the irradiation during neutron flux and plasma facing components (PFCs) erosion caused by disruptions, ELMs, etc.

In the frame of the EUROfusion Package of Safety and Environment (WPSAE) a methodology to scale and evaluate the source terms assessed for ITER [1][2] and the Fusion Power Plant Conceptual Study (PPCS) [3] has been studied due to the lack of relative data on the ongoing EUROFusion activities [4]. The aim of this paper is to show how this methodology is useful in identifying and qualifying source terms for accident scenarios. In particular, it is important to estimate the quantity of Tritium and APs, where they are generated and in which form they are presented. However, a particular issue is the dust inventory and its mobilization: special attention is given to the problems created by the Tritium and dust production and release with a preliminary comparison of the data in the ongoing activity. These results refer to the Helium Cooled Lead Liquid (HCLL) [5] and the Helium Cooled Pebble Bed (HCPB) [6] concepts and they are compared with the reference material. The actual results refer to the DEMO 2014 data updated with new factors in the ongoing activity in EUROFusion project WPSAE [7][8].

2. Summary of DEMO

The European DEMOnstration Power Station (DEMO) [4] is a proposed nuclear fusion power station that is intended to build upon the ITER experimental nuclear fusion reactor. DEMO aims at a stable production of electricity from fusion and at the breeding of the fuel (Tritium) necessary for the operation.

Among the breeder blankets the final reactor will be selected for the construction, after the optimization of performances. Currently the DEMO EU is sized for 2037 MW plasma power with a plant electricity output capability of 500 MW. A minimum Tritium breeding ratio >1.05 must be guaranteed to be self-sufficient. The source terms production and the consequent issues linked to the licensing process is affected by the types of materials used in the machine: tungsten as PFC, Eurofer as structural material, LiPb as breeder in HCLL, in Water Cooled Lead Lithium (WCLL) and in Dual Coolant Lead Lithium (DCLL) concept or Li4SiO4 in HCPB. DEMO will be a credible plant for energy production in the future if the problems of corrosion, erosion, evaporation, sputtering, activation, reactivity, resuspensions can be handled in a safe way.

3. Methodology

The source term inventories for design assessment purposes are based on facility end-of-life conditions. Due to the lack of neutronics and erosion data based for ongoing activity in other Work Packages (WPs), the safety approach in the methodology consists to use the assessments made in previous studies[1] [2] and to scale them based on peculiar factors. These numbers maximize the limits of the quantity of Tritium and activation products for the DEMO reactor. Such methodology is described by the following formula:

$$m_i = f(\Phi, m, V, A) \cdot m_{i,or} \qquad (1)$$

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 [1] [2] and DEMO 2012 [3].

The aim is to evaluate the inventories with a sufficient safety margin waiting for the details about design amendments, neutronic analyses and erosion data coming from other WPs.

Table 1 shows the factors applied in the calculation of the mass inventory based on the main differences in the phenomena and size between DEMO and ITER. Currently the table describes 2 main areas: Vacuum Vessel (VV) and the Breeder Blanket (BB). It was considered, for example, that the Tritium quantity during the accident depends partly on the dust accumulated directly inside the VV. In agreement with this general approach, the methodology is also prepared according to the type of source term (Tritium and APs). In the case of BB, the analysis refers directly from the value estimated by the [4][5][6][9] and other reference documents found in the first year of research activity. In addition, it is assumed that the first wall plasma facing the surface area is 18.874 m^2 and the thickness of the penetration layer off the Tritium is 0.01 mm according to [4] and [10].

The diffusion coefficient plays an important role because it represents physically the penetration of the Tritium inside the different material, so it is directly connected to the mobilization in FW and Tritium inside the dust. These two variables are the key parameters in order to estimate the Tritium in the VV. In addition, they are calculated based on different temperature because the diffusion constant depends directly on the temperature as shown in [10] and [11]. The correlations used in the analyses are Abramow's and Jones for Beryllium, while for the tungsten the correlation is Garcia-Rosales (Figure 1). The reference [10] is used because it has several common references with [1].

Table 1. Methodology based on the comparison between ITER [2] and DEMO [4]

Variable	**ITER**	**DEMO 2014**	**Factor *f***
Factors and data affecting source term production in VV			
Fusion power [MW]	500	1572	3.14
VV plasma volume [m^3]	837	1453	1.74
FW Material Diffusivity [m^2/s] (Material)	(Be) 4E-12 (Abramov Ex.) 8E-13 (Abramov H.) 2E-13 (Jones and Gibson)	(W) 9E-14 (Garcia-Rosales)	0.023 0.13 0.45
Brinell Hardness [MPa]	590 (Be)	2000 (W)	0.295
N. of disruptions (Dust production)	> 1 event/year	≥ 1 event/life of FPP	0.01
Max Disruption Power for FW [MW/m^2]	1.74	1.74	1
Tritium extraction pumping	Cryogenic	Turbo-molecular	0.8
Factors and data for source term mass estimation of BB			
SB/BB modules number	440	608	-

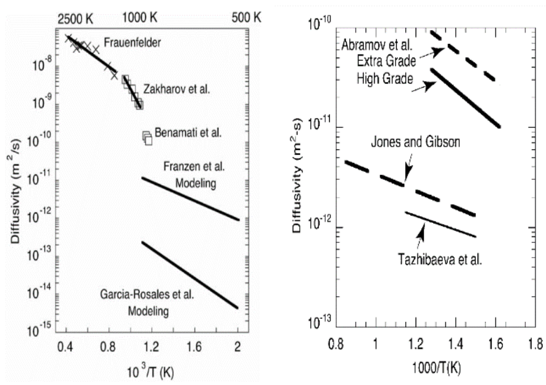

Figure 1. H_2 Diffusion Curve for W (left) and Be (right) [10]

In ITER, the uncertainties are estimated in the framework of control strategy [13], 30% for dust and 25% for Tritium productions.

4. Results

4.1 Tritium Source Term

According to the above methodology, it is possible to evaluate the Tritium inventory in the VV scaling the assumed values of ITER. The amount of the dust is strongly influenced by the plasma flux, so it directly depends on the fusion power. The FW and Divertor material with different diffusion coefficient as function of the operational temperature has an important role on the agreement with the methodology, the Tritium estimated is based on two main contributions: the dust presented in VV and deposited in the Divertor, and the tritium diffused into the FW.

The tritium and the dust for all DEMO concepts inside the VV are calculated using the methodology and scaling the mass supposed in ITER and it is a preliminary improvement on the results inside the documents [7] and [8]. The results of the analysis are presented in Table 2.

Table 2. Tritium results analyses using the methodology

	Scaling Factor	ITER tr. mass [g]	Uncertainty (25%)	DEMO 2014 tr. mass[g]
Abramov Ex.	0.0290	1000	1.25	36
Abramov H.	0.1678	1000	1.25	210
Jones-Gibson	0.5810	1000	1.25	726

For the HCLL [6], the exploitation of Fusion as an energy source also requires the demonstration of limited impact on the dose to the staff, public, and the environment, well below the limits established by international committees and national safety authorities. Therefore, a systematic safety analysis verifies continuously the design development to demonstrate that the safety objectives are met for each proposed solution. One of the most challenging accidents is a large break Loss of Coolant Accident (LOCA) of the Primary Heat Transfer System (PHTS) outside the VV. It can cause radiological releases consequences to the environment. However, because of relatively small radiological inventory and to the lower decay heat density, the risk associated with a break of the primary cooling loop in a fusion reactor is lower than the risk of the same event in a fission reactor.

As a conservative assumption for the HCLL breeding blanket concept it was consider that all mass of Tritium presented in the Helium and Lithium Lead is released during the accident (~63.9 g in total). It is the combination of total Tritium in the He (25.8 g) [17] and PbLi (38.1 g) [17][18] loops.

In the case of the HCPB [6] breeding blanket concept, it was assumed that normally the mass inventory of Tritium cannot be released because it is trapped inside the pebbles and required a high temperature to exit. During an accident, the only power production is the decay heat, that is the only energetic contribution after an accident with the failure of BB line, but without rupture of the BB module. In addition, it is important to consider the chemical reaction with a possible air ingress. As conservative assumption, it was considered that total mass of Tritium present in the helium is released during the accident. In addition, a fraction of Tritium trapped in the pebbles has to be evaluated scaling from 85 - 100 g of Tritium content [6] in the whole BB and being 608 the number of modules, each modules contains 0.183 g, on average. In such way the amount of Tritium released in case of accident will depend on the number of damaged modules. Considering total amount in the helium purge gas (around 0.101 g [6]) and in the helium coolant (around 0.41 g [6]), in the worst conditions (high temperature accident scenario), the Tritium that can be released during an accident will be 0.694 g in the case of HCPB concept considering one module failure condition.

4.2 Dust Source Term

The dust inventory in the DEMO design is based on assumptions for the ITER design [1] and the DEMO design of 2012 [16]. It is scaled taking into account the relevant factors for the dust production that are fusion power, vacuum vessel plasma volume, according to Table 1. Both in ITER [1] and in DEMO 2012 [16], the inventory was hypothesized to be 100 kg W dust.

Scaling to ITER the dust mass would result in 896 kg, but the disruption frequency specified for ITER is 10% in the total plant life and 30% during plasma development periods [14], while in DEMO the disruption occurrence is expected to be near to 0 [15].

Table 3. Scaling factors for dust mass estimation in DEMO 2014

Variable	DEMO 2014	ITER	Factor	DEMO 2012	Factor
Fusion power (MW)	1572	500	3.14	2119	0.74
VV Plasma volume (m^3)	1453	837	1.74	1527	0.95
Average Neutron Wall Load (MW/m^2)	1.067	0.65	1.64	1.384	0.77
Factor f			8.96		0.54

A factor 100 between the two disruptivities is adopted, 10% for ITER and 0,1% for DEMO. The uncertainties are accounted for 30% [13], leading the inventory to about 12 kg.

Scaling to DEMO 14 the dust mass would be 70 kg. To be conservative this higher value is accepted (Table 4).

Table 4. AP results analyses using the methodology

	Scaling factor	Dust mass (kg)	Disruptive factor	Uncertainty (30%)	DEMO 2014 dust mass (kg)
ITER	8.96	100	0.01	1.3	12
DEMO 2012	0.54	100	1	1.3	70

5. Conclusion

The methodology shows its potential for source term estimation based on feasible engineering consideration.

The Tritium values should be revised although the actual values seem promising in comparison of values in used in the other Work Packages, however they are not directly connected.

According to the methodology adopted, the dust inventory in any DEMO concept could be in the range of tens of kg. For the scaling rules used in the current evaluation and including a safety factor to account the uncertainties, 70 kg of dust is the outcome of this study.

In any case, the designed methodology needs to be confirmed with a validation program versus existing data of experimental machine before it could be included in the tools for the evaluation of the source terms.

Future investigations will require to improve the factors and to differentiate the source terms for accidental and normal conditions, including a revision of the uncertainties.

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