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# A novel integrated approach for the hazardous radioactive dust source terms estimation in future nuclear fusion power plants

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## Abstract

An open issue still under investigation by several international entities working on the safety and security field for the foreseen nuclear fusion reactors is the estimation of source terms that are a hazard for the operators and public, and for the machine itself in terms of efficiency and integrity in case of severe accident scenarios. Source term estimation is a crucial key safety issue to be addressed in the future reactors safety assessments, and the estimates available at the time are not sufficiently satisfactory. The lack of neutronic data along with the insufficiently accurate methodologies used until now, calls for an integrated methodology for source term estimation that can provide predictions with an adequate accuracy. This work proposes a complete methodology to estimate dust source terms starting from a broad information gathering. The wide number of parameters that can influence dust source term production is reduced with statistical tools using a combination of screening, sensitivity analysis, and uncertainty analysis. Finally, a preliminary and simplified methodology for dust source term production prediction for future devices is presented.

Keywords: Plasma physics, Physics methods, Nuclear physics, Nonlinear physics, Engineering

## 1. Introduction

Increased efficiency, renewables, sequestration of carbon dioxide but especially nuclear power are options for the world to sustainably meet future energy needs [1, 2, 3]. According to the European fusion program roadmap Horizon 2020, the second milestone following the demonstration of the feasibility of a fusion plant (i.e. International Thermonuclear Experimental Reactor, ITER) should be the delivery of a net electrical power to the grid in a tritium self-sufficient plant that would represent an ITER successor device (i.e. Demonstration power plant, DEMO) [1]. Power plant conceptual studies (PPCS) [4] have been conducted within the European Fusion Development Agreement (EFDA) to present five breeding blanket designs for DEMO. Assessing those models highlighted a number of issues to be addressed and different tasks to be completed to establish the DEMO physics, technology, safety and security [5, 6, 7].

A very important issue related to the reactor safety and security is the amount of activated material of different composition and shape that is produced inside the vacuum vessel as a consequence of the interactions between plasma and materials (PMIs) [8, 9, 10, 11]. Plasma-facing components can be eroded by the plasma particles, mostly during short pulses of high heat loads. These interactions are due to several phenomena taking place during the reactor operation, such as chemical and physical sputtering, arching, and off-normal events like edge localized modes ELMs, vertical displacement events VDEs, and plasma disruptions [11]. Material from the first wall, from the breeding blanket modules, and from the divertor could be eroded and dust of different size (from 10 micro meters to few mm) and composition [12, 13] is produced and consequently stored inside the vessel. This erosion process not only will call for replacement of the worn out targets, due to the shortening of its lifetime, but also will compromise the efficiency of wall conditioning. Eroded material produced could be made of several materials such as Be, W, stainless steel, and in particular tritiated dust chemically reactive and/or toxic [11]. Such deposits may accumulate inside the vacuum vessel on the first wall components. Dust source terms should be predicted to estimate the impact of dust on safety and security of the reactor, and consequently adjust the concepts designs to take into account this particular problem. Studies are going on focusing mostly on minimization of the tritium inventory inside the vessel, and to limit the possibility of metallic dust reaction with hot water during an accidental in-vessel water leak, which could lead to hydrogen formation or give rise to the possibility of explosion [14, 15, 16, 17]. The design of DEMO must limit the off-normal events in order to maintain dust inventories at reasonable levels and must also develop dust removal techniques. Dust represent an hazard to the integrity of the plant since

it is capable of being re-suspended in case of particular accidents (e.g. Loss Of Vacuum Accident, LOVA; Loss Of Coolant Accident, LOCA; Loss Of Flow Accident, LOFA) and consequently causing explosions [16, 17, 18, 19]. It is also a serious hazard to the operators since it is breathable and radioactive [13, 20].

Regarding the next generation fusion power plants like DEMO, operation flexibility along with a complete definition of the domain of the safe operation is obtained defining OLCs (Operating Limits and Conditions): a set of operating limits and conditions that include safety and operational limits on equipment and inventories, system settings, and administrative requirements (safety important class, SIC) [21]. OLCs safety limits (a few hundreds) include in-vessel dust inventories [21], that could challenge equipment and functions and/or could result in safety hazard if exceeded. With particular reference to those safety limits it is clear that source term production inside the vacuum vessel is crucial to be predicted and controlled in a proper way in order to ensure the safe and efficient operation of the reactor. Dust inventories guidelines should be set to limit the mobile products inside the vacuum vessel, to ensure that chemical reactivity is adequately controlled and also to avoid the hazard of dust explosion [4]. In order to establish administrative limits for the maximum source term quantity tolerable inside the vacuum vessel, the development of a reliable method for source term production prediction and quantification is required. Estimates for the foreseen reactors are missing for source term quantities, location, materials, composition, morphology, but only administrative limits imposed are available. The experience and data gained from the operation of tokamaks worldwide is crucial for ITER and DEMO design and safety analysis. The total mass collected from different locations divided by the area gives the surface mass density at that specific location, and the product of it and the total component area provides the quantity of dust production related to that component. Summing all quantities from all vacuum vessel components gives an estimate of the total amount of dust inside the reactor [4]. Such estimates along with characterization of the material collected have been done in tokamaks like JET, TFTR, JT 60, DIII-D, T15, ASDEX-U, Tore Supra, ALCATOR-C, FTU, and are available in several reviews [8, 11, 22]. While a considerable amount of data is available for existing devices, a model to predict quantities and help estimation of dust source terms for foreseen devices is yet to be found. It is still needed, due to lack of experimental experience, a full validation of the assumptions adopted in the safety analysis and results presented for the in-vessel source term inventory as one of the crucial OLCs identified [21].

## 2. Background

Quantification of dust source terms inside the vacuum vessel of a foreseen fusion power plant should be a key safety issue to be addressed in order to correctly tackle accident scenarios and to identify the impact of design options [23, 24]. In

addition, the evaluation of dust source terms is an essential input to calculate radiological consequences in severe accident research [25]. Dust source terms quantification for accident scenarios (e.g. LOVA; LOCA; LOFA) should take into account where and when the source term can be released during such accidents. Modeling of a fusion reactor vacuum vessel is crucial for accident analysis and to predict materials inventory and mobilization, both from the experimental and numerical point of view. For that reason, along with experimental facilities to reproduce source term mobilization phenomena [26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36] it is also very important to develop a numerical model [37, 38] in order to predict particles quantities, velocity and direction in case of accidents such as a loss of vacuum, and not referring just to administrative limits but to estimates based on a more accurate methodology.

In fact, at the state of the art, the source term evaluation for accident transients in foreseen reactors starts from the assumption of a certain inventory of material (such as dust and tritium) inside the vacuum vessel, mostly using figures from administrative limits and not from an estimation of the actual production.

For example, administrative limits of 100 kg of Be dust, 200 kg of C dust and 100 kg of W dust were set for the total mobilizable dust within first confinement barrier according to 2001 General Site and Safety Report (GSSR) for the International Thermonuclear Experimental Reactor (ITER) [14] as shown in Table 1.

The amount of W dust was then increased to 1000 kg in 2008 according to Safety Analysis Data List (SDL) [39] as evidenced in Table 2.

However, neither the GSSR limits nor SDL limits reflect a detailed calculation of source term inventories starting from a physical point of view, taking into account all the important parameters and laws involved in dust production process. Those limits came instead from a safety approach. This approach starts from considering the potential consequences of postulated accident scenarios, such as vacuum failures and dispersion of source terms inside the future plants. Doses are then calculated for each contaminant and each accident scenario and limits are set up

**Table 1.** Dust Inventory limits (kg) according to GSSR [14]. In addition, 5 kg of dust (diameter 0.1 micro-m) is assumed to be produced by a disruption. Also, tungsten dust limit was increased from 100 kg to 350 kg to account for uncertainties.

Location Unit	Be Dust kg	C Dust kg	W Dust kg
Plasma facing components of the divertor	6	6	6
Total mobilizable dust within 1st confinement barrier	100	200	350

**Table 2.** Dust Inventory limits (kg) according to SDL 2008 [39]. In addition, 5 kg of dust (diameter 0.1 micro-m) is assumed to be produced by a disruption.

Location Unit	Be Dust kg	C Dust kg	W Dust kg
Plasma facing components of the divertor	6	6	6
Total mobilizable dust within 1st confinement barrier	100	200	1000

accordingly inside the vessel (factors are introduced to address the uncertainties) in order to ensure the respect of the allowed quantities of source terms in different locations in the plant in case of different accidents. Source term figures are administrative limits calculated from safety approach, that likely overestimate the real production. The effects of different physical and technological parameters that were negligible for safety purposes in those reports are still waiting to be taken into account in a more detailed study.

Starting with the postulation of an amount of tritium equal to 1 kg, and 100 kg of dust (that are the today authorized upper limits for ITER), source term evaluation for ITER has been recently made [40] with ASTEC code developed by the French Institut de Radioprotection et Surté Nucléaire (IRSN) and the German Gesellschaft für Anlagen und Reaktorsicherheit (GSR), that is the European reference code for severe accident simulations in nuclear plants [41]. Also, integrated computer codes widely used in fission field such as MELCOR [42] have been applied to evaluate accident steps and consequences in fusion reactors [43, 44, 45, 46] but a precise estimation on source term inventories as input for the software is still missing. Along with initial inventories, design and operational parameters are essential inputs to run the safety codes for accident scenarios analysis.

In conclusion, the limits presented in the reports cited above for ITER and DEMO represent administrative figures useful for safety purposes in case of accidents but do not give us a real estimate of the source term production in order to give a precise order of magnitude of the phenomena taking place inside the reactor, to address technological and physical concerns such as the plasma performances in case of dust contamination, the first wall material surface behavior in case of erosion, and many other concerns that can affect design choices. Overestimation of source terms inside the vacuum vessel could lead to strongly conservative design choices that can dramatically increase complexity and costs.

### 3. Methodology

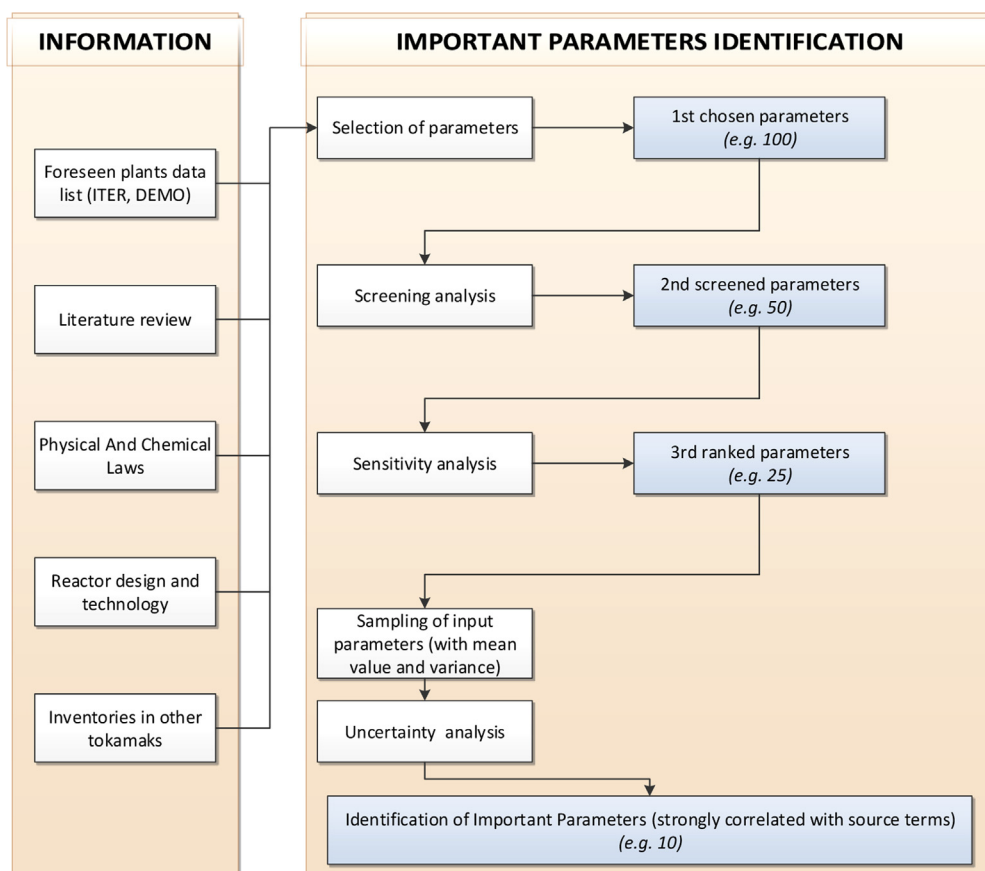
#### 3.1. Information gathering

First step of the work that has the objective of developing a methodology to estimate in-vessel source terms for future reactors, is a literature review on the

phenomena taking place during dust production, the Plasma-Material Interactions mechanisms, including the physical and chemical processes [7, 8, 9, 11]. Understanding of the off-normal events that are involved in reactor operation such as ELMs (Edge Localized Modes), VDEs (Vertical Displacement Events), and disruptions that can accelerate the dust production due to erosion is also crucial. In addition, information on databases of source terms collected in existing fusion devices, including dust characterization of the collected samples, is needed. The reviews, studies and data regarding the dust production phenomena will help to choose the first big block of parameters of interest that will be reduced and then used for scaling purposes as shown below.

### 3.2. Rough Screening

As shown in Fig. 1, the initial parameters selection is based on experience and engineering judgement among a wide number of physical, chemical, engineering parameters that can be chosen from experts. A first rough screening process (concerning for example a percentage increase/decrease of the values comparing to



**Fig. 1.** Parameters reduction block diagram overview.

base case) should decrease the number of selected parameters up to 50%. This first step should have a very low computational cost. The rough screening does not quantify exactly the relative importance of the inputs but is needed to weed out uninfluential variables.

### 3.3. Sensitivity Analysis

Following step would be a more proper screening, for the quantification of uncertainty in each input, to identify which input variables are significantly contributing to the output uncertainty rather than exactly calculate the sensitivity. This is necessary due to the fact that there is more than one good distribution that represents the expert's beliefs [46]. While the simplest way to perform a screening is a local analysis varying one factor at a time around a baseline point, the Morris elementary effects (EE) method [47] has been shown to be more effective but still simple at the same time [48, 49]. The scope of the Morris method is to identify which variables in input produces i) negligible effects, ii) linear and additive effects iii) non-linear effects iiiii) or interact with other variables, computing incremental ratios for each input. Such ratios (i.e. elementary effects) are averaged to assess the importance of the single input. At the end of the Morris sensitivity analysis the number of parameters should decrease of another 50% [47, 48, 49].

### 3.4. Uncertainty Analysis

The final set of parameters chosen, should be introduced into the uncertainty analysis. While the contribution of individual uncertain inputs to the uncertainty of the results refers to the sensitivity analysis, here the uncertainty analysis takes care of the uncertainty in analysis results that derives from uncertainty in analysis inputs [50]. A wide number of methods for uncertainty analysis have been developed and overviews are available in several reviews [51, 52, 53, 54]. Among them, sampling-based approaches are effective and widely used [55, 56, 57, 58, 59].

#### 3.4.1. Sampling-based Uncertainty Analysis

The sampling-based uncertainty methods include the following steps [60]. First, a very important step is the definition of distributions (e.g. uniform, normal), that determine both the uncertainty in the function and the sensitivity of the elements of the function to the elements of the parameters. It should be noticed that for each parameter an appropriate distribution should be assigned by the expert judgement. A possible solution to avoid a major cost is to perform an initial exploratory analysis to identify the most important analysis inputs and then concentrate the resources on characterizing the uncertainty in these inputs. Secondly, the generation of samples in consistency with the distributions could be performed with random or importance sampling or with Latin hypercube sampling [60, 61, 62], and then the

sample should propagate through the analysis to produce a mapping from analysis inputs to analysis results. Finally, the results are presented in form of presentation of uncertainty analysis [63].

### 3.5. Source terms simplified estimation

The output from parameter selection should be a list of parameters including a detailed description and information on its distribution. Moreover, a list of correlation coefficients between the production of a certain material and correlated input variables should be provided in order to choose important parameters for the source term estimation according to Eq. (1). Once a certain number of important parameters are finally found, they could be used for scaling purposes to get an estimation of the mass of the activated products. The problem of identify and quantify the source terms inside a future nuclear fusion reactor vacuum vessel is strongly limited by the lack of neutronic data [14, 15, 23]. Referring to Eq. (1), a possible solution could be deriving the  $m_l^j$  mass of material  $i$  in the location  $l$ , from the previous state-of-art  $m_l^{i,old}$  “old” mass of material  $i$  in the location  $l$  scaling based on a factor that is function of the parameters  $A, B, C, \dots$  chosen with the above analysis. The “old” mass could refer to the mass identified in an experimental reactor operated in the past or in operation, or could also refer to an estimation (such as an administrative limit, like the ones for ITER or DEMO-Demonstration Power Plant).

Just as an example, parameters  $A, B, C \dots$  could be “fusion power”, “area of the eroded component”, “first wall fluence”, “off-normal events frequency”, “material retention rate”, and/or dozens of other interesting parameters yet to be screened and chosen as shown above.

$$m_l^{j(new)=f(A,B,C,\dots)} = f(A,B,C,\dots) \cdot m_l^{j(old)} \tag{1}$$

where the function  $f$  could be written in different forms, for example like:

$$f(A, B, C, \dots) = A_1^\alpha \cdot B_1^\beta \cdot C_1^\gamma \cdot \dots \tag{2}$$

hence allowing to simplify and linearize the expression as follows:

$$m_1 = \left( A_1^\alpha \cdot B_1^\beta \cdot C_1^\gamma \cdot \dots \right) \cdot m_0 \tag{3}$$

$$\ln(m_1) = \alpha \ln(A_1) + \beta \ln(B_1) + \gamma \ln(C_1) + \dots + \ln(m_0) \tag{4}$$

To clarify with an example, according to the simplifications presented, the mass of the tungsten W produced in the divertor component of the DEMO reactor can be written as function of three parameters (A, B and C) as follows:

$$m_{DIV}^{W,DEMO,DEMO} = \left( A_{DEMO}^{\alpha 1} B_{DEMO}^{\beta 1} C_{DEMO}^{\gamma 1} \right) \cdot m_{DIV}^{W,old,old} \tag{5}$$



However, this methodology will need several data. The more parameters are taken into account, the more data regarding the source term production considered ( $m$ ) should be collected [64] for several fusion devices, to form vectors of data regarding the mass of the material  $i$  in the location  $l$  for the device  $x$ , and also regarding the values of the chosen parameters  $A, B, C \dots$  for the  $x_i$  devices:

$$\begin{pmatrix} ({}_{l1}^{i1} m_{x1} {}_{l2}^{i2} m_{x1} {}_{l3}^{i3} m_{x1} \dots) & ({}_{l1}^{i1} m_{x2} {}_{l2}^{i2} m_{x2} {}_{l3}^{i3} m_{x2} \dots) & ({}_{l1}^{i1} m_{x3} {}_{l2}^{i2} m_{x3} {}_{l3}^{i3} m_{x3} \dots) & (\dots) \end{pmatrix} \begin{pmatrix} A_{x1}, & B_{x1}, & C_{x1}, & \dots \\ A_{x2}, & B_{x2}, & C_{x2}, & \dots \\ A_{x3}, & B_{x3}, & C_{x3}, & \dots \\ \dots & & & \end{pmatrix} \tag{6}$$

This way it is possible, with statistical tools available in literature [64, 65], to estimate the exponents  $\alpha_i, \beta_i, \gamma_i, \dots$  in order to calculate the output desired. The values  $j m_x$ , once the database above is known, can be written for each material in each location of each device as  $y$ :

$$y = y_0 + \alpha \cdot f(A) + \beta \cdot f(B) + \gamma \cdot f(C) + \dots + \varepsilon \tag{7}$$

Where  $f(A), f(B), f(C), \dots$  are functions of the  $A, B, C, \dots$  parameters chosen. Assuming that  $y_0 = 0$  since there is no source term production when parameters are equal to zero, and assuming that  $\varepsilon$  has a normal distribution with zero mean and constant variance equal to  $\sigma^2$ , it is possible to express the average source term production  $\bar{y}$  as:

$$\bar{y} = \alpha \cdot f(A) + \beta \cdot f(B) + \gamma \cdot f(C) + \dots \tag{8}$$

It should be noticed that any of the functions may be powers of the independent variables  $A, B, C, \dots$ . For example,  $A = C^3$ , or a non-linear function such as  $B = \log(A)$ , or a cross-product term  $D = A \cdot C$ . For the purpose of estimation of a conservative and preliminary quantity for source term for foreseen fusion power plants reactors inventories, the problem should be reduced to a first-order model [65] in which each of the independent variables appears, but there are no cross-product terms or terms in powers of the independent variables. The so-called partial slopes  $\alpha, \beta, \gamma$  represents the expected change in  $y$  when all other slopes are constant. To find them, or in other words, to perform the estimation of the multiple regression coefficients, the residual minimization is needed by solving a set of simultaneous equations (i.e. normal equations). There are many software programs that help to calculate least-squares estimates for parameters for multiple regression [65].

### 4. Conclusions

Currently, the source term estimation in fusion power plants is based on rough assumptions and it does not account the physical and engineering parameter of the different plant designs taken into account. An integrated approach to estimate

hazardous source terms production in nuclear fusion power plants has been presented. The general methodology could be summarized as follows:

- i) information gathering: literature review on the phenomena taking place during dust production, including understanding of Plasma-Material Interactions, physical and chemical processes involved, off-normal events (ELMs, VDEs, disruptions) that can accelerate the dust production due to erosion, also information on databases of source terms collected in existing fusion devices, including dust characterization of the collected samples.
- ii) screening of the first parameters of interest among a wide number of physical, chemical, engineering parameters that can be chosen from experts.
- iii) sensitivity analysis to reduce up to 50% the number of parameters.
- iv) uncertainty analysis of the chosen set of parameters in order to take care of the uncertainty in analysis results that derives from uncertainty in analysis inputs.
- v) source term production calculation made with a preliminary methodology in order to produce a first estimation of inventories useful for safety analysis also as an input for safety softwares used for accident analysis in nuclear fusion power plants.

The authors believe that the proposed first-order model could give useful information about the magnitude of the phenomena but since the highly non-linear nature of plasma instabilities, and considering highly-correlated parameters, further development of the model is currently under investigation by the authors.

Furthermore, the engineering screening of parameters may be incomplete if data from current machines is used as input of the proposed methodology to obtain results for self-heating machines such as ITER, since a large internal heating source is not present in current tokamaks. Hence, safety factors should be included to account for uncertainties.

The authors want to encourage the scientific community and those involved in specific work packages related to source term evaluation in the main fusion institutions to share the data (especially the neutronic data) in order to let the scientific community able to deepen the studies in the field, and to consider a more detailed calculation of the source term in fusion plants starting from the methodology proposed and taking into account a wider range of parameters.

## Declarations

## Author contribution statement

Luigi Antonio Poggi: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; wrote the paper.

Andrea Malizia, Jean-François Ciparisse, Pasqualino Gaudio: conceived and designed the experiments; wrote the paper.

### Competing interest statement

The authors declare no conflict of interest.

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### Additional information

No additional information is available for this paper.

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