ANALYSES AND PRELIMINARY RESULTS OF AN UPDATED ITER RADIOACTIVE WASTE ASSESSMENT

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The scope, methodology, and preliminary results are presented of a series of neutron transport and activation analyses aimed at updating the ITER radioactive inventory assessment and assisting the waste management planning. Calculations are performed using state-of-the-art three-dimensional models, codes, and data libraries and thereby overcoming earlier conservative one-dimensional evaluations. The latest information on component design, maintenance, materials, and French regulatory framework is used. Results include categorization snapshots at different decay times, time histories of activation, IRAS index and other radiological quantities throughout the machine, and guidelines on interim decay times for different components. The aim is to provide information for the design and development of ITER systems, maintenance operations, and waste management processes and services.

KEYWORDS: *ITER, radioactive waste management, neutronics*

Note: The figures in this paper are in color only in the electronic version.

I. INTRODUCTION

ITER tokamak components will become radioactive because of activation by neutrons generated in the deuterium-tritium (D-T) fusion reactions. A nominal ITER D-T plasma will produce 1.78×10^{20} n/s during 400 s; over 30 000 of these pulses are foreseen during its lifetime. These neutrons escape from the plasma and travel throughout the structures surrounding it, thereby undergoing interactions with the nuclei in the materials. The neutron field throughout the machine intricately depends on three-dimensional (3-D) geometry details and material responses. The D-T fusion neutron energy, 14.1 MeV, is well above the threshold of reactions such as $(n,2n)$, (n,α), (n,p), and (n,t) that are rarely seen in fission environments. The activation field in D-T fusion conditions is therefore more complex in nature, and its analysis requires the use and coupling of very large, purpose-built codes and nuclear data libraries.

Activation inventories are essential for both safety and radioactive waste management assessments. For the purposes of radwaste evaluation and management planning, current knowledge is based on conservative, one-dimensional (1-D) analyses in 2003 (Refs. 1 and 2). The new updated radiation transport and activation calculations for ITER to revise the radioactive waste inventory estimation are being performed, using modern 3-D models and up-to-date techniques and nuclear data. The latest information on component design, maintenance, replacement schedules, and materials is also being adopted. This assessment informs the planning of waste segregation and treatment procedures as a function of activation characteristics.

Section II of this paper describes the methodology employed in this assessment, including models, operational scenario, and material information. Section III gives an overview of the French regulatory framework, and in Sec. IV some preliminary results are presented and discussed.

II. METHODOLOGY

The production of a radioactive waste inventory estimate for ITER comprises the following steps. First, it is necessary to model the transport of neutrons from the

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plasma source throughout the tokamak systems in order to ascertain the neutron flux distribution in space and energy throughout the machine. This is done using the well-established MCNP code coupled to the fusion-specific FENDL2.1 data libraries describing the material interaction cross sections that shape the neutron response of the system.[3,4] Second, the activation of the materials under such neutron field is computed using a nuclear inventory code FISPACT and appropriate EAF libraries.[5,6] The geometry models, material compositions, and operational scenarios (including plasma source and component maintenance/replacement schemes) are required to accomplish the above steps. Finally, the radiological data is used to produce inventory classifications and derive waste management parameters within the regulatory framework.

II.A. Models

The basis of all the modeling in this study is an ITER reference radiation transport model, Alite41 (Refs. 7 and 8). As shown in Fig. 1, this is a 3-D model in MCNP format covering a 40-deg sector of the machine inside the bioshield including the blanket first wall (FW), blanket shield blocks (SB), divertor, vacuum vessel (VV), toroidal field coil system (TFC), poloidal field coil system (PFC), and cryostat. In addition to this, several representative port plug systems are being analyzed:

1. one upper port (UP) containing a polarimetry diagnostic system
2. one lower port (LP) containing a cryopump system
3. one equatorial port (EQ) containing a core electron density diagnostic system (LIDAR)
4. one EQ port containing a core reflectometry diagnostic system
5. one EQ port containing an ion cyclotron microwave heating system (ICRH)
6. one EQ port containing a test blanket module system (TBM).

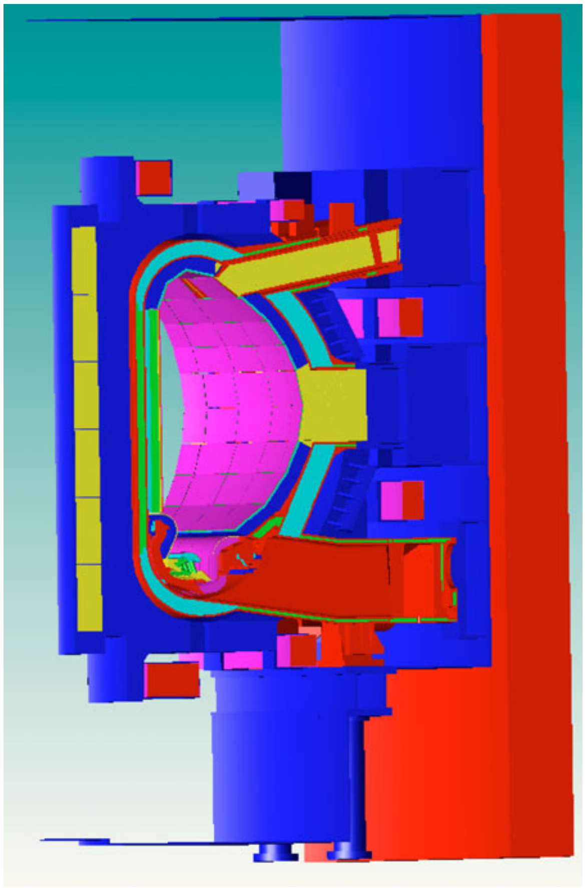

Fig. 1. ITER Alite model.

Models of these systems are obtained or built on purpose for this task, modified, and integrated into Alite41. A compromise is found between Monte Carlo efficiency and model development effort and, taking advantage of the dual port availability in the Alite model, five other Alite-based models are developed containing the following of the aforementioned port plugs: 1, 2, 3+6, 4, and 5. The majority of the processing and integration work for these models is done using the computer-aided-design–based MCAM software.[9]

II.B. Operational Scenario

The plasma source is taken to be that of a nominal 500-MW inductive D-T ITER plasma, as in Ref. 10, consisting of 1.78×10^{20} n/s and a radial profile following plasma density and temperature profiles. Irradiation scenarios for the activation analyses are based on the SA2 irradiation scenario,[11] in turn based on the baseline D-T campaign reference scenario,[12] consisting of 12 years of D-T pulses totaling 0.3 $\mathrm{MW\cdot yr/m^2}$ neutron fluence to the FW.

For each component, an irradiation schedule is developed from SA2 following the latest maintenance scheme information available[13]; these are summarized in Table I. In all cases, the last 20 pulses are modeled explicitly to account for short-lived activation products.

II.C. Materials

In the MCNP analyses, the material descriptions in Alite are used for the materials in this model. For the rest (port plugs), descriptions provided by or assumptions based on information from ITER are used. For the activation analyses, material compositions are taken from Ref. 14, except for a few unavailable cases in which assumptions were made.

TABLE I

Irradiation Scenarios

Component	D-T Irradiation Time (years)	Equivalent FW Neutron Fluence ($\mathrm{MW \cdot yr/m^2}$)
FW	13	0.3
SB	13	0.3
Divertor, batch 1	6	0.138
Divertor, batch 2	7	0.162
VV	13	0.3
TFCs	13	0.3
PFCs	13	0.3
Central solenoid	13	0.3
Cryostat	13	0.3
Port plugs	Variable (see below)	Variable (see below)
Polarimeter (UP)	10	0.231
Cryopump (LP)	5	0.115
LIDAR (EQ)	6	0.138
ICRH (EQ)	10	0.231
TBM (EQ) frame	8	0.185
TBM (EQ) system	4	0.092

III. REGULATORY FRAMEWORK

The criteria used for the classification and analysis of the radioactive inventory in this study are the latest French national directives on radioactive waste management.[1,15,16] In France, the national agency for radioactive waste management, ANDRA, is in charge of the overall radioactive waste management including inventory, collection and management of disposal facilities and research and development. Waste classification and management routes are based on nuclide half-life and activity, as described in Table II:

1. VTC (vie très courte): management based on interim storage and radioactive decay
2. TFA (très faible activité): disposal at the dedicated Morvilliers interim storage facility
3. FMA-VC (faible et moyenne activité—vie courte): disposal at the dedicated Centre de stockage de l'Aube (CSA), except for tritiated waste
4. FA-VL (faible activité—vie longe): ongoing studies
5. MA-VL (moyenne activité—vie longe): ongoing studies
6. HA (haute activité): ongoing studies—none from ITER.

TABLE II

ANDRA Waste Classification

	Very-Short-Lived (<100 days)	Short-Lived (<31 years)	Long-Lived (>31 years)
Very-low-level activity	VTC	TFA	
Low-level activity		FMA-VC	FA-VL
Intermediate-level activity			MA-VL
High-level activity		HA	

Nuclide-by-nuclide CSA acceptance criteria for FMA-VC waste can be found in Ref. 15. For Morvilliers, TFA status is established via comparison with the so-called IRAS (indice radiologique d'acceptabilite de stockage) index, defined as

$$\mathrm{IRAS} = \sum \frac{A_i}{10^{C_i}} < 1 \ ,$$

where

A_i = specific activity of nuclide i

C_i = nuclide class (0, 1, 2, or 3) as specified in Ref. 15.

In the ITER terminology used hereinafter, FMA-VC is defined as type A waste, whereas FA-VL and MA-VL are type B. No HA waste is generated in ITER.

IV. PRELIMINARY RESULTS

The models described previously are currently at different analysis stages. Preliminary results are presented here for the plain Alite model, used to assess the activation characteristics and waste classification of the vast majority of the components and masses in ITER, as described in Sec. II.A. As required by ultradeep penetration problems such as the one at hand, heavy variance reduction has to be developed in order to speed up the analyses while reducing Monte Carlo statistical uncertainty. The method employed is mesh-based weight windows developed in an automated fashion from analogue runs, as in Ref. 17. Computer time was ~2000 CPU hours in a parallel cluster of 120 64-bit processors running Linux and MPI.

Over 900 cell-based tallies are used to obtain the spatial variation of the neutron flux and spectrum throughout the geometry. It is ensured that all these MCNP results passed appropriate statistical checks before being automatically processed and fed to FISPACT. Finally, radiological inventories in each cell are produced according to the aforementioned irradiation schedules and at a series of decay times and assessed against the criteria described in Sec. III.

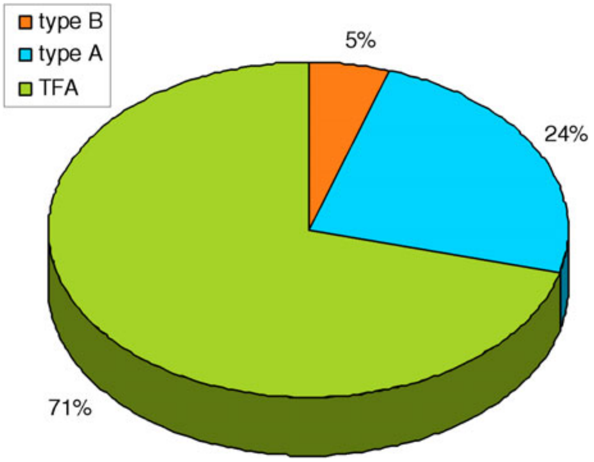

Fig. 2. Baseline scenario summary (at 50 years).

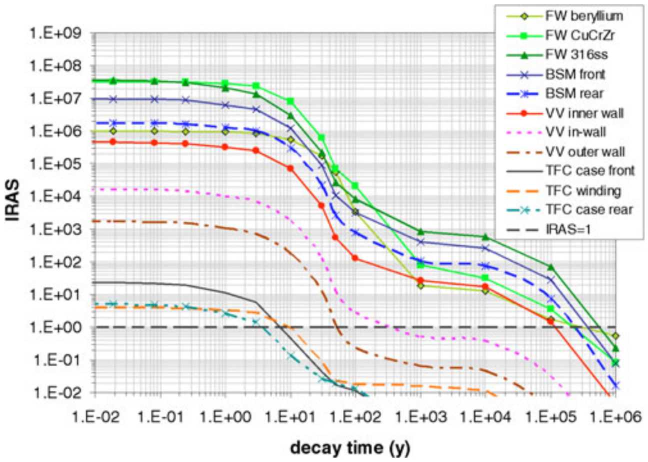

Fig. 3. Outboard IRAS histories.

Figure 2 is a snapshot summary of the waste classification for the baseline scenario at 50 years of decay time. Preliminary estimation of the total waste mass is ~20 786 tonnes; this excludes neutral beam injection (NBI), tritium plant, hot cell, bioshield, buildings, balance of plant, and the rest of the representative port plugs. About 2.7% of this waste arises during operation (from divertor replacement) and 97.3% during decommissioning. Component breakdown can be found in Table III by the comparison with the ITER design baseline up to 2010 (Refs. 12, 18, 19, and 20) and the previous analyses.[1] The earlier assessment[1] reports ~33 400-tonne total mass, including NBI, tritium plant, and fueling system with ~9% type B, ~34% type A, and ~57% TFA; ~10% operation and ~90% decommissioning.

Figure 3 shows time histories of the IRAS index at a series of outboard midplane locations. Based on the analysis of the vast amount of radiological information, in general, decay times to type A for type B waste are of the order of hundreds to thousands of years, whereas decay times to TFA for type A waste can be of only a few years. This is a consequence of the half-life dependency of the regulations. More details are as follows:

TABLE III

Mass Summary*

Component	2010 Estimation	2010 ITER[a]	2003 Analyses[b]
FW	330	1530	1553
SB	1296		
Divertor	624	654	660
VV	5061	5100	8024
TFC	6082	6012	5356
PFC	1641	1870	2340
Central solenoid	935	954	1007
Cryostat	4272	3500	4746
Port plugs	829	—	988

*In tonnes.
[a] References 12, 18, 19, and 20.
[b] Reference 1.

1. In all cases, the FW is type B at $t = 0$, and interim decay times to type A are >100 years; tritium from activation is responsible for this categorization, among others.

2. In all cases, the front, plasma-facing side of the SB is type B at $t = 0$, and interim decay times to type A are >100 years; the rear side of the SB is type A at $t = 0$, and interim decay times to TFA are >100 000 years.

3. The VV inner wall is type A at $t = 0$, and interim decay times to TFA are >100 000 years.

4. The VV in-wall shield is type A at $t = 0$, and interim decay times to TFA are >100 years.

5. The VV outer wall is type A at $t = 0$, and interim decay times to TFA are >30 years.

6. The classification of the TFCs and PFCs is very material and position dependent. In general, at $t = 0$ insulators are TFA whereas winding packs and casings are type A (except for a small amount of casing that is TFA). For the latter, interim decay times to TFA range from >10 to >1000 years for windings and from >1 to >100 years for the casings.

7. The central solenoid is TFA at $t = 0$.

8. The cryostat is type A at $t = 0$; interim decay times to TFA are between 10 and 30 years.

V. SUMMARY

A new study aimed at updating the ITER radioactive inventory assessment and assisting the waste management planning is to provide information for the design and development of ITER systems, maintenance operations, and waste management processes and services. Radiation transport and activation analyses are performed using state-of-the-art 3-D models, codes, and data libraries, thereby superseding earlier conservative 1-D evaluations. The latest information on component design, maintenance, materials, and French regulatory framework is used. More detailed results and the analyses of more components (representative port plugs) will be reported in the near future.[21,22] Furthermore, the tritium retention/permeation in plasma-facing components will need to be analyzed next.

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