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Activated corrosion product contamination assessments of DEMO WCLL breeding blanket primary heat transport system

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ABSTRACT

In water-cooled fusion reactors, the assessment of the primary system contamination is essential for waste management, machine availability, occupational radiation exposure, and radiological hazard determination. The primary cooling water is not only directly activated by the intense neutron field but is a contamination vector for a significant variety of gamma emitters with short to long decay half-lives. Corrosion products can be activated in those regions under neutron flux of the primary circuit and then released in the cooling water.

In the EU-DEMO fusion power plant equipped with the Water-Cooled Lithium Lead Breeding Blanket (WCLL-BB) concept, the primary coolant undergoes intense neutron fields in the first wall and the breeding zone regions of the blanket. Activated Corrosion Products (ACPs) are then formed, released into the water, transported in the cooling loop and finally deposited onto the ex -vessel surfaces of the Primary Heat Transport System (PHTS), where working personnel are susceptible to being radiologically exposed.

This work addresses the complete assessment of ACPs in the WCLL-BB PHTS of EU-DEMO. The simultaneous and multi-physical processes behind the ACP formation are tackled using the OSCAR-Fusion code, a comprehensive tool developed by the CEA (France) to assess contamination in fusion nuclear reactors. The whole system is modelled with zero-dimensional nodes with assigned geometrical, thermal-hydraulics, material and chemical parameters. Activation reaction rates integrated over the whole spectrum and calculated with MCNP are given to those regions exposed to the neutron flux. Results are provided in terms of mass and activity inventories of ACPs as deposit and inner oxide layers of components (pipes, heat exchangers, pumps...), ions in solution, particles in suspension, and filters and resins trapping.

Mobilizable inventories such as ions, particles and deposits are important source terms in accidental scenario evolutions, while the whole activity inventory constitutes the main long-term gamma emitting source for dose rate maps determination in the tokamak building rooms housing the main PHTS equipment.

1. Introduction

Activated Corrosion Products (ACPs) are important source terms in nuclear safety. They may affect significantly the collective occupational dose, the waste management procedures and classifications, the accident scenario consequences, the maintenance plan, and the component inspectability [1]. Austenitic steels (304 and 316 for instance), commonly used in nuclear power plants for the primary cooling systems, form, in contact with water, two oxide layers [2]. The inner, denser, and more adherent, passivation spinel oxide layer is richer in chromium and it is addressed in the following text as the “inner oxide”. An outer, coarse-grained layer, richer in iron, is formed on top of the Cr-rich spinel, and it is addressed here as “deposit” or “outer oxide”. For 304 L austenitic steels under nominal cooling conditions of Pressurized Water Reactors (PWRs), the outer layer is mainly formed by magnetite crystals, which are detachable and may constitute a realistic source term in Loss Of Coolant Accident (LOCA) simulations. The corrosion products formed in water-cooled primary circuits may be activated by the intense

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neutron flux, generating a wide variety of gamma emitting radionuclides, which can constitute a concerning radiological hazard for the working personnel, the environment, and the public.

A behavior similar to PWRs is expected in EU-DEMO. Primary Heat Transport Systems (PHTS) piping undergoes corrosion in contact with pressurized water at high temperatures (300 °C in the breeding blanket cooling circuit), forming a dual layer that may release contaminants into the coolant. The harder neutron spectra and the higher neutron fluence boost transmutation, and significant ACP inventories are expected in terms of surface contamination of the cooling pipes (inner oxide and deposits), particles in suspension, ions in solution, and filters and resins trapping.

In this manuscript, the assessment of ACPs in the EU-DEMO Water Cooled Lithium Lead (WCLL) Breeding Blanket (BB) PHTS is presented. Deposit, inner oxide, particles, and ions inventories have been estimated using OSCAR-Fusion v1.4.a [3], an ACP simulation tool developed by the French Alternative Energies and Atomic Energy Commission (CEA), in Cadarache.

The BB PHTS, including the in-vessel branches for the First Wall (FW) and the Breeding Zone (BZ), has been modelled in zero-dimensional connected nodes with assigned parameters of water chemistry, component geometry and material, thermal-hydraulics, and neutronics. Total activation reaction rates must be assigned to the nodes representing the in-vessel region under neutron flux. OSCAR-Fusion simulates the contamination of closed water-cooled circuits according to a specific operation scenario.

The main goal of this work was the establishment of procedures, in the early phases of the design process of the BB PHTS, aimed at conceiving simplified models to be used in exploring the design parameter and operation domain. Parametric calculations have been performed accordingly, to estimate the impact of technological choices on the final figures of merit in terms of deposit, inner oxide inventories, particles in suspension, ions in solution, and filters and resins contamination.

In Section 2 of the present manuscript, the OSCAR-Fusion model development is presented. This includes the design of a representative model of the thermal-hydraulics of the system, the calculation of the activation reaction rates, and the definition of an operation scenario that can be processed by the simulation tool with a sustainable computational overhead. In Section 3, the parametric runs are presented. Calculations have been performed perturbing water chemistry, the technological parameters linked to the pipe manufacturing, the design choices made on the in-vessel wet and heat-exchanging surfaces, and, finally, on the design configurations of the Chemical Volume Control System (CVCS).

2. Model development for ACP simulations

2.1. OSCAR-Fusion modeling

Several simulation tools that can assess ACPs in primary cooling circuit exist. Examples can be found in [4,5]. OSCAR-Fusion v1.4.a has been adopted as reference tool by the safety department of ITER Organization, and it is the reference code for ACP simulation in the Safety and Environment work package at EUROfusion.

Fig. 1 shows a picture of the thermal-hydraulic model adopted, relying on the latest DEMO WCLL PHTS design baseline [6]. Four in-vessel branches have been used to represent the regions under neutron flux. Heat-exchanging sections have been subdivided into multiple nodes in OSCAR-Fusion according to the temperature gradient. In this configuration, BZ cooling pipes are characterized by a double pass. The full description of the BB PHTS can be found in [6].

Fig. 2 shows the full BB PHTS model in OSCAR-Fusion v1.4.a. 4 in-vessel branches are visible in the top left corner of the scheme, where the in-board and out-board FW and BZ regions are reported. The FW has been modelled with 6 nodes, gathering into a single node the whole SW. The BZ has been modeled by two sets of 3 regions for each pass. The steam generator, in the top right corner of Fig. 2, has been modeled in 8 nodes, while the bottom branch is representing the whole CVCS.

Thermal-hydraulic characteristics have been derived by means of the

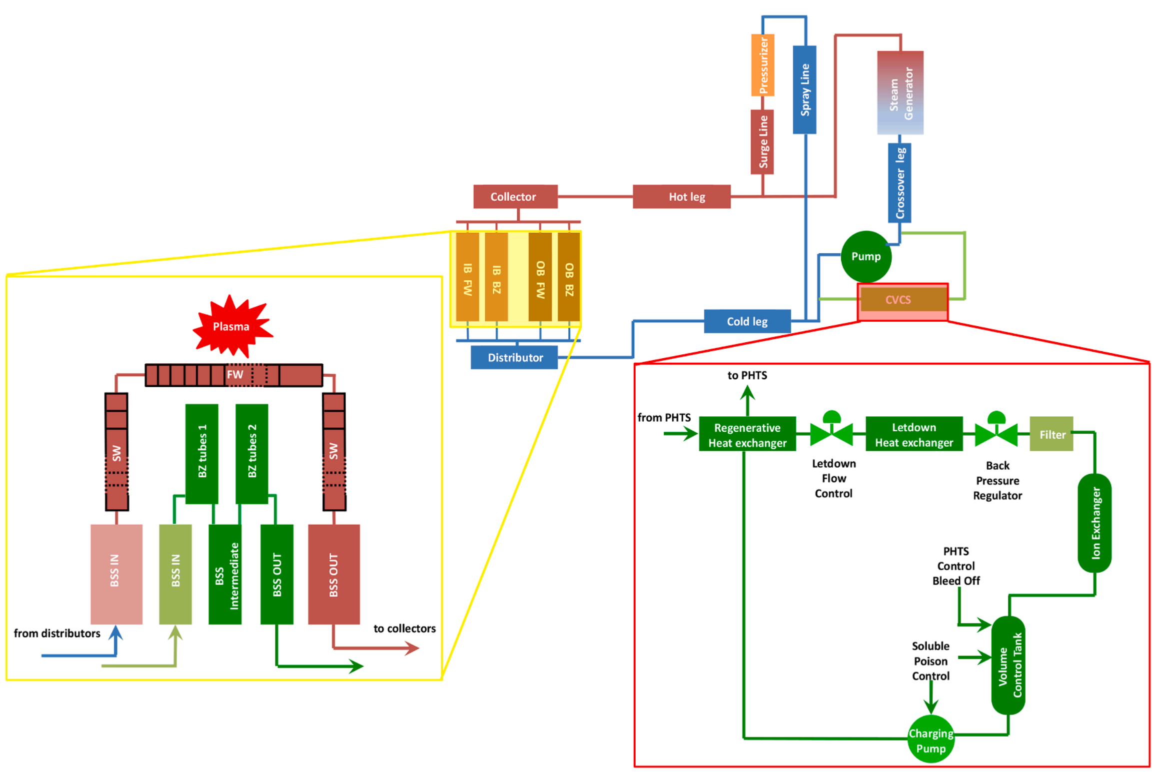

Fig. 1. Sketch of the thermal-hydraulic model adopted for the EU-DEMO BB PHTS.

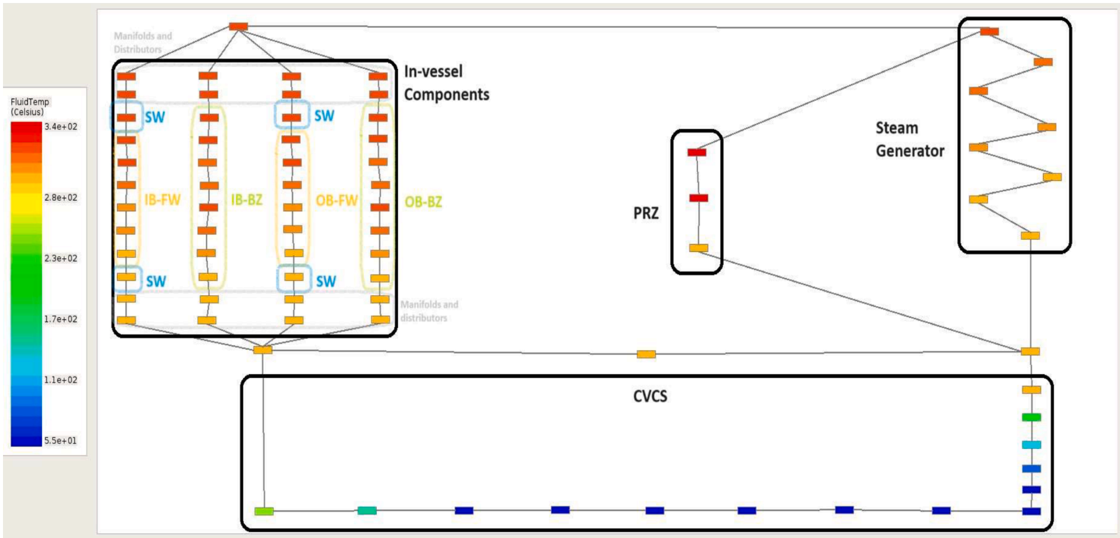

Fig. 2. OSCAR-Fusion v1.4a. model of the EU-DEMO BB PHTS displaying coolant temperatures. On the top left corner the in-vessel regions are represented by four branches. The top right corner hosts the steam generator, modelled by 8 nodes in this work. The CVCS is located in the bottom.

TRACE system code [7] as reported in [6]. Wet surfaces have been measured on the CAD drawing representing the single component of the PHTS. The whole set of parameters including the wall and bulk temperatures (300 °C in the first section of the FW), the wet surfaces, the absolute pressure (160 bar inside the FW), the hydraulic diameters, the fluid speed, the Reynolds numbers, and the flow rates (9754 kg/s, nominal) have been collected and assigned to the OSCAR-Fusion nodes.

Default corrosion modeling, relying on the Moorea law [3] (which is embedded in OSCAR-Fusion and normally adopted for stainless steel in PWRs), have been used throughout the whole circuit. Future activities will put more emphasis on the corrosion and release laws used for EUROFER, the Reduced Activation Ferritic-Martensitic (RAFM) steel used to manufacture the piping under neutron flux.

2.2. Activation reaction rate

OSCAR-Fusion is a multi-physical tool that combines thermal-hydraulics, corrosion, chemistry, fluid mechanics, and neutronics. The Bateman equation for radionuclides inventory evolution is embedded in the numerical kernel, and it is solved together with the mass balance equations governing the element content in a single medium (e.g. deposits, particles, or ions).

The correct representation of the radioactive isotopes contamination in the cooling circuit is achieved only if precise total activation reaction rates are calculated for those regions that are directly under the neutron flux, coming from the burning plasma. To this end, a fully heterogeneous MCNP model of the 2018 design of the WCLL DEMO [8] has been used together with a particular neutron source simulating the D-T plasma, and JEFF 3.3 nuclear data libraries. Neutron transport Monte Carlo calculations have been performed to assess integral averages of the production rates in the in-vessel nodes presented in Section 2.1, aiming at preserving the total reaction rates in the cooling pipes constituting the BB PHTS.

2.3. Operation scenario

The EU-DEMO operation scenario is made by 7200 s-long pulsed burning plasma phases separated by dwells and standbys. Referring to a 20-dpa operation, 9 plasma phases, gathering 6859 pulses, 3 in-vessel maintenances, and 5 ex-vessel maintenances are foreseen.

The real scenario, including ramp-up and ramp-down transients can be hardly represented in OSCAR-Fusion v1.4.a. The computational overhead leads to unsustainable runs, which make the parametric analysis unfeasible. A conservative condensed scenario has been designed to lump together pulses and dwell phases. Plasma phases have been modelled in 67-day cycles, while dwells and standbys have been taken equal to 2.3 and 6.7 days, respectively. In- and ex-vessel maintenance stops of 120 and 7 days, respectively, have been taken into account, as designed in the pre-conceptual maintenance plan.

Maintenance activities have been simulated with a constant temperature of 295 °C and flow rate scaled by a factor 200 (i.e. 49 kg/s).

Fig. 3 shows the mass of the deposits in the whole loop, comparing three different scenarios: the real one, with 7200 s-long pulses, simulated up to only 250 days for computer time issues (blue line), the lumped scenario with condensed pulses and dwells including the maintenance stops (green line), and the lumped scenario without any maintenance interventions (orange line). The lumped scenario without maintenance interventions is the most conservative, showing that the lumping procedure leads to operating envelope results.

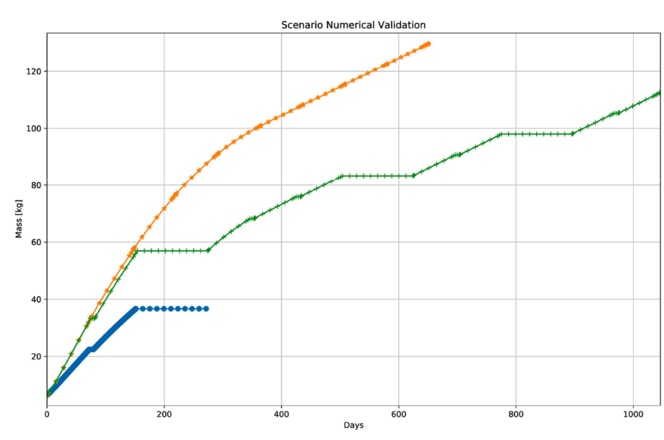

Fig. 3. Mass of the deposits for the whole BB PHTS loop. Comparison between different scenarios: real scenario (simulated up to 250 days), condensed scenario with in- and ex-vessel maintenance stops, condensed scenario without any maintenance stop.

3. Results

As mentioned in Section 1, several design parameters have been perturbed to explore the design and operating domain in terms of ACP inventories. Table 1 summarizes the calculation matrix aimed at investigating how water chemistry, technology, geometry, and CVCS design may affect the final amount of deposits and inner oxide (pipe surface contamination), particle in suspension, ions in solution, and filters and resins contamination. The whole set of cases from 0.1 to 6.2 have been derived from a reference configuration labeled as 0.0, where maintenance operations have been ignored. Cases have been labeled as n.m, where n is indicating the main cases characterized by a specific change in an operating or design parameter. Cases with $m = 1$ or 2 (i.e. n.1 and n.2) are referring to different CVCS design choices. The pH has been modified varying LiOH concentrations in water ($n = 1$ and $n = 2$). The hydrogen content, which is essential in high fluence systems to control water radiolysis (not directly simulated by OSCAR-Fusion), has been varied in cases with $n = 3$. The reference roughness and the in-vessel BZ wet surfaces have been perturbed in cases $n = 4$ and $n = 5$, respectively. Cases with $n = 6$ consider the variation of the initial oxide thickness, a parameter strongly dependent on the pre-commissioning tests. Finally, case 7.0 is a second reference case including maintenance activities. The CVCS design has been assumed to be varied according to the processed water flow rate, since only a bypass fraction undergoes purification through filters and resins.

Fig. 4 shows the surface contamination in terms of masses of the deposits and inner oxides in the whole loop. The cases with the highest and lowest inventories are the 2.0 and the 5.0, respectively. Technological parameters such as pipe roughness (case 4.0) or the initial deposit (case 6.0) seem not to have a significant impact on the final inventory, lying close to the reference scenario 0.0.

Surface contamination is an important figure of merit to be taken into account. The dual oxide layer, containing gamma emitting specimens coming from the in-vessel regions under intense neutron flux, is an important radiological source term for occupational radiation exposure of the working personnel. Fig. 5 shows the comparison of the surface activity of the last node of the steam generator, one of the most relevant out-of-flux component. The lower values seem to be achieved with higher piping roughness (increased in the whole piping loop). This is essentially due to the piping roughness increments which have been spread to the whole system, including the in-vessel components that may act as a particle trap for the activated particles inside the vessel. This may reduce the contamination of the ex-vessel components, shifting the oxide activation issues to other safety domains, such as waste management, and in-vessel maintenance scheduling. In the reference case 0.0, the total surface activities of all simulated radionuclides have been calculated to be of the order of 25 GBq/m^2 in the steam generator, at the end of the reference scenario. The most contributing radionuclide is ^{55}Fe (X emitter) with 20 GBq/m^2, while highly significant contributions from the radiation protection point of view are given by cobalt, manganese and chromium isotopes (^{60,58}Co, ^{54}Mn, and ^{51}Cr, with 0.4 GBq/m^2 in total). These levels of surface contamination are comparable to those measured in the steam generators of PWRs [9,10], except for the ^{55}Fe contamination, which is higher by about one order of magnitude due to the presence of EUROFER steel under neutron flux. Adopting RAFM steels under neutron flux reduces significantly material activation, except Fe. However, their presumable weaker resistance to general corrosion, especially in an oxidizing environment [11], should be further investigated in the framework of cooling system contamination studies.

Ions in solutions and particles in suspension are the most mobilizable

Table 1
Calculation matrix followed in the parametric analysis.

Case	Perturbed parameters
0.0	CVCS – total water volume processed in 8 h
Reference	pH – 7.4 at 300 °C
	H_2 – 10 ml/kg$_w$
	No maintenance
0.1	CVCS – total water volume processed in 12 h
0.2	CVCS – total water volume processed in 24 h
1.0	pH – 7.2 at 300 °C
1.1	pH – 7.2 at 300 °C
	CVCS – total water volume processed in 12 h
1.2	pH – 7.2 at 300 °C
	CVCS – total water volume processed in 24 h
2.0	pH – 6.9 at 300 °C
2.1	pH – 6.9 at 300 °C
	CVCS – total water volume processed in 12 h
2.2	pH – 6.9 at 300 °C
	CVCS – total water volume processed in 24 h
3.0	H_2 – 5 ml/kg$_w$
3.1	H_2 – 25 ml/kg$_w$
4.0	Twice the reference roughness
4.1	Twice the reference roughness
	CVCS – total water volume processed in 12 h
4.2	Twice the reference roughness
	CVCS – total water volume processed in 24 h
5.0	Breeding Zone tubes and manifolds wet surfaces halved
5.1	Breeding Zone tubes and manifolds wet surfaces halved
	CVCS – total water volume processed in 12 h
5.2	Breeding Zone tubes and manifolds wet surfaces halved
	CVCS – total water volume processed in 24 h
6.0	Twice the oxide initial thickness
6.1	Three times the oxide initial thickness
7.0	Maintenances included (in- and ex-vessel)

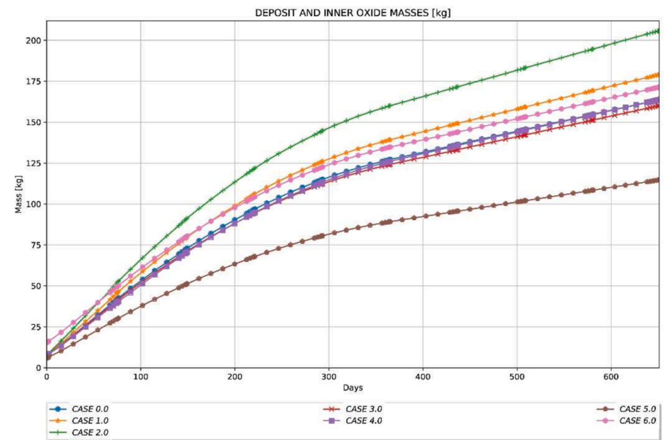

Fig. 4. Deposit and inner oxide masses for the whole loop. Comparison between different cases without any maintenances.

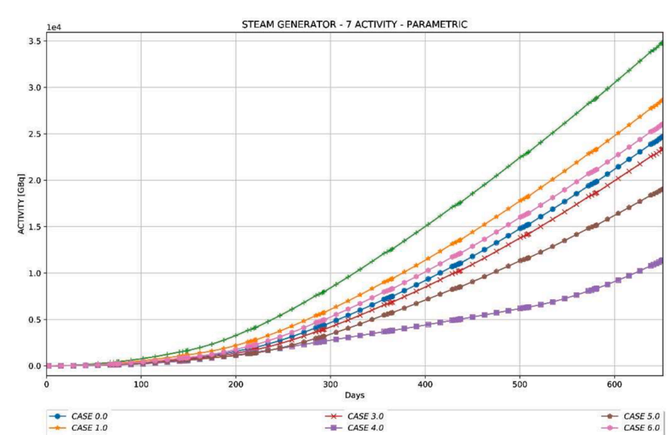

Fig. 5. Deposit and inner oxide activity of Section 7 of the steam generator. Comparison between different cases without any maintenances.

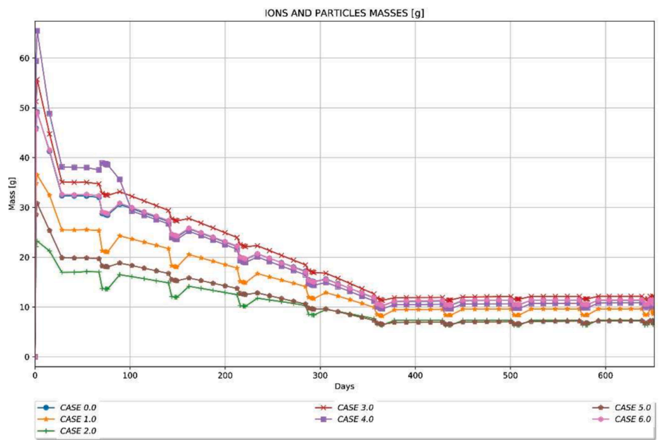

Fig. 6. Ions and particles masses for the whole loop. Comparison between different cases without any maintenances.

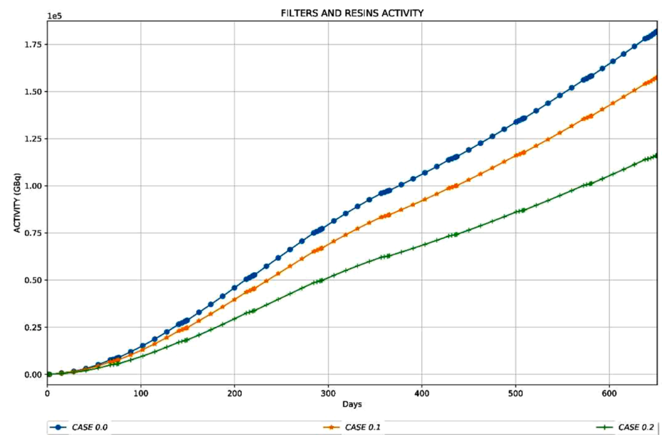

Fig. 7. Filters and resins activity. Comparison between different CVCS options derived from the reference case, 0.0, 0.1 and 0.2.

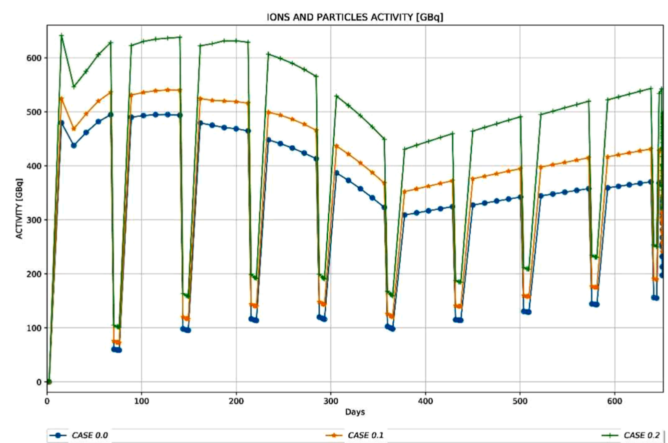

Fig. 8. Ions and particles activity of the whole loop. Comparison between different CVCS options derived from the reference case, 0.0, 0.1 and 0.2.

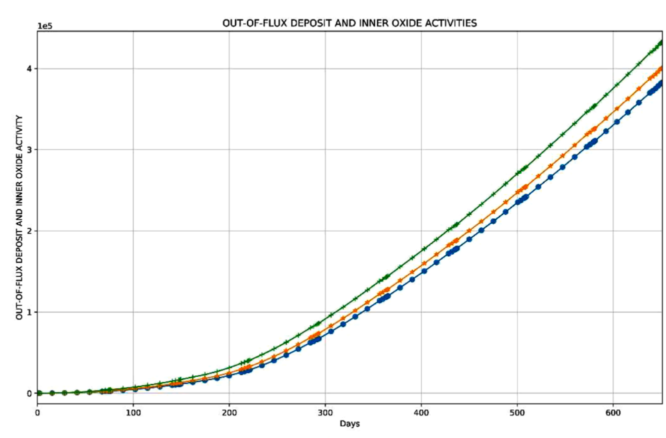

Fig. 9. Deposit and inner oxide activity of the out-of-flux components. Comparison between different CVCS options derived from the reference case, 0.0, 0.1 and 0.2.

inventories, and assume particular importance in accidental scenario source terms determination. The variation of the design parameters seem not to have significant implications on these figures of merit at the end of the operational scenario (see Fig. 6). More acid water chemistry, while enhancing pipe deposits, seems to be favorable for the ions and particles masses content in the cooling water. Halving the wet surfaces in the in-vessel regions looks to be the most promising mean to reduce ACP inventories.

The CVCS design drives the water chemistry and quality control in the cooling system, and so it affects evidently the final amount of ACPs. Different CVCS letdown flow rates have been simulated in order to understand the final impact of this design parameter on deposits, inner oxide, particles, ions, and filters and resins contamination. The CVCS design choices are generally a trade-off between the clear advantages given by larger purification systems, and the drawbacks, in terms of room consumption, exhausted filters and resins handling, and frequency of consumables replacement.

The three CVCS options are compared in Figs. 7–9. Case 0.2 refers to a CVCS with a lower throughput flow rate. It is capable of processing the whole water volume inventory in 24 h, while 0.1 and 0.0 do the same task in 12 and 8 h, respectively. Higher letdown flow rates, which imply larger beds, filters, and heat exchangers in the purification system, allows lower ions and particles masses in loop and larger filters and resins contamination, as shown in Figs. 7 and 8. Dips in ions and particles activities visible in Fig. 8 are due to short-lived radionuclides such as ^{56}Mn, which decay during the stand-by periods condensed in 7 days in the OSCAR-Fusion simulation.

Lower CVCS flow rates may be desirable to reduce filters and resins contamination and dimensioning, since their replacement could be a cumbersome task in terms of waste management. However, opting for lower letdown flow rates, as done in case 0.2, leads to enhanced deposit and inner oxide activities in the out-of-flux components, as shown in Fig. 9. This could have dramatic effects on the shut down dose rates around components that require hands-on maintenance activity, increasing the collective occupational dose.

4. Conclusions

ACPs are significant source terms, with relevant impact on nuclear safety. Parametric analyses have been carried out for the DEMO-WCLL BB PHTS using OSCAR-Fusion v1.4.a, a comprehensive tool developed by the CEA that can assess contamination in closed water-cooled circuits. Preliminary parametric results are presented, since some important driving parameters have not treated yet, as those linked to the corrosion models used for in-vessel components. The preliminary results for a 20 dpa scenario of the EU-DEMO show that component wet surfaces are certainly among the most sensitive parameters to be considered in ACP inventories assessments. As known, the wet surface is one of the most sensitive parameters to the final ACP inventories. The impact of the wet surface under neutron flux in the BZ to the total amount of ACPs in the loop has been assessed, providing reduced masses and activities, as expected. More acid water chemistries give higher deposits but lower inventories in filters and resins, with a lower particle mass. Increased roughness looks to give lower out-of-flux activities. This might be due to the increased roughness in the large in-flux components which might act as a trap, decreasing the inventories in the rest of the loop. The pre-conditioning and then the initial thickness of the deposits provides a shift in the final results, without any other significant effect on particles, ions, resins and filters. The CVCS letdown flow rate affects significantly the inventories as expected. Larger CVCS flow rates allow to have lower mobilizable inventories in water, such as particles and ions, and lower surface contamination in the out-flux regions (deposit and inner oxide), but they will lead to higher filters and resins dimensioning and contamination, with implications on waste management and occupational exposure. Future work will investigate the impact of the corrosion and release rate parameters on the final results, with particular attention to those concerning EUROFER, a RAFM steel constituting the piping in the under-flux regions. EUROFER, in fact, is apparently less resistant to general corrosion. Accurate analyses need to take into account corrosion and release models that can be representative of the latest experimental results, as those reported in Ref. [11] among others.

CRediT authorship contribution statement

Nicholas Terranova: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Pierluigi Chiovaro:** Data curation, Investigation. **Frédéric Dacquait:** Software, Supervision, Validation, Writing – review & editing. **Ivo Moscato:** Conceptualization, Funding acquisition, Investigation, Supervision, Validation, Writing – review & editing. **Eugenio Vallone:** Data curation, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nicholas Terranova reports financial support was provided by European Consortium for the Development of Fusion Energy. Ivo Moscato reports a relationship with European Consortium for the Development of Fusion Energy that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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