

CONFERENCE PRE-PRINT**NEUTRONICS ANALYSIS OF EU DEMO CONDUCTED AT THE LITHUANIAN ENERGY INSTITUTE**

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Abstract

The European Demonstration Fusion Power Plant (EU DEMO), developed under the EUROfusion program, requires comprehensive neutronics assessments to ensure safe operation. The paper presents results of neutron transport and activation analyses performed by the Lithuanian Energy Institute using MCNP6 with JEFF-3.2/FENDL-3.2 nuclear data and FISPACT-II with TENDL-2017 libraries. Neutron-induced activation, decay heat, and waste classification were investigated for 3 reactor components: divertor, vacuum vessel, and breeding blanket concepts (WCLL and HCPB). The analyses identified dominant activation products, such as ^{56}Mn , ^{187}W , and ^{52}V , along with long-lived isotopes, including ^{95}Nb and ^{14}C . Comparisons between breeding blanket designs demonstrated differences ranging from 1% to 9 times in different components. Waste classification revealed that most components were classified as intermediate-level waste 3 days after shutdown, and could be reclassified as a LLW after 100 years, except HCPB breeding materials and the inner and interspace of the vacuum vessel. The results highlight the importance of neutronics in EU DEMO design and emphasize the need for long-term waste management strategies in the development of fusion energy.

1. INTRODUCTION

Electricity demand in Europe is projected to reach around 60 petawatt-hours by 2050, increasing the need for secure and sustainable energy [1]. To address this, the European Green Deal sets a target of climate neutrality by 2050, with nuclear fusion considered a promising zero-carbon option [2,3]. Future energy systems are likely to rely on renewable, nuclear, and storage technologies [4-6]. Fusion offers unique advantages, including the absence of greenhouse gas emissions, no long-lived transuranic waste, and almost infinite fuel sources [7]. However, major scientific and engineering challenges remain [8]. Current experimental facilities, including Wendelstein [9], ASDEX-Upgrade [10], and WEST [11], are advancing plasma confinement and materials research to support the development of the European Demonstration Fusion Power Plant (EU DEMO) [12], which aims to generate hundreds of megawatts and establish a closed tritium cycle [13]. However, fusion also produces radioactive waste through neutron activation [14]. In deuterium-tritium reactions, high-energy neutrons not only provide heat but also simultaneously activate reactor structures, posing challenges for safety, waste management, and decommissioning in DEMO [15].

In this context, the Lithuanian Energy Institute (LEI) plays an important role within the EUROfusion consortium by contributing advanced neutronics and inventory analyses for EU DEMO. LEI has been engaged in neutronics calculations for nuclear applications for several decades, building expertise in neutron transport, activation, shielding, and radiological safety. Over the last years, this experience has been applied to fusion research, where the institute conducts detailed modelling of neutron interactions, activation studies, and waste assessments for EU DEMO reactor components. The paper presents results of neutronics studies performed at LEI, focusing on neutron transport, activation, decay heat, and waste classification in key EU DEMO components, thereby supporting the broader European effort to realize sustainable fusion power.

2. METHODOLOGY**2.1. Codes**

The neutron transport simulations were performed using the MCNP (Monte Carlo N-Particle) code [16]. To reduce computational time while maintaining acceptable accuracy, the ADVANTG (Automated Variance reduction Generator) tool was applied [17]. ADVANTG provides variance-reduction parameters and enables faster Monte Carlo simulations with statistical uncertainties of less than 10%.

The FISPACT-II code was used to calculate activity, decay heat, nuclide inventories, and dose rates based on discretized neutron spectra and defined irradiation scenarios [18].

Nuclear data libraries are crucial for neutron transport and activation studies, providing essential information such as cross sections, energy distributions, and decay chains. In this work, JEFF-3.2 was used for initial neutron interaction assessments in fusion reactor vacuum vessels [19], FENDL 3.2 for accurate fusion material modeling with updated decay and isotope data [20, 21], and TENDL 2017 for activation calculations across more than 2800 isotopes [22]. Together, these libraries ensured reliable neutron transport and activation modelling for material behaviour assessments in thermonuclear reactor environments.

2.2. Models

For the calculations, 3 EU DEMO geometrical models were used. All of them are based on the EU DEMO1 model. For the vacuum vessel calculations, the 2015 adaptation was used; for the divertor, the 2017 adaptation was used; and for the breeding blanket, the 2018 adaptation [23] was used.

The vacuum vessel was divided into three layers: an outer layer and an inner layer made of stainless steel 316L (N)-IG, and an interspace composed of a mixture of stainless steel and water [24].

The divertor has five different parts: pipes made of EUROFER that carry water; the cassette (CB), also constructed from EUROFER with water flow; linear and reflector plates consisting of EUROFER with a 3 mm tungsten layer; plasma-facing components (PFC) composed of three homogenized layers supported by a structural frame, where the first and third layers are made out of tungsten and the middle layer is a mixture of tungsten, CuCrZr alloy, and water; and finally, a Wishbone which is made out of titanium alloy with pins manufactured from a nickel-chromium alloy [25,26].

In this work, two blanket concepts, the HCPB and the WCLL, are each divided into three sections: the first wall (FW), the breeding zone (BZ), and the back supporting structure (BSS). In the heterogenized HCPB approach, the FW is built from a tungsten armour layer combined with EUROFER cooling pipes carrying water, while the BZ consists of layered lithium ceramics (Li_4SiO_4 and Li_2TiO_3 enriched with ^6Li up to 60%) together with BeTi acting as a neutron multiplier, and the BSS is made of EUROFER. The WCLL design differs in that it utilizes EUROFER with cooling passages in the FW, a BZ where liquid LiPb serves as both the tritium breeder and neutron multiplier, alongside embedded water-cooling tubes and stiffening plates to guide flow, and a EUROFER-based BSS connected to U-shaped tubes. While the HCPB emphasizes material stability and safety through solid ceramic breeders and helium cooling, the WCLL focuses on superior heat transfer by combining LiPb with water cooling, though it faces additional challenges with liquid-metal handling, corrosion, and high-pressure operation [27].

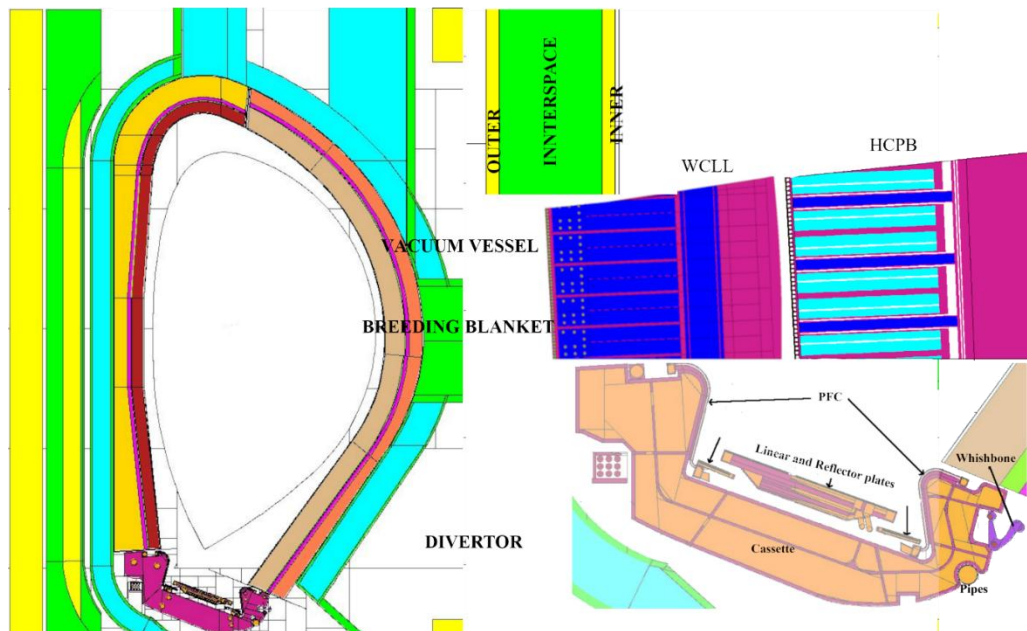


FIG. 1. The MCNP model used the EU DEMO model with enlarged main components.

2.3. Irradiation Scenario

The activation calculations were based on the operational scheme planned for the EU DEMO reactor. It is expected to operate for a total of 20 calendar years (CY), with an average of 30% of the nominal fusion power, corresponding to approximately 6 full power years (FPY). The operation is divided into two phases:

- Phase I – (used for breeding blanket and divertor calculations)
 - Duration: 5.2 years, with 1.57 years at full power.
 - Operational mode: Continuous operation at 30% nominal fusion power. During the final 10 days of this phase, 48 pulses are foreseen.
 - Pulse structure: Each pulse consists of 4 hours of full-power operation followed by a 1-hour dwell (shutdown) period.
- Phase II – (used for vacuum vessel calculations)
 - Duration: 14.8 years, with 4.43 years at full power.
 - Operational mode: Continuous operation at 30% nominal fusion power. Similar to Phase I, the last 10 days include 48 pulses, each comprising 4 hours at full power and a 1-hour dwell [28].

The activation analysis was performed using cooling times ranging from 1 second to 1000 years, with selected time steps to capture the short-term, medium-term, and long-term evolution of material activation. This allowed for the assessment of both immediate radiological hazards and the long-term buildup of radioactive materials. The selected intervals follow standard practice in activation analysis, ensuring a comprehensive evaluation of radionuclide inventories over time.

3. RESULTS

This section analyzes the time evolution of dominant radionuclides in key DEMO materials, compares the activity and decay heat behaviour of the HCPB and WCLL concepts, and outlines the resulting waste classifications. Before activation analysis, detailed neutron spectra were calculated for all materials in the respective reactor components: 102 cells of the vacuum vessel, 1805 cells of the divertor, and 24 and 14 cells of the breeding cells in the WCLL and HCPB concepts, respectively. Representative spectra are shown in Figure 2.

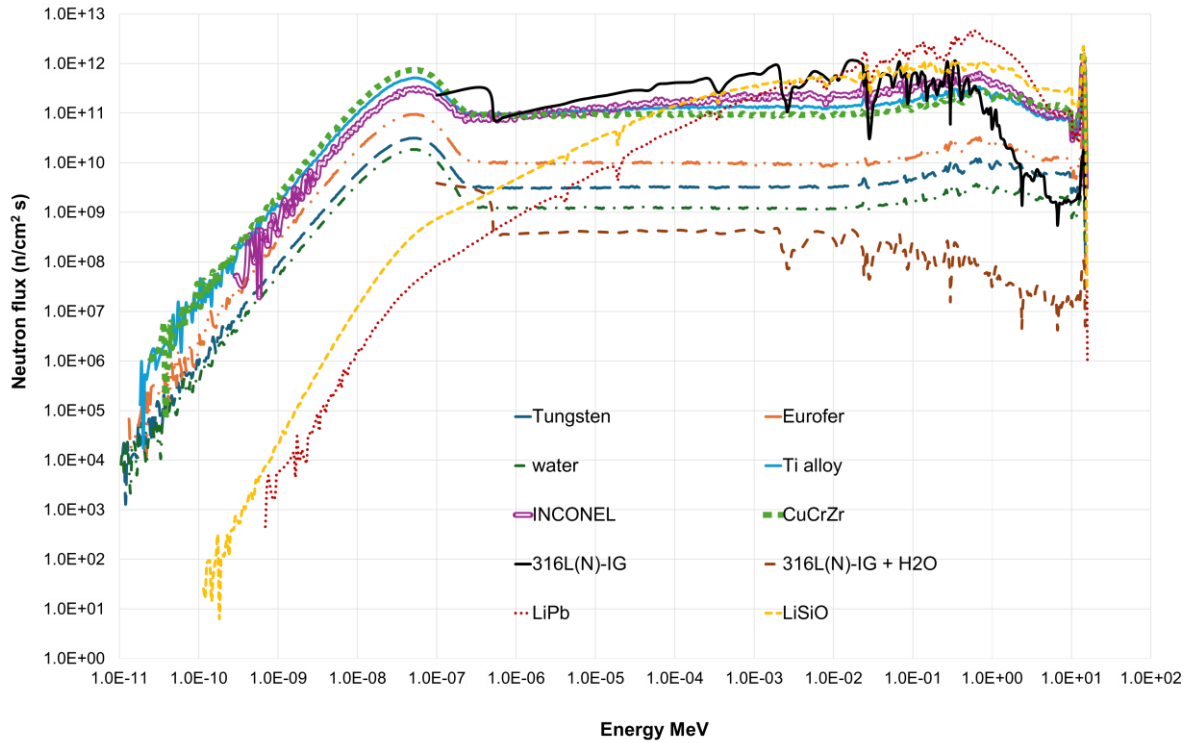


FIG. 2. Representative fluxes of all investigated materials.

1 second after the reactor shutdown, short-lived nuclides, including ^{56}Mn in stainless steels, ^{16}N in water and lithium orthosilicate, ^{187}W in tungsten, ^{52}V in titanium alloys, and ^{182}Ta in INCONEL are the dominant ones. After about a month to a year, longer-lived nuclides such as ^{55}Fe in steels, ^{185}W in tungsten, ^{48}Sc in titanium alloys, and ^{204}Tl in Li-Pb mixtures prevail. By 10 years, ^{63}Ni and ^{60}Co become significant in nickel- and tungsten-based alloys, while ^{14}C dominates in water, EUROFER, and Li_4SiO_4 . After 100 years, ^{14}C remains the main radionuclide in oxygen- and carbon-containing materials, whereas ^{64}Ni and ^{95}Nb are dominant in Ni- and Cr-rich alloys, ^{60}Co in tungsten, and ^{205}Pb in Li-Pb systems. Detailed information about dominant nuclides can be seen in Table 1.

TABLE 1. Dominant radionuclides in different time periods

	1 second	1 month	1 year	10 years	100 years
316L(N)-IG	^{56}Mn	^{55}Fe	^{55}Fe	^{63}Ni	^{14}C
EUROFER	^{56}Mn	^{55}Fe	^{55}Fe	^{55}Fe	^{14}C
Water	^{16}N	^{14}C	^{14}C	^{14}C	^{14}C
Tungsten	^{187}W	^{185}W	^{185}W	^{60}Co	^{60}Co
W + CuCrZr + Water	^{187}W	^{185}W	^{185}W	^{63}Ni	^{63}Ni
Titanium alloy	^{52}V	^{48}Sc	^{48}Sc	^{45}Ca	^{14}C
INCONEL	^{182}Ta	^{182}Ta	^{182}Ta	^{60}Co	^{95}Nb
Li_4SiO_4	^{16}N	^{46}Sc	^{45}Ca	^{14}C	^{14}C
Li-Pb	^{207}mPb	^{204}Tl	^{204}Tl	^{205}Pb	^{205}Pb

The evolution of these nuclide inventories directly affects the radiological characteristics of DEMO components. Differences appear between the HCPB and WCLL concepts in terms of activity and decay heat, as shown in Figure 3. For the vacuum vessel, HCPB consistently shows higher values, with ratios of approximately 9 compared to WCLL. In the divertor, however, WCLL dominates at shutdown, with activity and decay heat 19.46% and 17.24% higher, respectively. Over time, these differences narrow: after 100 years, WCLL activity remains only 6% higher, while its decay heat drops 1.32% below that of HCPB. The breeding blanket exhibits no stable trend, since the dominant nuclides change with time. Short-lived isotopes, such as ^{28}Al in HCPB, cause rapid early decreases, while longer-lived species, such as ^{203}Pb in WCLL, sustain activity for extended periods.

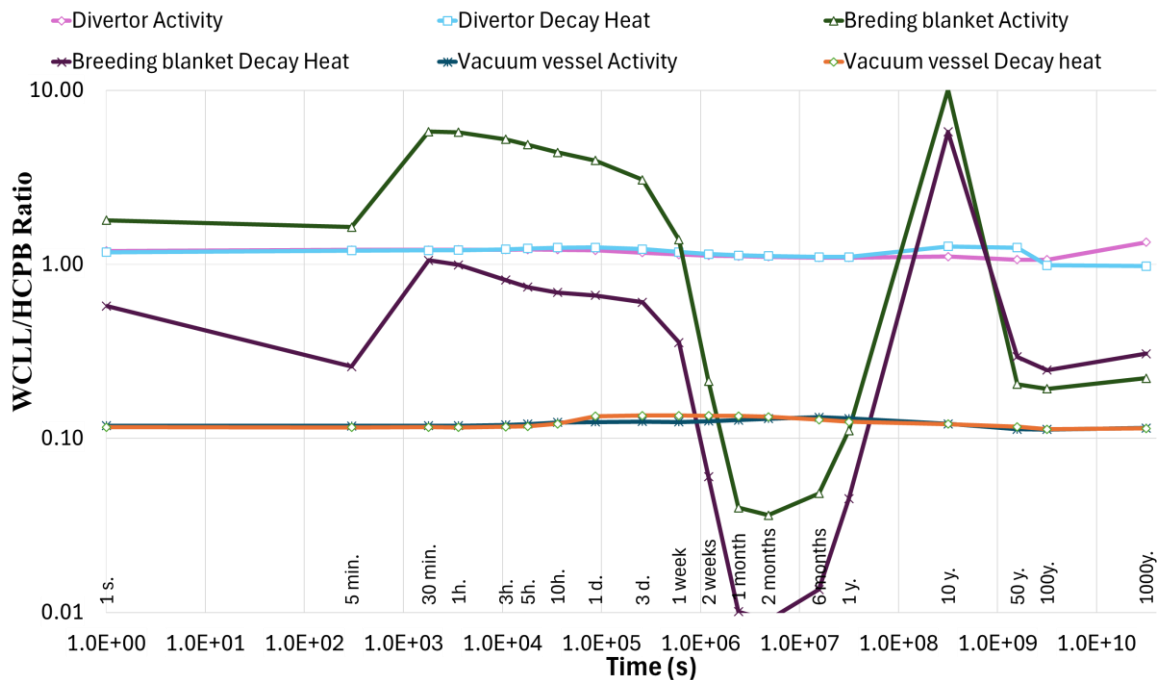


FIG. 3. WCLL/HCPB ratio of Activity and Decay Heat values in the EU DEMO components

Following the WNA framework, Low-Level Waste (LLW) is defined by beta and gamma activities below 1.2×10^7 Bq/kg. Intermediate-Level Waste (ILW) produces decay heat of up to 2 kW/m^3 , whereas High-Level Waste (HLW) surpasses this threshold, necessitating robust containment due to its high radioactivity and long-lived isotopes.

Divertor components are initially classified as HLW due to their high activity and decay heat. After around 3 days, all divertor components could be reclassified as ILW. After around 100 years, all divertor components gradually decay to LLW, with pipes, plates, and cassette body reaching this after 50 years.

The vacuum vessel components—Inner, Interspace, and Outer layers for both HCPB and WCLL concepts—start as ILW. The Outer layers of the vacuum vessel eventually reach LLW after about 100 years, whereas the Inner and Interspace layers remain ILW much longer, reflecting the persistence of long-lived radionuclides and higher neutron spectra values.

Breeding materials follow a similar evolution. Both HCPB and WCLL concepts are ILW immediately after shutdown. WCLL components may be reclassified as LLW after 50 years, whereas HCPB remains ILW even after 1000 years (see Figures 4 and 5).

These findings underscore the crucial importance of implementing effective long-term waste management strategies.

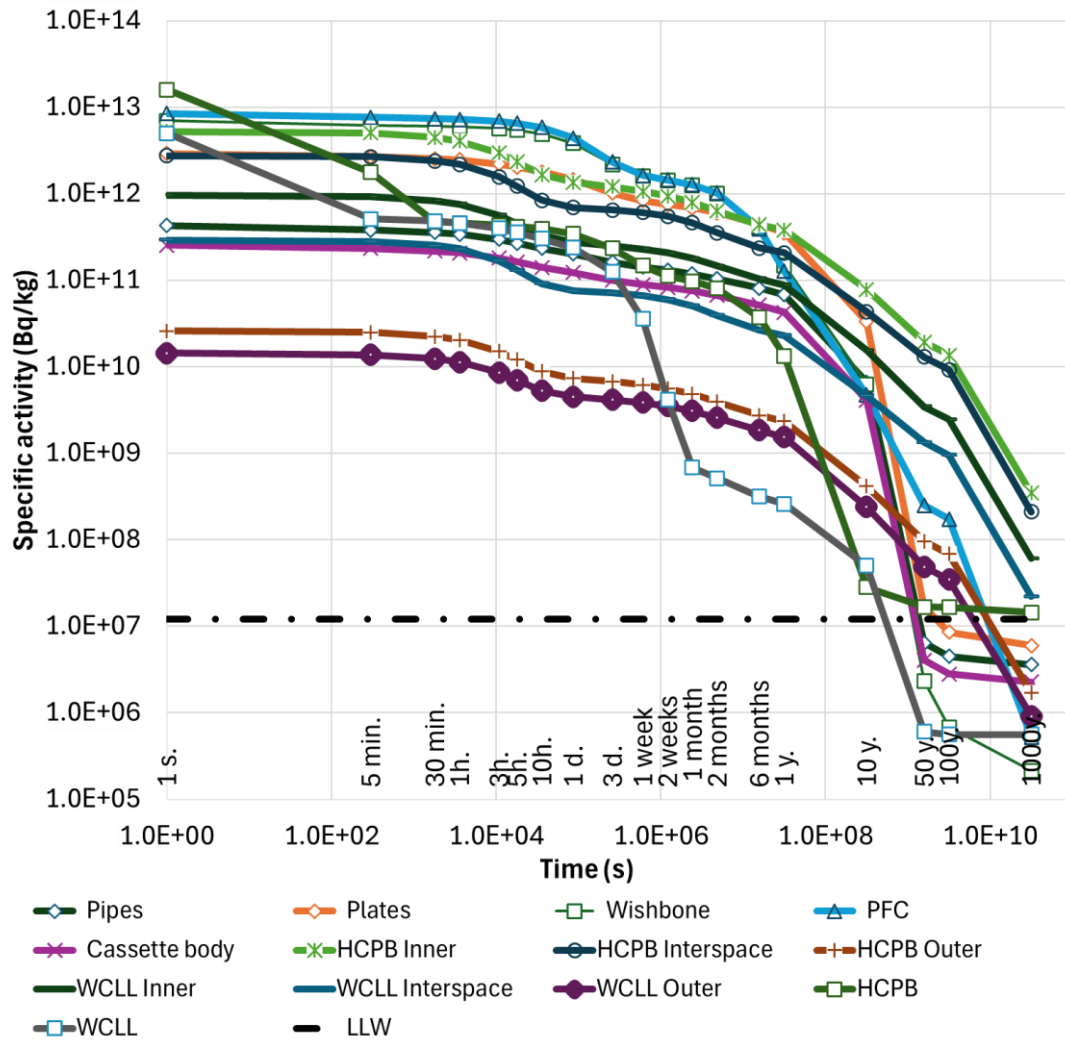


FIG. 4. Averaged specific activity in different parts of the EU DEMO

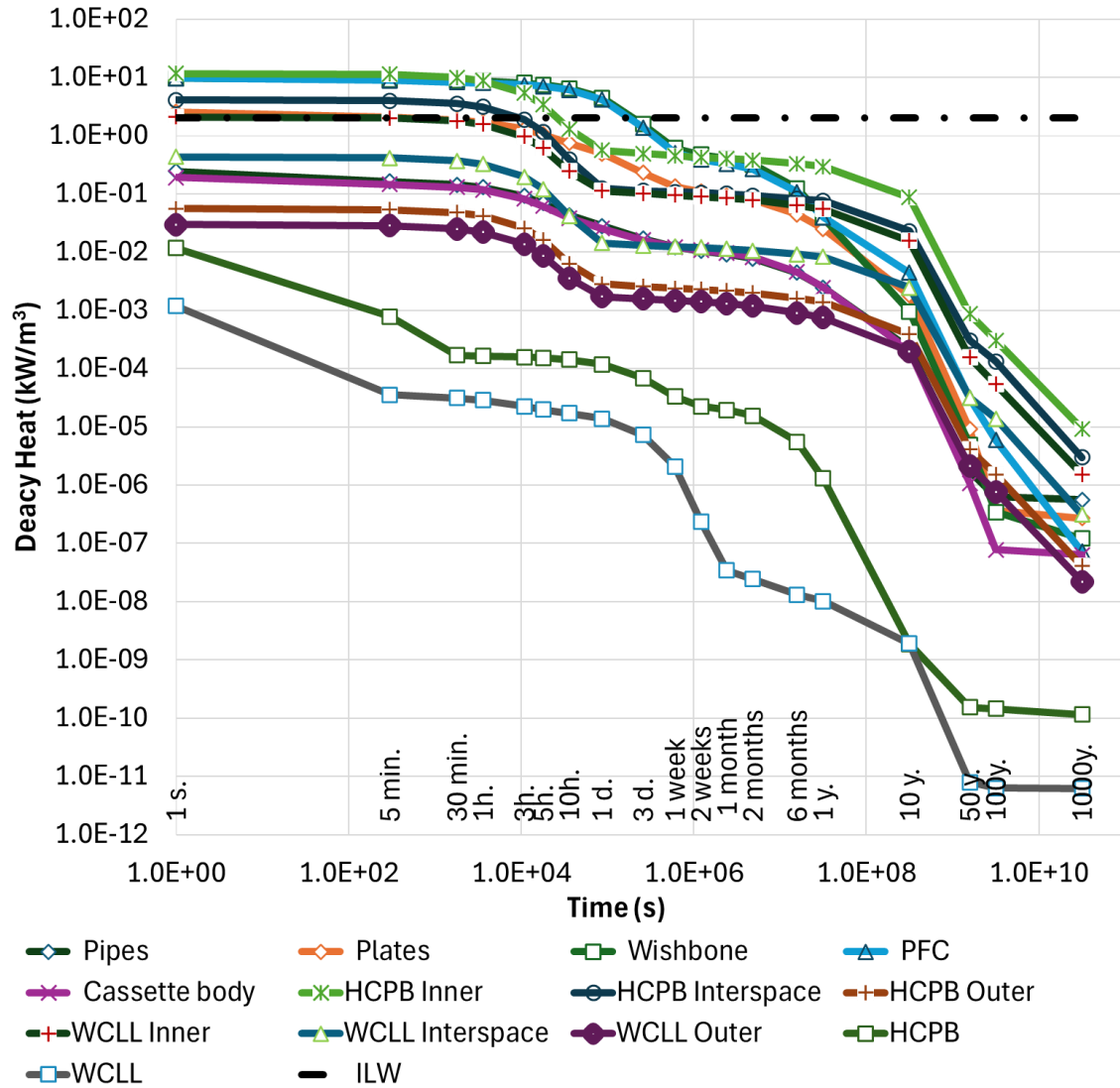


FIG. 5. Averaged decay heat in different parts of EU DEMO

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