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Waste implications from minor impurities in European DEMO materials

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Waste-production predictions for the future demonstration fusion power plant (DEMO) are necessary to produce an accurate picture of the likely environmental and economic costs of radioactive waste disposal at end-of-life (EOL). Even during the conceptual stage of DEMO design it is important to perform waste assessment so as to avoid potential surprises due to design flaws that could lead to unacceptable levels of long-term high-level waste. An integrated simulation process combining Monte-Carlo neutron transport simulations, high-fidelity inventory calculations, and extensive and reproducible post-processing algorithms is being used for the evolving European DEMO designs to quantify the time-varying mass inventories in different waste classes for individual regions and components of the reactor vessel, as well as for the reactor as a whole.

Neutron transport simulations have been performed for DEMO models of three tritium-breeding concepts: helium-cooled lithium-lead (HCLL); helium-cooled pebble-bed (HCPB); and water-cooled lithium-lead (WCLL). The resulting set of statistically-calculated neutron spectra provide the input to inventory simulations with FISPACT-II [1], which evolve the nuclide composition (inventory) of the homogenised material mixtures in each region of the DEMO-design geometry during the planned 22-year, 2-phase operational scenario of DEMO, followed by subsequent EOL decay-cooling. An automated post-processing algorithm takes these time-evolving nuclide inventories, which, by definition, also define the level and type (α, β, γ) of activation in the material, and uses them to predict the waste class according to waste categories based on UK regulations (see [2] for details).

Figure 1 shows how long different regions of the DEMO reactor (in this case for the WCLL concept) take to satisfy the low-level waste (LLW) criteria applied in these studies (must have less than 12 MBq/kg total combined activity from β and γ emission and less than 4 MBq/kg of α activity). The cross section shows, for example, that most of the large, homogenized breeder zones are predicted to remain as intermediate-level waste (ILW), or worse, for more than 100 years beyond DEMO EOL, although the shield behind the breeder zones (the majority of the mass and also part of the replaceable blanket modules) is predicted to be classifiable as LLW much sooner. Ongoing work indicates that the situation might be more favourable (less ILW at long timescales) in a fully-detailed (heterogenous) DEMO design. This demonstrates the need to plan and design for a blanket that can be dismantled to separate the localized, highly active regions, which could remain ILW for hundreds of years, from less active ones, and thus reduce the overall burden of long-lived waste requiring storage.

^{14}C production from the few hundredths of weight % nitrogen in Eurofer steel is the primary cause of this surprising result [3], which disagrees with earlier studies [4] into the activation response of Eurofer because in those cases the focus was on γ-dose for recycling and remote-handling considerations, while stored waste in, for example, an underground repository, must also satisfy β and α activity limits (^{14}C is a pure β emitter). This highlights the importance of considering minor impurities (intentional or otherwise) in materials for activation and waste analyses. Manufacturing impurities in the ITER-grade tungsten assumed in European DEMO designs can also produce long-lived dominant activation products [2]. In this work we also show how that the potentially unavoidable (it is very expensive and difficult to remove completely) uranium impurities in the beryllium used in the HCPB concept also produce long-lived radionuclides that

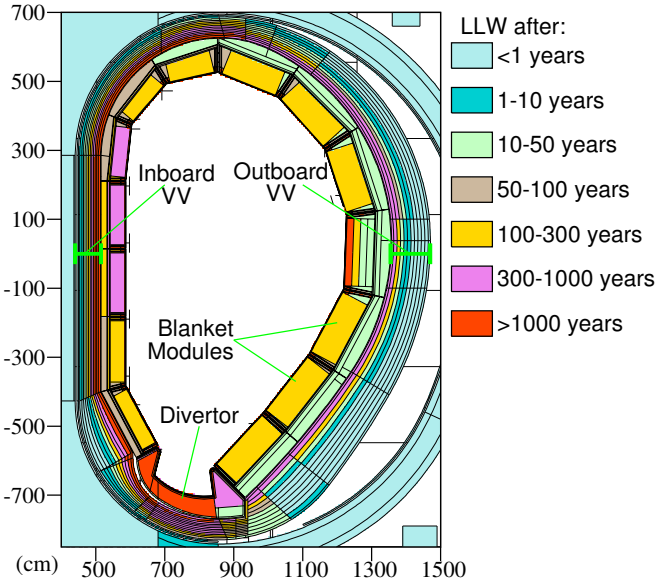

Figure 1: Poloidal slice of the DEMO model with the WCLL breeder blanket concept. Each homogenized material region (cell) is coloured according to the time-interval (shown in the key) during which each cell is predicted to satisfy the criteria to be classified as low-level waste (LLW).

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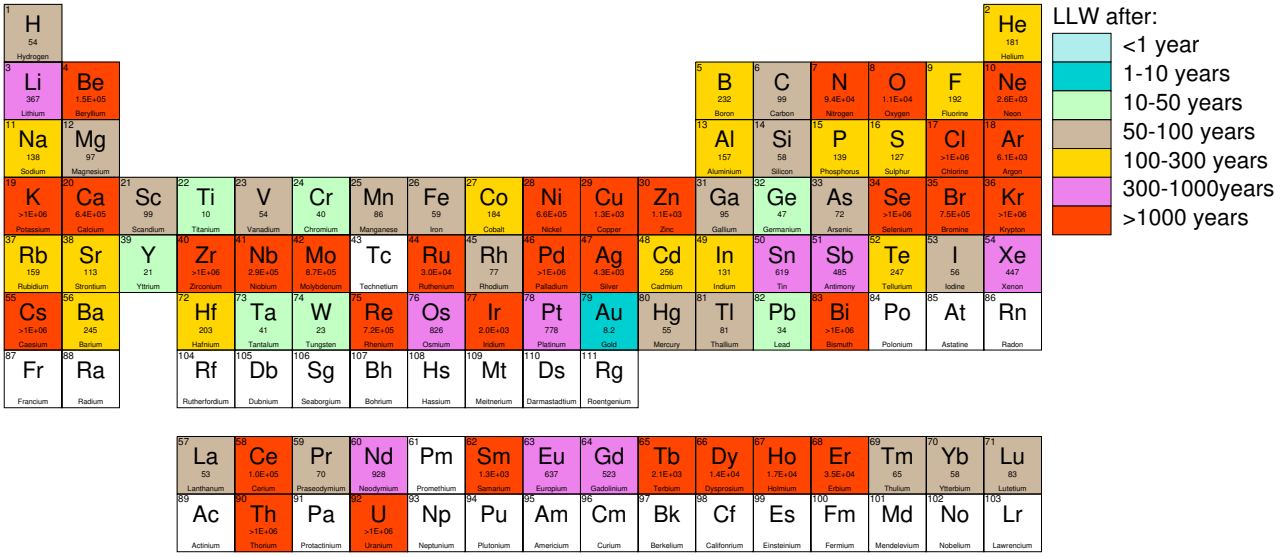

Figure 2: Periodic table with each naturally occurring element coloured according to the time-interval during which it would satisfy the LLW criteria after irradiation during one full operation cycle in the divertor cassette body. The actual "time-to-LLW" values are given below each element symbol. Note that no tritium removal is considered for this divertor environment, and this radionuclide is responsible for the long-lived waste in some of the lighter elements, such as He, and Li.

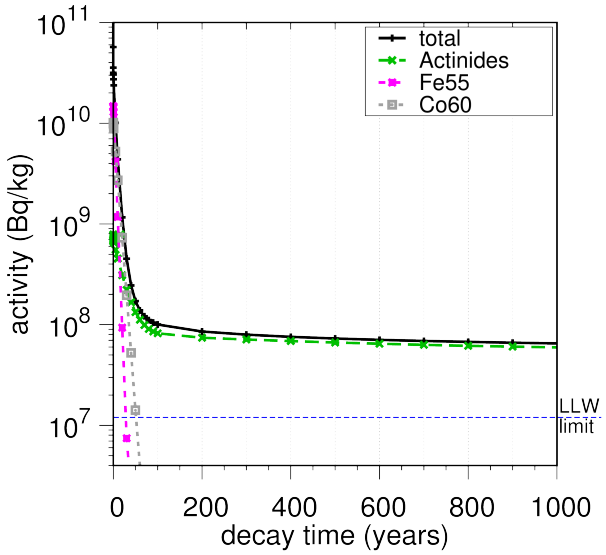

Figure 3: Nuclide contributions to Be activity under the predicted conditions in the inboard equatorial blanket breeder zone of the HCPB concept. The total activity is shown, together with curves representing the contributions from important radionuclides. The low-level waste (LLW) limit is also shown as a horizontal dashed line. The "pure" Be used for these calculations contained 0.01 weight % uranium, which in a ~1000-tonne blanket would equate to ~100 kg of uranium.

exceed the LLW limit. Figure 3 shows the contributions from different radionuclides to the activity of the Be grade assumed in the calculations, after an operational life in the inboard equatorial breeder zone. Radioactive actinide impurities have been grouped together in the plot and their total contribution is significant enough to exceed the LLW limit (shown in the plot). This observation is only a problem for the HCPB concept (other breeder-blanket concepts use, instead, Pb for neutron multiplication and moderation), and it is likely that much of the Be used will be extracted for reuse rather than being disposed of as waste with the other blanket components. However, it is still a potentially serious issue that might make this tritium-breeding option less desirable.

The likely significance of impurities in materials can be further assessed by using the waste simulation scheme to perform a "time-to-LLW" analysis for each element. Figure 2 shows the result of one such assessment for pure materials in the conditions expected for the divertor cassette body. The assessment confirms the previously mentioned problems with nitrogen (it is predicted to take more than 1000 years to become LLW if irradiated in a pure state), but also indicates which elements are likely to increase the amount of ILW (and on what timescale) in a component if they form part of the material composition of that component (e.g. Ni and Cu are both problematic but pure Cu has a shorter time-to-LLW and so could be allowable to higher concentrations).

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