WPPMI-CPR(17) 17172

MR Gilbert et al.

Waste assessment of European DEMO designs

Preprint of Paper to be submitted for publication in Proceeding of
13th International Symposium on Fusion Nuclear Technology
(ISFNT)

Waste assessment of European DEMO fusion reactor designs

M. R. Gilbert[a,*], T. Eade[a], C. Bachmann[b], U. Fischer[c], N. P. Taylor[a]

[a]*Culham Centre for Fusion Energy, United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, UK*
[b]*Eurofusion PMU, Boltzmannstr.2, Garching 85748, Germany*
[c]*Association KIT-Euratom, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*

Abstract

Predicting the amount of waste produced from a fusion power plant is vital to assess the likely environmental impact, disposal costs, and also to satisfy nuclear regulators. Inventory simulations are ideally suited to this task because they can be used to evolve in time, via numerically solving the ordinary differential rate equations, the chemical composition of reactor materials, both during operation, when exposed to neutron irradiation, and afterwards, during post-operation decay. The radiological response of the time-evolving material composition can then be used to assign a waste class to reactor components. Waste assessment has been performed for designs of the European demonstration power plant (DEMO) concept using the FISPACT-II inventory simulator, and using extensive Monte Carlo simulations of the neutron irradiation fields as input. The masses in each waste class (defined using the IAEA infrastructure) have been charted in time for in-vessel components (including the divertor and blanket), ex-vessel regions such as the coils, and for the reactor vacuum vessel (VV). Comparisons are made between the waste-class masses generated for different tritium breeding blanket concepts. Typical predictions include the observation that the majority of the VV will become low-level waste within 100 years, while plasma-facing components and tritium breeding units will remain classified as intermediate-level waste for longer. The waste classification implications of sub-dividing the large VV is considered, highlighting the potential benefits, for waste disposal and recycling prospects, of being able to separate low activity regions of a component from more active regions.

Keywords: DEMO fusion reactor, inventory simulations, radioactive waste assessment, neutron irradiation

---

1. Introduction

The conceptual designs of a demonstration fusion power plant (DEMO) are evolving as a result of the influence of different factors including changes in the understanding of the physics associated with the burning fusion plasma, technological improvements, variation in the timetable for construction, and a changing political landscape. The impact of these design changes on the radiological response of power plant components, including the likely environmental and disposal costs of radioactive waste, must be continuously assessed to ensure that the eventual reactor design meets the required targets and limits.

Radiological responses, including activity, decay heat, and γ-dose rate, for a particular DEMO reactor model are typically predicted using an integrated simulation scheme involving Monte-Carlo-based neutron

---

[*] Corresponding author, mark.gilbert@ccfe.ac.uk

Preprint submitted to Elsevier *August 8, 2017*

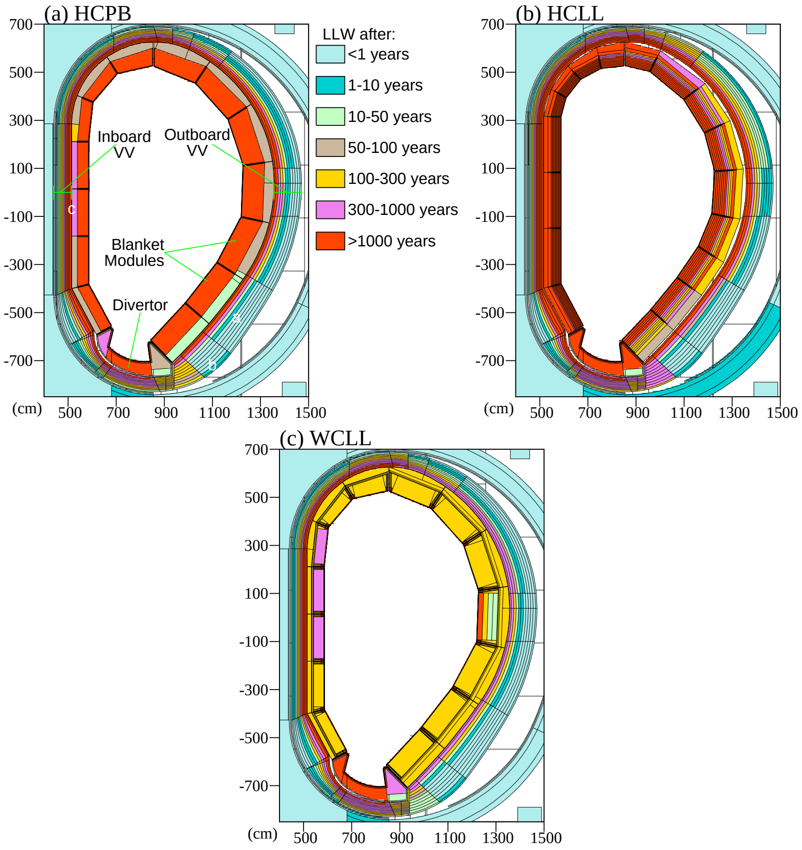

Figure 1: Toroidal cross-sections of the DEMO model for (a) the HCPB breeder blanket concept; (b) HCLL; and (c) WCLL. The a,b,c labels in (a) correspond to the cells considered in the three plots of figure 2. The colouring identifies the time interval during which each cell is predicted to satisfy the limits to be classified as low-level waste (as opposed to intermediate). Note that the large homogenized cells in the model, particularly in the blanket and divertor, can lead to (conservative) over-prediction of activation and hence the "time-to-LLW", which can only be properly predicted in a full-realistic design of in-vessel components. See the main text for further details.

transport calculations to define neutron-irradiation fields, which are then fed into an inventory code to quantify the resulting time evolution in material composition (and hence activity). An important output from these studies is the time-evolving masses of radioactive waste and its associated classification, which are needed for the planning of waste disposal and recycling strategies, including the economic and environmental costs.

In this paper we present some of the latest waste classification and quantification results from the European DEMO design programme, focussing on in-vessel components (IVCs) and the reactor vacuum vessel (VV). This work follows on from the extended study presented in [1], where the computational infrastructure to automatically and consistently track the evolution of waste masses in a complex reactor design was first developed. Comparisons are made between waste classification of components in DEMO designs with different tritium-breeding blanket concepts, and the potential improvement in waste mass evolution through heterogeneous radial division of large components such as the VV (as suggested in [1]) are discussed.

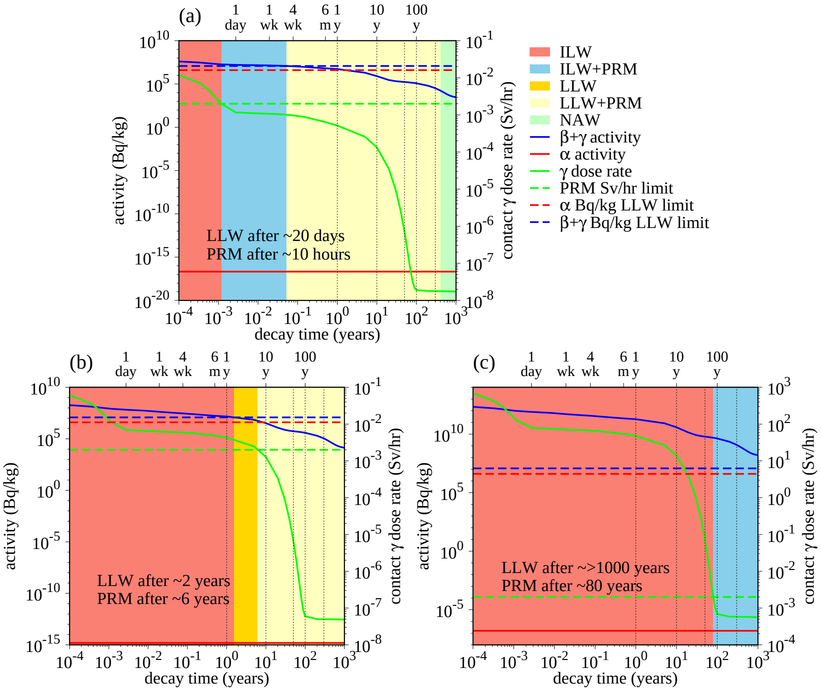

Figure 2: Waste and recycling classification evolution of three different cells of the Vacuum Vessel (VV) in the HCPB concept design: (a) the fifth layer of the interspace in the lower region of the outboard VV; (b) the outer shell in the lower outboard VV; and (c) the inner shell of the inboard equatorial VV. The labels in figure 1a indicate the approximate position of each cell in the geometry. The horizontal dashed lines in each plot are the category limits for LLW and PRM, and the solid curves show the radiological response (activity or dose) of the cell as a function of time. Where the solid curves cross (go below) the dashed lines determines the change in waste or recycling classification of the cell, which is signified by the changing background colour of the plots. The time of cross-over to LLW and PRM are estimated from the curves and given in each plot. See the main text for more details.

2. Computational approach

The waste classification analysis begins with simulated predictions of the spatial variation in neutron irradiation fields for a DEMO reactor design. The neutron transport code MCNP (version 6.1 [2]) was used to transport 10^{10} neutrons, using the same variance reduction techniques as described in [1], through a geometry for each of three different tritium breeding concepts. The baseline DEMO design used in the present work was created from the CAD model of the “EU DEMO1 2015” [3, 4] design created in 2015 as part of the European DEMO design studies program [5]. The model has a toroidal major and minor radii of 9.1 m and 3.1 m, respectively, and is designed to have a fusion power of 2037 MW [3]. In particular, this model is different from the 2014 EU model used for the calculations in [1], which makes direct comparison to those results difficult. The CAD conversion results in an MCNP geometry split up into “cells” enclosed by surfaces of various kinds.

This base model was modified as part of the European programme to specify three different tritium-breeder blankets concepts [6]: a Helium-Cooled ceramic Pebble-Bed of Be and Li_4SiO_4 (HCPB) [7]; a Helium-Cooled system with liquid Lithium-Lead (HCLL) [8]; and a Water-Cooled, liquid Lithium-Lead system (WCLL) [9]. Even though the total thickness, which varies poloidally, of the breeder zone was the same for each concept, the specific geometric make-up, and hence material composition, of the interior of the

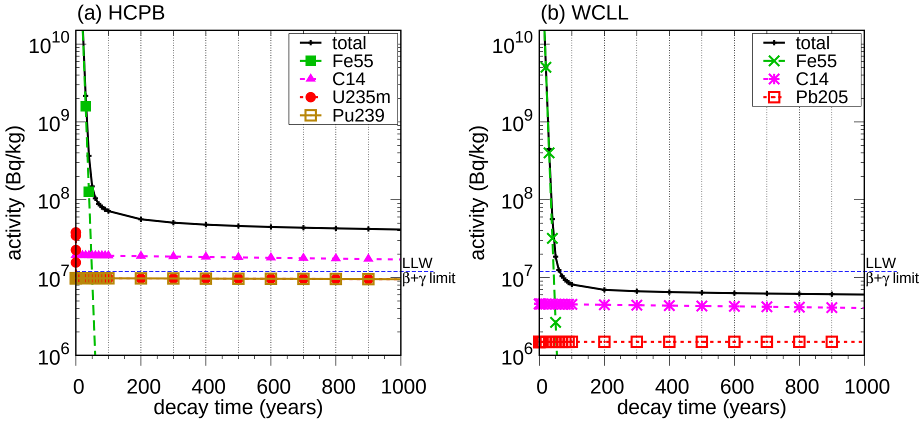

Figure 3: Nuclide contributions to activity in the blanket breeder-zone in the (a) HCPB and (b) WCLL. Each plot is the average result across all cells of the tritium-breeding zone in each concept. The total activity curve is shown, together with curves for the contributions from important radionuclides. The total $\beta + \gamma$ activity limit for material to be considered as LLW is shown has a horizontal, blue, dashed line. Note that it has been assumed that tritium (^{3}H) is completely removed from the breeder-zone during operation (or shortly after) and so there is no contribution from it in these plots. This is too conservative, as some will surely remain, but detailed modelling of the detritiation process of the breeder zone is required to precisely quantify the remainder.

blanket modules varies between the three concepts as a result of additional optimisation. A fourth breeder concept – a Dual-Cooled system with a self-cooling liquid Lithium-Lead and helium cooling elsewhere (DCLL) – is also part of the European programme (see [6]), but this was not considered here. Figure 1 shows toroidal cross sections through the three DEMO concept models (the associated waste classification colouring is discussed below). Notice that the blanket modules of the HCLL concept (figure 1b) have significantly more detail (heterogeneity) compared to the other two, although in all cases the level of detail in these highly-activated regions is relatively modest at this stage (the potential implications of this will be discussed later).

For these studies the MCNP models were modified further to investigate how the waste classification profile might be changed by increasing the spatial resolution (heterogeneity) in the modelling of the Vacuum Vessel (VV) – as suggested previously in [1] (section 3.3). The Vacuum Vessel (VV) originally consisted of three layers – 60 mm thick inner and outer shells of pure SS316L(N)-IG stainless steel (see [1] for the composition specification) surrounding an "interspace" composed of a 60% by volume SS316 and 40% water mix, which varies in thickness from 48 cm at the inboard equator, to 1 m at the outboard equator. In the refined model this interspace was subdivided radially into 10 equally-spaced layers with the same material composition. This radial sub-division of the VV can be seem clearly in the toroidal cross-sections of the three DEMO geometries shown in figure 1.

The MCNP calculations produce estimates via statistical tallies (with errors for in-vessel cells typically less than 5% after 10^{10} histories) of the neutron flux spectrum that each cell in the geometry will experience during reactor operation. In the next step each spectrum was used in an inventory simulation to predict the evolution in chemical composition (and hence activity) of the material in a particular cell during DEMO reactor operation and subsequent end-of-life (EOL) decay cooling. The FISPACT-II [10] inventory code system was used in conjunction with the EAF-2010 [11] data library containing neutron-energy dependent reaction cross sections and radioactive decay schemes for unstable nuclides. The material (taken from the composition definitions in the MCNP models) in each cell was exposed to the associated neutron flux and spectrum according to the planned two-phase, 22-year operational scenario for the European DEMO (see [12, 1] for further details). Since the waste mass analyses described below also include contributions from replaced components, additional inventory simulations were performed for those cells contained within components that are planned for replacement during the DEMO life-cycle. These additional simulations tracked the inventory history of cells exposed to only a part of the operational scenario (e.g. just phase 1).

An automated post-processing system has been developed to perform the waste classification analysis using these set of inventory simulation results, which themselves were generated by an automated tool that cycles over all cells in each geometry. The post-processing extracts the activity as a function of time (during operation and beyond EOL) for each cell in a model, converts this into a waste (and recycling) class evolution, and performs a variety of summing operations to attribute the mass of the cell to the appropriate class totals for specific reactor components (VV, blanket, divertor, etc.). The mass of each cell was computed from the material densities and MCNP-calculated volumes. Any additional results for a cell that is part of a component replaced during DEMO operation are processed in the same way, but with appropriate shifts in time.

The waste categorization used is based on the IAEA classification system [13] and defined according to the limits specified in UK regulations [14]. Non-active waste (NAW) is material with an IAEA clearance index [15] of less than 1. A material is Low-level waste (LLW) if both its α-producing activity is below 4 MBq kg^{-1} and if the sum of its β and γ activity is less than 12 MBq kg^{-1}. Otherwise a material was considered to be intermediate-level waste (ILW). An additional assessment was made of the potential recyclability of a component – material was considered to be potentially recyclable (PRM) if the contact γ dose rate calculated by FISPACT-II [10] was below 2 mSv h^{-1}, which is an estimate of the level at which a material could be manipulated by personnel via “shielded hands-on” [16].

Note that the above classification system is not expected to represent the actual limits that will be applied to a future DEMO reactor. The results from the waste analysis performed using these limits are intended as guidelines as to what could be expected, and to inform the future development of DEMO designs under the expectation that improvements in waste production under this classification system would also be beneficial under the eventual requirements in a country hosting a DEMO power plant.

Another important consideration here concerns the handling of tritium (^{3}H) produced in the breeding blankets or from unburnt fuel, which will permeate through most in-vessel components. Such considerations are beyond the scope of the present work, but ^{3}H is automatically included in analysis of cells where it will be produced via nuclear reactions – i.e. if it is produced during an inventory simulation for a cell then its activity would contribute to the subsequent decay-cooling and waste evolution of that cell. For the majority of cells there is no consideration of whether or not such tritium will be removed; except for the blanket tritium-breeder zones, where it is assumed that tritium will be completely removed during reactor operation (or shortly afterwards).

3. Results and discussion

Figure 2 demonstrates the evolution in waste and recycling classification according to the above limits for three typical cells of the VV behind the blanket modules of the HCPB DEMO concept. Each plot shows time evolution curves for α activity, $\beta + \gamma$ activity, and contact γ dose rate for the cell, and the corresponding waste/recycling category limits (as horizontal dashed lines). The background of the plot is coloured according to the classification at a particular decay time (the x-axis) following DEMO EOL. For the fifth (middle) layer of the interspace in the lower outboard VV (see labelling in figure 1a), figure 2a shows that the cell is initially (immediately after final DEMO shutdown) highly activated and thus classed as ILW. However, the γ dose rate (green curve) quickly falls, and within one day the material in the cell is PRM. The cell subsequently becomes LLW after around 20 days of decay cooling when the $\beta + \gamma$ activity of the material falls below the 12 MBq kg^{-1} limit shown by the dashed blue line (the α activity is never significant). At very long timescales – greater than 300 years – the predictions suggest that the material will even be classifiable as NAW, which is a relatively rare occurrence for in-vessel cells.

In figure 2b, on the other hand, for the outer shell of the lower outboard VV, the reclassification to LLW (after around 2 years) comes before the material is predicted to be recyclable (around 6 years), and the material never becomes NAW on the 1000-year timescale (this region may suffer additional activation relative to region (a) because of closer proximity to the divertor and lower port). For the highly-exposed inner shell of the inboard equatorial VV, whose waste evolution is shown in figure 2c, the situation is even worse – the material in the cell is predicted to never meet the criteria to become LLW within 1000 years, although it is PRM after around 80 years.

The automated post-processing scheme developed for this work allows the time limits for reclassification to be readily computed for all cells in the geometry. The toroidal slices of each DEMO concept shown in figure 1 are coloured according to the predicted time windows during which the individual cells shown in the plot (a subset of the total in the models) will decay sufficiently to meet the criteria to be considered as LLW. For replaced components in the divertor and blanket regions, the colouring corresponds to the "time-to-LLW" of the final replacement.

Differences can be seen in the predicted time to LLW in majority of the blanket module cells. For WCLL (figure 1c) the majority are predicted to become LLW on the 100 to 300-year timescale, whereas for both HCPB and HCLL most blanket module cells are expected to remain ILW beyond the 1000-year limit of the simulations. This is generally caused by minor variation in the amount of residual ^{14}C β-activity in the blanket module materials. ^{14}C is primarily produced via (n,p) reactions on the ^{14}N in Eurofer steel (containing 0.045 weight % nitrogen, which forms nitrides that are stable at high temperature and increase strength) and its production rate is strongly influenced by the local variation in neutron flux spectrum in the three DEMO concepts. Figure 3 shows a side-by-side comparison of the average activity across all cells of the blanket breeder-zone in the HCPB and WCLL models. Plot (b), for the WCLL, shows a residual ^{14}C activity that is below (on a logarithmic scale) the LLW $\beta + \gamma$-activity limit. Meanwhile, for HCPB in figure 3a, the ^{14}C activity is just above this limit and so, according to these waste classifications, the blanket is, on average, ILW for the entirety of the 1000-year simulation (^{14}C has a half-life of 5715 years). However, these results are sensitive the level of heterogeneity (or lack-of) in the MCNP model. As we demonstrate below in the analysis of results for a heterogeneous VV, a finer resolution in the model (perhaps reflecting the realistic division of a component into different material regions) can reduce the severity of the predicted waste classifications. In this context, figure 1 presents a conservative over-estimation of the waste picture.

Note that there is an additional contribution in the HCPB plot (figure 3a) from ^{239}Pu and ^{235m}U produced from the 0.004 weight % uranium impurity in beryllium. In this case the blanket modules would also exceed the α-activity limits for LLW (the nuclides are both α emitters). As with ^{14}C, the specific UK LLW limit is only just exceeded and alternative waste regulations, perhaps for a purpose-built DEMO waste repository, could produce a different set of predictions.

There are also differences in the time-to-LLW values of the divertor, despite the fact that the divertor is the same in all three geometries. The results show that the bulk regions of the divertor take longer to become LLW in the HCLL and WCLL concepts compared to HCPB. This results in the overall waste classification prospects of the entire divertor being worse in those former cases – whereas the entire divertor becomes almost 50% LLW after 100 years in the HCPB case, the divertor is still more than 50% ILW after a 1000 years in the other two concepts. This illustrates how the local environment around a component – in this case the blanket modules next to the divertor – can subtly influence the neutron field it is exposed to, and hence its activity. Again it is the specific amount of ^{14}C produced in the homogenized, bulk divertor regions (primarily from (n,p) reactions on ^{14}N) that causes the difference; in the HCPB model the average β activity is below the 12 MBq kg^{-1} LLW limit, while in the others it is above (and in the case of WCLL, only just above). In this situation alternative waste regulations including a specific limit for ^{14}C might provide a more meaningful prediction of the severity of the waste produced.

Another observation from figure 1 is the wide variation in time-to-LLW for the different layers of the VV – in particular in the new layers of the sub-divided VV interspace. This suggests that the more heterogeneous radial profile of the VV has resulted in a significant change in the waste classification of the VV as a whole. This is confirmed by the waste-class mass evolution of the VV in the different DEMO concepts shown in figure 4. This figure shows the evolution in ILW, LLW, and NAW waste mass from the total VV as a function of time, both during DEMO operation and beyond EOL. Also shown on the plot for each DEMO concept (figures 4a-c) is the ILW mass evolution produced using the original VV geometry, without the sub-division of the interspace. Note that the results from [1], which also considered a more homogeneous VV design, cannot be used for comparison because of differences in the baseline model used for that work, and so the "ILW-orig" curves shown in figure 4 come from additional simulations based on the EU-DEMO1-2015 design used here. Average neutron spectra were computed for each poloidal interspace VV region using a volume-weighted sum (equivalent to the method used by MCNP itself for tally averages [2]), followed by the same inventory simulations and post processing applied to individual interspace layers.

The difference between the ILW mass evolution using the present VV design and the original, more homogeneous one (ILW-orig) is remarkable. In all three DEMO concepts, the original geometry leads to the prediction that the VV remains around 80% ILW for more than 100 years (and for HCLL more than 200), while with the heterogeneous interspace all three VVs are around 50% LLW within 100 years of decay cooling. These results suggest that there could be a significant benefit, in terms of the amount of ILW to process (for recycling or disposal), if it was possible, via careful VV design, to plan for the separation of the VV into higher and lower activity radial regions, rather than a scheme where the entire VV is mixed and homogenized prior to further processing.

Finally, from figure 4d we see that the decay cooling of the VV varies between the three DEMO concepts. This is due to the different shielding characteristics of the blanket designs and material compositions, which causes, for example, the total flux experienced by the inboard equatorial VV inner shell to vary by more than an order of magnitude between the three concepts: calculated as 1.0×10^{14} n cm^{-2} s^{-1} behind the HCLL blanket (the highest), 2.0×10^{13} for HCPB, and only 6.5×10^{12} in the WCLL concept. This relative comparison is repeated in other poloidal regions and leads to the result shown in the figure, where the WCLL VV becomes 50% LLW after less than 10 years, closely followed by 50% LLW after just over 10 years in the VV behind the HCPB blanket. The HCLL result is somewhat worse, where the VV takes almost 50 years to decay cool to majority LLW.

4. Summary

A combination of neutron transport (neutronics) and inventory simulations have been used to perform detailed waste classification analyses for variants of a European DEMO design with different tritium-breeding blanket options, using a guideline classification system based on the IAEA system with UK limits.

The simulations suggest that a water-cooled lithium-lead (WCLL) concept produces a shorter decay-cooling period before the blanket modules are classifiable as low-level waste (LLW), although even in that case it takes more than 100 years. However, the designs of the blanket modules (and other components) suffer from a lack of heterogeneity (detail), and these results – based on the large homogenized cell volumes – could be a conservative overestimation of the actual severity of waste class as a function of time.

The specific optimisation of the blanket modules for each concept produces differences in the activity produced in the divertor, due to the local variation in neutron fields from the nearby blanket modules and resultant change in concentration of long-lived radionuclides. The bulk divertor in the WCLL and helium-cooled lithium-lead (HCLL) concepts is more activated and has a longer time-to-LLW than in a helium-cooled pebble-bed (HCPB) design.

In both the blanket and divertor the results show that the long-term activity and hence waste classification is largely determined, in all concepts, by the specific amount of ^{14}C produced via (n,p) reactions on the main isotope of nitrogen (^{14}N, which has been purposefully added to the material composition of the otherwise low-activation Eurofer steel to improve its mechanical and thermodynamic properties. This result highlights that even small levels of impurities could have significant impact on the severity of radioactive waste produced in DEMO. However, even in the worst cases, the long-lived ^{14}C activity in a component only exceeds the ILW limit applied here by a small margin (relative to the much higher activity at decay times of less than 100 years), and it is unlikely that this alone would necessitate a different processing route in a future “DEMO-waste repository” compared to material where the ^{14}C activity is just below the ILW limit.

Meanwhile, the HCLL blanket design (as currently optimized) does not offer as much protection for the Vacuum Vessel (VV) as either WCLL or HCPB, resulting in higher activity and a longer decay-cooling period before the cells of the VV are predicted to become LLW.

Radial sub-division of the VV significantly improves the waste classification predictions, producing a VV that is more than 50% low-level waste within 100 years (regardless of blanket choice), compared to remaining around 80% intermediate-level waste on that timescale when the VV is homogenized.

5. Acknowledgements

This work was carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement number 633053 and from the RCUK Energy Programme [grant number EP/P012450/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] M. R. Gilbert, T. Eade, C. Bachmann, U. Fischer, N. P. Taylor, Activation, decay heat, and waste classification studies of the European DEMO concept, Nucl. Fusion 57 (2017) 046015.
URL `https://doi.org/10.1088/1741-4326/aa5bd7`

[2] MCNP6 user manual, version 1.0, edited by D. B. Pelowitz, Los Alamos document number: LA-CP-13-00634, Rev. 0. Further details at `http://mcnp.lanl.gov/` (2013).

[3] R. Wenninger, et al., The physics and technology basis entering European system code studies for DEMO, Nucl. Fusion 57 (1) (2017) 016011.
URL `http://stacks.iop.org/0029-5515/57/i=1/a=016011`

[4] U. Fischer, et al., Methodological approach for DEMO neutronics in the European PPPT programme: Tools, data and analyses, Fus. Eng. Des.In press.
URL `http://dx.doi.org/10.1016/j.fusengdes.2017.01.053`

[5] G. Federici, et al., Overview of the design approach and prioritization of R&D activities towards an EU DEMO, Fus. Eng. Des. 109 (2016) 1464 – 1474, proceedings of the 12th International Symposium on Fusion Nuclear Technology-12 (ISFNT-12).
URL `http://dx.doi.org/10.1016/j.fusengdes.2015.11.050`

[6] L. V. Boccaccini, et al., Objectives and status of EUROfusion DEMO blanket studies, Fus. Eng. Des. 109 (2016) 1199 – 1206, proceedings of the 12th International Symposium on Fusion Nuclear Technology-12 (ISFNT-12).
URL `http://dx.doi.org/10.1016/j.fusengdes.2015.12.054`

[7] F. A. Hernández González, et al., HCPB Design Report 2015, Tech. rep., EUROfusion.

[8] J. Aubert, et al., HCLL Design Report 2015, Tech. rep., EUROfusion.

[9] E. Martelli, et al., WCLL Design Report 2015, Tech. rep., EUROfusion.

[10] J.-Ch. Sublet, J. W. Eastwood, J. G. Morgan, M. R. Gilbert, M. Fleming, W. Arter, FISPACT-II: An advanced simulation system for activation, transmutation and material modelling, Nucl. Data Sheets 139 (2017) 77–137, `http://dx.doi.org/10.1016/j.nds.2017.01.002`.

[11] J. -Ch. Sublet, L. W. Packer, J. Kopecky, R. A. Forrest, A. J. Koning, D. A. Rochman, The European Activation File: EAF-2010 neutron-induced cross section library, Tech. Rep. CCFE-R(10)05, available from `http://www.ccfe.ac.uk/EASY2007.aspx` (2010).

[12] J. Harman, DEMO Operational Concept Description, Tech. Rep. report number: 2LCY7A, EUROfusion/EFDA (2012).

[13] Iaea safety standards: Classification of radioactive waste, Tech. Rep. General Safety Guide: GSG-1, IAEA, Vienna (2009).
URL `http://www-pub.iaea.org/MTCD/publications/PDF/Pub1419_web.pdf`

[14] Strategy for the management of solid low level radioactive waste from the non-nuclear industry in the united kingdom, Tech. rep., Department of Energy & Climate Change, UK, available at `https://www.gov.uk/government/publications/` (2012).

[15] Clearance levels for radionuclides in solid materials: Application of the exemption principles, Tech. Rep. IAEA-TECDOC-855, IAEA, Vienna (1996).
URL `http://www-pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf`

[16] R. Pampin, M. O‘brien, Analysis of near-term fusion power plant designs from the material management stance, Fusion Engineering and Design 83 (10) (2008) 1419 – 1423, proceedings of the Eighth International Symposium of Fusion Nuclear Technology.
URL `http://dx.doi.org/10.1016/j.fusengdes.2008.05.018`

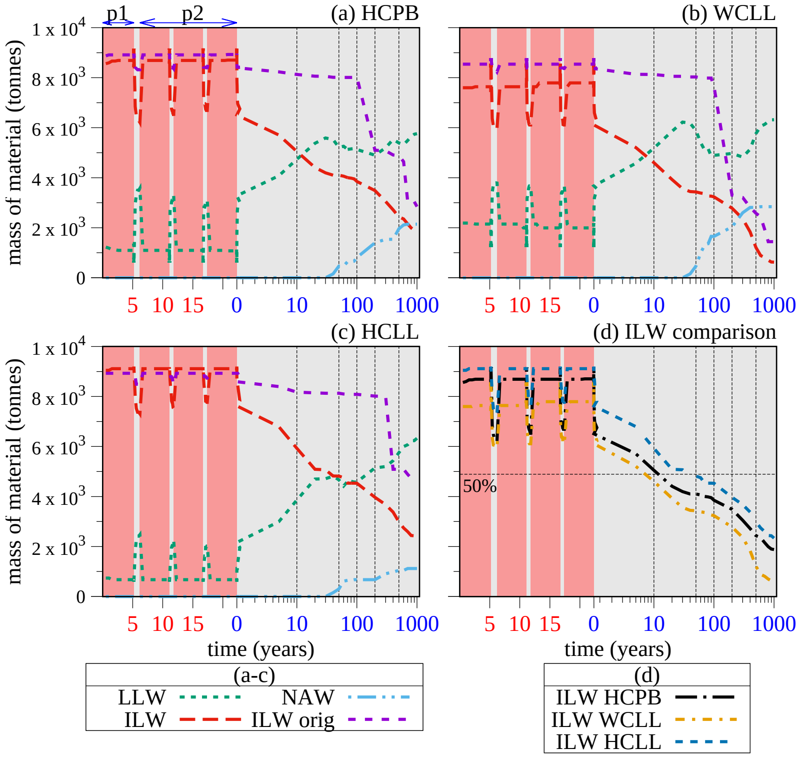

Figure 4: Evolution of waste mass from the Vacuum Vessel (VV) for three DEMO designs with different tritium breeding concepts. The red background regions represent the envisaged operation life (red time-axis labels) of DEMO, with a single-step phase-1 (p1) separated from phase-2 (p2) by a 1-year maintenance period (grey background) for blanket and divertor replacement. p2 is further broken-up by two 8-month maintenance periods for additional divertor replacements. See [1] for a fuller explanation of the schedule. The remaining grey background region is the EOL decay cooling out to 1000 years (blue time-axis labels). Vertical grid lines are included for 10, 50, 100, 200, and 500 years of decay cooling. Results are shown for (a) HCPB, (b) HCLL, and (c) WCLL, while (d) shows a direct comparison of the ILW mass from all three concepts. (a-c) also include the equivalent ILW mass analysis that results from calculations performed with the original un-divided VV interspace (labelled as "ILW-orig"). The horizontal line in (d) is for 50% of the total VV mass, which is the same in all three concepts – giving an indication of the expected time for the VV to decay-cool to an average of LLW. See the main text for further explanation.