Activation, decay heat, and waste classification studies of the European DEMO concept

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Introduction

- Inventory simulations of materials under neutron irradiation have a key role in designing future fusion (DEMO) power plants
  - can predict the time evolution in chemical composition, activation, decay heat, γ-dose, gas production, damage (dpa) dose, etc.
  - can provide information about the neutron shielding requirements, maintenance schedules & strategies, and waste disposal prospects
  - thereby guiding future design developments
- This work: inventory calculations for a reference European DEMO reactor model
  - to define in-vessel component activation, decay-heat and waste classifications
  - part of the 2015 EUROFusion programme

Overview of analysis

- Activation inventories as a function of time after shutdown for:
  - Divertor & Vacuum Vessel (VV)
  - including:
    - poloidal variation in activity & decay heat
    - breakdown of activity contributions by radionuclide
- Waste classification and recycling assessment for entire model (including VV, divertor, & blanket):
  - Mass per class as a function of time
  - based on IAEA classification system with UK limits
- For four European DEMO blanket concepts:
  - HCLL – Helium-Cooled Lithium Lead
  - HCPB – Helium-Cooled lithium orthosilicate Pebble Bed
  - WCLL – Water-Cooled Lithium Lead liquid breeder
  - DCLL – Dual-Cooled Lithium Lead liquid breeder

Inventory equations

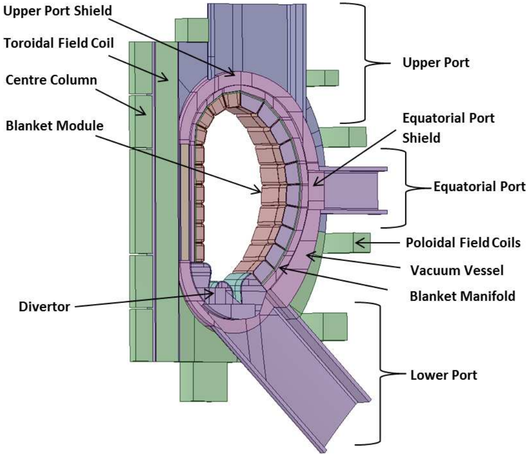
$$\frac{dN_i}{dt} = \underbrace{-N_i(\lambda_i + \sigma_i\phi)}_{\text{loss}} + \sum_{j\neq i} \underbrace{N_j(\lambda_{ji} + \sigma_{ji}\phi)}_{\text{creation}}$$

- coupled differential equations solved numerically by the FISPACT-II[§] inventory code
  - one equation for each nuclide i at concentration N_i
- σ_i, σ_{ji}:
  - energy-dependent reaction cross sections from EAF2010 nuclear data
  - folded with energy dependent (normalised) neutron spectra from neutron transport (neutronics) simulations
- total fluxes ϕ (also from neutronics)
- decay constants λ_i, λ_{ji}

[§] http://www.ccfe.ac.uk/fispact.aspx

Neutron transport model

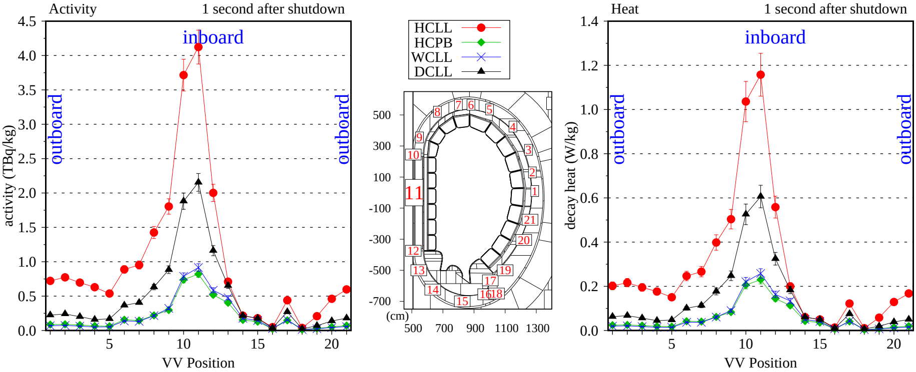
- 1.6 GW DEMO design
- Eurofer for in-vessel structures
  & SS316 Vacuum Vessel
- tungsten FW and (water-cooled) divertor armour
- homogenized blanket modules (no detailed structures)
- neutron flux spectrum simulated in each region (cell)



FW – first wall

Typical simulation results

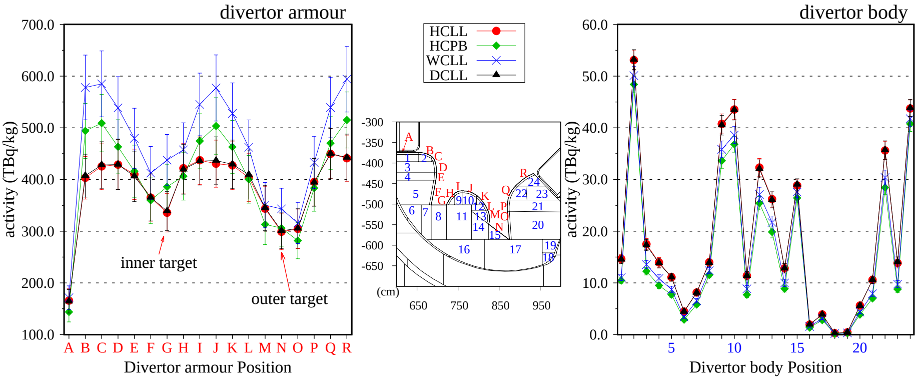
- Extensive inventory calculations with systematic analysis allow large scale comparisons
  - e.g. poloidal variation in vacuum vessel activity behind all four concepts
    - immediately after shutdown following 22-year operational lifetime§



§current conceptual schedule in European programme

Divertor activation

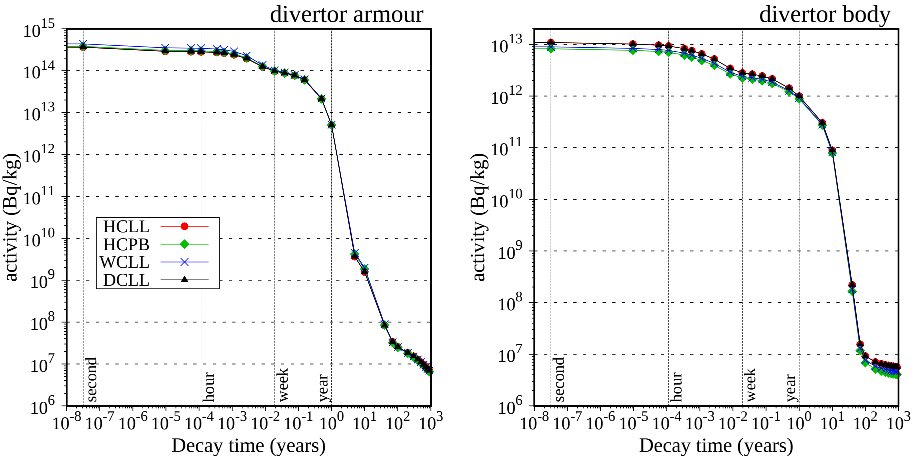
- Poloidal variation in activity immediately after shutdown:



- In W armour – difference between the concepts
  - mainly due to varying production of ^{187}W ($T_{1/2}$=24 hours)
  - caused by differing moderation characteristics of nearby blanket modules
  - variation on short timescales could be important in accident scenarios

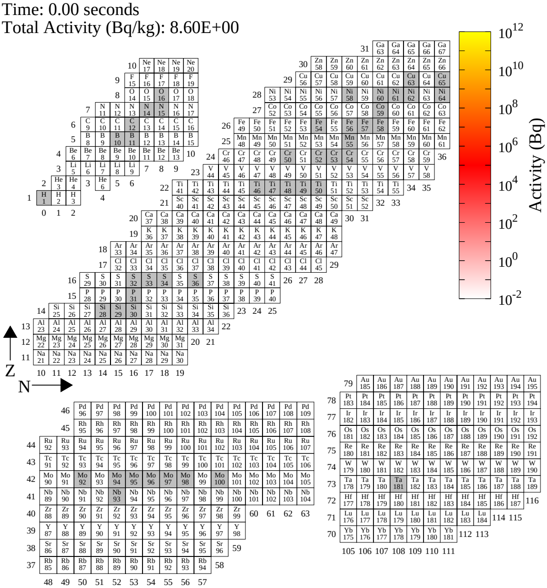
Divertor activation

- Divertor-averaged (by mass) variation in time shows that differences between concepts disappear at longer decay times



Activation inventories

- Activity simulation of outboard equatorial VV cell (HCLL)
- The FISPACT-II simulations can also trace contributions from individual (radio)nuclides



Activation inventories

- Activity simulation of outboard equatorial VV cell (HCLL)
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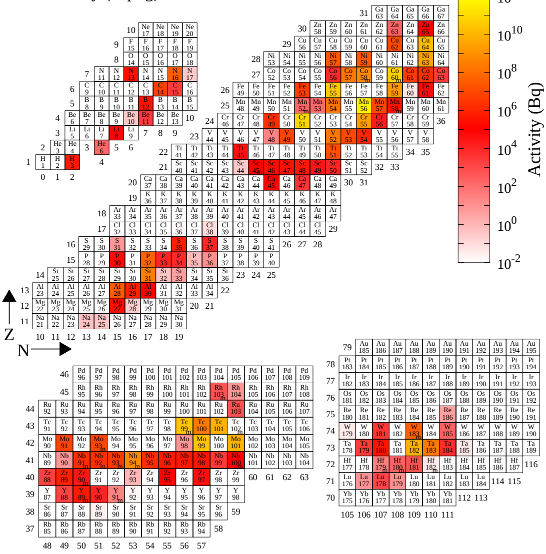
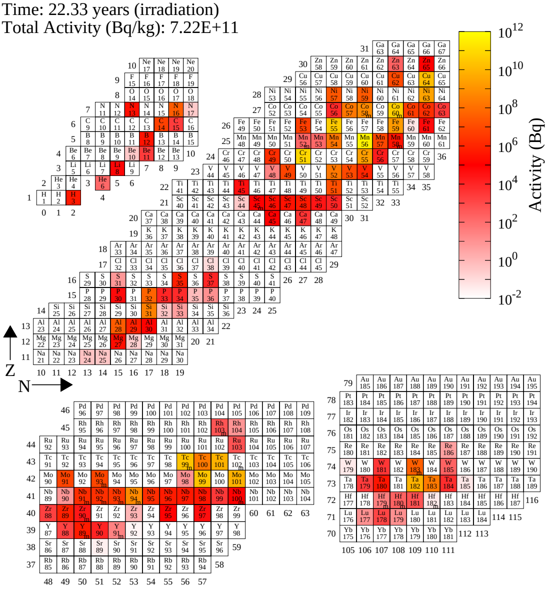
Time: 22.33 years (irradiation)
Total Activity (Bq/kg): 7.22E+11



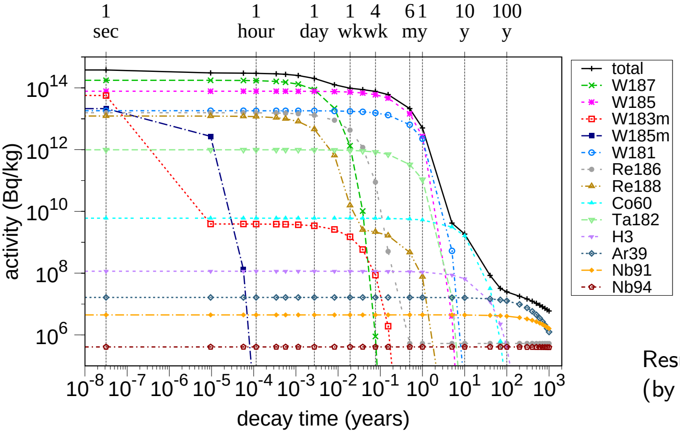
Activation inventories

- Activity simulation of outboard equatorial VV cell (HCLL)
- The FISPACT-II simulations can also trace contributions from individual (radio)nuclides
- e.g. showing long-lived Ni and Nb isotopes in SS316
- contributions from individual radionuclides as a function of time can be extracted ⟶



Activation Inventories

- e.g. W divertor PFC activity in HCPB

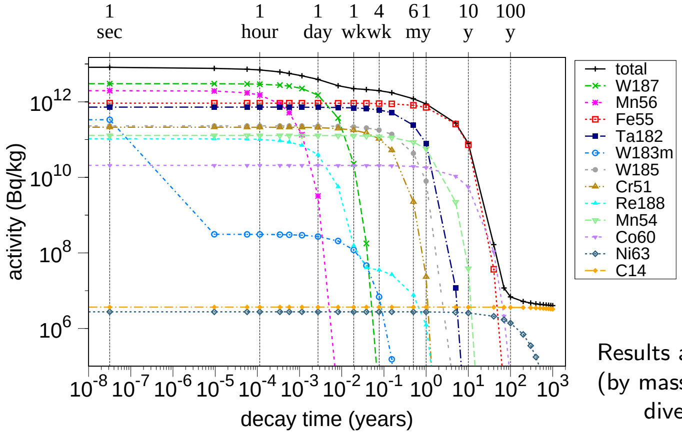


Results averaged (by mass) across divertor

- At short cooling times radionuclides from W (99.7 atm.%) dominate
- But very minor impurities of Co, K, Mo in composition produce all of the activity at decay times beyond 5 years

Activation Inventories

- Eurofer divertor body



Results averaged (by mass) across divertor

- At very long decay times Ni isotopes do not dominate as they do in SS316, but ^{14}C is still a problem

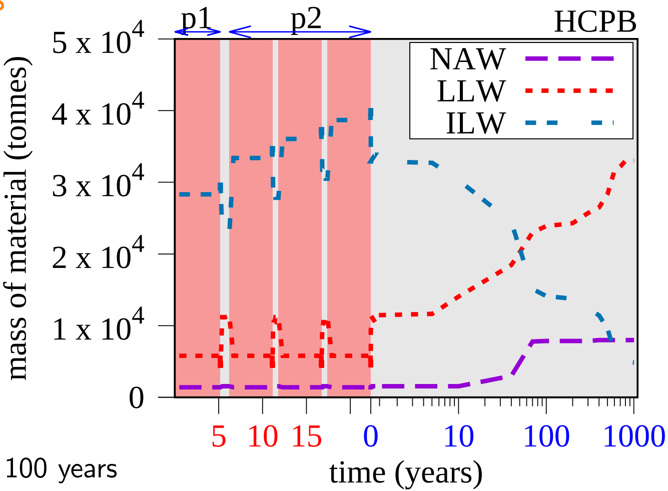
Waste classification

- Preliminary waste classes based on IAEA structure and UK limits§:
  1) **NAW** – (none active waste)
     - IAEA clearance index less than 1
  2) **LLW** – (low-level waste)
     - α activity less than 4 MBq kg^{-1} and combined β and γ activity of less than 12 MBq kg^{-1}
  3) **ILW** – (intermediate-level waste)
     - activities above LLW limits
- Recycling assessment:
  - component considered as being Recyclable Material (RM) if contact γ dose is below 2 mSv hr^{-1}
- Waste evolution charted during operation and after shutdown
  - replaced components included in waste inventory using additional inventory simulations
    (i.e. to simulate the decay-cooling of a removed component while DEMO is still operational)

§HLW (high-level waste) assumed to be zero

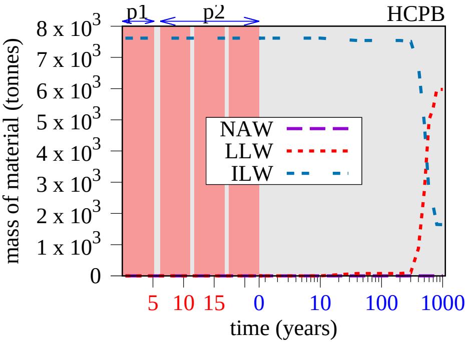
Total reactor waste results

- jumps in waste masses due to new components
- mainly ILW in first few decades after shutdown
- & very little NAW at any time
- takes more than 100 years for most of vessel to become LLW (dominated by blanket module masses)



blue time labels are post final shutdown; red during operational life. red regions of plots are for periods of irradiation; grey during shutdown

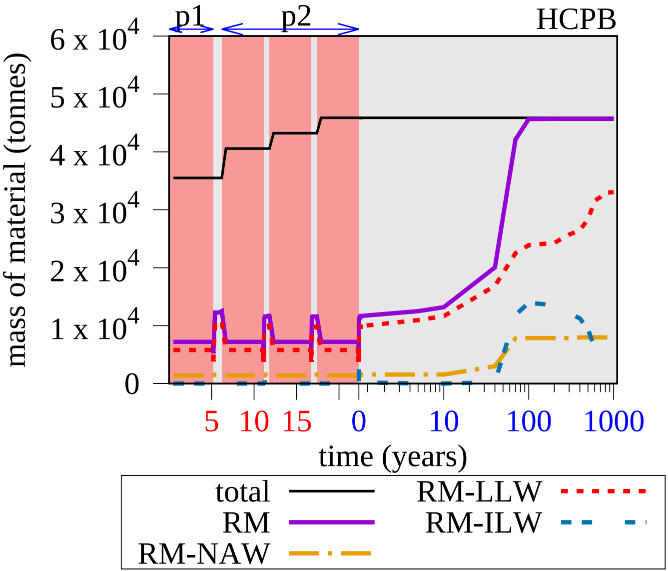
VV waste results



- Predominantly ILW for hundreds of years after shutdown due to Ni isotopes in SS316
- but results very sensitive to homogenization of cells & volume-averaged fluxes
- some variation with blanket concept due to under-optimization of designs

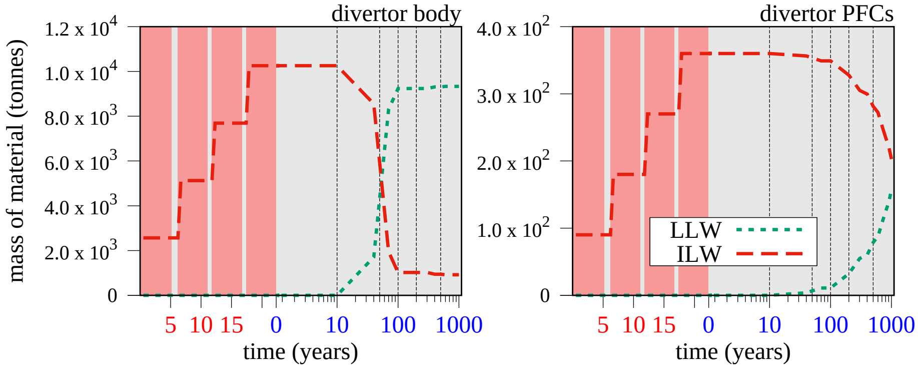
Total reactor recycling results

- entire design (including VV+IVCs) becomes potentially recyclable within 100 years despite waste classification



IVCs – in-vessel components

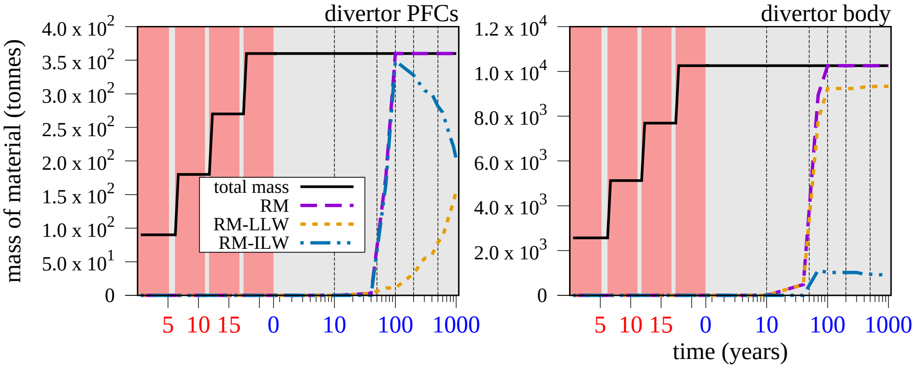
Divertor waste results



- four concepts equivalent (HCPB example shown)
- PFCs† remain ILW for much longer than body of divertor
  - due to long-lived ^{63}Ni produced from copper

†Plasma-Facing Components (PFCs) include W armour and coolant layer of W+CuCrZr+Cu+H_2O

Divertor recycling results



- But both PFCs and body of divertor recyclable according to 2 mSv hr^{-1} contact dose criterion on 100-year timescale

Summary

- Extensive inventory simulations with FISPACT-II for in-vessel components of the European DEMO model with four different blanket concepts
  - using detailed operational scenarios
  - using irradiation conditions predicted by neutron transport simulations
- Activation results as a function of decay time, blanket concept, & of position
  - processed automatically and consistently, allowing side-by-side comparisons
  - e.g. highlighting a variation in the short-term, post-shutdown activity of the divertor armour
    - higher near WCLL blanket modules due to increased moderation
- Activation inventories identify the dominant radionuclides
  - e.g. very minor impurities in W dominate the activity at long-timescales
- Waste and recycling analysis based on total mass and activity of components
  - mostly LLW and recyclable on 100-year timescale
  - parts of VV and divertor are likely to remain ILW for longer
  - but results sensitive to (lack of) heterogeneity in component modelling