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, $\gamma$-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

\[
\frac{dN_i}{dt} = -N_i(\lambda_i + \sigma_i \phi) + \sum_{j \neq i} N_j (\lambda_{ji} + \sigma_{ji} \phi)
\]

- coupled differential equations solved numerically by the FISPACT-II\( ^\S \) inventory code
  - one equation for each nuclide \( i \) at concentration \( N_i \)
- \( \sigma_i, \sigma_{ji} \):
  - energy-dependent reaction cross sections from EAF2010 nuclear data
  - folded with energy dependent (normalised) neutron spectra from neutron transport (neutronics) simulations
- total fluxes \( \phi \) (also from neutronics)
- decay constants \( \lambda_i, \lambda_{ji} \)
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)
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

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**Activity**

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**Divertor activation**

- Poloidal variation in activity immediately after shutdown:

  * Diagram showing activity distribution on divertor armour and body with position markers and depth indication.*

- 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
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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

\[
\begin{array}{cccccccc}
1 & 1 & 1 & 1 & 4 & 61 & 10 & 100 \\
\text{sec} & \text{hour} & \text{day} & \text{wk} & \text{wk} & \text{my} & \text{y} & \text{y}
\end{array}
\]

- 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

Results averaged (by mass) across divertor
Activation Inventories

- Eurofer divertor body

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)
     - $\alpha$ activity less than 4 MBq kg$^{-1}$ and combined $\beta$ and $\gamma$ 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 $\gamma$ 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)

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$^\&$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)
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
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