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Waste implications from minor impurities in European DEMO materials

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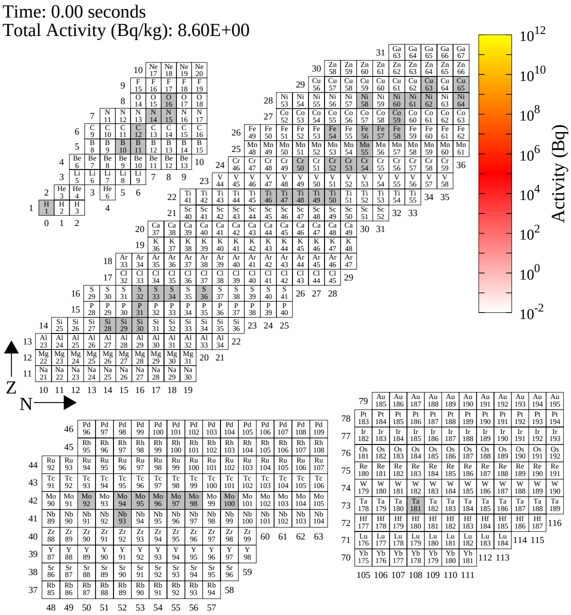
Introduction

- Waste-production predictions for a future demonstration fusion power plant (DEMO) are needed to assess the environmental and economic costs of radioactive waste disposal
- During DEMO operation neutron irradiation will alter chemical composition of materials in reactor components
  - leading to radioactivity
- Inventory simulations can quantitatively predict change in composition ("the inventory")
  - resulting in predictions of activity and thus waste severity
  - computed as a function of time (both operational and post-life shutdown)
- Can be used to assess the significance of every constituent of a material – even those in very low concentrations



Activation inventories

- E.g. Activity simulation of DEMO vacuum vessel (VV)
  - 316 stainless steel
- with FISPACT-II
  - traces concentrations of, and activity contributions from, individual (radio)nuclides

Sublet, Eastwood, Morgan, Gilbert, Fleming, and Arter, "FISPACT-II: An Advanced Simulation System for Activation, Transmutation and Material Modelling" *Nucl. Data Sheets* **139** (2017) 77-137
https://fispact.ukaea.uk

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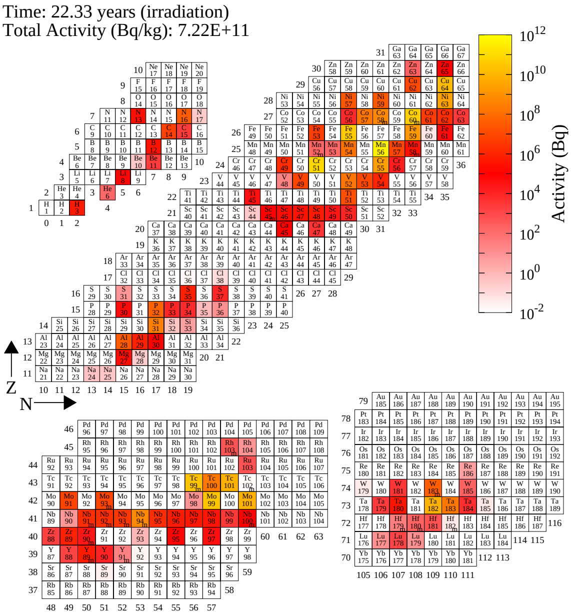

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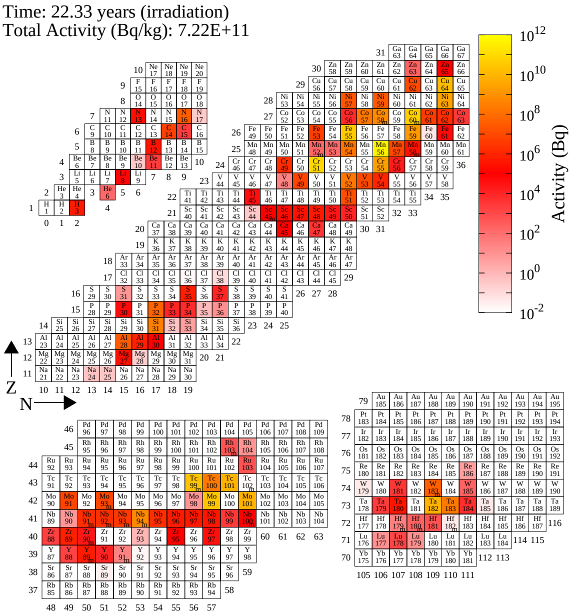

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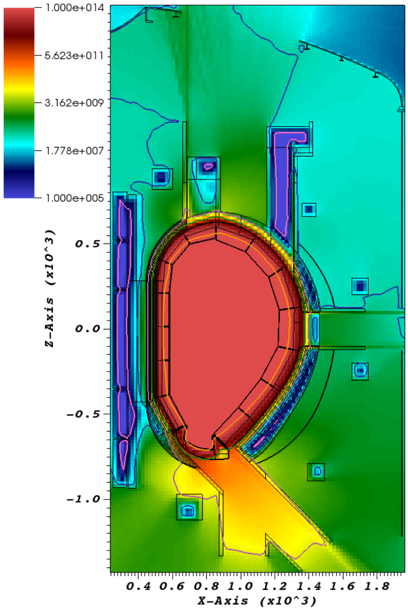
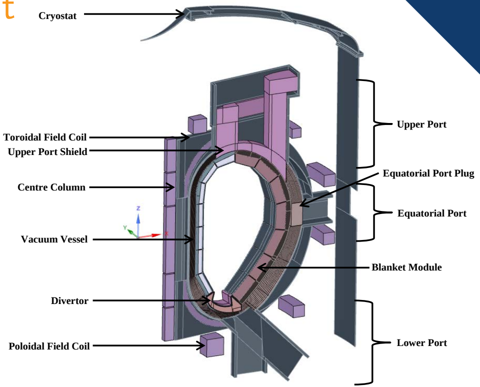
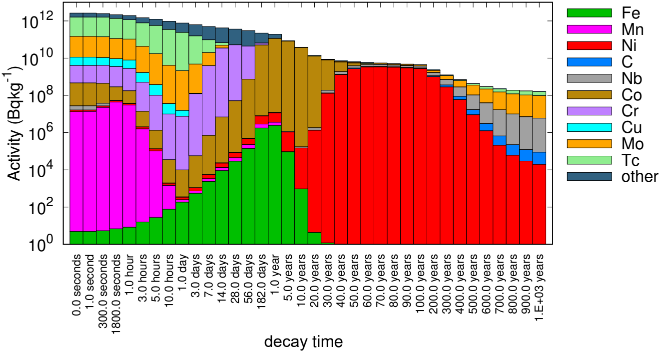
Input



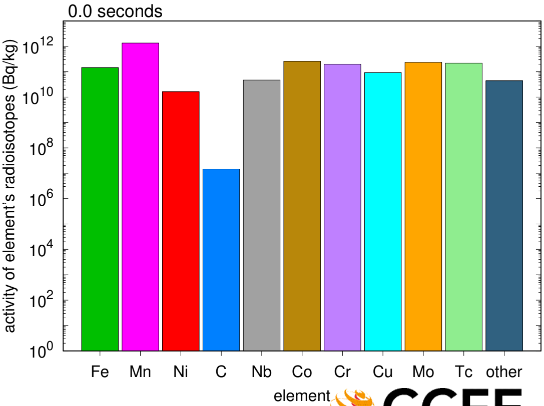


- neutron fluxes and spectra predicted by Monte-Carlo transport simulations
  - for a recent European DEMO design
- reactor operational scenario
  - $\sim$ 22 years (including maintenance phases)

SS316 total activity

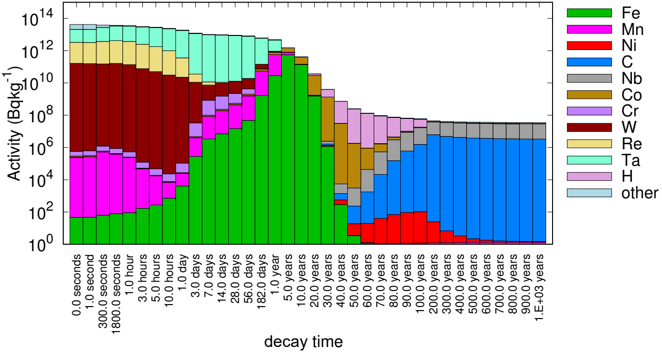


- Main steel assumed for VV (and ex-vessel) in current DEMO
- typical composition contains 12.5 wt.% Ni, 2.7% Mo, and 0.01% Nb

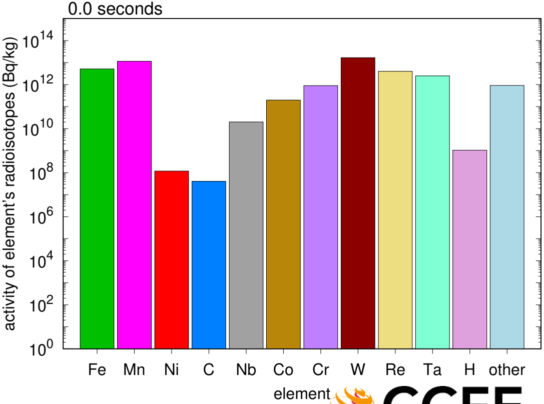


- After a typical VV lifetime, the first few decades of decay-cooling are dominated by the usual Fe/Mn/Co radionuclides
- But at later times it is the long-lived radionuclides produced in nickel that dominate the activity for 100s and 1000s of years

EUROFER total activity



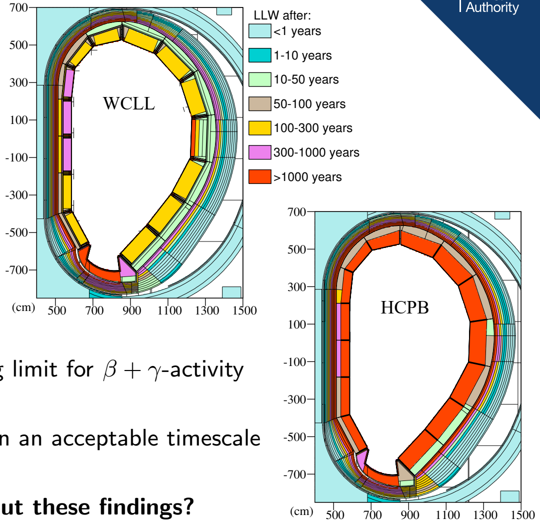
- A "reduced-activation" steel designed for in-vessel DEMO use
- only 0.01 wt.% Ni and 0.005% Mo; half of SS316's Nb content; also contains around 0.045% N



- Results after typical exposure in a near-surface blanket region (helium-cooled concept)
- From 100 years, the activity is dominated by ^{14}C nuclide of carbon – produced from the small amount of nitrogen in the steel (designed to improve high-temperature stability)

Waste Assessment

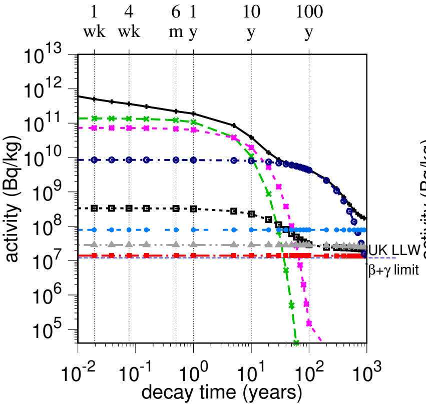
- A key objective for the design of DEMO is that the reactor should not generate any radioactive waste that requires long-term deep storage
- Any material not recycled at end-of-life (EOL) should ideally be low-level waste (LLW), or better, within a few decades
- Previous assessment* has shown that this is an issue for current DEMO designs and material specifications

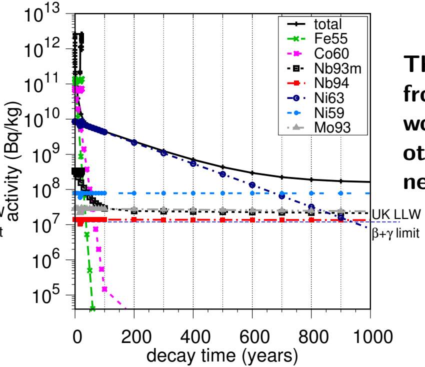


- e.g., UK near-surface LLW repositories have a 12 MBq/kg limit for $\beta + \gamma$-activity and a 4 Mq/kg limit for α decay
- many in-vessel and VV regions do not meet this criteria on an acceptable timescale (although some DEMO concepts are better than others)
- **what can analysis of the inventory simulations say about these findings?**

*Gilbert et al. *Nucl. Fusion* **57** (2017) 046015
Gilbert et al. *Fus. Eng. Des.* (2018) in press

SS316 in the vacuum vessel





The predicted activity from specific nuclides would be unacceptable in other international near-surface repositories

- ^{63}Ni (a β emitter) dominates activity from around 10 years after EOL (and exceeds the LLW limit for almost 1000 years)
- Some even longer-lived radionuclides of Ni, Nb, and Mo also exceed the UK-LLW limit

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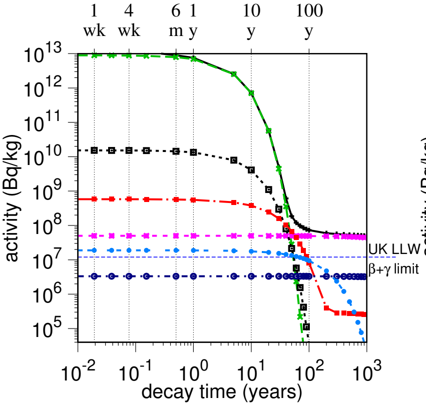
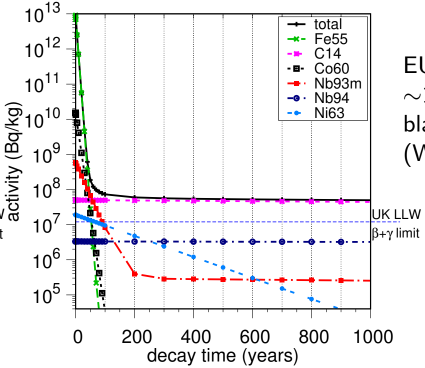
Carbon-14 from nitrogen in EUROFER



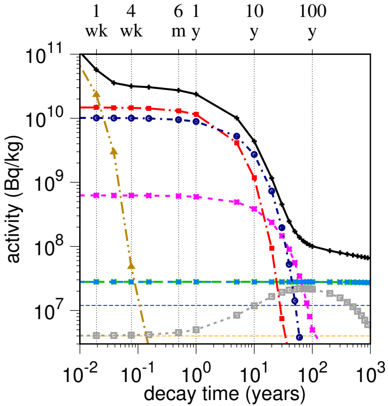


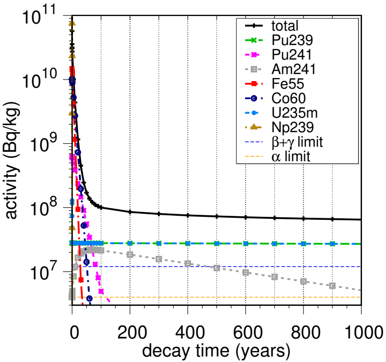
EUROFER activity after ∼10 years in a water-cooled blanket (WCLL DEMO)

Even when ^{14}C is not an issue, the level of ^{94}Nb could be a problem for repositories in other countries

- Despite the small amount of nitrogen in the typical EUROFER composition, it can still lead to the production of enough ^{14}C (via (n,p) reactions) to exceed LLW limits for 1000s of years
  - the $T_{1/2}$ of ^{14}C is more than 5700 years

Actinide impurities in Beryllium

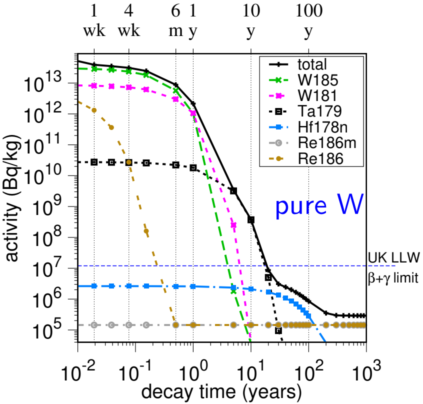


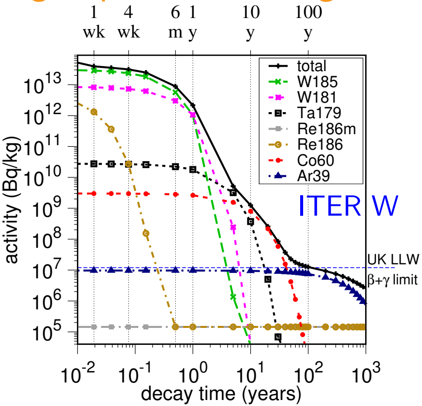


U content in Be can vary by source – could be as low as 0.001 wt.%

- Here the 0.01 wt.% uranium in beryllium leads to several alpha-emitting actinides that would be a problem for most near-surface disposal facilities around the world
- even with more optimistic (lower) U concentrations, there may still be disposal problems

Manufacturing impurities in tungsten





- "pure W" does not produce any long-lived problem radionuclides
- But the ITER-grade doesn't become UK-LLW for 100 years, mainly due to ^{60}Co from the 0.001 wt.% Co in the composition

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Summary

- Computational waste assessments for current European DEMO designs
  - highlight the potential issues surrounding minor impurities contained (sometimes deliberately) within many fusion materials
  - including EUROFER, where both nitrogen and niobium can cause problems
- Some components may not be acceptable in near-surface disposal facilities (low-level waste) for 100s of years due the production of various long-lived radionuclides
- Outlook:
  - detailed analysis of worldwide repositories shows the significant variation in acceptance limits
  - suggests that a new repository tailored for fusion waste might be preferable to allow a DEMO reactor to avoid the need for long-term deep disposal
  - if not, then there should be greater control of certain impurities in DEMO materials

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