radiation damage.

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Goal

For scenarios involving high-fluence irradiation, a large amount of radiative power needs to be absorbed and the total power needs to be diverted as much as possible. For example, in particle accelerator experiments or proposed medical isotope production facilities. This is done using a power dump. We designed such a power dump. A simplified octant of the geometry is shown in Fig. 1.

High-energy particles, emitted by the (primary or secondary) radiation source, cause displacement damage and produce gas in the form of He and H. Over time, these effects can lead to swelling and radiation hardening. The additional stresses that are caused by swelling, and the change in properties due to radiation hardening can lead to failure. This risk needs to be assessed and potentially mitigated.

Calculating how structural properties change under irradiation also allows proper assessment under design and construction codes for nuclear components (e.g. RCC-MRx).

We will need to answer the following questions:

- What is the relevant radiation damage?
- What is the subsequent swelling of the part?
- Can the part survive according to the appropriate criteria?

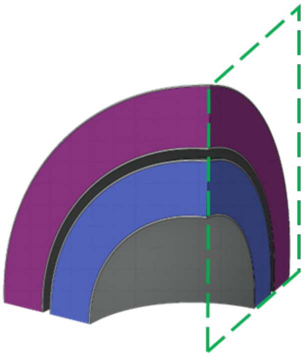

Figure 1. Power dump layered structure, showing one octant of the power dump with different materials in different colors.

Radiation damage

To obtain relevant radiological parameters, the radiation environment was simulated by modeling the target and the power dump, in the FLUKA radiation transport code. The irradiation of a target (not shown) with an electron beam is the source of radiation in the system. We model the full irradiation profile, bias relevant interactions, such as photonuclear and neutron interactions. By exploiting relevant geometric abstractions and the symmetry of the system we greatly speed up convergence in the Monte Carlo simulation.

A relevant metric for displacement damage is the number of displacements per atom (DPA). This captures the displacement damage that occurs as a consequence of high-energy particles knocking out atoms from the materials' crystal lattice. FLUKA allows us to directly capture this quantity while also taking into account defect recombination.

We also simulate the distribution of deposited energy in the form of heat. This heat load is necessary, as it causes thermal expansion (and stress) in the material. As gas production (H and He) due to irradiation can contribute to swelling, this was simulated as well. After evaluation, it was found to be negligible. We therefore do not consider gas production further.

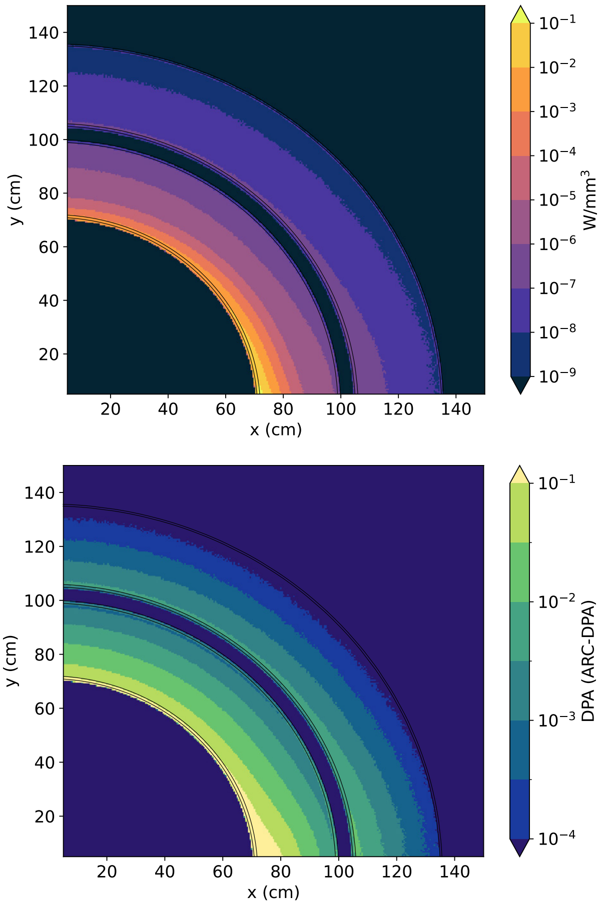

Figure 2. Heat load and DPA, as simulated by FLUKA.

The results can be seen in Fig. 2, showing a cylindrically symmetric simplified geometry of the right-half of the power dump. These results form the input for further structural analysis.

Stress analysis

With the input from the Monte Carlo radiation simulations, we can now perform a mechanical analysis on more detailed parts of the power dump. The part is shown in Fig. 3. We use COMSOL to directly import the part's geometry, and import the relevant parameters calculated with FLUKA. The spatial distribution of damage production (DPA/s) is used as an input to define a swelling strain that varies in space and time. Saturation of swelling is hereby taken into account.

From the heat load, a temperature distribution was calculated to make it possible to add the thermal strains on top of this. Thus, with re-presentative mechanical boundary conditions, stress distributions can be calculated. As the part is brittle, fast-fracture will be the primary mode of failure. Hence, it is appropriate to look at the first principal stress. We find a maximum of 115 MPa over the lifetime of the part.

For the fracture toughness of the material we assume a conservative value of $K = 5\ \mathrm{MPa}\sqrt{\mathrm{m}}$. The maximum expected crack size is much smaller than the part, so we can use a simple relation to deduce that such a crack will tear at a stress of 250 Mpa.

Using these conservative estimations, we conclude that the part is not likely to fail under these irradiation conditions.

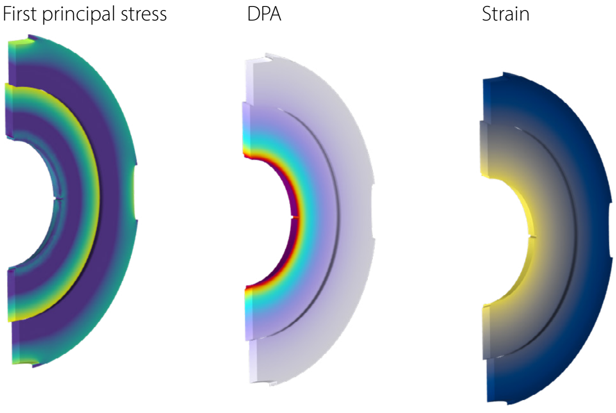

Figure 3. First principal stress, DPA and Strain. These results follow from COMSOL structural simulations which use input from FLUKA Monte Carlo calculations.

Impact

We can make predictions on the impact of radiation damage and directly couple radiation quantities such as heat load and DPA) to structural quantities. Failure modes can thus be evaluated and assessed. Analysis is also possible for materials which are ductile instead of brittle. This only requires looking at criteria other than fast fracture.

Further analysis and comparison to design and construction codes for nuclear components (RCC-MRx) is now possible, and will allow adherence to the highest standards in this field.

Bibliography

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