Neutronic considerations in nonlinear dynamic multibody systems: Enhanced analysis of the absorbed dose in remote handling equipment

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Abstract

Fusion reactors are an excellent carbon-free alternative to help meet our future energy demands. Zero emissions, no long-lived radiation waste, abundant fuel supplies, and inherent safety are the most important advantages of magnetic confinement fusion reactors. On the downside, developing a fusion power plant represents an extremely challenging task from the physics, material technology, and engineering perspectives. The damage caused by highly energetic neutrons to the in-vessel components requires regular maintenance operations for their replacement.

During shutdown, the activated materials decay, emitting gamma radiation. This ionizing field, along with the risk of contamination from activated dust, makes the use of remote handling equipment for all the in-vessel maintenance operations mandatory. Even for these mechatronic devices, the extremely high radiation fields in the range of kGy/h—as shown in Figure 1—represents a huge constraint on their design. The survival of their components is usually estimated by a simplistic approach. The maximum level of absorbed dose, along with the intervention time, gives an upper bound to the total damage. This has been sufficient for present experimental reactors, such as JET, as the radiation levels are orders of magnitude below those expected for future power plants [1]. What is more, heavily radiated assemblies need to cope also with the thermal effects arising from the surface and volumetric heat generation.

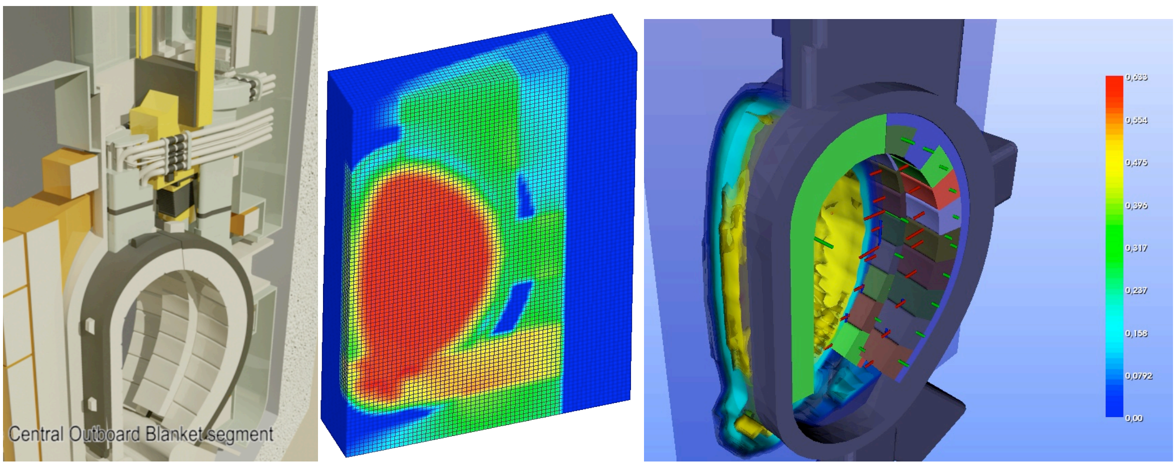

Figure 1: Active blanket segment handling (left) with remote handling equipment in yellow. Radiation environment (centre) and model (right); max. absorbed dose is 2 kGy/h.

The effects on fixed equipment by moving activated components during maintenance scenarios have been previously studied [2,3] and applied to ITER-related scenarios. These approaches use component activation sources generated using the FISPACT-II inventory code [4]. Monte Carlo-based radiation transport codes such as MCNP, together with a range of custom source routines are then used to simulate the radiation fields from both activated static and moving components. The results from the static and moving components can be combined to determine the full radiation field impinging on a component.

A first approach to the application of thermo-mechanical simulation of nonlinear flexible multibody systems to remote handling equipment was presented in [5]. The continuum bodies were discretized either by a set of finite elements or meshfree nodes and cells, for solving the coupled-field thermo-mechanical deterministic residual equations. The formulation used is detailed in [6] and has been extended to take advantage of meshfree approximation functions for joint modelling between dissimilar components: solid-flexible, thermal-adiabatic, continuum-discrete, etc. The simplified treatment of these connections allows reducing drastically the complexity of the constraint equations. In real problems this is a common source of singularities, which leads to ill-conditioned matrices in the global set of equations.

The content of the paper focuses on the coupled effects which have a geometric origin. This has been identified as the main cross effect, as the radiation field and absorbed dose vary when the configuration of the system changes. For the varying field, linear superposition of effects is used. As the majority of the activated components remain in place during a specific operation, a background field is set. The field corresponding to the component being handled is modelled on top of the background using a moving reference frame. The effects of the absorbed dose inside remote handling equipment are studied using the formulation presented in [5], where the radiation load feeds into the heat load terms. The heat load and the absorbed dose are calculated through the radiation field, its spectrum, and the material properties. To estimate the effective dose inside the systems in study, two separate effects are taken into account:

- Self-shielding corresponds to the variation of the field inside of the body, once the gamma flux is known in its boundary.
- Environment shielding is produced when there is not a line of sight from the radiation source to the body in study.

For the background field, the environment shielding is already considered at all points of the simulation space. Several methods can be applied to compute the self-shielding inside a body. The linear attenuation coefficient is chosen, as the simplest but robust approach, only depending on the average material densities and the average distance to the boundary. Level-set, RBFs and R-functions are explored to quickly estimate the signed distance function inside the continuum.

In summary, different detailed analysis techniques are already available for the study of fixed and moving systems, separately in the neutronic and mechanical fields. This work presents a first, geometrically, and deterministic based coupled approach. The final objective is to join the scope of radiation and multibody analyses, towards a more precise understanding of the working conditions, and a better capability for developing optimized designs of remote maintenance systems.

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