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USE OF COMSOL MULTIPHYSICS FOR THE EVALUATION OF RADIATION-INDUCED STRESSES IN THE PB-FHR

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1. INTRODUCTION

The Fluoride-Salt-Cooled, High Temperature Reactor (FHR) is an advanced reactor concept combining elements from other advanced reactor designs. Recently, the FHR has been explored in a joint collaboration between UC Berkeley (UCB), the University of Wisconsin, Madison, and MIT [1-4].

The design of a variant PB-FHR is being developed at UC Berkeley (UCB). The Pebble Bed FHR (PB-FHR) also includes TRISO fuel loaded into graphite pebbles, and a graphite moderator. In particular, this design variant has an annular core, with a graphite central reflector. The central reflector is integral in reactivity control and minimizing coolant pressure drop.

Components in reactor cores are limited in lifetime by a number of means, including the limitations in their material properties. Over time in high radiation, corrosive, and high temperature environments, reactor components and the material properties that comprise them are changed, and the reactor system is perturbed. Determining a lifetime of various core components is contingent upon evaluating whether the perturbations in the material or structure are within tolerance for operation.

The graphite central reflector will see a high flux due to its location within the core, and over its lifetime it will also see a high fluence. It is common to limit graphite components' lifetime based on the "turnaround point", a fluence at which the graphite stops shrinking and starts to swell [5]. Here COMSOL is used to evaluate the radiation-induced stresses in the graphite central reflector to determine the frequency at which this component needs to be replaced.

2. METHODOLOGY

COMSOL multiphysics can be utilized for a large spectrum of physics problems. However, it is not readily adept at evaluating radiation-induced stresses. The method used for this project involved using a "pseudo-temperature distribution" that utilized the thermal expansion module of COMSOL. Given the dimensional changes of a particular grade of graphite as a function of fluence, the pseudo-temperature distribution induced the same volumentric change in the model using thermal stresses rather than radiation-induced stresses.

First, an MCNP model was used to obtain the flux distribution in the reflector, the flux distribution was sent to COMSOL, and then the radiation-induced dimensional change of the central reflector was evaluated at different points in the lifetime of the core. The radiation-induced dimensional changes ultimately induce a stress distribution in the material, which is a function of the position-dependent fluence in the graphite. This distribution was evaluated and compared against material limits. This method was used to provide a first-order estimate of the central reflector lifetime, and can also be used as a starting point for component optimization in future studies.

3. MODELING OF THE CENTRAL REFLECTOR

The first design iteration of the central reflector was a solid graphite block with no coolant or control rod channels. The aim was to start with the simplest case for the analysis, which could then provide insight on the relative effect of design iterations of the central reflector in the future. We expect this particular variant of the central reflector design to be the most extreme case, as there is a large component with varying fluence depositions at different locations within the graphite. As such, at some point within its lifetime we should expect that the central reflector is undergoing both radiation-induced shrinkage and swelling.

3.1. MCNP5 Model

The MCNP5 model of the PB-FHR core was taken at the core equilibrium burnup state. After the equilibrium burnup state was found, a flux distribution in the central reflector was calculated. The MCNP model assumed no radial zoning of the fuel, and three axial burnup zones.

3.2. SolidWorks and COMSOL Models

The core geometry modeled in COMSOL closely resembled that of the MCNP model, but was ported from SolidWorks. The graphite used in the model was IG-110 graphite, which is considered an isotropic nuclear grade graphite. Fluence-dependent material properties were also included in the model [6,7]. As previously noted, the thermal expansion module of COMSOL was used to evaluate the radiation-induced stresses.

4. RESULTS

The analysis of the central reflector revealed a strongly flux-dependent stress distribution, as predicted. Fig. 1 includes three snapshots of the Von Mises stress distribution. The axial centerline of the reflector sees large induced stresses, especially in the outermost few centimeters of graphite. Additionally, the points where the converging region starts and the diverging region ends are locations where stress peaks, due to the presence of corners. A fast neutron in a graphite environment has a mean free path of a few centimeters, so the radial centerline of the central reflector saw little stress buildup, as did the lower and upper endpoints of the reflector itself, where fuel injection and defueling occur, respectively. Table I provides a summary of the maximum radial and axial stresses in the reflector. Note that a negative number indicates compression and a positive number indicates tension. Recall that for IG-110 graphite, pre-irradiation, the ultimate tensile stress is 25MPa and ultimate compressive stress is 71MPa [7].

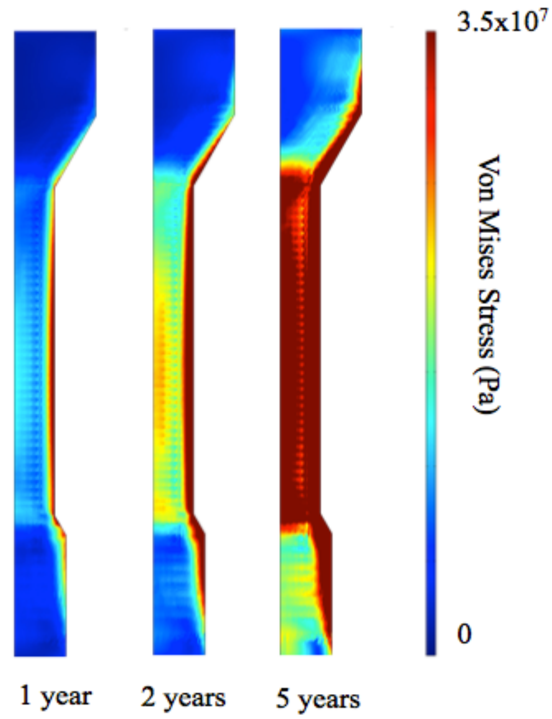

Figure 1: Central Reflector Von Mises Stress at Various Core Lifetimes

Table I. Stresses of the central reflector at various lifetimes

Time (EFPY)	Max Stress in R (MPa)	Max Stress in Z (MPa)	Volume Average Stress (MPa)
0.5	-6.7	22.2	3.8
0.75	-10.2	32.2	5.8
1.0	-13.5	42.6	7.7
2.0	-25.6	75.4	15.0
5.0	-48.9	83.6	30.5
10.0	-34.2	-173.8	39.5

The last column is added to emphasize the importance of calculating the local changes in stress. Because fast neutron damage is dependent on fast neutron population, only small volumes within the central reflector see extreme change early on. Using the volume-averaged stress would grossly overestimate the lifetime of this component.

5. CONCLUSIONS

It is evident that a solid cylindrical central reflector will begin to fail in tension early in the core's overall lifetime. The compression failure will occur much later, but the lifetime of the reflector will be dictated by this tensile failure. The short lifetime of this variant of the central reflector will limit the PB-FHR design in requiring frequent shutdown and significant re-construction of the core every few months. A redesign of the central reflector to minimize stresses and to anticipate long-term irradiation-induced swelling is required to make the PB-FHR a viable design.

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