Demonstration of Fusion Blanket Simulations for Anticipated Operational Occurrences with RELAP5-3D

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Working toward the development of commercial fusion reactor technology, RELAP5-3D was selected for the thermal-hydraulic analysis of the Dual Coolant Lead-Lithium (DCLL) blanket within the proposed Fusion Nuclear Science Facility (FNSF) design. Having been developed by the DOE with a validation basis for the licensing of commercial light water reactors (LWRs) [1], RELAP5-3D is an excellent candidate for developing a validation basis for commercial fusion systems. This will be done by performing safety analyses over all anticipated operational occurrences (AOOs), as similarly applied to current LWR safety analysis [2]. Transients that will be considered are changes in heat removal by the secondary system, changes in blanket flowrate, changes in blanket coolant inventory, and coolant behavior following changes in plasma power [2]. With this basis for analysis, we can determine which aspects of LWR safety analysis are relevant to this type of fusion reactor and define an appropriate set of AOOs for fusion safety analysis.

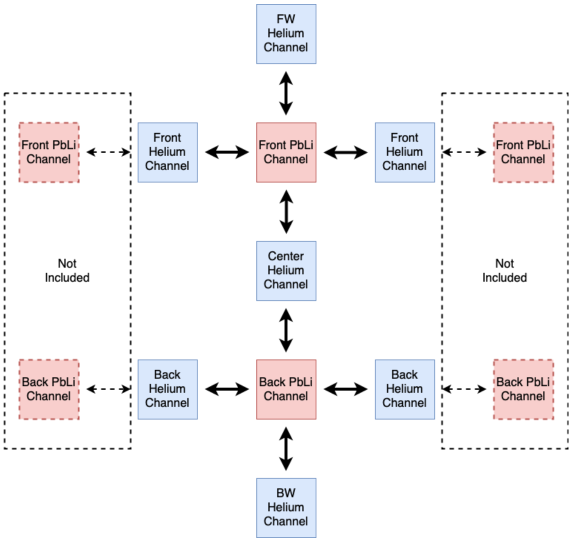

Figure 1 DCLL Model PbLi and He Channel Coupling Layout

The analysis presented focuses on the thermal-hydraulic analysis of the blanket during a representative startup transient. Our RELAP5-3D model consists of a pair of PbLi flow channels that are thermally coupled to their surrounding He coolant channels represented by Figure 1. The nodalization of the PbLi flow channels is shown in Figure 2 and a representative channel cross section is shown in Figure 3. The channel and flow specifications used for this model are from ref. [3-5] for the inboard blanket of the FNSF system. Within the PbLi channels, we are considering MHD pressure effects assuming the use of a SiC FCI with electrical conductivity reported in ref. [4]. The MHD effects within the channel are calculated using an equivalent friction factor, $FWF_{MHD_{RELAP}}$ as described in ref. [6], and applied within RELAP5-3D using Equation 1.

$$\mathrm{FWF}_{\mathrm{MHD}_{\mathrm{RELAP}}}=\left[\frac{2\Delta x}{v}\right]\left[\frac{1}{\rho_f}\right]\left[\frac{1}{M-1}+\frac{\phi}{1+\phi+\delta}\right]f_{\mathrm{config}}\sigma_f B^2 \tag{1}$$

Baseline multiphysics calculations are performed using a volumetric heating profile for the blanket developed using MCNP. The MCNP model is a 1/16 sector of the full FNSF tokamak with a neutron source representing the source plasma. Reflective boundary conditions are imposed in the toroidal direction to account for the symmetry of the system.

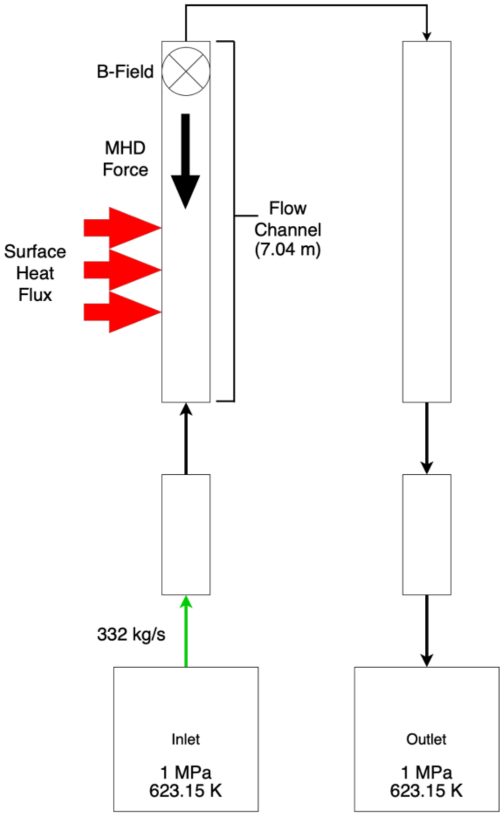

Figure 2 DCLL PbLi Flow Channel Nodalization

The heating profiles are generated by evaluating the heat from neutron interactions and tritium production reactions within the blanket regions at nominal reactor power and the results are averaged in the toroidal direction. We then take the most conservative heating profile at the midplane of the blanket region and apply the constant-shaped radial heating profile as an equivalent heat flux within the PbLi channels. The radial volumetric heating profile developed by the MCNP model is shown in Figure 4. The heating is scaled throughout the transient based on a normalized power curve representative of a startup transient based on a simulated long-term power pulse based on the TORE SUPRA experimental campaign [7, 8] using the code CRONOS. Based on a component-based analysis we performed within MCNP, we also determined that the gamma heating within the blanket is not negligible at ~25% of the total volumetric heating to the blanket. This is incorporated into the heating calculations as an additional scaling parameter of 1.25 for the volumetric heating profile. The relative power curve and transient PbLi channel outlet temperature is shown in Figure 5. Upon simulating the startup, we were able to closely match the design value outlet temperature in the back channel at full power, 823.5 K, as reported in Ref. [4]. The average temperature increase within the He channels was 100 K which also matches the design parameters of the FNSF [4]. The MHD pressure drop across the length of the blanket is 0.017 MPa which was in good agreement with the 3-D MHD pressure drop of 0.013 MPa [4].

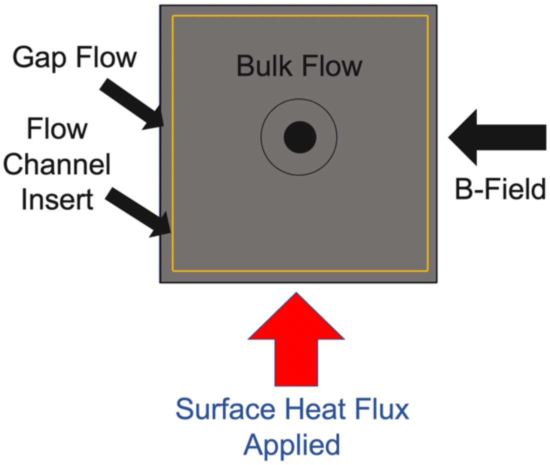

Figure 3 Representative DCLL PbLi Flow Channel Cross Section

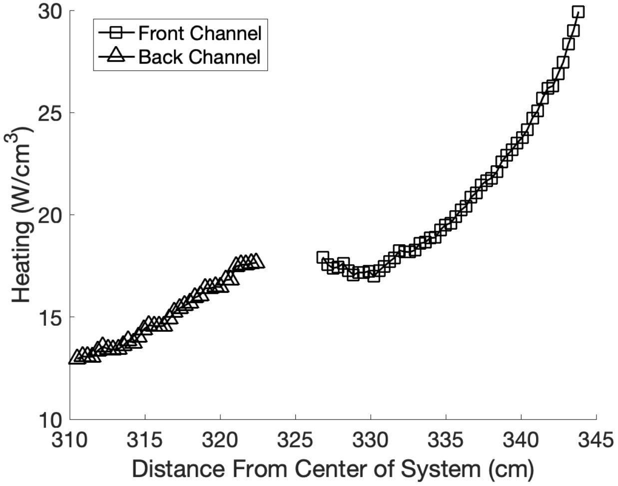

Figure 4 Toroidally Averaged Radial Blanket Heating Profile from MCNP

Future work on this model includes developing a more realistic startup transient that involves a much more gradual increase in power. The current startup transient is not feasible for a reactor such as the FNSF since the material stresses within the blanket region limit the rate of the reactor startup [9-11]. To account for the thermal expansion of the PbLi liquid, the power ramp to 100% power would occur over several incremental steps following the preheating of the channel materials as shown within [9-11]. We also plan to couple MCNP and RELAP5-3D for an iterative multiphysics calculation rather than the currently implemented loosely-coupled multiphysics calculation.

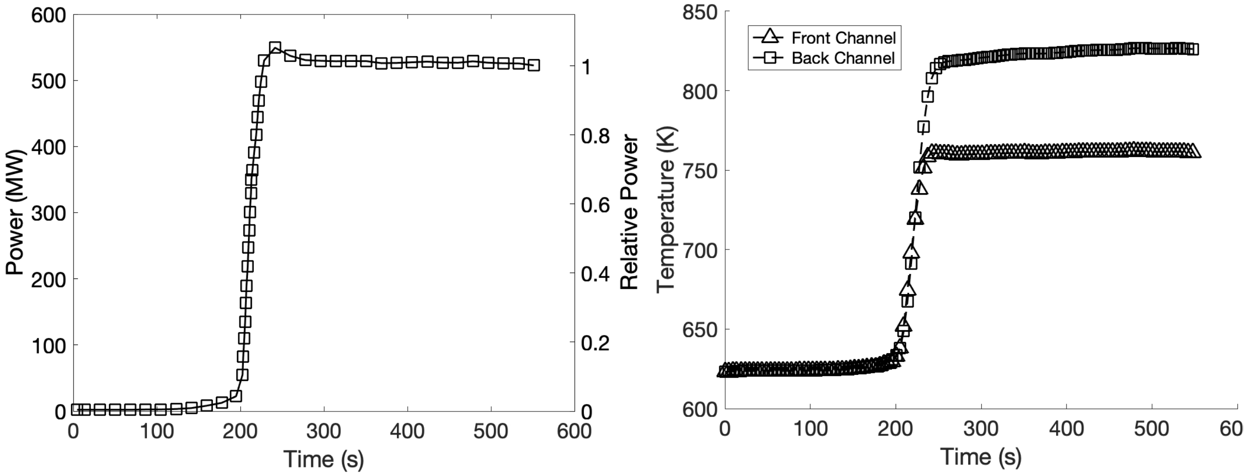

Figure 5 (Left) Power and Relative Power During the Startup Transient (Right) Transient Outlet Temperature of the Front and Back PbLi Channel

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