RELAP-5 Loss of Forced Cooling (LOFC) Transient Response Modeling for the PB-AHTR

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U.C. Berkeley completed the first full RELAP 5 modeling for the 2400 MW(t) Pebble Bed (PB) AHTR with a closed primary loop and separate buffer salt, for the Loss of Forced Cooling (LOFC) transient with scram. The version of RELAP used for the calculations was supplied by Cliff Davis at INL, who has added liquid salt properties to the code. The LOFC results may also apply to other fuel forms used with the closed AHTR primary loop configuration (stringer and prismatic), due to the relatively small contribution of the core pressure drop to the total pressure losses under natural circulation and the small impact of the core heat transfer coefficients on the transient.

Fig. 1 shows an elevation view of the PB-AHTR, showing the primary loop (left side) and PRACS/DRACS decay heat removal system (right side). The primary pumps have been selected to be identical to the existing MSBR pump design, to minimize development work. The PB-AHTR uses metallic Heatric-type compact heat exchangers for the intermediate heat exchangers (IHX). For electricity production, which requires a lower core outlet temperature (710°C, PB-AHTR-E), the IHX modules are constructed from Hastelloy N, a material already ASME code qualified for nuclear applications with liquid salts while for hydrogen production (900°C, PB-AHTR-H) a different high-temperature alloy is required.

Table 1. shows the reference design of the components used in the simulation. Of particular interest are the parameters for the PHX modules, which have a length that is is half of the core height, with the tops of the tubes at the same elevation as the top of the core. This design was selected as the reference design after parametric studies of the sizing of the PHX.

Fig. 2 shows the RELAP 5 model nodalization adopted for the simulations. It includes 4 radial core zones each divided into 12 axial nodes, and a fifth zone modeling the radial reflector and its bypass flow. Because the IHX's have high flow resistance and do not have significant flow after the primary pumps trip, their part of the primary loop is treated as a set of simple inflow/outflow boundaries that precondition the core and PHX's to their normal operating temperatures before LOFC is initiated. Fig. 3 shows the initial, steady-state temperature distribution along the centerline of the core at full power (2400 MW(t)), which provides the initial condition for the transient.

Fig. 4 shows the transient response of the PB-AHTR-E to LOFC for the reference design. Following LOFC, the core outlet temperature rises from the normal outlet temperature (electricity production) of 710°C to a peak temperature of 745°C less than one hour into the transient, and then gradually drops. The average temperature core rises by approximately 25°C, and the core inlet temperature by approximately 20°C. On the buffer salt side some thermal stratification occurs, with the surface of the pool rising from its initial temperature of 550°C to a maximum of approximately 650°C before heat removal by the DRACS balances heat addition by the PRACS.

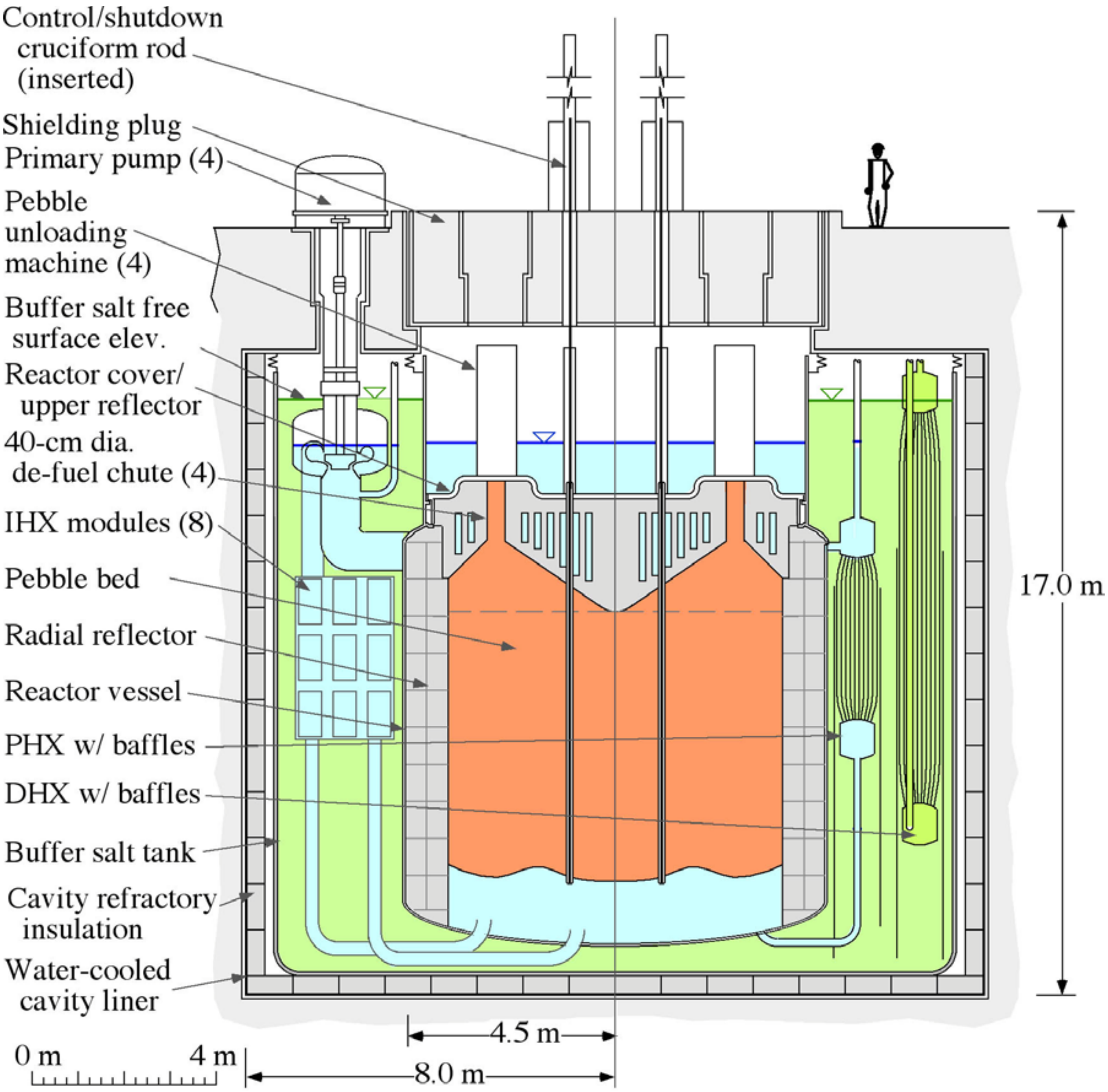

Fig. 1 Elevation view of the PB-AHTR, showing the elevation and height of the current reference PHX design.

Initial parametric studies for the PB-AHTR show that the core outlet, average, and inlet temperature histories can be tuned by adjusting the height of the PHX tubes, the PHX elevation in the buffer salt tank, and the number of PHX tubes. Moving the PHX upward in the buffer salt tank augments the natural circulation mass flow in the primary loop. Increased PHX flow tends to reduce the peak rise in the core outlet temperature, and increase the peak rise in the average coolant temperature.

Table 1 Reference design parameters used in the RELAP-5 model .

Component	Description
2400 MW(t) pebble bed core	L_c = 6.4 m length of the active core region A_c = 36.3 m^2 total flow area $\varepsilon = 0.4$ porosity D_c = 6 cm pebble diameter
PRACS heat exchangers (PHX)	L_{phx} = 3.2 m $A_{phx,p}$ = 1.96 m^2 primary salt flow area $A_{phx,b}$ = 2.94 m^2 buffer salt flow area D_{phx} = 2.5 cm corresponding to 4000 pipes E_{phx} = 3.5 cm pitch between pipes
Pipes connecting the core and PHX	L_p = 0.5 m A_p = 0.126 m^2 D_p = 10 cm corresponding to 16 pipes

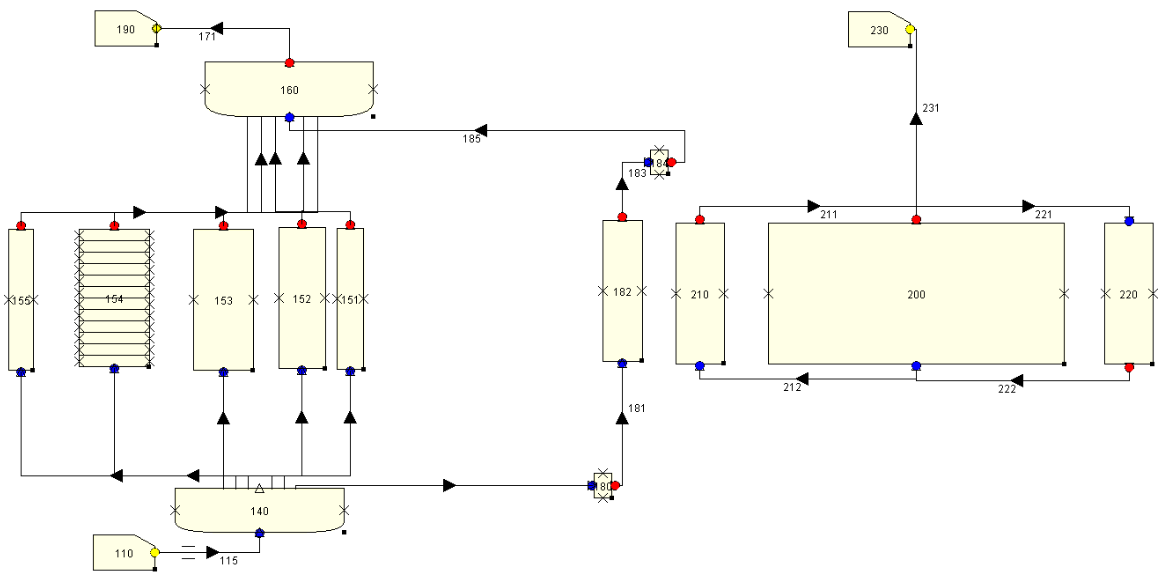

Fig. 2 RELAP-5 nodalization for LOFC transient analysis of the PB-AHTR. (151-154: Core (different radial positions); 155: Reflector; 140-160: Plenums; 181: Fluidic diode; 182: PHX (primary side); 200: Buffer tank; 210: PHX (buffer side); 220: DHX)

Upcoming work will begin to examine reactivity feedback, so that LOFC without scram can be modeled. In this case it will be important to optimize the PHX design parameters to provide a relatively low rise in the core outlet temperature, while allowing the average coolant temperature to rise sufficiently for the reactor to shut down on negative temperature feedback. Different fuel configurations, in particular an "annular pebble" design where kernels are concentrated in an annular layer around an inert graphite center in the pebbles, will also be studied to examine the potential to reduce the fuel stored energy, and the coolant temperature rise required for reactor shutdown based on negative temperature reactivity feedback.

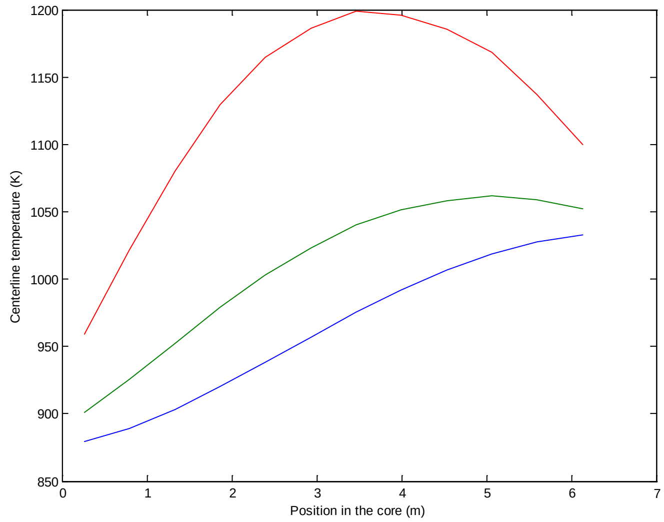

Fig. 3 Initial steady state temperature distribution, in Kelvin, along the centerline of the PB-AHTR core, for the coolant (blue), pebble surface (green) and pebble centers (red).

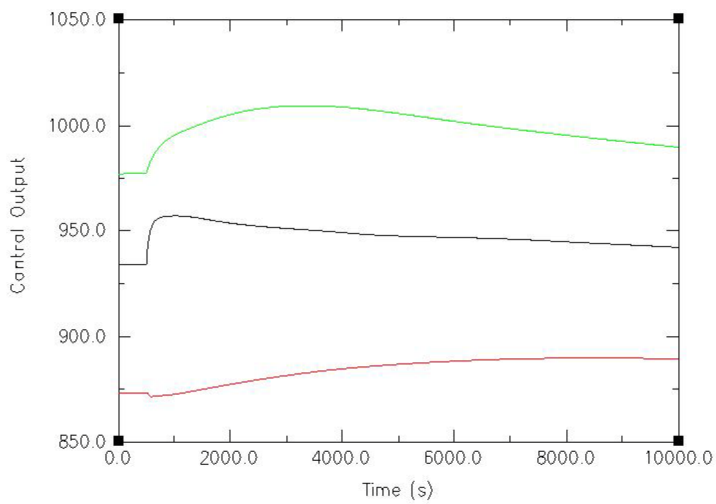

Fig. 4 Transient response of the reference PB-AHTR core inlet (red), average (blue), and outlet temperatures (green), in Kelvin, during a LOFC transient with scram.

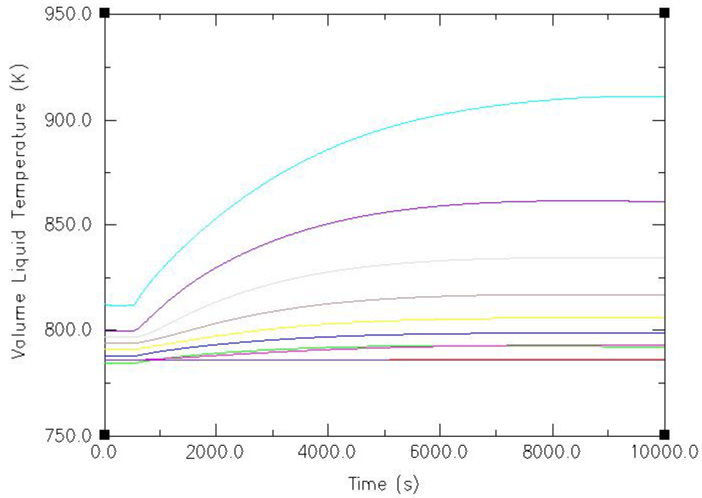

Fig. 5 Transient response of the reference PB-AHTR buffer salt temperature, in Kelvin, at various elevations.

The reference PB-AHTR-H design for hydrogen production has a target core outlet temperature of 900°C, and inlet temperature of 700°C. For the PB-AHTR-H, the goal for the PHX optimization will be to have a very small rise (or even a drop) in core outlet temperature following LOFC, with the average coolant temperature rising sufficiently to provide reactivity shut down due to negative temperature feedback. Preliminary analysis indicates that this PB-AHTR-H goal is achievable.

These preliminary results indicate that the AHTR has a very mild core outlet temperature response to LOFC with scram, consistent with the results of previous thermal hydraulics modeling of earlier AHTR designs. An important conclusion is that the PHX design can be adjusted to tune the relative rise in the core outlet temperature, versus the average primary coolant temperature, following LOFC.

Along with additional RELAP modeling, design work will be performed for a reduced area, reduced height integral effects test (IET) to validate the LOFC transient response model, using low-temperature heat transfer oil as a simulant fluid for the primary salt to match Pr, Re, Gr, Fr and Nu. The goal of the AHTR IET will be to provide an integral experiment capability for AHTR LOFC transients similar to that of the 1:1705 scale Semiscale IET at INL for PWR LOCA transients, at a total cost two orders of magnitude lower than the Semiscale IET.