MODELING AND TRANSIENT ANALYSIS FOR THE MODULAR PEBBLE-BED ADVANCED HIGH TEMPERATURE

A.Niquille, E.Blandford, C. Galvez, and P. Peterson
Department of Nuclear Engineering, University of California, Berkeley
aurelie_niquille@berkeley.edu; edb@berkeley.edu galvezc@berkeley.edu; peterson@nuc.berkeley.edu

ABSTRACT

The Pebble Bed - Advanced High Temperature Reactor (PB-AHTR) is a liquid-salt cooled reactor that uses conventional TRISO fuel. Due to the high thermal inertia of the liquid salt coolant, the PB-AHTR allows for a much higher power-density core than traditional gas-cooled high temperature reactors. High power density has a favorable economic impact. In 2007, the baseline design 2400MWth PB-AHTR was modified to incorporate a modular core with smaller pebbles (between 3 to 4 cm in diameter) flowing inside a large number of separate channels, inside a set of graphite reflector blocks. This configuration has a number of potential advantages over the large, homogenous core that was studied previously. The addition of graphite reflectors allows for a further increase in heavy metal loading, therefore reducing the number of pebbles required and lowering fuel costs and spent fuel volume.

A series of PB-AHTR transients were analyzed using the thermal-hydraulics code RELAP5-3D with the intent of determining an acceptable core power-density range while still meeting criteria for peak fuel and structural material temperatures. The range under consideration (between 15 to 30 MW/m$^3$) is much higher than the power density of a typical gas-cooled reactor core (4.8 to 6.5 MW/m$^3$). The initiating events considered were Loss of Forced Cooling (LOFC) transients as well as an Anticipated Transient Without Scram (ATWS) that consists of a LOFC transient without scram. Results presented in this paper show that the PB-AHTR response to the LOFC is very promising. Peak temperatures during an ATWS are also within the ASME code temperature range for high temperature alloys such as Alloy 800H. Results from parametric studies determining the optimal design for the decay heat removal system and subsequent configurations for the core and pebbles are presented.

1. INTRODUCTION

The Pebble Bed Advanced High Temperature Reactor (PB-AHTR) is an innovative reactor design that uses conventional TRISO high temperature fuel, but with a low-pressure liquid salt coolant rather than high-pressure helium [1]. This paper presents design and analysis information on a modular pebble-fueled variant of the originally conceived AHTR design.

One of the primary advantages of the AHTR includes the ability to operate at higher power density than helium cooled high temperature reactors while achieving comparable power conversion efficiency, which creates the potential for substantial reductions in the plant capital cost. Likewise, the lower neutron leakage provided by the cylindrical PB-AHTR core allows improved fuel utilization, reduced spent fuel generation, and lower fuel cycle costs than those for modular helium reactors.

The earlier PB-AHTR work was on a baseline 2400 MWth PB-AHTR design [2] with a 704°C core outlet temperature, a well understood and qualified fuel (TRISO-based pebble fuel) and available ASME code qualified materials for all high-temperature components (Alloy 800H clad with Hastelloy N), to prevent the need for any materials and fuel development programs. In this work, neutronics simulations [3] demonstrate that negative void reactivity can be achieved by increasing the heavy metal loading of the pebbles and RELAP-3D simulations showed that
the increase of the core outlet temperature was small during a loss of forced cooling (LOFC) transient.

Based on these results, a new configuration is being explored with higher power density between 20 to 30 MW/m$^3$, compared to the typical values of 4.8 to 6.5 MW/m$^3$ for the modular helium cooled reactors. This is achieved by using smaller pebbles (between 3 to 4 cm in diameter). This work presents and analyses a modular design with pebbles located in large numbers of separate channels inside a set of graphite reflector blocks, referred to as Pebble Channel Assemblies (PCAs).

2. THE PEBBLE-BED ADVANCED HIGH TEMPERATURE

2.1. Modular PB-AHTR Design

The Advanced High Temperature Reactor is a high-temperature reactor that uses conventional TRISO coated particle fuel together with a liquid fluoride salt coolant. The flow diagram in Fig. 1 provides a simple overview of the PB-AHTR design. The primary loop is represented by hot and cold legs connecting the core and the Intermediate Heat exchanger (IHX) modules. The annular space between the reactor vessel and the guard vessel is filled with a low-cost buffer salt, sodium fluoroborate, which minimizes primary salt inventory loss if the reactor vessel is faulted.

![Simplified Flow Diagram of the AHTR](image)

Figure 1: Simplified Flow Diagram of the AHTR

The key modifications introduced to develop the 900 MWth, high power density modular design were to switch to smaller pebbles than used in modular helium reactors, and to introduce a large number of separated channels in the core instead of a large cylindrical core configuration. The main advantages of this design include:

- Increase of heavy metal loading in the pebbles due to the moderation provided by the graphite reflectors. This reduces the number of pebbles required and the spent fuel volume.
- Reduction of the coolant void fraction in the core by a factor of 2.
- Creation of locations for insertion of control elements in the solid reflectors

2.2. Initiating Event Selection and Regulatory Design Criteria

Probabilistic Risk Analysis (PRA) methods are used to assess overall plant risk by first predicting the frequency of a particular event occurring and then determining the subsequent consequence(s) or end state of this event. The first component of PRA is beyond the scope of this work; however, assessing the reactor performance and associate consequences of particular events or transients is the main objective of this report. The two transients considered for this paper were selected due to their familiarity in the light water and modular helium reactor licensing landscape.

During a LOFC transient, a natural circulation flow loop is formed between the hot core and a set of Direct Reactor Auxiliary Cooling System (DRACS) heat exchangers (DHX modules). The DRACS heat exchangers transfer heat by natural circulation flow from the primary salt to heat exchangers cooled by outside ambient air. Under forced circulation the bypass flow through the DHX is minimized by a fluidic diode. The LOFC event is typically initiated by a primary pump trip.

In the event of an anticipated transient without scram (ATWS), the reactor is unable to shutdown through conventional means during an anticipated transient. The focus of this event is how the fuel responds during the event without the insertion of reactivity control elements. This event is initiated by a typical reactor trip followed by the failure of the control rod system to function.

In both these events considered, the two key design parameters are the maximum temperature of the fuel and the core outlet temperature. If either of these parameters exceeds design limits, the proposed design may violate governing regulatory design criteria (RDC). Key PB-AHTR RDC affected during these transients includes the need to control heat generation and remove core heat. Fashioned after 10CFR100 Design Criteria for the MHTGR [4], RDC for the PB-AHTR are developed such that top-level regulatory criteria established by the licenser are met. Ensuring the ability to control heat generation in the core and the ability to cool down safety-relate systems, structures and components is essential to assessing plant performance during the analyzed transients.

2.3. RELAP5-3D Modeling

The modeling considers a single hexagonal block core, as is the case for the Pilot Plant, and thus in effect neglects the radial power distribution in the full-scale Modular Plant. The main parameters of the full design and of the modeling are listed in the Table 1.
Integral design
Modular design
One-block modular

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Integral design</th>
<th>Modular design</th>
<th>One-block modular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pebble diameter (cm)</td>
<td>6.0</td>
<td>3.0/4.0</td>
<td>3.0/4.0</td>
</tr>
<tr>
<td>Thermal Power (MWTh)</td>
<td>2400</td>
<td>900</td>
<td>128.6</td>
</tr>
<tr>
<td>Power density in channel (MW/m³)</td>
<td>10.3</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Active height of core (m)</td>
<td>6.4</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Core mass flow rate (kg/s)</td>
<td>9670</td>
<td>3625</td>
<td>518</td>
</tr>
<tr>
<td>Average coolant velocity (m/s)</td>
<td>0.14</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>Bed packing fraction</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
</tbody>
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In the modular design, the complexity of the core configuration requires the use of a few additional modeling approximations. Currently RELAP cannot handle the hexagonal configuration of the channels in the graphite. This led to the approach of approximating the actual core configuration using an annular design with a succession of rings of pebble channels and graphite areas. Because the approximate annular core model contains the same total volume of graphite reflector material and pebble channels as the prototypical system, the model properly reproduces the thermal inertia of these materials in addition to the flow resistance and pressure loss across the core. However, this nodalization generates a distortion in the transient heat transfer between the pebble channels and reflector material.

2.4. Modeling Results

Figures 2 and 3 present results from RELAP5-3D for the LOFC and ATWS transients for the current reference 900-MWth modular PB-AHTR design with 3cm diameter annular pebbles. Figure 2 shows the modular PB-AHTR thermal response to a LOFC transient initiated at 500 seconds. The most important parameter is the coolant outlet temperature, which determines the peak temperature reached by the primary pumps, IHX’s, and DHX’s during the transient. For the PB-AHTR, the LOFC transient is very mild, with the coolant outlet temperature reaching 735°C at 1100 seconds.
Figure 3 shows the transient thermal response of the PB-AHTR to the ATWS transient, where reactor shut down occurs purely by negative fuel and coolant temperature reactivity feedback. As with other liquid cooled reactors, the ATWS transient is among the most severe transients that the reactor can be expected to potentially encounter. In the PB-AHTR, the negative Doppler feedback from the fuel and the negative fuel temperature feedback ultimately drive shutdown for an unmitigated ATWS transient. The maximum fuel temperature in the pebble bed is 1175°C. Even though this value is much larger than the peak temperature under LOFC with SCRAM, a very large margin exists to the TRISO particle failure limit of 1600°C, and the fuel spends only a short time at this temperature. Additionally, the temperature rise of the core outlet is also more severe in the ATWS accident; climbing up to 873°C, which is still below the 900°C Alloy 800H temperature limit in the ASME Section III code case currently being developed by ORNL.
Parametric studies show that several design parameters affect the maximum coolant outlet temperature in an ATWS transient, including the fuel geometry. These studies show that the peak outlet temperature is lower when using smaller pebbles (3 instead of 4cm) and an annular pebble geometry that concentrates fuel particles in an annular layer around an inert center graphite kernel (which results in less pebble stored energy than the homogeneous design). However, with the reactor vessel must be designed to a pressure rating determined by the pressure drop across the core which determines the thickness of the reactor vessel wall. Likewise, fuel particle power limits must be considered. This has led to parametric studies of the Pebbles Channels Assemblies (PCAs) design parameters that affect the core pressure loss and the maximum fuel particle power. By increasing both the flat-to-flat dimensions of the PCAs and the diameter of the channels, lower pressure drops and lower fuel particle peak power can be attained. Further design optimization will be carried out during the coming year.

3. CONCLUSIONS

This study shows that much higher power densities are attainable with the modular PB-AHTR baseline design than with helium gas cooled reactors or with the integral AHTR. The 900-MWth modular design has proven to be a viable choice. The LOFC transient is very mild with the peak core outlet temperatures never exceeding 750ºC. The ATWS transient has the potential to be more severe but the temperatures reached are within the code range for high temperature alloys such as Alloy 800H. The impacts of several parameters have been studied to optimize the design both in terms of peak temperatures during transients and pressure drops across the core. Near-term R&D for the PB-AHTR will focus in part on an integral experiment to confirm RELAP5-3D results for the LOFC transients, and also on the modeling of the closed primary loop to study pump trip, reverse flows and intermediate loop trips.
REFERENCES