Thermal hydraulics analysis of the Advanced High Temperature Reactor

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HIGHLIGHTS

- The TRACE AHTR model was developed and used to define and size the DRACS and the PHX.
- A LOFF transient was simulated to evaluate the reactor performance during the transient.
- Some recommendations for modifying PHR reactor system component designs are discussed.

ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form 11 August 2015
Accepted 15 August 2015

ABSTRACT

The Advanced High Temperature Reactor (AHTR) is a liquid salt-cooled nuclear reactor design concept, featuring low-pressure molten fluoride salt coolant, a carbon composite fuel form with embedded coated particle fuel, passively triggered negative reactivity insertion mechanisms, and fully passive decay heat rejection. This paper describes an AHTR system model developed using the Nuclear Regulatory Commission (NRC) thermal hydraulic transient code TRAC/RELAP Advanced Computational Engine (TRACE). The TRACE model includes all of the primary components: the core, downcomer, hot legs, cold legs, pumps, direct reactor auxiliary cooling system (DRACS), the primary heat exchangers (PHXs), etc. The TRACE model was used to help define and size systems such as the DRACS and the PHX. A loss of flow transient was also simulated to evaluate the performance of the reactor during an anticipated transient event. Some initial recommendations for modifying system component designs are also discussed. The TRACE model will be used as the basis for developing more detailed designs and ultimately will be used to perform transient safety analysis for the reactor.

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1. Introduction

The Advanced High Temperature Reactor is a molten salt cooled reactor design concept, which is intended to safely, efficiently and economically produce large amounts of electricity with minimal impact on the environment. The AHTR features low pressure molten fluoride salt coolant, a carbon–carbon composite fuel form featuring compacts of coated particle fuel, and fully passive decay heat rejection. An initial baseline mechanical design has been established based on preliminary core design studies (Varma et al., 2012), and system dynamics studies (Holcomb et al., 2011). It should be noted that the AHTR design is only at a preconceptual level of maturity and may be subject to significant revision during the development process.

Overall AHTR design objectives include:

- Plant operational life of at least 60 years,
- Net thermal efficiency of 45%,
- Plant availability of 92%,
- Essential safety features do not require operator action at any time,
- Construction time less than 36 months,
- All components transportable by rail or air,
- Levelized unit cost of electricity lower than competing technologies.

In order to achieve these goals, a molten salt coolant and coated particle fuel form have been selected which allow the reactor to operate at higher temperatures than conventional light water reactor (LWR) designs and enable fully passive decay heat rejection and reactor shutdown. The baseline AHTR design is a 3400 megawatt thermal (MWth) concept with a net electrical power rating of
1530 MWe assuming that 45% efficiency is achieved. The reactor uses carbon composite fuel assembly structures with embedded tristructural isotropic (TRISO) particle fuel that includes a uranium oxycarbide (UCO) kernel enclosed in a layer of pyrolytic graphite, a silicon carbide cladding layer, and another layer of pyrolytic graphite. The primary heat transfer fluid is 2LiF–BeF₂, commonly known as FLiBe. Alternate salts may be used for the intermediate heat transfer system and the direct reactor auxiliary cooling system (DRACS) which transfers decay heat directly to the atmosphere. AHTR heat transfer loops are illustrated in Fig. 1, and key parameters are described in Table 1.

This paper discusses one key technology area required to further define and develop the AHTR: the thermal hydraulic performance of the core and primary system. Up to this point, only scoping analysis has been performed to assist in the other supporting AHTR design activities. Although these calculations represent only the initial phases of thermal hydraulic analysis for this reactor, they will be used to provide feedback to other design features needed as this design advances. This analysis uses the information provided in (Varma et al., 2012; Holcomb et al., 2011), as a basis for developing thermal hydraulic models of the AHTR reactor. For this preliminary thermal hydraulic assessment, an AHTR system model was developed using the Nuclear Regulatory Commission (NRC) thermal hydraulic transient code TRAC/RELAP Advanced Computational Engine (TRACE) (U.S. NRC, 2012). For modeling fluoride salt–cooled reactors, four new liquid salt working fluids, LiF–BeF₂, NaF–ZrF₄, LiF–NaF–KF, and KF–ZrF₄, were recently added into TRACE (Richard et al., 2014). The TRACE model includes all of the primary components: the core, downcomer, hot legs, cold legs, pumps, the DRACS, the primary heat exchangers (PHXs), etc. The TRACE model was used to help define and size systems such as the direct reactor auxiliary cooling system (DRACS) and the PHX. A loss of flow transient was also simulated to evaluate the performance of the reactor during an anticipated transient event. Some initial recommendations for modifying system component designs are also discussed. The TRACE model will be used as the basis for developing more detailed designs and ultimately will be used to perform transient safety analysis for the reactor.

A complete compendium of the needs and requirements for AHTR thermal hydraulic analysis was presented in the AHTR roadmap report (Holcomb et al., 2013). The analysis presented here is the first step in progressing along that path. The work described in this paper provides initial investigation into AHTR thermal hydraulics. It serves as a starting point for additional studies needed to advance the AHTR thermal hydraulic design.

### 2. TRACE modeling

This section documents the development of a TRACE plant system model for the AHTR, including the reactor vessel, three primary coolant loops, and three DRACS. The TRACE AHTR model developed has been employed to optimize the component design and investigate system safety performance of the AHTR. The development of the TRACE AHTR model is largely based on the design characteristics and parameters presented in (Varma et al., 2012) which are intended to be useful for concept evaluation but do not reflect the optimization necessary to form a realistic design.
The development of the AHTR design is still at the early preconceptual stage. An initial candidate mechanical design of the reactor fuel and core was produced in 2012 (Varma et al., 2012). However, the 2012 effort lacked almost any details in the design of the DRACS system and primary and intermediate loops and the power cycle. One objective of the TRACE AHTR model development is to design and optimize system components where necessary based on system performance. For example, the DRACS system has been redesigned and optimized based on performance during a loss of forced flow (LOFF) transient. For the DRACS heat exchanger and air cooler components, the correlations of the shell-side heat transfer and pressure drop are implemented in the TRACE model. In addition, a preliminary design of the primary heat exchanger has been developed.

The TRACE AHTR model is shown in Fig. 2. The three DRACS loops are explicitly modeled. The DRACS heat exchanger (DHX) is a tube-shell design with three passes in the tube side. In this model, the intermediate loops and steam lines are not included.

The major TRACE components are discussed and described below.

2.1. Reactor vessel and internal components

The reactor vessel is cylindrical with a height of ~19 m and an inside diameter of 10.4 m, as shown in Fig. 3. The vessel wall is made of 800H with Hastelloy N cladding and a clad thickness is 0.05 m. The core barrel made of C–C composite, has an internal diameter (ID) of 9.6 m, and a thickness of 0.03 m. The reactor vessel is modeled in TRACE with 36 axial levels (#1 at the bottom of the vessel and #36 at the top), three radial rings, and eight azimuthal sectors. The two inner rings (1 and 2) are the core region. The radius

Fig. 2. TRACE SNAP model of AHTR.

Fig. 3. Sectional view of the reactor vessel.
of ring 1 is 2.76614 m and the radius of ring 2 is 4.83 m. The outermost ring 3 is the downcomer region. The core ranges from levels 6 through 17. The three DRACS heat exchangers (HXs) are located between levels 24 and 29 in three azimuthal sectors of ring 3. The primary loop cold legs are connected to the reactor vessel level 31, and the hot legs are connected to level 33.

The reactor core consists of 252 fuel assemblies supported by the upper and lower support plates. The geometric dimensions of a fuel assembly are shown in Fig. 4. The fuel assembly is a 6-m tall hexagonal prismatic box with 1-cm-thick walls made of C–C composite. The interior channel of the fuel box is divided into three symmetric regions by a 4-cm-thick Y-shaped structure, also made of C–C composite. In each of the three regions there are six fuel plates. The gap between the fuel plates forms the coolant flow path. More details of the fuel plate design can be found in (Varma et al., 2012). The core region is modeled with two radial rings in the TRACE model. The inner ring consists of 127 fuel assemblies, and the outer ring has 125 fuel assemblies.

2.2. Primary loops

The AHTR has three primary coolant loops, each consisting of the primary piping, the primary heat exchanger, and the primary salt pump, as shown in Fig. 5. The FLiBe salt mass flow rate of each loop is 9500 kg/s. The design temperature drop through the primary heat exchanger is 50 K. In the TRACE model, the hot leg length is 15.75 m, and the cold leg length is 9.37 m. Both the hot and cold legs have the same inside diameter of 1.29 m.

Table 2
PHX design parameters and coolant thermal properties.

<table>
<thead>
<tr>
<th></th>
<th>Primary loop</th>
<th>Intermediate loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt 1</td>
<td>Salt 2</td>
<td></td>
</tr>
<tr>
<td>Coolant salt</td>
<td>2LiF–BeF₂</td>
<td>KF–ZrF₄</td>
</tr>
<tr>
<td>HX inlet temp. (K)</td>
<td>973</td>
<td>873</td>
</tr>
<tr>
<td>HX outlet temp. (K)</td>
<td>923</td>
<td>948</td>
</tr>
<tr>
<td>Coolant flow rate (kg/s)</td>
<td>9500</td>
<td>14,400</td>
</tr>
<tr>
<td>Coolant density* (kg/m³)</td>
<td>1950</td>
<td>2850</td>
</tr>
<tr>
<td>Coolant viscosity* (Pas)</td>
<td>0.00609</td>
<td>0.00522</td>
</tr>
<tr>
<td>Coolant conductivity* (W/m K)</td>
<td>1.1</td>
<td>0.42</td>
</tr>
<tr>
<td>Coolant specific heat capacity* (J/kg K)</td>
<td>2416</td>
<td>1051</td>
</tr>
<tr>
<td>Coolant Pr²</td>
<td>13.32</td>
<td>12.95</td>
</tr>
</tbody>
</table>

* Evaluated at average temperature.

2.3. Preliminary heat exchanger design and modeling

The PHX is a tube-and-shell design. For simplicity, one pass is employed for both shell and tube sides. The temperature change and coolant thermal properties of the PHX design are given in Table 2.

A Microsoft Excel spreadsheet for the tube-and-shell HX design was developed according to Kern’s method (Kern, 1950). This method is based on experimental work on commercial exchangers and will give a reasonably satisfactory prediction of the heat transfer coefficient for standard designs. The pressure drop prediction is less satisfactory since pressure drop is more affected by leakage and bypass than heat transfer (Towler and Sinnott, 2007). The shell-side heat transfer factor (jₙ) and the friction factor (jᵢ) as a function of the Reynolds number (Re) are implemented in the spreadsheet HX model. The tube-side heat transfer coefficient is calculated based on the Gnielinski correction, and the friction factor is calculated using the McAdams correlation.

In the PHX design, the first decision is fluid allocation on the shell or tube sides. In general, there are a few factors in determining the allocation of the fluid streams to the shell or tube side (e.g., corrosion, fouling, fluid temperatures, operating pressures, pressure drop, viscosity, flow rates, etc.) (Towler and Sinnott, 2007). Table 3 summarizes major parameters of the three PHX design options examined based on the spreadsheet HX model. Option 1 has the primary loop on the tube side and the intermediate loop on the shell side. Option 3 uses FLiNaK as the coolant for the intermediate loop. It shows that Option 2 is better than Option 1 in terms of the size of the heat exchanger and the PHX pumping power. However, if the FLiNaK salt is used for the intermediate loop, the PHX pumping power of Option 3 is almost half that of Option 2. It should be noted that the PHX designs are very preliminary, and further study is needed to develop an optimum design.

In the TRACE model, Option 2 has been implemented for the PHX. The control systems are developed to calculate the heat transfer coefficient and friction factor for the shell side of the PHX based on the correlations given in (Towler and Sinnott, 2007).

2.4. DRACS design and modeling

Decay heat removal is provided by three DRACS cooling loops. A schematic drawing of the DRACS loops is shown in Fig. 6. The DRACS is a fully passive safety system. The salt KF–ZrF₄ is used as the working fluid for the DRACS loops. The flow in each intermediate DRACS loop is driven by the gravity head difference between the hot leg and cold leg of the DRACS, taking heat from the primary loop through the DRACS HX and transferring it to the atmosphere by the air cooler installed at the bottom of each DRACS cooling tower. All heat transfer in the DRACS system occurs through conduction and natural convection.
Table 3
PHX design options.

<table>
<thead>
<tr>
<th></th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
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<tbody>
<tr>
<td>Tube</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loop allocation</td>
<td>Primary</td>
<td>Interim.</td>
<td>Interim.</td>
</tr>
<tr>
<td>Coolant salt</td>
<td>FLiBe</td>
<td>KF-ZrF₄</td>
<td>KF-ZrF₄</td>
</tr>
<tr>
<td>Tube length (m)</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube OD (m)</td>
<td>0.019735</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube wall thickness (m)</td>
<td>0.001245</td>
<td></td>
<td></td>
</tr>
<tr>
<td># of tubes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube pitch (m)</td>
<td>1.5 OD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube arrangement</td>
<td>Square</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell inside diameter (m)</td>
<td>5.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baffle spacing (m)</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baffle cut</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTC (W/m² K)</td>
<td>2853.3</td>
<td>2530.5</td>
<td></td>
</tr>
<tr>
<td>Pressure drop (Pa)</td>
<td>2.10E+04</td>
<td>3.55E+04</td>
<td></td>
</tr>
<tr>
<td>PHX Pumping power (MW)</td>
<td>0.10</td>
<td>0.18</td>
<td></td>
</tr>
</tbody>
</table>

* Heat transfer coefficient

Fig. 6. Schematic drawing of the DRACS loops.

Table 4
Preliminary design parameters of DHX.

<table>
<thead>
<tr>
<th></th>
<th>DHX design</th>
<th>Shell and tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube arrangement</td>
<td>Staggered</td>
<td></td>
</tr>
<tr>
<td>Primary side</td>
<td>Shell</td>
<td></td>
</tr>
<tr>
<td>DRACS side</td>
<td>Tube</td>
<td></td>
</tr>
<tr>
<td># of tubes</td>
<td>1078</td>
<td></td>
</tr>
<tr>
<td># of tube rows</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td># of tube passes</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Tube length (m)</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Tube OD (m)</td>
<td>0.0254</td>
<td></td>
</tr>
<tr>
<td>Tube wall thickness (m)</td>
<td>1.651E–3</td>
<td></td>
</tr>
<tr>
<td>Tube material</td>
<td>Hastelloy N</td>
<td></td>
</tr>
</tbody>
</table>

The preliminary design parameters of the DHX are summarized in Table 4. The DRACS air cooler (DAC) plays an important role in passive decay heat removal. Decay heat is transferred out of the DRACS by natural convection air flow passing through the DAC outside surface. Because of the low volumetric heat capacity of the air, it requires a large flow rate to efficiently remove decay heat from the DAC. However, the flow rate is determined by the balance between the pressure drop through the DAC and the available buoyancy driving head in the air tower. In addition, the temperature change through the DAC should not be too high in order to prevent significant thermal impact on the DAC structure. The TRACE system model has been employed to perform design optimization of the DAC by varying a few design parameters such as circular fin height and spacing, number of tubes, and tube size. The preliminary design parameters of the DAC are given in Table 5.

2.4.1. An analytical approach to optimizing the DRACS design

In order to have a better understanding of the natural circulation flow in the DRACS and obtain insights about the design of the DRACS loop, it would be helpful to perform a simplified theoretical analysis of the DRACS natural circulation flow. A schematic drawing of the DRACS loop is shown in Fig. 7.

For a given constant heat load, it is assumed that the flow in the DRACS eventually stabilizes at a constant flow rate, that is, the loop pressure drop will be balanced by the buoyancy driving head, \( \Delta P_f = \Delta P_B \). The total pressure drop along the DRACS loop and the buoyancy head are calculated in the following two equations (1) and (2), respectively. Note that the pressure drop due to form loss is not considered since they are negligible as compared with friction loss.

\[
\Delta P_f = \left( \frac{f L \rho v^2}{D^2} \right)_{CL} + \left( \frac{f L \rho v^2}{D^2} \right)_{DL} + \left( \frac{f L \rho v^2}{D^2} \right)_{DHX} + \left( \frac{f L \rho v^2}{D^2} \right)_{DAC}
\]

\[
\Delta P_B = \beta \Delta T g L_2 = \beta \frac{\dot{Q}}{mc_P} g L_2
\]
where

\[ CL = \text{DRACS cold leg}; \]
\[ HL = \text{DRACS hot leg}; \]
\[ DHX = \text{DRACS heat exchanger}; \]
\[ DAC = \text{DRACS air cooler}; \]
\[ a = 0.184; \]
\[ n = 0.2 \text{ for turbulent flow}; \]
\[ L = \text{pipe length}; \]
\[ D = \text{pipe diameter (hydraulic diameter)}; \]
\[ A = \text{flow area}; \]
\[ \mu = \text{fluid viscosity}; \]
\[ m = \text{mass flow rate}; \]
\[ \bar{\rho} = \text{average density}. \]

\begin{align*}
  b &= \left[ a \left( \frac{D}{\mu A} \right)^{-n} \frac{L}{D} \frac{1}{2A^2} \right]_{CL} + \left[ a \left( \frac{D}{\mu A} \right)^{-n} \frac{L}{D} \frac{1}{2A^2} \right]_{HL} \\
  &+ \left[ a \left( \frac{D}{\mu A} \right)^{-n} \frac{L}{D} \frac{1}{2A^2} \right]_{DHX} + \left[ a \left( \frac{D}{\mu A} \right)^{-n} \frac{L}{D} \frac{1}{2A^2} \right]_{DAC} \tag{3}
\end{align*}

\( Q = \text{heat load}; \)
\( L_2 = \text{elevation change between DAC and DHX}; \)
\( \beta = -\left( \frac{\partial \rho}{\partial T} \right)_p = \text{temperature coefficient of the salt density, e.g., } \beta = 0.887 \frac{\text{kg}}{\text{m}^3 \cdot \text{K}} \text{ for KFZrF}_4; \)
\( g = \text{gravity constant}. \)

From Eqs. (1) and (2), the mass flow rate can be computed as

\[ \dot{m} = \left( \frac{\beta \rho g L_2}{b c_p} \right)^{1/(3-n)} \dot{Q}^{1/(3-n)} = d \dot{Q}^{1/(3-n)} \tag{4} \]

where \( d = \left( \frac{\beta \rho g L_2}{b c_p} \right)^{1/(3-n)} = \text{flow coefficient}. \)

Eq. (4) implies that the natural circulation flow rate in the DRACS loop is dependent on the overall flow coefficient \( d \), which is also a function of loop friction coefficient \( b \). So this equation can be used to optimize the DRACS design.

In order to obtain favorably high mass flow rate, the overall friction coefficient \( b \) should be reduced as much as possible. As shown in Eq. (3), the overall friction coefficient \( b \) consists of four friction loss contributors: cold leg, hot leg, DHX, and DAC. The friction losses through the DHX and DAC can be estimated based on their design parameters. The lengths of the cold and hot legs of the DRACS are estimated to be 35 m. Now the question is what is the diameter for the hot and cold legs? For this exercise the cold leg and hot leg are assumed to have the same diameter.

The total flow coefficient as a function of the diameter of the hot and cold legs is shown in Fig. 8. It is seen that the total coefficient \( d \) becomes insensitive to the diameter of the hot and cold legs when it is larger than 0.35 m, which means the friction loss in the hot and cold legs become relatively small relative to the losses in the tubes of the DHX and DAC. In the model, the diameter of 0.4 m is used for both hot and cold legs of the DRACS.

2.4.2. TRACE model of DRACS

The DHX consists of 1078 tubes configured in three tube passes. Each pass is modeled with two pipe components. Each pipe component models 179 or 180 tubes. The pressure drop and heat transfer coefficient of the DHX shell side are calculated by the control logic systems developed based on the empirical correlations for cross flow. The DAC employs one pass for the tubes, which are modeled with four pipe components. Each pipe models 50 tubes. The air cooling towers are modeled with TRACE vessel components. The height of each vessel component is 12.92 m with the radius of 3 m. The vessel components have two radial rings and 18 axial levels. The inside ring has the radius of 2.5 m, and the outside ring provides the downward flow path for the incoming cooling air. The DACs are located at the bottom of the air cooling towers (Level 3–6). The pressure drop and heat transfer coefficient of the DAC shell side are calculated by the control logic systems developed based on the empirical correlations for finned tube cross flow. A surface multiplier is applied to the shell side in accounting for the total area of the finned tubes.

2.5. Fuel plate modeling and decay power

A fuel assembly consists of 18 fuel plates. TRISO fuel particles are dispersed in the carbon composite stripes, which are located very close to the fuel plate surface. In this model, the TRISO fuel is analyzed assuming SiC properties. This assumption has little effect on plate thermal performance. With this fuel design, the fuel operates at a relatively low temperature with a flat profile. Therefore, the fuel temperature is not very sensitive to fuel thermal conductivity, which is very favorable from a safety point of view since it
will largely reduce initial stored energy. In the TRACE model, the fuel plates are modeled with the slab component. The fuel plates are divided into 12 axial nodes, which are coupled to the hydraulic flow channels in the reactor vessel. The fuel stripe region is modeled with SiC, and the central matrix is modeled with graphite. Each slab component has a surface multiplier to account for all of the fuel plates in that sector.

A typical pressurized water reactor (PWR) decay power curve is used for the TRACE AHTR model since the actual decay curve for the AHTR core is not available at this writing.

2.6. Shell-side heat transfer and pressure drop correlations for DHX and DAC

Each DHX consists of 1078 small tubes horizontally configured in 98 rows, and is located in one of the downcomer sectors. The DHX tubes are configured in a staggered array. Each DAC consists of 200 small finned tubes horizontally configured in four rows at the bottom of each air cooling tower, and the DAC tubes are configured in an inline fashion.

The heat transfer and pressure drop correlations on the shell side of the DHX and DAC are summarized in Appendices A and B (Gaddis and Gnielinski, 1985; Kakac et al., 1987), which are developed and implemented in the TRACE model using the control system components (e.g., signal variables, control blocks, tables).

3. Simulations

Calculations of steady state and a LOFF transient were carried out with the TRACE AHTR model. The steady-state simulation was performed to obtain initial conditions for the transient simulation. In the LOFF transient, all the primary coolant pumps are assumed to fail at the beginning of transient without any pump coastdown.

3.1. Steady-state

Table 6 summarizes the calculated steady-state conditions of the AHTR. It shows that TRACE calculated core inlet and outlet temperatures are in very good agreement with the AHTR design values. During normal operation a small amount of salt flows upward through the shell-side of the DHXs. However, the calculated DHX reverse flow is only about 3.9% of the total core flow rate. This indicates that the heat loss through the DRACs during normal operation is insignificant. Nevertheless, some amount of heat is needed to prevent freezing during normal operation. 3.9% bypass will set the DRACs loop insulation requirements.

3.2. Loss of forced flow

The LOFF transient was simulated to evaluate the DRACs design and its safety performance. In this transient, the DRACs is the only means available for decay heat removal. Fig. 9 illustrates TRACE animation snapshot. Fig. 10 plots the maximum fuel plate surface temperature.

Before the transient occurs (\(t=0\) s), the reactor system is assumed to be running at normal operating conditions. The core average coolant velocity was 1.93 m/s, and the calculated core Reynolds number \(Re\) was about 7400, so the core flow was in the turbulent regime. The DRACs coolant circulated at a speed of 1 m/s, with the mass flow rate at about 351 kg/s in each loop.

![AHTR LOFF animation](image)

**Fig. 9.** TRACE animation of AHTR LOFF (\(t=60,000\) s).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AHTR design values</th>
<th>TRACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated thermal power (MWt)</td>
<td>3400</td>
<td>3400</td>
</tr>
<tr>
<td>Core flow</td>
<td>28,500</td>
<td>28,500</td>
</tr>
<tr>
<td>Relative DHX shell side flow*</td>
<td>N/A</td>
<td>3.9%</td>
</tr>
<tr>
<td>Core Inlet temperature (K)</td>
<td>923</td>
<td>924</td>
</tr>
<tr>
<td>Core outlet temperature (K)</td>
<td>973</td>
<td>974</td>
</tr>
<tr>
<td>Core pressure drop (Pa)</td>
<td>N/A</td>
<td>1.903E+5b</td>
</tr>
<tr>
<td>DRACs loop flow rate (kg/m²)</td>
<td>N/A</td>
<td>351</td>
</tr>
<tr>
<td>DRACs hot leg temperature (K)</td>
<td>N/A</td>
<td>893</td>
</tr>
<tr>
<td>DRACs cold leg temperature (K)</td>
<td>N/A</td>
<td>859</td>
</tr>
</tbody>
</table>

* Relative to total core flow.

b Friction loss (62,900 Pa) + form loss through lower and upper core support plates (6300 Pa) + gravity head (121,100 Pa).
When the transient occurs, the three primary coolant pumps are shut down at time 0 s, resulting in an immediate reduction of core flow, and the reactor is shut down immediately, as well. Within a few seconds, the DHX shell side flow reverses from upwards to downwards, and natural circulation flow is established in the reactor vessel thereafter. The core starts to heat up.

At about 700 s into the transient, the coolant temperature reaches the maximum value 1040 K at the exit of the core as presented with the red curve on the top right plot in the figure (note that the blue curve is the core inlet coolant temperature, and the green curve is the coolant temperature at the top of the DHXs). After that, the coolant begins to gradually cool down as the decay heat decreases. The hot FLiBe coolant moves upwards through the core under natural circulation and mixes with the relatively cooler coolant in the guide tube region. The peak temperature seen by the tubes of the DHXs is about 996 K (green curve). Fig. 9 shows that after 5 h into the transient, the primary coolant temperature drops below 973 K (the nominal core outlet temperature). In a general, the system temperatures and core flow decrease as the decay heat continues decreasing.

The peak air temperature of the DAC exit during the transient reaches 650 K. The air inlet temperature is 303 K. Note that the nominal DAC exit air temperature is about 624 K. Such a significant temperature change of >300 K through the DAC poses some concern about its thermal impact on the DAC structure. Therefore, further study on the DAC system design is needed.

The maximum fuel plate surface temperature is predicted as shown in Fig. 10, which shows that the peak temperature of the fuel surface is about 1050 K, which occurs at 701 s. It should be noted that the fuel temperature profile is very flat inside the fuel plate, and the centerline temperature is close to the plate surface temperature because of its very unique fuel stripe design in which the fuel is placed near the plate surface. TRACE would tend to over predict the fuel plate surface temperature for this transient because the code does not have the HTC correlation for the narrow rectangular channel, which generally has higher HTC than the circular flow channel when the flow is laminar.

4. Summary and concluding remarks

A TRACE ATHWR system design has been developed to analyze the safety performance of the AHTR. The TRACE model is a detailed representation of the AHTR plant system, including the reactor core, reactor vessel, three primary loops, and three DRACS loops. The TRACE model consists of 124 hydraulic components, 206 control components (signal variables, control logic blocks, trips, and tables), 117 heat structures, and 1 power component. The intermediate loops, steam generators, and steam lines will be developed in the future.

The empirical correlations of heat transfer and pressure drop for the shell side of the DHX and DAC have been implemented in the TRACE model using TRACE control systems. The TRACE model has been employed to do an initial optimization of the DRACS design. A study on the PHX design has been performed and preliminary design characteristics are discussed. A steady-state calculation was carried out and the calculated initial conditions are in very good agreement with the nominal design values. A loss of forced flow transient was simulated, and the results show that the DRACS can effectively remove all decay heat from the primary loop under this extreme accident scenario.

Based on the study, some concluding remarks are summarized as follows:

1. In the DHX preconceptual design, a fluidic diode is installed underneath the DHX to limit the coolant flow through the DHX tubes during normal operation. The calculation shows that the reverse flow rate is only about 3.9% of the total core flow rate, and at least for this design, a fluidic diode may not be necessary. Additional design trade studies will be needed to confirm this as a general conclusion. In addition, it should be mentioned that there exists the potential for encapsulating the natural draft heat exchangers on the DRACS loops during normal operation to prevent tritium escape into the environment. Without the encapsulation, the DRACS would be a potentially significant tritium escape route. Upper and lower flaps on the heat exchanger would open upon heat up (or loss of power).

2. The primary heat exchanger employs a simple tube-and-shell type design. The primary side of the heat exchanger is FLiBe, and the intermediate side of the heat exchanger is a less expensive salt. A preliminary analysis of the PHX design shows that FLiNaK performs much better than KF–ZrF₄ as an intermediate coolant in terms of theHX size and the pressure drop through the heat exchanger. The FLiBe – FLiNaKHX requires only 60% the number of tubes of the FLiBe – KF–ZrF₄HX, and the pumping power for the FLiBe – FLiNaKHX is only about half that of the FLiBe – KF–ZrF₄HX. However, the reason that KF–ZrF₄ is being considered for the AHTR is to avoid the potential expense resulting from inadvertent mixing of lithium isotopes due to a heat exchanger tube leak.

3. If the primary coolant system is not pressurized, the primary pumps should be installed on the hot legs instead of cold legs because of the significant pressure drop through the primary heat exchangers.

4. Although not discussed in this paper, a sensitivity study was performed to investigate the effect of pump coastdown on core heatup during the LOFF transient. It was found that a short period of pump coastdown can effectively reduce the coolant peak temperature at the very beginning of the accident. Therefore, it is suggested that a fly-wheel be considered for the primary and intermediate pumps.

5. The correlations of heat transfer and pressure drop for the HX shell side cross flow should be further investigated. Perhaps experimentation is needed for a specific HX design.

6. The predicted HTC values for fluoride salts show large discrepancies when different correlations are used since the fluoride salts have relatively large Pr numbers (~13). For example, Fig. 11 shows that the Dittus–Boelter correlation would significantly underpredict HTC, but the Petukhov–Popov correlation (Petukhov, 1970) would overpredict HTC as compared with the Gnielinski correlation. It is recommended that the Gnielinski correlation be used for AHTR analysis.

7. In addition, the HTC correlation for the rectangular flow channel for both laminar and turbulent flow regimes should be implemented in the TRACE code in the future.
Fig. 11. Comparison of heat transfer correlations.

Acknowledgments

This manuscript has been authored by UT-Battelle LLC under Contract No. DE-AC05-00OR22725 with the US Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

Appendix A. Heat transfer and pressure drop correlations for DHX

Each DHX consists of 1078 small tubes, horizontally configured in 98 rows. Each DHX is located in one of the downcomer sectors. The tubes are configured in a staggered fashion. The heat transfer and pressure drop correlations on the shell side are summarized as follows (Gaddis and Gnielinski, 1985).

A.1. Heat transfer correlation for staggered tube bundle

\[
\text{Nu} = 1.04 \text{Re}^{0.4} \text{Pr}^{0.36} \left( \frac{\text{Pr}}{\text{Pr}_{\text{w}}} \right)^{0.25} \quad 1 \leq \text{Re} < 5 \times 10^2
\]

\[
\text{Nu} = 0.71 \text{Re}^{0.5} \text{Pr}^{0.36} \left( \frac{\text{Pr}}{\text{Pr}_{\text{w}}} \right)^{0.25} \quad 5 \times 10^2 \leq \text{Re} < 10^3
\]

\[
\text{Nu} = 0.35 \left( \frac{X_t}{X_l} \right)^{0.2} \text{Re}^{0.6} \text{Pr}^{0.36} \left( \frac{\text{Pr}}{\text{Pr}_{\text{w}}} \right)^{0.25} \quad 10^3 \leq \text{Re} < 2 \times 10^5
\]

\[
\text{Nu} = 0.031 \left( \frac{X_t}{X_l} \right)^{0.2} \text{Re}^{0.8} \text{Pr}^{0.36} \left( \frac{\text{Pr}}{\text{Pr}_{\text{w}}} \right)^{0.25} \quad 2 \times 10^5 \leq \text{Re} < 2 \times 10^6
\]

where,

\[
\text{Re} = \frac{\rho v d}{\mu}
\]

\[v = \text{fluid velocity at minimum tube spacing} \]

\[d = \text{tube outside diameter} \]

\[\text{Pr} = \text{Prantl number} \]

\[\text{Pr}_{\text{w}} = \text{fluid Prantl number at the tube wall temperature} \]

\[X_t = \text{relative transverse tube spacing} \]

\[X_l = \text{relative longitudinal tube spacing} \]

A.2. Pressure drop correlation for staggered configuration

\[
\Delta P = \xi N_r \left( \frac{\rho V_t^2}{2} \right)
\]

where,

\[
\xi = \xi_t f_{\text{fz},l} + (\xi_t f_{\text{fz},t} + f_{\text{n},l}) \left[ 1 - \exp \left( - \frac{\text{Re} + 200}{1000} \right) \right]
\]

\[
\xi_t = \frac{f_{\text{a},l}}{\text{Re}}
\]

\[
f_{\text{a},l} = \frac{280\pi \left( b^{0.5} - 0.6 \right)^2 + 0.75}{(4ab - \pi)^{1.6}}
\]

\[
f_{\text{fz},l} = \begin{cases} 
0.57 \left( \frac{N_r}{10} \right)^{0.25} & \text{for } N_r < 10 \\
\left( \frac{\text{Pr}_{\text{w}}}{\mu} \right)^{0.57} \left( \frac{4ab - \pi}{10} \right)^{0.25} & \text{for } N_r \geq 10
\end{cases}
\]

\[
f_{\text{fz},t} = \left( \frac{\mu_w}{\mu} \right)^{0.14}
\]

\[
f_{\text{n},l} = \begin{cases} 
0.57 \left( \frac{1}{N_r} - \frac{1}{10} \right) & \text{for } 5 \leq N_r < 10 \\
\left( \frac{2}{\text{Re}^{0.6} \text{Pr}^{0.36}} \right)^{0.25} & \text{for } N_r \geq 10
\end{cases}
\]

\[\mu_w = \text{liquid viscosity at tube wall temperature} \]

\[\mu = \text{liquid viscosity at average fluid temperature} \]

\[N_r = \text{number of tube rows} \]

\[a = \text{relative transverse tube spacing} \]

\[b = \text{relative longitudinal tube spacing} \]

\[c = \text{relative diagonal tube spacing} \]

\[\rho = \text{fluid density} \]

The above correlations for the heat transfer coefficient (HTC) and pressure drop factor (K-loss) on the tube outside surface (shell side) are developed and implemented in the TRACE model using the control system components (signal variables, control blocks, tables). A SNAP schematic of the control systems for calculating HTC and K-loss factor is shown in Fig. A.1.
Fig. A.1. Control systems for calculating HTC and K-loss of DHX.
Appendix B. Heat transfer and pressure drop correlations for DAC

Each DAC consists of 200 small finned tubes, horizontally configured in four rows at the bottom of each air cooling tower. The tubes are configured in an inline fashion. The heat transfer correlations and pressure drop correlations on the shell side are summarized as follows (Kakac et al., 1987):

B.1. Heat transfer correlation for finned tube bundle

\[ \text{Nu} = 0.192 \left( \frac{X_t}{X_l} \right)^{0.2} \frac{S}{d_o}^{0.18} \frac{e_f}{d_o}^{-0.14} \text{Re}^{0.65} \text{Pr}^{0.36} \left( \frac{\text{Pr}}{\text{Pr}_w} \right)^{0.25} \quad 100 < \text{Re} \leq 2 \times 10^4 \]

\[ \text{Nu} = 0.0507 \left( \frac{X_t}{X_l} \right)^{0.2} \frac{S}{d_o}^{0.18} \frac{e_f}{d_o}^{-0.14} \text{Re}^{0.8} \text{Pr}^{0.36} \left( \frac{\text{Pr}}{\text{Pr}_w} \right)^{0.25} \quad 2 \times 10^4 < \text{Re} \leq 2 \times 10^5 \]

\[ 1.1 < X_t^* < 4.0, \quad 1.03 < X_l^* < 2.5, \quad 0.006 < \frac{S}{d_o} < 0.36, \quad 0.07 < \frac{e_f}{d_o} < 0.715 \]

\[ \text{Nu} = 0.0081 \left( \frac{X_t}{X_l} \right)^{0.2} \frac{S}{d_o}^{0.18} \frac{e_f}{d_o}^{-0.14} \text{Re}^{0.95} \text{Pr}^{0.4} \left( \frac{\text{Pr}}{\text{Pr}_w} \right)^{0.25} \quad 2 \times 10^5 < \text{Re} \leq 2 \times 10^6 \]

\[ 2.2 < X_t^* < 4.2, \quad 1.27 < X_l^* < 2.2, \quad 0.125 < \frac{S}{d_o} < 0.28, \quad 0.125 < \frac{e_f}{d_o} < 0.6 \]

where,

\[ F = \frac{1}{3} \left[ \frac{2\delta_f}{t} \left( 1 + \frac{\delta_f}{d_o} \right) + \frac{\delta_f}{t} \left( 1 + \frac{2\delta_f}{d_o} \right) \right] \]

\[ t = S - \delta_f \]

\[ \delta_f = \text{fin thickness} \]

\[ S = \text{fin spacing} \]

\[ e_f = \text{fin height} \]

B.2. Pressure drop correlation for finned tube bundle

\[ \Delta P = \text{EuNu} \left( \frac{\rho V_n^2}{2} \right) \]

\[ \text{Eu} = 67.6 \text{Re}^{-0.7} X_t^{-0.55} X_l^{-0.5} F^{0.5} \quad 100 < \text{Re} \leq 1000 \]

\[ \text{Eu} = 3.2 \text{Re}^{-0.25} X_t^{-0.55} X_l^{-0.5} F^{0.5} \quad 1000 < \text{Re} \leq 10^5 \]

\[ \text{Eu} = 0.18 X_t^{-0.55} X_l^{-0.5} F^{0.5} \quad 10^5 < \text{Re} \leq 1.42 \times 10^6 \]

Note that the definitions for the other parameters are the same as those for the bared tube bundle. The above correlations for the heat transfer coefficient (HTC) and pressure drop factor (K-loss) on the tube outsider surface (shell side) is developed and implemented in the TRACE model using the control system components (signal variables, control blocks, tables). A SNAP schematic of the control systems for calculating HTC and K-loss factor is shown in Fig. B.1.
Fig. B.1. Control systems for calculating HTC and K-loss of DAC.
References