The Pennsylvania State University
The Graduate School
College of Engineering

MODELING THE MOLTEN SALT REACTOR EXPERIMENT WITH
THE NEAMS SYSTEM ANALYSIS MODULE

A Thesis in
Nuclear Engineering
by
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ABSTRACT

System analysis codes have a long history of providing best-estimate and conservative safety analysis for both light water and advanced reactor technologies. As interest continues to expand with advanced reactor concepts, system analysis codes will need revisions to accommodate the behavior of these technologies. The codes will also need to be updated to the latest numerical techniques to shorten execution time and increase the accuracy of results. One such tool that already encompasses these techniques is the System Analysis Module (SAM). An advanced reactor concept with recent interest is the Molten Salt Reactor (MSR). This concept is built upon the Molten Salt Reactor Experiment (MSRE), which provided early data and experience. Therefore, the objective of this work is to use legacy MSRE data as a basis of comparison with SAM results.

Two MSRE models are developed to evaluate SAM. One model is the SAM MSRE water mockup where experimental data was collected for pressure drop measurements. The other model is the complete MSRE primary loop. The MSRE system model incorporates fluoride salt fuel/coolant with heat transfer in both the core and heat exchanger. Estimates for the core coolant temperature profiles allow this reactor to be evaluated. The primary loop model is also altered for various additional studies, such as simulating varying coolant properties and a loss of flow (LOF) response.

The SAM model results for the pressure drop of the water mockup model are within 6% with measurements, which provides confidence that the model’s geometry is physically accurate over a range of flow rates. Coolant temperatures are also accurate for the primary loop model matching the expected axial change in temperature. Alternative coolant properties from the literature with different actinide content yield similar trends in core temperature profiles. A thermal hydraulic demonstration of a LOF transient shows the importance of coupling SAM thermal hydraulic analysis to neutronics. This coupling is essential for simulating MSR transients with system analysis codes.
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LIST OF VARIABLES

\( q \) = Power
\( \dot{m} \) = Mass flow rate
\( c_p \) = Specific heat capacity
\( T \) = Temperature
\( \rho \) = Density
\( t \) = Time
\( u \) = Velocity
\( z \) = Axial coordinate in the flow direction
\( p \) = Pressure
\( g \) = Acceleration due to gravity
\( k \) = Thermal conductivity
\( D_e \) = Equivalent hydraulic diameter
\( P_h \) = Heated perimeter
\( A_c \) = Cross sectional area
\( h \) = Convective heat transfer coefficient or height
\( k_{in} \) or \( k_{out} \) = Inlet or outlet loss coefficient
\( D_h \) = Hydraulic diameter
\( D \) = General Diameter
\( R \) = General Radius
\( A \) = General flow area
\( P_w \) = Wetted perimeter
\( P \) = Perimeter
\( P_t \) = Heat exchanger tube pitch
\( C_t \) = Heat exchanger tube clearance
\( B \) = Heat exchanger baffle spacing
\( t_s \) = Heat exchanger shell thickness
\( a_w \) = Surface area density
\( A_{surf} \) = Heated surface area
\( V \) = Liquid volume
\( L \) = Component length
\( w \) = Component width
\( v \) = Viscosity
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Chapter 1

Introduction

1.1 Background

The concept of molten salt reactors (MSRs) has existed for over half a century. MSRs have several potential advantages, such as near atmospheric operating pressure and coolant temperatures significantly below their boiling points. Additionally, the molten salt fuel can be continuously refueled online with no excess reactivity, reducing outage time of the reactor, although maintenance is still required. The fuel salt has a negative temperature coefficient of reactivity (Rosenthal et al., 1970). These advantages have the potential to reduce the risks of certain types of accidents.

The U.S. Department of Energy (DOE) sponsored the Advanced Demonstration and Test Reactor (ADTR) Options Study that compared different advanced reactor technologies. This study established four principal objectives that would characterize advanced reactor technology options (Petti et al., 2017).

1. “Deploy a high-temperature process heat application for industrial use and electricity demonstration using an advanced reactor system to illustrate the potential that nuclear energy has in reducing the carbon footprint of the U.S.”

2. “Demonstrate actinide management to extend natural resource utilization and reduce the burden of nuclear waste for future generations.”

3. “Deploy an engineering demonstration reactor for a less-mature reactor technology with the goal of increasing the technology readiness level (TRL) of the overall system for the longer term.”
4. “Provide an irradiation test reactor to support development and qualification of fuels, materials, and other important components/items of both thermal and fast-neutron based advanced reactor systems.”

This study noted that although MSRs seem viable for commercial implementation, several challenges existed. The challenges regard licensability and the chemical properties of actinide- and fission product-bearing salts (Petti et al., 2017).

In the 1960s, Oak Ridge National Laboratory (ORNL) constructed and operated the Molten Salt Reactor Experiment (MSRE). Data was obtained for the MSRE system that contained a fluoride salt-based fuel/coolant. To obtain thermal hydraulic data, ORNL also operated an open loop MSRE mockup that contained water as the working fluid. However, this program ended after nearly a decade. Today, knowledge on the behavior of MSRs can only be gained through computer simulations using system analysis codes that model both steady state and transient conditions. However, most system analysis codes, such as RELAP5-3D or TRACE, were developed for light water reactors (LWRs).

New simulation tools are currently under development that are oriented towards modeling advanced reactors that do not use water as their coolant. These tools also incorporate the newest numerical analysis techniques that can greatly increase computational speed. One such tool is being developed under DOE-NE’s Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. This tool is the System Analysis Module (SAM) developed by Argonne National Laboratory, the computer program used in this current project, which has already been demonstrated for sodium-cooled fast reactors (SFRs).
1.2 Original Contributions

The contribution of this work can be summarized in one central research question: can SAM be used to accurately model and reproduce data from the MSRE? This work focuses on several objectives to fully answer the central research question.

1. Develop a holistic 1-D system description of the MSRE water mockup and molten salt loop reactor using information that is publically available. Increasing interest in MSRs as a viable advanced reactor technology allows for the comprehensive MSRE system description to be used in a new DOE – NEAMS tool, SAM. This description can be adopted for any 1-D systems code.

2. Model the MSRE full-scale water mockup with SAM. Steady state pressure drop measurements exist for the MSRE water mockup serving as a basis of historical comparison for the SAM MSRE water mockup model.

3. Model the MSRE primary loop at steady state conditions with molten salt as the fuel/coolant with SAM. Limited experimental thermal hydraulic data exists, but approximate core and heat exchanger coolant temperatures are calculated and will serve as comparisons with the SAM MSRE primary loop model. Instrumentation was limited in the original MSRE. This study includes running different conditions such as varying fluid properties and modeling a flow perturbation.

It is important to note that this thesis does not make the case for a specific system analysis code. Rather, other system codes are shown to provide background or to serve as a basis of comparison for SAM results. It is also important to emphasize that all information pertaining to the MSRE comes from public documents that are available in open literature. All of these objectives will answer the central research question and provide detailed comparisons of simulated results obtained via SAM against legacy MSRE measurements and calculations.
Chapter 2

Literature Review

This chapter includes four main sections. The first section provides background on the MSRE with highlights of its safety features. The second section discusses several related studies of how MSRs (or similar variants, such as the Fluoride Salt-Cooled High Temperature Reactor) have been evaluated with system analysis codes. Next, the third section discusses the tool used to simulate the MSRE in this present study, SAM. Finally, this chapter will conclude with a discussion on the MSRE documentation used to construct the SAM models.

2.1 MSRE

2.1.1 MSRE History and Design

The concept of the MSR started in the late 1940s as the U.S. military was interested in developing nuclear powered aircraft for long haul nuclear weapons transport. Experiments were soon started to show the benefits of using molten salts, in particular molten salt fluorides. The Aircraft Reactor Experiment was built at ORNL to study the use of molten fluoride salts for airplane propulsion and to better understand the nuclear stability of a circulating fuel system (Rosenthal et al., 1970). The reactor operated for one-hundred hours at 2.5 MW with uranium-235 (U-235) dissolved in lithium, zirconium, and beryllium fluorides (Shi et al., 2016). The Aircraft Reactor Experiment was abandoned with the development of intercontinental ballistic missiles. Nevertheless, the project was valuable as it led to interest in using molten salt fuels for commercial purposes.
Construction of the MSRE began in 1962 and the first criticality was reached in 1965. The reactor system consisted of a primary side where the nuclear reaction takes place to heat the working fluid while being coupled to a secondary side via a shell-and-tube heat exchanger. The secondary side served to remove heat produced from the primary side to the environment via a radiator. The original fuel salt of the MSRE primary side was LiF-BeF$_2$-ZrF$_4$ mixed with UF$_4$. This fuel salt serves as both the fuel and coolant (fuel/coolant) of the MSRE. The secondary coolant was composed of LiF-BeF$_2$ (FLiBe) (Carbajo et al., 2017). Primary flow moved from the outlet of the heat exchanger through vertical and horizontal pipes before reaching the core vessel. The piping material was Hastelloy-N, which was a nickel-based alloy that was relatively insert with molten fluoride salts (Carbajo et al., 2017). It also had a high melting point, ideal for the high operating temperatures of the MSRE. The fuel/coolant then flowed down the annulus, or downcomer, of the MSRE core before being redirected upwards through the core. The fuel/coolant flowed throughout the reactor system at a flow rate of $75.7 \frac{L}{s}$ (Robertson, 1965). The core was divided into 1140 parallel and independent fuel channels that were predominantly surrounded by the graphite moderator (Kedl, 1970). The molten salt did not wet the graphite and did not leak into the graphite pores (Rosenthal et al., 1970). Nuclear fission occurred within these fuel channels heating the molten salt from approximately 908 $K$ to 936 $K$. Figure 2-1 below shows the MSRE core as it was being assembled.
Approximately 94% of the power was deposited into the molten salt and 6% into the graphite structure (Carbajo et al., 2017). The fuel/coolant was then pumped into the shell side of the heat exchanger to transfer its acquired heat to the secondary side. Figure 2-2 below shows a
basic flow diagram of the MSRE. The maximum power achieved with the MSRE was $8 \, MW_t$ although it was designed to reach $10 \, MW_t$.

Figure 2-2: MSRE Primary and Secondary Flow Diagram (Carbajo et al., 2017)

The MSRE contained all typical components of any nuclear reactor, but due to its molten salt fuel, some new components were necessary. One of these components was a cover gas, not pictured in Figure 2-2. The cover gas was a volume of gas that prevented the fuel/coolant of the MSRE from contacting air or moisture. For the MSRE, the cover gas was helium (Robertson, 1965). Although not unique to the MSRE, a fuel pump was needed to regulate the flow of the fuel/coolant throughout the varying orientations of pipes and components. The heat exchanger was also setup in a unique fashion since the primary, not the secondary fluid, flowed through the shell side of the component. The secondary fluid flowed through 159 Hastelloy-N tubes moving at $53.6 \, \frac{L}{s}$. 
Additionally, the secondary flow was heated from 825 $K$ to 866 $K$ (Engel and Haubenreich, 1962). This secondary side contained a radiator, which is unique to nuclear reactors. Typical reactor systems have a means of boiling the working fluid in order to spin a turbine to produce electricity. In the case of a demonstration or experimental reactor, producing electricity is unnecessary, meaning that a radiator is used to release heat into the atmosphere. At any time, the working fluid of both the primary and secondary sides remained single phase. There are many other unique components in the MSRE, but a discussion on these is unnecessary since they will not be modeled with SAM.

The MSRE operated with temperatures as high as 1200°F without significant reported corrosion of the materials (Rosenthal et al., 1970). Buildup of xenon poisons was mitigated with constant fission product removal. This was impossible to do when using solid fuel. The first phase of the MSRE operation ended in 1968 when the original U-235 fuel was removed and treated with fluorine gas. U-233 was mixed into the molten salt mixture shortly thereafter making it the first U.S. reactor to operate with this isotope (Rosenthal et al., 1970). This marked the first time that the idea of turning the MSRE into a breeder was conceived. Experiments showed that rare earth elements could be separated from lithium and beryllium fluoride salts that composed the fuel/coolant. This meant that certain isotopes and fissile material could be bred in the MSRE with breeding ratios in the range of 1.07 to 1.08 (Rosenthal et al., 1970). However, the concept never came to full fruition and was never implemented since the MSRE program ended in 1969. Figure 2-3 below shows a schematic of how the molten salt breeder reactor would function.
2.1.2 Benefits and Challenges of MSRs

MSR technologies have several potential advantages. Several of these advantages are related to using fluoride salts as the fuel/coolant and are listed below (Rosenthal et al., 1970).

- High solubility for uranium
- Chemically stable compound
- Very low vapor pressure
- Irradiation resistant
- Relatively inert with air or water
- Non-reactive to common structural metals, including Hastelloy-N

Liquid fuels also have some potential advantages (Shi et al., 2016):
- Large negative temperature coefficient of reactivity due to a high coefficient of thermal expansion
- Possibility of continuous fission product removal using online processes
- More efficient resource utilization with higher fuel burnup than conventional solid fuel
- No fuel assembly fabrication or handling (He, 2016)

Lithium or beryllium fluorides are often selected as liquid fuel salts due to their thermal stability, lower density, and relatively low melting point when compared to solid fuels (He, 2016).

Other potential advantages of MSR technologies include economic efficiency, natural resource utilization, sustainable development, and nuclear non-proliferation (some of these apply to a molten salt breeder) (Shi et al., 2016). Inherent safety features may also result in cost savings, if MSRs are commercially implemented. Additionally, MSRs operate at near atmospheric pressure, reducing the risk of certain accidents, such as a Loss of Coolant Accident (LOCA) (He, 2016). Second, the fuel/coolant salt has significant margin to reach its boiling point. According to Elsheikh (2013), the boiling point of MSR fuel is approximately $1670 \, K$. Because the molten fuel is always in the liquid phase, the risk of fuel melt is largely averted with the implication that no significant leakage of radioactive materials would occur (He, 2016). Moreover, fission products are continuously removed from the reactor (Rosenthal et al., 1970). Similarly, excess reactivity is removed by continuous fuel processing. Additionally, there is a prompt negative temperature coefficient when the fuel/coolant salt is being heated (Rosenthal et al., 1970). Finally, the MSRE would be fueled online meaning that the fuel can be injected into the primary system (or reprocessing unit) without the need for shutdown (He, 2016).

As with any reactor system, there are some challenges. Fission products may accumulate in the primary off-gas system, fuel storage tanks, and processing plant. Furthermore, Hastelloy-N becomes embrittled by helium that is produced when the alloy is irradiated, bringing about material limitations (Rosenthal et al., 1970). An improved alloy of Hastelloy-N will be needed for long-term
operation of an MSR. Research will also need to continue with fluoride molten salts to better understand their chemistry. Additionally, structures may become corroded over time, which is why a cover gas is a mandatory piece of equipment (He, 2016). A constant challenge remains with radioactive fuel/coolant circulating around the entire primary system carrying with it delayed neutron precursors. Fission products with long half-lives also travel out of the core potentially damaging system instrumentation (He, 2016). This issue causes shielding challenges. One major challenge is to model the solubility of the various nuclides in a multicomponent system at various temperatures. The thermodynamics of such complex systems is difficult to understand.

2.2 Similar Studies

2.2.1 Modeling MSRs with RELAP5

There are several studies in the literature related to modeling MSRs with the system analysis code RELAP5. This code is used for best-estimate analysis of both steady state and transient behavior in light water reactors (LWRs). The code is coupled between the core and coolant systems and can simulate the different thermal hydraulic and safety systems observed in a nuclear power plant (Shi et al, 2016).

One such study that gives confidence in using RELAP5 to model MSRs was performed by Shi et al. (2016). The study analyzed the point kinetics model with the effects of flowing fuel with an internal heat source in the RELAP/SCDAPSIM/MOD4.0 code. This code is an extension of RELAP5 that includes fluid properties for molten salts, such as LiF–NaF–KF (Shi et al., 2016).

The Shi et al. (2016) study assumed that there is reactivity feedback due to temperature change of the fuel and moderator. Thermal hydraulics were solved based on two-phase continuity, momentum, and energy equations with negligible vapor void fraction. Additionally, new heat
source terms were added into the RELAP5 energy equations. New control volumes were also added to include an internal heat source, which is needed since the working fluid of the MSR acts as both the fuel and coolant (Shi et al., 2016).

The work of Shi et al. (2016) was verified by comparisons with MSRE zero-power reactor physics experiments. The fuel pump startup results from RELAP5 showed a loss of reactivity as delayed neutron precursors were carried outside of the core and into the primary loop due to the dual nature of the fuel/coolant (Shi et al., 2016). Natural circulation can also be verified between the code and experiment. For example, with a near zero fuel/coolant flow rate, the heat removal rate of the heat exchanger was increased while the code was in a critical state. This decreased core inlet temperature and raised the reactivity due to the negative temperature feedback of the salt and graphite. This ultimately resulted in a higher power and fuel/coolant flow rate. Overall, Shi et al. (2016) concluded that the results from RELAP5 compared reasonably well with experimental values, verifying that RELAP5 can be used for MSRs with minor code modifications.

Similarly, Carbajo et al. (2017) modeled a specific reactor, the MSRE, with RELAP5-3D. They modeled both the MSRE system and the open-loop water mockup. The working fluid of both the primary and secondary sides of the MSRE system was set to reflect properties of FLiBe, which is not a direct match to the actual primary side fuel/coolant. Power was then deposited in the molten salt using the direct moderator heating option of RELAP5-3D. Furthermore, transients were not simulated because certain neutronics options were previously unavailable, such as delayed neutron precursor drift and the kinetics of liquid-fueled systems. The nodalization diagram for the RELAP5-3D water mockup is shown in Figure 2-4. The blue circles represent the connecting points between the different components.
Various experimental results exist for the MSRE water mockup. These are found in Table 2-1 alongside the values obtained by the RELAP5-3D model. The results showed good alignment, validating the MSRE water mockup simulation. However, differences existed between experimental and simulated results for the velocity at the bottom of the downcomer. Carbajo et al. (2017) attributed this difference to the 3-D physical flow of the MSRE downcomer region. 3-D flows were not captured with the RELAP5-3D downcomer model since it was a 1-D component. The values shown in the table are for a water mass flow rate of $75.7\frac{L}{s}$ and a temperature of 300 K. The experimental values were obtained from Kedl (1970).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental</th>
<th>RELAP5-3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pipe velocity (m/s)</td>
<td>5.85</td>
<td>5.85</td>
</tr>
<tr>
<td>Bottom of downcomer velocity (m/s)</td>
<td>1.68</td>
<td>0.66</td>
</tr>
<tr>
<td>Core velocity (m/s)</td>
<td>1.37</td>
<td>1.25</td>
</tr>
<tr>
<td>Core Head Loss (kPa)</td>
<td>1.79</td>
<td>1.78</td>
</tr>
<tr>
<td>System Head Loss (kPa)</td>
<td>44.8</td>
<td>44.7</td>
</tr>
</tbody>
</table>

On the other hand, experimental information for the MSRE closed loop model was more limited. No flow rates, powers, or pressures were measured in the MSRE experiments; only
temperatures outside of pipes were measured. However, Engel and Haubenreich (1962) calculated several parameters at a power of 10 MW. RELAP5-3D was also executed at this same power, generating the comparison shown in Table 2-2. The values from the code showed good alignment with the reference; however, there are some differences that were likely due to different molten salt properties used in the RELAP5-3D model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calculated</th>
<th>RELAP5-3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Inlet Coolant Temperature (K)</td>
<td>908</td>
<td>908</td>
</tr>
<tr>
<td>Outlet Coolant Temperature (K)</td>
<td>936</td>
<td>936</td>
</tr>
<tr>
<td>Coolant Flow (L/s)</td>
<td>75.7</td>
<td>76.7</td>
</tr>
<tr>
<td>Density (kg/m$^3$) at 920 K</td>
<td>2258</td>
<td>1956</td>
</tr>
<tr>
<td>Specific Heat Capacity (J/kg-K)</td>
<td>1966</td>
<td>2386</td>
</tr>
<tr>
<td>Maximum Fuel Temperature (K)</td>
<td>956</td>
<td>966</td>
</tr>
<tr>
<td>Maximum Graphite Temperature (K)</td>
<td>975</td>
<td>992</td>
</tr>
<tr>
<td>Core Velocity (m/s)</td>
<td>0.18 – 0.61</td>
<td>0.2 – 0.5</td>
</tr>
</tbody>
</table>

2.2.2 Modeling the MSRE with TRACE

This section discusses the work of He (2016), which validated the TRAC/RELAP Advanced Computational Engine (TRACE) for dynamic simulations of the MSR. TRACE can evaluate transients for safety system analysis using 1-D components along with a 3-D reactor core (He, 2016). The main objective of this work was to demonstrate that a modified version of TRACE can simulate both steady state and transient conditions for the MSRE. TRACE is a suitable code for the MSRE since thermal hydraulics can readily be coupled to point kinetics.

Several modifications were made to TRACE to properly simulate the MSRE. The point kinetics modeling in TRACE was improved by considering the neutron precursor drift that occurs in any MSR. Additionally, the TRACE model was 1-D with properties of the MSRE salt programmed in its source code. This implied that the fluid library of TRACE was modified by replacing sodium and lead-bismuth properties with those for the primary fuel/coolant (7LiF – BeF$_2$
– ZrF₄ – UF₄) and for the secondary coolant (⁷LiF – BeF₂), respectively (He, 2016). The physical properties of the primary fuel/coolant and secondary coolant, such as the density or viscosity, were entered in the TRACE source code as functions of temperature. Several control systems were also constructed to account for pump control, reactivity insertion, average graphite temperature, average primary fuel/coolant temperature, and transient power (He, 2016). Figure 2-5 shows a nodalization of the TRACE model constructed by He (2016) including the secondary side and radiator.

![TRACE Nodalization of MSRE (He, 2016)](image)

TRACE results aligned relatively well with MSRE data for steady state conditions. One unexpected result was that the temperature of the graphite within the core was always higher than that of the adjacent fuel in any axial position. This can be attributed to the Poppendieck Effect where the fuel temperature near the graphite wall is always higher than the centerline temperature (He, 2016). He (2016) also constructed a CFD model to obtain axial temperature profiles of the fuel/coolant and graphite that matched relatively well with experimental results. Several transients
were also simulated including a step insertion of reactivity, a ramp insertion of reactivity, and a primary pump failure. All results were in reasonable alignment with experimental data with negligible errors. This work also showed a reasonable shutdown margin and implied that the MSRE model would be self-regulating against reactivity-initiated accidents (He, 2016).

2.2.3 Modeling with Other System Analysis Codes

Since the MSR has several unique qualities, use of a spatial dynamics code might be useful to properly capture the physics associated with its attributes. Some of these unique qualities are listed as follows (Krepel et al., 2007):

- Delayed neutron precursors flowing throughout the primary system
- Fission energy predominantly released into the coolant
- Radiative heating of the graphite moderator

A spatial code can account for the first quality, the distribution of delayed neutron precursors, temperature distributions, and local perturbations, just to name a few. One such spatial code was the DYNamical 3-Dimensional code for MSRs (DYN3D-MSR) which used the diffusion approach for calculating MSR neutronics (Krepel et al., 2007). The drift of the delayed neutron precursors (DNPs) was accounted for by adding a convective derivative term to the standard form of the DNP equations. DYN3D-MSR accounted for thermal hydraulics using the FLOCAL model. This model was modified for MSRs by changing the source terms in the conservation of energy equations and changing water properties to that of the molten salt since DYN3D-MSR was originally setup for LWRs (Krepel et al., 2007).

Krepel et al. (2007) simulated the effective loss of delayed neutrons in steady state operation, fuel pump startup, fuel pump coast-down, and natural circulation. The pump startup and coastdown agreed well with experimental data from the MSRE, but differences existed with
tracking delayed neutrons and natural circulation of the primary system. These issues can be partially resolved by including a reactivity surge during the first few seconds of the simulation (Krepel et al., 2007).

Other reactor types that are similar to MSRs can also be evaluated with system analysis codes as modeling similarities will overlap. Zweibaum et al. (2016) modeled the Fluoride Salt-Cooled High Temperature Reactor (FHR) using both RELAP5-3D and the new 1-D FHR Advanced Natural Circulation Analysis Code (FANCY). The FHR that was specifically analyzed was the Compact Integral Effects Test (CIET 1.0) facility that would produce integral transient thermal hydraulic responses of the FHR design under forced and natural circulation conditions (Zweibaum et al., 2016). Experimental data from CIET 1.0 was used to validate the RELAP5-3D and FANCY models. CIET 1.0 is a $900 \text{MW}_t$ pebble-bed advanced high temperature reactor (PB-AHTR) (Zweibaum et al., 2016).

The primary objective of both RELAP5-3D and FANCY was to reproduce the geometry, pressure and temperature boundary conditions, and working fluid properties of CIET 1.0. The codes were run in transient mode until steady state temperatures and mass flow rates were obtained in the primary model and in the Direct Reactor Auxiliary Cooling System (DRACS) (Zweibaum et al., 2016). Both codes used DOWTHERM A oil rather than a FLiBe-based fluid. Furthermore, the codes verified experimental results with sensitivity studies of the natural circulation mass flow rate with a certain set of boundary conditions with different model discretizations. Zweibaum et al. (2016) developed three core questions for this verification study.

1. Is the heat input to the fluid equal to the sum of the heat removed through the heat exchanger and parasitic heat losses along the loop?
2. Is the mass flow rate uniform through each loop?
3. Is $q = \dot{m} c_p \Delta T$ verified in each loop?
The work of Zweibaum et al. (2016) found that both codes passed the above tests with only minor changes seen in the heat input to the fluid or heat exchanger.

The next part of this work was validation. The default heat transfer correlations of both codes underestimated heat losses by as much as 75% in the primary loop and 45% in the DRACS heat exchanger (Zweibaum et al., 2016). These issues can be fixed by calibrating multiplication factors on the heat transfer coefficients of these loops. Next, validation was completed for the DRACS loop natural circulation case. Results from RELAP5-3D and FANCY were compared to CIET 1.0 results and an analytical model for the natural circulation mass flow. The experimental, RELAP5-3D, and FANCY data overlapped very well with each other when comparing mass flow rates at different power levels.

2.3 The NEAMS Tool SAM

2.3.1 What is SAM?

The simulation tool used in this project is SAM, which is a part of the U.S. DOE NEAMS suite of tools. The objective of SAM development was to create a code that is user-friendly and fast while improving whole system safety analysis. This means that SAM can solve coupled reactor phenomena, such as fission and heat transfer, with current numerical capabilities at quicker speeds than legacy programs (Hu et al., 2015). More specifically, SAM has been designed to simulate and assess sodium fast reactors, lead-cooled fast reactors (LFRs), fluoride-salt-cooled high temperature reactors (FHRs), and molten salt reactors. These reactor types differ from light water reactors in multiple ways other than their working fluids. All of these advanced reactor designs utilize single-phase, low-pressure, and high-temperature coolants, which are advantageous from a reactor safety prospective (Hu et al., 2015). SAM has been designed for these reactor types with built-in equation
of state (EOS) modeling for the different coolants. Most importantly, SAM has a series of component types with system-level modeling that accurately depicts the functionality of advanced reactors.

SAM’s input environment utilizes the Multi-physics Object Oriented Simulation Environment (MOOSE) (Hu, 2017). The MOOSE framework allows for easy implementation of input for complex components. It also has underlying meshing with the finite-element library libMesh and linear and non-linear solvers (Hu, 2017), including the Portable Extensible Toolkit for Scientific Computation (PETSc) (Balay et al., 1997). At a high level, PETSc is utilized for portable numerical solutions of partial differential equations (PDEs). PETSc contains data structures so that it can be easily implemented into large-scale application codes (Balay et al., 1997).

2.4 References Used to Build SAM Model

Several of the references used in this work are legacy literature produced when the MSRE was in operation. These are mainly design manuals and reports used to log information gathered from the original MSRE project. These resources are mainly used to describe the SAM models built in this research project. They also allow for production of a holistic MSRE system description that can be tweaked for any system analysis code.

Rosenthal et al. (1970) mainly outlines the history of the MSRE along with advantages of the design and its potential as a breeder reactor. Engel and Haubenreich (1962) provides calculated data of the core temperatures, flow rates, and fluid velocities of the MSRE closed loop. This data was calculated based on the flow conditions of the MSRE water mockup rather than experimentally since instrumentation was limited in original experiments. Temperature nodes were only placed on the outside of the core vessel providing inaccurate data on the coolant. Guymon (1973) and Robertson (1965) explain all the details regarding the components used in the MSRE. Robertson
(1965) goes into more detail including schematics that show the exact measurements of the MSRE piping and equipment. Both of these references give schematics that were essential in determining the dimensions of the MSRE for SAM input. Haubenreich et al. (1964) gives details on the measurements of components within the core vessel, such as the core, downcomer, lower plenum, and upper plenum. Kedl (1970) explains the details and experimental results for the MSRE water mockup, in particular, head loss data. Holcomb et al. (2009) gives information on both the primary and secondary sides of the MSRE heat exchanger. This information is also available in Robertson (1965). Cantor et al. (1968) gives data on proposed fuel salts for other MSR designs. It gives information on molecular compositions along with temperature dependent expressions, including uncertainties that describe thermophysical properties (density, viscosity, specific heat capacity, enthalpy, thermal conductivity, and coefficient of thermal expansion).
Chapter 3
MSRE Water Mockup Model

This chapter discusses the details of the SAM simulation of the MSRE water mockup. The first section discusses details of the system description for the SAM model of the MSRE water mockup. The second section focuses on evaluation of the SAM model of the MSRE water mockup.

3.1 SAM MSRE Water Mockup Model Details

3.1.1 MSRE Water Mockup General Information

The MSRE water mockup was an open loop hydraulic mockup version of the MSRE. The primary purpose of the water mockup was to conduct hydraulic analysis of the MSRE since dimensions and geometries between the two facilities matched. The water mockup was setup to acquire data that would be nearly impossible to obtain from the operating reactor. Both water and surrogate fluids were used in the hydraulic mockup. The surrogate fluids were used since experiments with water yielded Reynolds Numbers approximately four times higher than expected for molten salt (Kedl, 1970). One such surrogate fluid was the addition of a thickening agent, Jaguar-508, to decrease the Reynolds Number (Kedl, 1970). The results in this work focus on water without a thickening agent. Additionally, a one-fifth scale model of the water mockup was built to verify design performance and to ensure that certain components could be used in the full-scale water mockup and MSRE. For example, this smaller water mockup was used for volute and swirling vane design (Kedl, 1970). The one-fifth scale model is not included in this work.
There were a few design modifications between the MSRE with molten salt and its water mockup. The most prominent was that the water mockup was an open loop rather than a closed loop. This design was adopted because the working fluid is not heated, meaning that a heat exchanger and secondary loop were unnecessary in the water mockup. Additionally, the system piping was made of carbon steel while the graphite blocks in the core were replaced with aluminum in the water mockup (Kedl, 1970). The water mockup was much more conducive for acquiring measurements when compared to the FLiBe model. Several transparent windows were inserted in the core vessel region for flow viewing while numerous holes were bored into the vessel wall to insert instrumentation (Kedl, 1970). Figure 3-1 shows the core vessel of the water mockup.

Figure 3-1: MSRE Water Mockup Core Vessel (Kedl, 1970)
3.1.2 SAM MSRE Water Mockup Model Description

The SAM MSRE water mockup is constructed of pipes connected together by junctions or branches. The SAM pipe component simulates 1-D fluid flow in a cylindrical pipe and heat conduction in the pipe wall (Hu et al., 2015). SAM branch or junction components connect pipes together. Branch components, which are zero volume junctions where multiple 1-D components can be connected, are used when loss coefficients must be specified (Hu et al., 2015). A junction is used when loss coefficients are unnecessary or when two 1-D components of identical flow areas are linked (Hu et al., 2015). Moreover, temperature and velocity are specified as inlet boundary conditions, whereas pressure is specified as an outlet boundary condition in the MSRE SAM water mockup model. Figure 3-2 shows a general nodalization of the SAM water mockup model. The diagram is not to scale, and the coordinate location of the inlet of each component is listed. SAM requires that each component’s inlet position be specified. The origin of the model is set at the inlet of the component titled “core1.”
Figure 3-2: MSRE Water Mockup Model Nodalization

Components titled “p102,” “p104,” “p119H,” and “p119V” are pipe components. These components, and all pipe components, are Schedule 40 (Sched-40) type with a wall thickness of 0.0066 m (5-inch diameter pipe nominal thickness for Sched-40). Additionally, these pipes are composed of the material carbon steel for the water mockup. All components in the SAM MSRE water mockup except for the core rings are composed of carbon steel. The cross-sectional area of these pipes is 0.0127 m$^2$ with hydraulic diameter of 0.127 m (Robertson, 1965). Furthermore, the initial velocity is set to 6.0 m/s to reflect a coolant flow rate of 75.7 L/s (Robertson, 1965). There are remaining component properties that differ between each pipe, and these are listed with references in Table 3-1 below.
Table 3-1: Listing of Parameters with References for Water Mockup Piping Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>p102</td>
<td>length</td>
<td>1.68 m</td>
<td>Robertson, 1965</td>
</tr>
<tr>
<td>p102</td>
<td>pipe roughness</td>
<td>1.00 x 10^{-4} m</td>
<td>Assumption</td>
</tr>
<tr>
<td>p104</td>
<td>length</td>
<td>2.71 m</td>
<td>Robertson, 1965</td>
</tr>
<tr>
<td>p104</td>
<td>pipe roughness</td>
<td>1.00 x 10^{-4} m</td>
<td>Assumption</td>
</tr>
<tr>
<td>p119H</td>
<td>length</td>
<td>1.63 m</td>
<td>Robertson, 1965</td>
</tr>
<tr>
<td>p119H</td>
<td>pipe roughness</td>
<td>1.00 x 10^{-4} m</td>
<td>Assumption</td>
</tr>
<tr>
<td>p119V</td>
<td>length</td>
<td>1.54 m</td>
<td>Calculated</td>
</tr>
<tr>
<td>p119V</td>
<td>pipe roughness</td>
<td>1.00 x 10^{-4} m</td>
<td>Assumption</td>
</tr>
</tbody>
</table>

Component name “p119V” is unique in that its length takes into account 0.397 m of height that is displaced by the fuel pump. A fuel pump is not used in the MSRE water mockup model, but it is required for the complete MSRE loop. Additionally, the two horizontal piping components, “p104” and “p119H,” length’s are approximated per ORNL DWG 64-8810 in Robertson (1965). This is done because the MSRE water mockup and closed loop models are both 3-D while SAM is a 1-D system analysis code.

The piping components are all linked via junctions or branches. More specifically, “p102,” “p104,” “p119H,” and “p119V” are linked with a SAM junction component. All of the remaining components are linked with branches. When using a SAM branch component, loss coefficients for an abrupt area expansion or contraction are specified. For example, the “junc3” component links the “p104” component to its downstream component “downc.” The cross-sectional area of this branch is 0.0342 m², consistent with a RELAP5-3D model made by Carbajo et al. (2017). The flow area of the junction was likely chosen to account for the MSRE volute, which physically lies in place of “junc3” in the MSRE. The volute is a 3-D component that creates complex flows before emptying into the annulus, or downcomer of the MSRE core vessel. Loss coefficients are entered for both the inlet and outlet of any branch. The loss coefficients are calculated per guidance in Todreas and Kazimi (2012).
Table 3-2 shows some of the input parameters for SAM branches or junctions. With the exception of “junc3,” the cross sectional areas of junctions were not given in references meaning that they are assumed to match that of the downstream component. Any loss coefficients of zero imply that the flow areas between adjacent components are equal.

Table 3-2: Listing of Parameters with References for Water Mockup Connection Components

<table>
<thead>
<tr>
<th>Branch</th>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>junc3</td>
<td>Flow area</td>
<td>0.0342 m²</td>
<td>Assumption</td>
</tr>
<tr>
<td>junc3</td>
<td>Inlet loss coefficient</td>
<td>0.397</td>
<td>Calculated</td>
</tr>
<tr>
<td>junc3</td>
<td>Outlet loss coefficient</td>
<td>0.496</td>
<td>Calculated</td>
</tr>
<tr>
<td>plenbranch</td>
<td>Flow area</td>
<td>1.71 m²</td>
<td>Assumption</td>
</tr>
<tr>
<td>plenbranch</td>
<td>Inlet loss coefficient</td>
<td>0.869</td>
<td>Calculated</td>
</tr>
<tr>
<td>plenbranch</td>
<td>Outlet loss coefficient</td>
<td>0</td>
<td>Calculated</td>
</tr>
<tr>
<td>core1junc</td>
<td>Flow area</td>
<td>0.332 m²</td>
<td>Assumption</td>
</tr>
<tr>
<td>core1junc</td>
<td>Inlet loss coefficient</td>
<td>0.649</td>
<td>Calculated</td>
</tr>
<tr>
<td>core1junc</td>
<td>Outlet loss coefficients</td>
<td>17.0, 16.7, 16.6, 16.4</td>
<td>Calculated</td>
</tr>
<tr>
<td>upjunc</td>
<td>Flow area</td>
<td>1.71 m²</td>
<td>Assumption</td>
</tr>
<tr>
<td>upjunc</td>
<td>Inlet loss coefficients</td>
<td>17.1, 17.0, 17.0, 16.9</td>
<td>Calculated</td>
</tr>
<tr>
<td>upjunc</td>
<td>Outlet loss coefficient</td>
<td>0</td>
<td>Calculated</td>
</tr>
<tr>
<td>p119Hjunc</td>
<td>Flow area</td>
<td>0.0127 m²</td>
<td>Assumption</td>
</tr>
<tr>
<td>p119Hjunc</td>
<td>Inlet loss coefficient</td>
<td>0.985</td>
<td>Calculated</td>
</tr>
<tr>
<td>p119Hjunc</td>
<td>Outlet loss coefficient</td>
<td>0</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

For branches “core1junc” and “upjunc,” there are multiple loss coefficients listed in Table 3-2. These loss coefficients account for the four core rings. The core rings are concentric and divide the total flow area into four regions. The core is divided this way for power distribution purposes, which are irrelevant in this section. Core rings are used here to maintain consistency in both the SAM water mockup and closed loop model. Due to a lack of information on the exact amount of graphite structure obstructing flow into and out of the core fuel channels, the loss coefficients are approximated. Form losses attributed by the change in geometry at the core inlet and outlet are
obtained using formulas given in Todreas and Kazimi (2012). The process of combining the loss coefficient contributions from both structure and geometry is repeated for the upper plenum.

The next components are “downe,” “lple1,” and “up.” The “downe” component is the SAM representation of the MSRE downcomer. The downcomer is a 3-D annulus that propels the working fluid flow into a lower plenum so that it can flow upwards through the core channels. The unique aspect of the downcomer flow is that it is not only 3-D, but contains radial, angular, and axial velocity components (Carbajo et al., 2017). SAM is only able to model this flow as 1-D. This complex flow emanates from the volute, or flow distributor, located atop the core vessel containing several ¼” diameter holes at 30° angles with the vertical, thus requiring 3-D modeling (Robertson, 1965). Computational fluid dynamics (CFD) would accurately depict flow going from the volute to the downcomer. Figure 3-3 shows the inlet pipe for the volute along with the flow distribution holes that lead into the annulus.
Table 3-4 shows parameters and references for the “downc” component, whose values are given in references. Using the annular geometry, the downcomer’s hydraulic diameter is found to be 0.0508 m.
The “lple1” component represents the lower plenum of the MSRE water mockup core. This component is unique in that its height has been minimized to 0.01 m to account for complex directional shifting flows observed in the lower plenum. The lower plenum transitions the flow from vertical downward to vertical upward over a short length. It is not resolved how much vertical displacement the fluid will have in the lower plenum since it could be minimal (neglecting a lower plenum) or maximal (including the entire length of the lower plenum). Figure 3-4 shows a demonstration of the lower plenum flow.

Figure 3-4: MSRE Lower Plenum Flow Diagram
Using a lower plenum height of 0.01 m assumes that the lower plenum component is essentially neglected meaning that flow directly transitions from vertical downward in the downcomer to vertically upward in the “core1” component (and all other core rings). Verification of this assumption will be shown in the results section.

The “up” component represents the upper plenum of the MSRE water mockup core. The length of this component is 0.249 m (Haubenreich et al., 1964). This length is derived by accounting for the upper head and vessel top of the core region. Figure 3-5 shows the simple diagram used in Haubenreich et al. (1964) from which the upper plenum length was calculated. Regions A, D, and E are assumed to represent the “up” component. Several geometric attributes and values for the components “downc,” “lple1,” and “up” are shown in Table 3-3.
The final components in the SAM MSRE water mockup are the core channels that are broken up into four regions, “core1,” “core2,” “core3,” and “core4.” According to Kedl (1970), the MSRE contains 1140 fuel channels that this current SAM model lumps into four core rings. These rings are used for implementation of a radial power distribution when using a 1-D systems code. Core channels are lumped into the hottest or coldest region, more applicable for variable radial power in the closed loop MSRE. The four core regions have adiabatic boundary conditions since no heat transfer occurs between the pipe wall and the environment. All of the core regions have a length of 1.60 m, consistent with Haubenreich et al. (1964).

The total cross sectional area of all 1140 channels is 0.332 m² with hydraulic diameter of 0.0159 m (Carbajo et al., 2017). These values can be confirmed using dimensions reported in

---

**Table 3-3: Listing of Parameters with References for “downc,” “lple1,” and “up”**

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>downc</td>
<td>flow area</td>
<td>0.116 m²</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>downc</td>
<td>outer radius</td>
<td>0.737 m</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>downc</td>
<td>inner radius</td>
<td>0.711 m</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>downc</td>
<td>pipe roughness</td>
<td>1.00 × 10⁻⁴ m</td>
<td>Assumption</td>
</tr>
<tr>
<td>downc</td>
<td>length</td>
<td>1.71 m</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>lple1</td>
<td>flow area</td>
<td>1.71 m²</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>lple1</td>
<td>hydraulic diameter</td>
<td>1.47 m</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>lple1</td>
<td>pipe roughness</td>
<td>1.00 × 10⁻⁴ m</td>
<td>Assumption</td>
</tr>
<tr>
<td>up</td>
<td>flow area</td>
<td>1.71 m²</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>up</td>
<td>hydraulic diameter</td>
<td>1.47 m</td>
<td>Haubenreich et al. (1964)</td>
</tr>
<tr>
<td>up</td>
<td>pipe roughness</td>
<td>1.00 × 10⁻⁴ m</td>
<td>Assumption</td>
</tr>
</tbody>
</table>
Haubenreich et al. (1964). The fuel channels are not completely circular nor rectangular, as shown in Figure 3-6.

![Figure 3-6: MSRE Fuel Channel Arrangement Surrounded by Graphite and Control Rods](Haubenreich et al., 1964)

The cross section of one core channel contains a rectangular component with two half-circles on its ends. The cross sectional area is determined by calculating the area of the rectangle and summing it with that of the two half-circles. Figure 3-7 gives a visual for this description.
Using the values from the above figure:

\[ A_{\text{one channel}} = A_{\text{rectangle}} + A_{\text{half-circles}} \]  

(3-1)

The area of one channel is multiplied by 1140 to account for all fuel channels. This area is 0.332 m², confirming the result from literature. The hydraulic diameter is determined in a similar manner using the wetted perimeter of one fuel channel. This is extrapolated to all channels giving a result of 0.0159 m, matching the result from literature. To be consistent with Carbajo et al. (2017), the following values shown in Table 3-4 for the cross-sectional area and hydraulic diameter are used for each of the four core regions.
This analysis also includes a water mockup model with equal flow areas for each core ring. To reflect the change in ring flow area, the loss coefficients at the inlet and exit of the core are also changed. Having two core geometries for the water mockup helps to verify that loss coefficients and dimensions have been properly modeled. It also allows for hydraulic analysis conducted over different geometries.

With either equal or non-equal flow areas, each core ring must be positioned apart from each other. For example, “core1” has been assigned as the origin for all SAM MSRE modeling. The three other rings extend out in the negative x-direction as it is impossible to capture the true radial nature of the rings when using a 1-D code. According to Haubenreich et al. (1964), the radius of the MSRE core is $0.705 \text{ m}$. Dividing this value by four (for four rings total) sets the position of the second ring, “core2,” at $0.176 \text{ m}$. It is then assumed that “core3” is at $2 \times 0.176 \text{ m}$ and that “core4” is at $3 \times 0.176 \text{ m}$. The value of $0.176 \text{ m}$ is essentially the ring thickness. Overall, the position of the core rings is irrelevant, as SAM has produced identical results for the case where all four rings were positioned at the origin. However, it makes physical sense with the actual MSRE design to place the core rings some distance apart from each other.

The final sets of input required for the SAM MSRE water mockup model include material and fluid properties along with initial conditions. Initial conditions for pressure, temperature, and velocity are assumed in the SAM calculation. Table 3-5 shows the fluid properties assumed in the

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>core1</td>
<td>flow area</td>
<td>0.0174 m²</td>
</tr>
<tr>
<td>core1</td>
<td>hydraulic diameter</td>
<td>0.0159 m</td>
</tr>
<tr>
<td>core2</td>
<td>flow area</td>
<td>0.0658 m²</td>
</tr>
<tr>
<td>core2</td>
<td>hydraulic diameter</td>
<td>0.0159 m</td>
</tr>
<tr>
<td>core3</td>
<td>flow area</td>
<td>0.105 m²</td>
</tr>
<tr>
<td>core3</td>
<td>hydraulic diameter</td>
<td>0.0159 m</td>
</tr>
<tr>
<td>core4</td>
<td>flow area</td>
<td>0.143 m²</td>
</tr>
<tr>
<td>core4</td>
<td>hydraulic diameter</td>
<td>0.0159 m</td>
</tr>
</tbody>
</table>
calculation. Since there is no heat transfer in the water mockup, the values for thermal properties are irrelevant to any calculations but are required SAM inputs.

Table 3-5: Values Used to Represent Properties of Water in SAM Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Reference Pressure</td>
<td>0.101 MPa</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>4.18 $\frac{kJ}{kg - K}$</td>
</tr>
<tr>
<td>Internal Enthalpy</td>
<td>113 $\frac{kJ}{kg}$</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.610 $\frac{W}{m - K}$</td>
</tr>
<tr>
<td>Dynamic Viscosity</td>
<td>$8.51 \times 10^{-4} \frac{kg}{m - s}$</td>
</tr>
<tr>
<td>Density</td>
<td>997 $\frac{kg}{m^3}$</td>
</tr>
</tbody>
</table>

Lastly, material properties are initialized for carbon steel and aluminum. For this case, the materials’ thermal conductivity, specific heat capacity, and density are specified in a similar manner as the fluid properties.

Other sections of the SAM code are required to output and post-process the data. Several post-processors are implemented to output a variety of information to a csv file. This is the preferred method to obtain component inlet and outlet data for pressure, velocity, or temperature, just to name a few. Preconditioning the Jacobian-Free Newton-Krylov Methods (JFNK) solver also takes place to assist in solving the governing equations (Hu, 2017). In this case, a single matrix preconditioner is used with preconditioning as the PETSc option and LU preconditioning in the Krylov solve (Hu, 2017). Furthermore, the model uses the trapezoidal integration rule with first order quadrature and the implicit-Euler temporal discretization to increase the accuracy of calculations. In this case, the code is run as a transient for 500 s using 2000 time steps. The maximum allowed time step is one second and the minimum allowed time step is 0.001 s. Changing any of the values discussed above can either increase or decrease the precision and accuracy of the SAM calculation.
3.1.3 SAM MSRE Water Mockup Model Results

The primary parameters to check the hydraulic model of the water mockup are pressure or head losses throughout the system. It is assumed that pressure taps exist at the inlet and outlet of each component in the physical MSRE.

To provide both a qualitative and quantitative assessment of the SAM MSRE water mockup model, pressure loss results from the code are compared to MSRE water mockup measurements provided by Kedl (1970). This serves as a preliminary validation exercise of the SAM water mockup model. The results from Kedl (1970) are for a variety of different flow rates. Therefore, SAM was run for a variety of flow rates to complete this comparative analysis. Head losses are compared for both the core and the complete mockup. Good alignment between experimental and simulated results indicates that the core geometry, loss coefficients, and dimensions have been modeled accurately on SAM over a range of flow rates. Figure 3-8 shows this comparison. This figure shows the core head loss results for the water mockup model with varying core ring flow areas.
The next step is a comparison of the system head loss. The system head loss is determined by summing each individual component’s contribution. Once again, values from SAM are plotted in comparison to experimental results presented by Kedl (1970). This comparison also includes the relative percent difference between both sets of data. Figure 3-9 shows this comparison and percent difference for the system head loss at different flow rates. The figure again only shows head loss data for the water mockup model with varying ring flow areas.
An additional SAM water mockup model was created with equal flow areas for each core ring. This model was simulated with varying coolant flow rates just like the non-equal flow area model. Figure 3-10 shows the head loss comparison between the two models and how they both compare to experimental results. This implies that the geometry and loss coefficients have been correctly applied to both water mockup models over a range of flow rates.
The relative percent differences between both SAM models and experimental results are both shown on Figure 3-11. These are shown as discrete points at each flow rate. As expected, both models align extremely well with experimental results with particularly good alignment between flow rates of 600 and 700 gpm. The figure shows some potential bias in SAM results. At lower flow rates, there is a positive bias in pressure drop while at higher flow rates there is a negative bias. The data point at 1200 gpm is considered an outlier as that flow rate might be at system limitations. No bias is shown at mid-range flow rates. The reasoning for this bias is not clear at this time. Nonetheless, this shows validation of the SAM MSRE closed loop model implying that the geometry and fluid dynamics are behaving as anticipated, especially for mid-range flow rates. This
analysis also gives confidence that the 1-D system description for the water mockup model is consistent over a range of flow rates.

Figure 3-11: Relative Percent Difference between Both SAM Models and Experimental Data

Some additional comparisons are made between the SAM MSRE water mockup model and experimental data found in Kedl (1970). One such comparison is for the system inlet velocity. This is the velocity at the inlet of the “p102” component, which is the pipe that directly connects to the inlet of the system. Kedl (1970) referenced this value as $5.85 \, \frac{m}{s}$, while SAM compares well to this with a value of $5.87 \, \frac{m}{s}$. On the other hand, the velocity at the downcomer exit did not compare well. Kedl (1970) references a velocity of $1.68 \, \frac{m}{s}$ whereas SAM calculates a velocity of $0.66 \, \frac{m}{s}$. This difference is likely caused by 1-D SAM modeling of the downcomer region. In reality, the MSRE water mockup has complex 3-D flow in this area. The 3-D flow is further complicated in the downcomer due to a series of holes and flow redistributions housed in the upper portion of the
downcomer, which is known as the volute. Flows observed here would be best modeled with a CFD code, a future work for this project. Nonetheless, the alignment between model and experiment for head loss gives preliminary validation of the SAM model with its physical counterpart. More specifically, SAM nearly replicates experimental data for two geometries over various flow rates. The overall results of this section are shown in comparison to those from both the MSRE in Kedl (1970) and RELAP5-3D model in Carbajo et al. (2017) in Table 3-6. The results shown reflect a flow rate of \(75.7 \frac{L}{s}\).

Table 3-6: Comparison of SAM MSRE Water Mockup with Other Models

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pipe velocity (m/s)</td>
<td>5.87</td>
<td>5.85</td>
<td>5.85</td>
</tr>
<tr>
<td>Bottom of downcomer velocity (m/s)</td>
<td>0.66</td>
<td>0.66</td>
<td>1.68</td>
</tr>
<tr>
<td>Core Head Loss (kPa)</td>
<td>1.91</td>
<td>1.78</td>
<td>1.79</td>
</tr>
<tr>
<td>System Head Loss (kPa)</td>
<td>44.9</td>
<td>44.7</td>
<td>44.8</td>
</tr>
</tbody>
</table>
Chapter 4
MSRE Primary Model

This chapter discusses the details of the SAM simulation of the MSRE primary loop. The first section discusses details of the SAM model for the complete MSRE loop. The second section delves into the preliminary assessment of this SAM model. Finally, several additional studies with varying input conditions help to show the versatility of the SAM model. This includes changing core components, coolant properties, axial nodalizations, core ring flow areas, and demonstrating a transient.

4.1 SAM MSRE Primary Model Details

4.1.1 MSRE Primary Loop General Information

The MSRE primary loop is very similar to its simplified water mockup counterpart. All piping components of the water mockup are of the same size in the closed loop. The 1140 core channels are consistent in the MSRE closed loop. However, the loop model describes MSRE operation with heat generated due to fission in the fuel channels. An additional difference is that the materials have changed. To transport molten FLiBe-based salt, the MSRE closed loop piping is made of Hastelloy-N rather than carbon steel. The core channels are surrounded by graphite in the closed loop as opposed to aluminum in order to facilitate neutron moderation necessary for thermal fission. The closed loop contains a heat exchanger that serves as the principle connection and heat transfer component of the model. A secondary side is necessary to serve as the heat sink for the primary loop. In the actual MSRE, the secondary side contains two main components: a
coolant pump and radiator. The coolant pump is necessary to circulate the highly dense FLiBe coolant around the secondary loop. The radiator serves as a heat sink to the atmosphere. Moreover, to facilitate the transport of the molten salt around the primary side of the MSRE, a fuel pump is installed to circulate the dense liquid. Finally, a cover gas is added to the closed loop to protect the molten salt from contact with air or moisture in order to mitigate pipe corrosion. There are many other components that constitute the MSRE; however, the ones discussed here capture the scope of SAM modeling completed in this project. Some of the other components are shown in the 3-D MSRE layout shown in Figure 4-1.

Figure 4-1: MSRE 3-D Layout (Guymon, 1973)
4.1.2 SAM MSRE Primary Loop Model Description

Figure 4-2 shows a detailed nodalization of the SAM MSRE primary loop model.

One difference between the MSRE water mockup and closed loop model are material properties. Properties for Hastelloy-N are added to the SAM input deck to represent the piping material. The thermal conductivity, specific heat, and density are specified in Robertson (1965). To represent the structure surrounding the core fuel channels, the SAM MSRE closed loop utilizes graphite properties. The specific heat and the density are specified in Robertson (1965). The density assumed for graphite is $\rho = 2266 \frac{kg}{m^3}$. The specific heat and thermal conductivity are given as
functions of temperature. The function for graphite’s thermal conductivity is consistent with Carbajo et al. (2017).

The final material modification is for coolant properties. The primary side coolant of the MSRE closed loop also acts as its fuel, whose functionality differs from its non-fissile secondary side. Nonetheless, the SAM MSRE closed loop model utilizes various built-in properties. This modeling capability allows the user to select the specific salt type that best represents the coolant being modeled. For this model, the salt selected is FLiBe, which very closely resembles the MSRE secondary side coolant. FLiBe also serves as an accurate approximation for the primary side fuel/coolant since it is mainly composed of the same elements. The specific correlations that SAM uses to represent FLiBe can be found in Hu (2017).

Although the core rings will maintain the same geometry and dimensions as the water mockup model, they must be heated by assuming a volumetric power for each ring segment. In the MSRE, the power in the core region is divided between the fuel/coolant and structure. 94% (or $9.4 \, MW$) is deposited into the fuel/coolant while the remaining 6% (or 0.6 $MW$) is deposited into the structure (Carbajo et al., 2017). However, for purposes of steady state SAM modeling, all power is assumed to be deposited into the fuel (10 $MW$). Taking the power deposited into the fuel/coolant and dividing by the fluid volume of the four rings gives $1.88 \times 10^7 \, \frac{W}{m^3}$. Preliminary analysis showed that this volumetric heat source gives linear axial heat transfer to the fuel/coolant, as expected. However, this is not what occurs physically since the temperature change should be more reflective of a sinusoidal power profile. An axial power profile must be input in order to simulate the proper core heat transfer. This analysis does not include any radial heat transfer. Radial heat transfer could be considered with the addition of a Bessel function. The Bessel function would be used to create a radial power distribution using normalized power based on the relative volumetric
heat generation in each ring. Different power levels would be established in each of the four core rings. Figure 4-3 below shows the assumed axial power profile.

![Assumed Power Profile for SAM MSRE Primary Loop Model](image)

Figure 4-3: Assumed Power Profile for SAM MSRE Primary Loop Model

For the core rings to capture the change in power over their axial length, each ring is divided into 20 equal segments to represent the nodes in the power profile. Each segment is of length 0.08 m and of fluid volume 0.0265 m$^3$. Summing the power in each pipe segment matches with the total power applied to the entire core, 10 MW.

The cover gas is a unique component necessary for modeling of the SAM MSRE closed loop. The pressure is assumed constant for the SAM cover gas and is set to 0.1 MPa, the approximate system pressure of the MSRE. An arbitrary pipe of the same material and geometry as the majority of other piping components in the closed loop model is used to connect the cover gas to the remainder of the system. The only difference is that its length is 0.1 m to minimize the
height of this artificial component. This is an approximate method for adding a cover gas component with SAM.

The next component in the SAM MSRE closed loop model is a fuel pump that maintains circulation of the fuel/coolant. It also acts as a junction point between two pipes. The pump’s reference area is $0.0127 \text{ m}^2$, consistent with its connecting pipes. To control the fuel/coolant mass flow rate throughout the system, the pump head is set to $0.092 \text{ MPa}$ which delivers the total expected mass flow rate to the core component, $171 \frac{kg}{s}$ per Robertson (1965). At the exit of the pump lies the “p101H” component, a horizontally oriented pipe that serves as the connection between the fuel pump and heat exchanger of the SAM MSRE closed loop model. The cross-sectional area of the “p101H” component is $0.0127 \text{ m}^2$ with hydraulic diameter of $0.127 \text{ m}$ (Robertson, 1965). The pipe roughness of this component is assumed to be $1.0 \times 10^{-4} \text{ m}$. The length of the “p101H” component is $1.68 \text{ m}$, per drawing ORNL DWG 64-8810 in Robertson (1965).

The most complex component in the model is the heat exchanger. It is a U-tube countercurrent heat exchanger with a primary side shell and secondary side tubes. Figure 4-4 below shows a cutaway drawing of the MSRE heat exchanger.
The heat exchanger is horizontally oriented at 1.83 m in length (Holcomb et al., 2009). Although the tubes are arranged into a U-tube configuration, the SAM modeling assumes that it is a single pass heat exchanger, which essentially doubles the number of tubes maintaining a consistent length of 1.83 m for both the primary and secondary sides of the heat exchanger. This heat exchanger has a 0.0197 m triangular pitch with outer tube diameter of 0.0127 m (Holcomb et al., 2009). This means that the equivalent diameter, or hydraulic diameter, of the secondary tube side can be determined as follows (Lee 2010):

\[
D_e = \frac{4 \left( \frac{\sqrt{3} P_t^2}{4} - \frac{\pi D_o^2}{8} \right)}{\pi D_o \frac{D_o}{2}}
\]

\[
\therefore D_e = 0.0209 \text{ m}
\]
This value for the equivalent diameter is entered on SAM as the secondary side hydraulic diameter. The flow area of the secondary side tubes can be found by first determining the inner tube diameter. This calculation requires the tube thickness, given as 0.00107 m per Holcomb et al. (2009).

\[ D_i = D_o - 2t \]

\[ \therefore D_i = 0.0106 \text{ m} \]

The secondary flow area can now be calculated using the total number of tubes, 318.

\[ A_{oobs} = n \frac{\pi}{4} D_i^2 \]

\[ \therefore A_{oobs} = 0.0279 \text{ m}^2 \]

Now the process is repeated for the primary side shell. First, the flow area of the shell side will be determined (Lee 2010).

\[ A_{shell} = \frac{D_i C_t B}{P_t} \]

Holcomb et al. (2009) gives the baffle spacing as 0.305 m. Additionally, the shell outer diameter is listed as 0.406 m and the shell thickness is 0.0127 m. The shell inner diameter is calculated as follows:

\[ D_i = D_o - 2t_s \]

\[ \therefore D_i = 0.381 \text{ m} \]

The tube clearance is defined as the difference between the tube pitch and tube thickness. For the MSRE, the tube clearance is calculated to be 0.00699 m. With all of these sub-calculations, the primary side shell flow area can be determined.

\[ \therefore A_{shell} = 0.0412 \text{ m}^2 \]

This analysis has determined the shell side inner diameter, but this dimension does not account for the secondary side tubes. Therefore, the hydraulic diameter of the primary side must be calculated. The hydraulic diameter is dependent on the heated perimeter, which reflects the total number of tubes. Therefore, the hydraulic diameter for the primary side is 0.013 m.
This series of calculations for flow areas and hydraulic diameters is necessary since both are mandatory SAM inputs for both sides of the heat exchanger.

One important parameter in the SAM input that describes heat transfer between the two sides of a heat exchanger is the surface area density. This parameter is defined as the ratio between the heated surface area and the fluid volume.

\[ a_w = \frac{A_{surf}}{V} \]  

(4-6)

Both the heated surface area, \( A_{surf} \), and liquid volume, \( V \), will vary for both sides of the heat exchanger. First, the surface area density of the primary side is determined. \( L \) is the length of the heat exchanger, 1.83 m.

\[ V_{shell} = A_{shell}L \]  

(4-7)

\[ V_{shell} = 0.0754 \, m^3 \]

\[ A_{surf\, shell} = n\pi D_o L \]  

(4-8)

\[ A_{surf\, shell} = 23.2 \, m^2 \]

\[ a_{w\, shell} = 308 \, m^{-1} \]

This process is repeated for the secondary tube side.

\[ V_{tubes} = A_{tubes}L \]  

(4-9)

\[ V_{tubes} = 0.0511 \, m^3 \]

\[ A_{surf\, tubes} = n\pi D_i L \]  

(4-10)

\[ A_{surf\, tubes} = 19.3 \, m^2 \]

\[ a_{w\, tubes} = 378 \, m^{-1} \]

Another input that assists the SAM calculation is the convective heat transfer coefficient. This coefficient will be calculated and input for both the primary and secondary sides of the heat exchanger. The heat transfer coefficient is calculated nearly identically for both sides of the heat exchanger.
exchanger with differences in the temperatures and heated surface area. The expected change in temperature for the primary side fuel/coolant is $28 \text{ K}$ and the expected change in temperature for the secondary side coolant is $41 \text{ K}$ (Engel and Haubenreich, 1962). Iteration is used to determine the two convective heat transfer coefficients across both sides of the heat exchanger that match these expectations. This preliminary approach gives satisfactory results for the primary loop without considering the complete geometry details of the heat exchanger or assessing the appropriateness of different heat transfer correlations. The preliminary values used for the heat transfer coefficients are listed below.

$$h_{	ext{sh ell}} = 3.1 \times 10^4 \frac{W}{m^2 - K}$$

$$h_{	ext{tubes}} = 2.0 \times 10^4 \frac{W}{m^2 - K}$$

The SAM model includes a very simplified representation of the secondary side of its heat exchanger. The flow rate on the secondary side is $53.6 \text{ L s}^{-1}$ according to Robertson (1965). The secondary side coolant is FLiBe, whose density is dependent on temperature, but it has an assumed average value of $2000 \text{ kg m}^{-3}$. The flow rate and density are used to calculate the mass flow rate that is converted to a flow velocity. The secondary side coolant velocity is set to $1.3 \text{ m s}^{-1}$. This velocity is set as the secondary side inlet boundary condition along with a temperature of $825 \text{ K}$, the expected inlet temperature (Engel and Haubenreich, 1962). Pressure is set on the secondary side outlet to $0.1 \text{ MPa}$. 
4.2 SAM MSRE Primary Loop Model Results

4.2.1 Core Pipe Model Results

This section includes the results of using SAM pipe components for the MSRE core rings. SAM channel components will be evaluated in the next section. Using the pipe component means that any heat deposited into the graphite structure is ignored. All of the power is deposited into the molten salt fuel/coolant. The primary results shown in this section are fuel/coolant temperatures in the core and heat exchanger (including secondary side coolant of the heat exchanger). Core axial coolant temperatures were calculated during the MSRE program using data on the properties of the molten salt and the initial conditions of the system. According to Haubenreich et al. (1964), the specific calculation method involved the flow distribution of the water mockup combined with the power-density distribution prediction. Per Engel and Haubenreich (1962), the coolant temperature at the core inlet and outlet were estimated to be 908 K and 936 K, respectively. These are historical predictions of the molten salt temperatures taken during MSRE operation.

ParaView (Ayachit, 2017) was used to visualize how the coolant temperature changes throughout the system. Figure 4-5 shows the temperature changes throughout the SAM MSRE closed loop model. The visualization shows the locations of the core and primary side heat exchanger. It also displays the four core rings, three of whom appear to be disconnected from the rest of the system. This is simply a product of the visualization since the junction connecting the lower plenum to the four core rings has zero volume.
Results for axial coolant temperature profile are shown in Figure 4-6. Figure 4-7 shows the ParaView visualization for the four identical core rings.
Figure 4-6 shows slight variation with the expected results for the core inlet and outlet. The SAM model shows a core coolant temperature of 905 K at the inlet and 933 K at the outlet. These are slightly different than the approximated 908 K at the inlet and 936 K at the outlet (Engel and Haubenreich, 1962). Although both the core coolant inlet and outlet temperatures differ by 3 K with estimated results, the SAM calculated temperature change is consistent with the historical estimates (28 K). The properties of FLiBe used in SAM versus those used for the actual MSRE coolant differ and may contribute to the slight variation in temperature.

The heat exchanger coolant temperatures for both the primary and secondary sides can also be compared to calculated values. For the primary side, the axial coolant temperature is expected to decrease from 936 K to 908 K. For the secondary side, the axial coolant temperature is expected
to increase from $825 \, K$ to $866 \, K$ (Engel and Haubenreich, 1962). Figure 4-8 shows both the primary and secondary coolant temperatures for the heat exchanger.

![Figure 4-8: Heat Exchanger Primary and Secondary Coolant Temperature Profiles](image)

As seen with the core, the heat exchanger coolant temperature profiles are not exact matches with historical estimates. SAM is giving a primary heat exchanger coolant inlet temperature of $933 \, K$ and an outlet temperature of $905 \, K$, which aligns with the temperature change in the core but slightly differs from what is given by Engel and Haubenreich (1962). For the secondary side, the coolant inlet temperature is $825 \, K$ and the outlet temperature is $882 \, K$. This outlet temperature differs from the expected value of $866 \, K$. This can be attributed to two factors. One is that the SAM model assumes the same coolant and properties for both sides of the heat exchanger. In reality, as discussed earlier, the primary and secondary coolants differed. The main difference is that the primary side contained actinides to induce fission whereas the secondary side did not, a difference
not captured when using built-in FLiBe properties on both sides of the heat exchanger. Additionally, the MSRE heat exchanger contains U-tubes, whereas SAM modeling assumes straight tubes. This means single pass primary flow occurs in the SAM model but double pass flow occurs in the MSRE. These approximations were deemed acceptable, as the focus of this work is on the modeling of the primary side of the system.

Parameters other than fuel/coolant temperature are also analyzed. Figure 4-9 shows a ParaView representation of the pressure variation throughout the entire SAM MSRE closed loop model. The figure shows that the calculated system pressure increases prior to entry into the heat exchanger due to the presence of the fuel pump.

![Figure 4-9: ParaView Visualization of Pressure around SAM MSRE Primary Loop Model](image)

A profile of the core pressure drop is included in Figure 4-10. It is linear since there are no changes in flow area or structure angle in the core. Note that this plot only accounts for the pressure between the inlet and outlet of the component. If the total core head loss is desired, the form losses at the inlet of the component must be taken into account.
Velocity throughout the primary loop is another parameter relevant to this analysis, as shown in Figure 4-11. Note that the fuel/coolant velocity remains relatively constant throughout any component. This is because SAM calculates fluid velocity based on the flow area, density, and mass flow rate of the system. Both flow area and mass flow rate remain constant in each component. Density is temperature dependent, but since temperature never fluctuates over 30 $^\circ$C, the change in density is negligible.
Engel and Haubenreich (1962) provide limited calculated results for thermal hydraulic parameters other than temperature. Measured pressure data for the MSRE closed loop is unavailable since it would have been difficult to insert pressure taps given the high temperatures of molten salt. The same goes for fluid velocity, which had to be calculated. The velocity within the core was given as a range from \(0.18 \, \text{m/s}\) to \(0.61 \, \text{m/s}\) to account for the different concentric rings (Engel and Haubenreich, 1962). This reference does not state the exact axial location from which the core velocity was determined. The results from SAM give a core velocity at both the inlet and outlet of \(0.227 \, \text{m/s}\) for all rings since they are of equal flow area. This value does sit within the expected range.

A final set of comparisons is made with the core pipe model and results obtained by Carbajo et al. (2017) using RELAP5-3D (see section 2.2.1 for details). The results from Carbajo et al. (2017) were also calculated using a core power of 10 MW. A comparison of the various parameters from this present study, Carbajo et al. (2017), and Engel and Haubenreich (1962) are shown in Table 4-1 below. Note that this work is not a code-to-code comparison, but provides a comparison and sanity check between two 1-D system analysis codes.
Table 4-1: Comparison of SAM MSRE Primary Loop Model with Other Models

<table>
<thead>
<tr>
<th></th>
<th>Present Study</th>
<th>Carbajo et al. (2017)</th>
<th>Engel and Haubenreich (1962)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Coolant T\text{in} (K)</td>
<td>905</td>
<td>908</td>
<td>908</td>
</tr>
<tr>
<td>Core Coolant T\text{out} (K)</td>
<td>933</td>
<td>936</td>
<td>936</td>
</tr>
<tr>
<td>Coolant Flow Rate (L/s)</td>
<td>75.6</td>
<td>76.7</td>
<td>75.7</td>
</tr>
<tr>
<td>Core Velocity (m/s)</td>
<td>0.227</td>
<td>0.200 – 0.500</td>
<td>0.180 – 0.610</td>
</tr>
</tbody>
</table>

This comparison with the literature for the MSRE primary loop adds confidence to the calculations and approximations of the SAM input. The holistic description of MSRE in this thesis can also be applied to other system analysis tools.

4.2.2 Core Channel Model Results

The second study in the analysis of the SAM MSRE closed loop model is the implementation of channel components rather than pipe components to represent the core rings. The channels allow for modeling of 1-D flow with heat structures. This allows for accurate modeling of the graphite moderator of the MSRE core, key for transient analysis.

New inputs are required when using channel components. Heat structures are used to simulate the graphite stringer that surrounds the fuel/coolant channels. One key input for the heat structure is its width. The width of the heat structure can be approximated based on the geometry of the MSRE core channels. Revisiting Figure 3-7, the estimated width of the heat structure, or graphite, is assumed to be equal to the distance between fuel channels. This is found by removing the fuel channel radii from the total width of the graphite stringer.

\[
w_{hs} = w_{graphite} - 2R_{fuel} \quad (4-11)
\]

\[
\therefore w_{hs} = 0.0406 \text{ m}
\]
This value for the width of the heat structure was verified for both the horizontal and vertical directions. Finally, the flow area, hydraulic diameter, fluid properties, orientation, length, and position of the four core rings remains the same for the channel model.

The difference between the channel model and the pipe model is the addition of power assigned to the solid structure. This value is set to $0.03 \, MW$, or 6% of the total power divided by 20. The value is divided by 20 to account for the 20 axial channel segments, as was done with the core pipe model. This means that the volumetric power must be adjusted to reflect only 94% power deposition into the fuel/coolant. Additionally, the heated surface area density is now required. The calculation for the heated surface area density of the channel component is identical to that of the heat exchanger component. The value calculated is $171 \, m^{-1}$.

With the above adjustments to the core ring components, the core axial coolant temperature profile is compared to that generated in the pipe model. This is shown in Figure 4-12.

![Figure 4-12: Core Temperature Profile Comparison between Pipe and Channel Model](image)
The figure shows that the pipe and channel models are offset by about 1 $K$ throughout the axial direction. Moreover, the axial change in coolant temperature of the core component is identical between the pipe and channel model. This is expected since the overall reactor power is the same between both models. Additionally, the same flow rate and heat capacity function are used between the two models.

The axial temperature profile of the graphite is plotted in Figure 4-13. The figure shows a linear increase in the temperature of the graphite, which is expected given the current SAM input. In reality, the graphite temperature profile should resemble sinusoidal characteristics with a distinct maximum critical point slightly off the axial center location, but there is no input in the model to obtain the expected curvature. A heat loss component or function has not been added to the SAM input.

![Graphite Temperature Profile](image)
Engel and Haubenreich (1962) gives a maximum graphite temperature of $975 \, K$. The SAM results give a maximum graphite temperature of $969 \, K$, which is reasonable compared to historical estimates. Finally, the temperature profiles of the primary and secondary sides of the heat exchanger are shown in Figure 4-14 to check consistency with the pipe model. The primary side of the heat exchanger shows the opposite behavior of the core, as expected. The secondary side of the heat exchanger matches the expected inlet coolant temperature of $825 \, K$, but is slightly high for the outlet at $889 \, K$, a similar trend seen when using pipe components in the core. Nonetheless, the similar trends observed with the heat exchanger temperature profiles for either channel or pipe core components shows model consistency. Overall, this section shows that channels can be used rather than pipes and still deliver reasonable results in comparison to MSRE data.

Figure 4-14: Heat Exchanger Coolant Temperature Profiles for Core Modeling with Channel Components
4.2.3 Alternative Coolant Properties Study

All of the previous results presented in this thesis utilized SAM built-in salt properties for FLiBe. However, the true fuel/coolant in the MSRE was not FLiBe, as described earlier. Although using the SAM built-in properties of FLiBe gives relatively accurate results, Robertson (1965) provided constant properties for three different salts used during original MSRE testing. These salts all had different concentrations of constituent molecules, as shown in Table 4-2. The three salts are labeled in this table as “MSRE 1”, “MSRE 2”, and “MSRE 3”. Robertson (1965) specified that “MSRE 1” was a thorium-uranium blend of fuel. It goes on to state that “MSRE 2” was composed of highly enriched uranium and “MSRE 3” was composed of partially enriched uranium. The enrichments of “MSRE 2” and “MSRE 3” were 93% and 35% U-235, respectively (Robertson, 1965). These three salts will be simulated in the SAM MSRE closed loop model.

Additionally, Cantor et al. (1968) provided temperature dependent properties for future MSR or Molten Salt Breeder Reactor (MSBR) test salts. The salts provided by Cantor et al. (1968) were never used in the MSRE; however, they allow for a comparison against those that were actually used. Table 4-2 below breaks down the molecular composition of these salts. The test salts given by Cantor et al. (1968) are labeled as “Salt 1”, “Salt 2”, “Salt 3”, and “Salt 4” in Table 4-2. Other than specific properties, there were two primary differences between the salts given by Robertson (1965) and Cantor et al. (1968). First off, the salts given by Robertson (1965) all contained ZrF₄ that assisted in protecting the fuel from UO₂ precipitation due to contact with air or water. Most importantly, the salts differed in their actinide chemistry. The salts provided by Cantor et al. (1968) contained about ten times more actinides than those given by Robertson (1965). These differences in chemistry will certainly have an impact with thermal hydraulic analysis when simulated in the SAM MSRE model.
Robertson (1965) gave constant thermophysical properties for the MSRE salts. On the other hand, Cantor et al. (1968) listed specific expressions used to describe the properties of these fuel/coolant salts. Below is an example of the expressions for Salt 1. The remainder can be found in Cantor et al. (1968). The thermal conductivity and coefficient of thermal expansion were given as constants, $0.01 \frac{W}{cm\cdot\mathbf{\circ}C}$ and $2.0 \times 10^{-4} \circ C^{-1}$, respectively (Cantor et al., 1968).

**Viscosity**

$$\nu = 0.084 \exp\left(\frac{4340}{T}\right)$$

(4-12)

$\nu$ = viscosity in centipoise

$T$ = temperature in K

**Specific Heat Capacity**

$$c_p = 0.22 + 12.7 \times 10^{-5} T$$

(4-13)

$c_p$ = specific heat capacity in $\frac{cal}{g\cdot\circ C}$

$T$ = temperature in $\circ C$

**Density**

$$\rho = 3.628 - 6.6 \times 10^{-4} T$$

(4-14)

$\rho$ = density in $\frac{g}{cm^3}$

$T$ = temperature in K
The properties that are in equation form are entered as functions of temperature on SAM. An additional change to the SAM input deck accounts for the difference in density of these salts. Most of the salts have an average density that is 1.5 times greater than that of SAM built-in properties for FLiBe. This implies that the discharge head on the fuel pump must be adjusted to maintain a volumetric flow rate of about $75.7 \frac{L}{s}$.

With the previously mentioned code modifications, SAM is executed using the properties of the seven different fuel salts. Axial core coolant temperature profiles are generated with the different fuel/coolant salts of the four-ring model. Figure 4-15 shows the comparison of these temperature profiles against one another and SAM built-in FLiBe properties.

![Figure 4-15: Core Coolant Temperature Profile Comparison of Different Fuel Salts](image)

As seen in Figure 4-15, the core coolant temperature profiles of the different fuel salts exhibit the same trends as the profile for built-in FLiBe properties. The MSRE salts all have a positive bias.
when compared to built-in FLiBe properties, whereas the proposed salts all have a negative bias. This is further demonstrated by directly comparing the inlet and outlet core fuel/coolant temperatures and the change in temperature between these points. This is shown in Table 4-3.

Table 4-3: Core Fuel/Coolant Temperature Comparisons

<table>
<thead>
<tr>
<th></th>
<th>T&lt;sub&gt;in&lt;/sub&gt; (K)</th>
<th>T&lt;sub&gt;out&lt;/sub&gt; (K)</th>
<th>ΔT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLiBe</td>
<td>905.4</td>
<td>933.3</td>
<td>27.9</td>
</tr>
<tr>
<td>MSRE 1</td>
<td>906.8</td>
<td>940.6</td>
<td>33.8</td>
</tr>
<tr>
<td>MSRE 2</td>
<td>908.6</td>
<td>939.9</td>
<td>31.3</td>
</tr>
<tr>
<td>MSRE 3</td>
<td>908.0</td>
<td>939.8</td>
<td>31.8</td>
</tr>
<tr>
<td>Salt 1</td>
<td>901.2</td>
<td>929.9</td>
<td>28.7</td>
</tr>
<tr>
<td>Salt 2</td>
<td>903.4</td>
<td>929.1</td>
<td>25.7</td>
</tr>
<tr>
<td>Salt 3</td>
<td>903.3</td>
<td>929.4</td>
<td>26.1</td>
</tr>
<tr>
<td>Salt 4</td>
<td>903.4</td>
<td>929.8</td>
<td>26.4</td>
</tr>
</tbody>
</table>

According to Table 4-3, the axial difference in coolant temperature between the core inlet and outlet also varies with the FLiBe case. The differences can be attributed to different correlations or values used for the specific heat capacity between all of the cases in Table 4-3. Additionally, the differences in temperatures can be attributed to the significant differences in actinide chemistry between the classes of salts. In other words, having a greater concentration of thorium or uranium makes a significant difference in coolant heat transfer as thermophysical properties will vary. Furthermore, the molecular compositions of LiF and BeF<sub>2</sub> are likely different for the built-in properties when compared to the seven different fuel/coolant salts. This is also true when considering actinide content since SAM built-in properties do not contain any. Overall, the reasonable alignment between the built-in properties and the different fuel/coolant salts shows that either form can be used to simulate the MSRE with SAM; however, actinide content likely contributes to the differences seen in the temperature profiles.
4.2.4 SAM Nodalization Study

Several studies are performed to confirm that the nodalization selected for the SAM primary loop model is adequate. The first nodalization study is applied to the pipe components that compose the core rings. 5, 10, and 20 axial nodes are simulated on each of the 20 pipe segments. Figure 4-16 shows a comparison of the core fuel/coolant temperature profiles using different number of nodes. The results indicate there are no significant changes to the temperature profile for 10 or 20 nodes, but using 5 nodes is insufficient. This analysis shows that either 10 or 20 axial nodes can be used in the core to deliver similar results. This means simulating more than 20 nodes is unnecessary since convergence is obtained once 20 axial nodes are simulated.

![Figure 4-16: Axial Node Variation Comparison for Core Temperature Profile](image-url)
The same process is repeated for the heat exchanger. Figure 4-17 shows the primary coolant temperature profile of the heat exchanger using the different nodalizations, indicating convergence for all cases.

Figure 4-17: Axial Node Variation Comparison for Heat Exchanger Primary Coolant Temperatures

The secondary side coolant temperatures are also analyzed. These results are shown in Figure 4-18. As observed with the primary side, all nodalizations align nearly identically with one another meaning that any can be used for analysis of the MSRE.
For both the core and heat exchanger, the temperature changes over time are checked for the different nodalizations. While this remains a spatial discretization, it is important to ensure that the different nodalization schema behave similarly over the time domain. Only one of the nodalizations needs to be checked to ensure that SAM has truly converged to a solution. Nonetheless, all of the axial nodalizations are shown on the next two figures for both the core and heat exchanger. Both plots feature the inlet coolant temperature of the specified component. They also show convergence to a certain temperature after around 450 s. Figure 4-19 shows the temporal convergence for the core coolant inlet temperature while Figure 4-20 shows the same for the inlet of the primary side of the heat exchanger.
Figure 4-19: Axial Node Variation Comparison over Time for Core Inlet Coolant Temperature
Figure 4-20: Axial Node Variation Comparison over Time for Primary Side of Heat Exchanger Coolant Temperature

Performing this nodalization check on other parameters verifies that physical solutions are obtained universally with the same discretization. For example, Figure 4-21 shows how well the core outlet pressure converges with different axial node sizes over time. Figure 4-21 shows that convergence is reached for the core outlet pressure after around 450 s, just like the core inlet coolant temperature.
Figure 4-21: Axial Node Variation Comparison over Time for Core Outlet Pressure

Figure 4-22 shows the same information as Figure 4-21 but only shows data up to 25 s. Figure 4-22 shows general alignment early in the run amongst the three nodalizations with poorer results from the 5 node case, as expected. The figure also shows that the 5 node case does not run for the entirety of the sequence. Similarly, the process is repeated for the outlet coolant velocity of “p101H,” the pipe component that connects with the inlet of the heat exchanger. This result is shown in Figure 4-23.
Figure 4-22: Zoomed-in Axial Node Variation Comparison over Time for Core Outlet Pressure

Figure 4-23 shows that convergence is reached for the velocity after around 300 s, earlier than with temperature. Figure 4-24 shows a zoomed-in version of Figure 4-23. Once again, good alignment is seen between the finer nodalizations.
Figure 4-23: Axial Node Variation Comparison over Time for “p101H” Coolant Inlet Velocity
4.2.5 Alternative Core Ring Modeling

Up to this point, all results for the SAM MSRE closed loop model have reflected four equally sized core rings. These simulations have given reasonable alignment with calculated results; however, different sized core rings, or regions, were used in order to calculate the expected temperature distributions of the MSRE (Engel and Haubenreich, 1962). These core regions all contained slightly different flow areas as different numbers of fuel channels were included in each one. All but two of the fuel channels were included in the analysis bringing the total to 1138 (Engel
and Haubenreich, 1962). Incorporating this modeling strategy means some alterations are needed for the SAM input deck.

Table 4-4 shows a summary of the changes made to the core regions of the SAM MSRE closed loop model. The fluid dynamic changes involve the flow areas, ring x-coordinate positions, and loss coefficients. Loss coefficients are listed in order of core inlet followed by core outlet. The most prevalent change is that the flow areas now differ for each core ring. Table 4-4 also shows the values used in the original SAM runs of this work.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ring 1</th>
<th>Ring 2</th>
<th>Ring 3</th>
<th>Ring 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels</td>
<td>12</td>
<td>940</td>
<td>108</td>
<td>78</td>
</tr>
<tr>
<td>New Flow Area (m²)</td>
<td>0.00346</td>
<td>0.271</td>
<td>0.0311</td>
<td>0.0225</td>
</tr>
<tr>
<td>Original Flow Area (m²)</td>
<td>0.0829</td>
<td>0.0829</td>
<td>0.0829</td>
<td>0.0829</td>
</tr>
<tr>
<td>New x-Coordinate (m)</td>
<td>0</td>
<td>−0.0960</td>
<td>−0.629</td>
<td>−0.663</td>
</tr>
<tr>
<td>Original x-Coordinate (m)</td>
<td>0</td>
<td>−0.176</td>
<td>−0.352</td>
<td>−0.528</td>
</tr>
<tr>
<td>New Loss Coefficient</td>
<td>17.1, 17.1</td>
<td>16.1, 16.8</td>
<td>16.9, 17.1</td>
<td>17.0, 17.1</td>
</tr>
<tr>
<td>Original Loss Coefficient</td>
<td>16.7, 17.0</td>
<td>16.7, 17.0</td>
<td>16.7, 17.0</td>
<td>16.7, 17.0</td>
</tr>
</tbody>
</table>

The new flow areas are determined by taking the flow area of one fuel channel \(2.88 \times 10^{-4} \text{ m}^2\) and multiplying by the number of channels per ring shown in Table 4-4. The x-coordinate positions of each ring reflect the effective outer radii of each core region given in Engel and Haubenreich (1962). Finally, the loss coefficients for both the inlet and outlet of each ring are determined by using the same methods shown in Section 3.1.2.

Heat transfer related parameters should also change since non-equal flow areas are now being tested. The volumetric heat source is the primary SAM input that drives heat transfer in the core rings. With the new flow areas, the volume of each ring segment correspondingly changes. Fuel fractions are then calculated for each ring by taking the individual ring flow area divided by the total flow area.
Results are obtained for various thermal hydraulic parameters of this study. Two main input decks area executed: one with built-in FLiBe properties and the other with user-defined EOS for Salt 1 (see Section 4.2.3 for details). The next two figures show the core coolant axial temperature profiles for both of these cases. Both plots compare the temperature profiles of the equal and non-equal ring flow areas. Similar trends are seen between the two figures when using non-equal ring flow areas. Overall, these plots serve as sanity checks to ensure that consistency is maintained with equal versus non-equal core ring flow areas. The maximum differentiation between the two profiles is near the core inlet and outlet where differences in loss coefficients are prevalent. However, these attributes only have a maximum relative difference of 0.214% for built-in EOS and 0.107% for user defined EOS. The expected axial change in temperature should be $28 \, K$ for this analysis but it is $30 \, K$ and $29 \, K$ for the built-in EOS and user-defined EOS, respectively. This results in as high as a 7.14% relative difference between expected results. Figure 4-25 shows this comparison with built-in EOS while Figure 4-26 shows the same comparison using user-defined functions for the EOS.
Figure 4-25: Coolant Temperature Profile Comparison between Equal vs. Non-Equal Ring Flow Areas Using Built-In EOS
A more thorough comparison is possible using the expected flow rates and effective velocities for each core region given by Engel and Haubenreich (1962). The only downside of the effective velocities is that the reference does not state where in the core rings the data was measured. Rather, the values were estimated based on experimental results on the one-fifth scale water mockup of the MSRE. Therefore, a precise comparison between the reference’s data and SAM simulations is unlikely. Nonetheless, the data set provided by Engel and Haubenreich (1962) should trend in a similar manner as the results from SAM. Table 4-5 below shows a comparison between the flow rates from Engel and Haubenreich (1962), the built-in EOS SAM model (FLiBe), and the user-defined EOS SAM model (Salt 1). Flow rates from the SAM model are based on the flow area of the core rings along with the inlet velocity and density of the fuel/coolant (see Section 4.1.2 for details). Table 4-6 shows a similar comparison but with effective fluid velocity. The discharge head
of the fuel pump was adjusted in order to maintain a total volumetric flow rate of approximately \(75.7 \frac{L}{s}\) for all runs.

Table 4-5: Comparison of Flow Rates between Estimated Data and SAM Models

<table>
<thead>
<tr>
<th></th>
<th>Ring 1</th>
<th>Ring 2</th>
<th>Ring 3</th>
<th>Ring 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engel and Haubenreich (1962) (L/s)</td>
<td>4.54</td>
<td>49.9</td>
<td>14.1</td>
<td>5.62</td>
</tr>
<tr>
<td>SAM Built-In EOS (L/s)</td>
<td>0.733</td>
<td>64.1</td>
<td>6.72</td>
<td>4.82</td>
</tr>
<tr>
<td>SAM User Defined EOS (L/s)</td>
<td>0.702</td>
<td>61.6</td>
<td>6.43</td>
<td>4.64</td>
</tr>
</tbody>
</table>

Table 4-6: Comparison of Effective Fluid Velocities between Estimated Data and SAM Models

<table>
<thead>
<tr>
<th></th>
<th>Ring 1</th>
<th>Ring 2</th>
<th>Ring 3</th>
<th>Ring 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engel and Haubenreich (1962) (m/s)</td>
<td>0.607</td>
<td>0.183</td>
<td>0.454</td>
<td>0.250</td>
</tr>
<tr>
<td>SAM Built-In EOS (m/s)</td>
<td>0.212</td>
<td>0.236</td>
<td>0.215</td>
<td>0.215</td>
</tr>
<tr>
<td>SAM User Defined EOS (m/s)</td>
<td>0.203</td>
<td>0.226</td>
<td>0.206</td>
<td>0.205</td>
</tr>
</tbody>
</table>

Both tables show misalignment between SAM results and estimated data. The SAM results for the flow rates do trend in the same direction as the results given by Engel and Haubenreich (1962). No trends are observed for the velocities. SAM gives relatively constant fluid velocities for each core ring, whereas the reference gives slightly varying values. The differences in both the flow rates and the effective fluid velocities can be attributed to loss coefficient modeling. It is unclear how Engel and Haubenreich (1962) accounted for loss coefficients in their estimates and measurements. It is also unknown as to what the effective fluid velocity exactly represents (e.g. it might be an averaged value). With SAM, the velocity was observed to remain relatively constant throughout the entire axial length of the core rings. This is unknown with MSRE measurements and estimates. Further understanding of how data was recorded and/or calculated with the MSRE may shed some light on the differences seen in this particular study. This section of the project brings about questions about the validity of the data given by Engel and Haubenreich (1962) for the varying ring flow areas.
4.2.6 SAM Flow Perturbation Response

Steady state analysis, which reflects the results shown previously, does not mimic the conditions associated with accident scenarios. However, different accidents have various repercussions for all reactor types. For MSRs, one of the design basis accidents (DBA) is a flow perturbation that leads to a loss of flow accident. A flow perturbation can be caused by a pump failure, which could be due to station blackout. This means that the molten salt fuel/coolant remains nearly stationary in the MSRE loop. This fuel/coolant is heated and needs to reach the heat exchanger to cool. Fission will still occur in the core meaning that a flow perturbation leads to rising fuel/coolant temperatures, which changes the physical properties of the system. Depending on how high these temperatures reach, certain structural components could potentially melt creating the hazard of radiation leakage to containment. Therefore, the transient run with SAM is a pump trip, which incorporates a pump coastdown curve.

A pump coastdown curve describes how the pump discharge head changes over time as it approaches zero, the condition of no pump power. The pump curve used in this work is derived from Gao et al. (2010). Figure 4-27 below shows the pump coastdown curve incorporated into the SAM model. It is initialized as a function to represent the fuel pump discharge head following the point where steady state is reached. Steady state is reached at around 450 s, but for programming purposes, this value is rounded up to 500 s. This implies that the flow perturbation begins at 500 s. Essentially, a null transient is performed up to this point. Therefore, all plots for this simulation are scaled to begin at 500 s meaning the null transient is not displayed. It is also important to note that the specific SAM model used to run this demonstration utilizes channel components rather than pipe components for the core rings. This is an acceptable modeling approach since channel components are needed to simulate any feedback to the graphite that would occur during an accident.
Figure 4-27: Pump Coastdown Curve Incorporated into SAM Fuel Pump

SAM is executed for a total of 900 s to simulate both steady state and transient conditions. It is important to note that this work only reflects a transient demonstration since a SCRAM and reactivity feedback are not modeled. Results are then analyzed for the fuel pump and core. First off, the pump discharge head is analyzed as a sanity check of the pump coastdown. This is shown in Figure 4-28.
Figure 4-28: Fuel Pump Discharge Pressure Before and After Transient

The discharge head trend after 500 s closely resembles the pump curve shown in Figure 4-27 giving confidence that the pump coastdown function has been properly implemented on SAM. Additionally, the fuel pump coolant velocity is plotted over time to ensure that it is also decreasing towards zero after the pump curve was initiated. This also sheds light on delayed neutron precursors that are transported around the primary loop in MSRs. Delayed neutron precursors are not accounted for here since this project only covers thermal hydraulic analysis; however, this phenomena would be observed if this analysis were coupled to a neutronics tool. The fuel pump coolant velocity is shown in Figure 4-30. Note that the actual coolant velocity decreases to around $0.9 \frac{m}{s}$, not zero, since there is very minor discharge head still exiting the pump. The lowest pump discharge head is near 400 $Pa$ since complete shutoff was not simulated. When complete pump shutoff is incorporated, SAM encountered convergence challenges since the discharge head is too
low (around 100 Pa or less) causing the molten salt to have difficulty maintaining flow throughout the system. Therefore, natural circulation has not been reached in this simulation.

Figure 4-29: Fuel Pump Coolant Velocity Before and After Transient

Some of the thermal hydraulic parameters that describe the SAM core rings also show changes once the flow perturbation is initiated. One such change is with the core coolant mass flow rate, which greatly decreases after the transient begins, as expected. The mass flow rate through the outlet of one of the four core rings is shown in Figure 4-30. This parameter decreases to roughly $5.0 \frac{kg}{s}$ at 900 s. Further, the curvature on Figure 4-30 closely resembles that of the pump coastdown curve, which is also expected.
More differences are observed when analyzing the core inlet and outlet coolant temperatures before and after the transient is initiated. The core coolant temperatures over time are shown in Figure 4-31.
Figure 4-31: Core Inlet and Outlet Coolant Temperatures Before and After Transient

Once the transient begins, the core inlet temperature decreases while the core outlet temperature increases. This divergence, or increase in the axial change in coolant temperature, indicates that power is being conserved. When the fuel pump starts to fail, the mass flow rate of the coolant decreases everywhere, including the core as seen in Figure 4-30. In order to maintain the same power, the change in coolant temperature must increase as coolant mass flow rate decreases. Maintaining a consistent power is what leads to the divergence in temperatures seen in Figure 4-31. Furthermore, coupling to neutronics helps to further understand reactivity feedback of MSRs. As the change in temperature continues to increase, the coolant density will also change, affecting feedback and potentially fission power. Moreover, the safety potential of commercially implementing the MSR is demonstrated by executing this transient. Although the coolant temperature increases to near 1000 $K$ towards the end of the transient, the molten salt is still well
below its boiling point of nearly 1670 K (Elsheikh, 2013). This demonstration also shows that during a pump trip accident, operators will have enough time (roughly 8.33 minutes in this case) to act in order to prevent the situation from further deteriorating. This action could be draining the molten salt out of the system and into a large volume at lower temperatures to freeze the salt. Nonetheless, this brief transient demonstration shows that SAM can qualitatively model a postulated accident, yet shows the benefits of coupling this work to neutronics.
Chapter 5

Conclusions and Recommendations for Future Work

A new system analysis code, SAM, is specialized for advanced reactor designs, such as SFRs and MSRs. SAM utilizes modern numerical methods, has second order accuracy, and has several options to assist in resolving numerical instabilities. This work adds to preliminary validation of SAM using MSRE data. This work also contributes two detailed MSRE model descriptions, one for the water mockup, and one for the molten salt based closed loop.

Measured data exists for the open flow MSRE water mockup and approximate temperatures were calculated for the FLiBe-based MSRE primary loop. Steady state data from both the water mockup and primary loop are compared to results generated by SAM to complete a preliminary comparison. Other studies are also conducted to further demonstrate that SAM behaves in a physically accurate manner under various conditions. This work does not advocate for or against using SAM for MSR analysis, rather it demonstrates the application of a new DOE – NEAMS tool for comparative analysis with legacy MSRE data.

This work can be broken down into three main contributions:

1. A holistic 1-D MSRE system description of both the water mockup and molten salt based primary loop that can be used for any system analysis code. This consolidates legacy MSRE plant descriptions into one source of information.
2. A SAM MSRE water mockup model with results for total system head loss. Various flow areas are used for the core rings to check model geometry. Comparisons are made between SAM results and measured data to compare the code with water mockup historical data.
3. A SAM MSRE primary loop model with results for core and heat exchanger coolant axial temperature profiles. This includes brief information regarding core pressure and
fluid velocity. Comparisons are made between SAM results and calculated legacy data to preliminarily compare the code with the FLiBe-based MSRE primary loop. Additional studies are conducted to compare core component selection, alternative coolant properties, finer versus coarser component nodalizations, different core ring modeling, and transient demonstration analysis.

The comprehensive MSRE model description is split between the water mockup and primary loop. This description discusses how legacy MSRE design details have been transformed into SAM input. The section also details any modeling assumptions made as a result of SAM limitations, such as 1-D modeling. Overall, this section provides a consolidated comprehensive description of the MSRE design and functionality that had been scattered in prior works.

The SAM MSRE water mockup model is built to compare against measured system head loss data. Two water mockup models are constructed: one with equal and one with varying core ring flow areas. SAM shows that regardless of how the core ring flow areas were modeled, the simulated results align very well with measured data, within a relative percent difference of 6% maximum. SAM also calculates flow velocities that align well with MSRE data, but challenges include the complex 3-D flows of the volute and downcomer. However, the precise alignment of the SAM results with measured pressure drops over several coolant flow rates provides confidence in the model description and SAM input for the MSRE water mockup.

The most detailed SAM MSRE modeling is conducted for the primary molten salt loop. Several different SAM models are constructed to further compare code results with various sets of data. The primary model contains pipe components for the core rings and showed slightly cooler fuel/coolant temperatures in the core and primary side heat exchanger, within 0.4% of the estimated results; however, the SAM model has reproduced the same axial change in temperature that was calculated in reference. The minimal difference with approximate results is likely due to unique characteristics in the thermophysical properties between the code and experiments. Furthermore,
the pipe core modeling shows physically accurate results with core pressure and fluid velocity. The quantitative and qualitative agreement between both the simulation and expected results marks the beginning of validation for the primary loop MSRE. These results utilize SAM built-in properties for FLiBe; however, other coolant properties for various salts are given in reference. These varying properties, which include salt chemistries used in the MSRE, all show the same trends as the axial core temperature profile for built-in properties but either have a positive or negative bias showing the impact of different actinide concentrations. The results from these two studies give a preliminary comparison of SAM for the MSRE primary loop.

Additional studies establish further comparative analysis with expected results. A further alteration is completed to the flow area of the core rings, similar to what is done with the water mockup. This study shows similar temperature results with the equal flow area model, but did not compare well with expected data for effective fluid velocity and flow rates. There is uncertainty in how and where Engel and Haubenreich (1962) calculated velocities. The location of the core coolant velocity calculations is key since flow areas may differ near the core inlet and outlet (additional graphite structure is present at the core inlet).

Additionally, a nodalization study is performed on the axial spatial discretizations of the core and heat exchanger. This study shows that using 10 or more axial nodes gives nearly identical convergence both spatially and temporally. Moreover, the pipe core rings are swapped for channel components. Channel components are necessary to model the graphite moderator and structure of the MSRE core. This is needed since in the MSRE, 6% of the total thermal power was deposited into the graphite. This means heat structures are placed around the fuel/coolant channels to simulate this heating. Substituting channel components provides similar coolant temperature profiles, but gives linear graphite temperature profiles as SAM is assuming linear heat transfer to the structure. Modeling with a channel component is necessary when simulating a transient since the graphite will cause temperature feedback.
A transient is demonstrated to simulate one of the potential DBA scenarios in an MSR, a loss of flow accident. Results from this thermal hydraulic demonstration of a DBA show that SAM can demonstrate a transient without SCRAM or feedback. The demonstration also reinforces the importance of coupling SAM thermal hydraulic modeling with neutronics.

Some of the challenges faced during this project can be resolved with suggested items for future work. The recommended action items for the continuation of this project are as follows:

- CFD modeling of the MSRE volute and downcomer.
  - Complex 3-D flows circulate into the downcomer from a series or angled holes in the volute, causing flow conditions that SAM cannot emanate.
  - CFD, whether coupled or isolated from SAM, can accurately predict fluid velocity in this region leading to a more enhanced comparison with measurements from the MSRE water mockup.

- Revisit the channel modeling of SAM MSRE primary loop.
  - Linear temperature profiles for the graphite core structure are inaccurate since these temperatures should peak then start to fall after the midpoint of the core length.
  - Input a heat loss mechanism for the graphite structure so that the graphite channel is not heated linearly.

- Investigate other parameters of the MSRE primary loop.
  - Current comparison focuses on the core and heat exchanger axial coolant temperature profiles.
  - Coolant velocity or pressure drop calculated data may be available for other components in the FLiBe-based MSRE.
  - Additional comparisons can also be made with different water mockup components.
• Explore the bias observed in the pressure drop results for the water mockup

• Continuation of alternative SAM studies for different conditions.
  o Add a radial power distribution to the core rings.
  o Alter the number of core rings, both lower and higher than four.
  o Change the convergence criteria and solvers of SAM to enhance the nodalization study.
  o Investigate the bias observed with different coolant salts by further analyzing their chemistries.

• Couple to neutronics modeling.
  o This current work only addresses thermal hydraulic analyses.
  o Many neutronics DBAs have direct impacts on reactor thermal hydraulics.
  o Coupling will create a more accurate depiction of what occurs during transients in MSRs. The following can be modeled with neutronics and thermal hydraulics coupling:
    ▪ Delayed neutron precursor drift
    ▪ Point Kinetics Equations
    ▪ Reactivity feedback
    ▪ Other DBAs with neutronics implications
References


