MSRE RELAP Report

Authors: Kyle Duke, Spencer Jensen, Jacob Purser
Professor: Matthew Memmott
Class: Nuclear Reactor Transient Modeling; Chemical Engineering 512

Executive Summary

For our class project, we modeled the design and function of the Molten-Salt Reactor Experiment (MSRE) from Oak Ridge National Lab by creating our own RELAP5-3D input decks. By taking values tabulated from scientific sources and our own calculated data, we were able to approximate the properties of the MSRE. Starting from the values reported in our sources, we ran a steady state RELAP deck. When that deck reached new steady state values for RELAP's solvers, we used PYGI to rewrite our RELAP deck inputs at the new steady state. We used a trip to initiate our LOFA transient by turning off the fuel salt pump. Temperatures increased and fuel loop pressure decreased, but all parameters stayed within safe operating limits. Power generation decreased, but due to convection within the core, fuel salt flow did not stop entirely and thus power reached a new steady state at about a quarter of original power levels. This convective flow is a safety feature of molten salt reactors that does not exist in PWR designs. Because of this, despite heat buildup within the primary loop, core temperatures did not exceed safe operating limits. We conclude that the MSRE was exceptionally safe in the examined scenario and poses no significant risk to public health or safety.

Reactor Overview

We created a RELAP5-3D model of the Molten-Salt Reactor Experiment (MSRE) from Oak Ridge National Lab. The MSRE was graphite moderated and utilized a eutectic mixture of lithium fluoride and beryllium fluoride (known as FLiBe) for the cooling and fuel. Although originally designed to produce 10 megawatts of thermal power, due to imprecise data used by the engineers designing it, it only produced around 7.3 MW. The fuel salt was circulated through a heat exchanger, where the heat was deposited into a secondary loop of coolant salt, before flowing back into the core to heat back up. The coolant loop was then pumped through a radiator to dispel the heat to the outside air.

The MSRE was operational for 4 years, during which it served as a valuable research tool for molten salt science and reactor technologies. It demonstrated the inherent safety of molten salt reactors, gave us valuable knowledge of how high-temperature molten salts behave, and operated safely with no incidents throughout its lifespan, despite an attempt to melt down the reactor by an operator. Our project attempts to model this system and provide insight into what the consequences of a catastrophic failure would be.

Nodalization Diagram

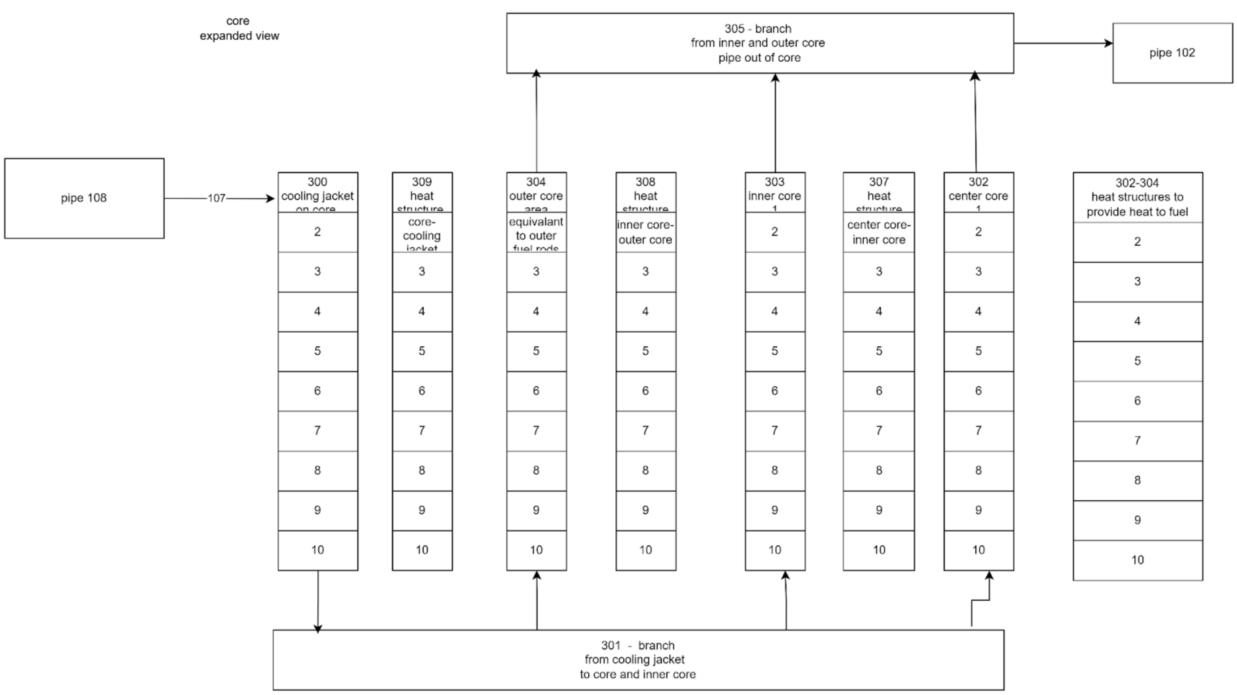

Figure 1: Nodalization diagram for the MSRE core. The core is divided into three sections to reflect differences in neutron flux and heat generation.

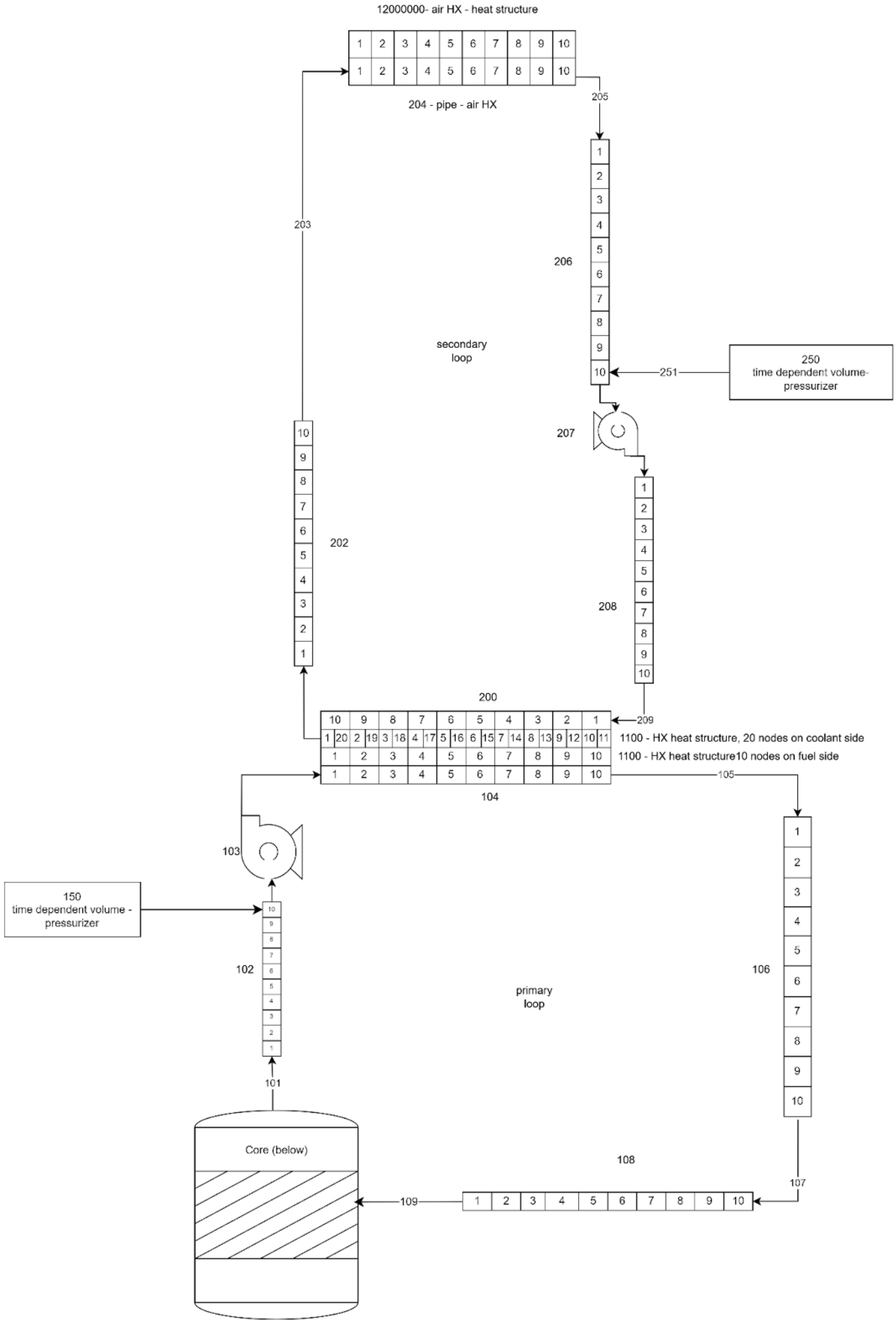

Figure 2: Nodalization diagram for the MSRE cooling system.

Input Values

Acquiring and implementing our input data was one of the most time consuming aspects of this project. We sourced our information from a wide variety of reliable sources, most particularly the 'MSRE DESIGN AND OPERATIONS REPORT' from Oak Ridge National Lab, 'Thermal Properties of G-348 Graphite' and 'Release on the Virtual Test Bed of an MSRE thermal hydraulics model' from the Idaho National Lab, and many others.

Due to the small size of the reactor, the simplicity of the piping, and the power of modern processors, we decided to overspecify the geometry and create more hydrodynamic nodes than was likely necessary. As such, each pipe contains ten volumes, except for the tube side of the primary heat exchanger, which contains twenty. Although this came at the cost of slightly longer computation time, it provided us with a greater degree of accuracy. If we were to perform significantly more analyses using this model, it would be beneficial to perform an analysis to optimize the model and its runtime, but for our purposes, this was the more time-effective solution.

The MSRE was constructed out of Hastelloy-N and graphite. Hastelloy-N is composed of 71wt% Nickel, 16% Molybdenum, 16wt% chromium, 7wt% iron, 5wt%, and about 1wt% of other trace materials Hastelloy-N formed the primary material used in the construction of the pipes, core, and pump construction. Hastelloy-N was utilized due to its ductility and durability, and is considered corrosion resistant even when dealing with the stresses of the MSRE. Graphite was chosen to be the moderator due to its heat-resistant nature. Properties of these materials were taken from the report and used accordingly.

The MSRE core is heavily documented within the official report. The incoming fuel salt enters at the side near the top, where it is distributed to a cooling annulus surrounding the graphite core. The salt flows downward, preheating itself and cooling the outside of the core, before entering the lower plenum. The plenum distributes the salt through more than a thousand small channels between graphite stringers, whose dimensions are shown in Fig. 3. As it flows through the channels, the graphite provides moderation to continue the neutron chain reaction, leading to the fuel salt heating up. Three gadolinium oxide control rods sit in the center of the graphite arrangement and allow for operator control of the reaction. The salt exits the channels into the upper plenum, where it is directed towards the fuel salt pump.

Our model closely follows this arrangement: a single pipe models the outer cooling jacket, branches model the lower and upper plenums, three pipes model the collection of channels within the graphite core, and heat structures allow for conduction between the various pipes. As RELAP is designed primarily for solid-fuel reactors, we added heat structures with almost zero volume to act as the sources of fission heat. We chose to subdivide the channels into three because of the relatively high peaking factor of the neutronics within the core. All of the dimensions involved were taken from the official report or calculated based on it.

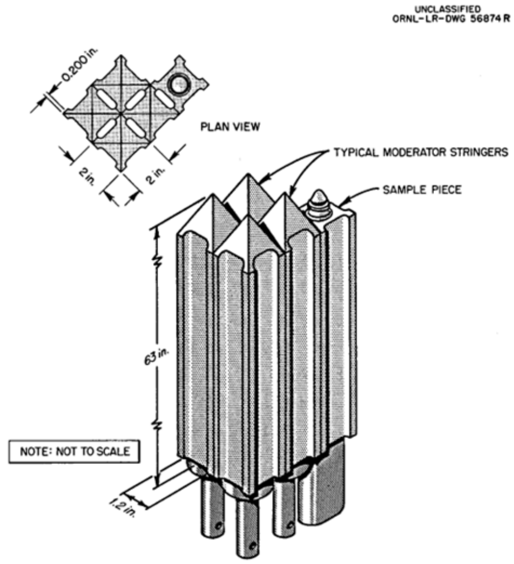

FIG. 5.6.
TYPICAL GRAPHITE STRINGER
ARRANGEMENT

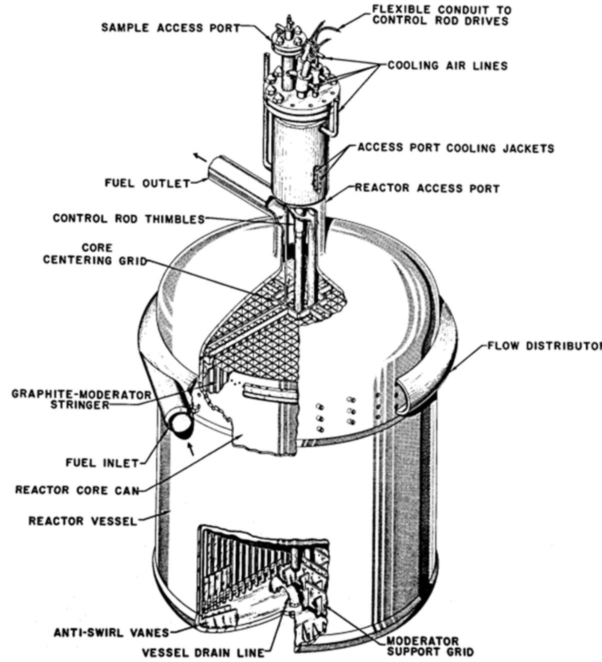

Fig. 2.2. Reactor Vessel.

Figure 3: Graphite stringer arrangement within the MSRE core.
Figure 4: Overall layout of MSRE reactor core vessel.

We used the specified operational power as contained in the report—10 MW—even though the MSRE only ran at approximately 7.3 MW. This discrepancy is due to imprecise neutron cross-section data in the engineers' original estimates. We decided to stick with 10 MW in order to model a worst-case scenario, where the reactor is operating near its maximum rated power directly before the transient.

A description of the neutron flux or power distribution throughout the core was required, so we used the distribution calculated by Zhang et al. (2023). This was used to calculate the fraction of power to be distributed to our three core sections, which represent a center cylinder and two concentric annuli around it.

Temperature-reactivity coefficients were given in the official report, and these were adapted into tables for RELAP input. For our purposes, a point kinetics model is sufficiently accurate. These inputs all combined to specify our core, reactivity, and core power for the model.

Piping specifications and layout were also extracted from the official report. This included parameters such as pipe diameter, length, and elevation. Fig. 5 shows an overview of this layout. Our model did not include the drain tanks and related piping or the air blowers and corridor. In the name of simplicity, we decided to tune our heat structure that modeled the radiator so that it had a constant outside temperature of 825 K, which according to the report, is the outlet salt temperature of the radiator.

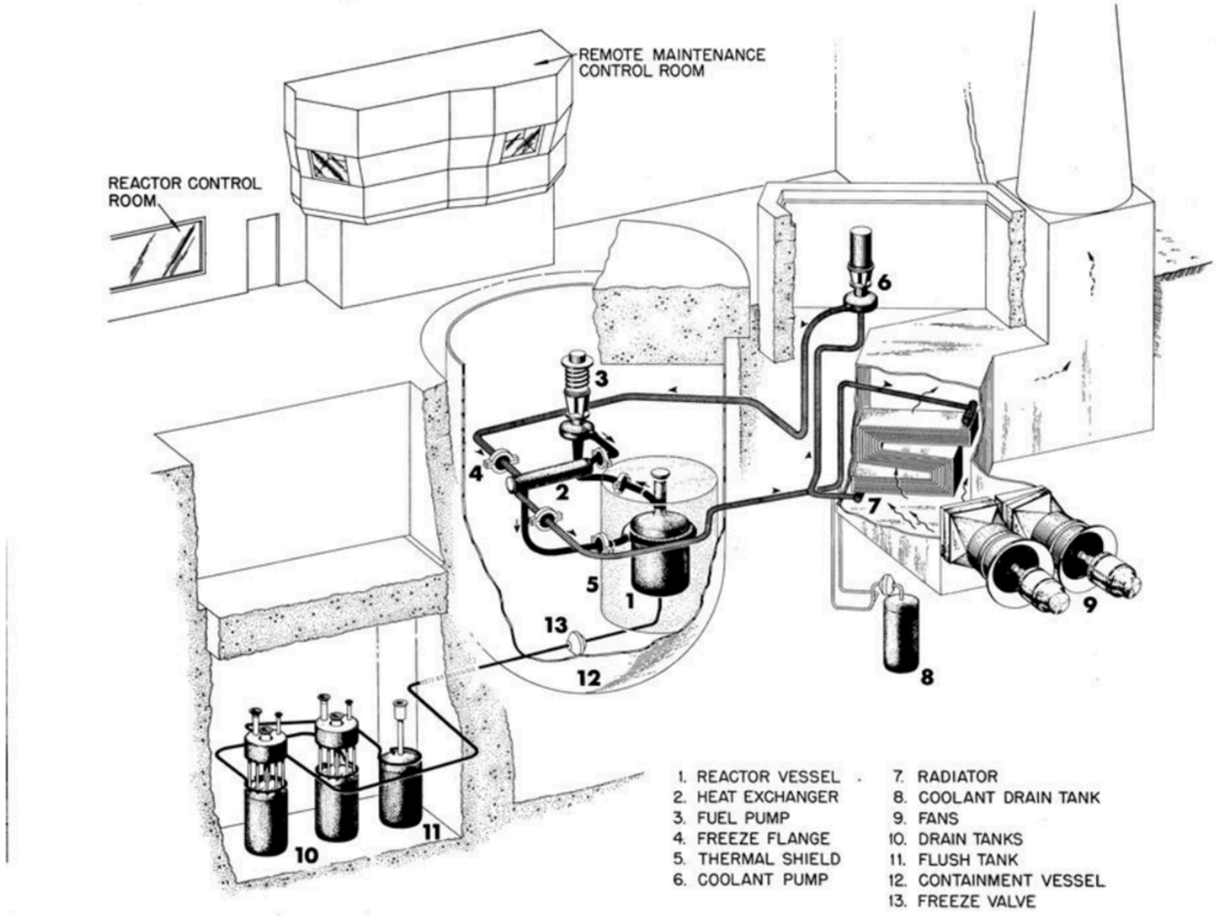

Figure 5: Piping layout of the MSRE.

Pump curve data was extracted from Figs. 6 and 7, below, using WebPlotDigitizer (automeris.io). The two pumps are stated to be identical, but they run at different speeds, providing different levels of flow and head. Unfortunately, the pump curve data for the fuel pump did not extend far enough to successfully run the transient. This forced us to rely primarily on the coolant salt pump data, which did not account for the differing angular velocities of the pump impellers. We suspect that many of the differences between the report specifications and our steady-state run values are due to this difference.

The flow of salt through our two loops was determined by the pumps and the piping layout. Pressure was moderated by a small time-dependent volume attached to each loop just before the inlet of each pump, which ensured that the required NPSH was provided and that the system would equilibrate to the correct pressure. The pressures of the time-dependent volumes were set to the pump's inlet pressures as documented in the official report.

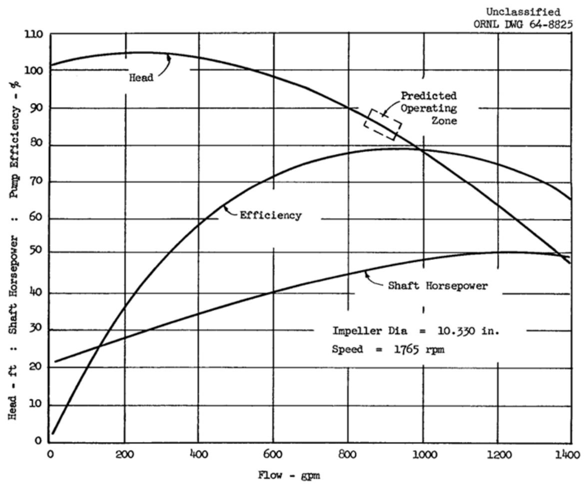

Figure 8.2. Performance Curves for Coolant-Salt Pump

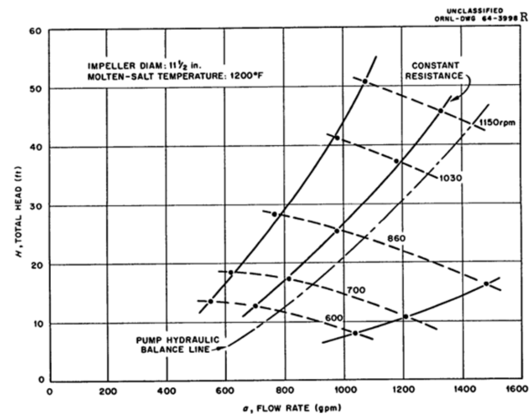

Figure 5.24. Hydraulic Performance of Fuel Pump.

Figure 6, 7: Pump curves of the MSRE salt pumps.

The system contains two heat exchangers: one between the primary and secondary loops, and one to cool the secondary loop. The official report describes the primary heat exchanger to be a shell-and-tube type with two passes. It is 8 feet and 3 inches long with 159 ½" OD tubes and roughly 254 sq. ft. of heat transfer area. The radiator contains 120 ¾" OD tubes with 706 sq. ft. of heat transfer area.

Steady State Results

In order to prepare for our model's transient, we first ran the model in steady-state mode in order to get all of our values to equilibrate. This would also serve to verify the accuracy of our model against the MSRE. We removed the code that would initiate the transient and ran the model for 8000 seconds, or just over two hours. The model reached steady state approximately three-quarters of the way through the run. We monitored several key variables, which are displayed below in Table 1.

These results show a few key differences between our model and the values given in the official report. First, the primary loop was stated to run at a higher head and lower flow rate than the secondary. Our model shows the opposite, which is likely due to the issue of pump curves as mentioned above. Second, our core temperatures are slightly higher than reported, which is likely primarily due to the lack of radiative heat transfer in our model. The MSRE would have dispersed a significant amount of heat into the gas surrounding the reactor core and piping, which RELAP is incapable of accurately modeling.

Parameter	Value	Reactor power	10 MW
Peak core temp	997.3 K	Primary heat exchanger duty	10.1 MW
Avg core temp	976.3 K	Secondary heat exchanger duty	10.3 MW
Peak primary loop pressure	3.82 bar	Primary loop flow rate	186.3 kg/s
Peak secondary loop pressure	6.09 bar	Secondary loop flow rate	159.4 kg/s

Table 1: Steady-state reactor variables of interest.

Despite these slightly higher temperatures, there is no risk of boiling or freezing our salt. With the freezing and boiling point of FLiBe being 732 and 1703 Kelvin, respectively, we were well within safe operating temperatures.

Our reactor also accurately modeled the 10 MW that we were aiming for. To put this number in perspective, if the MSRE's heat output was used to run a turbine, this would generate somewhere between 3-3.5 MW of electricity—enough to continuously power around 1750 homes.

Overview of Transient

After evaluating several possible failure modes, we identified a loss of fuel-salt flow as one of the most likely and most serious potential failure states. As a result, our analysis focused on modeling this specific transient to understand the risks and system behaviors associated with such a failure.

To simulate the event, we shut off the electrical power to our fuel salt pump at a defined time. This would eliminate the main driving force behind the fuel salt's motion, leading to a partial or total loss of flow.

Loss of flow is exceedingly serious because it means our reactor is not transferring heat appropriately. Without sufficient circulation, the fuel salt no longer transfers energy to the cooling salt and begins to heat up due to residual thermal and nuclear processes. If temperatures rise unchecked, the reactor components—particularly the graphite moderator and structural materials—may begin to fail. Such overheating could result in melting, which in turn risks releasing radioactive and toxic materials, severely impacting the health and safety of the plant operators, workers, and public.

We chose to begin the transient at 1000 seconds. This time was chosen to give our reactor sufficient time to reach steady state after the simulation restart. The modeled transient is simple in nature, but its consequences are widespread and affect various conditions throughout the MSRE. In particular, we chose to observe changes in pressure, mass flow, heat transfer, and peak core and fluid temperatures. The results of the transient are described below.

Transient Results

As expected, the transient greatly affects the results that the steady state predicts. It is impossible to run a reactor at peak efficiency when there is no fluid flow. We need to account for the worst possible scenarios to ensure that our reactor operates safely. Despite the critical set back a total loss of flow would instigate, our model of the MSRE performed excellently even under these strenuous conditions. Figures 8-12, below, show the model's response.

Contrary to our first guesses, the FLiBe in the primary loop does not stop moving once the transient is initiated by pump shutdown. In fact, even after the pump finished spinning down, the salt continued to flow at about 10% of the original mass flow rate. We suspect that this is due to natural convection, produced by the temperature difference between the salt in the core and the salt in the primary heat exchanger. This temperature difference produces a density gradient, which induces natural convection. This means the reactor is still producing a significant amount of power and completely transferring it to the cooling system, even when the fuel salt pump is completely shut off. After system failure our reactor was still producing 2.4 Megawatts of power, or 24% percent of the steady-state power.

In addition, although the primary loop was unable to remove the same 10 MW of heat from the core, the temperatures within the core did not reach critical levels. As heat built up within the core, the fuel salt and graphite moderator expanded, which decreased the reactivity of the system. As the fuel salt expands, two effects take place. First, the salt expansion decreases the uranium atoms per volume in the core. Second, the salt expansion also increases the distance between uranium atoms. The graphite expanding with increased temperature decreases the atomic density of carbon atoms in the graphite, which reduces the moderating effect. This created a negative feedback loop that led to the system finding a new steady state.

We inspected the results to determine if this increased temperature would lead to unsafe thermal stress on the reactor systems. The peak core temperature did not exceed 1007 K, which is well below the safe intermittent operating temperature of Hastelloy N (1356 K). No other variables that could have posed a risk to the reactor's integrity were identified.

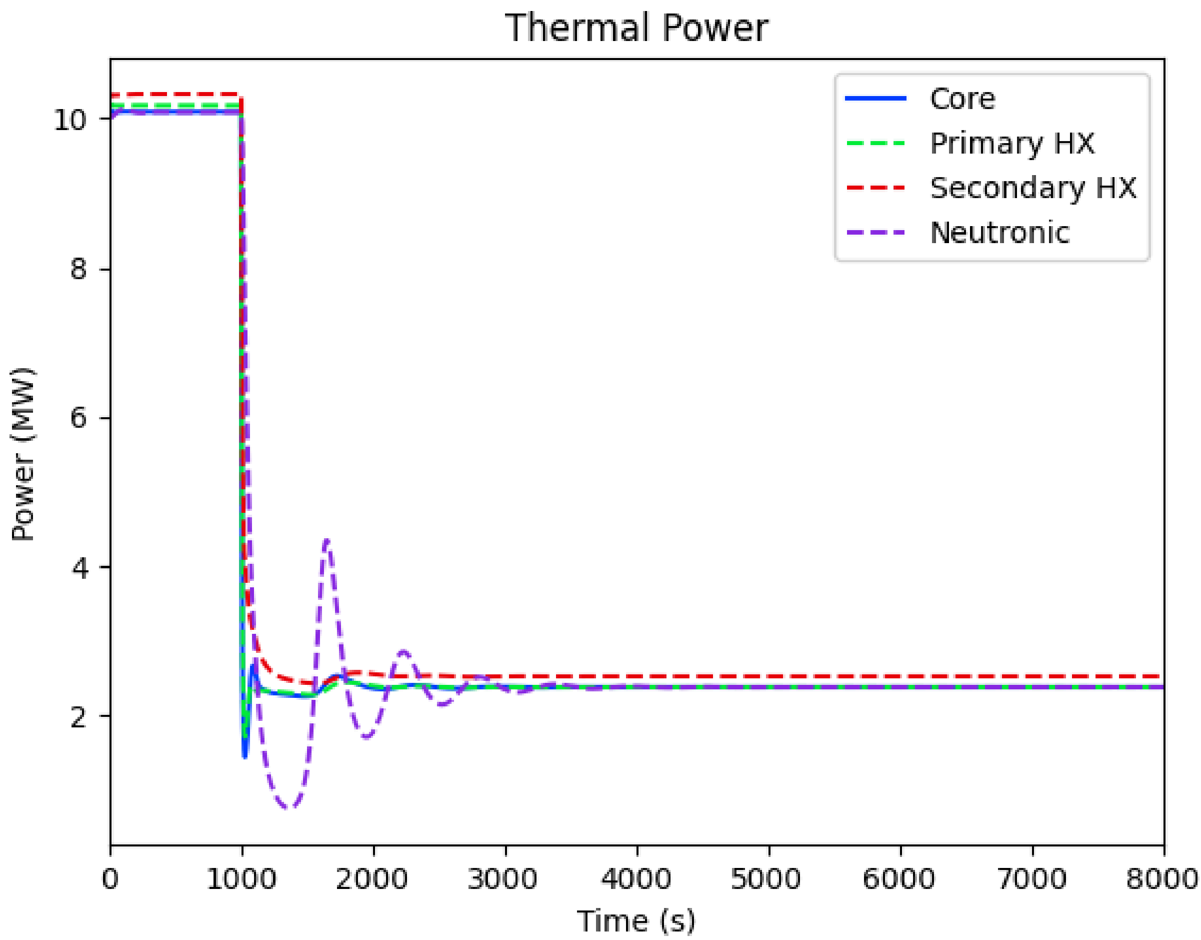

Figure 8: Four variables that monitor reactor power within the MSRE over the transient run.

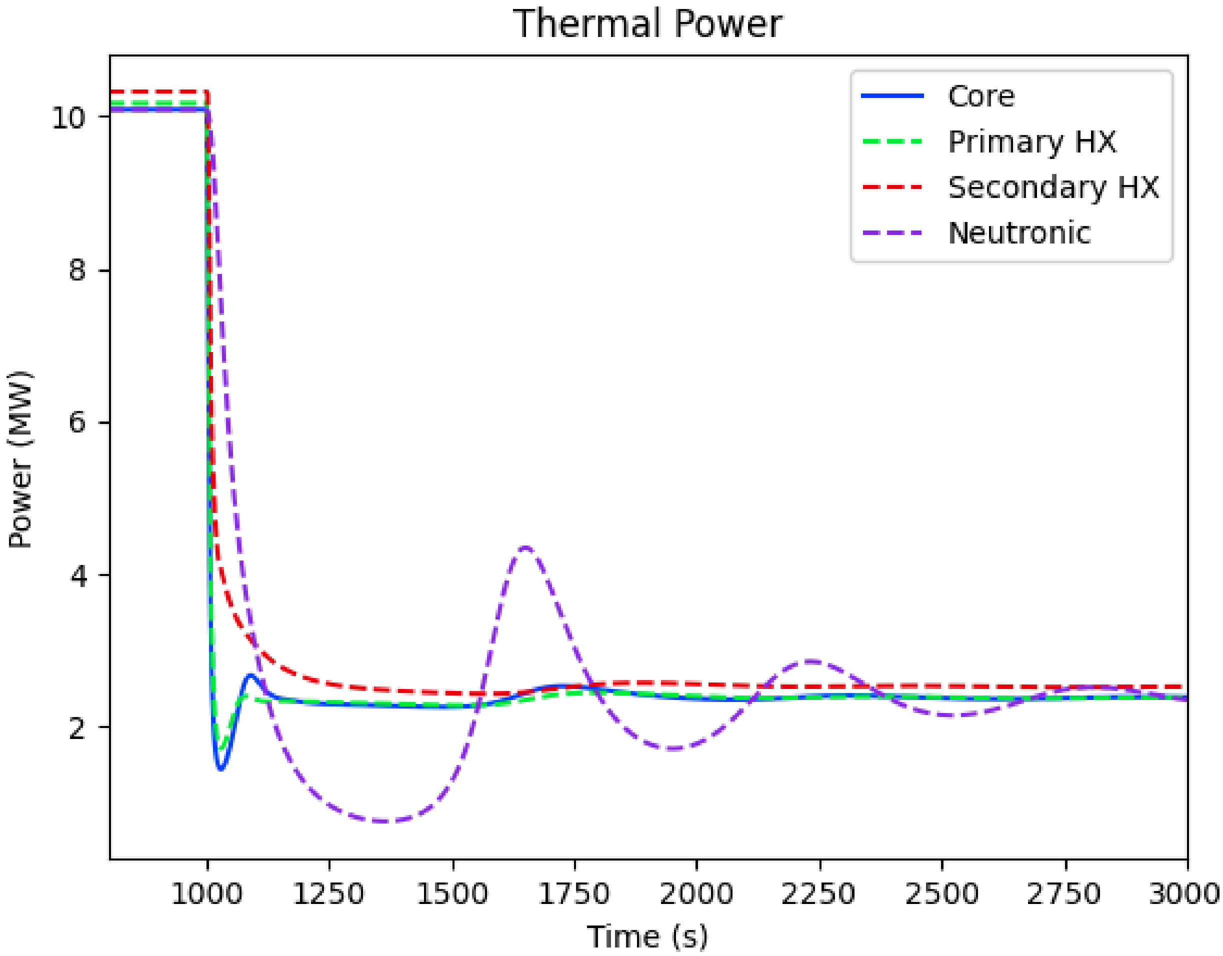

Figure 9: Zoomed-in copy of Fig. 8.

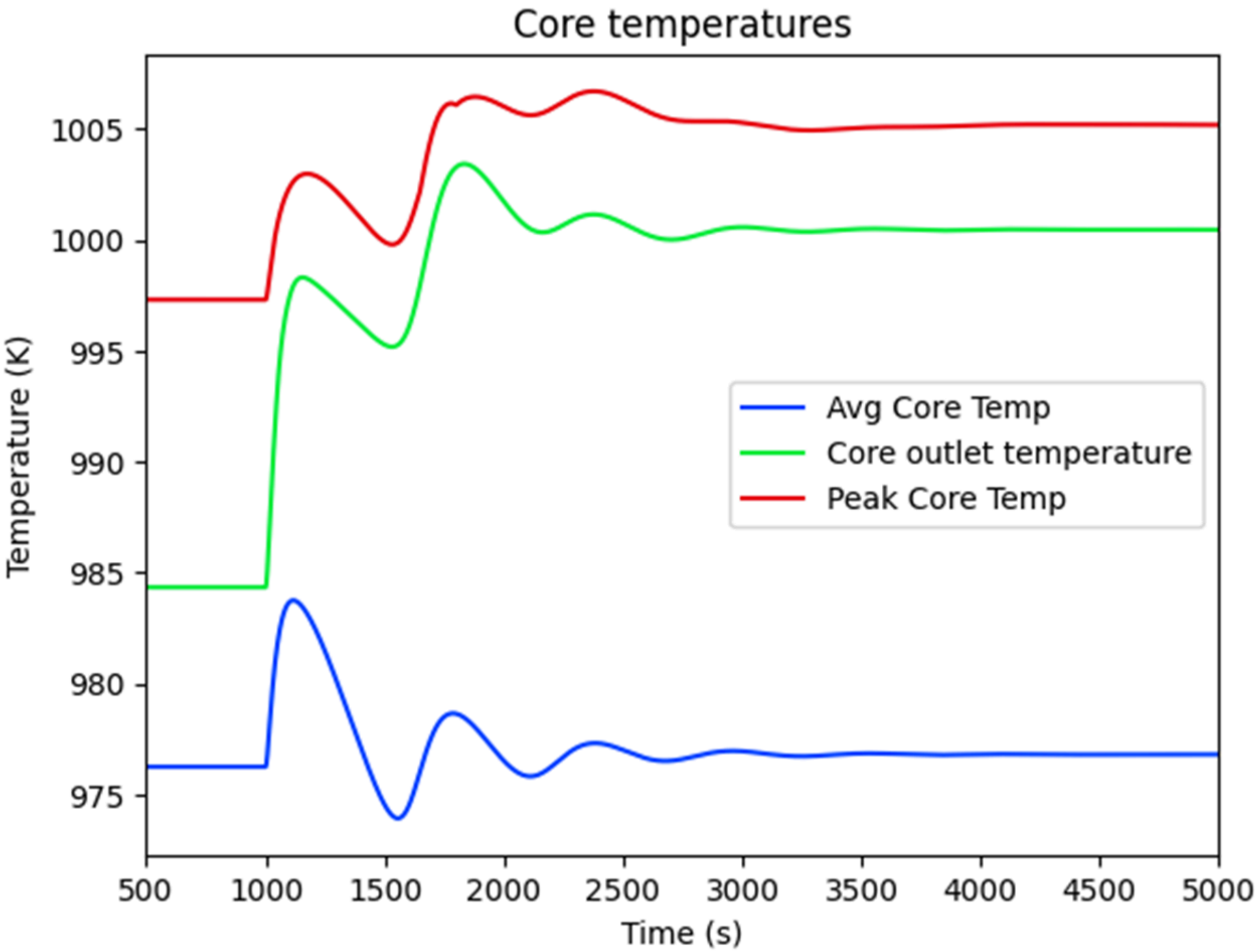

Figure 10: Core temperatures as a function of time across the transient.

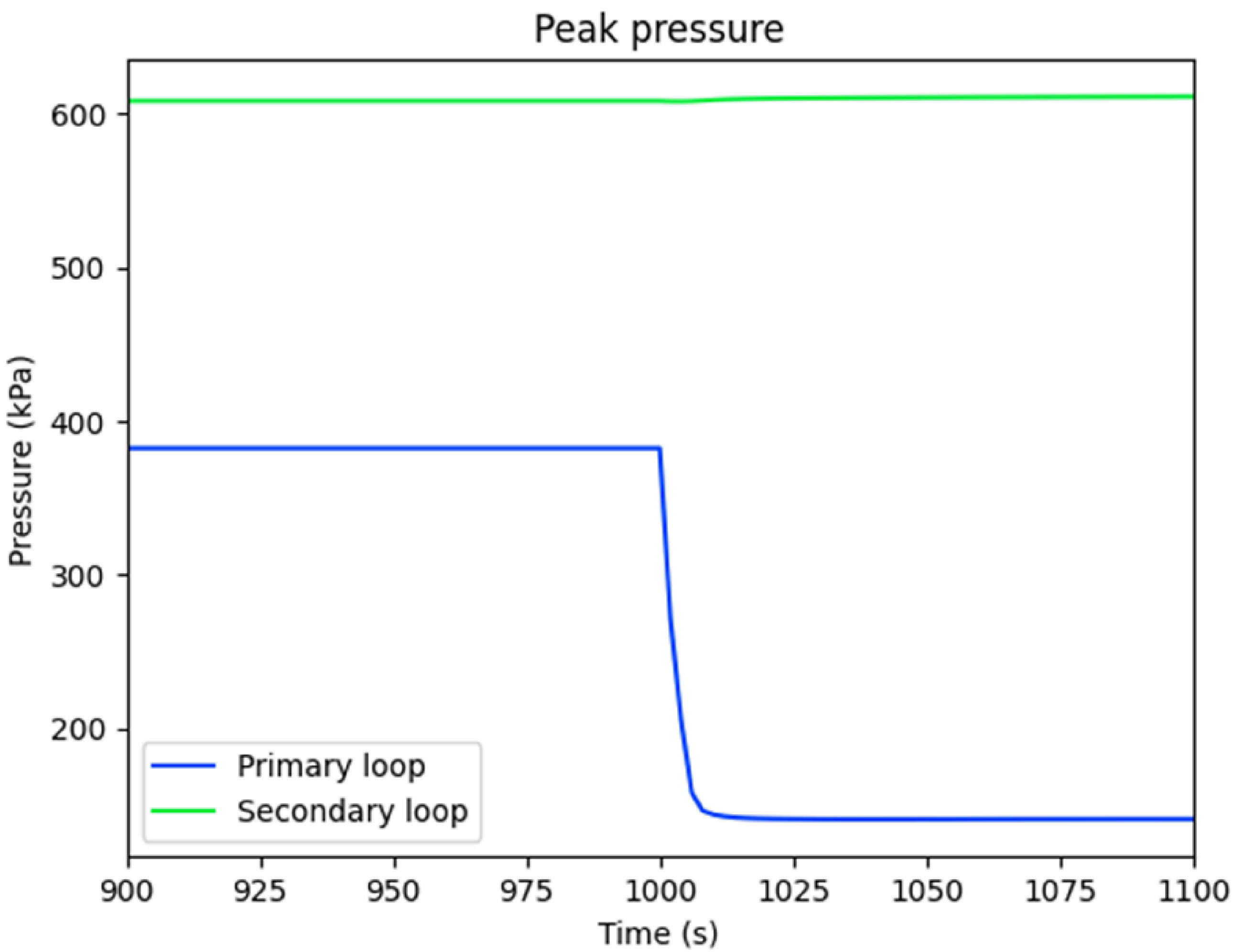

Figure 11: Peak pressure within primary and secondary loops across the transient.

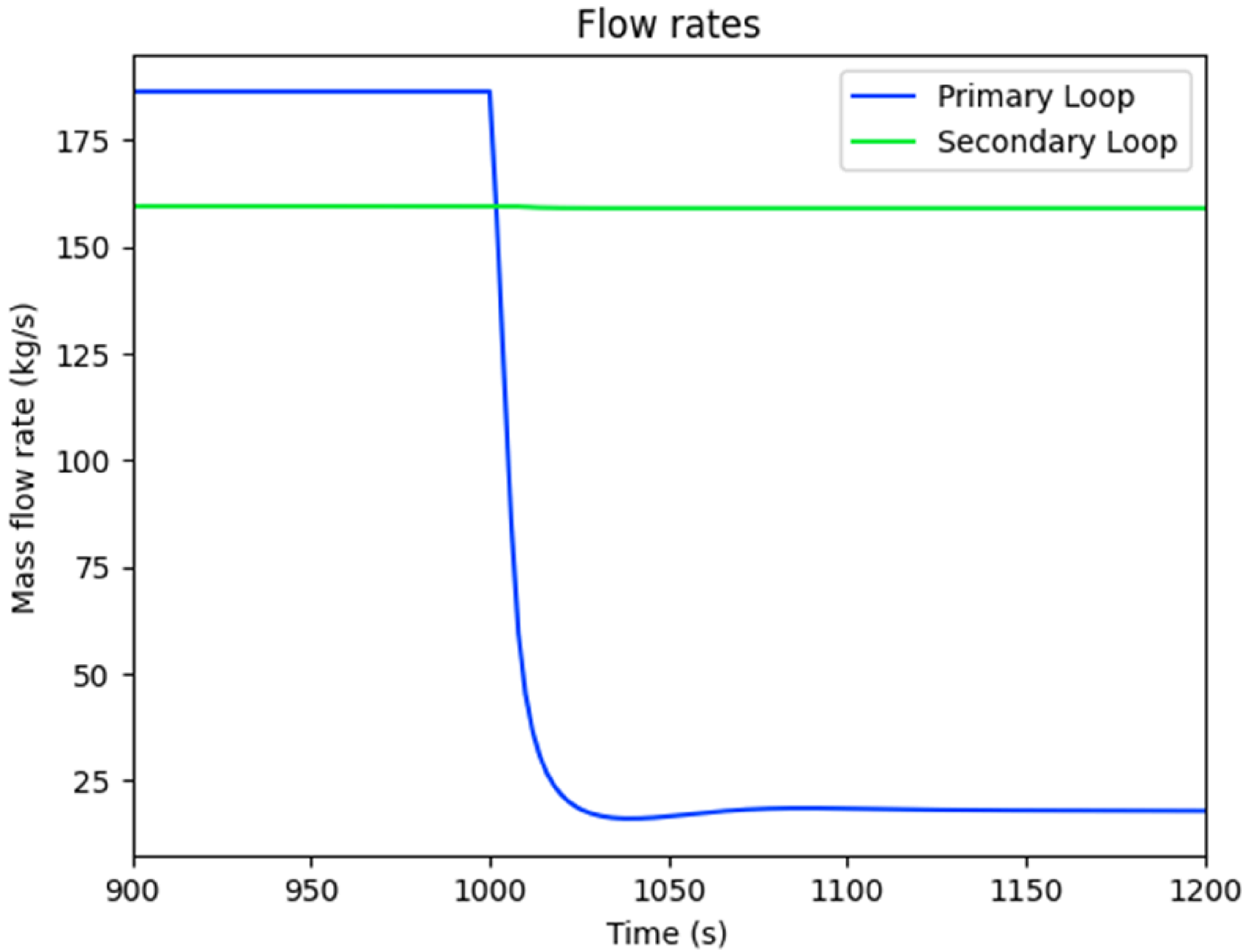

Figure 12: Flow rates with primary and secondary loops across the transient.

Conclusion

Upon thorough examination and testing, it is clear that our MSRE design functions accurately and as desired. Our results reflect the real-life reactor created and used by Oak Ridge National Lab with relative accuracy. Some discrepancies remain, such as the differences in temperature and flow rate, and more accurate data than is available in the ORNL report would be required to fix these discrepancies.

Our reactor reaches a safe steady state quickly and without any complications. Just as the original MSRE was designed for a regular power output of 10 MW, our reactor reaches a steady-state power of 10 MW. Even in the unlikely instance of a loss of flow transient occurrence, our reactor still functions and produces an impressive 24% power output. This power output is an inherent safety feature of molten salt reactors, providing cooling to the core despite pump failures. Peak core temperatures remain well within safe operating limits, and the risk of catastrophic failure or release of radioactive material into the atmosphere is near zero.

The MSRE model that we created shows that the reactor was safe in all examined scenarios, with the lowest possible risk to human health and safety.

Source Document

https://web.archive.org/web/20160303211133if_/https://dl.dropboxusercontent.com/u/15726934/Historic_Molten_Salt_Reactor_Experiment_Brochure_ORNL_1965-1972.pdf

https://moltensalt.org/references/static/downloads/pdf/ORNL-TM-2111.pdf

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