Development and Transient Analysis of a Helical-coil Steam Generator for High Temperature Reactors

Nathan V. Hoffer[1], Nolan A. Anderson, M.S.[2], and Piyush Sabharwall, Ph.D.[2]

[1]*Utah State University*
[2]*Idaho National Laboratory*

Correspondence to: nathan.hoffer@aggiemail.usu.edu

ABSTRACT

A high temperature gas-cooled reactor (HTGR) is under development by the Next Generation Nuclear Plant (NGNP) Project at the Idaho National Laboratory (INL). Its design emphasizes electrical power production which may potentially be coupled with process heat for hydrogen production and other industrial applications. NGNP is considering a helical-coil steam generator for the primary heat transport loop heat exchanger based on its increased heat transfer and compactness when compared to other steam generators. The safety and reliability of the helical-coil steam generator is currently under evaluation as part of the development of NGNP. Transients, such as loss of coolant accidents (LOCA), are of interest in evaluating the safety of steam generators. In this study, a complete steam generator inlet pipe break (double ended pipe break) LOCA was simulated by an exponential loss of primary side pressure. For this analysis, a model of the helical-coil steam generator was developed using RELAP5-3D, an INL in-house systems analysis code. The steam generator model behaved normally during the transient simulating the complete steam generator inlet pipe break LOCA. Further analysis is required to comprehensively evaluate the safety and reliability of the helical-coil steam generator design in the NGNP setting.

INTRODUCTION

The Next Generation Nuclear Plant (NGNP) Project at the Idaho National Laboratory (INL) is developing a high temperature gas-cooled reactor (HTGR). The NGNP design integrates electrical power production with high temperature process heat—heat generated by the reactor in the form of steam that can be used for industrial purposes—at temperatures from 700 to 950°C, improving upon existing light water reactor technology, which operates near 300°C (Idaho National Laboratory, 2009). NGNP process heat exhibits potential utility in applications such as: hydrogen production, industrial manufacturing, coal gasification, and enhanced oil recovery (Sabharwall, 2009). The steam generator is a key component in transferring the high temperature process heat from the NGNP to industrial applications as well as to power production systems as illustrated in Figure 1 (Park, 2011).

A steam generator is a type of heat exchanger specifically designed to transfer heat from a coolant into water, producing steam that can be used for power generation, industrial applications, or to

© 2011 The Journal of Young Investigators

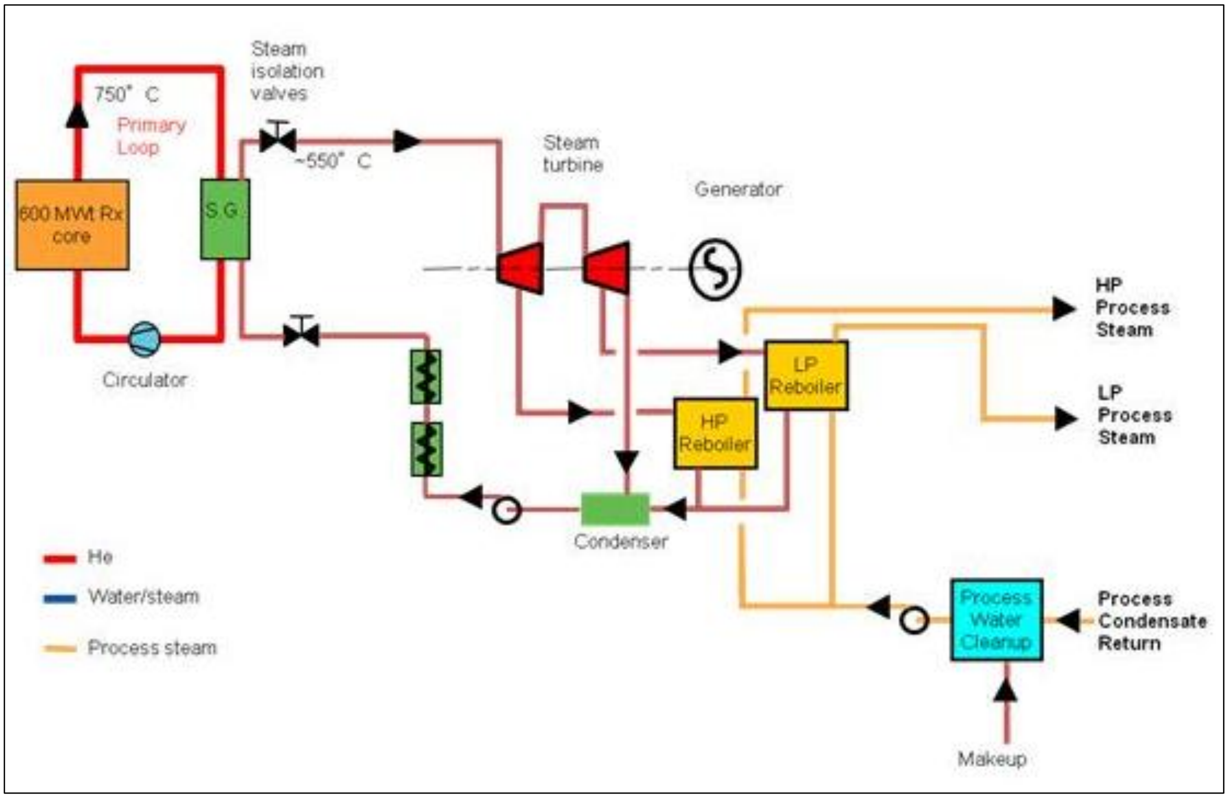


Figure 1. NGNP reference design (NGNP Senior Advisory Group 2009).

simply transfer heat to some other location. A steam generator consists of an outer shell inside of which are several small tubes, centimeters in diameter, which are bundled together. Steam generators typically transfer heat from the shell side (primary side or side connected to the reactor) coolant to the tube side (secondary side or side connected to the power production system) coolant, producing steam within the tubes. There are several shell and tube steam generator configurations, each meeting certain design parameters such as compactness, corrosion resistance, structural strength, and heat transfer.

The NGNP project is currently evaluating several different heat exchangers as candidates for the primary heat transport loop, which consists of the reactor, primary heat exchanger and power production system. A helical-coil steam generator is currently the design of choice for the primary heat transport loop heat exchanger. The helical-coil offers compactness and a 16 to 43% higher heat transfer coefficient than straight pipe shell and tube heat exchangers (Prabhanjan et al., 2002). The main difference between the helical-coil steam generator and other steam generators is the tubes which are wound into helical coils, forming a large bundle as shown in below in Figure 2 (Areva, 2008).

The NGNP pre-concept helical-coil steam generator design is based on a modular high temperature gas-cooled reactor (MHTGR) steam generator. Modular reactors are small, self-contained reactors that can be combined together to achieve a desired power output. The steam generator is a vertically oriented, once-through, up-boiling, cross-counter-flow, shell and tube heat exchanger (General

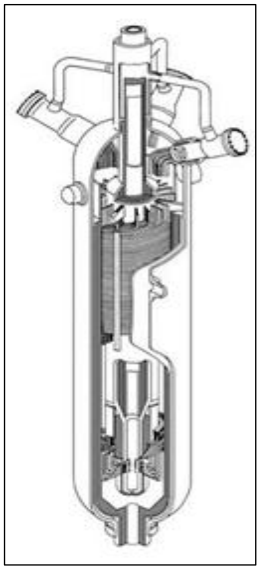


Figure 2. Figure 2. Cutaway of a helical-coil steam generator.

Atomics, 2010). The multiple tubes involved in this steam generator are helically wound into bundles and are divided into lower and upper bundles. The upper bundle, which experiences very high temperatures (~750°C) is made of either Inconel 617 or Incoloy 800H, which have high corrosion resistance and structural strength at high temperatures (General Atomics, 2008). The lower bundle is not exposed to such high temperatures and will not be made of high temperature alloys but rather of 2¼Cr-1Mo. These two bundles are joined together by a bimetallic weld. A schematic of the sections and flow path of the helical-coil steam generator is detailed below in Figure 3.

Though the helical-coil steam generator design is compact and has a high heat transfer coefficient, it does not resolve certain issues related to steam generators in nuclear power plants. For example, fouling (buildup of minerals in tubing disrupting fluid flow) and plugging of tubes remains a major concern, as this can decrease the efficiency of the steam generator in addition to causing regular plant shutdowns for servicing (Electric Power Research Institute, 1994). Helical-coil steam generators are also still at risk of tube rupture and the consequent mixing of reactor coolant (primary coolant) and steam (secondary coolant) or loss of primary or secondary coolant, disrupting reactor conditions and potentially leading to a radiation leak (Electric Power Research Institute, 1994).

Safety and reliability—critical to the success of the NGNP—are currently under evaluation as part of the NGNP development. Analysis of transients such as loss of coolant accidents (LOCA) is an integral part of the safety and reliability evaluation of the NGNP helical-coil steam generator (Munshi et al., 1986). This study

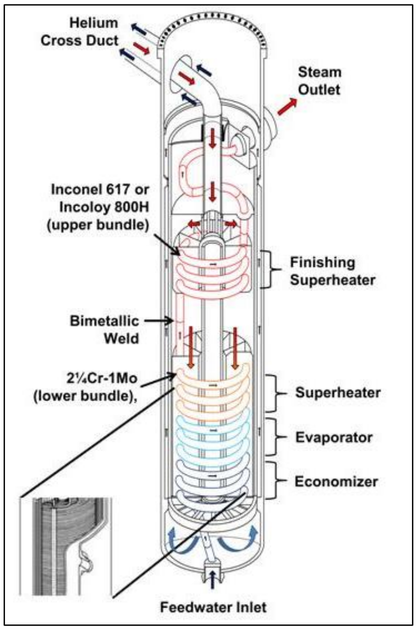


Figure 3. NGNP helical-coil steam generator pre-concept design:

Primary side flow path: Helium from the reactor enters the steam generator through the cross duct and is directed down through a central pipe. The central pipe opens up into a bell-shaped area called the inner plenum. The helium then flows over the individual helical-coil tubes, transferring heat from the helium to the steam in the tubes. At the base plenum, the helium is redirected up through the annulus between the outer and inner shrouds, pouring out into the upper plenum. The helium then exits out the cross duct back into the reactor.

Secondary side flow path: Liquid water enters through the feedwater inlet and flows up through the helical-coil tubes. The helical-coil tubes, wound into bundles, can be divided into a lower and upper bundle. The lower bundle can be divided into three sections: economizer, evaporator and initial superheater. The economizer preheats the liquid water, called feedwater, as it is fed in to the steam generator. The evaporator converts the water into steam. The last section of the lower bundle is the initial superheater which converts left over liquid water into steam. The upper bundle, joined to the lower bundle by a bimetallic weld, functions as the finishing superheater that converts steam still mixed with liquid water completely into steam free of liquid water to prevent damage to the power turbine.

focuses on the transient analysis of a simulated complete NGNP helical-coil steam generator inlet pipe break and the development of the computer model used in the analysis. This analysis is only one part a larger set of safety and reliability analyses and cannot by itself prove the safety and reliability of the steam generator in the NGNP setting. However this study, coupled with others, will be able to form a clear and concise picture of the reliability and safety of the helical-coil steam generator as the primary heat transport loop heat exchanger for the NGNP.

METHODS

Model Development

Since the NGNP helical-coil steam generator is in the pre-concept phase of development, there is no final design on which to base the steam generator model. The flow path of the steam generator model is thus based on a steam generator design for a modular high temperature gas-cooled reactor (General Atomics, 2008). No single reference contains all dimensions, and inlet and outlet conditions of the steam generator. These parameters were thus referenced from several reports to create a complete model (General Atomics, 2008; General Atomics, 2009; Westinghouse Electric Company LLC, 2009; Oh et al., 2010). The design parameters for the NGNP helical-coil steam generator model are summarized below in Table 1.

RELAP5-3D software was used to develop a computer model of the steam generator. RELAP5 is an Idaho National Laboratory in-house system analysis code, and is used to simulate operational transients and LOCAs within a nuclear plant. Modeling a three-dimensional helical-coil bundle in RELAP5 required several simplifications, as seen in Figure 4.

The helical-coil heated tube length was an unknown parameter at this phase of the NGNP design. Having determined the number of tubes, inlet and outlet conditions, and heat load as given parameters, the helical-coil heated tube length was adjusted until the heat transfer surface area could transfer a 600 MW heat load. In order to fine-tune the heat transfer of the model, the secondary mass flow was used as a variable and the heated tube length was set to 144 meters in length. This allowed for relative ease in varying the mass flow rate—which is a single parameter change in RELAP5—than to a change the heated tube length, which required changing the entire model nodalization. With the heated tube length set at 144 meters, the secondary mass flow rate was adjusted to until the steam generator reached the 600 MW heat load.

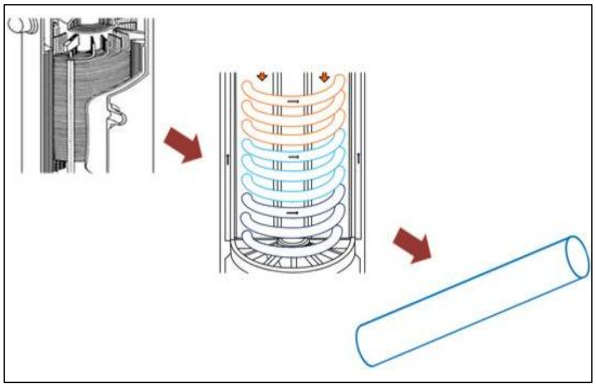


Figure 4. Helical-coil bundle simplifications: First the helical-coil bundle of 441 tubes was modeled as a single tube with equivalent flow area, heat transfer surface area, hydraulic diameter, and heated hydraulic diameter. Equivalent areas and diameters ensure that there are no differences in heat transfer and flow characteristics of the single tube compared to the actual bundle of tubes. The helically-coiled single tube was further simplified by unwinding the coil to make a straight pipe of the same length. The single straight tube was inclined to correspond to the bundle height. A heat transfer multiplier and flow loss coefficients were added to the model to simulate improved heat transfer and increased pressure loss as observed in helical-coils compared with straight tubes.

© 2011 The Journal of Young Investigators

Once all the parameters of the model were determined, the RELAP5 steam generator model was run at steady-state conditions until the flow and heat transfer within the model reached steady-state values.

Part of model development involved developing a transient that could be simulated using RELAP5-3D. A LOCA representing a complete rupture of the primary inlet pipe was chosen as a suitable transient. The complete rupture was simulated by an exponential decrease in the primary inlet and outlet pressure. Other steam generator transient studies have also simulated LOCAs using ramp inputs for pressure (Munshi et al., 1986; Munshi et al., 1985; Bhatnagar et al., 1985). Feedback from the primary and secondary sides was not considered in this model.

Model Description

The steam generator model's primary and secondary systems are divided into several nodes. Nodes in RELAP5 are represented by hydrodynamic structures that are subdivided into volumes or heat structures. The primary or shell side system (Figure 5) begins with an inlet boundary condition made of a time dependent volume (TMDPVOL 110) and a time dependent junction (TMDPJUN 115). The time dependent volume acts as a source and controls the temperature and pressure with respect to time. The time dependent junction controls the mass flow rate. The time dependent volume is connected directly to the time dependent junction and then to a pipe component (PIPE 120), which has six volumes. PIPE 120 models the inner pipe of the cross duct, the inlet pipe, and inner plenum. PIPE 120 is connected to ANNULUS 130 via a single junction (SNGLJUN 125). ANNULUS 130 models the surrounding regions of the upper and lower bundles. ANNULUS 130 contains 39 vertically oriented volumes and has a downward flow. There are abrupt area changes between the 9th and 10th, 11th and 12th, and 38th and 39th volumes, which represent the flow area change between helical-coil and straight pipe sections. ANNULUS 130 is connected to ANNULUS 140 via SNGLJUN 135. ANNULUS 140, which is vertically oriented with up-flow, models the annular section between the outer and inner shrouds. ANNULUS 140 is connected to PIPE 150 via SNGLJUN 145. PIPE 150 represents a horizontal annular section in the cross duct. Because ANNULUS components must be oriented vertically, a PIPE must be used. PIPE 150 is connected to TMDPVOL 160 via SNGLJUN 155. TMDPVOL 160 acts as a sink for the primary system.

Parameter	NGNP Value
Heat Load (MWt)	600
Primary Inlet Temperature (K)	1023
Primary Outlet Temperature (K)	595
Primary Mass Flow Rate (kg/s)	250
Primary Inlet Pressure (MPa)	7.0
Primary Outlet Pressure (MPa)	6.976
Secondary Inlet Temperature (K)	473
Secondary Outlet Temperature (K)	813
Secondary Mass Flow Rate (kg/s)	216
Secondary Inlet Pressure (MPa)	18.2
Secondary Outlet Pressure (MPa)	17.2
Number of Tubes	441

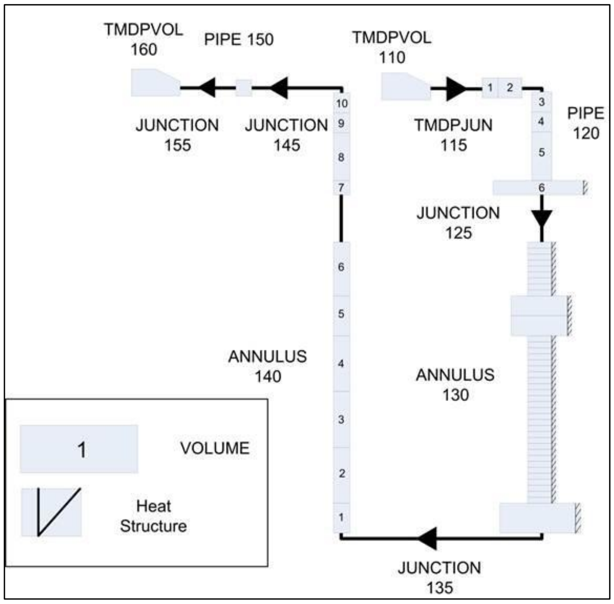
Table 1. Pre-concept NGNP helical-coil steam generator design parameters (General Atomics, 2008; General Atomics, 2009).

© 2011 The Journal of Young Investigators

The secondary system, show in Figure 6, has inlet boundary conditions that are modeled by TMDPVOL 210 and TMDPJUN 215, providing control of the inlet temperature, pressure, and mass flow rate. The TMDPVOL 210 is connected to PIPE 220, which represents the helical coil of the steam generator. The first volume of PIPE 220 models the feed water inlet, followed by 28 volumes with a vertical angle of 3.184 degrees. These 28 volumes model the lower helical bundle and are followed by vertical volumes 29 and 30, which provide a separation point for the bimetallic weld to be modeled. Volumes 30-39 model the upper helical bundle and are followed by a vertically oriented volume. Volumes 41–44 model the steam outlet section of the steam generator. Volumes 41, 43, and 44 are horizontal while volume 42 is vertical. PIPE 220 is connected to TMDPVOL 230 via SNGLJUN 235.

Heat structures are used to join the primary and secondary systems together thermally. This thermal connection is how RELAP5 models heat transfer. The model is divided up into three main heat structures (220, 230, and 240) modeling the upper and lower helical-coil bundles and the short straight section just above the upper helical bundle The subdivided heat structures are connected to volumes in a PIPE structure that nodalize the component. Because a written description of each of the connections between hydrodynamic components and heat structures would be very cumbersome, Figure 7 has been provided to show how the system is connection.

Figure 5. RELAP5-3D/ATHENA steam generator model node visualization: primary system.



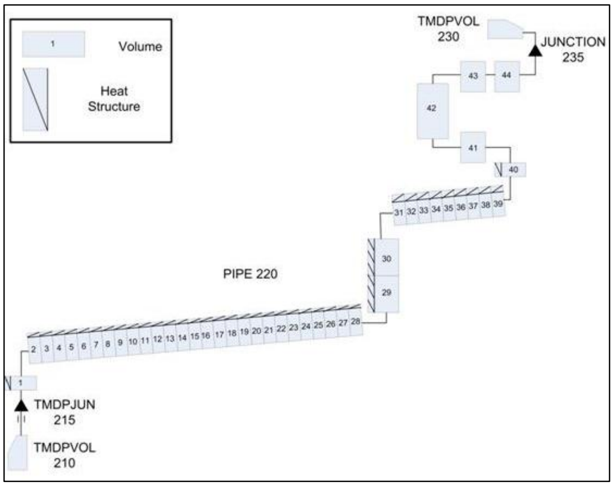


Figure 6. Figure 6. RELAP5-3D/ATHENA steam generator model node visualization: secondary system.

RESULTS

Steady State

In order to simulate a transient using RELAP5, a steady-state case must be run first. Table 2 (Appendix A) shows the values RELAP5 returned once reaching a steady-state flow for the helical-coil steam generator model. NGNP current design values as well as calculated values are also displayed.

Since the exact dimensions of the NGNP helical-coil steam generator design have yet to be finalized, several dimensions were based on other comparable steam generator designs. As

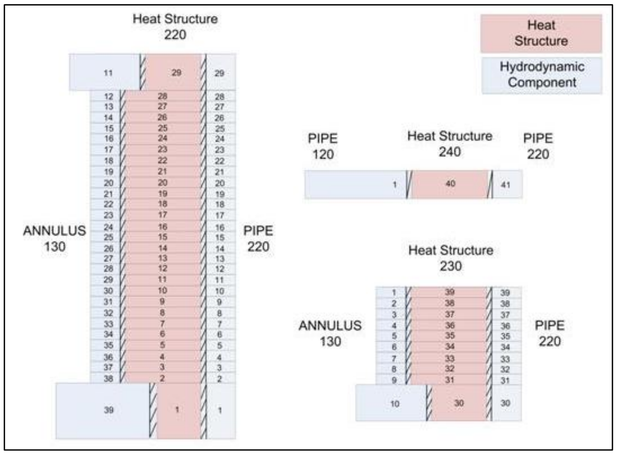


Figure 7. Heat structure connections with hydrodynamic component.

the design progressed, it became evident that either mass flow rate or helical-coil heated length needed to be changed in order to attain the design primary and secondary outlet temperatures. Heated length was initially varied until the outlet primary and secondary temperatures were close to the design temperatures. Mass flow rate was chosen to reach the exact temperature. This decision was made because mass flow rate changes required fewer changes to the model than heated length. Emphasis was placed on the secondary steam outlet temperature as the parameter that governed the model design process, since the steam outlet temperature directly affected process steam capabilities.

The helical-coil steam generator model used a single tube length of 144 m to achieve the design steam outlet temperature. This length is consistent with other helical-coil steam generator designs (Westinghouse Electric Company LLC, 2009). Once the NGNP helical-coil steam generator design matures the actual dimension should be used to improve model accuracy.

Transient

A LOCA transient, representing a complete rupture of the primary inlet pipe, was simulated by an exponential decrease in the primary inlet and outlet pressures. The pressure decrease occurred over a 20 second period and decreased the inlet pressure from 7.0 to 0.1013 MPa (ambient condition) at the inlet and from 6.976 to 0.1013 MPa at the outlet. In order to fully represent the LOCA transient, both inlet and outlet pressures in the time dependent volumes had to decrease at the same rate. Table 3 (Appendix A) shows the values used to simulate the exponential decrease in inlet and outlet pressures. Neglecting to decrease the outlet pressure would result in a negative pressure drop across the primary side or back pressure, invalidating the results.

The exponential decrease in pressure, is shown in Figure 8. The transient begins at 10 seconds and ends at 30 seconds, after which the pressure stays a constant at 0.1013 MPa at both the inlet and outlet.

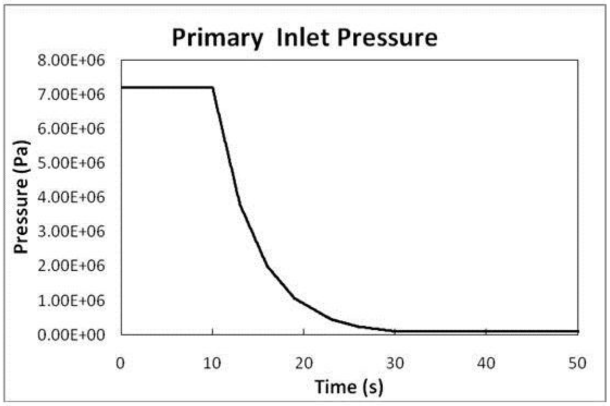


Figure 8. Exponential pressure decrease of primary inlet pressure.

As pressure in the primary side decreases, primary and secondary side temperatures decrease. The secondary side pressure, as shown in Figure 9, responds by decreasing by about 200 kPa for the inlet and only slightly of the outlet. The inlet pressure drop is greater because

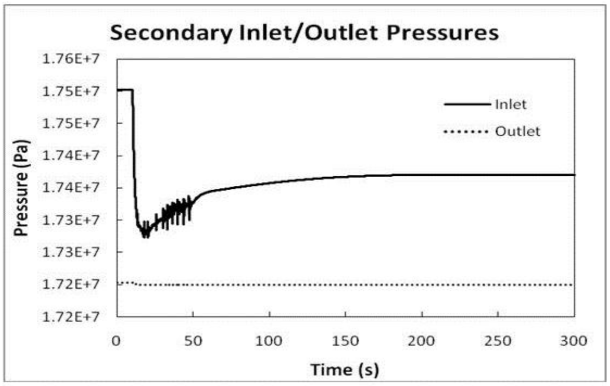
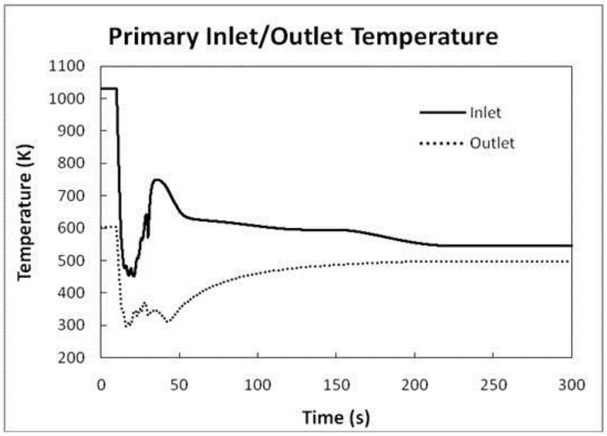


Figure 9. Secondary inlet/outlet pressure response.

energy is being transferred to the much cooler primary system.

The primary inlet and outlet temperature responses are shown in Figure 10. Inlet temperature decreases as the primary coolant expands in response to the decrease in pressure. The helium quickly cools until it has a lower temperature than the finishing superheater tubes. As the cooled gas comes in contact with the hotter tubes, the gas increases in temperature, creating the spike seen around 33 seconds. This spike in temperature indicates a reversal of heat transfer. Normally heat is transferred from the hot primary fluid to the colder secondary fluid, but this trend reverses after the pressure loss so that heat is transferred from the hotter secondary fluid to the now colder primary fluid. The temperature of the inlet and outlet level off as the primary and secondary temperatures equalize.

Figure 10. Primary inlet/outlet temperature response.



The secondary inlet and outlet temperatures lag in response to the primary side changes. The outlet temperature as shown in Figure 11 has a characteristic small oscillation because of steam condensation. Once all the steam has condensed into liquid water, the temperature response becomes smooth and continues to decrease until it equals the inlet temperature, at which point the primary and secondary systems have reached steady-state.

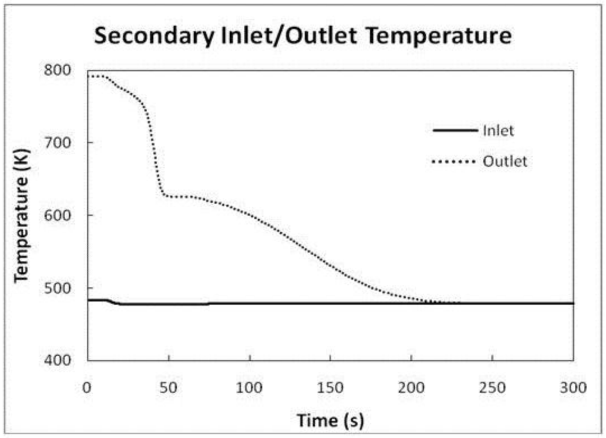


Figure 11. Secondary inlet/outlet temperature response.

© 2011 The Journal of Young Investigators

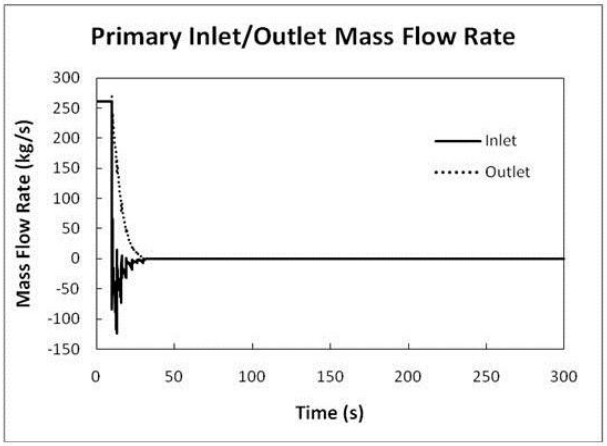


Figure 12. Primary inlet/outlet mass flow rate response.

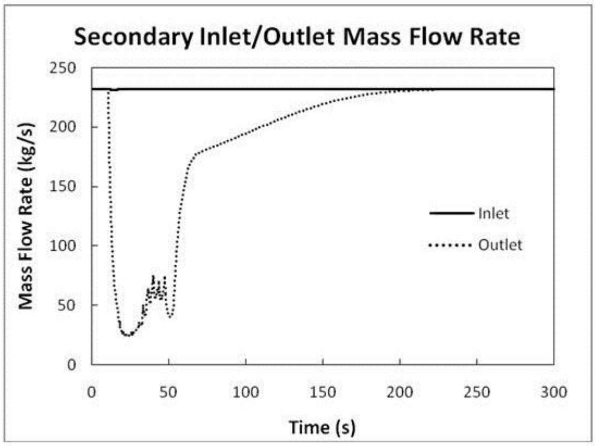


Figure13. Secondary inlet/outlet mass flow rate response.

The primary inlet and outlet mass flow rate responses showed interesting results. Figure 12 indicates that there was a flow reversal for the inlet. The flow reversal occurs because of the rapid decrease in pressure at the inlet. The primary gas rushes out the inlet as the pressure decreases. The cold primary gas comes into contact with the hot tubes, causing the gas to expand which contributes to flow reversal. The mass flow rates then quickly returns to 0.0 kg/s at 30 seconds when both the inlet and outlet pressures are equal.

While the secondary inlet mass flow rate is held constant, the outlet mass flow rate experiences a brief flow reversal as shown in Figure 13. This response is caused by an entirely different phenomenon than the primary response. As superheated steam cools, it condenses back into liquid water. Because the helical-coil is inclined, the liquid water flows back down the tubes until the tubes are filled with water. As the tubes are filled with liquid water, the mass flow rate increases back to its initial rate.

CONCLUSIONS

A loss of primary pressure transient was simulated as an exponential decrease of primary pressure using the RELAP5-3D helical-coil steam generator model. Heat transfer between the primary and secondary systems experienced a reversal. The heat was initially transferred from the primary system to the secondary system. After the pressure loss, the heat was transferred from the secondary system to the primary system. Analyzed sections of the steam generator displayed large variation in the response of the primary and secondary systems. The steady-state model that was developed solved for the design steam outlet temperature using a lower mass flow rate than was calculated because of conservative inputs.

ACKNOWLEDGEMENTS

The authors would like to convey special thanks to Mr. Michael W. Patterson, Mr. Cliff B. Davis and Mr. Paul D. Bayless for their expertise, guidance, and willingness to assist with the project. Also thanks to the Idaho National Laboratory for providing me with the opportunity to grow as an engineer and for

© 2011 The Journal of Young Investigators

opening up an array of possibilities for my future.

REFERENCES

Idaho National Laboratory. (2009) Next Generation Nuclear Plant Project 2009 Status Report. INL-EXT-09-17505, 1.

Sabharwall, P. (2009) Engineering Design Elements of a Two-Phase Thermosyphon to Transfer NGNP Thermal Energy to a Hydrogen Plant. INL-EXT-09-15383, 1.

Park, C. V. (2011) NGNP Process Heat Applications: Hydrogen Production Accomplishments for FY 2010. INL-EXT-11-20781, 1.

NGNP Senior Advisory Group. (2009) Senior Advisory Group Meeting Reference Configuration. Meeting Minutes, January 28, 2009.

Prabhanjan, D.G. et al. (2002) Comparison of Heat Transfer Rates Between a Straight Tube Heat Exchanger and a Helically Coiled Heat Exchanger. International Communications in Heat and Mass Transfer. Vol. 29, No. 2, 185–191.

AREVA. (2008) NGNP with Hydrogen Production IHX and Secondary Heat Transport Loop Alternatives. 12-9076325-001, 30.

General Atomics. (2010) Next Generation Nuclear Plant Prismatic HTGR Conceptual Design Project. NGNP-S00217, 1, 32.

General Atomics. (2008) NGNP Steam Generator Alternatives Study. 911120, 6, 16.

Electric Power Research Institute. (1994) Steam Generator Reference Book Volume I. Electric Power Research Institute, Inc. EPRI TR-103824s-V1R1.

Munshi, P. et al. (1986) Steam-Generator Simulation With None-Equilibrium Two-Phase Flow Models. Ann. Nucl. Energy Vol. 13, No. 11, 617–621.

General Atomics. (2009) Nuclear Heat Supply System Point Design Study for NGNP Conceptual Design. 911167.

Westinghouse Electric Company LLC. (2009) Next Generation Nuclear Plant: Intermediate Heat Exchanger Development and Trade Studies. NGNP-NHS-HTS-RPT-M-00004, 75.

Oh, C. H. et al. (2010) Design Option of Heat Exchanger for the Next Generation Nuclear Plant. Journal of Engineering for Gas Turbines and Power. Vol. 132, No. 3, 4.

Munshi, P. et al. (1985) Steam Generator Transient Studies Using a Simplified Two-Fluid Computer Code. Ann. Nucl. Energy. Vol. 12, No. 3, 155–157.

Bhatnagar, R. (1985) A Simplified Two-Fluid Model of a Steam Generator for Digital Simulation of Operation Transients. Ann. Nucl. Energy. Vol. 12, No. 7, 349–355.

© 2011 The Journal of Young Investigators

APPENDIX A

Parameter	NGNP Value	Calculated Value	RELAP5-3D Value
Heat Load (MWt)	600	-	-
Primary Inlet Temperature (K)	1023	-	1030.37
Primary Outlet Temperature (K)	595	595	606.35
Primary Mass Flow Rate (kg/s)	250	270.17	270.17
Primary Inlet Pressure (MPa)	7.0	-	7.2168
Primary Outlet Pressure (MPa)	6.976	-	6.982
Secondary Inlet Temperature (K)	473	-	478.32
Secondary Outlet Temperature (K)	813	813.04	813.54
Secondary Mass Flow Rate (kg/s)			
Secondary Inlet Pressure (MPa)	18.2	-	17.516
Secondary Outlet Pressure (MPa)	17.2	-	17.203
Number of Tubes	441	-	-
Single Tube Heated Length (m)	-	-	115
Heat Transfer Surface Area (m²)	-	5022.51	-
LMTD (K)	-	161.95	-
Overall Heat Transfer Coefficient (J/m² · s · K)	-	708.762	-

Table 2. Steady State Results.

Time (s)	Primary Inlet Pressure (MPa)	Primary Outlet Pressure (MPa)
10	7.2	6.976
13	3.8	3.68
16	2.0	1.941
19	1.06	1.024
23	0.45	0.437
26	0.2377	0.2303
30	0.1013	0.1013

Table 3. Primary inlet/outlet pressure inputs.

© 2011 The Journal of Young Investigators