INL/EXT-10-19621

Modeling a Helical-coil Steam Generator in RELAP5-3D for the Next Generation Nuclear Plant

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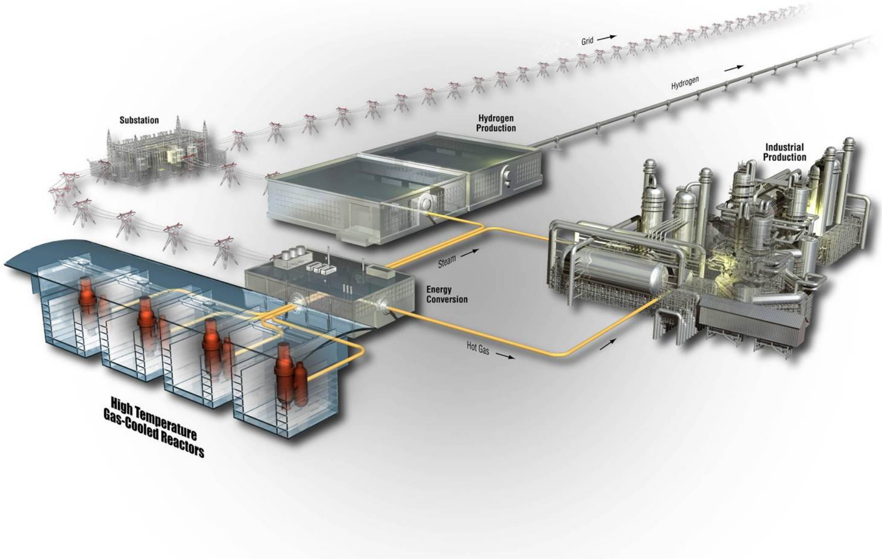

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Next Generation Nuclear Plant Project

Modeling a Helical-coil Steam Generator in RELAP5-3D for the Next Generation Nuclear Plant

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ABSTRACT

Options for the primary heat transport loop heat exchangers for the Next Generation Nuclear Plant (NGNP) are currently being evaluated. A helical-coil steam generator is one heat-exchanger design under consideration. Helical-coil steam generators are preferred over other steam generators for their increased heat transfer and compactness. Safety and reliability are an integral part of the helical-coil steam generator evaluation for NGNP. Transient analysis plays a key role in evaluating the safety of steam generators. Operational transients, such as start up, shut down, and loss of coolant accidents, are transients of interest. The helical-coil steam generator is modeled using RELAP5-3D, an Idaho National Laboratory in-house code. The transient response of an exponential loss of pressure (simulating double-ended shear) in the primary side of the steam generator is simulated. The exponential loss of pressure models a break of the steam generator inlet pipe.

This report details the development of the helical-coil steam generator model and the loss of pressure transient. Background on high temperature gas-cooled reactors and steam generators is provided to aid the reader in understanding the material presented. A detailed description of the RELAP5-3D helical-coil steam generator model is presented. An explanation is given of each of the RELAP5-3D components used in modeling the steam generator. Also reported is the response of the steam generator primary and secondary systems to the exponential loss of primary pressure.

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.

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ACRONYMS

HTGR	High Temperature Gas-cooled Reactor
INL	Idaho National Laboratory
LOCA	loss of coolant accident
LMTD	log mean temperature difference
NGNP	Next Generation Nuclear Plant
PWR	pressurized water reactor
SG	steam generator

NOMENCLATURE

C_P	Heat capacity [kJ/kg·K]
$C_{P_{ave}}$	Average heat capacity [kJ/kg·K]
d	Tube diameter [m]
l	Heated tube length [m]
$\dot{m}$	Mass-flow rate [kg/s]
N	Number of tubes
p	Tube perimeter [m]
ΔQ	Difference in heat load [MWt]
Q	Heat load [MWt]
S	Heated surface area [m^2]
ΔT	Difference in temperature [K]
T	Temperature [K]
U	Overall heat transfer coefficient [J/m^2·s·K]

Subscripts

inlet	Inlet of primary or secondary system of steam generator
LMTD	Log mean temperature difference
o	Tube outer dimension

RELAP5-3D Coding

ANNULUS	Annulus component: used to model an annulus
PIPE	Pipe component: used to model pipe or tubes
SNGLJUN	Single junction component: a hydrodynamic component used to join other hydrodynamic components together, model abrupt area changes, and pressure loss coefficients.
TMDPJUN	Time dependent junction component: controls the mass-flow rate
TMDPVOL	Time dependent volume component: controls the temperature and pressure and acts as a source or sink

Modeling a Helical-coil Steam Generator in RELAP5-3D for the Next Generation Nuclear Plant

1. INTRODUCTION

With the recent advances in nuclear technologies, the possibility of using nuclear plants for process heat production is closer than ever before. The Next Generation Nuclear Plant (NGNP), a high temperature gas-cooled reactor (HTGR) design, is based on providing process heat to a wide range of high temperature processes. NGNP will be able to provide electrical power and process heat to be used in hydrogen production, industrial applications, coal gasification, enhanced oil recovery (Sabharwall, 2009), and several other petro-chemical processes. Safety and reliability are paramount to the success of the NGNP. A key component of the NGNP reference design is the steam generator (SG) as shown in Figure 1 (NGNP Senior Advisory Group, 2009). Analysis of the steam generator under operational as well as transient conditions is an integral part of the safety and reliability of the NGNP (Munshi et al. 1986). To analyze transients in the steam generator, it is necessary to develop accurate models. RELAP5-3D is an industry-accepted code that provides a platform for steam generator two-phase flow transient analysis.

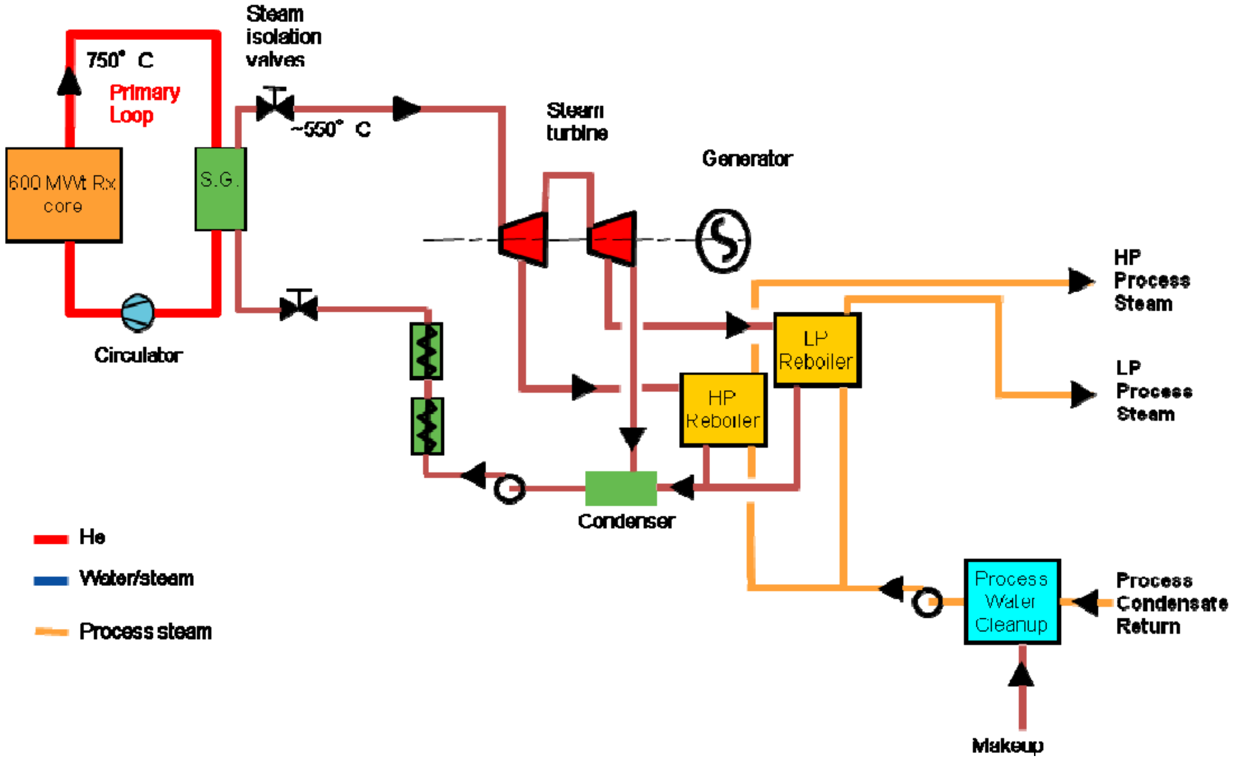

Figure 1. NGNP reference design.

1.1 Historical Development and Background of HTGRs

Since the inception of nuclear power there have been several advances in nuclear power plant design, especially with regard to reactor core design. Several different designs are being considered for the next generation of nuclear power plants. One such design is the HTGR concept, which has the goal of providing high temperature process heat (General Atomics, 2009).

HTGRs use helium as the coolant because of its non-reactivity at high temperatures. The inert nature of helium is also beneficial to the reactor core structure as well as to the steam generator where other coolants corrode the structure at high temperatures (Melese and Katz, 1984). Also, as helium passes through the core, it does not become radioactive, which provides added safety in the event of a breach in the reactor.

1.1.1 HTGR Core Designs

There are two distinct core designs for HTGRs: prismatic and pebble bed.

1.1.1.1 Prismatic Core Design

The prismatic core is made up of an outer core barrel, permanent and replaceable side reflectors, annular core, and a replaceable central reflector, as shown in Figure 2. The annular core consists of hexagonal graphite blocks stacked on top of each other. Each graphite block contains cylindrical holes. Helium coolant passes through these holes, which also house cylindrical fuel compacts and control rods.

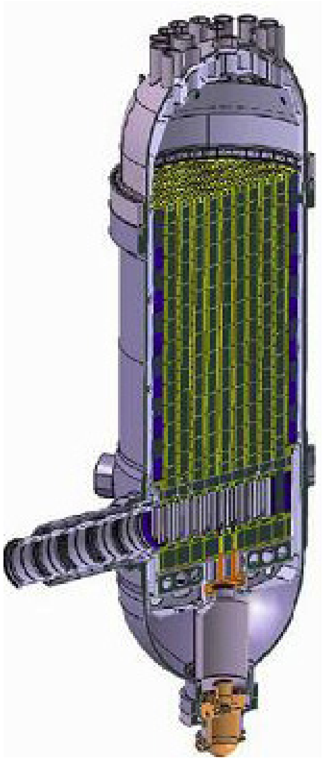

Figure 2. Schematic of a prismatic reactor vessel.

1.1.1.2 Pebble-Bed Core Design

The main characteristic of a pebble-bed reactor is its fuel form. As with a prismatic core, the pebble bed core has a core barrel with side reflectors, a central reflector, an annulus for fuel, and helium for coolant. Unlike the prismatic core hexagonal fuel elements, the pebble bed uses billiard-ball-sized spheres packed with fuel particles suspended in a graphite matrix. The spheres slowly flow down through the annular section of the core and are then cycled back into the core. The annular geometry of the pebble bed core provides the same benefits with regard to heat transfer and passive safety. A cross section of a pebble-bed reactor is shown in Figure 3 (Idaho National Laboratory, May 2009).

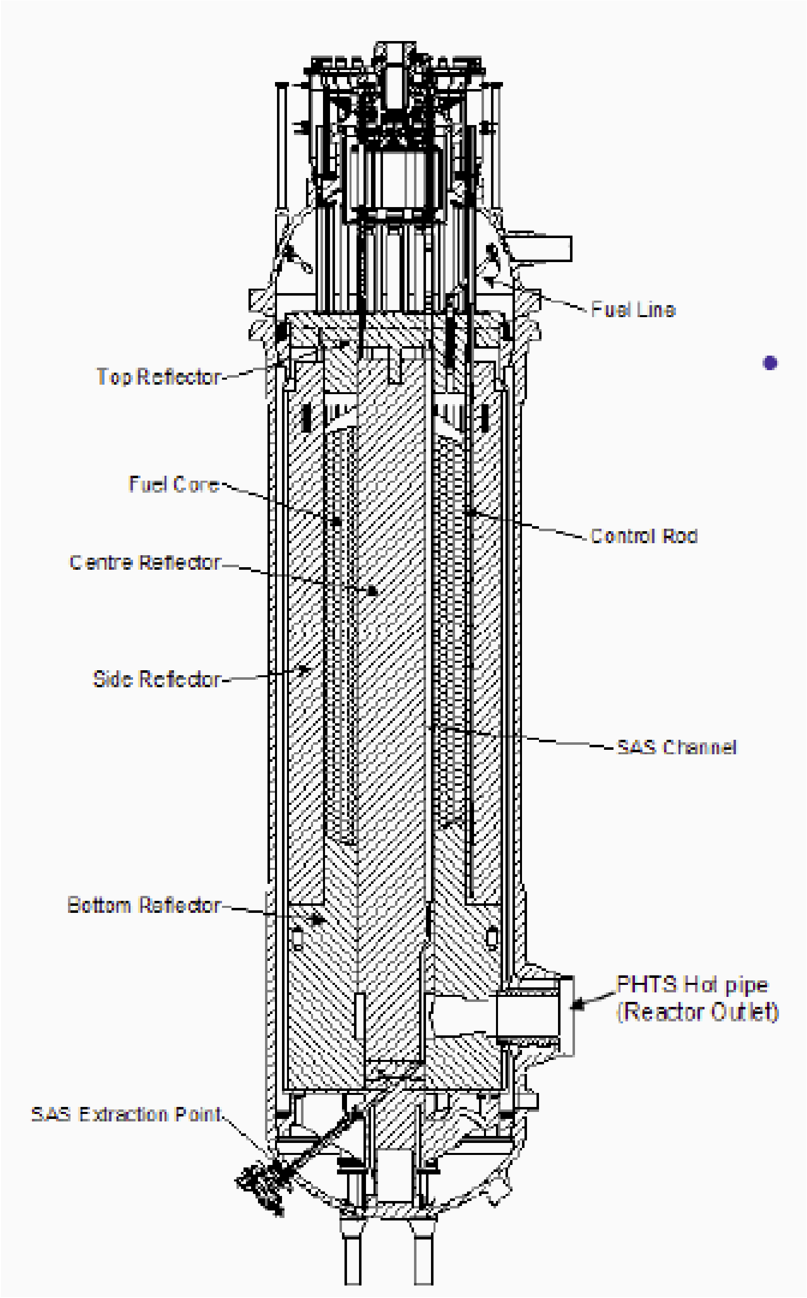

Figure 3. Schematic of the pebble-bed reactor vessel.

1.2 Historical Development and Background of Steam Generators

A steam generator is a heat exchanger made up of a shell (primary side) and several small tubes (secondary side), on the order of centimeters in diameter, which are bundled together. There are several shell and tube configurations. To increase heat transfer, baffles can be used to force the shell side coolant to cross over the tubes. Baffle designs vary widely, but serve the same purpose to increase the effectiveness of the heat exchanger. Tubes can also make more than one pass through the shell to increase the heat exchanger effectiveness. The tubes can be modified to have fins that increase heat transfer area.

Steam generators typically transfer heat from the shell side coolant to the tube side coolant, producing steam within the tubes. However, in PWRs, lower-pressure steam is produced on the shell side, and the high-pressure reactor coolant is circulated through the tubes. This design minimizes the shell wall thickness, but also makes the shell susceptible to corrosion (Melese and Katz, 1984). An advance in steam-generator design is the helical-coil design which offers compactness and increased heat transfer (Prabhanjan, et al., 2002). The tubes of the steam generator are wound into helical coils, forming a large bundle as shown in the Figure 4 (Areva, 2008). Helical-coil heat exchangers can have a 16 to 43% higher heat transfer coefficient than straight pipe heat exchangers (Prabhanjan, et al., 2002). Several issues still exist related to steam generators in nuclear power plants. For example, fouling and plugging of tubes is a major concern because it decreases the efficiency of the steam generator and requires a complete plant shutdown for servicing. Steam generators are also at risk of bursting tubes, which causes the mixing of the primary and secondary fluids, disrupting reactor conditions (Electric Power Research Institute, 1994).

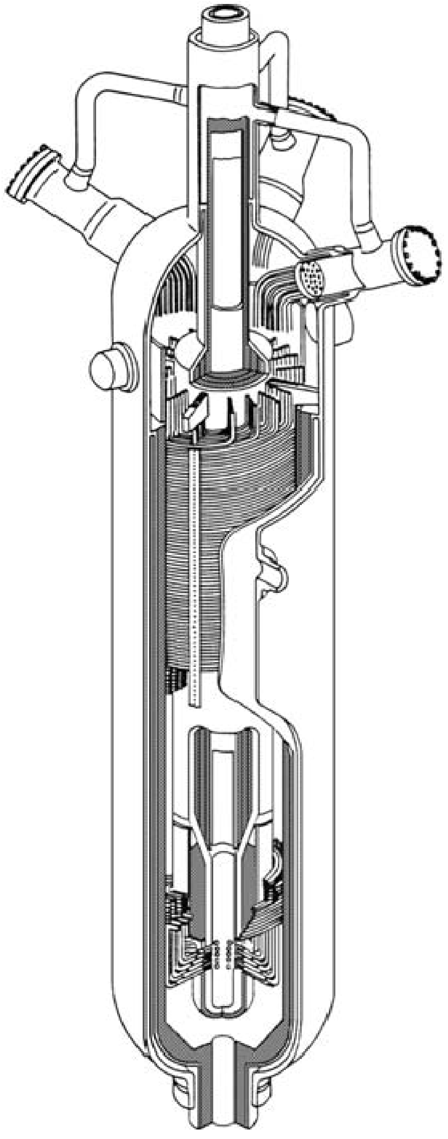

Figure 4. Cutaway of a helical-coil steam generator.

2. NGNP STEAM GENERATOR DESIGN

The NGNP project is evaluating several different heat exchangers as candidates for the primary heat transport system. The primary heat transport system consists of the reactor, heat exchanger, and power-production system. The helical-coil steam generator design is currently at the forefront of these heat exchangers. The NGNP design is based on a modular HTGR (MHTGR) steam-generator design. The steam-generator reference design is a vertically oriented, once-through, up-boiling, cross-counter-flow, shell and tube heat exchanger (Idaho National Laboratory, August 2009), shown in Figure 5. The multiple tubes are helically wound into bundles. The NGNP design has an upper bundle and lower bundle. The upper bundle experiences very high temperatures (~750°C) which require high temperature alloys like Inconel 617 and Incoloy 800H (General Atomics, 2008). These alloys have high corrosion resistance and structural strength at high temperatures. The upper and lower bundles are joined by a bimetallic weld. The lower bundle experiences lower temperatures and is made of a lower temperature alloy 2-1/4Cr-1Mo. The lower bundle can be divided into three sections. The first section can be thought of as an economizer that preheats the feedwater. The second section can be thought of as an evaporator that converts water into steam. The last section of the lower bundle represents the initial superheater that converts left-over liquid water into steam. The upper bundle acts as the finishing superheater that completely converts saturated steam into dry steam to prevent damage to the turbine.

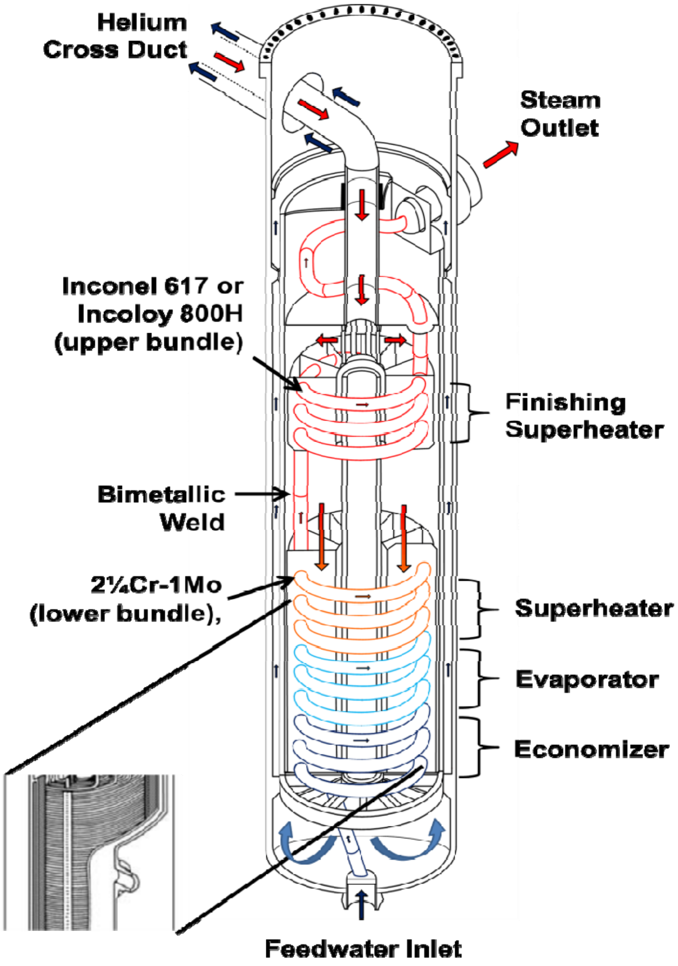

Figure 5. NGNP helical-coil steam-generator preconceptual design.

Helium enters the steam generator through the cross duct and is directed down through a central pipe. The central pipe opens up into an inner plenum. The helium then flows down around the individual helical-coil tubes. At the base plenum, the helium is redirected up through the annulus between the outer and inner shrouds, combining into the upper plenum. The helium then exits out the cross duct back into the reactor.

On the shell side, liquid water enters through the feedwater inlet and passes through the economizer, evaporator, and superheater sections, producing steam. The steam continues to the finishing superheater, which converts all steam into dry steam, before entering the turbomachinery.

The design parameters for the NGNP helical-coil steam generator (General Atomics, 2008; General Atomics, 2009) are shown in Table 1.

Table 1. Preconceptual NGNP helical-coil steam generator design parameters.

Parameter	NGNP Value
Heat Load, MWt	600
Primary Inlet Temperature, ºC	750
Primary Outlet Temperature, ºC	322
Primary Mass-Flow Rate, kg/s	250
Primary Inlet Pressure, MPa	7.0
Primary Outlet Pressure, MPa	6.976
Secondary Inlet Temperature, ºC	200
Secondary Outlet Temperature, ºC	540
Secondary Mass-Flow Rate, kg/s	216
Secondary Inlet Pressure, MPa	18.2
Secondary Outlet Pressure, MPa	17.2
Number of Tubes	441

3. CALCULATIONS

A heat-load balance was performed as the basis for the steady-state RELAP5 steam-generator model. The steam generator's secondary side was split into three sections, as shown in Figure 6. The lower section (points marked Tin to T4) consists of the feedwater inlet to the point at which water begins to vaporize at the inlet pressure. The next section (points marked T4 to T5) lies between the water vaporization point and the bimetallic weld (point marked T5), being the separation point of the two different tube materials; within this section, the secondary fluid is a two-phase fluid. The third section (points marked T5 to T6) consists of the portion above the bimetallic weld to the steam outlet. This section is assumed to be completely steam. It is assumed that the value of the specific heat, C_P can be averaged between temperature points. Table 2 shows the initial conditions that were used in calculating the heat load balance for the secondary system.

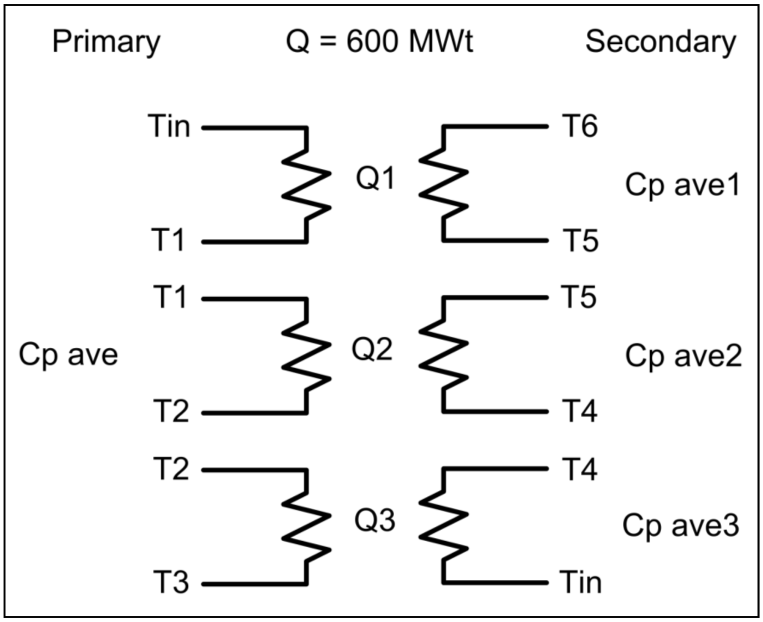

Figure 6. Calculation sections with corresponding notation.

3.1 Heat Load Balance: Secondary System Initial Calculations

Table 2. Heat-load balance: secondary system initial conditions.

Parameter	Value
Heat Load, MWt	600
Secondary inlet temperature, ºC (ºF)	200 (392)
Secondary inlet pressure, MPa (psi)	18.2 (2640)
H_2O phase change temperature, ºC (ºF)	358 (676.4)
Secondary mass-flow rate, kg/s (lbm/s)	216 (476.2)

Solving for heat load from inlet to H_2O phase change of the secondary side.

1. Calculate average heat capacity:

$$C_{P_{inlet}} = 4.4085\ \frac{kJ}{kg \cdot ℃}$$

$$C_{P_{4\ liquid}} = 13.467\ \frac{kJ}{kg \cdot ℃}$$

$$C_{P_{ave\ 3}} = \frac{C_{P_{4\ liquid}} + C_{P_{inlet}}}{2} = 8.935\ \frac{kJ}{kg \cdot ℃}$$

2. Calculate the temperature difference:

$$\Delta T_3 = T_4 - T_{inlet} = 158℃$$

3. Calculate heat load:

$$Q_3 = \dot{m} * C_{P_{ave\ 3}} * \Delta T_3 = 304.925\ MW$$

Solving for the heat load form the H_2O phase change to the change in tube material of the secondary side:

1. Assume that the fluid temperature at the point where the material change occurs is 450ºC.

$$T_5 = 450℃$$

2. Calculate average heat capacity:

$$C_{P_{4\ vapor}} = 24.265\ \frac{kJ}{kg \cdot ℃}$$

$$C_{P_5} = 3.709\ \frac{kJ}{kg \cdot ℃}$$

$$C_{P_{ave\ 2}} = \frac{C_{P_{4\ vapor}} + C_{P_5}}{2} = 13.867\ \frac{kJ}{kg \cdot ℃}$$

3. Calculate temperature difference:

$$\Delta T_2 = T_5 - T_4 = 92℃$$

4. Calculate heat load:

$$Q_2 = \dot{m} * C_{P_{ave\ 2}} * \Delta T_2 = 275.575\ MW$$

5. Calculate heat load difference between total heat load and Q_3:

$$\Delta Q = Q - Q_3 = 295.075\ MW$$

Solve for the heat load from the change in tube material to the steam outlet.

$$Q_1 = \Delta Q - Q_2 = 19.5\ MW$$

Solving for the secondary outlet temperature:

1. Assume an outlet temperature of 540ºC for outlet heat capacity.

2. Calculate average heat capacity:

$$C_{P_6} = 2.9045\ \frac{kJ}{kg \cdot ℃}$$

$$C_{P_5} = 3.709 \frac{kJ}{kg \cdot ℃}$$

$$C_{P_{ave\,1}} = \frac{C_{P_6} + C_{P_5}}{2} = 3.306 \frac{kJ}{kg \cdot ℃}$$

3. Calculate outlet temperature:

$$T_6 = T_5 + \frac{Q_1}{\dot{m} * C_{P_{ave\,1}}} = 477.31℃.$$

The outlet temperature is significantly lower than the design temperature of 540ºC. Since the heat capacity and the heat load are assumed to be parameters, the secondary mass-flow rate must be adjusted to achieve the desired steam outlet temperature.

3.2 Heat Load Balance: Secondary System Mass-Flow Rate

The secondary mass-flow rate was solved for iteratively by assuming a heat load for the section containing the secondary inlet to the temperature at which H_2O changes phase for a pressure of 18.2 MPa. The heat load choice was checked against the steam outlet temperature until it coincided with the design steam outlet temperature of 540ºC.

Solving for mass-flow rate of the secondary side:

1. Assume a heat load of 346.3 MW from the inlet to the phase change section. This heat load value is an iterative estimation which is then used to determine the mass-flow rate necessary to obtain an outlet temperature of 540 ºC.

$$Q_3 = 346.3\ MW$$

2. Calculate average heat capacity:

$$C_{P_{inlet}} = 4.4085\ \frac{kJ}{kg \cdot ℃}$$

$$C_{P_{4\,liquid}} = 13.467 \frac{kJ}{kg \cdot ℃}$$

$$C_{P_{ave\,3}} = \frac{C_{P_{4\,liquid}} + C_{P_{inlet}}}{2} = 8.935 \frac{kJ}{kg \cdot ℃}$$

3. Calculate the temperature difference:

$$\Delta T_3 = T_4 - T_{inlet} = 158℃$$

4. Calculate secondary mass-flow rate:

$$\dot{m} = \frac{Q_3}{C_{P_{ave\,3}} * \Delta T_3} = 245.309\ \frac{kg}{s}$$

Solving for the heat load from the H_2O phase change to the change in tube material of the secondary side.

1. Assume material change occurs at a fluid temperature of 450ºC.

$$T_5 = 450°\text{C}$$

2. Calculate heat load difference between total heat load and Q_3.

$$\Delta Q = Q - Q_3 = 253.70\ MW$$

3. Calculate average heat capacity:

$$C_{P_{4\,vapor}} = 12.504\ \frac{kJ}{kg \cdot °\text{C}}$$

$$C_{P_5} = 3.560\frac{kJ}{kg \cdot °\text{C}}$$

$$C_{P_{ave\,2}} = \frac{C_{P_{4\,vapor}} + C_{P_5}}{2} = 8.035\frac{kJ}{kg \cdot °\text{C}}$$

4. Calculate temperature difference:

$$\Delta T_2 = T_5 - T_4 = 92°\text{C}$$

5. Calculate heat load:

$$Q_2 = \dot{m} * C_{P_{ave\,2}} * \Delta T_2 = 181.271\ MW$$

Solve for the heat load from the change in tube material to the steam outlet.

$$Q_1 = \Delta Q - Q_2 = 72.429\ MW$$

Solving for the secondary outlet temperature:

1. Assume an outlet temperature of 540ºC at 17.2 MPa for outlet heat capacity.
2. Calculate average heat capacity:

$$C_{P_6} = 2.8492\ \frac{kJ}{kg \cdot °\text{C}}$$

$$C_{P_5} = 3.709\frac{kJ}{kg \cdot °\text{C}}$$

$$C_{P_{ave\,1}} = \frac{C_{P_6} + C_{P_5}}{2} = 3.279\frac{kJ}{kg \cdot °\text{C}}$$

Calculate steam outlet temperature:

$$T_6 = T_5 + \frac{Q_1}{\dot{m} * C_{P_{ave\,1}}} = 540.04°\text{C}$$

The calculated temperature now coincides with the design temperature of 540ºC. The secondary mass-flow rate was adjusted from 216 to 245.31 kg/s.

3.3 Heat Load Balance: Primary System Mass-Flow Rate

The primary system coolant is helium, which has little variation in heat capacity over large temperature ranges. Because of this characteristic, the primary system mass-flow rate is solved without dividing the system into three sections. The section temperatures will however be calculated. Table 3 shows the initial conditions that were used in calculating the primary system mass-flow rate.

Table 3. Heat-load balance: primary system initial conditions for mass-flow rate calculations.

Parameter	Value
Heat Load, MWt	600
Primary Inlet Temperature, ºC (ºF)	750 (1382)
Primary Outlet Temperature, ºC (ºF)	322 (611.6)
Primary Inlet Pressure, MPa (psi)	7.0 (1020)

Solving for mass-flow rate of the secondary side:

1. Calculate average heat capacity:

$$C_{P_{inlet}} = 5.1898 \frac{kJ}{kg \cdot ℃}$$

$$C_{P_3} = 5.1879 \frac{kJ}{kg \cdot ℃}$$

$$C_{P_{ave}} = \frac{C_{P_3} + C_{P_{inlet}}}{2} = 5.189 \frac{kJ}{kg \cdot ℃}$$

2. Calculate the temperature difference:

$$\Delta T = T_{in} - T_3 = 428℃$$

3. Calculate primary mass-flow rate:

$$\dot{m} = \frac{Q}{C_{P_{ave}} * \Delta T} = 270.17 \frac{kg}{s}$$

The calculated primary outlet temperature matches the design temperatures. The primary mass-flow rate was adjusted from 250 to 270.17 kg/s so that the design outlet temperature could be obtained.

3.4 Overall Heat-Transfer Coefficient

Table 4 shows the conditions that were used in solving for the overall heat transfer coefficient.

Table 4. Conditions used in solving for the overall heat-transfer coefficient.

Parameter	Value
Heat Load, MWt	600
Number of Tubes	441
Tube Outer Diameter, m (ft)	0.0318 (0.104)
Assumed Single Heated Tube Length, m (ft)	144 (472.4)
Primary Inlet Temperature, ºC (ºF)	750 (1382)

Primary Outlet Temperature, ºC (ºF)	322 (611.6)
Secondary Inlet Temperature, ºC (ºF)	200 (392)
Secondary Outlet Temperature, ºC (ºF)	540 (1004)

Solving for the overall heat transfer coefficient

$$N = 441\ tubes$$

$$l = 144\ m$$

1. Calculate single tube perimeter:

$$p = 2 * \pi * \frac{d_o}{2} = 0.099\ m$$

2. Calculated heated surface area:

$$S = N * p * l = 5022.51\ m^2$$

3. Calculate the log mean temperature difference:

$$T_1 = 750℃$$

$$T_2 = 322℃$$

$$T_3 = 200℃$$

$$T_4 = 540℃$$

$$\Delta T_{LMTD} = \frac{(T_1 - T_4) - (T_2 - T_3)}{\ln\left(\frac{T_1 - T_4}{T_2 - T_3}\right)} = 162.04℃$$

4. Calculate the overall heat transfer coefficient

$$U = \frac{Q}{S * \Delta T_{LMTD}} = 737.25\ \frac{J}{m^2 \cdot s \cdot ℃}$$

4. RELAP5-3D STEAM GENERATOR MODEL DEVELOPMENT AND DESCRIPTION

4.1 Model Development

Since the NGNP helical-coil steam generator is still being developed, several steam generators were referenced for flow path and dimensions. Flow path was based on an MHTGR steam generator (MHTGR, circa 1987). Dimensions and inlet and outlet conditions were referenced from other reports (Westinghouse Electric Company, LLC, 2009, General Atomics 2008, General Atomics 2009, Oh et al. 2010).

RELAP5-3D software was used to develop a computer model of the steam generator. RELAP5 is an Idaho National Laboratory in-house code used to simulate operational transients and loss of coolant accidents (LOCAs) within a nuclear power plant. Modeling a three-dimensional helical-coil bundle in

RELAP5 required several simplifications, as show in Figure 7. 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 of the single tube estimate the heat-transfer and flow characteristics of the actual bundle of tubes. The single tube helical coil was further simplified by unwrapping the coil tube to make an inclined straight pipe of the same length as a single tube and a vertical change in elevation corresponding to the bundle height. A heat transfer multiplier was added to the model to simulate improved heat transfer as observed in helical coils. With these simplifications, the helical-coil steam-generator model was developed.

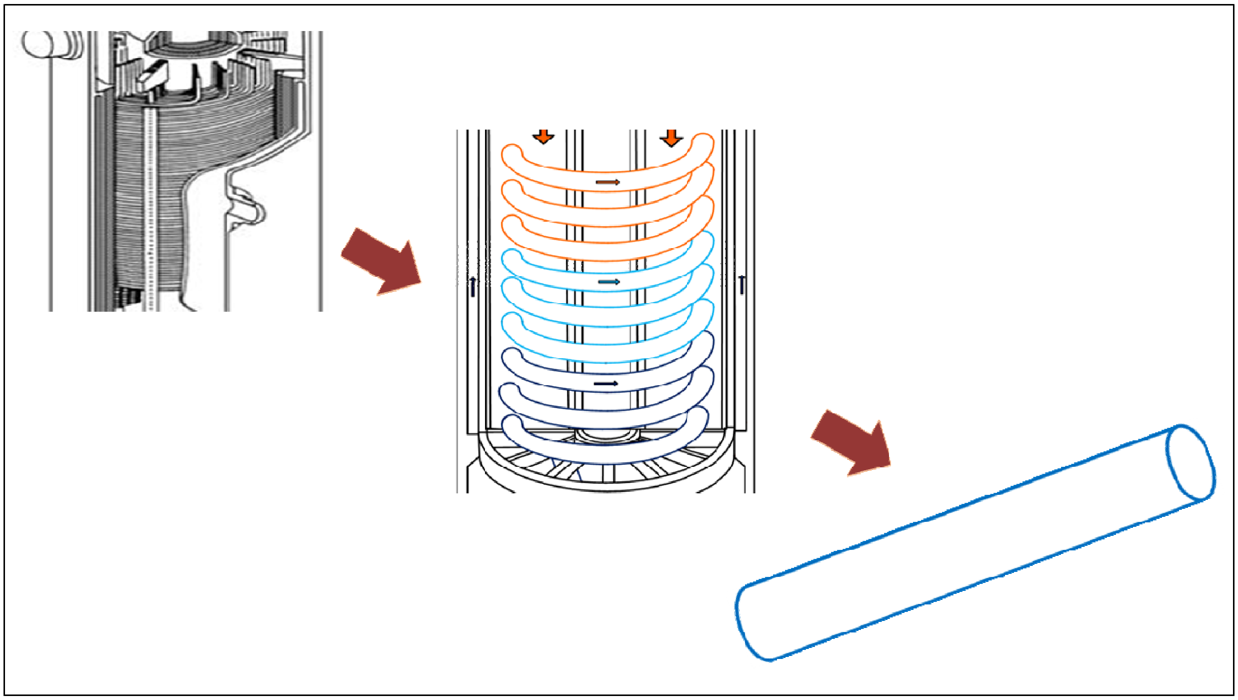

Figure 7. Helical-coil bundle simplifications.

Since all of the exact dimensions of the NGNP helical-coil steam-generator design needed for 600 MWt were unavailable, some dimensions were based on other steam-generator designs. As 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 varied to reach the exact temperature. This decision was made because a variation in mass-flow rate required less coding changes than a variation in the heated length. Changing the heated length required re-nodalization of a large portion of the steam generator model. 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. Once the design was completed, the model was run at steady-state conditions until the flow within the model reached steady-state values.

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 compared in Appendix A. Once the NGNP helical-coil steam generator design matures, the actual dimension should be used to improve model accuracy.

Part of model development was developing a transient that would be feasible using RELAP5-3D. A LOCA representing a rupture of the primary inlet and outlet pipes was chosen as the transient. The rupture was simulated by an exponential decrease in the primary inlet and outlet pressures. Other steam generator transient studies have also simulated LOCAs using ramp inputs for pressure (Munshi et al. 1985, Bhathagar et al. 1985, Munshi et al. 1986). Feedback from the reactor and power-conversion system were not considered in this model.

4.2 Model Description

The primary and secondary systems of the steam generator model 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 8) starts with an inlet boundary condition made up 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, which connects to a pipe component (PIPE 120) having six volumes. PIPE 120 models the inner pipe of the cross duct, the inlet pipe, and the inner plenum. PIPE 120 is connected to ANNULUS 130 via a single junction (SNGLJUN 125). ANNULUS 130 models the upper and lower bundles regions. ANNULUS 130 contains 39 volumes, vertically oriented, with a downward flow. There are abrupt area changes between the 9 and 10 volumes, 11 and 12 volumes, and the 38 and 39 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 inner and outer 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.

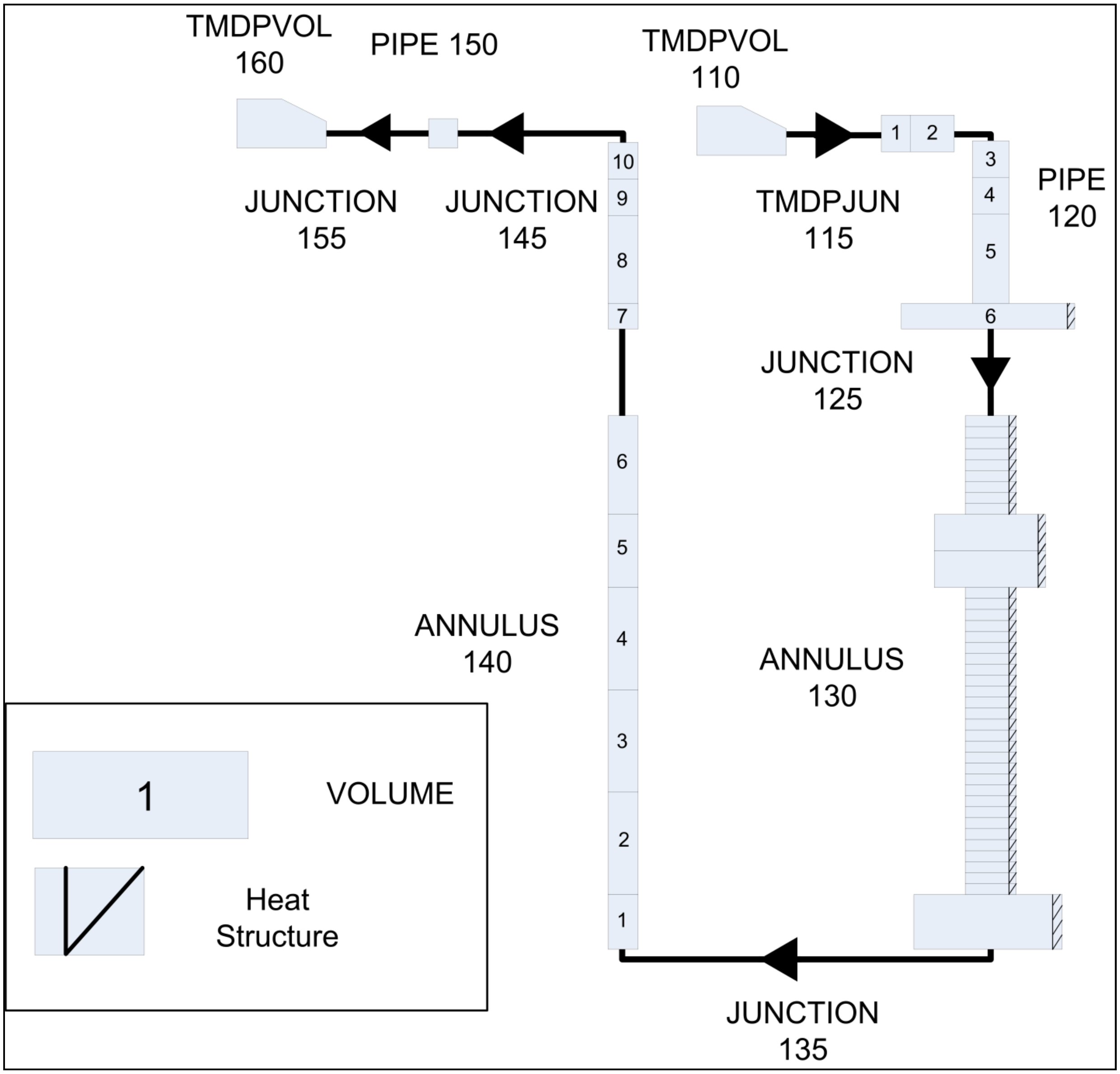

Figure 8. RELAP5-3D/ATHENA steam-generator model node visualization: primary system.

The secondary system, show in Figure 9, has inlet boundary conditions that are modeled by TMDPVOL 210 and TMDPJUN 215, providing control of the inlet temperature, pressure, and mass-flow rate. TMDPVOL 210 is connected to PIPE 220, which represents the helical coils 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 two vertical volumes, volumes 29 and 30, which allow for the bimetallic weld to be modeled, providing a separation point for two different tube materials. 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.

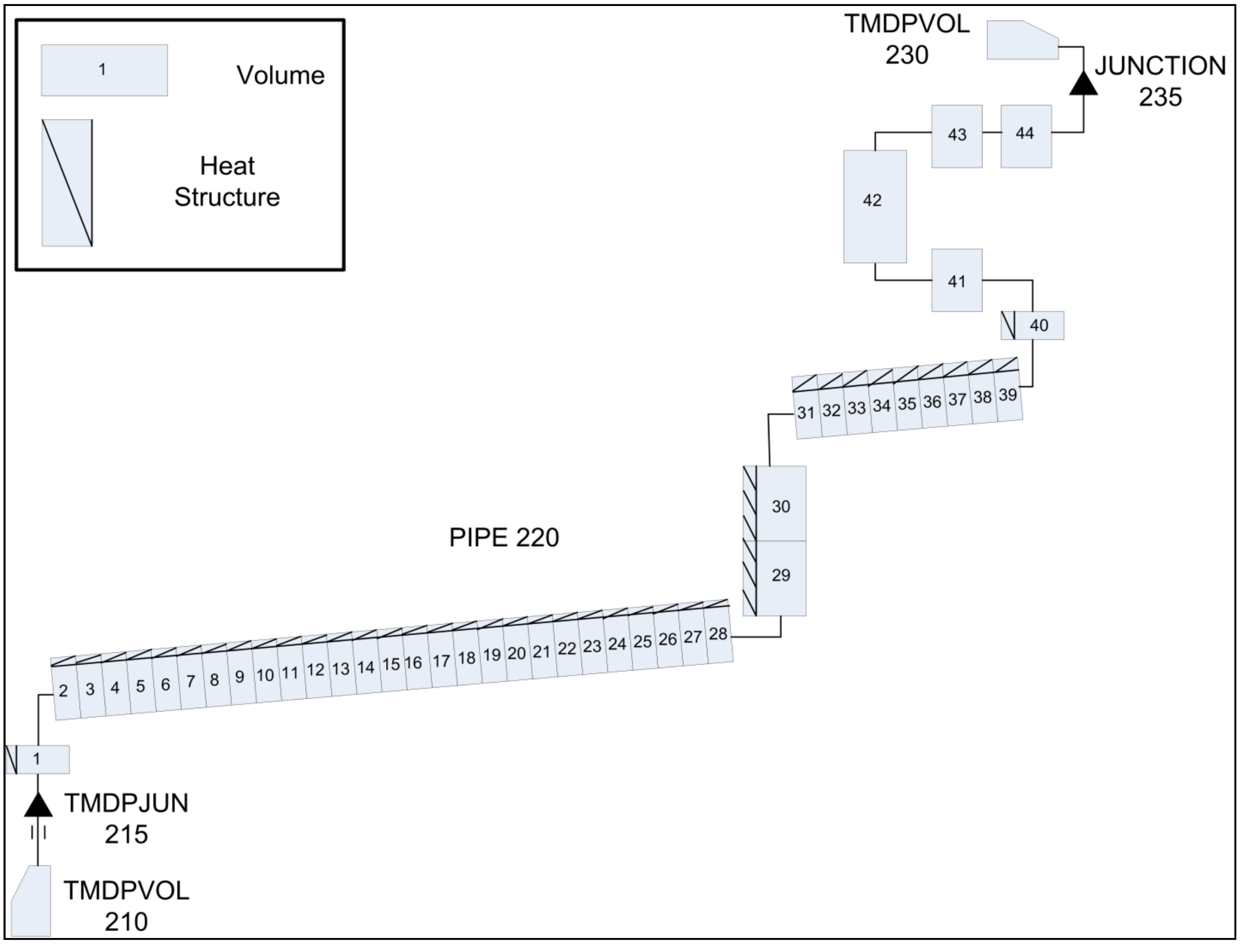

Figure 9. RELAP5-3D/ATHENA steam-generator model node visualization: secondary system.

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. Since a written description of each of the connections between hydrodynamic components and heat structures would be very cumbersome, Figure 10 has been provided to show each connection.

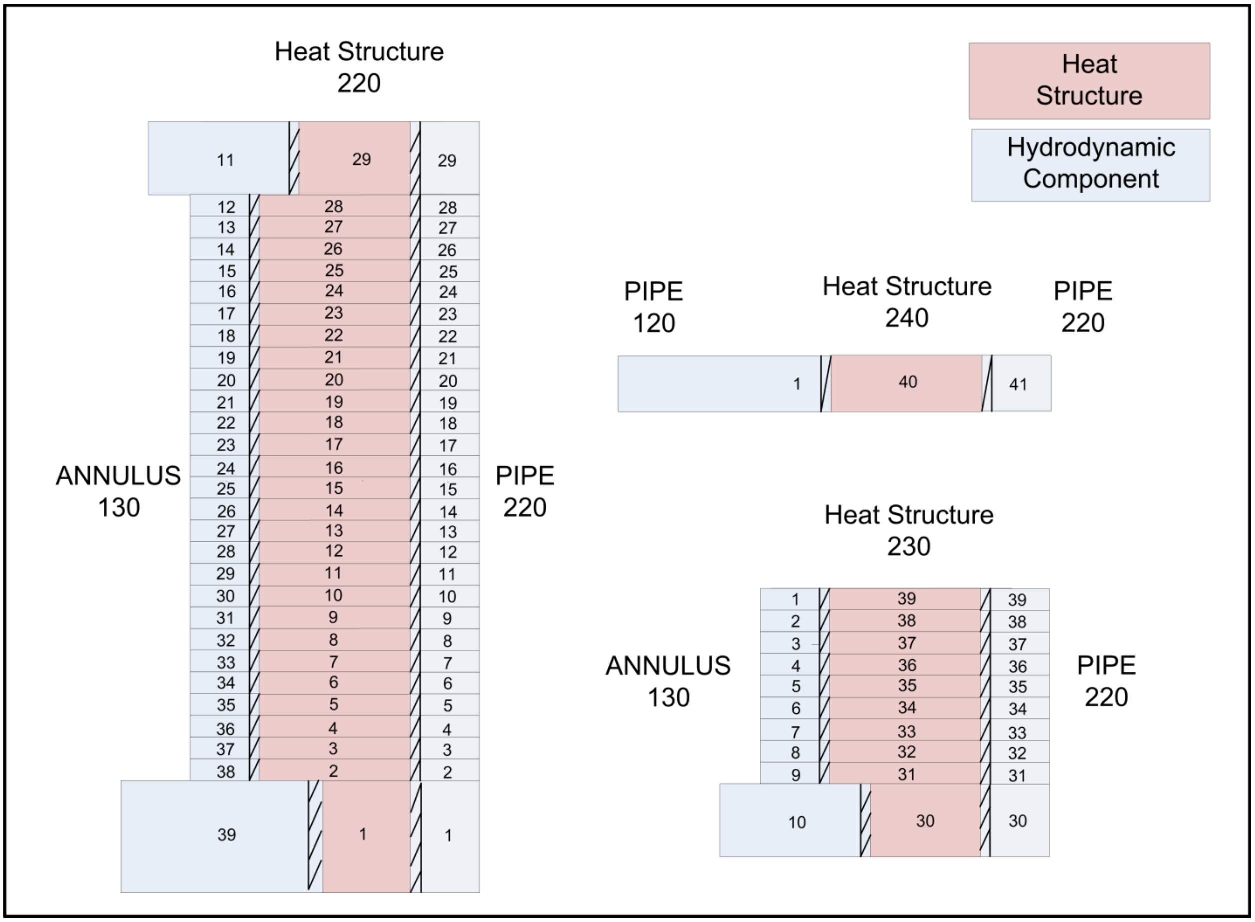

Figure 10. Heat structure connections with hydrodynamic component.

5. RESULTS

5.1 Steady-State Results

In order to simulate a transient using RELAP5, a steady-state case must first be run. Table 5 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 displayed.

To achieve the desired primary and secondary outlet temperature, the secondary mass-flow rate was adjusted from the calculated value. The secondary mass-flow rate decreased from 245.31 to 232.0 kg/s due to conservative inputs in the calculations. The single tube heated length required to achieve the desired secondary outlet temperature was 144 m, which is consistent with steam generator tube lengths in Appendix A.

Table 5. Steady state results.

Parameter	NGNP Value	Calculated Value	RELAP5-3D Value
Heat load, MWt	600	—	—
Primary inlet temperature, ºC	750	—	757.37
Primary outlet temperature, ºC	322	322	333.35
Primary mass-flow rate, kg/s	250	270.17	270.17
Primary inlet pressure, MPa	7.0	—	7.22
Primary outlet pressure, MPa	6.976	—	6.982
Secondary inlet temperature, ºC	200	—	205.32
Secondary outlet temperature, ºC	540	540.04	540.54
Secondary mass-flow rate, kg/s	216	245.31	232.0
Secondary inlet pressure, MPa	18.2	—	17.516
Secondary outlet pressure, MPa	17.2	—	17.203
Number of tubes	411	—	—
Single tube heated length, m	—	144	144
Heat-transfer surface area, m^2	—	5022.51	5022.51
LMTD, ºC	—	162.04	—
Overall heat-transfer coefficient, $J/m^2·s·ºC$	—	737.25	—

5.2 Transient Results: Exponential Decrease in Primary Pressure

A LOCA transient, representing a 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 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. In the event of a complete rupture, the reduction in pressure will occur over a much shorter period of time. This transient pressure decrease was chosen in order to better understand the results of a complete rupture of the inlet and outlet pipes. Table 6 shows the values used to simulate the exponential decrease in inlet and outlet pressures. Neglecting to decrease the outlet pressure would result in either a negative pressure drop across the primary side or back pressure, invalidating the results.

Table 6. Primary inlet/outlet pressure inputs.

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

The exponential decrease in pressure, as shown in Figure 11, begins at 10 seconds and ends at 30 seconds, after which the pressure stays constant at 0.1013 MPa at both the inlet and outlet.

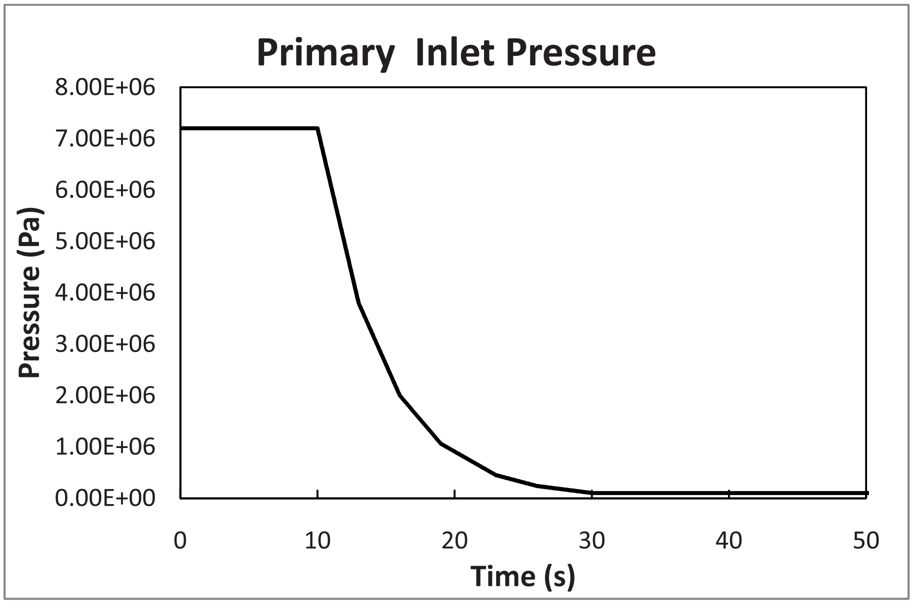

Figure 11. Exponential pressure decrease of primary inlet pressure.

As the primary pressure decreases, primary and secondary side temperatures decrease. The secondary side pressure, as shown in Figure 12, responds to the decrease in secondary temperature, initially decreasing by about 200 kPa for the inlet and slightly decreasing for the outlet. The inlet pressure drop is greater because the rapid pressure loss in the primary system causes energy to be transferred from the secondary to the primary.

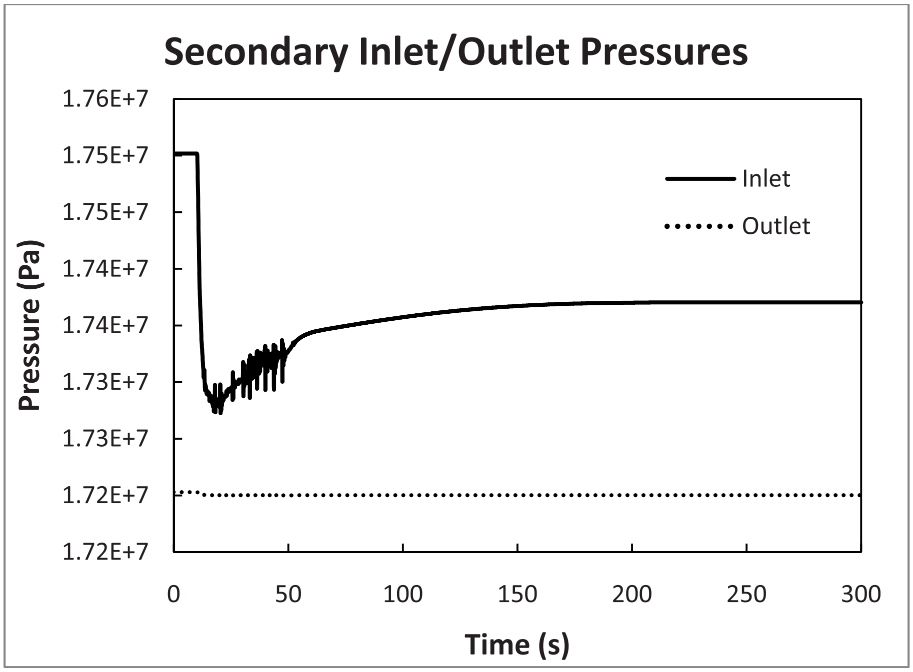

Figure 12. Secondary inlet/outlet pressure response.

The primary inlet and outlet temperature responses are shown in Figure 13. 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 begin to equalize.

The secondary inlet and outlet temperatures lag in response to the primary side changes. The outlet temperature, as shown in Figure 14, decreases rapidly as the steam condenses into a liquid. The large change in the rate of decrease of temperature around 45 seconds occurs as the steam reaches the saturation temperature. The steam then continues to condense until it all 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 a new steady-state.

The primary inlet and outlet mass-flow rate responses showed interesting results. Figure 15 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 rapid loss of coolant causes the helium temperature to decrease rapidly as well. 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 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 large decrease as shown in Figure 16. This response is caused by an entirely different phenomenon than the primary response. Due to the temperature decrease in the primary loop, the superheated steam cools, causing it to condense to 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.

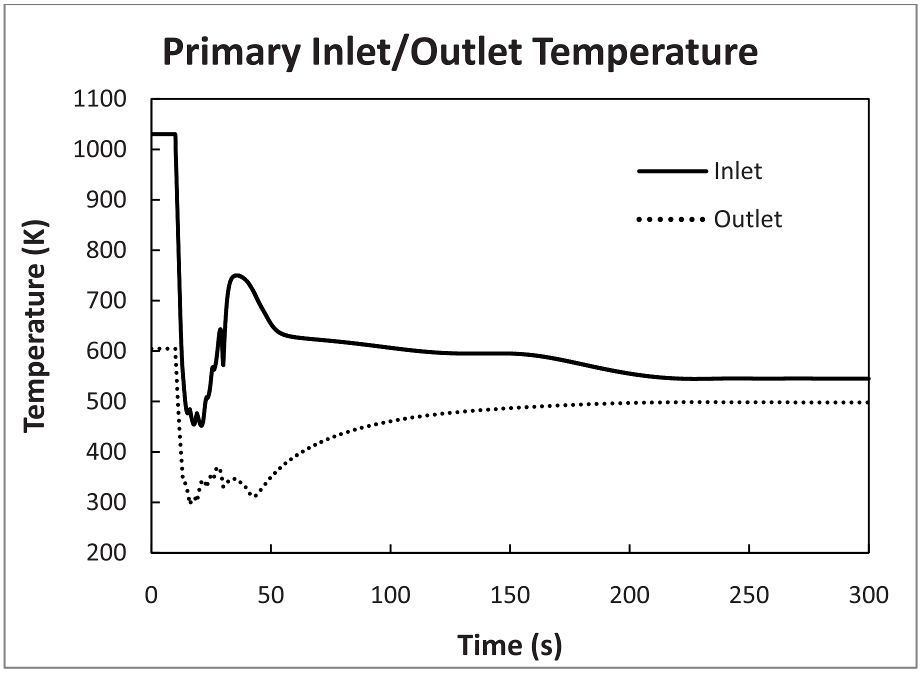

Figure 13. Primary inlet/outlet temperature response.

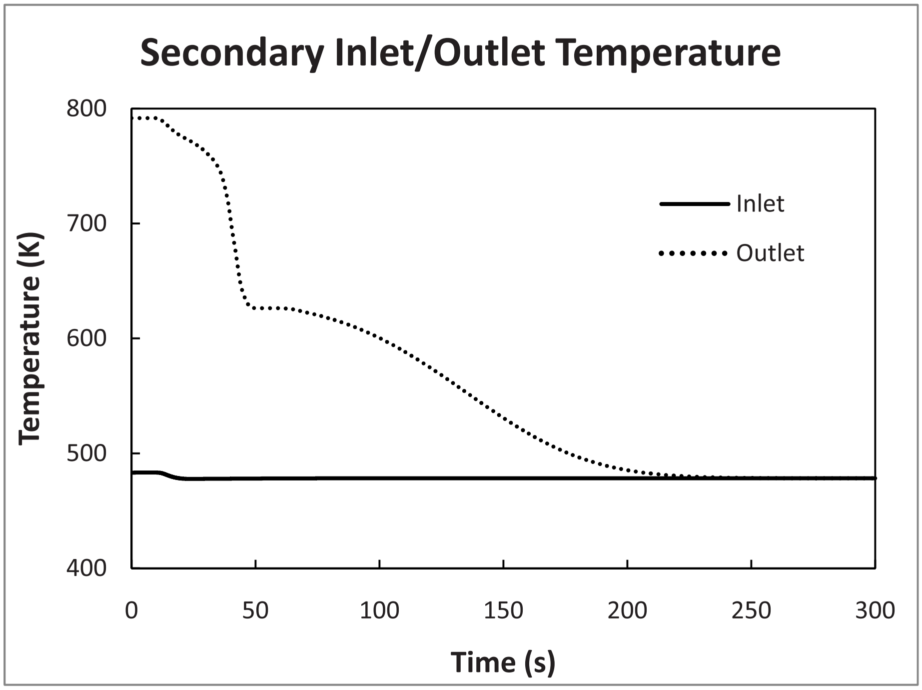

Figure 14. Secondary inlet/outlet temperature response.

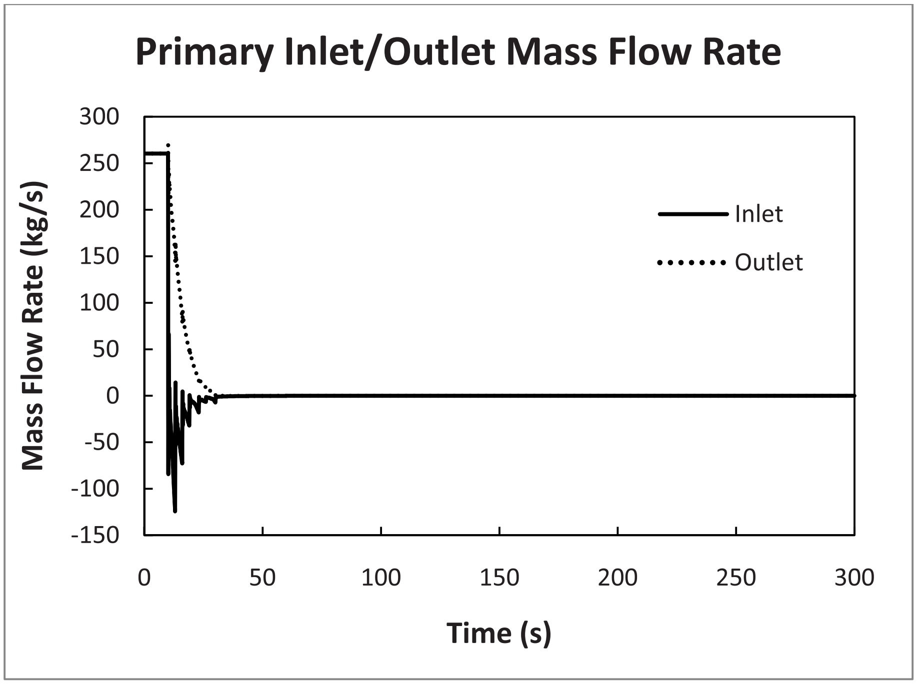

Figure 15. Primary inlet/outlet mass-flow rate response.

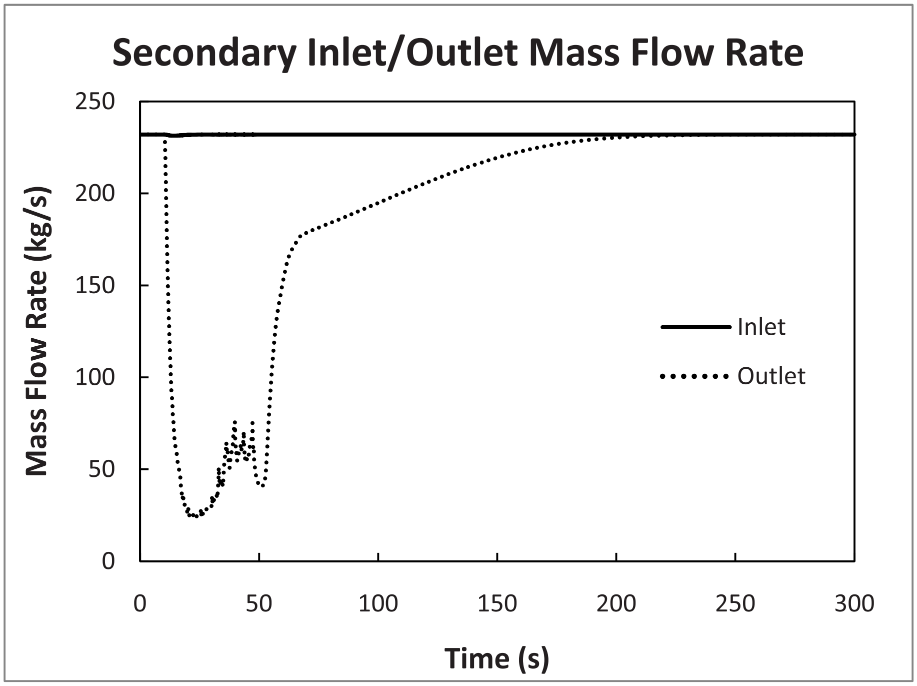

Figure 16. Secondary inlet/outlet mass-flow rate response.

6. CONCLUSIONS AND FUTURE WORK

6.1 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. The primary inlet mass-flow rate experiences a flow reversal. 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.

6.2 Future Work

In order to fully simulate operational and LOCA transients within the helical-coil steam-generator model, the model must be coupled with a reactor core model. Future work includes the development of a working reactor model. Coupling the reactor and steam-generator models would allow for a feedback loop between the reactor and steam generator, realistically changing the steam-generator inlet conditions. Work will also be done on other transients including, but not limited to, start-up and shutdown operations and plugged and fouled tubes.

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Appendix A

Comparison of Heat Exchangers Reference Next Generation Nuclear Plant: Intermediate Heat Exchanger Development and Trade Studies

Appendix A
Comparison of Heat Exchangers Reference Next Generation Nuclear Plant: Intermediate Heat Exchanger Development and Trade Studies

Table 7. Comparison of Heat Exchanger (Westinghouse Electric Company LLC, 2009).

Section/Page	NA/S	NA/S	3.3.1.1.1/21	3.3.1.2/31	5.4.2/192	4.3.1.2/51	4.3.1.2/51	4.3.1.2/51	2.4/55
Source	INL	INL	Sulzer/KVK	JAERI/HTTR	AREVA	GA/Toshiba	GA/Toshiba	GA/Toshiba	PBMR
Total Load, MWt	612	612	10	10	580	534	216	384	510
Number of IHXs	1	1	1	1	2	3	3	3	1
Load, MWt	612	612	10	10	290	178	72	128	510
HX Type	Helical Coil	PCHE	Helical Coil	Helical Coil	Helical Coil	Helical Coil	Helical Coil	Helical Coil	PFHE
Primary Side									
Tin, °C	900	900	950	950	900	900	900	750	800
Tout, °C	594.5	594.5	293	390	490	480	750	481	268
Nominal Pressure, MPa	7	7	4		5	7	7	7	8.7
Flow Rate, kg/s	385	385	2.95	12	136	81.8	91.96	91.96	185
Secondary Side									
Tin, °C	492.5	492.5	220	330	415	308	673	312	218
Tout, °C	884.8	884.8	900	860	825	700	875	673	750
Nominal Pressure, MPa	7.6	7.6	4		5.5	7	7	7	8.9
Flow Rate, kg/s	300	300	2.85	12	136	87.64	68.44	68.44	185
LMTD, °C	46	46	61	90	75	186	46	117	50
Tubes									
Number	5025		119	96	2966	500	1025	914	
OD, mm	20		22	31.8	21	45	31.8	31.8	
Thickness, mm	1		2	3.5	2.2	5	3.5	3.5	
Length, m	42.9		43		18.3	22.05	21.39	17.62	
Inner Coil Diameter, mm	490				1500	1870	1600	1600	
Outer Coil Diameter, mm	4600				3490	4080	3950	3762	
Coil Height, m	9.86				7.8	4.58	4.45	3.66	
Coil Layer						18	26	24	
Modules									
Number		34							180
Length, mm		430							553.7
Width, mm		600							50
Height, mm		600							1000
HT Core Volume, m^3	162.0	5.29			60.8	47.3	45.6	33.3	4.98
Total HT Area, m^2	13540	5805	348		3581	1714	2190	1609	16879
U, W/ m^2 * K	1189	2313	473		1080	559	711	680	604

Vessel									
ID, mm			2400	2000	6380	5000	5000	4750	3500
Height, mm			24980	11000		18350	18500	17500	7819
Approx. Volume, m^3 [2]	163.8		177	61		275	278	246	70
Surface Efficiency, kW/ m^3 [3]			29		81	104	33	80	30
Core Compactness, MW/ m^3	3.8	116			5	4	2	4	102
HX compactness, MW/ m^3	3.74		0.06	0.16		0.65	0.26	0.52	7.29

Notes:

[1] AREVA IHX diameter from Fig. 5-5, Ref. 3-6; believed to be flange OD

[2] Assumes spherical heads

[3] Heat Transfer Active Area Only

Appendix B

Transient Helical-coil Steam Generator, RELAP5-3D Input Deck

Appendix B
Transient Helical-coil Steam-generator RELAP5-3D Input Deck with Comments

```
=Steam Generator 1
*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
*  *  *
*                         Transient Steam Generation Problem
*     Coded by: Nathan Hoffer
*      start: 6/24/10 end
* Problem: Develop a vertical, up-flow boiling, cross-counter flow,
* once-through, shell-and-tube heat exchanger, helically-wound tube
bundled
* steam generator with the following properties (NGNP Steam Generator
* Alternatives Study):
* He inlet temp, K                            1173.0
* He oulet temp, K                             753.0
* He flow rate, kg/s                           250.0
* He inlet pressure, MPa                         7.0
* He pressure drop, kPa                         24.0
* Water inlet temp, K                          473.0
* Steam outlet temp, K                         811.0
* Water flow rate, kg/s                        216.0
* Feedwater inlet pressure, MPa                 18.2
* Steam outlet pressure, MPa                    17.2
* Number of tubes                              441.0
* Economizer tube material               2 1/4Cr-1Mo
* Evaorator tube material                2 1/4Cr-1Mo
* Finishing Superheater material         2 1/4Cr-1Mo
* Abitrary parameters
*      Assumptions:
*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
*  *  *
*    run     option
100   newath  transnt *stdy-st
*    in   out
102   si   si
*   CHF
*107   1   1   1
*    refv       refh  fluid name
120   120010000  19.0  he   'Shell'
*    refv       refh  fluid name
121   220010000  0.0   h2o  'Tube'
*
*===========================================================*
*          time step card              *
*===========================================================*
*    end       min     max    tt   minor   major restar
201   200.0     1.0-6   .005   16   10  10   2000
*
```

```
*===========================================================*
*                     minor edit variables                  *
*===========================================================*
*
*301 tempf  120150000
*
*302 mflowj 215000000
*
*===========================================================*
*                       plot variables                      *
*===========================================================*
*
*        varname   var#
20800001  cntrlvar  4
*
*
*===========================================================*
*                        trip cards                    *
*===========================================================*
*  varcode par        rel varcode par +const  li
*501 tempf   125001000  lt  null    0   400.0   n
*  varcode par        rel varcode par +const  li
*502 tempf   125001000  gt  null    0   400.0   n
*  trip#  op  trip#  li
*601 501    or  502    n
*
*===========================================================*
*                   --PRIMARY SYSTEM--He                    *
*===========================================================*
*===========================================================*
*                    shell side source                      *
*===========================================================*
*card #  name    type
1100000   coreout tmdpvol
*     flwA    lngth vol  azangl vrtangl elev  walr  hydrd  flg
1100101   0.7854  1.0   0.0  0.0    0.0    0.0   0.0    0.0    10
*     cntrlwrd  trip#  ctrlname   ctrl#
1100200   003
*     time   press   temp
1100201   0.0    7.2+6   1030.0
1100202   10.0    7.2+6   1030.0
1100203   13.0    3.8+6     1030.0
1100204   16.0    2.0+6     1030.0
1100205   19.0    1.06+6     1030.0
1100206   23.0    0.45+6     1030.0
1100207   26.0    0.2377+6  1030.0
1100208   30.0    0.1013+6  1030.0
*
*===========================================================*
*                 shell side inlet-junction                 *
*===========================================================*
*card #  name        type
```

```
*1150000   heinjun    tmdpjun
*        from vol    to vol      flwA     flag
*1150101   110010000  120000000   0.0      0
*        cntrlwrd  trip#  ctrlname   ctrl#
*1150200   1
*       time   liqmflow  vapmflow   interf vel
*1150201   0.0    0.0       270.17     0.0
*
*card #  name       type
1150000   junction   sngljun
*        from vol   to vol     flwA  f.loss  r.loss  flag
1150101   110010000  120000000  0.0   0.0     0.0    0
*       flag       liqmflow   vapmflow  interf vel
1150201   0          96.388     96.388  0. * 260.422
*
*==============================================================*
*     inner cross duct/He inlet pipe/shell inlet plenum     *
*==============================================================*
*card #  name    type
1200000   crsdct  pipe
*     vn
1200001   6
*     flwA     vn
1200101   0.7854   5
*     flwA     vn
1200102   17.6605  6
*        flwA     jn
1200201   0.7854   5
*     length   vn
1200301   1.0      1
*     length   vn
1200302   2.385    2
*     length   vn
1200303   2.0      4
*     length   vn
1200304   3.0      5
*     length   vn
1200305   1.0      6
*        vol      vn
1200401   0.0      6
*        incl     vn
1200601   0.0      2
*        incl     vn
1200602  -90.0     6
*        elev     vn
1200701   0.0      2
*        elev     vn
1200702  -2.0      4
*        elev     vn
1200703  -3.0      5
*        elev     vn
1200704  -1.0      6
```

```
*        walr    hydrd   vn
1200801   1.0-6   1.0     5
*        walr    hydrd   vn
1200802   1.0-6   4.4816  6
*        floss   rloss   jn
1200901   0.0     0.0     5
*        flag    vn
1201001   0       6
*        jefvcahs  jn
1201101   000       4
*        jefvcahs  jn
1201102   100       5
*        ebt     press   temp                  vn
1201201   0       7199932. 3212785. 3212785. 1. 0. 1
1201202   0       7199700. 3212820. 3212820. 1. 0. 2
1201203   0       7199434. 3212843. 3212843. 1. 0. 3
1201204   0       7199228. 3212872. 3212872. 1. 0. 4
1201205   0       7198971. 3212920. 3212920. 1. 0. 5
1201206   0       7200190. 3204678. 3204678. 1. 0. 6
*        cntrlwrd
1201300   0
*        liqv    vapv    intv   jn
1201301   96.389  96.389  0.     1 * 260.422
1201302   96.3916 96.3916 0.     2 * 260.422
1201303   96.3942 96.3942 0.     3 * 260.422
1201304   96.3966 96.3966 0.     4 * 260.422
1201305   96.3998 96.3998 0.     5 * 260.422
*
*===========================================================*
*      junction between inlet plenum and shell annulus      *
*===========================================================*
*card #  name       type
1250000   junction   sngljun
*        from vol   to vol     flwA  f.loss  r.loss  flag
1250101   120010000  130000000  0.0   0.0     0.0    0
*       flag       liqmflow   vapmflow  interf vel
1250201   0          11.02578   11.02578  0. * 260.422
*
*===========================================================*
*             shell side inner shroud - annulus             *
*===========================================================*
*card #  name    type
1300000   shell   annulus
*     vn
1300001   39
*     flwA     vn
1300101   6.8486   9
*     flwA     vn
1300102   15.8972  11
*     flwA     vn
1300103   6.8486   38
*     flwA     vn
```

```
1300104   17.8139  39
*        flwA     jn
1300201   6.8486   8
*        flwA     jn
1300202   15.8972  9
*        flwA     jn
1300203   6.8486   38
*     length   vn
1300301   0.1666   9
*     length   vn
1300302   1.0      11
*     length   vn
1300303   0.1666   38
*     length   vn
1300304   3.0      39
*        vol      vn
1300401   0.0      39
*        incl     vn
1300601  -90.0     39
*        elev     vn
1300701  -0.1666   9
*        elev     vn
1300702  -1.0      11
*        elev     vn
1300703  -0.1666   38
*        elev     vn
1300704  -3.0      39
*        walr    hydrd     vn
1300801   1.0-6   0.7509    9
*        walr    hydrd     vn
1300802   1.0-6   3.1057    11
*        walr    hydrd     vn
1300803   1.0-6   0.7509    38
*        walr    hydrd     vn
1300804   1.0-6   4.5026    39
*        floss   rloss   jn
1300901   0.0     0.0     8
*        floss   rloss   jn
1300902   0.0     0.0     9
*        floss   rloss   jn
1300903   0.0     0.0     10
*        floss   rloss   jn
1300904   0.0     0.0     38
*        flag    vn
1301001   0       39
*        jefvcahs  jn
1301101   100       8
*        jefvcahs  jn
1301102   000       9
*        jefvcahs  jn
1301103   100       10
*        jefvcahs  jn
```

```
1301104   100       38
*        ebt     press   temp                   vn
1301201   0       7200030. 3153104. 3153104. 1. 0. 1
1301202   0       7200042. 3098155. 3098155. 1. 0. 2
1301203   0       7200055. 3040024. 3040024. 1. 0. 3
1301204   0       7200068. 2979100. 2979100. 1. 0. 4
1301205   0       7200082. 2916053. 2916053. 1. 0. 5
1301206   0       7200096. 2851918. 2851918. 1. 0. 6
1301207   0       7200110. 2788069. 2788069. 1. 0. 7
1301208   0       7200125. 2727728. 2727728. 1. 0. 8
1301209   0       7200140. 2672551. 2672551. 1. 0. 9
*        ebt     press   temp                   vn
1301210   0       7200310. 2663402. 2663402. 1. 0. 10
*        ebt     press   temp                   vn
1301211   0       7200138. 2654696. 2654696. 1. 0. 11
*        ebt     press   temp                   vn
1301212   0       7199968. 2613416. 2613416. 1. 0. 12
1301213   0       7199980. 2574266. 2574266. 1. 0. 13
1301214   0       7199992. 2536702. 2536702. 1. 0. 14
1301215   0       7.2+6    2499976. 2499976. 1. 0. 15
1301216   0       7200016. 2460961. 2460961. 1. 0. 16
1301217   0       7200028. 2424913. 2424913. 1. 0. 17
1301218   0       7200039. 2391596. 2391596. 1. 0. 18
1301219   0       7200050. 2360779. 2360779. 1. 0. 19
1301220   0       7200062. 2332246. 2332246. 1. 0. 20
*        ebt     press   temp                   vn
1301221   0       7200073. 2305736. 2305736. 1. 0. 21
1301222   0       7200084. 2280685. 2280685. 1. 0. 22
1301223   0       7200095. 2256325. 2256325. 1. 0. 23
1301224   0       7200106. 2232454. 2232454. 1. 0. 24
1301225   0       7200116. 2208925. 2208925. 1. 0. 25
1301226   0       7200128. 2185629. 2185629. 1. 0. 26
1301227   0       7200138. 2162481. 2162481. 1. 0. 27
1301228   0       7200150. 2139397. 2139397. 1. 0. 28
1301229   0       7200160. 2116323. 2116323. 1. 0. 29
*        ebt     press   temp                   vn
1301230   0       7200172. 2093202. 2093202. 1. 0. 30
1301231   0       7200183. 2069983. 2069983. 1. 0. 31
1301232   0       7200194. 2046616. 2046616. 1. 0. 32
1301233   0       7200206. 2023055. 2023055. 1. 0. 33
1301234   0       7200218. 1999262. 1999262. 1. 0. 34
1301235   0       7200230. 1975212. 1975212. 1. 0. 35
1301236   0       7200242. 1950873. 1950873. 1. 0. 36
1301237   0       7200254. 1926216. 1926216. 1. 0. 37
1301238   0       7200266. 1901207. 1901207. 1. 0. 38
*        ebt     press   temp                   vn
1301239   0       7200418. 1889335. 1889335. 1. 0. 39
*        cntrlwrd
1301300   0
*        liqv    vapv    intv   jn
1301301   10.84826 10.84826 0.   1 * 260.422
1301302   10.65897 10.65897 0.   2 * 260.422
```

```
1301303   10.45872 10.45872 0.   3 * 260.422
1301304   10.24885 10.24885 0.   4 * 260.422
1301305   10.03166 10.03166 0.   5 * 260.422
1301306   9.81073  9.81073  0.   6 * 260.422
1301307   9.59078 9.59078 0.     7 * 260.422
1301308   9.38292 9.38292 0.     8 * 260.422
1301309   3.96033 3.96033 0.     9 * 260.422
1301310   3.9467  3.9467  0.     10 * 260.422
1301311   9.13134 9.13134 0.     11 * 260.422
1301312   8.98926 8.98926 0.     12 * 260.422
1301313   8.8544  8.8544  0.     13 * 260.422
1301314   8.725   8.725   0.     14 * 260.422
1301315   8.59848 8.59848 0.     15 * 260.422
1301316   8.46408 8.46408 0.     16 * 260.422
1301317   8.3399  8.3399  0.     17 * 260.422
1301318   8.22512 8.22512 0.     18 * 260.422
1301319   8.11896 8.11896 0.     19 * 260.422
1301320   8.02067 8.02067 0.     20 * 260.422
1301321   7.92934 7.92934 0.     21 * 260.422
1301322   7.84305 7.84305 0.     22 * 260.422
1301323   7.75913 7.75913 0.     23 * 260.422
1301324   7.6769  7.6769  0.     24 * 260.422
1301325   7.59584 7.59584 0.     25 * 260.422
1301326   7.51559 7.51559 0.     26 * 260.422
1301327   7.43585 7.43585 0.     27 * 260.422
1301328   7.35632 7.35632 0.     28 * 260.422
1301329   7.27684 7.27684 0.     29 * 260.422
1301330   7.19719 7.19719 0.     30 * 260.422
1301331   7.1172  7.1172  0.     31 * 260.422
1301332   7.03671 7.03671 0.     32 * 260.422
1301333   6.95554 6.95554 0.     33 * 260.422
1301334   6.87358 6.87358 0.     34 * 260.422
1301335   6.79073 6.79073 0.     35 * 260.422
1301336   6.70688 6.70688 0.     36 * 260.422
1301337   6.62194 6.62194 0.     37 * 260.422
1301338   6.53579 6.53579 0.     38 * 260.422
*
*===========================================================*
*         junction of inner shell and base plenum           *
*===========================================================*
*card #  name       type
1350000   ssjun     sngljun
*        from vol   to vol     flwA    f.loss  r.loss  flag
1350101   130010000  140000000  0.0     0.6     0.6     0
*       flag       liqmflow   vapmflow  interf vel
1350201   0          98.539     98.539    0. * 260.422
*
*===========================================================*
*                  outter shroud-annulus                    *
*===========================================================*
*card #  name    type
1400000   shroud  annulus
```

```
*     vn
1400001   10
*     flwA     vn
1400101   0.4514   8
*     flwA     vn
1400102   0.4434   9
*     flwA     vn
1400103   16.1029  10
*        flwA     jn
1400201   0.4514   7
*        flwA     jn
1400202   0.4434   9
*     length   vn
1400301   3.0      1
*     length   vn
1400302   1.5      4
*     length   vn
1400303   2.0      5
*     length   vn
1400304   1.5      6
*     length   vn
1400305   1.0      7
*     length   vn
1400306   3.0      8
*     length   vn
1400307   2.0      10
*        vol      vn
1400401   0.0      10
*        incl     vn
1400601   90.0     10
*        elev     vn
1400701   3.0      1
*        elev     vn
1400702   1.5      4
*        elev     vn
1400703   2.0      5
*        elev     vn
1400704   1.5      6
*        elev     vn
1400705   1.0      7
*        elev     vn
1400706   3.0      8
*        elev     vn
1400707   2.0      10
*        walr    hydrd    vn
1400801   1.0-6   0.06      8
*        walr    hydrd    vn
1400802   1.0-6   0.05893  9
*        walr    hydrd    vn
1400803   1.0-6   3.270     10
*        floss   rloss    jn
1400901   0.0     0.0       9
```

```
*        jefvcahs  jn
1401101   100       1
*        jefvcahs  jn
1401102   000       9
*        flag    vn
1401001   0       10
*        ebt     press   temp                  vn
1401201   0       7146579. 1888036. 1888036. 1. 0. 1
1401202   0       7133603. 1888151. 1888151. 1. 0. 2
1401203   0       7124985. 1888519. 1888519. 1. 0. 3
1401204   0       7116368. 1888883. 1888883. 1. 0. 4
1401205   0       7106312. 1889450. 1889450. 1. 0. 5
1401206   0       7096236. 1889716. 1889716. 1. 0. 6
1401207   0       7089024. 1889859. 1889859. 1. 0. 7
1401208   0       7077510. 1890916. 1890916. 1. 0. 8
1401209   0       7061712. 1891161. 1891161. 1. 0. 9
1401210   0       7085319. 1892673. 1892673. 1. 0. 10
*        cntrlwrd
1401300   0
*        liqv    vapv    intv   jn
1401301   98.877   98.877   0.   1 * 260.422
1401302   98.985   98.985   0.   2 * 260.422
1401303   99.0731  99.0731  0.   3 * 260.422
1401304   99.1618  99.1618  0.   4 * 260.422
1401305   99.2738 99.2738 0.     5 * 260.422
1401306   99.3712  99.3712  0.   6 * 260.422
1401307   99.4392  99.4392  0.   7 * 260.422
1401308   101.3894 101.3894 0.   8 * 260.422
1401309   101.5415 101.5415 0.   9 * 260.422
*
*===========================================================*
*       junction of outer shroud and upper SG annulus       *
*===========================================================*
*card #  name       type
1450000   upperjun   sngljun
*        from vol   to vol     flwA  f.loss  r.loss  flag
1450101   140010000  150000000  0.0   0.0     0.0     0
*       flag       liqmflow   vapmflow  interf vel
1450201   0          184.6733   184.6733  0. * 260.422
*
*===========================================================*
*                  upper steam generator-pipe                *
*===========================================================*
*card #  name    type
1500000   uppersg pipe
*     vn
1500001   1
*     flwA     vn
1500101   0.2435   1
*     length   vn
1500301   1.0      1
*        vol      vn
```

```
1500401   0.0      1
*        incl     vn
1500601   0.0      1
*        elev     vn
1500701   0.0      1
*        walr    hydrd   vn
1500801   1.0-6   0.1     1
*        flag    vn
1501001   0       1
*        ebt     press   temp                  vn
1501201   0       6981901. 1886808. 1886808. 1. 0. 1
*
*===========================================================*
*       junction of upper SG annulus and cross junction     *
*===========================================================*
*card #  name       type
1550000   upcjjun    sngljun
*        from vol   to vol     flwA    f.loss  r.loss  flag
1550101   150010000  160000000  0.0     0.0     0.0     0
*       flag       liqmflow   vapmflow  interf vel
1550201   0          185.8346   185.8346   0. * 260.422
*
*===========================================================*
*                      shell side sink                      *
*===========================================================*
*card #  name     type
1600000   soulet   tmdpvol
*     flwA    lngth vol  azangl vrtangl elev  walr  hydrd flg
1600101   0.2435  1.0   0.0  0.0    0.0    0.0    0.0   0.0   10
*     select data types
1600200   003
*     time  press       temp
1600201   0.0   6.976+6     606.35
1600201   10.0  6.976+6     606.35
1600203   13.0  3.680+6     606.35
1600204   16.0  1.941+6     606.35
1600205   19.0  1.024+6     606.35
1600206   23.0  0.437+6      606.35
1600207   26.0  0.2303+6    606.35
1600208   30.0  0.1013+6    606.35

*===========================================================*
*                  --TUBES--H20                       *
*===========================================================*
*===========================================================*
*                        tube source                        *
*===========================================================*
*card #  name   type
2100000   h2oin  tmdpvol
*     flwA     lngth vol  azangl vrtangl elev  walr  hydrd flg
2100101   0.213  1.0   0.0  0.0    90.0    1.0   0.0   0.0   10
*     select data types
```

```
2100200   003
*     time  press   temp
2100201   0.0   1.75+7  478.3
*
*============================================================*
*                    tube inlet-junction                     *
*============================================================*
*card #  name      type
2150000  h20injun  tmdpjun
*        from vol    to vol      flwA       flag
2150101   210010000   220000000   0.0         0
*        ctrlwrd  trip# ctrlname   ctrl#
2150200   1  *      0     cntrlvar   2
*       time   liqmflow  vapmflow   interf vel
2150201  0.0     232.0     0.0        0.0
*
*============================================================*
*                        TUBE BUNDLE                         *
*============================================================*
*============================================================*
*                     lower tube bundle                      *
*============================================================*
*card #  name    type
2200000   lower   pipe
*     vn
2200001   44
*     flwA       vn
2200101   0.213      44
*        flwA       jn
2200201   0.213      43
*     length     vn
2200301   3.0        28
*     length     vn
2200302   1.0        30
*     length     vn
2200303   3.0        39
*     length     vn
2200304   1.0        40
*     length     vn
2200305   4.75       41
*     length     vn
2200306   3.0        42
*     length     vn
2200307   4.75       43
*     length     vn
2200308   1.0        44
*        vol        vn
2200401   0.0        44

*============================================================*
* The following cards change the elevation from 0.0 meters   *
* to 13.0  meters                                            *
```

```
*===========================================================*
*        incl       vn
2200601   90.0       1
*        incl       vn
2200602   3.18474    28
*        incl       vn
2200603   90.0       30
*        incl       vn
2200604   3.18474    39
*        incl       vn
2200605   90.0       40
*        incl       vn
2200606   0.0        41
*        incl       vn
2200607   90.0       42
*        incl       vn
2200608   0.0        44
*        elev       vn
2200701   3.0        1
*        elev       vn
2200702   0.1666     28
*        elev       vn
2200703   1.0        30
*        elev       vn
2200704   0.1666     39
*        elev       vn
2200705   1.0        40
*        elev       vn
2200706   0.0        41
*        elev       vn
2200707   3.0        42
*        elev       vn
2200708   0.0        44
*        walr    hydrd     vn
2200801   1.0-6   0.0248    44
*
*===========================================================*
* The following cards change the loss rate at the junctions *
* of pipes with bends.                                      *
*===========================================================*
*        floss   rloss   jn
2200901   0.0     0.0     43
*        flag    vn
2201001   0       44
*        flag    jn
2201101   0       43
*        ebt     press   temp                   vn
2201201   0      17501800. 883921. 2394549. 0. 0. 1
*        ebt     press   temp                   vn
2201202   0      17487060. 930015. 2394981. 0. 0. 2
2201203   0      17484346. 975440. 2395060. 0. 0. 3
2201204   0      17481642. 1020260. 2395138. 0. 0. 4
```

```
2201205   0      17478948. 1064526. 2395217. 0. 0. 5
*        ebt     press   temp                  vn
2201206   0      17476260. 1108294. 2395295. 0. 0. 6
2201207   0      17473580. 1151611. 2395373. 0. 0. 7
2201208   0      17470906. 1194539. 2395450. 0. 0. 8
2201209   0      17468236. 1237167. 2395528. 0. 0. 9
2201210   0      17465570. 1279579. 2395606. 0. 0. 10
*        ebt     press   temp                  vn
2201211   0      17462904. 1321865. 2395683. 0. 0. 11
2201212   0      17460240. 1364123. 2395760. 0. 0. 12
2201213   0      17457576. 1406439. 2395838. 0. 0. 13
2201214   0      17454908. 1448970. 2395916. 0. 0. 14
2201215   0      17452236. 1491848. 2395993. 0. 0. 15
*        ebt     press   temp                  vn
2201216   0      17449556. 1535257. 2396071. 0. 0. 16
2201217   0      17446864. 1579442. 2396150. 0. 0. 17
2201218   0      17444156. 1624730. 2396228. 0. 0. 18
2201219   0      17441418. 1668231. 2396308. .02109797 0. 19
2201220   0      17438634. 1676889. 2396389. .192476  0. 20
*        ebt     press   temp                  vn
2201221   0      17435482. 1677860. 2396455. .3328553 0. 21
2201222   0      1.7432+7  1677875. 2396523. .446225 0. 22
2201223   0      17428170. 1677689. 2396606. .538182 0. 23
2201224   0      17423860. 1677458. 2396702. .601068 0. 24
2201225   0      17419254. 1678308. 2482943. .63805  0. 25
*        ebt     press   temp                  vn
2201226   0      17413922. 1678140. 2535315. .66909 0. 26
2201227   0      17407766. 1677907. 2565664. .696018 0. 27
2201228   0      17400860. 1677661. 2583793. .73285  0. 28
2201229   0      17394896. 1677561. 2397871. .92182  0. 29
*        ebt     press   temp                  vn
2201230   0      1.7392+7  1677466. 2397821. .928885 0. 30
*        ebt     press   temp                  vn
2201231   0      17386382. 1677218. 2459598. .916175 0. 31
2201232   0      17378744. 1676914. 2452869. .969221 0. 32
2201233   0      17370034. 1676566. 2501054. .99958  0. 33
2201234   0      17361180. 1676211. 2594541. .999998 0. 34
2201235   0      17350250. 1675772. 2685656. 1. 0. 35
*        ebt     press   temp                  vn
2201236   0      17337926. 1675278. 2772924. 1. 0. 36
2201237   0      17324208. 1674727. 2855662. 1. 0. 37
2201238   0      17309132. 1674122. 2933763. 1. 0. 38
2201239   0      17292766. 1673464. 3007104. 1. 0. 39
2201240   0      17280500. 1672970. 3018913. 1. 0. 40
*        ebt     press   temp                  vn
2201241   0      1.7264+7  1672305. 3019054. 1. 0. 41
2201242   0      17241488. 1671399. 3018972. 1. 0. 42
2201243   0      17218966. 1670490. 3019028. 1. 0. 43
2201244   0      17202820. 1669838. 3018878. 1. 0. 44
*        cntrlwrd
2201300   0
*        liqv    vapv    intv   jn
```

```
2201301   1.25917  1.427534 0.   1 * 232.
2201302   1.277304 1.277304 0.   2 * 232.
2201303   1.296472 1.296472 0.   3 * 232.
2201304   1.316612 1.316612 0.   4 * 232.
2201305   1.33789  1.33789  0.   5 * 232.
2201306   1.360435 1.360435 0.   6 * 232.
2201307   1.384396 1.384396 0.   7 * 232.
2201308   1.40997  1.40997  0.   8 * 232.
2201309   1.437283 1.437283 0.   9 * 232.0003
2201310   1.466665 1.466665 0.   10 * 232.0003
2201311   1.498495 1.498495 0.   11 * 232.0004
2201312   1.533274 1.533274 0.   12 * 232.0005
2201313   1.571743 1.571743 0.   13 * 232.0007
2201314   1.613987 1.613987 0.   14 * 232.001
2201315   1.661526 1.661526 0.   15 * 232.001
2201316   1.715557 1.715557 0.   16 * 232.001
2201317   1.777753 1.777753 0.   17 * 232.0014
2201318   1.851096 2.46382 0.    18 * 232.0016
2201319   1.966355 2.131197 0.   19 * 232.0026
2201320   2.27818  2.635737 0.   20 * 232.0034
2201321   2.561367 3.301065 0.   21 * 232.004
2201322   2.82192 3.919805 0.    22 * 232.0045
2201323   3.04009  4.56111 0.    23 * 232.005
2201324   3.08896 5.35482 0.     24 * 232.005
2201325   3.24906 6.31192 0.     25 * 232.0053
2201326   3.29774  7.2523  0.    26 * 232.0055
2201327   3.24471 8.18609 0.     27 * 232.0057
2201328   3.24241 8.97588 0.     28 * 232.006
2201329   6.63819 6.96388 0.     29 * 232.006
2201330   6.73069 7.10493 0.     30 * 232.006
2201331   4.59015 8.55405 0.     31 * 232.0064
2201332   4.10592 9.31524  0.    32 * 232.007
2201333   1.192595 10.4335  0.   33 * 232.007
2201334   12.02192 12.0197  0.   34 * 232.007
2201335   13.64731 13.64731 0.   35 * 232.0054
2201336   15.27255 15.27255 0.   36 * 232.0055
2201337   16.8603  16.8603  0.   37 * 232.0056
2201338   18.37262 18.37262 0.   38 * 232.0056
2201339   19.79245 19.79245 0.   39 * 232.0057
2201340   20.0312  20.0312  0.   40 * 232.0057
2201341   20.05315 20.05315 0.   41 * 232.006
2201342   20.07785 20.07785 0.   42 * 232.006
2201343   20.1053  20.1053  0.   43 * 232.006
*
*===========================================================*
*                  tube side outlet-junction                *
*===========================================================*
*card #  name       type
2350000   outjun     sngljun
*        from vol   to vol     flwA      f.loss  r.loss  flag
2350101   220010000  230000000  0.0        0.0     0.00    0
*        flag       liqmflow   vapmflow  interf vel
```

```
2350201   0          20.12134   20.12134   0. * 232.006
*
*============================================================*
*                      tube side sink                        *
*============================================================*
*card #  name  type
2300000   h2oulet   tmdpvol
*     flwA     lngth vol  azangl vrtangl elev  walr  hydrd flg
2300101   0.213    1.0   0.0   0.0   0.0     0.0   0.0   0.0   10
*     select data types
2300200   003
*     time  press    temp
2300201   0.0   1.72+7   813.0

*============================================================*
*                    --HEAT STRUCTURES--                     *
*============================================================*
*============================================================*
*                lower bundle heat structure                 *
*============================================================*
*============================================================*
*              economizer,evaoprator,superheater             *
*============================================================*
*        hsn    mp    geotyp   flg   lftbnd
12200000  29      6     2        0     0.0124
*        flg    flg
12200100  0      1
*        mp-1   rcoordnt

12200101  5      0.0159
*        comp#  mp-1
12200201  1      5    * 2 1/4Cr-1Mo
*        Qi     mp-1
12200301  0.0    5
*        temp   mp
12200401  600.0  6

* the next set of cards specify the flow direction by lining
* up the node of the heat structure to the pipe.
* LEFT BOUND
*        bc        incrmnt bctype   scode lenght    hsn
12200501  220010000 10000   1        1     1323.0    28
*        bc        incrmnt bctype   scode lenght    hsn
12200502  220290000 0       1        1     441.0     29
* RIGHT BOUND
*        bc        incrmnt bctype   scode lenght    hsn
12200601  130390000 -10000  110      1     1323.0    28
*        bc        incrmnt bctype   scode lenght    hsn
12200602  130110000 0       110      1     441.0     29
*         pwr      Pf       lmult    rmult  hsn
12200701   0        0.0     0.0      0.0    29
```

```
*         lbndopt
12200800   1
*         heat_hydrd hlf hlr glf glr glcf glcr boil ncl ratio fsct
12200801 .0248 10. 10. 0. 0. 0. 0. 1. .0248 1.1 1.0 1
*         heat_hydrd hlf hlr glf glr glcf glcr boil ncl ratio fsct
12200802 .0248 10. 10. 0. 0. 0. 0. 1. .0248 1.1 1.2 28
*         heat_hydrd hlf hlr glf glr glcf glcr boil ncl ratio fsct
12200803 .0248 10. 10. 0. 0. 0. 0. 1. .0248 1.1 1.0 29

*         rbndopt
12200900   1
*         heat_hydrd hlf hlr glf glr glcf glcr boil ncl ratio fsct
12200901  0.0318 10. 10. 0. 0. 0. 0. 1. 3. 1.1 1.0 1
*         heat_hydrd hlf hlr glf glr glcf glcr boil ncl ratio fsct
12200902  0.0318 10. 10. 0. 0. 0. 0. 1. 1.5 1.1 1.2 28
*         heat_hydrd hlf hlr glf glr glcf glcr boil ncl ratio fsct
12200903  0.0318 10. 10. 0. 0. 0. 0. 1. 1. 1.1 1.0 29
*
*===========================================================*
*      upper bundle heat structure(superheater finisher)    *
*===========================================================*
*        hsn    mp    geotyp   flg   lftbnd
12300000  10      6     2        0     0.0124
*        flg    flg
12300100  0      1
*        mp-1   rcoordnt
12300101  5      0.0159
*        comp#  mp-1
12300201  2      5     * Inconel 617
*        Qi     mp-1
12300301  0.0    5
*        temp   mp
12300401  600.0  6

* the next set of cards specify the flow direction by lining
* up the node of the heat structure to the pipe.
*        bc        incrmnt bctype   scode lenght    hsn
12300501  220300000 0       1        1     441.0     1
*        bc        incrmnt bctype   scode lenght    hsn
12300502  220310000 10000   1        1     1323.0    10
*        bc        incrmnt bctype   scode lenght    hsn
12300601  130100000 0       110      1     441.0     1
*        bc        incrmnt bctype   scode lenght    hsn
12300602  130090000 -10000  110      1     1323.0    10
*         pwr      Pf      lmult    rmult  hsn
12300701   0        0.0     0.0      0.0    10
*         lbndopt
12300800   1
*         heat_hydrd hlf  hlr  glf  glr  glcf glcr boil ncl   ratio
fsct
12300801 .0248 10. 10. 0. 0. 0. 0. 1. .0248 1.1 1.0 1
```

```
*         heat_hydrd hlf  hlr  glf  glr  glcf glcr boil ncl   ratio
fsct hsn
12300802 .0248 10. 10. 0. 0. 0. 0. 1. .0248 1.1 1.2 10
*         rbndopt
12300900   1
*         heat_hydrd hlf  hlr  glf  glr  glcf glcr boil ncl   ratio
fsct hsn
12300901  .0318 10. 10. 0. 0. 0. 0. 1. 1. 1.1 1.0  1
*         heat_hydrd hlf  hlr  glf  glr  glcf glcr boil ncl   ratio
fsct
12300902  .0318 10. 10. 0. 0. 0. 0. 1. 1.5 1.1 1.2 10
*
*===========================================================*
* upper bundle heat structure 2(after superheater finisher) *
*===========================================================*
*        hsn    mp    geotyp   flg   lftbnd
12400000  1      6     2        0     0.0124
*        flg    flg
12400100  0      1
*        mp-1   rcoordnt
12400101  5      0.0159
*        comp#  mp-1
12400201  2      5     * Inconel 617
*        Qi     mp-1
12400301  0.0    5
*        temp   mp
12400401  600.0  6

* the next set of cards specify the flow direction by lining
* up the node of the heat structure to the pipe.
*        bc        incrmnt bctype   scode lenght    hsn
12400501  220400000 0       110      1     441.0     1
*        bc        incrmnt bctype   scode lenght    hsn
12400601  120060000 0       110      1     441.0     1

*         pwr      Pf      lmult    rmult  hsn
12400701   0        0.0     0.0      0.0    1
*         lbndopt
12400800   1
*         heat_hydrd hlf  hlr  glf  glr  glcf glcr boil ncl   ratio
fsct hsn
12400801   0.0248     10.0 10.0 0.0  0.0  0.0  0.0  1.0  0.0248   1.1
1.0  1

*         rbndopt
12400900   1
*         heat_hydrd hlf  hlr  glf  glr  glcf glcr boil ncl   ratio
fsct hsn
12400901   0.0318     10.0 10.0 0.0  0.0  0.0  0.0  1.0  2.0  1.1
1.0  1
*
*===========================================================*
```

```
*                 --THERMAL PROPERTY DATA--                 *
*===========================================================*
*         material type  flg flg
20100100   tbl/fctn       1   1  *Inconel 617
*          temp      thermal conductivity
20100101    293.0     13.4
20100102    373.0     14.7
20100103    473.0     16.3
20100104    573.0     17.7
20100105    673.0     19.3
20100106    773.0     20.9
20100107    873.0     22.5
20100108    973.0     23.9
20100109   1073.0     25.5
20100110   1173.0     27.1
20100111   1273.0     28.7
*          temp      heat capacity
20100151    293.0     3.5028E+6
20100152    373.0     3.6784E+6
20100153    473.0     3.8874E+6
20100154    573.0     4.0964E+6
20100155    673.0     4.3054E+6
20100156    773.0     4.4810E+6
20100157    873.0     4.6900E+6
20100158    973.0     4.8990E+6
20100159   1073.0     5.1080E+6
20100160   1173.0     5.3170E+6
20100161   1273.0     5.5343E+6

*         material type  flg flg
20100200    tbl/fctn       1   1

*          temp     thermal conductivity
20100201   283.00    36.0
20100202   310.78    36.3
20100203   338.56    36.7
20100204   366.33    36.9
20100205   394.11    37.0
20100206   421.89    37.2
20100207   449.67    37.2
20100208   477.44    37.2
20100209   505.22    37.2
20100210   533.00    37.0
20100211   560.78    36.9
20100212   588.56    36.5
20100213   616.33    36.2
20100214   644.11    35.8
20100215   671.89    35.5
20100216   699.67    35.0
20100217   727.44    34.6
20100218   755.22    34.1
20100219   783.00    33.6
```

```
20100220   810.78    33.1
20100221   838.56    32.5
20100222   866.33    32.0
20100223   894.11    31.7
20100224   921.89    31.2
20100225   949.67    30.6
20100226   977.44    29.8
20100227  1005.22    28.4
20100228  1033.00    27.0
20100229  1060.78    26.7
20100230  1088.56    26.5
*           temp     heat capacity
20100251    296.0    3.4653E+6
20100252    800.0    5.3939E+6
20100253   1000.0    7.5970E+6
*
*===========================================================*
*          --CONTROL SYSTEM--                      *
*===========================================================*
* Pourpose of control system: In order to accurately model a
* steam generator the core inlet(shell outlet) temperature
* should remain a constant 595 K. To keep the constant temp
* the mass-flow rate of the tube side will be adjusted. The
* control is set up using a sum type card and a integral
* type card. Since there is not a subtraction type a
* negitvie sign is given to the cnstA0 value (word 1 on the
* card 101 to make a sum a subtraction. The scale factor
* innitial value for the sum type is set to 0.0 . The
* equation for the sum is of the form Y = S(A0+A1*V1+A2*V2+...)
* where S is a scale factor and As are constants. Word 3 of
* card 101 is the variable of interest. In this case it is
* temeprature of the gas at in the pipe 150 volume 01.

*         name     type     sclfctr iv     flg
20500100  qsg      sum      1.0e-6     569.551 0
*         cnstA0   cnstA1   varname var#
20500101  0.0      1.0      q        220010000
20500102           1.0      q        220020000
20500103           1.0      q        220030000
20500104           1.0      q        220040000
20500105           1.0      q        220050000
20500106           1.0      q        220060000
20500107           1.0      q        220070000
20500108           1.0      q        220080000
20500109           1.0      q        220090000
20500110           1.0      q        220100000
20500111           1.0      q        220110000
20500112           1.0      q        220120000
20500113           1.0      q        220130000
20500114           1.0      q        220140000
20500115           1.0      q        220150000
20500116           1.0      q        220160000
```

```
20500117           1.0      q        220170000
20500118           1.0      q        220180000
20500119           1.0      q        220190000
20500120           1.0      q        220200000
20500121           1.0      q        220210000
20500122           1.0      q        220220000
20500123           1.0      q        220230000
20500124           1.0      q        220240000
20500125           1.0      q        220250000
20500126           1.0      q        220260000
20500127           1.0      q        220270000
20500128           1.0      q        220280000
20500129           1.0      q        220290000
20500130           1.0      q        220300000
20500131           1.0      q        220310000
20500132           1.0      q        220320000
20500133           1.0      q        220330000
20500134           1.0      q        220340000
20500135           1.0      q        220350000
20500136           1.0      q        220360000
20500137           1.0      q        220370000
20500138           1.0      q        220380000
20500139           1.0      q        220390000
20500140           1.0      q        220400000
20500141           1.0      q        220410000
20500142           1.0      q        220420000
20500143           1.0      q        220430000
20500144           1.0      q        220440000

*         name      type   sclfctr iv   flg
20500200  mult1      mult   1.0     550.166 0
*         varname var#   varname var#
20500201  voidf,220080000 tempf,220080000
*         name      type   sclfctr iv   flg
20500300  mult2      mult   1.0     0.   0
*         varname var#   varname var#
20500301  voidg,220080000 tempg,220080000
*         name     type     sclfctr iv     flg
20500400  tempfg   sum      1.0     551.166 0
*         cnstA0   cnstA1   varname var# cnstA2  varname var#
20500401  1.0      1.0      cntrlvar 2   1.0     cntrlvar 3
*

*===========================================================*
*          --control variables--                  *
*===========================================================*

. End of input.
```

Appendix C

Beginner's RELAP5-3D User Guide

Appendix C
Beginner's RELAP5-3D User Guide

C-1. Background

RELAP5 is based on FORTRAN77, and parts have been updated to newer versions of FORTRAN. RELAP originated as a program designed to model loss of coolant accidents (LOCAs) and other transients in nuclear power plants.

C-2. The Basics of RELAP

RELAP is coded in a text editor. Information is entered onto a card. The card is reminiscent of the ways data were literally entered into a computer on a physical data card. The card can now be thought of as a line of code. The pieces of data on a card are referred to as words. A card can only hold up to 80 characters. Words can be alphanumeric, real, or integer characters. Words act as pieces of data and can also act like a directory or a set of on or off switches that determine the meaning of the words of following cards.

C-3. Simplify

Modeling in RELAP requires simplification of the actual structures. A model is started as simply as possible. For example, a bundle of tubes in a heat exchanger can be modeled as one large tube with the same surface area, cross-sectional area, hydraulic diameter, and heated hydraulic diameter as the tube bundle.

C-4. Required/Optional entries

It is important to understand which cards are required for the code to run and which are optional. In the same way, it is vital to know when optional cars should be used and when they can be left out.

C-5. What Every User Should Know

- Don't use tabs.
- Use lower caps while coding. Comment can be capitalized.
- Break up sections and give them descriptive titles.
- Comment everything, including each word of a card. These comments will serve as a reminder during debugging.
- If using a fluid other than H_2O, enter NEWATH for card 100. This adds a new module which allows for the use of other fluids.
- Before the code, write a brief description of the purpose of the code and the parameters used so that others may use the code with ease.
- Before the code, state the assumptions that have been made about the model.
- Asterisk (*) or a dollar symbol ($) is used to indicate comments.
- 0********** in the ."p" file shows where errors have occurred.

- Area, length and volume are input parameters for all types of volumes. Only two of the three parameters need to be entered. The third value will be calculated and should be left **blank** to avoid errors.
- Make sure units match the input units.
- The number of junctions is always one less that the number of volumes.
- A single heat structure can be linked to multiple hydrodynamic volumes.
- The sign of the elevation must match the sign of the inclination.
- Spiral pipes can be modeled by unraveling the spiral, making a long tube that is slightly angled above horizontal but ends up at the same elevation as the spiral tube originally reached.
- Phase changes depend on temperature and pressure and do not need to be specified in the model.
- Be careful of inputs. Some only alter the geometry and are not accounted for in the calculations.
- If words of a card are missing, RELAP automatically looks to the next card to find the missing values. If these values do not correspond in type and number, RELAP will give an error. Also, if the words of one card are too long, they can be placed on the next card of the same type.

C-6. Hydrodynamic structures

In RELAP5, the azimuthal or horizontal angle is only used for visualization purposes and not in calculations. Positive angles are a rotation from the x to the y axis and can have value from 0 to 360 degrees.

The inclination or vertical angle is used in determining which flow regime will be used. RELAP considers a component that has an angle of 30 degrees or less from horizontal and will use the horizontal flow regime. If the angle is 60 degrees or more, the vertical flow regime is used. RELAP will interpolate between 30 and 60 degrees. In order to have an elevation change, a component must have an inclination angle; otherwise, an error will result.

An annulus must be vertical; otherwise, use a pipe with the same flow area.

C-6.1 Hydrodynamic Components and Their Input Name

Component	Input Name
Single volume	snglvol
Time-dependent volume	tmdpvol
Single Junction	sngljun
Time-dependent junction	tmdpjun
Branch	branch
Separator	separatr
Pipe	pipe
Annulus	annulus
Pressurizer	prizer
Feedwater heater	fwhtr
Jetmixer	jetmixer
Turbine	turbine
EEC mixer	eccmix
Valve	valve

Pump	pump
Multiple junction	mtpljun
Accumulater	accum
Multi-dimensional component	multid

C-6.2 Time-Dependent Volume Component

The time-dependent volume is used to initialize pressure and temperature in the model. The time-dependent volume usually serves as a source or inlet for the model. Temperature and pressure can be varied with time. This is one way of modeling transients. The volume flow area should be the same as the next hydrodynamic component.

C-6.3 Time-Dependent Junction Component

The time-dependent junction sets the initial mass-flow for the system and can also be used in the modeling of transients. Generally, a time-dependent volume is followed by a time-dependent junction.

C-6.4 Heated Perimeter/Diameter

$$D_{Heated\ Hydraulic} = \frac{4 * A_c}{P_{Heated}}$$

$$D_{Hydraulic} = \frac{4 * A_c}{P_{Hydraulic}}$$

$$P_{Heated} = 2 * \pi * r_{Heated}$$

$$P_{Hydraulic} = 2 * \pi * r_{Hydraulic}$$

C-6.5 Thermal Property Data

- Table data must be given in increasing order
- Temperature must be given in K or °F
- Thermal conductivity units are W/m*K or Btu/s*ft*°F

C-6.6 Flags

Flags are used to control options for card inputs, correlations, models, and so on. Inputs for a flag consist of several integers. Each integer corresponds to a particular option. Integer options and meaning can be found in Appendix A, RELAP5-3D Input Data Requirements manual. It is important to understand that REALP reads the flag integers from right to left or back to front. This allows the modeler to enter in fewer numbers as flags can contain upwards of seven integers.

C-6.7 Major/Minor Edits

Major edits are like taking a snap shot of all model parameters. The frequency of the edits can be specified using Card 201. The major edits are used in generating data for plots. When running an input deck to verify that the code works and gives results, the major edits can be infrequent so that run time is minimized. If detailed plots need to be generated from a transient run, major edits should be taken often depending on how long the code is actually running. Short transients require frequent major edits while long transients may not need as frequent edits for data resolution.

Minor edits specify individual parameters to be taken at the specified interval. Minor edits are useful if only one parameter or a parameter that is not on the major edits or needs to be taken often, but no other parameters are required.