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CAPABILITIES OF THE ATHENA COMPUTER CODE FOR
MODELING THE SP-100 SPACE REACTOR CONCEPT

C. D. Fletcher

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Idaho National Engineering Laboratory
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Informal Report

Prepared For The
U.S. DEPARTMENT OF ENERGY
Idaho Operations Office
Under DOE Contract No. DE-AC07-76ID01570

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EG&G Idaho, Inc.
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ABSTRACT

The capability to perform thermal-hydraulic analyses of an SP-100 space reactor was demonstrated using the ATHENA computer code. The preliminary General Electric SP-100 design was modeled using ATHENA. The model simulates the fast reactor, liquid-lithium coolant loops, and lithium-filled heat pipes of this design. Two ATHENA demonstration calculations were performed simulating accident scenarios. A mask for the SP-100 model and an interface with the Nuclear Plant Analyzer (NPA) were developed, allowing a graphic display of the calculated results on the NPA.

SUMMARY

The capability to perform thermal-hydraulic analyses of an SP-100 space reactor was demonstrated using the ATHENA computer code.

The preliminary General Electric SP-100 design employs a reflector-controlled 2 MW_t fast reactor with three liquid-lithium coolant loops. Lithium-filled high temperature heat pipes transfer heat to radiatively-coupled thermoelectric generators. Residual heat is radiated to space via potassium-filled low temperature heat pipes.

The ATHENA computer code has capabilities similar to RELAP5/MOD2, but in addition can represent working fluids other than water, including helium, lithium, and freon. Capabilities for modeling zero gravity environments and heat pipes were added to ATHENA specifically for this analysis.

An ATHENA model of the preliminary General Electric SP-100 design was developed. This model included representations of the core, primary coolant loops, and high temperature heat pipes. Because potassium is currently not an available ATHENA working fluid, behavior within the low temperature heat pipes was not simulated.

The ATHENA SP-100 model was used to perform demonstration calculations for two accident scenarios: loss of one half pumping capability in one loop, and loss of all low temperature heat pipes on one loop. ATHENA provided reasonable simulations of thermal-hydraulic response for both accident scenarios.

The Nuclear Plant Analyzer (NPA) was used to display the results of the demonstration calculations. A mask of the SP-100 model and an interface with the NPA were developed.

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1. INTRODUCTION

The capability to evaluate the performance of advanced reactor concepts is being developed at the Idaho National Engineering Laboratory (INEL) as part of the Technical Development Program. The capability to analyze advanced reactors is being developed in an effort to obtain new programs at the INEL. The advanced reactor designs under consideration are intended to be smaller, less expensive, and inherently safer than existing commercial reactors. The advanced concepts currently under consideration are the Training Research and Investigation Gulf Atomic (TRIGA) reactor, the Modular High Temperature Gas Reactor (MHTGR), the Compact Liquid Metal Reactor (CLMR), the Process Inherent Ultimate Safety (PIUS) Reactor, the SP-100 space reactor, and the Multimegawatt space reactor. INEL capabilities in modeling a TRIGA reactor were previously reported in Reference 1.

The purpose of this report is to demonstrate the INEL capability to perform thermal-hydraulic analysis of the SP-100 space reactor. A preliminary design of the General Electric SP-100 concept was selected for this demonstration. The design incorporates liquid-lithium primary coolant loops that transfer heat to lithium-filled high temperature heat pipes. These pipes are radiatively coupled to thermoelectric generating material on the evaporators of potassium-filled low temperature heat pipes which, in turn, radiate to space.

Due to unique features of the SP-100 reactor, it is not possible to model it with commonly used light water reactor thermal-hydraulic systems codes, such as RELAP5/MOD2 and TRAC-PF1, specifically the liquid metal fluids and heat pipe components of the SP-100 reactor are beyond the capabilities of these codes. However, the ATHENA code, which has similar capabilities to RELAP5 can model liquid metal systems and has been upgraded through the inclusion of heat pipe and zero gravity capabilities. The purpose of the present work is to evaluate the capability of ATHENA to

model the preliminary General Electric SP-100 reactor concept. This evaluation required developing an ATHENA model of SP-100 and performing demonstration calculations. The model was then linked with the Nuclear Plant Analyzer (NPA), a color graphics analysis tool at INEL.

Section 2 describes the SP-100 reactor, Sections 3 and 4 describe the ATHENA computer code and the ATHENA SP-100 model, respectively. Section 5 describes the SP-100 NPA mask and interface. Section 6 describes the results from the ATHENA demonstration calculations. Section 7 summarizes the conclusions of the study.

2. REACTOR DESCRIPTION

A schematic of the preliminary General Electric SP-100 space reactor concept is shown in Figure 1. A detailed description of the reactor is given in Reference 2. The concept consists of a reflector-controlled fast reactor operating at 2 MW_t that is directly cooled by three liquid-lithium coolant loops. Forced loop flow is maintained by the use of one or more thermoelectric electromagnetic (TEM) pumps in each loop.

The TEM pump operates on the Faraday principle: when a current-carrying conductor is surrounded by a magnetic field a force is applied on the conductor. In the TEM pump a magnetic field is produced around, and an electrical current is passed through the lithium coolant thus causing the pumping force. To power the pump, a portion of the heat in the primary system coolant is allowed to conduct through a thermoelectric converter and be radiated to space. Based on the Seebeck effect, heat passing through the converter's P-N junction causes an electric potential to form across the junction. The electric power so generated may then be used to produce both the magnetic field and coolant electric current required for pumping. The TEM pump is thus reliable, since no moving parts are involved, and inherently safe, since the pumped flow varies directly with coolant temperature.

Heat is transferred from the primary coolant to the high temperature lithium-filled heat pipes through a "finger and thimble" heat exchanger on each loop. Each heat exchanger interfaces 40 high temperature heat pipes with a primary coolant loop.

A heat pipe is a closed system thermal-hydraulic device with a very low thermal resistance, allowing transfer of heat over long distances with very small temperature losses. Heat pipes typically contain evaporator, adiabatic, and condenser sections. Heat is added to a heat pipe in the evaporator section and extracted in the condenser section. A simplified

Figure 1. Schematic of preliminary General Electric SP-100 concept

schematic of a heat pipe is shown in Figure 2. Heat is transferred along the pipe because the enthalpy of the vapor flowing from the evaporator to the condenser exceeds that of the liquid flowing in the reverse direction. To drive this countercurrent flow, a wick structure is introduced into the pipe adjacent to the inner wall, as diagramed in Figure 2. The depth of the meniscus within the wick varies inversely with the liquid fraction present. In the condenser section, the wick is fully saturated and no meniscus exists, in the evaporator section the meniscus depth is large. The presence of a meniscus indicates a higher pressure in the vapor than in the liquid. The wick thus introduces a capillary head, caused by the surface tension of liquid acting to form menisci within the pores of the wick. Axial differences in the capillary head produce the desired countercurrent flow of vapor and liquid within the heat pipe.

In the SP-100 reactor, the condenser ends of the high temperature heat pipes are radiatively coupled to the thermoelectric converters. These low-efficiency converters, which operate as a result of the Seebeck effect, are used to generate the reactor's electrical output. Rated power output is 100 Kw electrical.

Heat passing through the thermoelectric converters is then routed into the 240 potassium-filled low temperature heat pipes that transfer the heat to radiator panels for dissipation to space.

One or more accumulators will be employed on each loop. The accumulators are passive spring-and-bellows devices that provide pressure control for the primary coolant system. As primary coolant expands or contracts with varying temperature, the accumulators relieve or donor coolant with the primary coolant system, thus controlling its pressure.

Figure 2. Simplified heat pipe schematic

3. ATHENA CODE DESCRIPTION

The Advanced thermal-hydraulic Energy Network Analyzer (ATHENA) computer code³ is based on the RELAP5/MOD2 computer code⁴ and has similar but expanded capabilities. A brief description of RELAP5, which also applies to ATHENA, will be presented followed by a description of the differences between the codes. RELAP5 is an advanced computer code designed for best-estimate thermal-hydraulic analysis of transients in light water reactors and related experimental systems. RELAP5 is based on a two-fluid hydrodynamic model that allows unequal phasic velocities and temperatures within a control volume. RELAP5 has models to represent the physical processes of critical flow, vertical and horizontal stratified flow, and heat transfer from structures. The code also has models to represent point reactor kinetics, control systems, and components such as valves, pumps and turbines.

The major difference between ATHENA and RELAP5 is related to the additional capabilities of ATHENA. RELAP5 is designed to model light-water systems, whereas ATHENA can represent systems which utilize working fluids other than water, including helium, lithium, and freon-11. ATHENA utilizes functions to represent fluid thermodynamic properties while RELAP5 uses a "table-lookup" to determine fluid properties.

ATHENA can represent the effect of a magnetic field on fluid motion. However, current ATHENA capabilities do not allow for the mechanistic modeling of an electromagnetic pump. This capability would require simulation of the interaction between a magnetic field and a coolant carrying an electrical current. It is recommended that an ATHENA capability to mechanistically model an electromagnetic pump be developed.

To perform the analysis presented in this report, ATHENA was modified to allow user specification of the acceleration due to gravity. Previously, this acceleration was assumed at its earth surface value and

modification was beyond the control of the code user. Currently the user may specify any constant acceleration desired. In this analysis zero acceleration due to gravity was specified.

Also, to perform the analysis presented in this report ATHENA was upgraded to provide the capability for modeling heat pipes. The ATHENA heat pipe model assumes a complete separation of the liquid and vapor phases inside the heat pipe with interphase drag forces removed. A separate pressure solution is generated within each phase. The pressure solutions are consistent axially within the phases. The pressure solutions are also consistent radially, with the vapor and liquid pressures differing by the capillary head:

$$P_v - P_\ell = \frac{2\sigma}{r} \cos \theta$$

where

P_v = Vapor pressure

P_ℓ = Liquid Pressure

σ = Surface tension of liquid

r = Effective wick pore radius

θ = Angle between the heat pipe radial direction and the meniscus tangential contact direction within the wick.

While the ATHENA heat pipe model simulates the basic thermal-hydraulic phenomena of heat pipe operation, it must be considered a preliminary model at this time. The demonstration calculations in this report represent the first applications of the ATHENA heat pipe model. The heat pipe model does

not contain features simulating the limiting of heat pipe performance due to critical flow within the vapor or entrainment of liquid by the vapor. It is recommended that the ATHENA heat pipe model be upgraded to include these limiters and verified against heat pipe experimental data.

A unique feature of the space reactor concept is the launching of the reactor with the primary and heat pipe working fluids in a solid form. After attaining proper orbit the reactor would be started up to a low power level allowing the primary and heat pipe working fluids to melt. Calculating the thermal-hydraulic phenomena associated with this heatup process is currently beyond the capabilities of the ATHENA code. Specifically, capabilities for simulation of a solid phase or the melting process do not exist. Furthermore, the addition of a capability for axial heat conduction through solids and liquids would be required. It is recommended that ATHENA be upgraded to have the capability of simulating the entire heatup transient. Reactor response during such a transient is currently of great interest.

4. ATHENA SP-100 MODEL DESCRIPTION

The primary source of information used to assemble the ATHENA SP-100 model was Reference 2. This reference contains most, but not all, detailed geometrical and operational data to assemble the model. Some dimensions were estimated by scaling from drawings. In other instances estimates based on engineering judgement were used when no other source was available.

A nodalization diagram for the ATHENA SP-100 model is shown in Figure 3. The diagram shows the layout of calculational cells, connecting junctions, and heat structures for the model. Components 110, 120, 130, and 140 represent the reactor vessel. Components 200, 210, and 220 represent the loop 1 hot leg. Component 230 represents the loop 1 heat exchanger and component 240 represents the loop 1 cold leg. Note the component numbering schemes for loops 2 and 3 are identical to those for loop 1 incremented by 100 for loop 2 and 200 for loop 3. Components 500, 600, and 700, respectively, simulate the high temperature heat pipes connected to loops 1, 2, and 3. Note the 40 heat pipes on each loop were combined together into a single ATHENA component.

Heat structures were used to simulate the most important metal structures in the reactor: core rods, TEM pump radiators, and high temperature heat pipe evaporator and condenser section walls. If desired, however, all metal structures of the reactor system could have been modeled. For simplicity a limited number of heat structures were modeled in this analysis.

For this demonstration analysis the ATHENA model was abbreviated by excluding the low temperature heat pipes. These pipes are potassium-filled, a working fluid not currently available in ATHENA. The ATHENA capability to simulate heat pipe behavior will be demonstrated with the high temperature lithium-filled pipes. The capability with other heat pipe working fluids is expected to be comparable. It is recommended that potassium be added as an ATHENA working fluid. In lieu of the low temperature heat pipes, the ATHENA model placed temperature boundary

Figure 3. SP-100 ATHENA nodalization

conditions on the high temperature heat pipe condenser section outside wall surfaces. These boundary temperatures were calculated independently for each loop by ATHENA, during each computational time step. The boundary temperatures were calculated based on the heat transfer rates out of the heat pipes and the resistances of the two radiation heat transfer paths in series between that location and space. A 255K space background temperature was assumed and, for stability, the temperature boundary condition was lagged by 1 second.

The core power was calculated by the ATHENA point reactor kinetics model. Reactor kinetics feedback due to Doppler (fuel temperature) and expansion (coolant and structure temperature) effects were simulated. Insufficient information was available concerning control of the reflector drums during reactor transients. For the demonstration calculations presented here no movement of the reflector drums from their full power operational position was assumed. If reflector drum control characteristics had been known then the associated reactivity insertion could have been modeled. In the current model, total reflector drum and central poison plug worth were summed into a scram reactivity worth. This large scram reactivity insertion was available through a trip in the model, however, in the demonstration calculations that follow, scram was not assumed.

As discussed in Section 3 a mechanistic electromagnetic pump model is not currently available in ATHENA. To simulate the behavior of the TEM pumps, ATHENA time-dependent junction components were employed in each loop. In Figure 3 these pumped junctions are between components 210 and 220, 310 and 320, and 410 and 420. The pumped flow was calculated by ATHENA, independently for each loop, as a function of the coolant temperatures at the pump locations. Given the coolant temperatures, TEM pump radiator heat loss rates were calculated. From these, and the efficiencies involved with the thermoelectric material and electromagnetic pump, the mass flow rates were calculated and used to drive the junctions.

To simulate the heat losses from the TEM pump radiator panels the heat loss rates, calculated in the process of determining the pump flow rates, were also used as boundary conditions for heat structures on components 220, 320, and 420 (See Figure 3).

The primary system coolant pressure control of the accumulators was simulated with an ATHENA time dependent volume (component 295 in Figure 3). The primary coolant system pressure is controlled at this location in the model as a function of system average coolant temperature. To determine the pressure, ATHENA calculated the deviation in average coolant temperature and determined the effect of this deviation on coolant volume (due to coolant thermal expansion and compressibility). The deviation in coolant volume was then used to calculate a new spring deflection, spring force, and system pressure.

The SP-100 electric power output was calculated by an ATHENA control variable that summed the heat transfer rates from the heat pipe condenser sections and multiplied by the efficiency of the thermoelectric generators.

Table 1 presents a comparison of full-power steady-state operating conditions as calculated by ATHENA with desired conditions from Reference 2. All comparisons are in excellent agreement indicating the ATHENA model well represents the SP-100 design.

TABLE 1. DESIRED AND ATHENA CALCULATED FULL POWER CONDITIONS

Parameter	Desired	Calculated
Core Power (W_t)	2,000,000	2,000,000
Mass Flow Per Loop (kg/s)	4.4	4.396
Loop Pressure Differential (Pa)	24,440	31,058
Loop Operating Pressure (Pa)	100,000	99,432
Hot Leg Temperature (K)	1546	1538.6
Cold Leg Temperature (K)	1506	1502.7
High Temperature Heat Pipe Temperature (K)	1500	1480.9
Low Temperature Heat Pipe Temperature (K)	775	a.
Pump Radiator Power Dissipation Per Loop (W_t)	45,670	45,334
Radiator Heat Pipe Power Dissipation Per Loop (W_t)	620,997	621,332
Electric Power Output (W_e)	100,000	100,937
a. Not included in the model		

5. NUCLEAR PLANT ANALYZER MODEL

The Nuclear Plant Analyzer (NPA) is a color graphics analysis tool at INEL. The NPA presents a visual simulation of thermal-hydraulic phenomena occurring during a transient in a reactor system.

A mask of the ATHENA SP-100 model and an interface with the NPA were developed during this task. Calculated results from the ATHENA model can be graphically displayed by the NPA in playback mode. The format of the visual display was determined by the mask while the content of the display was determined by the interface. The SP-100 model and the ATHENA code currently don't have the capability to utilize the interactive features of the NPA.

A sample display of the SP-100 NPA mask is shown in Figure 4. The NPA mask represents the primary and heat pipe systems of the SP-100 reactor and has a similar format to the ATHENA model nodalization shown in Figure 3. There generally is a one-to-one correspondence between the nodes in the mask and the control volumes in the ATHENA model. The primary exception is that, for completeness, the NPA mask includes representations of the low temperature heat pipes that are not directly modeled with ATHENA. The temperature behavior displayed for these pipes was calculated by ATHENA based on the heat transfer rate from the high temperature heat pipes and the space background temperature. The void fraction behavior displayed for the low temperature heat pipes was typically identical to that calculated by ATHENA for the high temperature heat pipes.

The color of each node in the mask is driven by the thermodynamic conditions in the corresponding region of the ATHENA model. The ATHENA-calculated fluid temperature determines the color displayed. Colors range from red (hottest) to blue (coolest). In addition, the ATHENA-calculated void fraction determines the intensity of the color displayed. Full intensity corresponds to liquid, white corresponds to vapor, and, between these, the intensity of the color varies with the void fraction.

TEM RADIATOR Q

LOOP 1 - MW
 LOOP 2 - MW
 LOOP 3 - MW

MPa

ACCUMULATOR

TEM

TEM

TEM

MW
 CORE POWER

MW

LOOP 1
 HEAT PIPES

ELECTRIC
 POWER OUTPUT

KW

MW

LOOP 2
 HEAT PIPES

MW

LOOP 3
 HEAT PIPES

EEJ00240

Figure 4. SP-100 Nuclear Plant Analyzer Mask.

The NPA mask is designed to present the most pertinent thermal-hydraulic operating parameters from the SP-100 reactor. In addition to the color display of temperature and void fraction behavior, digital display of the following information is also made: primary system pressure, accumulator level, core power, TEM radiator powers, heat pipe powers, electric power output, primary loop mass flow rates, and fluid temperatures in the cold legs, high-, and low-temperature heat pipes.

6. DEMONSTRATION CALCULATION RESULTS

The results of two transient demonstration calculations are described below. Section 6.1 describes results for a loss of one half the pumping capability in one of the SP-100 coolant loops. Section 6.2 describes results for a loss of all low temperature heat pipes on one of the SP-100 loops. Both transient calculations began from the steady full-power conditions presented in Section 4.

6.1 Transient 1: Partial Loss of Loop 1 Flow

The SP-100 primary coolant loop pump configuration has not yet been completely defined. At least one pump per loop will be required, however, for reliability more likely the design will include multiple pumps in each loop. The multiple pumps could be aligned in either parallel or series arrangements. SP-100 performance during failed pump scenarios will likely be of interest. To demonstrate the ATHENA capability to model a scenario of this nature, a transient calculation was performed. The calculation assumed that one-half of the loop 1 pumping capacity is lost over a 2.5 s period. This assumption is consistent, for example, with a scenario where: (1) each SP-100 loop contains two identical pumps in parallel, each with its own radiator and thermoelectrics and (2) one of the loop 1 pump radiators is damaged due to meteorite impingement. Under these conditions, the surviving loop 1 pump would be expected to continue pumping at the same rate as before the event. Thus the total loop 1 flow would fall to one-half its original rate. The remainder of this section discusses the ATHENA calculation results for this transient.

As the loop 1 flow slowed, the reactor outlet temperature increased as shown in Figure 5. With loop 1 flowing slower, its cold leg temperature fell while the loop 2 and 3 cold leg temperatures rose. Thus little change in reactor inlet temperature was noticed.

Figure 5. Transient 1 primary system temperature responses

The rising reactor outlet temperature resulted in higher hot leg temperatures in all three loops. Figure 6 shows that the pump radiator heat loss rates initially increased slightly with the increasing temperatures. The pumped flows also increased slightly in response to the higher pump radiator heat loss rates.

With the hot leg temperatures rising and the cold leg temperatures stable, the primary system average temperature rose moderately and, as it did, the thermal expansion of primary coolant caused the accumulator level to rise as shown in Figure 7. Also, the rising primary system average temperature caused an initial negative reactivity insertion. Rising fuel temperature induced a positive doppler insertion component. However, a larger negative moderator temperature/expansion insertion component was induced, resulting in the negative net reactivity insertion shown in Figure 8. The reactor power fell, as shown in Figure 9, in response to the negative reactivity insertion.

Figure 10 shows the heat transfer rates at the condensers of the high temperature heat pipes. The lower loop 1 primary side flow resulted in a decreasing power though the high temperature heat pipes connected to that loop. The decreasing power, however, caused the loop 1 low temperature heat pipe temperatures to fall and this caused the loop 1 high temperature heat pipe sink temperature to fall. The loop 1 heat pipe power thus fell until the reduction in its sink temperature stabilized it. The loop 2 and 3 high temperature heat pipe powers initially rose, in response to the lower loop 1 power, then fell, in response to the declining core power.

Electric power output response is shown in Figure 11. This power was calculated by summing the high temperature heat pipe powers from Figure 10 and multiplying by the thermal electric generator efficiency.

Primary system and high temperature heat pipe pressure responses are shown in Figure 12. Only minor changes in primary system pressure are observed. The changes are in response to the varying accumulator level, shown in Figure 7, and the associated compression and expansion effects of the accumulator spring. The loop 1 high temperature heat pipe pressure

Figure 6. Transient 1 thermoelectric electromagnetic pump radiator power response

Figure 7. Transient 1 accumulator level response

Figure 8. Transient 1 reactivity response

Figure 9. Transient 1 core power response

Figure 10. Transient 1 high temperature heat pipe powers

Figure 11. Transient 1 electric power output

Figure 12. Transient 1 pressure responses

fell in response to the decreasing loop 1 heat pipe power and sink temperature. Similarly, loop 2 and 3 high temperature heat pipe pressures rose in response to increasing heat pipe powers and sink temperatures.

Vapor velocities at the centers of the high temperature heat pipes are shown in Figure 13. The loop 1 velocity fell and the loop 2 and 3 velocities rose over the first 7 s of the transient in response to the diverging heat pipe powers shown in Figure 10. Interestingly, the velocity trends reversed after about 7 s, with the loop 1 velocity rising above, and the loop 2 and 3 velocities falling below, their initial values. With the loop 2 and 3 heat pipe powers greater than that of loop 1, one would expect the loop 2 and 3 vapor velocities to be greater, not less, than the loop 1 vapor velocity. This paradox is explained by observing the heat pipe pressure responses in Figure 12. Because of the very low heat pipe pressures, a small change in pressure results in a large change in vapor density. With these changes in pressure, the high temperature heat pipe vapor density in loop 1 fell dramatically while the loop 2 and 3 vapor densities rose dramatically shortly after the transient began. The loop 1 high temperature heat pipe power was less (than that of loops 2 and 3), but since its vapor was much less dense, its vapor velocity was actually higher. Changes in heat pipe pressure can thus have a dramatic effect on transient heat pipe behavior.

The transient calculation was continued until 200 s. By that time reactor response had essentially stabilized. The core power fell until the decline in primary system average temperature caused a positive reactivity insertion. A new steady operating condition was thus being approached at 200 s. The new condition includes a lower-than-original core power, lower core flow, asymmetric loop flows, asymmetric heat pipe behavior, and lower electric power output.

Figure 13. Transient 1 high temperature heat pipe vapor velocities

6.2 Transient 2: Loss of Loop 1 Low Temperature Heat Pipes

Impingement of meteorites on the SP-100 reactor will be a likely transient initiator. Since the low temperature heat pipe radiator panels are on the exterior of the reactor, perforation of these pipes is thus a most likely consequence. To demonstrate the ATHENA capability to model a scenario of this nature, a transient calculation was performed. The transient assumed all of the eighty low temperature heat pipes carrying heat from loop 1 (one-third of the total heat sink) are penetrated by meteorites allowing their working fluids to escape to space. In the model the effects of this event were simulated by removing all of the condenser heat structures on the high temperature heat pipes. In other words, loss of the low temperature heat pipes was simulated by removing all effects of their heat removal capability from the model. The remainder of this section discusses the ATHENA calculation results for this transient.

When the loop 1 low temperature heat pipe effectiveness is lost, a power mismatch exists, with the core power far exceeding the total of the heat removal rates through loops 2 and 3. As a result primary system temperatures rose as shown in Figure 14. Note the loop 1 cold leg temperature diverged from those of loops 2 and 3 and approached the hot leg temperatures. The reactor inlet temperature is shown to exceed the loop 2 and 3 cold leg temperatures. This is because loop 1 continued to flow and warm fluid exited from the loop 1 cold leg.

The rising reactor outlet temperature caused the thermoelectric pump radiator heat loss rates to increase, as shown in Figure 15, and this caused a slight increase in loop mass flow rates. With the rising primary system average temperature, the primary coolant expanded, which caused the accumulator level to increase as shown in Figure 16.

As core temperatures rose, a net negative reactivity insertion was experienced as shown in Figure 17. This insertion caused the decline in core power shown in Figure 18.

Figure 14. Transient 2 primary system temperature responses

Figure 15. Transient 2 thermoelectric electromagnetic pump radiator power response

Figure 16. Transient 2 accumulator level response

Figure 17. Transient 2 reactivity response

Figure 18. Transient 2 core power response

The high temperature heat pipe power responses are shown in Figure 19. The loop 1 heat pipe power vanished at time zero as a result of the transient initiator. The loop 2 and 3 heat pipe powers initially increased to carry the excess core power, then decreased in response to declining core power.

Electric power output response is shown in Figure 20. This power was calculated by summing the high temperature heat pipe powers from Figure 19 and multiplying by the thermoelectric generator efficiency.

Primary system and high temperature heat pipe pressure responses are shown in Figure 21. Primary system pressure changes are in response to the varying accumulator level, shown in Figure 16, and the associated compression and expansion effects of the accumulator spring. Even though its heat transfer rate vanished, the loop 1 heat pipe pressure increased as its fluid was heated gradually to the hot leg temperature. The loop 2 and 3 heat pipe pressures increased as well, but not as much as for loop 1 because condensation continued within these pipes.

Figure 22 shows the high temperature heat pipe vapor velocities at mid-pipe. The loop 1 heat pipe vapor flow is shown to stop completely by about 90 s. Loop 2 and 3 heat pipe vapor velocities followed the same behavior experienced for Transient 1. Vapor velocity primarily tended to vary inversely with pressure, rather than directly with heat pipe power. A discussion of this phenomena is found in Section 6.1.

The transient was continued until 400 s. By that time reactor response had essentially stabilized. The core power stabilized at a new lower level, with power dissipation evenly split between loops 2 and 3. Reactor temperatures at the new steady condition are near their original values.

Figure 19. Transient 2 high temperature heat pipe powers

Figure 20. Transient 2 electric power output

Figure 21. Transient 2 pressure responses

Figure 22. Transient 2 high temperature heat pipe vapor velocities

7. CONCLUSIONS AND RECOMMENDATIONS

The capability of the ATHENA computer code to simulate a SP-100 space reactor has been demonstrated. This demonstration included the simulation of transient heat pipe behavior in a zero gravity environment. Furthermore the ATHENA model represents the first known space reactor integral system model incorporating heat pipes. ATHENA calculated results appear reasonable, both at steady state full power conditions, and for the two demonstration transient sequences.

It is recommended the ATHENA model be updated to simulate the current General Electric SP-100 design. To perform this update, detailed information on the new design (similar to Reference 2) would be required. Addition of potassium properties to ATHENA would be required for modeling the new design.

It is recommended that the addition of a mechanistic electromagnetic pump model to ATHENA be considered. While the approximations used for pump behavior are adequate for transients such as demonstrated here, lack of a mechanistic pump model could prove limiting for more severe or unique transients.

It is recommended the ATHENA heat pipe model be improved by including heat pipe performance limits, such as sonic and entrainment limits. Furthermore assessment of the ATHENA heat pipe model against experimental data is needed to confirm its validity.

Finally, the addition of three phase (solid-liquid-vapor) capability to ATHENA should be evaluated. This capability will be required for analysis of the startup and shutdown transients which are currently of great interest.

8. REFERENCES

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