Reliability Analysis of a Passive Cooling System Using a Response Surface with an Application to the Flexible Conversion Ratio Reactor

by

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B.S. Nuclear and Radiological Engineering
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1. ABSTRACT

A comprehensive risk-informed methodology for passive safety system design and performance assessment is presented and demonstrated on the Flexible Conversion Ratio Reactor (FCRR). First, the methodology provides a framework for risk-informed design decisions and as an example two design options for a decay heat removal system are assessed and quantitatively compared. Next, the reliability of the system is assessed by quantifying the uncertainties related to system performance and propagating these uncertainties through a response surface using Monte Carlo simulation. Finally, a sensitivity study is performed to measure the relative effects of each parameter and to identify ways to maintain, improve, and monitor system performance.

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2. ACKNOWLEDGMENTS

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Two PhD students provided valuable technical insights. Anna Nikiforova was largely responsible for the design and modification of the RELAP5-3D model of the FCRR. Without her help, I would still be debugging! Michael Elliott greatly assisted in the application of the Analytic Deliberative Process to the design of the PSACS. His knowledge of the ADP and risk-informed decision-making was very helpful in shaping the final design of the PSACS.

I am extremely grateful to the United States Nuclear Regulatory Commission for generously providing a fellowship, as well as an academic allowance to support this research effort. In particular, I thank Luis Reyes for selecting me to participate in the Graduate Fellowship Program.

Finally, I would like to acknowledge my grandfather, Joseph Zupanick. In addition to being an accomplished engineer and inventor, he served as a Navy Officer in WWII and later earned a Masters Degree from MIT. Although he is no longer with us, his memory inspires me nearly every day.

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6. INTRODUCTION

Many advanced reactor designs rely on both traditional defense-in-depth measures (e.g., multiple fission product barriers) and new design features such as inherently safe design characteristics and passive safety systems. Unlike the active systems common in the current reactor fleet, passive systems do not require external driving forces or operator actions and are thus considered to be simpler and more reliable. Several classes of passive safety systems exist. Table 1 lists the four categories of passive safety systems defined by the International Atomic Energy Agency [1].

A common characteristic of passive safety systems is that their driving force tends to be weak and therefore adverse or off-normal conditions may substantially degrade system performance [2]. Under certain conditions, system performance may be degraded to a level that results in unacceptable consequences. These consequences are typically identified by the system designer and are referred to as failure criteria. Failure criteria can be defined at the system level (e.g., flow rate, fluid temperature) or at a higher level (e.g., peak cladding temperature, containment pressure). Therefore, the conditional failure probability of a passive system can be defined as the probability that, given an initiating event, a set of thermal-hydraulic conditions will exist that cause the system to exceed one or more failure criteria.

Category & Description	System Initiation Signal	Fluid Movement	Moving Parts	Examples
A. Inherent Safety Features	None	None	None	Physical barriers against the release of fission products, such as nuclear fuel cladding and pressure boundary systems
B. Fluid system with no moving parts	None	Due only to thermal-hydraulic conditions	None	Reactor emergency cooling systems based on air or water natural circulation in heat exchangers immersed in water pools (inside containment) to which the decay heat is directly transferred
C. Fluid system with moving parts	None	Due to thermal hydraulic conditions and state change of mechanical components (valves, dampers, etc)	Yes, but no external energy sources	Emergency injection systems consisting of accumulators or storage tanks and discharge lines equipped with check valves
D. Active Initiation/ Passive Execution	Stored energy – no AC or manual initiation permitted	Due to thermal hydraulic conditions and state change of mechanical components (valves, dampers, etc)	Yes, but no external energy sources	Emergency reactor shutdown systems based on gravity driven or static pressure driven control rods activated by fail-safe logic

Table 1 - IAEA Passive Safety System Classification [1]

System conditions leading to failure are the result of adverse combinations of system parameter values such as pressure, temperature, and void fraction. Prediction of the exact values of these parameters is made difficult by several sources of uncertainty and typically, we can only assume a range of expected values and a corresponding probability distribution. We will refer to this type of uncertainty as parametric uncertainty. Second, there are uncertainties associated with the models used to predict system behavior. These can involve equations or empirical correlations used to model various phenomena or may stem from the numerical methods employed by computer codes. We will refer to this type of uncertainty as model uncertainty. Both parametric and model uncertainties are classified as epistemic since they are related to a lack of knowledge as opposed to aleatory uncertainty, which is related to randomness [3]. An estimate of system reliability can be obtained by quantifying parametric and model uncertainty and observing their effect on system performance. Further insights can be gained by evaluating the sensitivity of system performance to each parameter, and we will demonstrate several ways in which this can be done.

The reliability of passive safety systems has been the subject of a great deal of research this decade both in the United States and internationally. System failure is assumed to occur when a physical quantity such as temperature exceeds a value that is considered acceptable, a phenomenon sometimes referred to as "functional failure" [4]. A systematic methodology for the reliability assessment of passive systems is described by Marqués et al in [2].

Past efforts at MIT have been focused on design tradeoffs [5-6]. System reliability is assessed by performing a large number of simulations using the code RELAP5-3D [7] coupled with Latin Hypercube Sampling (LHS). These simulations cover a range of thermal hydraulic (T-H) conditions. The probability of system success (reliability) is estimated simply by dividing the number of simulations that result in success by the total number of simulations:

$$\Pr(success) = \frac{\sum_{i=1}^{N} A(i)}{N} \tag{1}$$

N is the total number of simulations and A(i) is a binary variable equal to unity when all success criteria are met and zero otherwise. A sufficient number of simulations must be performed to provide confidence in the results.

Mackay et al performed 128 simulations, observed 39 failures, and recommended several risk-informed design improvements based on these results [5]. Patalano et al supplemented the Gas-cooled Fast Reactor (GFR) design with these improvements and added several others. These changes reduced the number of failures to 16 out of 128 [6].

Initially, we considered using this methodology to perform a reliability study of the lead-cooled, fast spectrum, Flexible Conversion Ratio Reactor (FCRR) under development at

MIT as part of the Department of Energy's Nuclear Energy Research Initiative (NERI). During the planning phase of this effort, a concern about computational time was identified.

Both previous efforts at MIT studied the GFR, a direct-cycle design with a relatively simple RELAP5-3D model. Furthermore, these papers focused on a fast-developing transient (LOCA) with a coolant (helium) that changes temperature quickly during transients due to its relatively low specific heat capacity. Consequently, both papers obtained temperatures exceeding the peak cladding temperature (PCT) and the peak decay heat removal (DHR) pipe temperature within the first three hours of the transient. Exceeding either peak temperature is considered a failure.

The FCRR operates at ambient primary pressure and employs a guard vessel, so LOCA is not a major concern. Instead, Station Blackout (SBO) has been shown to be the most severe transient in terms of PCT. This is due to the sudden loss of both primary and secondary forced flow. Analysis of this transient presents a challenge because PCTs are not observed until more than 60 hours into the SBO event [8]. This is mostly due to the very large heat capacity of lead, the FCRR primary coolant. Because the primary coolant can absorb a large amount of energy, it heats up slowly during an SBO and, therefore, fuel and cladding temperatures rise slowly as well.

In addition to the long duration of the SBO transient, the FCRR RELAP5-3D model is somewhat more complex than that of the GFR. The FCRR uses a super-critical CO_2 (S-CO_2) power conversion system rather than the direct-cycle system found in the GFR. Additionally, the GFR uses a single two-loop decay heat removal (DHR) system. The FCRR uses two systems to accomplish decay heat removal. The Reactor Vessel Auxiliary Cooling System (RVACS) is a passive system that provides primary system cooling via natural convection of air around the reactor vessel. The Passive Secondary Auxiliary Cooling System (PSACS) is a passive system that removes heat from the primary system via the intermediate heat exchangers by providing natural circulation of S-CO_2 fluid to a large tank of water that serves as the ultimate heat sink. These factors combine to produce a model that takes substantially longer to run than those used in the GFR studies. A summary of the reactor differences and the required simulation times is presented in Table 2.

A faster computer was used during the FCRR study, but the long transient time and additional model complexity still increase the amount of computing time per simulation by a factor of three to four compared to the GFR studies. Performing a reasonable number of simulations would still require substantial computing time, a fact that provides motivation for the use of response surface methodology.

Project	Cooling system	Fluids	Computer	Transient time	Time per trial	Number of trials
GFR, MacKay et al [5]	DHR	Helium & Water (DHR)	P4 3.2 GHz; 1 GB RAM	> 3 hours	≈ 8 hrs	128
GFR, Patalano et al [6]	DHR	Helium & Water (DHR)	P4 3.2 GHz; 1 GB RAM	> 2 hours	≈ 10 hrs	128
FCRR	PSACS RVACS	Lead, S-CO_2, Water (PSACS), Air (RVACS)	P4 Quad Core 2.6 GHz, 4 GB RAM	72 hours	≈ 30 hrs with 3 simultaneous runs	
			P4 3.2 GHz; 1 GB RAM	72 hours	≈ 36 hrs	

Table 2 - Comparison of GFR and FCRR

A different approach to passive system reliability assessment, known as the Assessment of Passive System Reliability (APSRA) methodology, is being proposed by the Bhabha Atomic Research Centre (BARC). The APSRA focuses on mechanical failures and their effect on passive system performance [9].

This paper focuses on functional failures of passive systems. First, a model of the system is constructed using RELAP5-3D. Next, a set of simulations are performed to construct a response surface that models system performance during an SBO. Finally, the reliability of the system is assessed by performing a Monte Carlo simulation with the response surface.

7. SYSTEM DESCRIPTION

The FCRR is a 2400MWth lead-cooled fast reactor currently under development by MIT's Nuclear Science and Engineering department as part of the Department of Energy's Nuclear Energy Research Initiative [8]. The FCRR core can be configured to support various conversion ratios (CRs), although the analyses were performed only for two bounding CRs: (1) near zero to transmute legacy waste and (2) near unity to operate in a sustainable closed cycle. Because this paper focuses on reactor safety, only the more challenging case of a near unity conversion ratio was investigated due to its higher decay heat loads. The reactor is coupled to a power conversion system (PCS) consisting of a Brayton cycle utilizing S-CO_2. The PCS consists of four 600 MWth loops, each consisting of an in-vessel Intermediate Heat Exchanger (IHX), a turbine, high- and low-temperature recuperators, a pre-cooler, and two compressors. Diagrams of the primary and secondary system are displayed in Figures 1 and 2, respectively. Details regarding the S-CO_2 PCS are given in [9]. Decay heat removal during both normal and emergency conditions is provided by a pair of passive systems that work in tandem: the RVACS and PSACS. These systems are represented graphically in Figures 1 and 3 respectively.

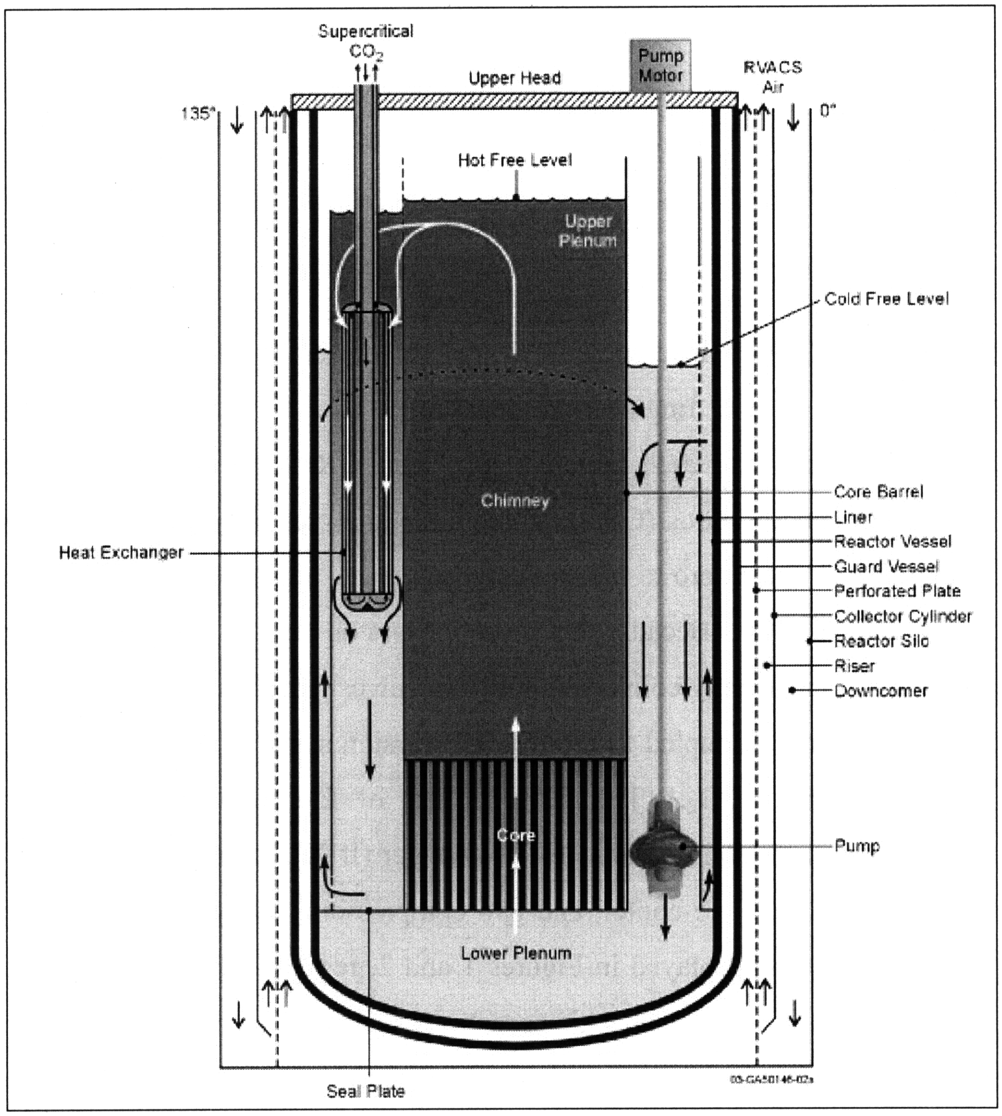

Figure 1 - FCRR Primary System and RVACS [10]

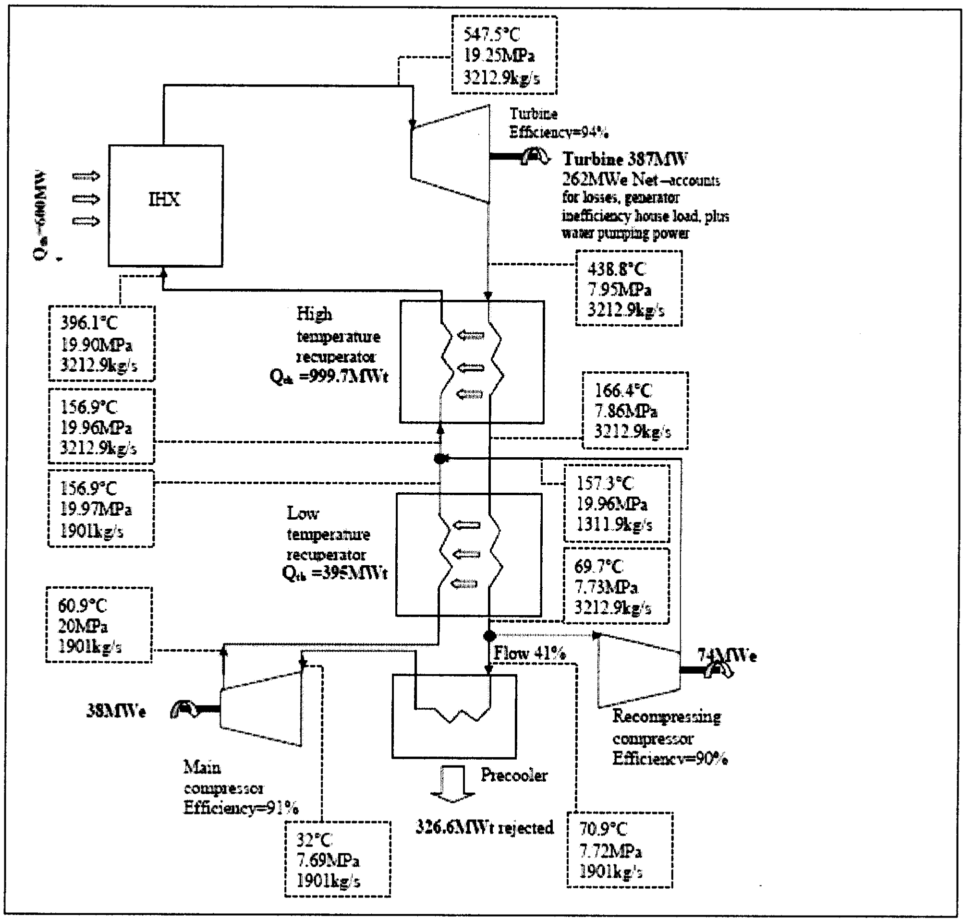

Figure 2 – State Point Diagram of the FCRR Power Conversion System [8]

Figure 1 shows the major primary system components and the RVACS. The reactor vessel houses the fuel, primary coolant (lead), reactor coolant pumps, and in-vessel heat exchangers. Surrounding the reactor vessel is the reactor guard vessel which serves as a defense against coolant leaks. The reactor guard vessel is enveloped by the RVACS, which provides heat removal via natural convection to air that is drawn through inlet ducts and flows upward over the reactor guard vessel due to buoyancy effects. Ambient air outside the containment building is the ultimate heat sink. The RVACS is classified as an IAEA Category B passive system since it does not require external power, moving parts, control signals, or operator actions to accomplish its design function. The RVACS concept was originally developed for the much smaller 1000MW_{th} S-PRISM reactor [12]; therefore, a key design challenge was to increase the heat removal capability to a level appropriate for the 2400 MW_{th} FCRR.

Design enhancements include the addition of a perforated plate in the air gap, lead-bismuth eutectic within the gap between the reactor vessel and guard vessel, and the use of dimples on the guard vessel wall. The use of a perforated plate was first identified by General Electric during the S-PRISM design, while the addition of a lead-bismuth eutectic and dimples are design improvements developed by an INL/MIT team for a lead-alloy cooled medium power reactor. Together, these enhancements have improved RVACS performance to decay heat removal rates between 15 MW_{th} and 17 MW_{th} under accident conditions [8].

Although these improvements are noteworthy, transient analyses have shown that this performance is not sufficient under some accident scenarios such as the bounding transient, which is SBO. During this accident sequence, the heat removal rate of the enhanced RVACS would be insufficient to maintain the PCT below the design limit of 725°C. Consequently, additional decay heat removal options to supplement the enhanced RVACS were investigated.

Initially, use of the PCS as an emergency decay heat removal system was considered since this equipment was already available; however, this would require most, if not all, of the PCS to be classified as safety- related [13]. Within the current regulatory framework, safety-related components must be seismically qualified to withstand the Safe Shutdown Earthquake, also known as the Design Basis Earthquake [14], and the Quality Assurance rules of 10 CFR 50, Appendix B [15] would apply to nearly all PCS systems and subsystems. The reclassification of nearly the entire PCS as safety related would lead to a substantial increase in construction, maintenance, and procurement costs. Therefore, the decision was made to use the PCS as a non-safety related DHR system that is backed up by a stand-alone safety-grade DHR system.

Several supplemental alternatives for a safety-related DHR system were evaluated:

- A Direct Reactor Auxiliary Cooling System (DRACS) consisting of a separately designed lead-bismuth eutectic loop connected to an air cooled heat exchanger located in the chimney of the RVACS riser.

- A Passive Secondary Auxiliary Cooling System (PSACS) that removes decay heat via the existing lead/S-CO_2 IHX and a standby loop filled with secondary S-CO_2, which transports heat by natural circulation from the IHX to a heat exchanger cooled passively by either air or water.

The DRACS was discarded because of space constraints in the reactor vessel, and PSACS was selected for further analysis. Since both the PSACS air and water designs were deemed to have merit, a formal decision-making process was utilized to complete the selection process. The Analytic Deliberative Process (ADP) [16] was used to assess the two design options against a variety of performance measures such as economics, reliability, and thermal hydraulic performance. Using the ADP, the PSACS-water option was selected as the final design option and RELAP5-3D simulations were used to test and optimize the design.

The final PSACS design consists of four independent, 50% capacity each, safety-grade trains – one for each PCS loop (Figure 3). Each PSACS train is connected to an IHX loop by two PSACS isolation valves in parallel (B). The train also consists of an inlet header or "hot leg (A)," a Passive Auxiliary Heat Exchanger (E), PSACS Storage Tank (D) and a return header to the PCS or "cold leg (F)". The hot and cold legs connect the PSACS to the PCS and the PSACS Storage Tank (PST). The latter stores a large volume of water that acts as the ultimate heat sink during PSACS operation (Figure 3).

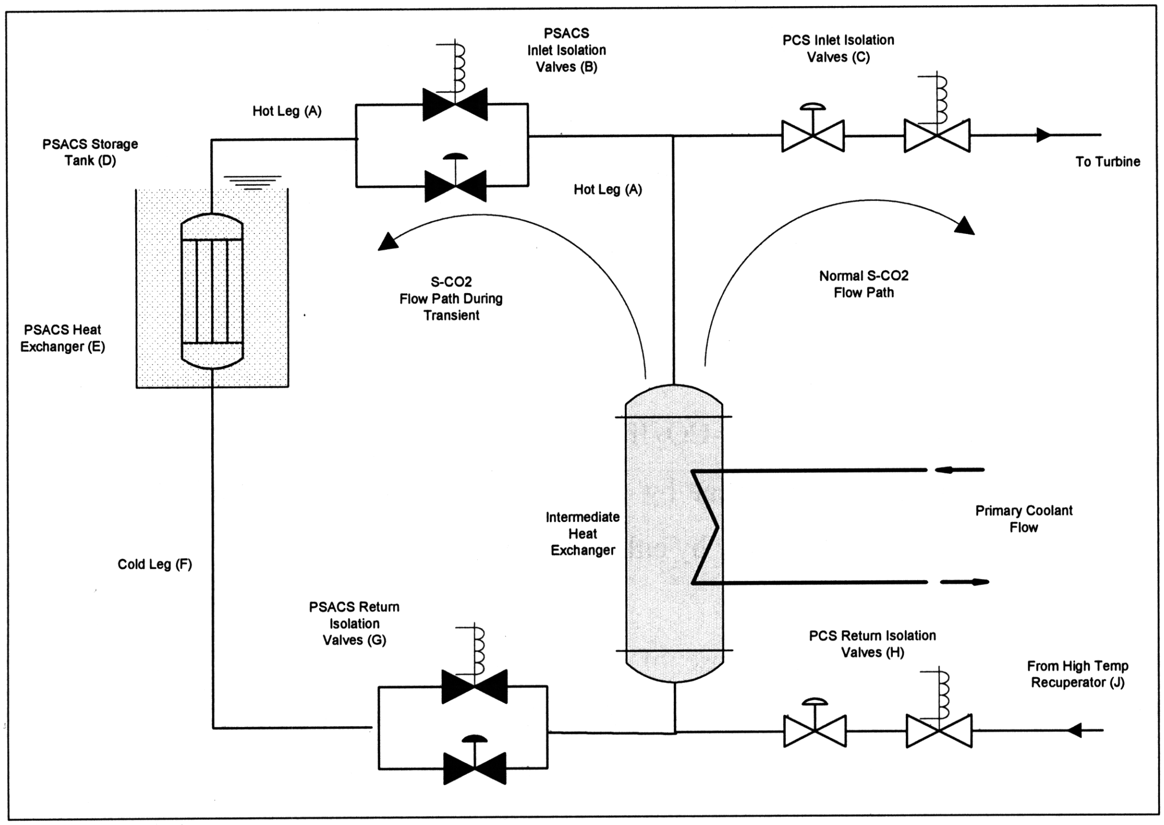

Figure 3 - One Train of the Passive Secondary Auxiliary Cooling System (PSACS)

The PSACS Auxiliary Heat Exchanger (PAHX) is a vertical bank of parallel tubes submerged in the PSACS Storage Tank (PST), which is filled with ambient temperature water. S-CO_2 flow enters the tube bank through a plenum near the top of the PAHX and travels downward through the tubes, rejecting heat into the water. The bottom of the PAHX is located 2 meters above the top of the IHX to provide a suitable elevation difference for natural circulation. Each PCS loop has a corresponding PSACS train so failure to isolate a PCS loop during a transient creates a bypass around that train, compromising natural circulation. To minimize the probability of this occurrence, each PCS loop contains two PCS isolation valves in series rather than a single valve. Additionally, the PSACS trains are not interconnected, so a depressurization of one train will not affect the others. The PSACS is classified as an IAEA Category C passive system because it relies on thermal hydraulic conditions for fluid flow and contains isolation valves that change state with no initiation signal [1].

Tube height	4 meters
Tube outer diameter	1.4 cm
Number of tubes per PAHX	700
Pitch / Diameter	3.5
PST height	10 m
PST diameter	6 m
Nominal PST Water Volume	282 m^3

Table 3 - PSACS Design Specifications

The PSACS design specifications listed in Table 3 were selected to allow the PSACS to suppress PCT below the 725°C accident limit during all credible accident scenarios even with the complete loss of two-out-of-four trains [8]. We selected this scenario for further analysis because it is the bounding case.

8. FRAMEWORK

8.1 Accident Scenario

An SBO is defined as the complete loss of alternating current (AC) to the essential and non-essential switchgear buses in a nuclear power plant, i.e., loss of offsite power concurrent with a turbine trip and loss of emergency onsite power [13]. This is a beyond-design-basis accident under the present regulations but one that the current fleet of reactors in the United States must have the capability to manage per 10 CFR 50.63. An SBO event presents a significant operational challenge as it leads to a loss of forced primary flow (the reactor coolant pumps rely on AC) and disables several ways of primary and secondary heat removal such as the motor-driven pumps used by the emergency core cooling system or auxiliary feedwater system.

Passive cooling systems provide a distinct advantage during SBOs because they rely on natural phenomena rather than AC power to perform their safety functions. The RVACS and PSACS both provide cooling during this accident using natural circulation and neither has any components that require AC power to perform their safety-related functions. We are interested in the conditional failure probability of the RVACS and PSACS given that an SBO occurs and AC power is not recovered.

When AC power is lost, the reactor coolant pump (RCP) trip breakers are opened, resulting in a loss of forced circulation of primary coolant. The RCPs slowly coast down and natural circulation of primary coolant is established due to thermal head. On the secondary side, the PCS isolation valves fail shut and the PSACS isolation valves fail open. Each set of isolation valves are held in their normal position by either a solenoid or instrument air actuator and require AC to remain in their respective positions [Figure 3]. When AC power is lost they swap positions, isolating the PCS and placing the PSACS into service. Fuel and primary coolant temperature rise slowly due to decay heat and this heat is transferred to the S-CO_2 via the four IHXs. As the S-CO_2 heats up, a density difference between the PSACS hot leg and cold leg is established and natural circulation begins. As the PSACS removes heat from the secondary system, a temperature differential is established across the IHXs. This draws heat out of the primary system and leads to a reduction in primary coolant temperature and fuel temperature. The reduction of PCT is displayed in Figure 4.

As the hot S-CO_2 rejects heat into the PST, the water heats up, eventually boiling approximately two hours into the SBO. This phase change temporarily improves heat transfer, but the PSACS gradually loses effectiveness as inventory is boiled off. Assuming conservatively no operator intervention, the PSACS will boil dry in about 24 hours and will cease to provide cooling. At this point, primary temperature again begins to rise due to decay heat.

As the primary coolant temperature rises, the guard vessel heats up and RVACS flow rate increases due to natural circulation; this slows the temperature rise until a maximum temperature is reached at about 68 hours.

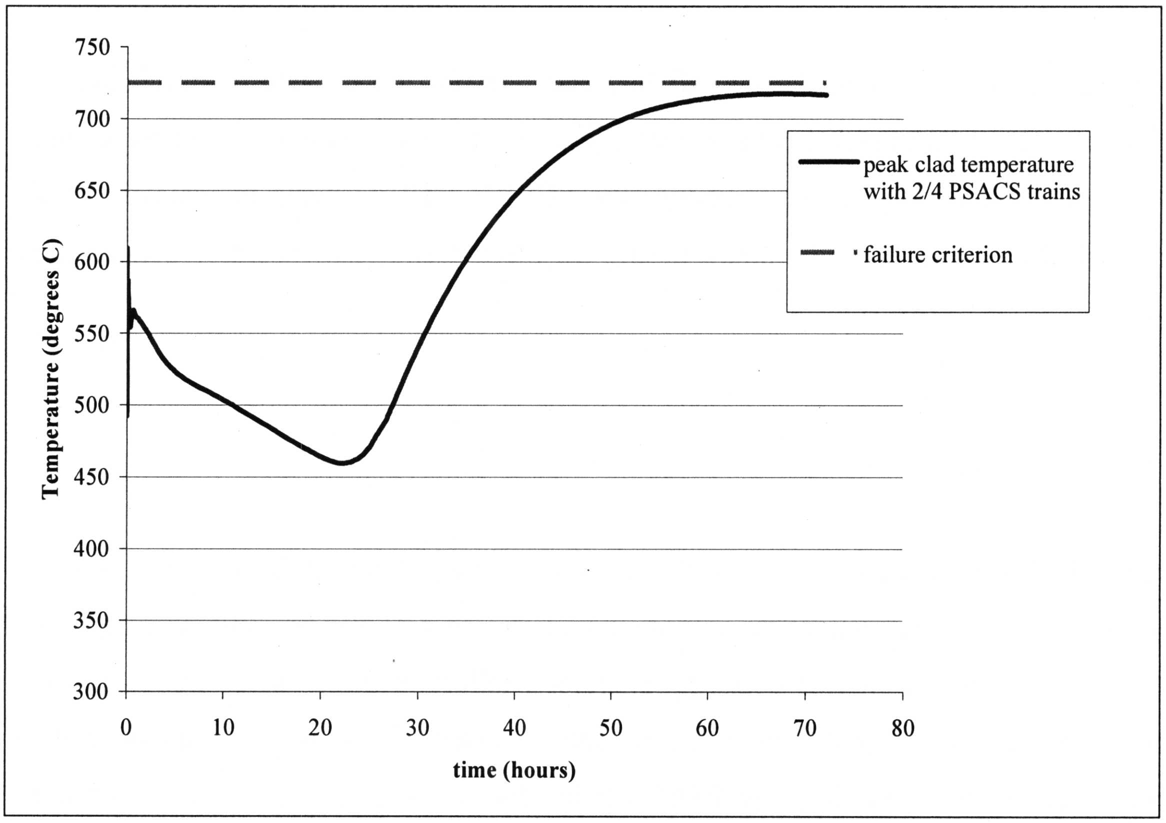

Figure 4 - PCT During SBO

8.2 Success Criteria

The deterministic limit for PCT is 725°C. This limit does not correspond to prompt fuel or cladding damage; rather, this temperature leads to the onset of fuel/cladding chemical interaction. Temperatures higher than 725°C can cause actinide diffusion into the cladding and lead to low-melting-point regions resulting in clad thinning and potential failure [17]. These conditions have therefore been deemed unacceptable.

Because Gen III+ designs like the AP1000 and ESBWR are capable of mitigating an SBO for at least 72 hours, this value was chosen as the assumed duration of the event. Therefore, a successful mission requires the FCRR's DHR systems to maintain PCT below 725°C for at least 72 hours during an SBO event. No operator actions are assumed.

8.3 System Reliability

Unlike the RVACS, which is constantly operating, the PSACS is isolated during normal operation. There are four 50% capacity trains and several valves must change state before each train can provide cooling. Therefore, failure of these valves can challenge PSACS performance by affecting the number of available trains. To quantify the probability of losing one or more PSACS trains due to valve failure, we constructed a fault tree of each train. The fault tree captures the system logic and models the effect of valve reliability on PSACS reliability. In addition, it shows which combinations of valve failures lead the loss of a PSACS train. These combinations (minimal cut sets) are useful to the designer because they identify potential weaknesses or single point failures.

These insights were used to support PSACS design and led to several key features. First, the PSACS inlet and return isolation valves are in parallel so that a single valve failure does not prevent a PSACS train from actuating. As long as at least one inlet and one return isolation valve are open, the PSACS train can perform its design function. Similarly, the PCS inlet and return isolation valves are in a series configuration so that a single valve failure does not create a bypass around the PSACS train or lead to PSACS depressurization should a PCS leak occur. These features ensure that no single valve failure can disable a PSACS train.

Although multiple independent component failures are unlikely, several failures can occur simultaneously for the same reason. Improper maintenance, installation errors, design flaws, and adverse environmental factors can all lead to multiple dependent failures. These failures are known as common cause failures (CCFs) and it is important to account for them in our PSACS model. To do so, we make use of the Beta Factor model, which is somewhat conservative but simple and accurate enough for our purposes. In this model, we assume that a certain fraction of component failures are due to a common cause and lead to the failure of all identical components in the system. This fraction, β, is typically assigned a value of about 0.10 [18]. There are two distinct types of PSACS and PCS valves: Solenoid Operated Valves (SOVs) and Air-Operated Valves (AOVs).

Prior to calculating PSACS train reliability, let us examine the minimal cut sets for one train of PSACS.

Cut Set No.	Failures	Basis	Mean Probability
1	PSACS Inlet AOV and PSACS Inlet SOV	The PSACS train remains isolated and can not provide any decay heat removal	9×10^{-6}
2	PSACS Return AOV and PSACS Return SOV		9×10^{-6}
3	PCS Inlet AOV and PCS Inlet SOV	Failure to isolate a PCS loop creates a flow bypass around the corresponding PSACS train. Hot S-CO_2 exiting the IHX could instead flow through the PCS rather than the PSACS. Furthermore, PCS piping is non-safety related and therefore less robust than the PSACS piping. Without isolation, a rupture or leak in the PCS could depressurize the PSACS thereby challenging its effectiveness.	9×10^{-6}
4	PCS Return AOV and PCS Return SOV		9×10^{-6}
5	CCF –SOV and PSACS Inlet AOV	Same as 1 & 2	1.5×10^{-5}
6	CCF –SOV and PSACS Return AOV	Same as 1 & 2	1.5×10^{-5}
7	CCF –SOV and PCS Inlet AOV	Same as 3 & 4	1.5×10^{-5}
8	CCF –SOV and PCS Return AOV	Same as 3 & 4	1.5×10^{-5}
9	CCF-AOV and PSACS Inlet SOV	Same as 1 & 2	1.5×10^{-5}
10	CCF-AOV and PSACS Return SOV	Same as 1 & 2	1.5×10^{-5}
11	CCF-AOV and PCS Inlet SOV	Same as 3 & 4	1.5×10^{-5}
12	CCF-AOV and PCS Return SOV	Same as 3 & 4	1.5×10^{-5}

Table 4 - PSACS Minimal Cut Sets

To determine the probability of these cut sets, we use valve reliability data from the Nuclear Computerized Library for Assessing Reactor Reliability [19]. No specific failure rates were available for valves in an S-CO_2 environment, so we substituted data from valves in a liquid sodium environment, which were the most conservative numbers available. Based on this information, the probability of either valve type failing to open/close was modeled as a lognormal distribution with a mean value of 3×10^{-3} per demand and an error factor of 10. The computer code SAPHIRE 7 was used so that these values, rather than just point estimates, could be incorporated [20]. Using SAPHIRE's fault tree analysis feature, we calculated the mean probability of losing a single train of PSACS due to valve failure:

Pr[PSACS train fails on demand] = 1.6×10^{-4}

Losing one train of PSACS does not disable the system. In fact, the PSACS is designed to meet the success criteria discussed in Section 8.2 with up to two trains simultaneously unavailable. This is accomplished by selecting conservative design values for the PAHX and PST, which are displayed in Table 3.

We can calculate the probability of two simultaneous PSACS train failures using the following expression:

Pr[failure of two trains] = Pr[independent failure] + Pr [CCF] (2)

The probability of CCF is determined using the very conservative Beta Factor model, which assumes that a CCF of one valve type (AOV or SOV) in one PSACS train is always accompanied by CCF of all valves of that type in the other three trains. Therefore, if one train experiences CCF, another train is assumed to fail if at least one valve in the opposite valve group fails. We can now write Equation (2) as:

Pr [failure of two trains] = Pr [independent failure] + Pr[CCF of AOVs] x Pr[at least one SOV fails] + Pr[CCF of SOVs] x [Pr at least one AOV fails] (3)

Adding the probabilities of minimal cut sets that share basic events, known as the minimal-cut-set upper bound approximation, is appropriate when the probability of the top level event is small [20]. Using this approach, the probability of independent failure for a given train is determined by summing of the probabilities of minimal cut sets 1 – 4 in Table 4 and the probability of CCF can be determined by summing the probabilities of minimal cut sets 5-12. The probability of at least one AOV or SOV failing in another train is equal to 0.035. Inserting these numbers into Equation (3), and assuming that Beta is lognormally distributed with a mean value of 0.10 and an error factor of 3, we find that the mean probability of simultaneous failure of two PSACS trains is 4.0 x 10^{-6} and the 95th percentile is 1.4 x 10^{-5}.

This probability is quite low even with our conservative assumptions and we will consider the probability of losing more than two trains of PSACS negligible. The overall system failure probability then becomes:

$$\Pr[failure] = \sum_{i=2}^{i=4} \Pr[failure|N = i] \bullet \Pr[N = i] \tag{4}$$

where N = the number of operational PSACS trains. In this context, operational means that a PSACS train is not isolated and the corresponding PCS loop is isolated. Once a PSACS train is operational, all flow is due to natural circulation and no external energy sources, mechanical components, or operator actions are needed. Therefore, operational PSACS trains are subject only to functional failures and can be analyzed by constructing a model of the system and performing a Monte Carlo simulation in the manner described in Section 1. Performing this analysis provides values for the first half of Equation (4), the conditional failure probability given a number of operational trains.

When three or four PSACS trains are operational (i = 3 or 4 in Equation 4), there is a substantial amount of margin between PCT and the 725 °C failure criterion at all times. In fact, simulations have shown that even when all input variables are set to their worst case values, the PSACS can meet the success criteria outlined in Section 8.2 provided that at least three trains are operational. This indicates that functional failure when at least three trains are operational is negligible and we should focus our uncertainty analysis on the case when two trains are available. Therefore, Equation (4) reduces to:

$$\Pr[failure] = \Pr[failure|N = 2] \bullet \Pr[N = 2] \tag{4a}$$

The next step is to evaluate this case using a computer model to measure system performance.

8.4 Simulation Code

A RELAP5-3D model was used to develop steady-state operating parameters for the FCRR and to ensure that design constraints such as primary coolant flow rate and reactor vessel size were met. Construction of this model took place in four stages:

1. A model of the primary system was constructed with the core represented as two subchannels: hot and average.
2. A detailed IHX model was created separately, optimized, and then connected to the primary system model.
3. The enhanced RVACS with dimples on the guard vessel and perforated plate in the air riser region was added to the model.
4. The complete S-CO_2 PCS was coupled to the primary system

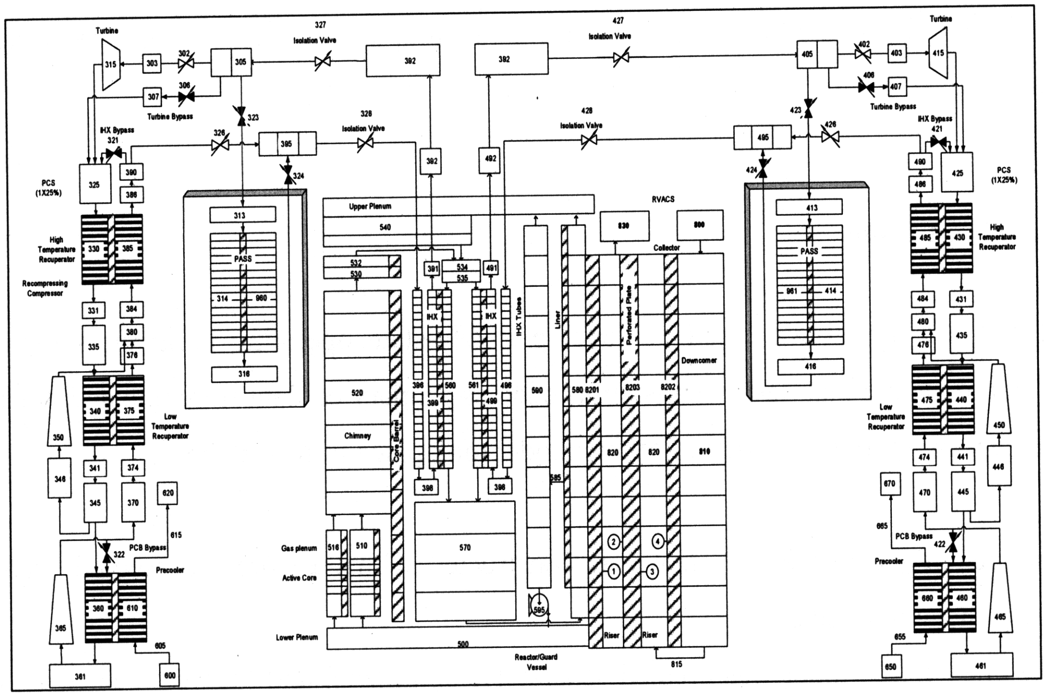

Figure 5 - RELAP5-3D Nodalization Diagram Showing Two PSACS Trains

In the FCRR RELAP5-3D model, the primary coolant system is characterized by components 500 through 595. The nodalization starts with the lower plenum, component 500. The flow is subsequently split into two parallel channels: hot channel (component 516) and average channel (component 510). The hot channel represents four lumped assemblies with the highest peaking factor of 1.21. The average channel represents the remaining assemblies. The flow is recombined in the chimney, component 520. Component 540 corresponds to the upper vessel plenum. Four heat exchangers are represented by components 560 and 561. Component 560 depicted in Figure 5 corresponds to lead-side coolant channels of one heat exchanger. The other three IHXs are lumped together in component 561. For some transient calculations, lumping was eliminated to allow for individual loop modeling. The heat exchanger downcomer, vessel liner, and the pump downcomer are represented by components 570, 580 and 590, respectively. The flow exits the heat exchangers, flows downward through the IHX downcomer, then upward behind the liner, and finally returns to the lower vessel plenum through the pump downcomer. As the coolant passes through the space between the liner and the vessel, heat transfer between the vessels and RVACS occurs. The position of valve 585 which directs the flow from the liner to the pump downcomer was selected based on the pressure drop through the primary system.

Hatched components correspond to the heat structures. Heat structures are connected thermally to the attached hydrodynamic volumes. The primary system includes five main structures: average fuel pins, hot fuel pins, core barrel, heat exchanger tubes, and the reactor vessel liner. The RVACS heat structures include reactor and guard vessels with lead-bismuth as the conducting fluid, the perforated plate, and the collector cylinder.

The fuel pin model is quite detailed and includes a lead-alloy bond, cladding and an oxide layer on the outside of cladding. The heat exchanger tube heat structure also includes an oxide layer on the lead-side. Finally, the CO_2-side of the IHX heat structure includes tube surface augmentation (helical ribs) to model enhanced heat transfer.

The parameter values generated by the steady-state model were used to supply initial conditions to the RELAP5-3D transient analysis. This analysis uses the same RELAP5-3D model displayed in Figure 5, but tracks reactor parameters (e.g. peak clad temperature) throughout the duration of the transient. In this case, we modeled an SBO event but the same process can be used to model other transients such as inadvertent rod withdrawal or loss of primary system flow.

8.5 Methodology Overview

As discussed in Section 1, the methodology used to evaluate the reliability of the PSACS and RVACS is similar to previous efforts at MIT [5, 6] except that uncertainty analysis is conducted using a response surface rather than the RELAP5-3D model itself. Response Surface Methodology (RSM) replaces the output of a best estimate code (in this case, RELAP5-3D) with a function of the form [21]:

$$Y = g(\underline{X}) \qquad (5)$$

Y is an output variable of interest (in our case, PCT) that depends on X, a vector of input parameters also known as factors or predictor variables. Experiments are conducted with the predictor variables $X_1, X_2, \ldots, X_n$ a sufficient number of times to define the response surface to the level of accuracy desired. In general, experiments may be conducted at a test facility, but computer simulations are typically used for nuclear applications.

The resulting data can be used to construct a response surface with a variety of forms: linear, polynomial, thin plate splines, and others. Once formed, the response surface replaces the slow-running thermal-hydraulic code and is used to model system performance. Because calculations with the response surface can be performed very quickly, the problem of long simulation times is circumvented. We have integrated the use of a response surface into a reliability analysis methodology that consists of the following steps:

1. Definition of the system, its mission and failure modes.
2. Construction of a system model using RELAP5-3D.
3. Identification of the sources of epistemic uncertainty and the important parameters, including the definition of specific failure criteria.
4. Quantification of uncertainties by selecting appropriate probability distributions. Literature searches and expert judgment were used when appropriate.
5. Determination of central and enveloping values for the parameters, based on these distributions.
6. Construction of a response surface based on 27 RELAP5-3D simulations and the PCT values that each predicts.
7. Propagation of parametric uncertainty through the response surface using Monte Carlo simulations.
8. Determination of passive system reliability.
9. Performance of a model uncertainty sensitivity study.
10. Performance of a parametric sensitivity study.

9. ANALYSIS

9.1 Construction and Validation of Response Surface

Based on expert judgment, literature review, and RELAP5-3D data, five predictor variables were considered likely to have an appreciable effect on decay heat removal performance. To account for potential non-linear effects, a quadratic model was selected and each variable was then assigned a lower, center, and upper level. This was done because construction of a quadratic response surface requires at least three levels per factor. The lower and upper levels were selected to envelope all expected values; this is an important step in creating a response surface that can predict system performance accurately. Using a response surface with predictor variable values outside of this envelope requires extrapolation and can reduce accuracy greatly [21]. The predictor variables and their three levels are displayed in Table 5.

Factor	**Lower**	**Central**	**Upper**
X_1, PSACS plugged tubes (fraction)	0	0.075	0.15
X_2, PSACS initial water temperature (°C)	7	27	47
X_3, RVACS emissivity (unit-less)	0.65	0.75	0.85
X_4, RVACS blockage (fraction)	0	0.075	0.15
X_5, RVACS inlet temperature (°C)	7	27	47

Table 5 - Predictor Variables and Levels

Twenty-seven combinations of these values were then used to create a response surface experiment in the manner described by Xu et al [21]. This design allows for a full quadratic response surface including linear terms, quadratic (squared) terms, and two-factor interactions. Each set of predictor variables were entered into the RELAP5-3D model and a simulation was performed to determine the corresponding PCT.

Following the collection of the data from the simulations, we used the statistical program MINITAB 14 [22] to construct the following response surface:

$$Y(\underline{X}) = 711.5 + 4.2X_1 + 2.7X_2 - 9.2X_3 + 1.4X_4 - 15.6X_5 + 4X_1^2 + 0.5X_2^2 - 0.5X_3^2 - 4.3X_4^2 + 3.5X_5^2 - 2.7X_1X_2 - 0.4X_1X_3 - 4.8X_1X_4 + 1.5\,X_1X_5 - 2.7X_2X_3 + 5.9X_2X_4 - 0.8X_2X_5 - 9.5X_3X_4 + .1X_3X_5 - 1.7X_4X_5 \quad (6)$$

MINITAB 14 uses a least-mean-squares approach to fit an equation that best fits the data; however, a number of checks should be performed on any response surface to ensure that it accurately models the process in question. In our case, we wanted confidence that the response surface would serve as an appropriate substitute for our RELAP5-3D model of the Station Blackout event.

The following checks were performed:

1. Coefficient of determination (R^2 value). R^2 is a value in the interval [0,1] that expresses what fraction of the output variability can be accounted for by the input variability. It is more formally defined as:

$$R^2 \equiv \frac{SSR}{SST} \quad (7)$$

where the variability explained by the regression line, the regression sum of squares

$$SSR = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2 \quad (8)$$

is divided by the total variability in the dependent variable, the total sum of squares

$$SST = \sum_{i=1}^{n} (y_i - \bar{y})^2 \quad (9)$$

In a "perfect" model, all output variance would be explained simply by input variance and R^2 would equal unity. In reality, models are an approximation and therefore add a degree of error or variance. An effective model should have a value of R^2 as close to unity as possible.

2. Size and distribution of residuals. Residuals from a fitted model are the differences between the responses observed at each input variable value and the corresponding prediction of the response computed using the response surface. Mathematically:

$$e_i = y_i - g(\underline{x}_i) \tag{10}$$

with y_i denoting the i^{th} response in the data set and $\underline{x}_i$ representing the vector of input variables.

If the response surface fits the data well, the residuals should approximate the random errors that make the relationship between the input variables and the output variable a statistical relationship. Therefore, random residual behavior is an indication that the response surface fits the data well. On the other hand, if a non-random structure is evident in the residuals, it is a clear sign that the response surface does not fit the data well.

A scatter plot is a useful way of examining residual behavior. If truly random, the residuals should be split 50-50 between positive and negative and should exhibit something resembling a normal distribution. The residuals also should not trend with observation order; i.e. residual size should not be a function of the experiment number. A histogram is one way to visually check the distribution shape of residuals. Another is a normal probability plot. This plot compares the empirical cumulative distribution function (CDF) against the CDF of a normal function with the same mean and standard deviation; a close fit indicates data that are distributed normally.

The response surface (Equation 6) has been compared against these metrics and the results are favorable. The coefficient of determination is high and the residuals exhibit good balance around zero and follow a normal distribution. The residuals are small and do not trend with observation order. Quantitative metrics are shown in
Table 6 and a graphical representation of the residuals is shown in Figure 6.

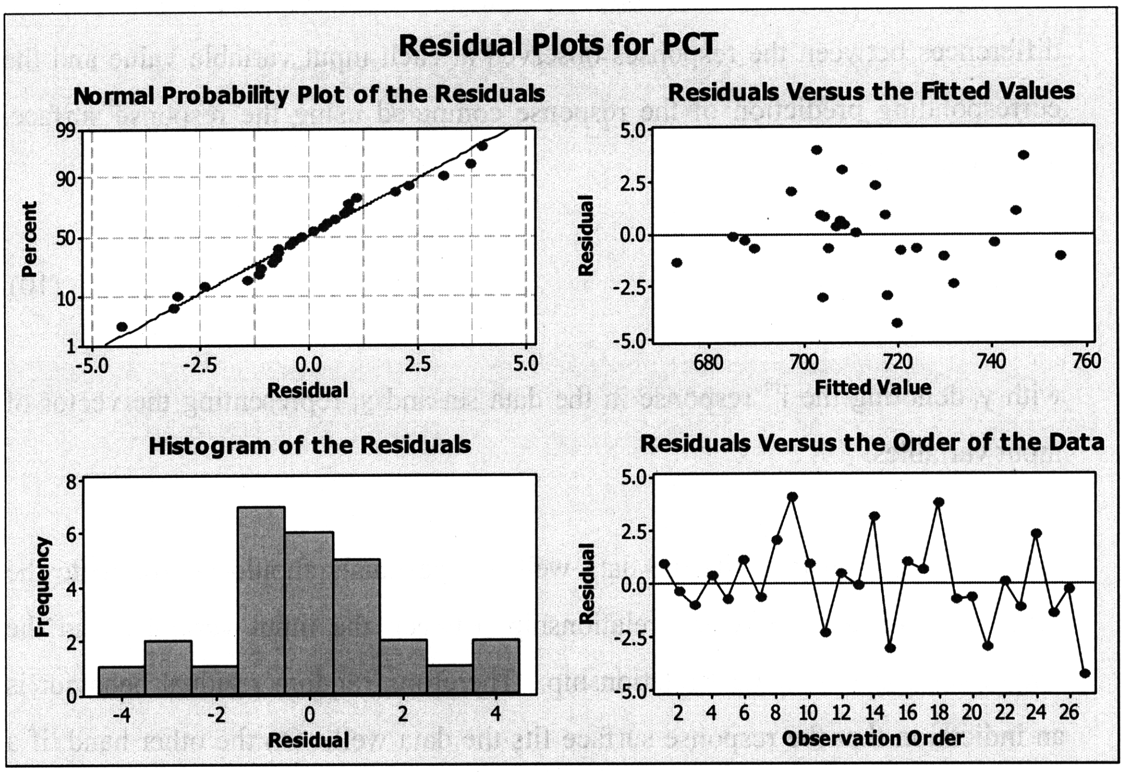

Figure 6 - Residual Plots

RS Criterion	Results / Observations
Small residuals	Average residual size was 1.5° C
Coefficient of determination	$R^2 = 0.985$ (out of 1.0)
Residuals are centered around zero	Residuals are well balanced: 14 are above zero and 13 are below zero

Table 6 - Response Surface Evaluation

For future steps in this analysis, the response surface was used as a substitute to replace RELAP5-3D simulations. Note that several terms in the response surface were observed to have low statistical significance, but their removal had no appreciable effect on the results of this paper and they were therefore retained.

9.2 Quantitative Reliability Assessment

The range of values used to develop a response surface is not necessarily based on values that are considered to be likely. For example, when used to support system design, the ranges may be based on values the designer feels are economically viable or able to meet design constraints. Consequently, we must perform some additional steps if we wish to use a response surface to assess system reliability.

First, we must take a slightly different approach to the selection of predictor variable ranges. In this case, we select each range based on the values we expect to see during system operation. The selection of this range is usually based on engineering judgment and may be supplemented by back-of-the-envelope calculations or simplified code runs to verify that these values are reasonable. It should be noted that these ranges may also be specific to the accident sequence under consideration. We may also choose variables that cannot be directly controlled by the system designer (e.g., RVACS inlet air temperature) but that we feel are likely to impact system performance.

This approach was used to select the predictor variables and the ranges listed in Table 5. Each range was chosen with the objective of enveloping the values that might be seen for the variables during an SBO event. Note that the choice of each range also expresses a degree of epistemic uncertainty with respect to the variables. For example, RVACS emissivity may vary according to manufacturing practices but it is expected to be no less than 0.65 and no greater than 0.85.

To quantify this uncertainty, probability distributions are assigned to each variable.

These distributions reflect the degree of epistemic uncertainty surrounding the value of each predictor variable and allow us to estimate system reliability by coupling the response surface to a Monte Carlo simulation.

Consistent with information available in the open literature, partial flow conditions such as leakage and blockage are modeled using the exponential distribution [2, 5, 6]. This reflects the assumption that the PSACS and RVACS are most likely unblocked and that the probability of a blockage decreases rapidly with its severity level. PSACS blockage is unlikely because it is a closed system and the RVACS blockage is unlikely because of its large inlet area. In addition, an effective foreign material exclusion program, consistent with industry best practices, would reduce the likelihood of RVACS and PSACS blockage.

PSACS and RVACS temperatures are modeled probabilistically using the truncated normal distribution. This decision is consistent with information available in the open literature and reflects the assumption that ambient temperatures are more likely to be near their mean value than extreme values [2].

A literature search did not identify previous probability density functions involving emissivity but material conditions are often modeled using the truncated normal distribution and this was therefore deemed acceptable [2].

When predictor variables take on values outside of those used to formulate a response surface, extrapolation (rather than interpolation) is required and substantial inaccuracies may occur. To avoid this pitfall, the upper and lower bounds of each range should be consistent with the extreme percentiles of the selected distributions. In addition, we must recognize that some distribution values may be possible mathematically but not physically. For example, PSACS water temperatures greater than 100 °C could be seen with a normal distribution but are not physically possible. In this case, the distributions are truncated and renormalized to avoid simulation of non-physical scenarios. This becomes particularly important when using a computer code that does not recognize values that fall outside of what is physically possible. For example, RELAP5-3D cannot model PSACS tube blockage of greater than 100%, as this would require a negative flow area.

Response Surface Uncertainty

An important step to be performed prior to Monte Carlo simulation is the addition of an error term to account for response-surface model uncertainty. A response surface is a model used to approximate the behavior of a T-H code. Like any model, there is a degree of uncertainty regarding its predictive capabilities. This uncertainty plays an important role when calculating system reliability because near misses may actually become failures when model uncertainty is taken into account. To account for this, we quantify the effect of the residuals by assigning them an appropriate probability distribution.

Because residuals are distributed in a somewhat normal fashion, we can account for their effect by adding an error term to each Monte Carlo simulation:

$$Y_i = Y_{i,RS} + e_i \tag{11}$$

where Y_i = Peak Clad Temperature for simulation i

$Y_{i,RS}$ = Peak Clad Temperature generated by response surface

e_i = Error term to account for response surface model uncertainty

The residuals under consideration have an important property: they follow a near normal distribution (Fig. 6). As a second check, MINITAB 14 was used to check the residuals against other types of distributions to verify that normal is the best choice. We can now assign an error term to account for response-surface uncertainty that is normally distributed:

$$e \sim N(\mu,\sigma) \tag{12}$$

The mean value of the error term, μ, is equal to the statistical mean of the residuals:

$$\mu = \bar{x} = \frac{\sum_i x_i}{n} = \frac{-0.001}{27} = -3.7\times10^{-5} \tag{13}$$

The standard deviation of the error term, σ, is equal to the statistical standard deviation of the residuals:

$$\sigma = s = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n-1}} = \sqrt{\frac{103.9}{26}} = 2.0 \tag{14}$$

The reliability of the PSACS-RVACS with two-out-of-four trains available was assessed by performing a Monte Carlo simulation and observing the percentage of simulations that met the PCT failure criterion. The simulation program Crystal Ball [23] was used to perform 10^6 simulations of an SBO event. Table 7 shows that that the reliability converges rather quickly and only about 10^4 simulations are needed, although performing more requires little extra time. Of the 10^6 simulations, approximately 110,000 resulted in PCT > 725°C indicating a PSACS-RVACS unreliability of 0.11. It should be emphasized that this value applies strictly to the case where only two-out-of-four PSACS trains are operational. A histogram displaying the results of this effort is shown in Figure 7.

Number of	**Reliability**

Simulations	
10^2	0.856
10^3	0.881
10^4	0.891
10^5	0.890
10^6	0.890

Table 7 - Convergence of Reliability Estimation

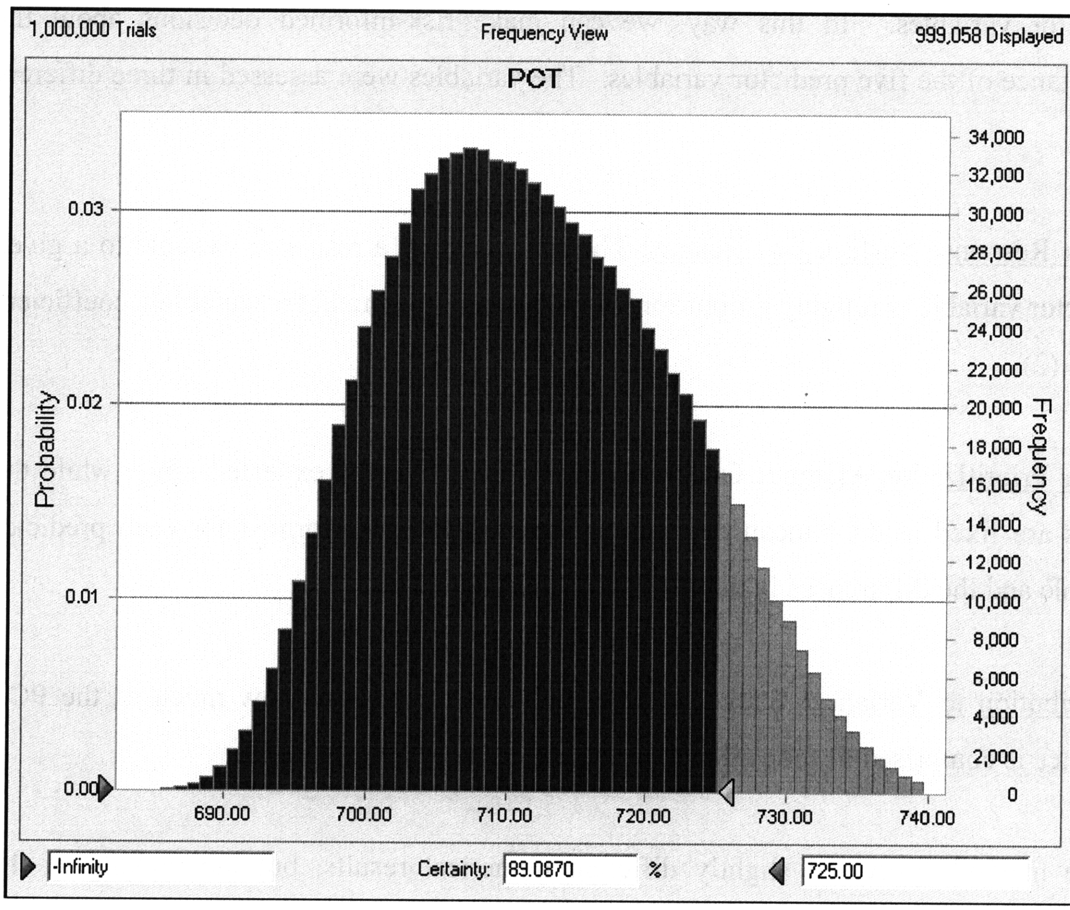

Figure 7 - PCT Histogram

As shown in Equation (4a), the overall system unreliability is the product of the probability that two trains are down and the remaining two trains experience functional failure. Using our numbers found previously we get a mean value of $(0.11)(4.0\text{x}10^{-6})$ = $4.4\text{x}10^{-7}$ and a 95th percentile of $(0.11)(1.4 \text{ x } 10^{-5}) = 1.54\text{x}10^{-6}$.

9.3 Sensitivity Study

In order to identify potential design improvements and/or to bound safe operating conditions it is useful to quantify the sensitivity of the response variable (PCT) to the predictor variables. In this way, we can make risk-informed decisions about the importance of the five predictor variables. The variables were assessed in three different ways.

Linear Response Surface Coefficients: The sensitivity of a response variable to a given predictor variable is roughly proportional to the size of the predictor variable's coefficient in Eq. (2).

Factor Prioritization Method: One variable is varied over its expected range while the others are fixed at their mean or central values. This is performed for each predictor variable and the differences in delta PCT are compared.

Contribution to Variance: Statistical tests are used to measure how much of the PCT variance is comprised of the variance regarding each predictor variable.

These methods provided slightly different numerical results, but the ranking of the parameters was similar. The results are displayed in Figure 8.

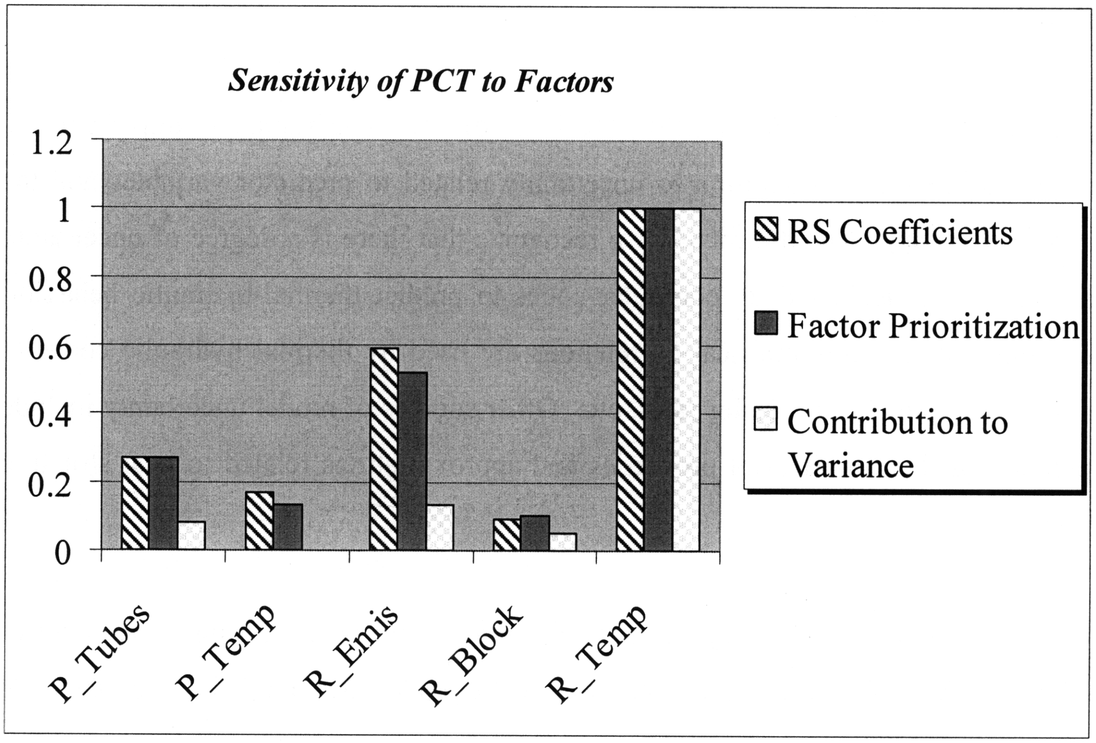

Figure 8 - Normalized Parameter Importance Ranking

These results provide insights that are useful to both the design and operation of the PSACS and RVACS. They show a strong sensitivity of PCT to RVACS inlet temperature indicating that the FCRR may be inappropriate for climates with consistently high temperatures. Another insight from this effort is that RVACS emissivity plays a substantial role in system performance. If design improvements are not practical, this factor should be carefully monitored by a robust QA program during the manufacturing process to ensure adequate emissivity and a long term aging management program should be implemented to ensure emissivity values do not degrade to unacceptable levels.

9.4 Model Uncertainty

Although not an explicit step in RSM, the issue of code uncertainty is important and should be considered. In addition to uncertainty related to predictor variables and the response surface approximation itself, we recognize that there is a degree of uncertainty inherent in the models used by computer codes to predict thermal-hydraulic behavior. Often, empirical or semi-empirical correlations are used by thermal hydraulic codes to determine flow rates, heat transfer rates, etc. Other sources of model uncertainty include interpolation of thermo-physical properties and approximations related to heat structure meshing.

Therefore, let us designate Y_{actual} the true PCT that would occur during a given set of conditions and Y_{code} the PCT predicted by a computer code. We can then define the code uncertainty related to a given simulation as [3, 24]:

$$\varepsilon_i = Y_{actual,i} - Y_{code,i} \tag{15}$$

One approach to this issue is to conduct experimental benchmarking tests. This is an important step in the APSRA methodology discussed in Section 1. In this case, we would perform a series of tests to compare Y_{actual} and Y_{code}. The values of ε obtained from these tests are similar to the residuals used to compare response surface results to code results. The same approach described in Section 9.2 can then be used to characterize a distribution that represents code uncertainty.

Lacking the capability for experimental benchmarking, we can examine the effect of code uncertainties by performing a sensitivity study. Although this will not identify the magnitude of code uncertainty, it will shed some light on its overall effect on reliability.

Let us assume that code uncertainty, ε, is normally distributed with a mean, μ_c, and a standard deviation, σ_c. Let us also account for response surface error by using Equation (11). Our true estimate for PCT then becomes:

$$Y_{actual} = Y_{RS} + e + \varepsilon \tag{16}$$

Note that we are now accounting for model uncertainty in both the response surface (e) and the code itself (ε). Ideally, this uncertainty should be quantified by comparing code predictions to experimental results. Such an analysis is beyond the scope of this paper. We note, however, that quantification of code uncertainty is part of the APSRA methodology [9]. This methodology identifies key drivers of code uncertainty that are specific to the design in question. This is important because previous studies have shown that the accuracy of best estimate codes such as RELAP5-3D varies depending on the application. For example, benchmarking experiments performed at MIT identified substantial discrepancies between code correlations and experimental data, particularly in transitional flow regimes of gas coolants [25]. Other studies involving comparisons of RELAP5-3D calculations to data from light water reactors have been more favorable [26]. Once these drivers are identified, experimental benchmarking can be used to quantify the amount of code error present under various conditions [24]. If enough experiments are performed, a histogram of ε can be created and a distribution fit to the data. This distribution is then combined with the PCT histogram to create an estimation of reliability that incorporates known code-based uncertainty drivers. This methodology may be preferable in situations where design changes are not possible and/or the addition of margin cannot be easily accomplished.

Since the quantification of code uncertainty is beyond our scope, we will attempt to draw insights from a sensitivity study. We examine the effect on system reliability of various combinations of mean and standard deviation for ε (performing a Monte Carlo simulation for each). These results are displayed in Figure 9.

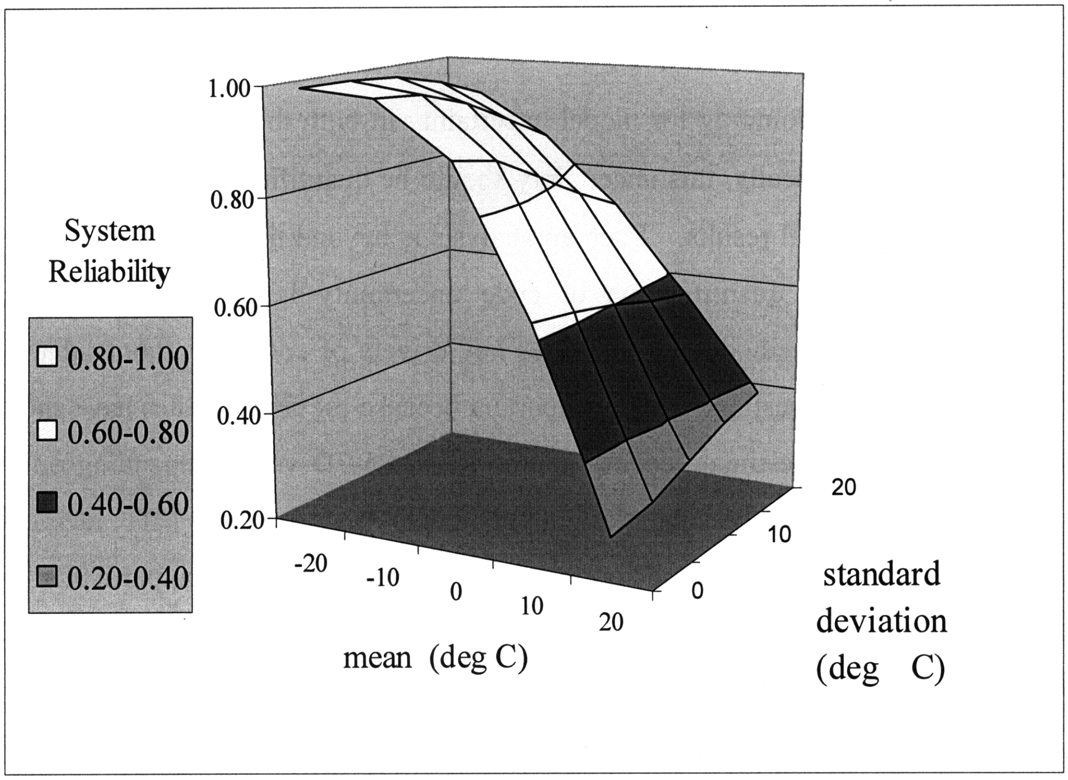

Figure 9 - The Effect of Code Uncertainty

Each point on the surface shown in Figure 9 represents a Monte Carlo simulation consisting of 10^5 trials. Each trial is of the form shown in Equation (16). The assumed mean (μ_c) and standard deviation (σ_c) of code error are represented by the x and y axes. Note that we are not supposing to know these values, but rather we are measuring their effect on reliability, which is shown on the z-axis. The value of reliability for each point is calculated by observing the fraction of trials that meet the success criteria of 725 °C. The legend to the left of the figure displays the ranges of reliability that are expected to occur for various combinations of μ_c and σ_c.

Figure 9 several useful insights. First, we observe that a negative code bias (mean value of $\varepsilon < 0$) only improves reliability slightly, while a positive code bias leads to a sharp decrease in reliability. The reason for this can be seen by observing the simulations that come close to the failure limit of 725°C in Figure 7. There is a sizable amount of "near misses" (PCT just below the limit) and the addition of code uncertainty changes many of these into failures. On other hand, there aren't many "near successes" and so although the addition of code uncertainty changes some of them into successes, the net effect on reliability is negative.

The second major insight is that system reliability in this case study is more sensitive to the mean value of ε than to its standard deviation. This suggests a risk-informed design strategy to reduce failure probability. During safety system design, computer simulations are used to test system performance and optimize design parameters such as heat exchanger size or pitch to diameter ratio. To account for uncertainty, the system designer selects values that provide margin between calculated system performance and failure criteria. By examining the slope of reliability with respect to μ_c, the designer can determine the sensitivity of system reliability to code uncertainty. A large slope indicates acute sensitivity to code uncertainty and provides motivation for experimental benchmarking and/or large design margin. By contrast, a smaller slope indicates that model uncertainty is less important, possibly justifying reduced margin and/or lack of benchmarking, which may allow for a more economic design.

10. CONCLUSIONS

The PSACS and RVACS safety systems play a vital role in FCRR accident mitigation. Therefore, these systems must be able to operate under a variety of conditions and each must perform its design function when called upon. Several phases of the FCRR project utilized risk insights. During the design phase, a risk-informed decision making process known as the ADP was used to facilitate the selection of a heat sink for the PSACS. Next, a fault tree model was used to select a valve configuration that would minimize the probability of PSACS failure. Finally, design verification was conducted by performing an uncertainty analysis to assess the performance of the PSACS and RVACS under a variety of T-H conditions. This effort led to several insights about safety system performance; most notably, that RVACS inlet temperature plays a very large role during an SBO event and that a design change to increase RVACS emissivity would be beneficial. Additional insights were gained by performing an investigation of two sources of model uncertainty: response surface and code.

By substituting a response surface for a T-H code, a certain degree of uncertainty is introduced. This uncertainty was quantified by examining the difference between values predicted by the code and those predicted by the response surface, also known as residuals. We accounted for these residuals by adding a normally distributed error term to each response surface simulation as shown in Equation (11).

Next, the issue of code uncertainty was addressed. An error term was used to account for code inaccuracies and their effect on system reliability. This allowed us to observe the relationship between code uncertainty and reliability. This relationship, displayed in Figure 9, identifies the sensitivity of reliability to code uncertainty and provides a quantitative metric for addressing this issue. This information can be used to choose between two approaches for code uncertainty treatment.

The first potential approach focuses on quantification of code uncertainty, as discussed in Section 9.4.

The second approach circumvents the issue of code-uncertainty quantification by implementing design improvements to increase PCT margin. The addition of model uncertainty reduces reliability because it pushes simulations close to 725°C over the failure criterion. In other words, it turns "close calls" into failures. Furthermore, because there are more simulations with PCT slightly below 725°C than slightly above 725°C, even a non-biased uncertainty term will reduce calculated reliability.

To address this issue, design improvements can be made to lower the probability of conditions that lead to a PCT near the failure limit. A great deal of effort has already been expended on improving RVACS performance. Design enhancements include the addition of a perforated plate in the air gap, a liquid metal within the gap between the reactor vessel and guard vessel, and the use of dimples on the guard vessel wall. On the other hand, the heat removal capacity of the PSACS could be improved with relatively inexpensive design changes. For example, the PCT with all factors set to their mean values was 714°C. A 25% increase in nominal PST volume lowers this value to 700°C, more than doubling margin. Improvements such as these would serve to offset code uncertainty and would therefore provide greater confidence in the analysis results.

In summary, the methodology described by this paper can be used to support both passive system design and reliability assessment. It provides a framework that can be applied to various types of passive safety systems and can therefore be used as a tool for both current and future reactor designs.

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12. APPENDICES

12.1 Appendix A – Valve Configuration Analysis and Supporting SAPHIRE 7 Calculations

The Passive Secondary Auxiliary Cooling System (PSACS) is a decay heat removal system described in Section 7 of the main body of this paper. Its design function is to remove decay heat during transients at a rate that maintains peak cladding temperature (PCT) below 725°C for at least 72 hours with no operator actions. The PSACS is classified as an IAEA Category C passive system because it requires no external initiation signal but does require several valves to change state [1]. The system contains four identical trains, each with 50% capacity and each coupled to a power conversion system (PCS) loop. One PSACS train is shown in Figure A.1.

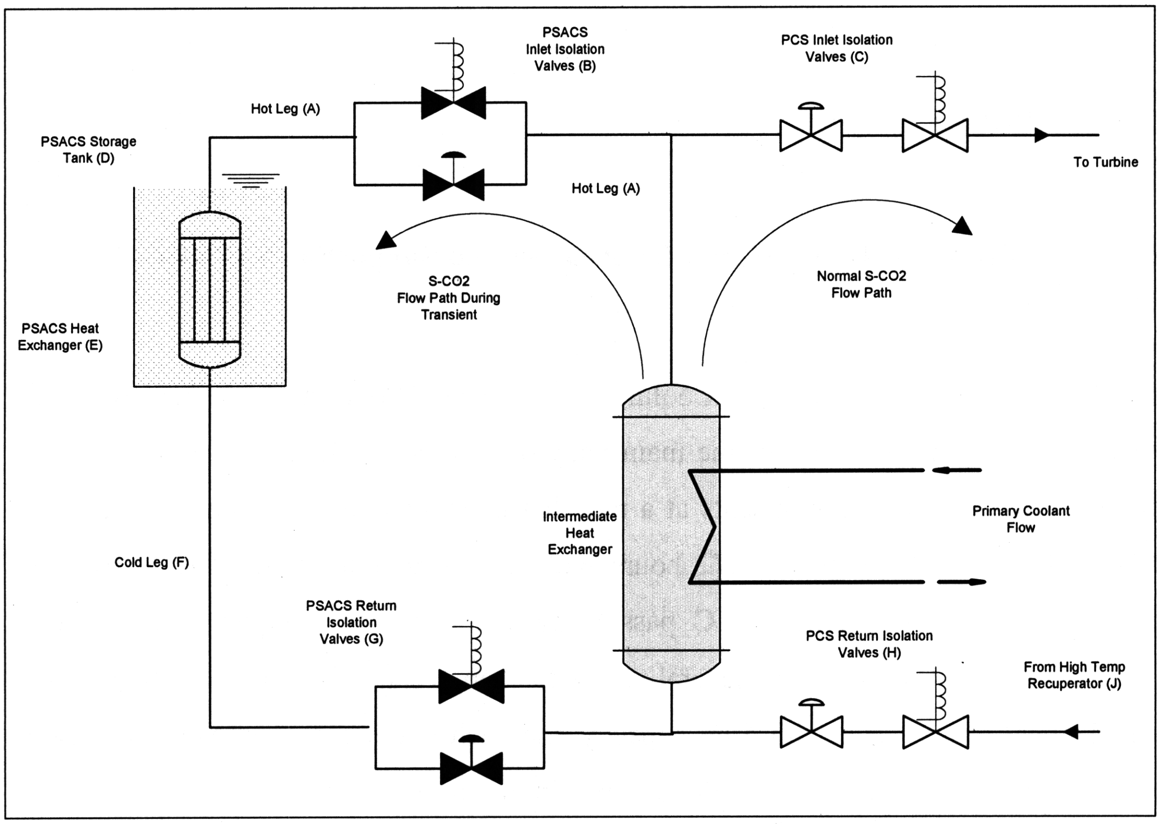

Figure A.1 – One PCS Loop and PSACS Train

The PSACS must be isolated during normal operations. This limits heat removal from the primary system and ensures that adequate inventory will be available in the PSACS Storage Tank (PST) by preventing boiling. Furthermore, each PCS loop must be isolated so as not to create a bypass around the PSACS. This concept is discussed in Section 8.3 of the main body of the thesis. Both the normal and transient S-CO_2 flow paths are shown in Figure A.1.

To support a risk-informed design effort, a fault tree of the PSACS was constructed using the code SAPHIRE 7. This fault tree captures the logic of the PSACS and PCS valve configurations and allows for a quantitative assessment of their reliability. It is displayed in Figure A.2

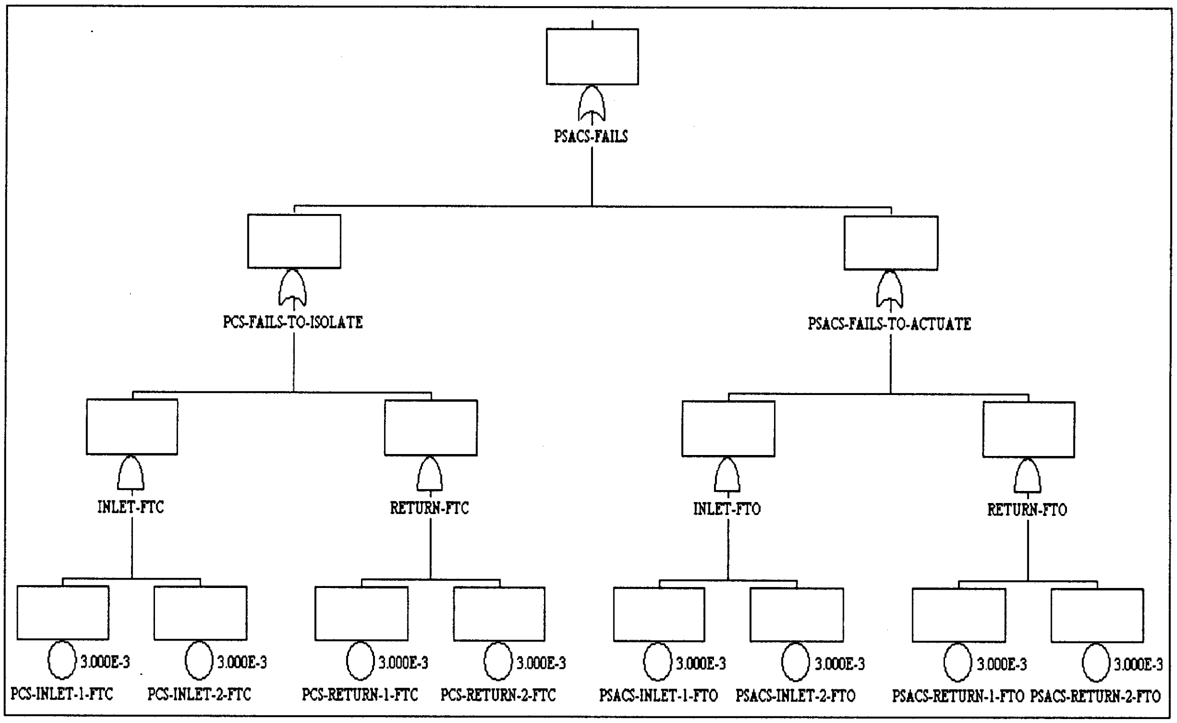

Figure A.2 – PSACS Train Fault Tree

The top level event, failure of a PSACS train, occurs when either the PSACS fails to actuate or the PCS fails to isolate. There are four ways this can occur and each requires the simultaneous failure of two valves. Table A.1 lists these valves and their location on Figure A.1. These failures can occur independently or due to common cause failure (CCF). CCF events are not displayed explicitly in Figure D.2 but are accounted for using the Beta Factor model. This methodology is discussed in Section 8.3 of the thesis.

Valve Pair	**Location in Figure A.1**
PSACS Inlet Isolation Valves	B
PSACS Return Isolation Valves	G
PCS Inlet Isolation Valves	C
PCS Return Isolation Valves	H

Table A.1 – Valve Failures that Disable a PSACS Train

In order to assess the probability of these valve failures, we needed the probability that a given valve would fail to open (PSACS) or close (PCS). No data for super critical CO_2 (S-CO_2) valves could be found, but we were able to locate data for both air and solenoid operated valves with several different working fluids.

Air Operated Valves		**Pr[fail to change state]**
Water/Steam	Mean	1×10^{-3}
	95^{th} percentile	4×10^{-2}
Sodium	Mean	3×10^{-3}
	95^{th} percentile	1×10^{-2}
Helium	Mean	1×10^{-4}
	95^{th} percentile	4×10^{-4}
Solenoid Operated Valves		
Water/Steam	Mean	5×10^{-4}
	95^{th} percentile	2×10^{-3}
Sodium	Mean	3×10^{-3}
	95^{th} percentile	1×10^{-2}
Helium	Mean	3×10^{-4}
	95^{th} percentile	1×10^{-3}

Table D.1 – Valve Reliability Data [16]

These data demonstrate that reliability is affected by the working fluid the valves are operating in. We selected conservatively the reliability numbers for sodium to use in our PSACS model because they bounded the other values. Consistent with the guidance contained in [16], the probability of valve failure is modeled as a lognormal distribution. A graph of this distribution is displayed as Figure A.2. Should reliability data for S-CO_2 valves become available in the future, it could easily be inserted into our fault tree model.

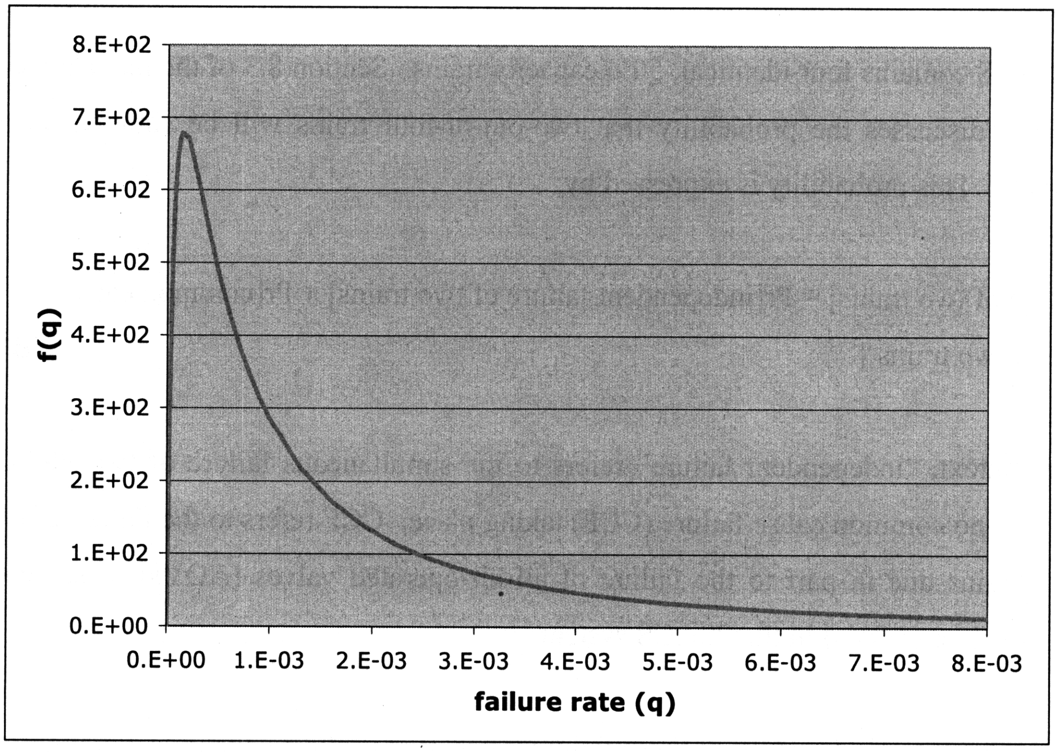

Figure A.2 – Probability Density Function of the Valve Failure Rate (per demand)

12.2 Appendix B – PSACS Valve Failure Probability Calculation

The PSACS contains four identical, 50% capacity trains. Section 8.3 of the main body of this thesis discusses the probability that two-out-of-four trains will be simultaneously inoperable. This probability is expressed by:

Pr[failure of two trains] = Pr[independent failure of two trains] + Pr[common cause failure of two trains] (B1)

In this context, "independent failure" refers to the simultaneous failure of two PSACS trains with no common cause failure (CCF) taking place. CCF refers to the failure of two PSACS trains due in part to the failure of all air-operated valves (AOVs) or solenoid operated valves (SOVs) in the PSACS system.

To get a clearer understanding of these failure types, it is useful to examine a diagram of the PSACS along with a list of the minimal cut sets for the failure of one PSACS train.

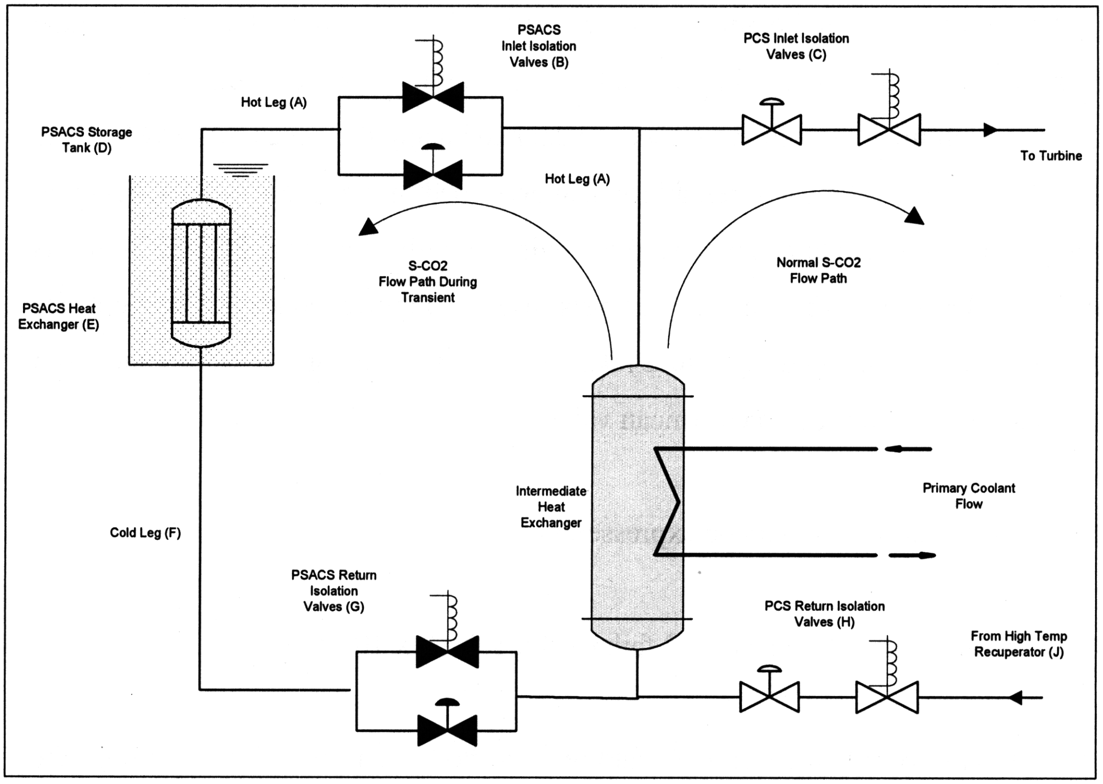

Figure B.1 – One PCS Loop and PSACS Train

Cut Set No.	Failures	Mean Probability
1	PSACS Inlet AOV and PSACS Inlet SOV	9×10^{-6}
2	PSACS Return AOV and PSACS Return SOV	9×10^{-6}
3	PCS Inlet AOV and PCS Inlet SOV	9×10^{-6}
4	PCS Return AOV and PCS Return SOV	9×10^{-6}
5	CCF –SOV and PSACS Inlet AOV	1.5×10^{-5}
6	CCF –SOV and PSACS Return AOV	1.5×10^{-5}
7	CCF –SOV and PCS Inlet AOV	1.5×10^{-5}
8	CCF –SOV and PCS Return AOV	1.5×10^{-5}
9	CCF-AOV and PSACS Inlet SOV	1.5×10^{-5}
10	CCF-AOV and PSACS Return SOV	1.5×10^{-5}
11	CCF-AOV and PCS Inlet AOV	1.5×10^{-5}
12	CCF-AOV and PCS Return AOV	1.5×10^{-5}

Table B.1 – PSACS Minimal Cut Sets

Each cut set represents a combination of valve failures that leads to the failure of a single PSACS train. Cut sets 1-4 contain only independent failures and cut sets 5-12 contain CCFs. The probabilities of each cut set were calculated using the codes SAPHIRE 7 and Crystal Ball, along with the valve reliability data described in Appendix A. The function of this appendix is to explain how the probability of failure of two PSACS trains is calculated. Therefore, although our analysis used computer codes to account for epistemic uncertainty surrounding failure rates and the Beta Factor, all values shown in these calculations are point estimates (mean values).

The probability of cut sets 1-4 can be expressed as:

Pr[1…4] = Pr[valve 1 fails] x Pr[valve 2 fails] = $3 \times 10^{-3} \cdot 3 \times 10^{-3} = 9 \times 10^{-6}$

The total probability of independent failure can be determined by summing the probabilities of cut sets 1-4. This approach, known as the minimal cut set upper bound approximation, is accurate provided that the probability of the top level event (in this case, failure of a PSACS train) is small.

Pr[independent failure of one train] = $4\ (9 \times 10^{-6}) = 3.6 \times 10^{-5}$

Since no CCF is present in these cut sets, we can express the probability that two trains fail in this way as simply:

Pr [independent failure of two trains] = (Pr[independent failure of one train])^2 = 1.3×10^{-9}

Cut sets 5-12 involve CCF and make use of the conservative Beta Factor model. Here, we are assuming that a fraction of all valve failures, β, results in CCF of all nominally identical valves in the PSACS. Based on common practice, β is assumed to be lognormally distributed with a mean value of 0.10 and an error factor of 3. Again, this is quite conservative because it assumes that, on average, the failure of one AOV or SOV results in the failure of all 15 other valves of that type in the PSACS system 10% of the time.

The probability of each cut set 5-8 can be expressed as:

Pr[5…8] = Pr [CCF of all SOVs] • Pr[any AOV in the train fails]

= β • Pr[any SOV in system fails] • Pr[any AOV the in train fails]

Similarly, the probability of each cut set 9-12 can be expressed as:

Pr[9…12] = Pr [CCF of all SOVs] • Pr[any AOV in the train fails]

= β • Pr[any SOV in system fails] • Pr[any AOV in the train fails]

To find the total probability of SOV CCF of one train, we sum the probabilities of cut sets 5-8:

$4\ (1.5 \times 10^{-5}) = 6 \times 10^{-5}$

Likewise, to find the total probability of AOV CCF of one train, we sum the probabilities of cut sets 5-8:

$4\ (1.5 \times 10^{-5}) = 6 \times 10^{-5}$

Cut sets 5-12 result in just one disabled train of PSACS; however, the remaining three trains have all AOVs or SOVs failed. Therefore, each of the remaining three trains is just one valve failure away from also becoming inoperable.

In either case, one failure of the opposite valve type will result in a second failed PSACS train. The PSACS contains four AOVs and four SOVs per train, for a total of 16 of each type. When one train has already failed, there are 12 AOVs and 12 SOVs in the remaining three trains. Given CCF of all SOVs (cut sets 5-8) only one AOV failure is needed to fail one of the remaining three PSACS trains. Conversely, if CCF of all AOVs has occurred (cut sets 9-12), then failure of one SOV in a remaining PSACS train results in that train being disabled.

Therefore, when one PSACS train has failed due to CCF, the probability that another train will fail is equal to the probability that at least one valve of the opposite type will fail somewhere in the remaining three trains. Since there are twelve such valves, we can express this probability using the binomial theorem:

$$\Pr[\text{at least one valve fails}] = 1 - \Pr[\text{no valves fail}] = 1 - (1 - q)^n$$

where n = the number of valves

q = the probability of valve failure

Using our valve reliability numbers, we obtain:

$$\Pr[\text{at least one valve fails}] = 1 - (1 - 3 \times 10^{-3})^{12} = 0.035$$

Therefore, any time a PSACS train fails due to CCF, there is a 3.5% chance that a second PSACS train will also fail. Plugging in our numbers from earlier, we have:

$$\Pr[\text{two trains fail due to AOV CCF}] = 6 \times 10^{-5} \bullet 0.035 = 2.1 \times 10^{-6}$$

$$\Pr[\text{two trains fail due to SOV CCF}] = 6 \times 10^{-5} \bullet 0.035 = 2.1 \times 10^{-6}$$

Finally, we write the total failure probability of two trains as the sum of the probability of independent failures and the two CCF scenarios:

$$\Pr\,[\text{two trains fail}] = 1.3 \times 10^{-9} + 2.1 \times 10^{-6} + 2.1 \times 10^{-6} \approx 4.2 \times 10^{-6}$$

Note that this value is a point estimate because we model q and β as point estimates. Using the codes SAPHIRE 7 and Crystal Ball allows us to model q and β as distributions to account for epistemic uncertainty surrounding their values. We then obtain a mean value of 4.0×10^{-6} and a 95th percentile of 1.4×10^{-5}.

12.3 Appendix C - Screened Predictor Variables

During development of the response surface, a number of predictor variables factors were analyzed and determined to be of negligible importance to the SBO case. It is important to note that while these factors were screened out, they may play an important role in other transients or design configurations. For example, when analyzing an unprotected transient, consideration of reactivity coefficients would be very important.

Input Parameter	**Basis for non-inclusion**
Core oxidation heat transfer resistance	Very low ΔT_{film}
PSACS heat exchanger fouling factor	Order of magnitude difference between enthalpy of H_2O and S-CO_2
Core roughness	Natural circulation of primary coolant is not an issue
Non-condensable gas buildup in PCS	PCS utilizes a non-condensing power cycle
Piping layout error	Head loss in IHX >> Head loss in piping
Heat loss through piping (missing or damaged insulation)	Captured by pipe-to-fluid heat transfer assessment
PSACS pipe roughness	Head loss in IHX >> Head loss in piping
IHX fouling factor	Large surface area of IHX – substantial margin
Partially failed PSACS isolation valve	Extremely low probability due to parallel configuration
Partially failed PCS isolation valve	Extremely low probability due to series configuration
Pressure loss due to PSACS leakage	RELAP5-3D simulations demonstrated effects to be very low
Reactivity Coefficients	Negligible effects due to SCRAM

Table C.1 –Screening Justifications

12.4 Appendix D – RELAP5-3D Input Deck

```
= 2400 Lead-cooled Reactor Model with PCS and PSACS
0000001 11
0000100 restart transnt
0000101 run
0000103 -1 reset
*-------------------------------------------------------------------
0000102          si          si
107 1 1 1
*-------------------------------------------------------------------
*
0000201   3.  1.0e-8 0.001  0007   100  20000   200000 * trancalc
0000202   200.  1.0e-8 0.01 0007   100  20000   200000 * trancalc
0000203   500.  1.0e-6 0.05 0007   100  20000   200000 * trancalc
0000204   1000.  1.0e-6 0.05  0007   100  20000   200000 * trancalc
0000205   10000.  1.0e-6 0.1  0007   1000  20000   200000 * trancalc
0000206   20000.  1.0e-6 0.1  0007   1000  20000   200000 * trancalc
0000207   50000.  1.0e-6 0.1  0007   1000  20000   200000 * trancalc
0000208   260000.  1.0e-6 0.1 0007   1000  20000   200000 * trancalc
**=======================================================================
=================*
**=======================================================================
=================*
20600000  expanded
**=======================================================================
=================*
**  TRIPS
**=======================================================================
=================*
**  ACTIVE
**=======================================================================
=================*
20605010  time  0  ge   null  0  0.      1      * rx trip
20605100  time  0  ge   null  0  0.000   1      * rx trip
20605950  time  0  ge   null  0  0.000   1      * trip pump
20603010  time  0  ge   null  0  0.000   1      * tdvlm pump
20604010  time  0  ge   null  0  0.000   1      * tdvlm pump
** decouple generators from grid
20606000  time  0  ge   null  0  0.000   1      * trip x1 generator
20607010  time  0  ge   null  0  0.000   1      * trip x3 generators
20607020  time  0  ge   null  0  0.000   1      * trip x3 generators
20607030  time  0  ge   null  0  0.000   1      * trip x3 generators
**
**
**
```

```
*** open gas cycle bypass valves (this line sets delay between LOEL and valve actuation
20606090  time  0  ge   timeof 600 0.000    n       * open PCB and turbine bypass valves
1x
20607090  time  0  ge   timeof 701 0.000    n       * open PCB and turbine bypass valves
3x
20608090  time  0  ge   timeof 702 0.000    n       * open PCB and turbine bypass valves
3x
20609090  time  0  ge   timeof 703 0.000    n       * open PCB and turbine bypass valves
3x
**
**
**==================================================================
================*
*Transient Conditions - scenario A
**==================================================================
================*
* determines how long to leave the inlet ihx valves open before reclosing - 323
* when timeof = 0.0, the valve remains closed
20605860  time 0  ge   timeof 609 100000.  n      * timer to reclose 1x inlet ihx vlvs
****
20605960  time 0  ge   timeof 709 100000.  n      * timer to reclose 3x inlet ihx vlvs
****
20605810  time 0  ge   timeof 809 0.000    n     * timer to reclose 3x inlet ihx vlvs
20605820  time 0  ge   timeof 909 0.000    n     * timer to reclose 3x inlet ihx vlvs
*
* determines how long to leave the outlet ihx valves open before reclosing - 324
* * when timeof = 0.0, the valve remains closed
20605890  time 0  ge   timeof 609 100000.  n      * timer to reclose 1x outlet ihx vlvs
****
20605990  time 0  ge   timeof 709 100000.  n      * timer to reclose 3x outlet ihx vlvs
****
20605910  time 0  ge   timeof 809 0.000    n     * timer to reclose 3x outlet ihx vlvs
20605920  time 0  ge   timeof 909 0.000    n     * timer to reclose 3x outlet ihx vlvs
**
**
**
**
* logical trips for gas cycle bypass valve opening and closing
20615860 609 and -586 n  * inlet ihx 1x - 323
20615960 709 and -596 n  * inlet ihx 3x - 423
20615810 809 and -581 n  * inlet ihx 3x - 223
20615820 909 and -582 n  * inlet ihx 3x - 123
20615890 609 and -589 n  * outlet ihx 1x - 324
20615990 709 and -599 n  * outlet ihx 3x - 424
20615910 809 and -591 n  * outlet ihx 3x - 224
20615920 909 and -592 n  * outlet ihx 3x - 124
```

```
*****************************************************************************
*********
*-----------------------------------------------------------------------------*
5950000  rcp1     pump
*-----------------------------------------------------------------------------*
*          area                    length           volume
5950101  1.332            2.05          0.0
*        azim angle   Incl angle       elevation       flags
5950102  0.00        -90.0          -2.05       00000
*       Suction junction                          flag
5950108  590000000 0.0     0.02      0.02   001000
*       Discharge jnction
5950109  500010004 0.0     0.02      0.02   001000
*       Suction junction diameter
5950110  0.65      0.00      1.00      1.00
5950111  0.65      0.00      1.00      1.00
*       Pump volume IC
*        ebt
5950200  3       8.80109E+05   751.650
*       Suction junction IC
5950201  1       173600.0  0.0  0.
*       Discharge jnction IC
5950202  1       173600.0  0.0  0.
*       Pump index and options
*               Westinghouse pump
*               |           two-phase option is not to be used
*               |       |        W(2)=-1 -> W(3)=-3
*               |       |        |        no pump motor torque table index
*               |       |        |        |        pump velocity table is entered
*               |       |        |        |        |        PUMP TRIP number index
*               |       |        |        |        |        |        no reverse
5950301   -2    -1    -3   -1    -1  595    0
*        Pump description
*               Rated pump velocity (rads/sec)
*               |                 Ratio of initial pump velocity to rated pump velocity
*               |                 |        Rated flow (m3/s)
*               |                 |        |        rated head (m)
*               |                 |        |        |
*5950302    102.77    .999474  17.087 8.76143
5950302    102.77    .999474  17.087 8.76143
*               Rated torque (N*m)
*               |                 Moment of inertia (kg*m2)
*               |                 |        Rated density (kg/m3)
*               |                 |        |                 Rated pump motor torque (N*m)
*               |                 |        |                 |
*5950303  1.45187E+05  28720.6 10160.     0.00
```

```
5950303  1.45187E+05  28720.6 10160.     0.00
*                Second frictional torque coefficient (N*m)
*                |        Constant frictional torque coefficient (N*m)
*                |        |                First frictional torque coefficient (N*m)
*                |        |                |        Third frictional torque coefficient (N*m)
*                |        |                |        |
5950304  1451.87  1451.87    0.00  0.00
**==============================================================
================
* Beginning of PSACS water-side model     - 1
*==============================================================
================*
*==============================================================
================*
* Beginning of PSACS water-side model
*==============================================================
================*
***=============================================================
=========$
*hydro          component name     component type
9410000            lwrplen            branch
*-------------------------------------------------------------------$
*        no. juns  vel/flow
9410001   2        1
*hydro         area             length            volume
9410101        28.27433388        1.0              0.0
*
*hydro       horz angle        vert angle          delta z
9410102        0.0              90.0             1.0
*
*hydro        roughness         hyd diam             fe
9410103        0.0              5.656854249               0
*
*hydro  ebt  pressure    tempe
9410200   3  2.e5      300.00
*        from       to        area      Kf    Kr   efvcahs
9411101   941010000 960000000 0.0       0.0   0.0  0001100
9412101   939010000 941010000 0.0       0.0   0.0  0001100
*        velf      velg     veli
9411201   0.0        0.0     0.0
9412201   0.0        0.0     0.0
*        hyd dia   beta      y-int    slope
9411110   0.0       0.00      1.00      1.00
9412110   0.0       0.00      1.00      1.00
**==============================================================
================*
```

```
9600000   htrcph     pipe
*---------------------------------------------------------------------------*
*        no. vols
9600001   10
*        vol area
9600101   1.3477723    10
*        length
9600301   0.4        10
*        volume
9600401   0.0        10
*        azim angle
9600501   0.0        10
*        incl angle
9600601   90.0       10
9600701   0.4       10
*        roughness hyd dia
9600801   4.572e-6  0.1751058   10
*        kf        kr
9600901   0.0       0.0       9
*        pvbfe
9601001   00000      10
*        fvcahs
9601101   001000     9
*        ebt
9601201    3  1.5E5   300.00     0.0      0. 0.    10
*        vel/flow
9601300   0
*        liquid    vapor    int-face
9601301   0.0       0.0       0.0       9
*hydro jun diam     beta  intercept slope    jun
9601401   0.1751058  0.0     1.0     1.0      9
*==================================================================
=================*
*hydro            component name      component type
9400000              inlet               sngljun
*---------------------------------------------------------------------------*
*hydro    from         to          area       f loss     r loss   vcahs
9400101   960010000    937000000   0.0        0.0        0.0    01100
*
*hydro    vel/flw      f flowrate     g flowrate      j flowrate
9400201   0            0.0            0.0          0.
*hydro    dhjun        beta          c           m
9400110   0.1751058    0.0           1.0         1.0
*
**===================================================================
========$
```

```
*hydro         component name     component type
9370000             upplen             pipe
*------------------------------------------------------------------------$
*       no. vols
9370001  8
*       vol area
9370101  28.27433388  8
*       length
9370301  1.0      8
*       volume
9370401  0.0      8
*       azim angle
9370501  0.0      8
*       incl angle
9370601  90.0     8
9370701  1.0      8
*       roughness hyd dia
9370801     0.0   6.0    8
*       kf       kr
9370901  0.0      0.0      7
*       pvbfe
9371001  00000    8
*       fvcahs
9371101  001000   7
*       ebt
9371201    3 1.5e5   300.00     0.0     0. 0.  1
9371202    3 1.1e5   300.00     0.0     0. 0.  8
*       vel/flow
9371300  0
*       liquid    vapor    int-face
9371301  0.0      0.       0.       7
*hydro jun diam      beta  intercept slope   jun
9371401  4.638663543  0.0     1.0     1.0   7
*===============================================================
================*
*hydro          component name     component type
9380000              inlet             sngljun
*--------------------------------------------------------------------------*
*hydro   from         to          area      f loss    r loss  vcahs
9380101  937000000   939000000   0.0       0.0       0.0   01100
*
*hydro   vel/flw      f flowrate     g flowrate     j flowrate
9380201  0            0.0            0.0         0.
*hydro   dhjun        beta           c           m
9380110  4.638663543    0.0          1.0         1.0
*
```

```
**==================================================================
========$
*hydro          component name     component type
9390000            maintube         annulus
*---------------------------------------------------------------------$
*       no. vols
9390001  4
*       vol area
9390101  26.8188  4
*       length
9390301  1.0      4
*       volume
9390401  0.0      4
*       azim angle
9390501  0.0      4
*       incl angle
9390601  -90.0     4
9390701  -1.0      4
*       roughness hyd dia
9390801     0.0   4.302037559 4
*       kf       kr
9390901  0.0      0.0      3
*       pvbfe
9391001  00000    4
*       fvcahs
9391101  001000   3
*       ebt
9391201    3 1.6e5   300.00     0.0     0. 0.   1
9391202    3 1.9e5   300.00     0.0     0. 0.   4
*       vel/flow
9391300  0
*       liquid   vapor    int-face
9391301  0.0      0.       0.        3
*hydro jun diam      beta  intercept slope    jun
9391401  4.302037559  0.0     1.0     1.0    3
*==================================================================
================*
9350000   source    tmdpvol
*
*--------------------------------------------------------------------------*
*       area              length         volume
9350101  100.              1.0            0.0
*       azim angle         incl angle      delta z
9350102  0.00              0.0            0.0
*       roughness          hyd dia        pvbfe
9350103  0.00000           0.0000         00010
```

```
*      ebt      trip        search var
9350200  003      0
*      indep var
*                          pressure (Pa) / temperature (K)
9350201   0.00    1.E5   300.00
*===============================================================
================*
*9360000   outlet    tmdpjun
*---------------------------------------------------------------------*
*hydro    from         to          area
*9360101  935010000    937000000   1.05
*      vel/flow  trip      search var
*9360200   1        0
*      indep var
* mass flow rate          liq.    gas     interface
*9360201    0.0      0.0      0.0      0.0
*9360202   0.0      0.0      0.0      0.0
*
**---------------------------------------------------------------------*
9360000              exit              sngljun
*---------------------------------------------------------------------*
9360101    937010000    935000000    0.001     100.0      100.0   01100
9360201   0            0.0           0.0     0. *
9360110   0.0          0.0           1.0         1.0
*===============================================================
================*
*===============================================================
================*
**===============================================================
================
* Beginning of PSACS water-side model     - 2
*===============================================================
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*===============================================================
================*
* Beginning of PSACS water-side model
*===============================================================
================*
***===============================================================
=========$
*hydro           component name     component type
9110000             lwrplen             branch
*-----------------------------------------------------------$
*        no. juns  vel/flow
9110001   2        1
*hydro           area            length            volume
```

```
9110101        28.27433388        1.0              0.0
*
*hydro     horz angle       vert angle        delta z
9110102        0.0             90.0            1.0
*
*hydro      roughness        hyd diam            fe
9110103       0.0              6.0              0
*
*hydro  ebt  pressure    tempe
9110200  3  2.e5      300.00
*       from      to       area     Kf    Kr   efvcahs
9111101   911010000 961000000 0.0      0.0   0.0  0001100
9112101   909010000 911010000 0.0      0.0   0.0  0001100
*       velf     velg    veli
9111201  0.0       0.0     0.0
9112201  0.0       0.0     0.0
*       hyd dia   beta     y-int    slope
9111110  0.0      0.00      1.00      1.00
9112110  0.0      0.00      1.00      1.00
**============================================================
================*
9610000  htrcph     pipe
*-------------------------------------------------------------------------*
*       no. vols
9610001  10
*       vol area
9610101  1.23636    10
*       length
9610301  0.4       10
*       volume
9610401  0.0       10
*       azim angle
9610501  0.0       10
*       incl angle
9610601  90.0      10
9610701  0.4       10
*       roughness hyd dia
9610801  4.572e-6  0.1751058   10
*       kf       kr
9610901  0.0      0.0      9
*       pvbfe
9611001  00000     10
*       fvcahs
9611101  001000    9
*       ebt
9611201    3  1.5E5   300.00     0.0      0. 0.    10
```

```
*       vel/flow
9611300  0
*       liquid   vapor    int-face
9611301  0.0      0.0       0.0      9
*hydro jun diam      beta  intercept slope   jun
9611401  0.1751058  0.0     1.0     1.0     9
*=================================================================
================*
*hydro           component name     component type
9100000             inlet             sngljun
*---------------------------------------------------------------------------*
*hydro    from         to          area       f loss    r loss  vcahs
9100101  961010000   907000000  0.0        0.0       0.0    01100
*
*hydro   vel/flw      f flowrate     g flowrate     j flowrate
9100201  0             0.0             0.0          0.
*hydro   dhjun        beta          c           m
9100110  0.1751058   0.0           1.0         1.0
*
**================================================================
========$
*hydro           component name     component type
9070000             upplen            pipe
*-------------------------------------------------------------------$
*       no. vols
9070001  8
*       vol area
9070101  28.27433388  8
*       length
9070301  1.0       8
*       volume
9070401  0.0       8
*       azim angle
9070501  0.0       8
*       incl angle
9070601  90.0      8
9070701  1.0       8
*       roughness hyd dia
9070801      0.0   6.0    8
*       kf       kr
9070901  0.0       0.0      7
*       pvbfe
9071001  00000     8
*       fvcahs
9071101  001000    7
*       ebt
```

```
9071201   3 1.5e5   300.00    0.0     0. 0.   1
9071202   3 1.1e5   300.00    0.0     0. 0.   8
*      vel/flow
9071300  0
*      liquid   vapor    int-face
9071301  0.0       0.        0.        7
*hydro jun diam     beta  intercept slope    jun
9071401  4.638663543  0.0     1.0     1.0    7
*==============================================================
================*
*hydro          component name     component type
9080000             inlet             sngljun
*---------------------------------------------------------------------------*
*hydro    from         to          area      f loss    r loss  vcahs
9080101  907000000    909000000   0.0       0.0       0.0    01100
*
*hydro    vel/flw      f flowrate    g flowrate     j flowrate
9080201  0           0.0           0.0         0.
*hydro    dhjun        beta          c           m
9080110  4.638663543    0.0          1.0         1.0
*
**==============================================================
========$
*hydro          component name     component type
9090000            maintube          annulus
*-------------------------------------------------------------------$
*       no. vols
9090001  4
*       vol area
9090101  26.8188  4
*       length
9090301  1.0       4
*       volume
9090401  0.0       4
*       azim angle
9090501  0.0       4
*       incl angle
9090601  -90.0      4
9090701  -1.0       4
*       roughness hyd dia
9090801      0.0    4.302037559 4
*       kf       kr
9090901  0.0       0.0       3
*       pvbfe
9091001  00000     4
*       fvcahs
```

```
9091101   001000   3
*      ebt
9091201   3 1.6e5   300.00     0.0     0. 0.  1
9091202   3 1.9e5   300.00     0.0     0. 0.  4
*      vel/flow
9091300  0
*      liquid   vapor   int-face
9091301  0.0     0.      0.      3
*hydro jun diam     beta  intercept slope   jun
9091401  4.302037559  0.0    1.0    1.0   3
*===================================================================
=================*
9050000   source   tmdpvol
*
*---------------------------------------------------------------------------*
*      area            length        volume
9050101  100.             1.0           0.0
*      azim angle        incl angle      delta z
9050102  0.00              0.0           0.0
*      roughness         hyd dia       pvbfe
9050103  0.00000           0.0000        00010
*      ebt      trip       search var
9050200  003       0
*      indep var
*                        pressure (Pa) / temperature (K)
9050201   0.00    1.E5   300.00
*---------------------------------------------------------------------------*
9060000            exit            sngljun
*---------------------------------------------------------------------------*
9060101   907010000   905000000   0.001   100.0     100.0   01100
9060201  0          0.0          0.0    0. *
9060110  0.0         0.0          1.0        1.0
*===================================================================
=================*
*===================================================================
=================*
***=================================================================
=========$
*hydro          component name     component type
9210000            lwrplen           branch
*-------------------------------------------------------------------$
*      no. juns  vel/flow
9210001   2       1
*hydro          area            length          volume
9210101        28.27433388        1.0             0.0
*
```

```
*hydro      horz angle       vert angle        delta z
9210102        0.0              90.0            1.0
*
*hydro       roughness        hyd diam           fe
9210103       0.0               6.0              0
*
*hydro  ebt  pressure    tempe
9210200  3  2.e5      300.00
*       from      to        area     Kf    Kr   efvcahs
9211101   921010000 962000000 0.0       0.0   0.0  0001100
9212101   919010000 921010000 0.0       0.0   0.0  0001100
*       velf      velg     veli
9211201   0.0       0.0     0.0
9212201   0.0       0.0     0.0
*       hyd dia   beta     y-int     slope
9211110   0.0       0.00      1.00      1.00
9212110   0.0       0.00      1.00      1.00
**=====================================================================
================*
9620000  htrcph     pipe
*----------------------------------------------------------------------------*
*       no. vols
9620001   10
*       vol area
9620101   1.23636    10
*       length
9620301   0.4        10
*       volume
9620401   0.0        10
*       azim angle
9620501   0.0        10
*       incl angle
9620601   90.0       10
9620701   0.4       10
*       roughness hyd dia
9620801   4.572e-6  0.1751058   10
*       kf       kr
9620901   0.0       0.0       9
*       pvbfe
9621001   00000      10
*       fvcahs
9621101   001000     9
*       ebt
9621201    3  1.5E5   300.00      0.0       0. 0.    10
*       vel/flow
9621300   0
```

```
*      liquid   vapor    int-face
9621301   0.0      0.0       0.0      9
*hydro jun diam      beta  intercept slope   jun
9621401   0.1751058  0.0     1.0     1.0     9
*===========================================================
================*
*hydro            component name     component type
9200000              inlet              sngljun
*---------------------------------------------------------------------------*
*hydro    from         to          area       f loss    r loss  vcahs
9200101   962010000    917000000   0.0       0.0       0.0    01100
*
*hydro    vel/flw     f flowrate    g flowrate    j flowrate
9200201   0            0.0           0.0         0.
*hydro    dhjun        beta          c          m
9200110   0.1751058    0.0           1.0        1.0
*
**==========================================================
========$
*hydro            component name     component type
9170000              upplen             pipe
*------------------------------------------------------------------$
*      no. vols
9170001   8
*      vol area
9170101   28.27433388  8
*      length
9170301   1.0       8
*      volume
9170401   0.0       8
*      azim angle
9170501   0.0       8
*      incl angle
9170601   90.0      8
9170701   1.0       8
*      roughness hyd dia
9170801      0.0    6.0     8
*      kf       kr
9170901   0.0      0.0      7
*      pvbfe
9171001   00000     8
*      fvcahs
9171101   001000    7
*      ebt
9171201    3 1.5e5   300.00     0.0     0. 0.   1
9171202    3 1.1e5   300.00     0.0     0. 0.   8
```

```
*       vel/flow
9171300  0
*       liquid   vapor    int-face
9171301  0.0      0.        0.       7
*hydro jun diam     beta  intercept slope    jun
9171401  4.638663543  0.0     1.0     1.0    7
*==================================================================
================*
*hydro          component name     component type
9180000              inlet              sngljun
*----------------------------------------------------------------------------*
*hydro    from          to          area      f loss    r loss  vcahs
9180101  917000000    919000000   0.0       0.0       0.0    01100
*
*hydro    vel/flw      f flowrate    g flowrate    j flowrate
9180201  0            0.0           0.0         0.
*hydro    dhjun        beta          c           m
9180110  4.638663543    0.0          1.0         1.0
*
**==================================================================
========$
*hydro          component name     component type
9190000            maintube          annulus
*-------------------------------------------------------------------$
*       no. vols
9190001  4
*       vol area
9190101  26.8188  4
*       length
9190301  1.0       4
*       volume
9190401  0.0       4
*       azim angle
9190501  0.0       4
*       incl angle
9190601  -90.0      4
9190701  -1.0       4
*       roughness hyd dia
9190801      0.0    4.302037559 4
*       kf       kr
9190901  0.0       0.0       3
*       pvbfe
9191001  00000     4
*       fvcahs
9191101  001000    3
*       ebt
```

```
9191201   3 1.6e5   300.00    0.0    0. 0.  1
9191202   3 1.9e5   300.00    0.0    0. 0.  4
*     vel/flow
9191300  0
*     liquid   vapor    int-face
9191301  0.0     0.      0.       3
*hydro jun diam     beta  intercept slope   jun
9191401   4.302037559  0.0    1.0    1.0   3
*================================================================
================*
9150000   source   tmdpvol
*
*------------------------------------------------------------------------*
*      area              length         volume
9150101   100.             1.0            0.0
*      azim angle        incl angle      delta z
9150102   0.00              0.0            0.0
*      roughness         hyd dia        pvbfe
9150103   0.00000           0.0000         00010
*      ebt       trip         search var
9150200   003       0
*      indep var
*                        pressure (Pa) / temperature (K)
9150201   0.00   1.E5   300.00
*------------------------------------------------------------------------*
9160000             exit            sngljun
*------------------------------------------------------------------------*
9160101   917010000   915000000   0.001    100.0     100.0   01100
9160201   0           0.0          0.0    0. *
9160110   0.0         0.0          1.0       1.0
*================================================================
================*
***===============================================================
=========$
*hydro          component name     component type
9310000            lwrplen           branch
*---------------------------------------------------------------$
*       no. juns  vel/flow
9310001   2        1
*hydro          area             length           volume
9310101          28.27433388        1.0              0.0
*
*hydro      horz angle         vert angle         delta z
9310102          0.0              90.0             1.0
*
*hydro       roughness          hyd diam            fe
```

```
9310103       0.0           6.0           0
*
*hydro  ebt  pressure    tempe
9310200  3  2.e5      300.00
*      from      to      area    Kf   Kr   efvcahs
9311101   931010000 963000000 0.0      0.0   0.0  0001100
9312101   929010000 931010000 0.0      0.0   0.0  0001100
*      velf      velg    veli
9311201   0.0      0.0    0.0
9312201   0.0      0.0    0.0
*      hyd dia   beta     y-int    slope
9311110   0.0      0.00     1.00     1.00
9312110   0.0      0.00     1.00     1.00
**==============================================================
================*
9630000  htrcph     pipe
*--------------------------------------------------------------------------*
*      no. vols
9630001  10
*      vol area
9630101  1.23636   10
*      length
9630301  0.4       10
*      volume
9630401  0.0       10
*      azim angle
9630501  0.0       10
*      incl angle
9630601  90.0      10
9630701  0.4       10
*      roughness hyd dia
9630801  4.572e-6 0.1751058  10
*      kf       kr
9630901  0.0      0.0      9
*      pvbfe
9631001  00000     10
*      fvcahs
9631101  001000    9
*      ebt
9631201   3  1.5E5  300.00    0.0     0. 0.   10
*      vel/flow
9631300  0
*      liquid    vapor    int-face
9631301  0.0      0.0       0.0      9
*hydro jun diam     beta  intercept slope   jun
9631401  0.1751058  0.0    1.0    1.0     9
```

```
*=============================================================
================*
*hydro         component name     component type
9300000             inlet            sngljun
*------------------------------------------------------------------------*
*hydro   from        to          area       f loss    r loss  vcahs
9300101  963010000   927000000   0.0        0.0       0.0   01100
*
*hydro   vel/flw     f flowrate    g flowrate    j flowrate
9300201  0           0.0           0.0           0.
*hydro   dhjun       beta          c             m
9300110  0.1751058   0.0           1.0           1.0
*
**=============================================================
========$
*hydro         component name     component type
9270000            upplen            pipe
*------------------------------------------------------------------$
*       no. vols
9270001  8
*       vol area
9270101  28.27433388  8
*       length
9270301  1.0       8
*       volume
9270401  0.0       8
*       azim angle
9270501  0.0       8
*       incl angle
9270601  90.0      8
9270701  1.0       8
*       roughness hyd dia
9270801     0.0   6.0    8
*       kf       kr
9270901  0.0      0.0      7
*       pvbfe
9271001  00000    8
*       fvcahs
9271101  001000   7
*       ebt
9271201   3 1.5e5   300.00    0.0     0. 0.  1
9271202   3 1.1e5   300.00    0.0     0. 0.  8
*       vel/flow
9271300  0
*       liquid   vapor    int-face
9271301  0.0      0.       0.       7
```

```
*hydro jun diam     beta  intercept slope    jun
9271401  4.638663543  0.0     1.0     1.0    7
*==================================================================
=================*
*hydro           component name     component type
9280000            inlet             sngljun
*---------------------------------------------------------------------------*
*hydro    from         to          area      f loss    r loss  vcahs
9280101  927000000   929000000   0.0       0.0       0.0   01100
*
*hydro    vel/flw      f flowrate    g flowrate     j flowrate
9280201   0           0.0          0.0         0.
*hydro    dhjun        beta          c           m
9280110  4.638663543    0.0          1.0          1.0
*
**==================================================================
========$
*hydro           component name     component type
9290000            maintube          annulus
*----------------------------------------------------------------------$
*       no. vols
9290001  4
*       vol area
9290101  26.8188  4
*       length
9290301  1.0      4
*       volume
9290401  0.0      4
*       azim angle
9290501  0.0      4
*       incl angle
9290601  -90.0     4
9290701  -1.0      4
*       roughness hyd dia
9290801     0.0   4.302037559 4
*       kf       kr
9290901  0.0      0.0      3
*       pvbfe
9291001  00000    4
*       fvcahs
9291101  001000   3
*       ebt
9291201   3 1.6e5  300.00    0.0     0. 0.  1
9291202   3 1.9e5  300.00    0.0     0. 0.  4
*       vel/flow
9291300  0
```

```
*       liquid    vapor    int-face
9291301   0.0       0.        0.         3
*hydro jun diam       beta  intercept slope    jun
9291401   4.302037559   0.0     1.0     1.0    3
*================================================================
================*
9250000   source    tmdpvol
*
*------------------------------------------------------------------------*
*       area                length          volume
9250101   100.               1.0             0.0
*       azim angle          incl angle      delta z
9250102   0.00               0.0             0.0
*       roughness           hyd dia         pvbfe
9250103   0.00000            0.0000          00010
*       ebt       trip          search var
9250200   003        0
*       indep var
*                           pressure (Pa) / temperature (K)
9250201   0.00    1.E5    300.00
*------------------------------------------------------------------------*
9260000              exit              sngljun
*------------------------------------------------------------------------*
9260101   927010000    925000000    0.001     100.0     100.0   01100
9260201   0            0.0           0.0     0. *
9260110   0.0          0.0           1.0        1.0
*================================================================
================*
*pass
**-----------------------------------------------------------------------
* turbine bypass valve 1x
3230000   inlet     valve
*------------------------------------------------------------------------*
3230101   305010000    312000000     .1       0.0       0.0   00100
3230201   0            0.            0.       0. * 0.
3230300   mtrvlv
3230301   1586    586    2.5    0.    306
**================================================================
================
3120000   hotduct1   pipe
*------------------------------------------------------------------------*
*       no. vols
3120001   1
*       vol area
3120101   0.2     1
*       length
```

```
3120301  2.0     1
*       volume
3120401  0.0     1
*       azim angle
3120501  0.00    1
*       incl angle
3120601  90.0    1
*       delta z
3120701  2.0     1
*       roughness hyd dia
3120801  0.0     0.54627    1
*       pvbfe
3121001  00000    1
*       fvcahs
*3121101  001000   2
*       ebt
*3121201  0    19250782.  872104. 872104. 1. 0. 1
*3121202  0    19250124.  872104. 872104. 1. 0. 2
3121201  0    13419192.  828592. 828592. 1. 0. 1
*=============================================================
========$
*hydro          component name     component type
3130000              upplen             branch
*------------------------------------------------------------------$
*       no. juns  vel/flow
3130001  2       0
*hydro          area            length            volume
3130101          0.35             0.5              0.0
*
*hydro       horz angle        vert angle          delta z
3130102          0.0            -90.0             -0.5
*
*hydro        roughness          hyd diam             fe
3130103          0.0             0.667558          0
*
*hydro  ebt  pressure     tempe
3130200  0  13418526.   822879. 822879. 1.
*       from      to       area     Kf   Kr   efvcahs
3131101  312010000 313000000 0.0      0.0   0.0  0001100
3132101  313010000 314000000 0.0      0.0   0.0  0001100
*       velf     velg    veli
3131201  1.022885-9 1.022885-9 0. * 1.85752-8
3132201  1.917845-8 1.917845-8 0. * 2.691416-8
*       hyd dia   beta     y-int    slope
3131110  0.0      0.00     1.00     1.00
3132110  0.0      0.00     1.00     1.00
```

```
*=========================================================================
================*
3140000   htrcpc     pipe
*-----------------------------------------------------------------------*
*       no. vols
3140001   10
*       vol area
3140101   0.0613274  10
*       length
3140301   0.4      10
*       volume
3140401   0.0      10
*       azim angle
3140501   0.0      10
*       incl angle
3140601   -90.0    10
*       roughness hyd dia
3140801     0.0    8.00E-03 10
*       kf      kr
3140901   0.0      0.0      9
*       pvbfe
3141001   00000    10
*       fvcahs
3141101   001000    9
*       ebt
3141201    3  1.97E7   773.31     0.0     0. 0.    10
*       vel/flow
3141300   1
*       liquid    vapor    int-face
3141301   0.0      0.0     0.    9
*hydro jun diam      beta  intercept slope   jun
3141401   8.00E-03   0.0     1.0     1.0     9
*=========================================================================
========$
*hydro           component name     component type
3160000              lwrplen             branch
*-----------------------------------------------------------------$
*       no. juns  vel/flow
3160001   2        0
*hydro          area             length             volume
3160101          0.35              0.5               0.0
*
*hydro        horz angle          vert angle          delta z
3160102          0.0              -90.0              -0.5
*
*hydro         roughness           hyd diam            fe
```

```
3160103      0.0            0.667558          0
*
*hydro  ebt  pressure     tempe
3160200  0  13452753.   775247. 775247. 1.
*      from      to       area      Kf   Kr    efvcahs
3161101   314010000 316000000 0.0       0.0   0.0   0001100
3162101   316010000 317000000 0.0       0.0   0.0   0001100
*      velf       velg     veli
3161201   -2.54965-8 -2.54965-8 0. * -3.85307-8
3162201   -1.513218-9 -1.513218-9 0. * -2.98207-8
*      hyd dia   beta     y-int     slope
3161110   0.0       0.00      1.00      1.00
3162110   0.0       0.00      1.00      1.00
*===================================================================
================*
3170000   htrcpc     pipe
*---------------------------------------------------------------------------*
*      no. vols
3170001   3
*      vol area
3170101   0.2      3
*      length
3170301   1.0      3       *1.666666667
*      volume
3170401   0.0      3
*      azim angle
3170501   0.0      3
*      incl angle
3170601   90.0     3
*      roughness hyd dia
3170801      0.0    0.504627      3
*      kf        kr
3170901   0.0       0.0       2
*      pvbfe
3171001   00000     3
*      fvcahs
3171101   001000     2
*      ebt
3171201    0  13452511.    775445.     775445.  1. 0.   1
3171202    0  13451545.    775422.     775422.  1. 0.   2
3171203    0  13450579.    775413.     775413.  1. 0.   3
*      vel/flow
3171300   0
*      liquid    vapor     int-face
3171301   -1.008844-9 -1.008844-9 0. 1 * -1.988044-8
3171302   -5.04444-10 -5.04444-10 0. 2 * -9.94011-9
```

```
*hydro jun diam      beta  intercept slope   jun
3171401   0.504627   0.0     1.0     1.0     2
*--------------------------------------------------------------------------*
* turbine bypass valve 1x
3240000   outlet     valve
*--------------------------------------------------------------------------*
3240101   317010000    395000000     .1       0.0       0.0   00100
3240201   0            0.            0.       0. * 0.
3240300   mtrvlv
3240301   1589    589    2.5    0.    306
*pass
**-------------------------------------------------------------------------
* turbine bypass valve 1x
2230000   inlet     valve
*--------------------------------------------------------------------------*
2230101   205010000    212000000     .1       0.0       0.0   00100
2230201   0            0.            0.       0. * 0.
2230300   mtrvlv
2230301   1581    581    2.5    0.    206
**=========================================================================
================
2120000   hotduct1   pipe
*--------------------------------------------------------------------------*
*       no. vols
2120001   1
*       vol area
2120101   0.2     1
*       length
2120301   2.0      1
*       volume
2120401   0.0      1
*       azim angle
2120501   0.00     1
*       incl angle
2120601   90.0      1
*       delta z
2120701   2.0      1
*       roughness hyd dia
2120801   0.0       0.54627     1
*       pvbfe
2121001   00000     1
*       fvcahs
*3121101   001000    2
*       ebt
*3121201   0     19250782.  872104. 872104. 1. 0. 1
*3121202   0     19250124.  872104. 872104. 1. 0. 2
```

```
2121201  0    13419192.  828592. 828592. 1. 0. 1
*===========================================================
========$
*hydro          component name     component type
2130000              upplen            branch
*------------------------------------------------------------------$
*       no. juns  vel/flow
2130001  2        0
*hydro          area            length            volume
2130101         0.35             0.5               0.0
*
*hydro       horz angle        vert angle          delta z
2130102         0.0            -90.0             -0.5
*
*hydro        roughness          hyd diam              fe
2130103        0.0               0.667558          0
*
*hydro  ebt  pressure     tempe
2130200  0  13418526.   822879. 822879. 1.
*       from      to        area     Kf   Kr   efvcahs
2131101  212010000 213000000 0.0      0.0   0.0  0001100
2132101  213010000 214000000 0.0      0.0   0.0  0001100
*       velf      velg     veli
2131201  1.022885-9 1.022885-9 0. * 1.85752-8
2132201  1.917845-8 1.917845-8 0. * 2.691416-8
*       hyd dia   beta     y-int    slope
2131110  0.0      0.00      1.00     1.00
2132110  0.0      0.00      1.00     1.00
*===========================================================
================*
2140000  htrcpc     pipe
*--------------------------------------------------------------------------*
*       no. vols
2140001  10
*       vol area
2140101  0.0613274  10
*       length
2140301  0.4      10
*       volume
2140401  0.0      10
*       azim angle
2140501  0.0      10
*       incl angle
2140601  -90.0     10
*       roughness hyd dia
2140801      0.0    8.00E-03 10
```

```
*       kf      kr
2140901  0.0      0.0      9
*       pvbfe
2141001  00000    10
*       fvcahs
2141101  001000    9
*       ebt
2141201   3  1.97E7   773.31     0.0     0. 0.   10
*       vel/flow
2141300  1
*       liquid   vapor    int-face
2141301  0.0      0.0    0.    9
*hydro jun diam      beta  intercept slope   jun
2141401   8.00E-03   0.0     1.0     1.0     9
*===================================================================
========$
*hydro          component name     component type
2160000              lwrplen              branch
*-------------------------------------------------------------------$
*       no. juns  vel/flow
2160001   2       0
*hydro          area            length            volume
2160101          0.35              0.5              0.0
*
*hydro        horz angle        vert angle          delta z
2160102          0.0             -90.0               -0.5
*
*hydro        roughness         hyd diam             fe
2160103          0.0             0.667558            0
*
*hydro  ebt  pressure     tempe
2160200  0  13452753.    775247. 775247. 1.
*       from       to        area     Kf    Kr    efvcahs
2161101   214010000 216000000 0.0       0.0   0.0   0001100
2162101   216010000 217000000 0.0       0.0   0.0   0001100
*       velf      velg     veli
2161201   -2.54965-8 -2.54965-8 0. * -3.85307-8
2162201   -1.513218-9 -1.513218-9 0. * -2.98207-8
*       hyd dia   beta      y-int    slope
2161110   0.0      0.00      1.00      1.00
2162110   0.0      0.00      1.00      1.00
*===================================================================
=================*
2170000   htrcpc     pipe
*--------------------------------------------------------------------------*
*       no. vols
```

```
2170001  3
*        vol area
2170101  0.2     3
*        length
2170301  1.0     3       *1.666666667
*        volume
2170401  0.0     3
*        azim angle
2170501  0.0     3
*        incl angle
2170601  90.0    3
*        roughness hyd dia
2170801     0.0   0.504627      3
*        kf       kr
2170901  0.0      0.0      2
*        pvbfe
2171001  00000    3
*        fvcahs
2171101  001000    2
*        ebt
2171201   0 13452511.    775445.    775445.  1. 0.   1
2171202   0 13451545.    775422.    775422.  1. 0.   2
2171203   0 13450579.    775413.    775413.  1. 0.   3
*        vel/flow
2171300  0
*        liquid    vapor    int-face
2171301   -1.008844-9 -1.008844-9 0. 1 * -1.988044-8
2171302   -5.04444-10 -5.04444-10 0. 2 * -9.94011-9
*hydro jun diam      beta  intercept slope    jun
2171401  0.504627   0.0     1.0     1.0     2
*---------------------------------------------------------------------------*
* turbine bypass valve 1x
2240000  outlet     valve
*---------------------------------------------------------------------------*
2240101  217010000    295000000     .1       0.0       0.0   00100
2240201  0           0.           0.       0. * 0.
2240300  mtrvlv
2240301  1591     591     2.5    0.   206*pass
**--------------------------------------------------------------------------
* turbine bypass valve 1x
1230000  inlet     valve
*---------------------------------------------------------------------------*
1230101  105010000    112000000     .1       0.0       0.0   00100
1230201  0           0.           0.       0. * 0.
1230300  mtrvlv
1230301  1582     582     2.5    0.   206
```

```
**=============================================================
================
1120000   hotduct1   pipe
*---------------------------------------------------------------------------*
*       no. vols
1120001   1
*       vol area
1120101   0.2     1
*       length
1120301   2.0      1
*       volume
1120401   0.0      1
*       azim angle
1120501   0.00     1
*       incl angle
1120601   90.0     1
*       delta z
1120701   2.0      1
*       roughness hyd dia
1120801   0.0      0.54627     1
*       pvbfe
1121001   00000     1
*       fvcahs
*3121101   001000    2
*       ebt
*3121201   0    19250782.  872104. 872104. 1. 0. 1
*3121202   0    19250124.  872104. 872104. 1. 0. 2
1121201   0    13419192.  828592. 828592. 1. 0. 1
*=============================================================
========$
*hydro           component name     component type
1130000              upplen            branch
*------------------------------------------------------------------$
*       no. juns  vel/flow
1130001   2        0
*hydro         area             length           volume
1130101         0.35             0.5              0.0
*
*hydro      horz angle          vert angle          delta z
1130102         0.0              -90.0            -0.5
*
*hydro       roughness          hyd diam            fe
1130103        0.0              0.667558          0
*
*hydro  ebt  pressure    tempe
1130200   0  13418526.   822879. 822879. 1.
```

```
*      from      to       area      Kf   Kr   efvcahs
1131101   112010000 113000000 0.0      0.0   0.0  0001100
1132101   113010000 114000000 0.0      0.0   0.0  0001100
*      velf      velg      veli
1131201   1.022885-9 1.022885-9 0. * 1.85752-8
1132201   1.917845-8 1.917845-8 0. * 2.691416-8
*      hyd dia   beta      y-int     slope
1131110   0.0      0.00      1.00      1.00
1132110   0.0      0.00      1.00      1.00
*===========================================================
================*
1140000   htrcpc     pipe
*---------------------------------------------------------------------------*
*      no. vols
1140001   10
*      vol area
1140101   0.0613274  10
*      length
1140301   0.4      10
*      volume
1140401   0.0      10
*      azim angle
1140501   0.0      10
*      incl angle
1140601   -90.0    10
*      roughness hyd dia
1140801      0.0    8.00E-03 10
*      kf        kr
1140901   0.0      0.0      9
*      pvbfe
1141001   00000     10
*      fvcahs
1141101   001000    9
*      ebt
1141201    3  1.97E7   773.31     0.0      0. 0.    10
*      vel/flow
1141300   1
*      liquid    vapor    int-face
1141301   0.0      0.0     0.    9
*hydro jun diam     beta  intercept slope    jun
1141401   8.00E-03   0.0     1.0     1.0    9
*===========================================================
========$
*hydro          component name     component type
1160000            lwrplen            branch
*------------------------------------------------------------------$
```

```
*       no. juns  vel/flow
1160001   2       0
*hydro        area            length          volume
1160101        0.35              0.5            0.0
*
*hydro      horz angle        vert angle        delta z
1160102        0.0              -90.0            -0.5
*
*hydro       roughness         hyd diam           fe
1160103        0.0              0.667558          0
*
*hydro  ebt  pressure    tempe
1160200  0  13452753.    775247. 775247. 1.
*       from       to       area     Kf    Kr    efvcahs
1161101   114010000 116000000 0.0      0.0   0.0   0001100
1162101   116010000 117000000 0.0      0.0   0.0   0001100
*       velf      velg     veli
1161201   -2.54965-8 -2.54965-8 0. * -3.85307-8
1162201   -1.513218-9 -1.513218-9 0. * -2.98207-8
*       hyd dia   beta      y-int     slope
1161110  0.0      0.00      1.00      1.00
1162110  0.0      0.00      1.00      1.00
*===========================================================================
================*
1170000   htrcpc     pipe
*----------------------------------------------------------------------------*
*       no. vols
1170001   3
*       vol area
1170101   0.2      3
*       length
1170301   1.0      3      *1.666666667
*       volume
1170401   0.0      3
*       azim angle
1170501   0.0      3
*       incl angle
1170601   90.0     3
*       roughness hyd dia
1170801     0.0    0.504627      3
*       kf       kr
1170901   0.0      0.0      2
*       pvbfe
1171001   00000     3
*       fvcahs
1171101   001000    2
```

```
*       ebt
1171201   0 13452511.    775445.    775445. 1. 0.   1
1171202   0 13451545.    775422.    775422. 1. 0.   2
1171203   0 13450579.    775413.    775413. 1. 0.   3
*       vel/flow
1171300  0
*       liquid   vapor    int-face
1171301  -1.008844-9 -1.008844-9 0. 1 * -1.988044-8
1171302  -5.04444-10 -5.04444-10 0. 2 * -9.94011-9
*hydro jun diam      beta  intercept slope   jun
1171401  0.504627   0.0     1.0     1.0    2
*------------------------------------------------------------------------*
* turbine bypass valve 1x
1240000  outlet     valve
*------------------------------------------------------------------------*
1240101  117010000    195000000    .1       0.0       0.0   00100
1240201  0            0.            0.       0. * 0.
1240300  mtrvlv
1240301  1592    592    2.5    0.   206
*pass
**------------------------------------------------------------------------
* turbine bypass valve 1x
4230000  inlet     valve
*------------------------------------------------------------------------*
4230101  405010000    412000000    .1       0.0       0.0   00100
4230201  0            0.            0.       0. * 0.
4230300  mtrvlv
4230301  1596    596    2.5    0.   406
**==========================================================================
================
4120000  hotduct1  pipe
*------------------------------------------------------------------------*
*       no. vols
4120001  1
*       vol area
4120101  0.2     1
*       length
4120301  2.0     1
*       volume
4120401  0.0     1
*       azim angle
4120501  0.00     1
*       incl angle
4120601  90.0     1
*       delta z
4120701  2.0     1
```

```
*       roughness hyd dia
4120801   0.0      0.54627    1
*       pvbfe
4121001   00000    1
*       fvcahs
*3121101   001000   2
*       ebt
*3121201   0     19250782.  872104. 872104. 1. 0. 1
*3121202   0     19250124.  872104. 872104. 1. 0. 2
4121201   0    13419192.  828592. 828592. 1. 0. 1
*===================================================================
========$
*hydro          component name     component type
4130000            upplen            branch
*-------------------------------------------------------------$
*       no. juns  vel/flow
4130001   2       0
*hydro         area            length           volume
4130101        0.35             0.5              0.0
*
*hydro      horz angle        vert angle         delta z
4130102        0.0            -90.0             -0.5
*
*hydro      roughness          hyd diam             fe
4130103        0.0             0.667558          0
*
*hydro  ebt  pressure    tempe
4130200   0  13418526.   822879. 822879. 1.
*       from       to        area      Kf    Kr   efvcahs
4131101   412010000 413000000 0.0       0.0   0.0  0001100
4132101   413010000 414000000 0.0       0.0   0.0  0001100
*       velf      velg     veli
4131201   1.022885-9 1.022885-9 0. * 1.85752-8
4132201   1.917845-8 1.917845-8 0. * 2.691416-8
*       hyd dia   beta     y-int     slope
4131110   0.0       0.00      1.00      1.00
4132110   0.0       0.00      1.00      1.00
*===================================================================
=================*
4140000   htrcpc     pipe
*---------------------------------------------------------------------*
*       no. vols
4140001   10
*       vol area
4140101   0.0613274  10
*       length
```

```
4140301  0.4    10
*       volume
4140401  0.0    10
*       azim angle
4140501  0.0    10
*       incl angle
4140601  -90.0   10
*       roughness hyd dia
4140801     0.0   8.00E-03 10
*       kf      kr
4140901  0.0     0.0     9
*       pvbfe
4141001  00000    10
*       fvcahs
4141101  001000    9
*       ebt
4141201    3  1.97E7   773.31     0.0     0. 0.    10
*       vel/flow
4141300  1
*       liquid   vapor    int-face
4141301  0.0      0.0    0.    9
*hydro jun diam     beta  intercept slope   jun
4141401  8.00E-03   0.0     1.0     1.0    9
*=================================================================
========$
*hydro          component name     component type
4160000              lwrplen            branch
*-----------------------------------------------------------------$
*       no. juns  vel/flow
4160001  2        0
*hydro          area            length            volume
4160101         0.35              0.5              0.0
*
*hydro       horz angle        vert angle         delta z
4160102         0.0               -90.0              -0.5
*
*hydro       roughness        hyd diam            fe
4160103        0.0               0.667558           0
*
*hydro  ebt  pressure    tempe
4160200  0  13452753.    775247. 775247. 1.
*       from      to       area     Kf   Kr    efvcahs
4161101  414010000 416000000 0.0      0.0  0.0   0001100
4162101  416010000 417000000 0.0      0.0  0.0   0001100
*       velf      velg     veli
4161201   -2.54965-8 -2.54965-8 0. * -3.85307-8
```

```
4162201   -1.513218-9 -1.513218-9 0. * -2.98207-8
*       hyd dia   beta     y-int    slope
4161110  0.0      0.00     1.00     1.00
4162110  0.0      0.00     1.00     1.00
*==========================================================================
================*
4170000  htrcpc     pipe
*------------------------------------------------------------------------*
*       no. vols
4170001  3
*       vol area
4170101  0.2      3
*       length
4170301  1.0      3       *1.666666667
*       volume
4170401  0.0      3
*       azim angle
4170501  0.0      3
*       incl angle
4170601  90.0     3
*       roughness hyd dia
4170801     0.0   0.504627      3
*       kf       kr
4170901  0.0      0.0      2
*       pvbfe
4171001  00000     3
*       fvcahs
4171101  001000    2
*       ebt
4171201    0  13452511.    775445.    775445.  1. 0.   1
4171202    0  13451545.    775422.    775422.  1. 0.   2
4171203    0  13450579.    775413.    775413.  1. 0.   3
*       vel/flow
4171300  0
*       liquid    vapor    int-face
4171301   -1.008844-9 -1.008844-9 0. 1 * -1.988044-8
4171302   -5.04444-10 -5.04444-10 0. 2 * -9.94011-9
*hydro jun diam      beta  intercept slope    jun
4171401   0.504627   0.0      1.0      1.0     2
*------------------------------------------------------------------------*
* turbine bypass valve 1x
4240000  outlet      valve
*------------------------------------------------------------------------*
4240101   417010000     495000000      .1       0.0        0.0   00100
4240201   0             0.             0.        0. * 0.
4240300   mtrvlv
```

```
4240301   1599    599    2.5   0.   406
*=======================================================================
================*
* Beginning of the CO2 side model
*=======================================================================
================*
***=====================================================================
=================
3000000   source   tmdpvol
*-----------------------------------------------------------------------*
*       area            length        volume
3000101   0.9             100.0          0.0
*       azim angle        incl angle     delta z
3000102   0.00              0.0           0.0
*       roughness         hyd dia        pvbfe
3000103   0.00000           0.0           00010  *1.07047
*       ebt       trip        search var
3000200   003       301
*       indep var
3000201   0.00    19.25e6   820.85  *
3000202   1.00    19.25e6   820.85  *
*=======================================================================
================*
3010000   makeup   tmdpjun
*-----------------------------------------------------------------------*
*       from      to       area
3010101   305010000 300000000 0.0
*       vel/flow  trip     search var
3010200   1        *301       cntrlvar  301
*       indep var
3010201   0.0      0.0     3189.1     0.0
3010202   0.5      0.0     0.0      0.0
3010203   100.     0.0     0.0      0.0
*=======================================================================
================*
3600000   source   tmdpvol
*-----------------------------------------------------------------------*
*       area            length        volume
3600101   0.9             10000.         0.0
*       azim angle        incl angle     delta z
3600102   0.00              0.0           0.0
*       roughness         hyd dia        pvbfe
3600103   0.00000           0.0000         00010
*       ebt       trip        search var
3600200   003       0
*       indep var
```

```
3600201   0.00   19.80e6  669.25
*==============================================================
=================*
3700000   inlet    tmdpjun
*-----------------------------------------------------------------------*
*hydro    from         to          area
3700101   360000000    395000000    0.9
*        vel/flow  trip      search var
3700200   1        0
*        indep var
3700201   0.0      0.0      3189.1    0.0
3700202   0.5      0.0      0.        0.0
3700203   100.0    0.0      0.        0.0
*
****============================================================
==================
2000000   source    tmdpvol
*-----------------------------------------------------------------------*
*        area              length         volume
2000101   0.9                100.0           0.0
*        azim angle          incl angle      delta z
2000102   0.00                0.0             0.0
*        roughness           hyd dia         pvbfe
2000103   0.00000             0.0             00010  *1.07047
*        ebt       trip        search var
2000200   003       301
*        indep var
2000201   0.00    19.25e6   820.85  *
2000202   1.00    19.25e6   820.85  *
*==============================================================
=================*
2010000   makeup    tmdpjun
*-----------------------------------------------------------------------*
*        from       to        area
2010101   205010000 200000000 0.0
*        vel/flow  trip      search var
2010200   1        *301       cntrlvar  301
*        indep var
2010201   0.0      0.0      3189.1     0.0
2010202   0.5      0.0      0.0       0.0
2010203   100.     0.0      0.0       0.0
**==============================================================
=================*
2600000   source    tmdpvol
*-----------------------------------------------------------------------*
*        area              length         volume
```

```
2600101  0.9            10000.          0.0
*        azim angle     incl angle      delta z
2600102  0.00           0.0             0.0
*        roughness      hyd dia         pvbfe
2600103  0.00000        0.0000          00010
*        ebt      trip  search var
2600200  003      0
*        indep var
2600201  0.00  19.80e6  669.25
*=================================================================
==================*
2700000  inlet  tmdpjun
*-------------------------------------------------------------------------*
*hydro  from       to          area
2700101  260000000  295000000  0.9
*        vel/flow  trip  search var
2700200  1         0
*        indep var
2700201  0.0    0.0    3189.1  0.0
2700202  0.5    0.0    0.0     0.0
2700203  100.0  0.0    0.0     0.0
*
****==============================================================
===================
1000000  source  tmdpvol
*-------------------------------------------------------------------------*
*        area           length          volume
1000101  0.9            100.0           0.0
*        azim angle     incl angle      delta z
1000102  0.00           0.0             0.0
*        roughness      hyd dia         pvbfe
1000103  0.00000        0.0             00010  *1.07047
*        ebt      trip  search var
1000200  003      301
*        indep var
1000201  0.00  19.25e6  820.85  *
1000202  1.00  19.25e6  820.85  *
*=================================================================
==================*
1010000  makeup  tmdpjun
*-------------------------------------------------------------------------*
*        from   to    area
1010101  105010000 100000000 0.0
*        vel/flow  trip   search var
1010200  1         *301   cntrlvar  301
*        indep var
```

```
1010201  0.0    0.0    3189.1    0.0
1010202  0.5    0.0    0.0    0.0
1010203  100.   0.0    0.0    0.0
*============================================================
================*
1600000  source  tmdpvol
*---------------------------------------------------------------------------*
*      area           length        volume
1600101  0.9            10000.          0.0
*      azim angle       incl angle     delta z
1600102  0.00            0.0           0.0
*      roughness        hyd dia       pvbfe
1600103  0.00000          0.0000        00010
*      ebt      trip       search var
1600200  003      0
*      indep var
1600201  0.00  19.80e6  669.25
*============================================================
================*
1700000  inlet   tmdpjun
*---------------------------------------------------------------------------*
*hydro   from        to          area
1700101  160000000   195000000   0.9
*      vel/flow  trip     search var
1700200  1       0
*      indep var
1700201  0.0     0.0     3189.1  0.0
1700202  0.5     0.0     0.0     0.0
1700203  100.0   0.0     0.0     0.0
*
****============================================================
==================
4000000  source  tmdpvol
*---------------------------------------------------------------------------*
*      area           length        volume
4000101  0.9            100.0         0.0
*      azim angle       incl angle     delta z
4000102  0.00            0.0           0.0
*      roughness        hyd dia       pvbfe
4000103  0.00000          0.0         00010  *1.07047
*      ebt      trip       search var
4000200  003      301
*      indep var
4000201  0.00   19.25e6   820.85  *
4000202  1.00   19.25e6   820.85  *
```

```
*=========================================================================
=================*
4010000   makeup   tmdpjun
*-----------------------------------------------------------------------*
*       from     to       area
4010101   405010000 400000000 0.0
*       vel/flow  trip     search var
4010200   1       *301       cntrlvar  301
*       indep var
4010201   0.0      0.0     3189.1     0.0
4010202   0.5      0.0     0.0      0.0
4010203   100.    0.0      0.0      0.0
**========================================================================
=================*
4600000   source   tmdpvol
*-----------------------------------------------------------------------*
*       area             length         volume
4600101   0.9              10000.           0.0
*       azim angle         incl angle      delta z
4600102   0.00              0.0             0.0
*       roughness          hyd dia        pvbfe
4600103   0.00000           0.0000        00010
*       ebt       trip        search var
4600200   003       0
*       indep var
4600201   0.00   19.80e6  669.25
*=========================================================================
=================*
4700000   inlet    tmdpjun
*-----------------------------------------------------------------------*
*hydro    from         to         area
4700101   460000000    495000000   0.9
*       vel/flow  trip     search var
4700200   1       0
*       indep var
4700201   0.0     0.0     3189.1   0.0
4700202   0.5     0.0     0.0      0.0
4700203   100.0   0.0     0.0      0.0
*
***************************** STRUCTURE 3141 *****************
*
*=====================================================================
*ht str ht.strs  m.pts  geom  init  l.coord  refl  b.vol
11141000   10     5   2    1   0.005280844     0
*
*      loc      flag
```

```
11141100 0       1
*
*     #      r
11141101 4       0.0070
*
*     compos.   #
11141201   3     4
*
*      source   #
11141301 0.0     4
*
*     temperature flag
11141400 0
*
*      temperature #
11141401 700.00    5
*
*      vol      inc      type     code     factor
11141501 114010000 10000   160       1      280.   10
*      vol      inc      type     code     factor
11141601 960010000 10000   111       1      280.   10
*
*
*      type     mult     D-lt      D-rt      #  *sour
11141701   0      0.0      0.0      0.0      10
*
11141800   1
*      Dhe  LHEf    LHEr    LGSf LGSr Kfwd Krev  Fboi  nclf povd  ff   #
11141801 0.0  10.0   10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   1
11141802 0.0  10.0   10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   5
11141803 0.0  10.0   10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   10
*
11141900   1
*      Dhe  LHEf    LHEr   LGSf  LGSr Kfwd  Krev  Fbo
11141901 0.0  10.0   10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.0   10
*
***************************** STRUCTURE 3141 ******************
*
*=======================================================
*ht str ht.strs  m.pts  geom  init  l.coord  refl  b.vol
12141000  10     5   2    1   0.005280844     0
*
*     loc     flag
12141100 0       1
*
*      #       r
```

```
12141101  4        0.0070
*
*     compos.   #
12141201   3      4
*
*      source    #
12141301  0.0      4
*
*     temperature flag
12141400  0
*
*      temperature #
12141401  700.00     5
*
*      vol      inc       type     code      factor
12141501  214010000  10000   160        1       280.   10
*      vol      inc       type     code      factor
12141601  961010000  10000   111        1       280.   10
*
*
*      type     mult     D-lt     D-rt      #  *sour
12141701   0       0.0       0.0       0.0       10
*
12141800   1
*      Dhe   LHEf    LHEr    LGSf LGSr Kfwd Krev  Fboi  nclf povd  ff    #
12141801  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   1
12141802  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   5
12141803  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   10
*
12141900   1
*      Dhe   LHEf    LHEr   LGSf  LGSr Kfwd  Krev  Fbo
12141901  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.0   10
*
**************************** STRUCTURE 3141 *****************
*
*=============================================================
*ht str ht.strs  m.pts  geom  init  l.coord  refl  b.vol
13141000   10     5   2    1   0.005280844     0
*
*     loc     flag
13141100  0        1
*
*       #        r
13141101  4        0.0070
*
*     compos.   #
```

```
13141201   3      4
*
*      source   #
13141301  0.0      4
*
*     temperature flag
13141400  0
*
*      temperature #
13141401  700.00     5
*
*      vol      inc       type     code      factor
13141501  314010000  10000   160       1       280.   10
*      vol      inc       type     code      factor
13141601  962010000  10000   111       1       280.   10
*
*
*      type     mult     D-lt      D-rt      #   *sour
13141701   0       0.0       0.0       0.0       10
*
13141800    1
*      Dhe  LHEf     LHEr     LGSf LGSr Kfwd Krev  Fboi  nclf povd  ff    #
13141801  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   1
13141802  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   5
13141803  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.   10
*
13141900    1
*      Dhe  LHEf     LHEr    LGSf  LGSr Kfwd  Krev  Fbo
13141901  0.0  10.0    10.0   10.0 10.0 0.0   0.0   1.0  4.0  3.0  1.0   10
*
**************************** STRUCTURE 3141 ******************
*
*============================================================
*ht str ht.strs  m.pts  geom  init  l.coord  refl  b.vol
14141000   10     5   2    1    0.005280844     0
*
*     loc     flag
14141100  0        1
*
*      #        r
14141101  4        0.0070
*
*     compos.   #
14141201   3      4
*
*      source   #
```

```
14141301 0.0     4
*
*     temperature flag
14141400 0
*
*      temperature #
14141401 700.00    5
*
*      vol      inc      type    code     factor
14141501 414010000 10000   160      1       280.  10
*      vol      inc      type    code     factor
14141601 963010000 10000   111      1       280.  10
*
*
*      type    mult    D-lt    D-rt    #  *sour
14141701  0      0.0     0.0     0.0     10
*
14141800   1
*      Dhe  LHEf    LHEr    LGSf LGSr Kfwd Krev  Fboi  nclf povd  ff   #
14141801 0.0 10.0   10.0  10.0 10.0 0.0  0.0  1.0 4.0 3.0 1.  1
14141802 0.0 10.0   10.0  10.0 10.0 0.0  0.0  1.0 4.0 3.0 1.  5
14141803 0.0 10.0   10.0  10.0 10.0 0.0  0.0  1.0 4.0 3.0 1.  10
*
14141900   1
*      Dhe  LHEf    LHEr   LGSf  LGSr Kfwd  Krev  Fbo
14141901 0.0 10.0   10.0  10.0 10.0 0.0  0.0  1.0 4.0 3.0 1.0  10
*=============================================================
================*
* approximate scram curve with 1 s delay
*=============================================================
================*
20299000        reac-t        501
20299001   0.0   0.0
20299002   1.0   0.0
20299003   1.5  -0.2
20299004   2.0  -0.5
20299005   2.5  -3.0
20299006   3.0  -8.4
$=============================================================
========
*---------------------------------------------------------------------------*
* decay power based on eugene's calculations for new core
*---------------------------------------------------------------------------*
20270600   power    510   1.0  1.0
*        time          p/po
20270601  -1.0          0.0
```

```
20270602   0.1          0.0589144
20270603   1.0          0.0551549
20270604   1.5          0.0536907
20270605   2.0          0.0524328
20270606   4.0          0.0487971
20270607   6.0          0.0464603
20270608   8.0          0.0447893
20270609   10.0         0.0435018
20270610   15.0         0.0411928
20270611   20.0         0.0395791
20270612   40.0         0.0357397
20270613   60.0         0.0334909
20270614   80.0         0.0319063
20270615   100.0        0.0307046
20270616   150.0        0.0286318
20270617   200.0        0.0272649
20270618   400.0        0.0242200
20270619   600.0        0.0224554
20270620   800.0        0.0211546
20270621   1000.0       0.0201120
20270622   1500.0       0.0181624
20270623   2000.0       0.0167732
20270624   4000.0       0.0137039
20270625   6000.0       0.0122575
20270626   8000.0       0.0114053
20270627   10000.0      0.0108279
20270628   15000.0      0.0099174
20270629   20000.0      0.0093461
20270630   40000.0      0.0080769
20270631   60000.0      0.0073531
20270632   80000.0      0.0068500
20270633   100000.0     0.0064680
20270634   150000.0     0.0057910
20270635   200000.0     0.0053224
20270636   400000.0     0.0042407
20270637   600000.0     0.0036697
20270638   800000.0     0.0033155
20270639   1000000.0    0.0030754
*==============================================================
========
*==============================================================
========
30000000 point separabl
*--------------------------------------------------------------------
*       fp-decay  power    rinit  beta/lambda fp-y  u239-y G-factor
30000001 gamma   2400.e6  -1.0e-60  666.67    1.0  1.e-60   0.
```

```
*      fp-type
*30000002  ans79-3    200.  0.0   0.0  1.0
*
30000011    990  * scram curve
30000012  10506  * radial expansion          * trancalc
30000013  10508  * crd expansion            * trancalc
* Coolant density coefficient
*        density  reactivity                     *cliff for LBE
*30000501  8707.2   0.5984605              * trancalc      -8.366
*30000502  9533.7   0.6315505              * trancalc       0.527
*30000503 10073.6    0.00                * trancalc       0.879
*30000504 10155.6   -0.0959595             * trancalc       0.703
*30000505 10276.1   -0.2369395             * trancalc       0.0
**30000506 10593.     0.1663  * extrapolated    * trancalc      -0.102
*        density    reactivity
30000501 7347.2    -7.6162502        * trancalc
30000502 9017.60   -0.4459169        * trancalc    -7.6162502
30000503 9574.40   0.1924165         * trancalc    -0.4459169
30000504 9797.12   0.2025009         * trancalc     0.1924165
30000505 9852.80   0.1831248         * trancalc     0.2025009
30000506 9908.48   0.1549898         * trancalc     0.1831248
30000507 9964.16   0.1180959         * trancalc     0.1549898
30000508 10019.84  0.0724432         * trancalc     0.1180959
30000509 10041.00  0.0527985          * trancalc    0.0724432
30000510 10055.48  0.0386287          * trancalc    0.0527985
30000511 10078.86  0.0144883          * trancalc    0.0386287
30000512 10092.22  0.0000000          * trancalc    0.0144883
30000513 10103.36  -0.0124589         * trancalc    0.0000000
30000514 10110.04  -0.0201025          * trancalc   -0.0124589
30000515 10136.77  -0.0519379          * trancalc   -0.0201025
30000516 10156.81  -0.0771388          * trancalc   -0.0519379
30000517 10186.88  -0.1170685          * trancalc   -0.0771388
30000518 10242.56  -0.1977569          * trancalc   -0.1170685
30000519 10298.24  -0.2872041          * trancalc   -0.1977569
30000520 10353.92  -0.3854102          * trancalc   -0.2872041
**                                   -0.3854102
* Doppler =-0.111 c/K ~as calculated by ES, ae=-0.117 c/K
*        temp     reactivity (includes thermal expansion)
*30000601  300.     0.0                  * trancalc
*30000602  1154.    -1.94712                  * trancalc      -1.05042
*30000603  1873.15   -3.586782  * extrapolated   * trancalc     -1.93497
*
* New Doppler 4.408620E-09x2-1.198005E-05x+0.02755847 + thermal expansion
30000601  300.00  0.0
30000602  400.00  -0.364056
30000603  600.00  -1.018691
```

```
30000604 900.00 -1.816951
30000605 1000.00 -2.034053
30000606 1200.00 -2.39478
30000607 1500.00 -2.752178
30000608 1600.00 -2.822326
30000609 1800.00 -2.889145
*
30000701  510010000  0  0.1454887  0.0
30000702  510020000  0  0.2473204  0.0
30000703  510030000  0  0.3330110  0.0
30000704  510040000  0  0.1986532  0.0
30000705  510050000  0  0.0753286  0.0
30000706  516010000  0  0.0000288  0.0
30000707  516020000  0  0.0000490  0.0
30000708  516030000  0  0.0000660  0.0
30000709  516040000  0  0.0000394  0.0
30000710  516050000  0  0.0000149  0.0
*
30000801  5101001  0  0.1454887  0.0
30000802  5101002  0  0.2473204  0.0
30000803  5101003  0  0.3330110  0.0
30000804  5101004  0  0.1986532  0.0
30000805  5101005  0  0.0753286  0.0
30000806  5161001  0  0.0000288  0.0
30000807  5161002  0  0.0000490  0.0
30000808  5161003  0  0.0000660  0.0
30000809  5161004  0  0.0000394  0.0
30000810  5161005  0  0.0000149  0.0
$=============================================================
========
* compute tfuel, tmod, and rhomod to check reactivity feedback
* use power squared weighting
*=============================================================
========$
*ctlvar    name    type    factor   init  f c   min   max
20505000   rhomod  sum     1.0      10089.6 1
*
*ctlvar  a0   a1   v1    p1     a2   v2    p2
20505001 0.0 0.1454887 rho 510030000 0.2473204 rho 510040000
20505002     0.3330110 rho 510050000 0.1986532 rho 510060000
20505003     0.0753286 rho 510070000 0.0000288 rho 516030000
20505004     0.0000490 rho 516040000 0.0000660 rho 516050000
20505005     0.0000394 rho 516060000 0.0000149 rho 516070000
*
*ctlvar    name    type    factor   init  f c   min   max
20505020   tmod    sum     1.0      798.15  1
```

```
*
*ctlvar   a0   a1  v1     p1        a2  v2       p2
20505021  0.0  0.1454887  tempf 510030000 0.2473204 tempf 510040000
20505022       0.3330110  tempf 510050000 0.1986532 tempf 510060000
20505023       0.0753286  tempf 510070000 0.0000288 tempf 516030000
20505024       0.0000490  tempf 516040000 0.0000660 tempf 516050000
20505025       0.0000394  tempf 516060000 0.0000149 tempf 516070000
*
*ctlvar     name   type    factor   init  f c    min    max
20505040    tfuel   sum     1.0     954.9   1
*
*ctlvar   a0   a1  v1     p1        a2  v2       p2
20505041  0.0  0.1454887  htvat  5101001  0.2473204  htvat  5101002
20505042       0.3330110  htvat  5101003  0.1986532  htvat  5101004
20505043       0.0753286  htvat  5101005  0.0000288  htvat  5161001
20505044       0.0000490  htvat  5161002  0.0000660  htvat  5161003
20505045       0.0000394  htvat  5161004  0.0000149  htvat  5161005
*
$==============================================================
========
* radial expansion feedback coefficient = -0.00135$/deg C; control on
* average moderator temperature  (-0.0023$/deg C used by Cliff)
* crd expansion feedback coefficient = 0.0 $/deg C
$==============================================================
========
*ctlvar     name    type    factor   init  f c    min    max
*20505050    tmodexp  sum      1.0     792.975 1            * Cliff
20505050    tmodexp  sum      1.0     798.15 1
*
*ctlvar   a0   a1  v1     p1        a2  v2       p2
20505051 0.0   0.20  tempf  510030000   0.20  tempf  510040000
20505052       0.20  tempf  510050000   0.20  tempf  510060000
20505053       0.20  tempf  510070000
*
*ctlvar     name    type    factor   init  f c    min    max
20505060    radexp   sum     1.0     -1.0775025  1
*20505060    radexp   sum     1.0     -1.83575 1
*
*ctlvar   a0   a1  v1     p1        a2  v2       p2
20505061 0.0 -0.00135  cntrlvar 505
*20505061 0.0 -0.0023  cntrlvar 505
*
*ctlvar     name    type    factor   init  f c    min    max
20505080    crdexp   constant 0.0
*
```

```
$=================================================================
========
* maximum clad temperature for transient limit; based on inner surface
$=================================================================
========
*ctlvar   name   type   factor  init  f c   min   max
20501010   mtclad  stdfnctn 1.0    903.11  1
*
*ctlvar  type  v1     p1          v2     p2
20501011  max   httemp  516100107    httemp  516100207
20501012       httemp  516100307    httemp  516100407
20501013       httemp  516100507
*
*ctlvar   name   type   factor  init  f c   min   max
20501020   tclad   sum     1.0     629.96  1
*
*ctlvar  a0   a1  v1     p1       a2  v2      p2
20501021 -273.15 1.0  cntrlvar 101
*
*ctlvar   name   type   factor  init  f c   min   max
20501030   maxclad  stdfnctn  1.0    647.63 1
*
*ctlvar  type  v1     p1          v2     p2
20501031  max   cntrlvar 102         cntrlvar 103
*
*ctlvar   name   type   factor  init  f c   min   max
20501040   terr   sum     1.0     20.04   1
*
*ctlvar  a0   a1  v1     p1       a2  v2      p2
20501041  0.0  1.0  cntrlvar 100      -1.0  cntrlvar  102      * fpsscalc
*
*ctlvar   name   type   factor  init  f c   min   max
*20507060   corepow  integral  5.e5    0.0   0 3   0.0   4000.e6
*
*ctlvar  v1      p1
*20507061  cntrlvar  704
*20507060   corepow  constant  6.5e6  * dpsscalc
*
*ctlvar   name   type   factor  init  f c   min   max
20501050   tabdecy  function  2400.e6  0.    0 0
*
20501051   time   0   706
*
*ctlvar   name   type   factor  init  f c   min   max
20501060   decayp  stdfnctn  1.0    131182320. 0 0
*
```

```
20501061    max    cntrlvar 105    rkgapow  0
*
20501070    core-w   sum     1.0     2.4+9   1
*
*ctlvar   a0   a1  v1     p1       a2  v2      p2
20501071  0.0  1.0  rkfipow  0        1.0  cntrlvar  106
*
*ctlvar    name    type    factor   init  f c    min   max
20501080    pramp   sum     1.0     1.+9   1 2        1000.e6   * fpsscal
*
*ctlvar   a0   a1  v1     p1       a2  v2      p2
20501081  0.0 1000.e5 time   0                            *fpsscalc
*
*ctlvar    name    type    factor   init  f c    min   max
20501100    fpower   stdfnctn  1.0     2.4+9   1 0
*
20501101    min     cntrlvar 107    cntrlvar 107
*
*ctlvar    name    type    factor   init  f c    min   max
20501120    core-mw  sum     1.0e-6  2400.  1
*
*ctlvar   a0   a1  v1     p1       a2  v2      p2
20501121   0.0   1.0  cntrlvar 110
*
* factor = 1/(hg - hfw); trying for 200 c superheat
*ctlvar    name    type    factor   init  f c    min   max
*20507140    mfw     sum    4.54965e-7 333.2525 1
*20507140    mfw     sum    4.73164e-7 0.0    1                *fpsscal
*20507140    mfw     sum    4.77713e-7 0.0    1                *fpsscal
*20507140    mfw     sum    4.76075e-7 333.2525 1
*
*ctlvar   a0   a1  v1     p1       a2  v2      p2
*20507141   0.0   1.0  cntrlvar 710                      *fpsscal
*********************************** RVACS
************************************
*===========================================================================
=================*
*********************************** RVACS
************************************
*===========================================================================
=================*
8000000   supply    tmdpvol
*---------------------------------------------------------------------------*
*       area            length        volume
8000101   1.e5             1.0            0.0
*       azim angle        incl angle     delta z
```

```
8000102   0.00            -90.0          -1.0
*         roughness        hyd dia       pvbfe
8000103   0.00000          0.0000        00010
*         ebt      trip       search var
8000200   004      0
*         indep var
8000201   0.00     1.e5    298.15  0.0
*=====================================================================
================*
*8000000   supply   tmdpvol
*-------------------------------------------------------------------------*
*         area             length         volume
*8000101   13.823          20.0           0.0
*         azim angle       incl angle     delta z
*8000102   0.00            -90.0          -20.0
*         roughness        hyd dia        pvbfe
*8000103   4.572e-5        0.8            00010
*         ebt      trip       search var
*8000200   004     0
*         indep var
*8000201   0.00    1.e5    310.93  0.0
*=====================================================================
================*
*hydro            component name     component type
8050000            inlet              sngljun
*-------------------------------------------------------------------------*
*hydro   from         to          area      f loss   r loss  vcahs
8050101  800010000    810000000   29.6566   0.5      1.0     01000
*
*hydro   vel/flw      f flowrate    g flowrate    j flowrate
8050201  0            2.415627      2.415627      0. * 83.7017
*hydro   dhjun        beta          c             m
8050110  1.6          0.0           1.0           1.0
*
*=====================================================================
================*
8100000   dwncmr   pipe
*-------------------------------------------------------------------------*
*         no. vols
8100001   15
*         vol area
8100101   29.6566  15  *~AN
*         length
8100301   1.0      1
8100302   1.0      11
8100303   1.3      13  *~AN
```

```
8100304  1.30    14
8100305  1.50    15
*      volume
8100401  0.0     15
*      azim angle
8100501  0.00    15
*      incl angle
8100601  -90.0   15
*      delta z
8100701  -1.0     1
8100702  -1.0    11
8100703  -1.3    13
8100704  -1.30   14
8100705  -1.50   15
*      roughness hyd dia
8100801  4.572e-5  1.6  15
*      pvbfe
8101001  00000    15
*      fvcahs
8101101  001000   14
*      ebt
8101201   6   100000.6  372429.   372429.    1. 1. 1
8101202   6   100012.   372577.5  372577.5   1. 1. 2
8101203   6   100023.4  372759.   372759.    1. 1. 3
8101204   6   100034.8  372950.   372950.    1. 1. 4
8101205   6   100046.2  373134.   373134.    1. 1. 5
8101206   6   100057.6  373339.6  373339.6   1. 1. 6
8101207   6   100069.   373535.   373535.    1. 1. 7
8101208   6   100080.3  373720.   373720.    1. 1. 8
8101209   6   100091.6  373894.4  373894.4   1. 1. 9
8101210   6   100103.   374059.   374059.    1. 1. 10
8101211   6   100114.3  374213.   374213.    1. 1. 11
8101212   6   100127.3  374398.5  374398.5   1. 1. 12
8101213   6   100142.   374567.   374567.    1. 1. 13
8101214   6   100156.8  374718.   374718.    1. 1. 14
8101215   6   100172.6  374868.   374868.    1. 1. 15
*      vel/flow
8101300  0
*      liquid   vapor   int-face
8101301   2.41721   2.41721  0.  1   * 83.7017
8101302   2.4186    2.4186   0.  2   * 83.7017
8101303   2.42037   2.42037  0.  3   * 83.7017
8101304   2.42224   2.42224  0.  4   * 83.7017
8101305   2.424035  2.424035 0.  5   * 83.7017
8101306   2.426067  2.426067 0.  6   * 83.7016
8101307   2.427984  2.427984 0.  7   * 83.7016
```

```
8101308   2.42979   2.42979  0.  8   * 83.7016
8101309   2.431477  2.431477 0.  9   * 83.7016
8101310   2.43305   2.43305  0.  10  * 83.7016
8101311   2.434506  2.434506 0.  11  * 83.7016
8101312   2.436273  2.436273 0.  12  * 83.7016
8101313   2.43781   2.43781  0.  13  * 83.7016
8101314   2.439142  2.439142 0.  14  * 83.7016
*                          jun
8101402  1.6    0.0    1.0    1.0    14
*
*=====================================================================
=================*
*hydro          component name     component type
8150000             turn              sngljun
*-----------------------------------------------------------------------------*
*hydro   from        to         area     f loss    r loss  vcahs
8150101  810010000   820000000  0.0       0.327    0.327  01000
*
*hydro   vel/flw     f flowrate    g flowrate    j flowrate
8150201  0          5.7248      5.7248         0. * 83.7016
*hydro   dhjun       beta         c          m
8150110  0.5       0.0          1.0        1.0
*
*=====================================================================
=================*
8200000  riser   pipe
*-----------------------------------------------------------------------------*
*      no. vols
8200001  15
*      vol area
8200101  12.6424  15
*      length
8200301  1.50    1
8200302  1.30    2
8200303  1.3     4
8200304  1.00    14
8200305  1.00    15
*      volume
8200401  0.0     15
*      azim angle
8200501  0.00    15
*      incl angle
8200601  90.0    15
*      delta z
8200701  1.50    1
8200702  1.30    2
```

```
8200703  1.3     4
8200704  1.00    14
8200705  1.00    15
*       roughness hyd dia
8200801  4.572e-5  0.475  15
*       pvbfe
8201001  00000     15
*       fvcahs
8201101  001000     14
*       ebt
8201201   6   100150.8  381796.    381796.     1.  1.  1
8201202   6   100133.5  387765.    387765.     1.  1.  2
8201203   6   100117.8  393644.    393644.     1.  1.  3
8201204   6   100102.5  399432.4  399432.4   1.  1.  4
8201205   6   100089.   403830.    403830.     1.  1.  5
8201206   6   100077.6  408175.    408175.     1.  1.  6
8201207   6   100066.4  412466.    412466.     1.  1.  7
8201208   6   100055.2  416703.    416703.     1.  1.  8
8201209   6   100044.3  420887.    420887.     1.  1.  9
8201210   6   100033.4  425024.    425024.     1.  1.  10
8201211   6   100022.8  428010.    428010.     1.  1.  11
8201212   6   100012.3  430921.4  430921.4   1.  1.  12
8201213   6   100002.   433128.    433128.     1.  1.  13
8201214   6   99992.    433005.    433005.     1.  1.  14
8201215   6   99982.1   432898.    432898.     1.  1.  15
*       vel/flow
8201300  0
*       liquid    vapor    int-face
8201301   5.90844   5.90844  0.  1   * 83.7016
8201302   6.06643   6.06643  0.  2   * 83.7016
8201303   6.22183   6.22183  0.  3   * 83.7016
8201304   6.37469   6.37469  0.  4   * 83.7016
8201305   6.49085   6.49085  0.  5   * 83.7016
8201306   6.60544   6.60544  0.  6   * 83.7016
8201307   6.71854   6.71854  0.  7   * 83.7016
8201308   6.83015   6.83015  0.  8   * 83.7016
8201309   6.94028   6.94028  0.  9   * 83.7016
8201310   7.04912   7.04912  0.  10   * 83.7016
8201311   7.12791   7.12791  0.  11   * 83.7026
8201312   7.20479   7.20479  0.  12   * 83.7042
8201313   7.26323   7.26323  0.  13   * 83.7058
8201314   7.26087   7.26087  0.  14   * 83.7069
*                              jun
8201402  0.475     0.0    1.0    1.0    14
*
```

```
*============================================================
================*
*hydro         component name     component type
8250000          outlet          sngljun
*-----------------------------------------------------------------------*
*hydro   from        to        area     f loss   r loss  vcahs
8250101  820010000   830000000   12.6424   0.0     0.0   01000
*
*hydro   vel/flw     f flowrate    g flowrate    j flowrate
8250201  0         7.25881     7.25881     0. * 83.7073
*hydro   dhjun       beta        c          m
8250110  0.475       0.0        1.0        1.0
*
*============================================================
================*
8300000   sink     tmdpvol
*-----------------------------------------------------------------------*
*      area             length        volume
8300101   56.            20.0          0.0
*      azim angle        incl angle     delta z
8300102   0.00            90.0          20.0
*      roughness         hyd dia       pvbfe
8300103   0.00000          4.2000        00010
*      ebt      trip       search var
8300200   004      0
*      indep var
8300201   0.00     1.e5    310.93  0.0
***********************************************************************
*************************** STRUCTURE 8201
***************************
* reactor and containment vessel walls; gap filled with lead bismuth
*============================================================
========$
*ht str ht.strs  m.pts  geom  init  l.coord  refl  b.vol   ax.incr.
18201000   16     13    2    1    4.920E+00 0
*
*     loc     flag
18201100  0       1
*
*      #       r
18201101  4       4.970E+00
18201102  2       5.000
18201103  6       5.100
*
*     compos.   #
18201201    3     4
```

```
18201202   6     6
18201203   3     12
*
*      source    #
18201301  0.0     12
*
*     temperature flag
18201400  0
*
*      temperature #
18201401  600.00     13
*
*      vol       inc       type     code      factor     #
18201501 500010000    0       1          1       1.500      1
18201502 580010000    0       1          1       1.300      2
18201503 580020000    10000    1          1       1.300      4
18201504 580040000    10000    1          1       1.000     14
18201505 580140000    10000    1          1       0.500     16
*
*      vol       inc       type     code      factor     #
18201601 820010000    0       1          1       1.500      1
18201602 820020000    0       1          1       1.300      2
18201603 820030000    10000    1          1       1.300      4
18201604 820050000    10000    1          1       1.000     14
18201605 820150000    0       1          1       0.500     16
*
*      type     mult     D-lt     D-rt     #  *source
18201701   0       0.0       0.0       0.0      16
*
18201800   1
*     Dhe  LHEf  LHEr LGSf  LGSr Kfwd  Krev  Fboil nclf povd ff   #
18201801 0.0  10.   10.  10.   10.  0.0   0.0   1.0   1.50 1.0  1.0  1
18201802 0.0  10.   10.  10.   10.  0.0   0.0   1.0  14.90 1.0  1.0  16
*
18201900   1
*     Dhe  LHEf  LHEr LGSf  LGSr Kfwd  Krev  Fboil nclf povd ff   #
18201901 0.0  10.   10.  10.   10.  0.0   0.0   1.0  16.4  1.0  2.5  16
*
**************************** STRUCTURE 8202
****************************
* collector cylinder wall
*=================================================================
========$
*ht str ht.strs  m.pts  geom  init  l.coord  refl  b.vol   ax.incr.
18202000   16      5   2    1   5.490    0
*
```

```
*       loc     flag
18202100  0       1
*
*       #       r
18202101  4       5.500
*18202102  1       3.604325
*
*       compos.   #
18202201   3      4
*18202202   5      5           *asbestos
*
*       source    #
18202301  0.0      4
*
*       temperature flag
18202400  0
*
*       temperature #
18202401  600.00     5
*
*       vol       inc      type     code     factor     #
18202501  820010000  0       1        1       1.50      1
18202502  820020000  0       1        1       1.30      2
18202503  820030000  10000   1        1       1.300     4
18202504  820050000  10000   1        1       1.00      14
18202505  820150000  0       1        1       0.50      16
*
*       vol       inc      type     code     factor     #
18202601  810150000  0       1        1       1.50      1
18202602  810140000  0       1        1       1.30      2
18202603  810130000  -10000  1        1       1.300     4
18202604  810110000  -10000  1        1       1.00      14
18202605  810010000  0       1        1       0.50      16
*
*       type     mult     D-lt     D-rt     #  *source
18202701  0       0.0      0.0      0.0      16
*
18202800   1
*       Dhe  LHEf  LHEr LGSf  LGSr Kfwd  Krev  Fboil nclf povd ff   #
18202801 0.0  10.   10.  10.   10.  0.0   0.0   1.0  16.4 1.0  2.0  16
*
18202900   1
*       Dhe  LHEf  LHEr LGSf  LGSr Kfwd  Krev  Fboil nclf povd ff   #
18202901 0.0  10.   10.  10.   10.  0.0   0.0   1.0  16.4 1.0  1.0  16
*
```

```
**************************** STRUCTURE 8203
****************************
* perforated plate
*==================================================================
========$
*ht str ht.strs  m.pts  geom  init  l.coord  refl  b.vol   ax.incr.
18203000  16     3   2    1   5.290   0
*
*     loc     flag
18203100  0       1
*
*      #        r
18203101  2       5.300
*
*     compos.   #
18203201   3      2
*
*      source    #
18203301  0.0      2
*
*     temperature flag
18203400  0
*
*      temperature #
18203401  600.00     3
*
*      vol      inc      type     code      factor      #
18203501  820010000  0      1        1       0.90      1
18203502  820020000  0      1        1       0.78      2
18203503  820030000  10000   1        1       0.78      4
18203504  820050000  10000   1        1       0.60      14
18203505  820150000  0      1        1       0.30      16
*
*      vol      inc      type     code      factor      #
18203601  820010000  0      1        1       0.90      1
18203602  820020000  0      1        1       0.78      2
18203603  820030000  10000   1        1       0.78      4
18203604  820050000  10000   1        1       0.60      14
18203605  820150000  0      1        1       0.30      16
*
*      type     mult     D-lt     D-rt     #  *source
18203701   0      0.0      0.0      0.0      16
*
18203800   1
*     Dhe  LHEf  LHEr LGSf  LGSr Kfwd  Krev  Fboil nclf povd ff  #
18203801 0.0  10.   10.  10.   10.  0.0   0.0   1.0  16.4 1.0  2.0  16
```

```
*
18203900   1
*     Dhe  LHEf  LHEr LGSf  LGSr Kfwd  Krev  Fboil nclf povd ff  #
18203901 0.0  10.   10.  10.   10.  0.0   0.0   1.0  16.4 1.0  2.0  16
*
*************************** radiation ********************************
*              nset
60000000          16
************************************************************************
*  from outer wall of containment vessel to inner wall of collector
************************************************************************
*       nrh   trmin  alpha  set
60100000  4     273.  0.0
*       htnum    jlr emis
60101001 8201001   1   0.75
60102001 8203001   0   0.75
60103001 8203001   1   0.75
60104001 8202001   0   0.75
*
* 1      view factor  surface
60101101    0.0          1   * F1-1
60101102    0.60         2   * F1-2
60101103    0.0          3   * F1-3
60101104    0.40         4   * F1-4
* 2
60102101    0.964083     1   * F2-1
60102102    0.035917     2   * F2-2
60102103    0.0          3   * F2-3
60102104    0.0          4   * F2-4
* 3
60103101    0.0          1   * F3-1
60103102    0.0          2   * F3-2
60103103    0.0          3   * F3-3
60103104    1.0          4   * F3-4
* 4
60104101    0.371585     1   * F4-1
60104102    0.0          2   * F4-2
60104103    0.579235     3   * F4-3
60104104    0.049180     4   * F4-4
*
*       nrh   trmin  alpha  set
60200000  4     273.  0.0    01
*       htnum    jlr emis
60201001 8201002   1   0.75
60202001 8203002   0   0.75
60203001 8203002   1   0.75
```

```
60204001 8202002  0  0.75
*
*       nrh  trmin  alpha  set
60300000  4    273.  0.0   01
*       htnum    jlr emis
60301001 8201003  1  0.75
60302001 8203003  0  0.75
60303001 8203003  1  0.75
60304001 8202003  0  0.75
*
*       nrh  trmin  alpha  set
60400000  4    273.  0.0   01
*       htnum    jlr emis
60401001 8201004  1  0.75
60402001 8203004  0  0.75
60403001 8203004  1  0.75
60404001 8202004  0  0.75
*
*       nrh  trmin  alpha  set
60500000  4    273.  0.0   01
*       htnum    jlr emis
60501001 8201005  1  0.75
60502001 8203005  0  0.75
60503001 8203005  1  0.75
60504001 8202005  0  0.75
*
*       nrh  trmin  alpha  set
60600000  4    273.  0.0   01
*       htnum    jlr emis
60601001 8201006  1  0.75
60602001 8203006  0  0.75
60603001 8203006  1  0.75
60604001 8202006  0  0.75
*
*       nrh  trmin  alpha  set
60700000  4    273.  0.0   01
*       htnum    jlr emis
60701001 8201007  1  0.75
60702001 8203007  0  0.75
60703001 8203007  1  0.75
60704001 8202007  0  0.75
*
*       nrh  trmin  alpha  set
60800000  4    273.  0.0   01
*       htnum    jlr emis
60801001 8201008  1  0.75
```

```
60802001 8203008  0  0.75
60803001 8203008  1  0.75
60804001 8202008  0  0.75
*
*      nrh  trmin alpha  set
60900000  4    273.  0.0   01
*      htnum   jlr emis
60901001 8201009  1  0.75
60902001 8203009  0  0.75
60903001 8203009  1  0.75
60904001 8202009  0  0.75
*
*      nrh  trmin alpha  set
61000000  4    273.  0.0   01
*      htnum   jlr emis
61001001 8201010  1  0.75
61002001 8203010  0  0.75
61003001 8203010  1  0.75
61004001 8202010  0  0.75
*
*      nrh  trmin alpha  set
61100000  4    273.  0.0   01
*      htnum   jlr emis
61101001 8201011  1  0.75
61102001 8203011  0  0.75
61103001 8203011  1  0.75
61104001 8202011  0  0.75
*
*      nrh  trmin alpha  set
61200000  4    273.  0.0   01
*      htnum   jlr emis
61201001 8201012  1  0.75
61202001 8203012  0  0.75
61203001 8203012  1  0.75
61204001 8202012  0  0.75
*
*      nrh  trmin alpha  set
61300000  4    273.  0.0   01
*      htnum   jlr emis
61301001 8201013  1  0.75
61302001 8203013  0  0.75
61303001 8203013  1  0.75
61304001 8202013  0  0.75
*
*      nrh  trmin alpha  set
61400000  4    273.  0.0   01
```

```
*       htnum    jlr emis
61401001 8201014  1  0.75
61402001 8203014  0  0.75
61403001 8203014  1  0.75
61404001 8202014  0  0.75
*
*       nrh  trmin alpha  set
61500000  4    273.  0.0   01
*       htnum    jlr emis
61501001 8201015  1  0.75
61502001 8203015  0  0.75
61503001 8203015  1  0.75
61504001 8202015  0  0.75
*
*       nrh  trmin alpha  set
61600000  4    273.  0.0   01
*       htnum    jlr emis
61601001 8201016  1  0.75
61602001 8203016  0  0.75
61603001 8203016  1  0.75
61604001 8202016  0  0.75
*
**ctlvar    name    type    factor   init  f c    min    max
20507210    anna    stdfnctn  1.0     873. 1
*
*ctlvar  type  v1     p1          v2     p2
20507211  max    httemp  516100107     httemp  516100207
20507212       httemp  516100307    httemp  516100407
20507213       httemp  516100507
*
20508210    gvtemp   stdfnctn  1.0     873. 1
*
*ctlvar  type  v1     p1          v2     p2
20508211  max    httemp      820100107    httemp      820100207
20508212        httemp      820100307   httemp      820100407
20508213        httemp      820100507   httemp      820100607
20508214        httemp      820100707   httemp      820100807
20508215        httemp      820100907   httemp      820101007
20508216        httemp      820101107   httemp      820101207
20508217        httemp      820101307   httemp      820101407
20508218        httemp      820101507
*
**ctlvar    name    type    factor   init  f c    min    max
20508220    rvtemp   stdfnctn  1.0     873. 1
*
*ctlvar  type  v1     p1          v2     p2
```

```
20508221  max   httemp    820100101   httemp    820100201
20508222        httemp    820100301   httemp    820100401
20508223        httemp    820100501   httemp    820100601
20508224        httemp    820100101   httemp    820100801
20508225        httemp    820100901   httemp    820101001
20508226        httemp    820101101   httemp    820101201
20508227        httemp    820101301   httemp    820101401
20508228        httemp    820101501
**$==============================================================
=========
* compute COLLAPSE LEVEL IN WATER TANK*
$==============================================================
========
**ctlvar   name   type   factor  init  f c   min   max
20509010   PSACS   sum    1.0     10.  1
*
*ctlvar  a0   a1  v1    p1      a2  v2     p2
20509011  0.0  1.00 voidf  941010000  0.40 voidf   960010000
20509012       0.40 voidf  960020000  0.40 voidf   960030000
20509013       0.40 voidf  960040000  0.40 voidf   960050000
20509014       0.40 voidf  960060000  0.40 voidf   960070000
20509015       0.40 voidf  960080000  0.40 voidf   960090000
20509016       0.40 voidf  960100000  1.00 voidf   937010000
20509017       1.00 voidf  937020000  1.00 voidf   937030000
20509018       1.00 voidf  937040000  1.00 voidf   937050000
20509019       1.00 voidf  937060000  1.00 voidf   937070000
*+           1.00 voidf  937080000  1.00 voidf   937090000
**$==============================================================
=========
* compute COLLAPSE LEVEL IN WATER TANK*
$==============================================================
========
**ctlvar   name   type   factor  init  f c   min   max
20509020   PSACS   sum    1.0     10.  1
*
*ctlvar  a0   a1  v1    p1      a2  v2     p2
20509021  0.0  1.00 voidf  911010000  0.40 voidf   961010000
20509022       0.40 voidf  961020000  0.40 voidf   961030000
20509023       0.40 voidf  961040000  0.40 voidf   961050000
20509024       0.40 voidf  961060000  0.40 voidf   961070000
20509025       0.40 voidf  961080000  0.40 voidf   961090000
20509026       0.40 voidf  961100000  1.00 voidf   907010000
20509027       1.00 voidf  907020000  1.00 voidf   907030000
20509028       1.00 voidf  907040000  1.00 voidf   907050000
20509029       1.00 voidf  907060000  1.00 voidf   907070000
*+           1.00 voidf  907080000  1.00 voidf   907090000
```

```
**$=============================================================
=========
* compute COLLAPSE LEVEL IN WATER TANK*
$=============================================================
========
**ctlvar    name    type    factor   init  f c    min    max
20509030    PSACS    sum     1.0        10.  1
*
*ctlvar   a0   a1  v1      p1        a2  v2       p2
20509031  0.0  1.00 voidf   921010000  0.40 voidf    962010000
20509032       0.40 voidf   962020000  0.40 voidf    962030000
20509033       0.40 voidf   962040000  0.40 voidf    962050000
20509034       0.40 voidf   962060000  0.40 voidf    962070000
20509035       0.40 voidf   962080000  0.40 voidf    962090000
20509036       0.40 voidf   962100000  1.00 voidf    917010000
20509037       1.00 voidf   917020000  1.00 voidf    917030000
20509038       1.00 voidf   917040000  1.00 voidf    917050000
20509039       1.00 voidf   917060000  1.00 voidf    917070000
*+          1.00 voidf   917080000   1.00 voidf    917090000
*
***$=============================================================
==========
* compute COLLAPSE LEVEL IN WATER TANK*
$=============================================================
========
**ctlvar    name    type    factor   init  f c    min    max
20509040    PSACS    sum     1.0        10.  1
*
*ctlvar   a0   a1  v1      p1        a2  v2       p2
20509041  0.0  1.00 voidf   931010000  0.40 voidf    963010000
20509042       0.40 voidf   963020000  0.40 voidf    963030000
20509043       0.40 voidf   963040000  0.40 voidf    963050000
20509044       0.40 voidf   963060000  0.40 voidf    963070000
20509045       0.40 voidf   963080000  0.40 voidf    963090000
20509046       0.40 voidf   963100000  1.00 voidf    927010000
20509047       1.00 voidf   927020000  1.00 voidf    927030000
20509048       1.00 voidf   927040000  1.00 voidf    927050000
20509049       1.00 voidf   927060000  1.00 voidf    927070000
*+          1.00 voidf   927080000   1.00 voidf    927090000
*
*
.*
```