The Impact of Passive Safety Systems on Desirability of Advanced Light Water Reactors

by

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B.S. Electrical Engineering
United States Naval Academy, 1998

Submitted to the Engineering Systems Division
and the Department of Nuclear Science and Engineering
in Partial Fulfillment of the Requirements for the Degrees of

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ABSTRACT

This work investigates whether the advanced light water reactor designs with passive safety systems are more desirable than advanced reactor designs with active safety systems from the point of view of uncertainty in the performance of safety systems as well as the economic implications of the passive safety systems. Two advanced pressurized water reactors and two advanced boiling water reactors, one representing passive reactors and the other active reactors for each type of coolant, are compared in terms of operation and responses to accidents as reported by the vendors.

Considering a simplified decay heat removal system that utilizes an isolation condenser for decay heat removal, the uncertainty in the main parameters affecting the system performance upon a reactor isolation accident is characterized when the system is to rely on natural convection and when it is to rely on a pump to remove the core heat. It is found that the passive system is less certain in its performance if the pump of the active system is tested at least once every five months. In addition, a cost model is used to evaluate the economic differences and benefits between the active and passive reactors. It is found that while the passive systems could have the benefit of fewer components to inspect and maintain during operation, they do suffer from a larger uncertainty about the time that would be required for their licensing due to more limited data on the reliability of their operation.

Finally, a survey among nuclear energy experts with a variety of affiliations was conducted to determine the current professional attitude towards these two competing nuclear design options. The results of the survey show that reactors with passive safety systems are more desirable among the surveyed expert groups. The perceived advantages of passive systems are an increase in plant safety with a decrease in cost.

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Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

AB1600	Advanced Boiling Hybrid Reactor
ABWR	Advanced Boiling Water Reactor
ACIWA	AC Independent Water Addition
ADS	Automatic Depressurization System
ALWR	Advanced Light Water Reactor
AOV	Air Operated Valves
AP1000	Advanced Passive Pressurized Water Reactor
APRM	Average Power Range Monitor
ATWS	Anticipated Transients Without Scram
BWR	Boiling Water Reactor
CCF	Common Cause Failure
CMT	Core Makeup Tanks
COL	Combined Operating License
CRD	Control Rod Drive
CDF	Core Damage Frequency
CST	Condensate Storage Tank
CV	Check Valve
DBA	Design Base Accidents
DOE	Department of Energy
DPV	Depressurization Valve
DVI	Direct Vessel Injection
ECCS	Emergency Core Cooling System
EFWS	Emergency Feed Water System
EIA	Energy Information Administration
EPR	Evolutionary Power Reactor
ESBWR	Economic Simplified Boiling Water Reactor
ESP	Early Site Permit
FMCRD	Fine Motion Control Rod Drive
FP	Fire Protection
FPC	Fuel Pool Cooling
GDCS	Gravity Drain Cooling System
GE	General Electric
HPCF	High Pressure Core Flooder
HPSI	High Pressure Safety Injection
IAEA	International Atomic Energy Agency
ICS	Isolation Condenser System
IRWST	Incontainment Refueling Water Storage Tank
IVR	In-vessel Retention
LHSI	Low Head Safety Injection
LOCA	Loss of Coolant Accident
LOOP	Loss of Onsite Power
LPFL	Low Pressure Flooding
MCL	Main Coolant Line

MHSI	Medium Head Safety Injection
MIT	Massachusetts Institute of Technology
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
PCS	Passive Containment Cooling System
PCCS	Passive Containment Cooling System
PRA	Probabilistic Risk Analysis
PRHR	HX Passive Residual Heat Removal Heat Exchanger
PWR	Pressurized Water Reactor
PXS	Passive Core Cooling System
RCIC	Reactor Core Isolation Cooling System
RHR	Residual Heat Removal
RIP	Reactor Internal Pump
RPV	Reactor Pressure Vessel
S/P	Suppression Pool
SBO	Station Blackout
SBWR	Simplified Boiling Water Reactor
SG	Steam Generator
SIS	Safety Injection System
SRV	Steam Relief Valve
T-H	Thermal Hydraulic

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Chapter 1. Introduction

1.1 General

As the power generation market in the United States continues its transition towards deregulation, each company must constantly decide on the most optimal energy producing portfolio. In the past, new technological breakthroughs were the driving force behind changes in the market. Today with deregulation, the emphasis is placed on technologies that are inexpensive, can be deployed in a short time, and reliable in a way to maximize profits to its investors. This financial driver of the market is changing the decision making process in the power generation industry. Certainly, federal legislation and other local public policies are factors that must be taken into account to find this optimal alternative as these policies can often make one energy alternative more or less costly than originally planned. Invoking carbon taxes, emission standards, and waste restrictions are just a few of the ways that lawmakers can make one energy alternative more attractive than another.

Nuclear power is one of potential energy alternatives for the U.S. power generation industry. Currently, nuclear power comprises approximately 20 percent (~780 trillion kilowatt hours annually) of the electrical energy generation in the United States, second only to coal. Nuclear energy production has increased over the years, although no new nuclear plant has been started by the industry since 1994. Even though most of the currently operating 103 nuclear reactors will apply for 20-year license extensions from the Nuclear Regulatory Commission (NRC), the capacity factor for these plants is already about 90%. This means that new plants will need to be built to meet national energy growth demands over the next 50 years if nuclear power is to keep or increase its 20% share of the power generation portfolio. The Energy Information Administration (EIA) estimates the anticipated growth of electricity in the United States at 1.9 percent annually.[1] This expected annual increase yields an increase in U.S. nuclear capacity from 100 to 300 GWe by 2050 in order to maintain a national energy portfolio with 20 percent nuclear power generation. With little room left to increase the capacity factors of operating plants, it will take adding 2-3 new reactors per year (with capacities ranging from 1 to 1.5 GWe each) in addition to re-licensing all 103 currently operating reactors, and even to replace some of them, in order to meet this demand. Considering it's been almost 30 years since the last reactor was ordered to be built, this is no small feat.

In 2003, the Massachusetts Institute of Technology (MIT) produced an interdisciplinary study called The Future of Nuclear Power. The study observed that nuclear power's future hinged on four key areas: Cost, safety, proliferation, and waste management. It concluded that based on these four factors, nuclear power should remain an energy option but that it had some hurdles to clear before becoming attractive in a deregulated market. First, it had to significantly reduce its cost while maintaining an optimal level of safety and proliferation resistance to the public. Second, it had to finish a solution to long term nuclear waste management. The study supported the open, "once-through" fuel cycle, light water reactor design as the best model to achieve these goals. "Once-through" fuel cycles simply mean that the spent reactor fuel is not reprocessed, and the light water design means that H_2O is used as the moderator.

Concurrent with the MIT study, the United States Department of Energy (DOE) developed its "2010 Initiative" which reduces costs through cost-sharing in new design certification, site banking, and combined construction and operation licenses so that new plants can compete in a deregulated energy market. Its goal, stated specifically on its website, is to "expand the number of new advanced nuclear power plants (Generation III+) in the United States and have a new nuclear plant ordered by 2010."[2] Furthermore, The Energy Policy Act of 2005 outlined even more benefits for new nuclear power plants to help ignite a rebirth in the industry. This policy offered among other things:

-Loan guarantees: up to 80% of the project cost
-Production tax credits: 1.8 cents per kilowatt-hour for 6,000 megawatts (MW) of capacity from new nuclear power plants for the first eight years of operation
-"Standby Support" for new reactor delays: provides for 100 percent coverage of the cost of delays for the first two new plants (up to $500 million each) and 50 percent of the cost of delays for the next four plants (up to $250 million each)

The Generation III+ reactors, also known as Advanced Light-Water Reactors, in competition for this order are the:

1. Advanced Boiling Water Reactor (ABWR)
2. Economic Simplified Boiling Water Reactor (ESBWR)
3. Evolutionary Power Reactor (EPR)
4. Advanced Passive Pressurized Water Reactor (AP1000)

All four of the reactors are "once-through" fuel cycle plants with light water moderators supported by the MIT study as the best model choice for the future of nuclear power. The question becomes which of the four designs is the most optimal choice for nuclear power in order for it to compete with other alternatives such as coal, natural gas, and renewables (solar, wind)? First, one must understand their differences.

1.2 Advanced Light Water Reactors (ALWRs)

All four of the advanced light water reactors are based on evolutionary designs from predecessor reactors. While the four Generation III+ designs share a common fuel cycle and moderator design, they have their differences. The ABWR and ESBWR are boiling water reactors (BWR) while the EPR and AP1000 are pressurized water reactors (PWR). The boiling water reactor operates in essentially the same way as a fossil fuel generating plant. Steam is produced when the water (coolant) moves upward along the fuel in the core absorbing its heat. The steam formed rises and passes through moisture separators out of the top of the pressure vessel and then proceeds to the turbine. The pressurized water reactor differs from the BWR in that the steam to run the turbine is produced in a steam generator (in a secondary loop) which receives its heat from the primary loop of water (coolant) leaving the core. This primary, or first loop, has a pressurizer unit to prevent its higher temperature coolant water from boiling as it circulates through the core. Its coolant water transfers the core's heat to the secondary water in the steam generator producing steam. The general diagrams for each are shown in Figures 1.1 and 1.2.

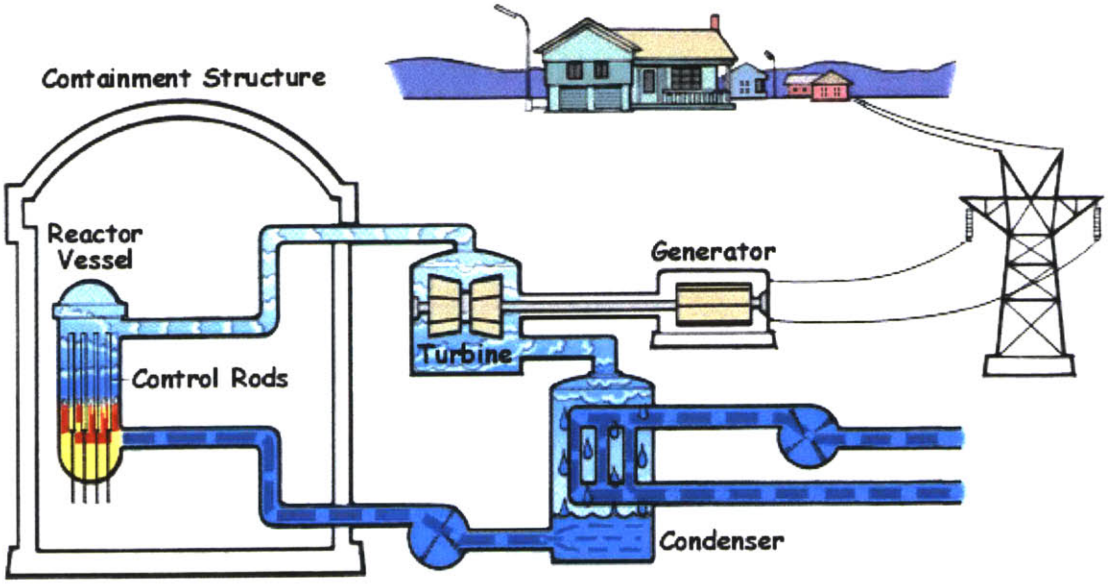


Figure 1.1 BWR Schematic[3]

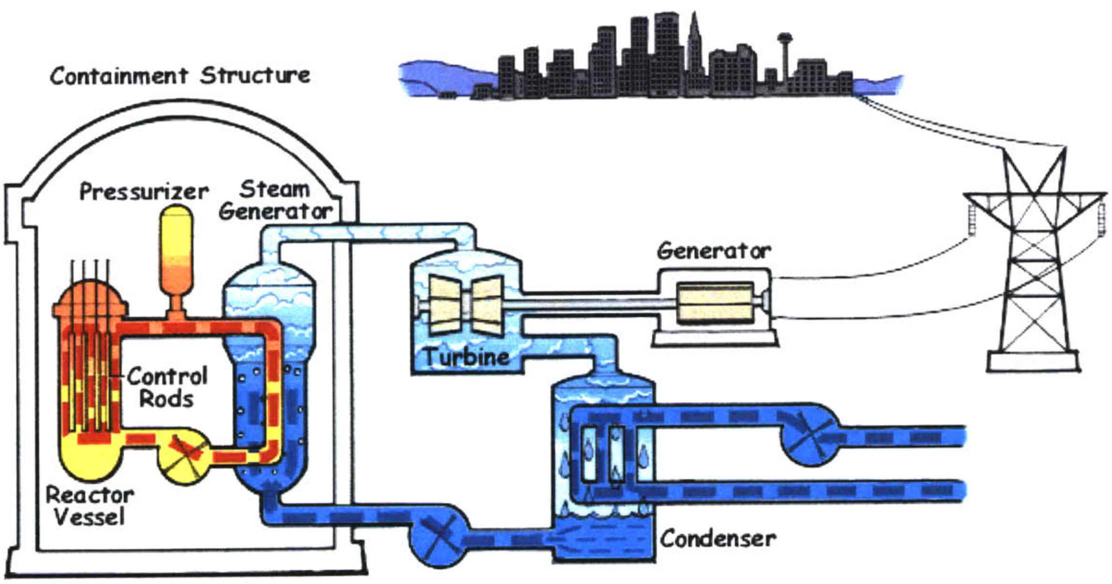


Figure 1.2 PWR Schematic[3]

Approximately two-thirds of the 103 operating reactors in the U.S. are PWRs. This is not to say that BWRs are inferior. Each reactor type has its own advantages and disadvantages. Some utilities may prefer one type over another to suit their own experience, but for the most part, they are comparable designs as far as energy production is concerned. Neither design difference impacts the desirability of the reactors as a whole.

The other, more important difference in the aforementioned Generation III+ reactors besides reactor type, is their safety system design. The ABWR and EPR use advanced active safety system designs with pumps while the AP1000 and ESBWR use passive safety system designs utilizing natural circulation. Current U.S. reactors use active designs, although not as advanced as the ABWR and EPR. Passive safety systems, while simple in design, are relatively new in nuclear reactor design, and therefore lack a deep record of demonstrated performance.

Another possibility are "hybrid" reactors, like Toshiba's AB1600 (a BWR), that utilize both active and passive systems to maximize the advantages that each system has to offer. Most of the safety systems on these hybrid reactors are taken from the ESBWR and ABWR designs with minor improvements. These types of reactors will be discussed more in depth in Chapter 8.

1.3 Passive Safety

It is important to define what is considered "passive" in the scope of this study. In addition, there is also the difference between passive components and passive systems which must be defined. The International Atomic Energy Agency's (IAEA) definitions[4] are as follows:

<u>Passive component</u>: A component whose functioning does not depend on an external input. A passive component has no moving part, and, for example, only experiences a change in pressure, in temperature, or in fluid flow in performing its functions. In addition, certain components that function with very high reliability based on irreversible action or change may be assigned to this category. Examples of passive components are heat exchangers, pipes, vessels, electrical cables and structures. Certain components, such as rupture discs, check valves, safety valves, injectors

and some solid state electronic devices, have characteristics which require special consideration before designation as an active or passive component. Any component that is not a passive component is an active component.

Passive system: A passive system is either a system which is composed of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation. Passive systems are further classified into four subgroups based on their dependence on active components.

> *Category A*: This category is characterized by no signal inputs of "intelligence", no external power sources or forces, no moving mechanical parts, and no moving working fluid.
>
> Examples: physical barriers against the release of fission products, such as nuclear fuel cladding and pressure boundary systems, hardened building structures for the protection of a plant against seismic and other external events, core cooling systems relying only on heat radiation and/or conduction and static components of safety related passive systems (e.g. tubes, pressurizers, accumulators) as well as structural parts (e.g. supports, shields).
>
> *Category B*: This category is characterized by no signal inputs of "intelligence", no external power sources or forces, no moving mechanical parts, but moving working fluids. The fluid movement is only due to thermal-hydraulic conditions occurring when the safety function is activated.
>
> Examples: reactor shutdown/emergency cooling systems based on injection of borated water from an external water pool, reactor emergency cooling systems based on air or water natural circulation in heat exchangers immersed in water pools (inside the containment), containment cooling systems based on natural circulation of air flowing around the containment walls.

Category C: This category is characterized by no signal inputs of "intelligence", no external power sources or forces, moving mechanical parts, whether or not moving working fluids are also present. The fluid motion is characterized as in category B; mechanical movements are due to imbalances within the system (e.g., static pressure in check and relief valves, hydrostatic pressure in accumulators) and forces directly exerted by the process.

Examples: emergency injection systems consisting of accumulators or storage tanks and discharge lines equipped with check valves, and mechanical actuator, such as check valves and spring-loaded relief valves.

Category D: This category addresses the intermediary zone between active and passive where the execution of the safety function is made through passive methods as described in the previous categories except that internal intelligence is not available to initiate the process. In these cases an external signal is permitted to trigger the passive process.

Examples: emergency core cooling systems, based on gravity-driven flow of water, activated by valves which break open on demand.

A simplified breakdown of the four categories is shown in Table 1.1 below:

Table 1.1 Passive Safety Categories[4]

Characteristic	Category A	Category B	Category C	Category D
Signal Inputs of intelligence	No	No	No	Yes
External power sources or forces	No	No	No	No
Moving mechanical parts	No	No	Yes	Yes/No
Moving working fluid	No	Yes	Yes	Yes/No

As previously mentioned, the ESBWR and AP1000 utilize various categories of passive safety systems. A simplified summary of the four Generation III+ reactor designs is shown in Table 1.2. It is important to note that all four reactors use a mixture of both active and passive systems throughout their designs; however, as discussed in Chapter 2, these general classifications speak to the degree of passive safety usage in the design, with a specific focus on the emergency core cooling systems.

Table 1.2 Generation III+ Summary

	Design	Safety
BWR	ABWR	Active
	ESBWR	Passive
PWR	EPR	Active
	AP1000	Passive

1.4 Reactor Design Status

The ABWR and ESBWR are designed by General Electric (GE) and manufactured by GE and a host of other companies. Currently, there are four ABWRs operating in Japan, two under construction in Taiwan, and more planned in Japan. The ABWR has already passed its U.S. design certification by the NRC and if ordered by a utility, claims it could be operational by 2012.[5] The ESBWR is currently under design certification by the NRC and GE believes it can achieve certification that would support commercial operation of ESBWRs by 2014.[5]

The EPR is manufactured by AREVA who has one EPR under construction in Finland that began construction in 2005. That EPR is scheduled to come into commercial operation in 2009. AREVA also has another order for an EPR in France where construction is expected to start in 2007, with expected commercial operation beginning 2012. In the U.S., AREVA has completed phase one of its U.S. EPR design certification pre-application process with the NRC. It is expected that the complete design certification application will be submitted by the end of 2007, in order to support the company's plans to have a U.S. EPR be licensed and ready for operation in 2015.

In January 2006, the NRC approved the final design certification for the AP1000. Thus, utilities can place on order on it just like the ABWR. Two AP1000s are planned by southern utilities working on site permits.

As of right now, the ABWR and AP1000 are the only two certified reactors that can be ordered by U.S. utilities out of the four Generation III+ types discussed. It is unclear whether the ESBWR and EPR will complete their design certifications in time to meet the potential initial demand for new nuclear plants in the U.S. Currently the process for building a new nuclear plant requires utilities to complete an early site permit (ESP) and combined operating license (COL) with the NRC. The ESP is a partial construction permit, good for 10 to 20 years, that addresses site safety issues including emergencies along with any environmental protection issues. The ESP is completed at a site selected by the utility independent of the review of a specific nuclear plant design. The COL authorizes construction and conditional operation of a nuclear power facility. In addition, the plant design itself must pass its own final design certification. Table 1.3 provides a summary of the planned orders for ESPs and COLs for each plant type from the NRC including those that are already in progress or completed.

Table 1.3 Requests for ESPs and COLs to the NRC[6]

	COLs	ESPs	Units
ABWR	2	1	4
ESBWR	3	2	3
EPR	5	0	5
AP1000	6	1	11
Unspecified	3	3	3
TOTAL	19	7	26

1.5 Goals

The immediate future of nuclear power in the United States rests in the potential of these four generation III+ reactors. Two of the four concerns discussed in the MIT study, safety and cost, will have a major impact on which of the four reactors will dominate the deregulated market. The other two concerns, proliferation and waste, are similar for all four Generation III+ reactors since they have the same fuel cycle. Market drivers and political drivers will steer a path of least resistance for one of these alternatives. This study focuses on the impact of passive safety systems on desirability of these advanced light water reactors.

Chapter 2 provides the background for understanding the competing safety designs of ALWRs.

Chapter 3 provides vendor safety claims for these four reactors and discusses advantages and disadvantages of each system in terms of safety.

Chapter 4 describes an industry accepted methodology for analyzing passive safety system reliability when thermal hydraulic uncertainty is introduced into the transient.

Chapter 5 describes the simplified safety system modeled, per the methodology outlined in Chapter 4, that is used to compare active and passive system responses and discusses these safety results with regards to passive safety desirability.

Chapter 6 outlines the cost model used in the previous MIT study and how it can be used to identify potential cost benefits between Generation III+ designs.

Chapter 7 discusses a ten question survey conducted among nuclear energy experts of various affiliations to determine their views and opinions on the safety, cost, and licensing of reactors with passive safety systems, especially in comparison to reactors with active safety systems.

Chapter 8 discusses the current and future energy policies and their impact on passive safety desirability.

Chapter 9 concludes with a summary and recommendations for future work.

Chapter 2. Background

2.1 Advanced Boiling Water Reactor (BWR) Designs

The BWR nuclear plant, like the PWR, has its origins in the technology developed in the 1950's for the U.S. Navy's nuclear submarine program. The purpose of the BWR evolutionary design changes has been to simplify the reactor while improving the economics and safety. Historically, the GE BWR design has been simplified in two key areas—the reactor systems and the containment design. Table 2.1 chronicles the development of the GE BWR.

Table 2.1 GE BWR History Before Introducing the ESBWR[7]

Product Line	First Commercial Operation Date	Representative Plant/ Characteristics	
BWR/1	1960	Dresden 1 Initial commercial-size BWR	
BWR/2	1969	Oyster Creek Plants purchased solely on economics Large direct cycle	**Mark-I Containment**
BWR/3	1971	Dresden 2 First jet pump application Improved ECCS: spray and flood capability	
BWR/4	1972	Vermont Yankee Increased power density (20%)	
BWR/5	1977	Tokai 2 Improved ECCS Valve flow control	**Mark-II Containment**
BWR/6	1978	Kuo Sheng Compact control room Solid-state nuclear system protection system	**Mark-III Containment**
ABWR **(Advanced BWR)**	1996	Kashiwazaki-Kariwa 6 Reactor internal pumps Fine-motion control rod drives Advanced control room, digital solid-state microprocessors Fiber optic data transmission / multiplexing Increased number of fuel bundles Titanium condenser Improved ECCS: high/low pressure flooders	**ABWR Containment**

A major improvement over this evolutionary process was the elimination of the steam generators and the use of five external recirculation loops in the BWR/2. Later, reactor systems were further simplified by the introduction of internal jet pumps in BWR/3 which produced enough recirculation flow to reduce the number of external loops from five to two. The ABWR design uses 10 internal reactor pumps, further simplifying the recirculation system design. By using these 10 pumps mounted directly to the vessel itself, the external recirculation systems, with all their pumps, valves, piping, and scrubbers, have been eliminated altogether. This design feature is the source of many of the ABWR's safety and operational advantages to be discussed later. Figure 2.1 illustrates the evolution of the GE BWR system design.

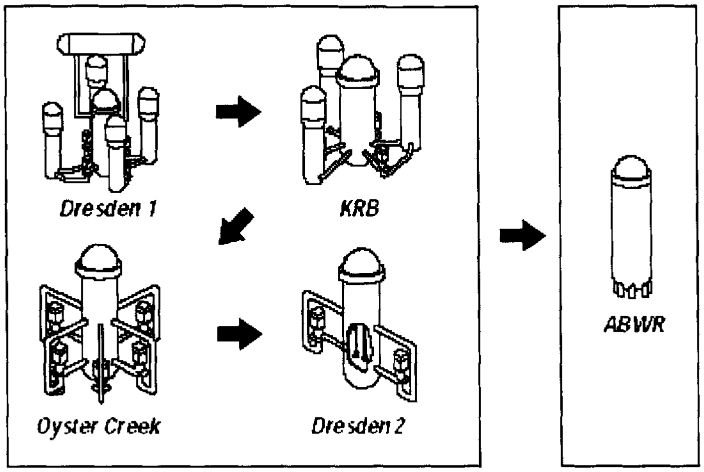


Figure 2.1 GE BWR System Design Evolution[7] (KRB=Kernkraftwerk RWE-Bayernwerk GmbH from Germany)

In addition to these reactor improvements, positive changes to BWR containment have occurred. BWR containments have shifted from "dry" spherical structures to a "pressure suppression" containment design, which includes a suppression pool, because of its many advantages. Among these advantages[7] are:

- High heat capacity.
- Lower design pressure.
- Superior ability to accommodate rapid depressurization.
- Unique ability to filter and retain fission products.
- Provision of a large source of readily available makeup water in the case of accidents.
- Simplified, compact design.

It is the reduction in containment design pressures through these measures, together with the elimination of the external recirculation loops, that allows the containment, and thus the reactor building to be more compact. The containment shape has shifted over time from the Mark I (light bulb) to the Mark III (right cylinder) which is much easier and less costly to construct. The ABWR containment is smaller than the Mark III containment due to the elimination of the external recirculation loops. There are other general improvements for the ABWR outlined in Table 2.2 below:

Table 2.2 Advanced BWR Improvements[8]

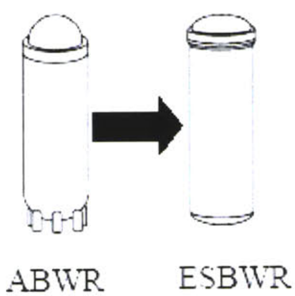
Feature	BWR/6	ABWR	ESBWR
Recirculation	Two external loop Recirc systems with jet pumps inside RPV	10 vessel mounted internal reactor pumps	natural circulation
Control Rod Drives	Locking Piston CRDs	Fine-motion CRDs	Fine-motion CRDs*
ECCS	2-division ECCS plus HPCS	3-division ECCS	4-division ECCS
Control/Instrumentation	Analog, hardwired, Single-channel	Digital, multiplexed, fiber optics, multi-channel	Digital, multiplexed, fiber optics, multi-Channel

*This was the initial proposal, later given up to allow speedy certification

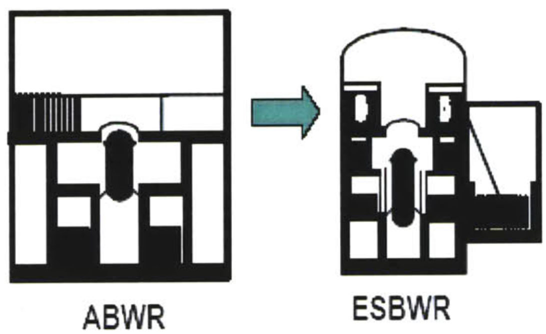
The containment and recirculation improvements have already been discussed briefly. All other improvements will be discussed in more detail in the next section. Most of these improvements have a large impact on increased safety and reduction in cost. This study will compare some aspects of these "advanced" active safety system upgrades with the passive safety system upgrades of GE's next evolutionary design--the ESBWR.

Following the ABWR, GE started to introduce the Simplified Boiling Reactor (SBWR), a 600 MWe reactor with passive safety systems, through the government's ALWR funding program. In 1996, GE cancelled the SBWR stating "GE Nuclear Energy is redirecting the focus of its SBWR technology programs to plants of 1000 MWe or larger since extensive evaluations of the market competitiveness of a 600 MWe size ALWR have not established the commercial viability of these designs, particularly in light of the increasingly competitive nature of the electric industry throughout the world."[9] Thus, the ESBWR concept was born to try and make a more market competitive reactor using a continued evolutionary design from ABWR to SBWR to ESBWR.

The ESBWR design continued to push towards simplicity and incorporate more passive safety features. Figure 2.2 shows the difference between ABWR and ESBWR reactor designs and containments.



(Reactor Vessel)



(Containment)

Figure 2.2 ABWR/ESBWR Comparisons[10]

A comparison of key parameters also illustrates the move towards simplicity and the higher rated power (1550 MWe) achieved shown in Table 2.3.

Table 2.3 Comparison of ESBWR Key Parameters to Previous BWRs[10]

Parameter	BWR/6	ABWR	ESBWR
Power (MWt)	3293	3926	4500
Power (MWe)	1290	1350	1550
Vessel Height (m)	21.8	21.1	27.7
Vessel Diameter (m)	6.4	7.1	7.1
Fuel Bundles (number)	800	872	1132
Active Fuel Length (m)	3.6	3.6	3.0
Number of CRDs	193	205	269
Power Density (kW/l)	54.2	51	54.3
Number of RIPs	N/A	10	0

By changing many of these parameters, the ESBWR was able to achieve 2 to 3 times greater natural circulation in its core and nearly similar power-to-flow ratio as pumped plants at rated conditions. Generally, a typical BWR/6 can be operated on natural circulation up to about 25 percent of rated power. Beyond that level, pumps are required. The ESBWR operates completely under natural circulation at all rated power levels which greatly simplifies vessel construction and reduces cost. Figure 2.3 illustrates the comparison of natural circulation flow for BWRs and shows the ESBWR has a large margin to unstable regions.

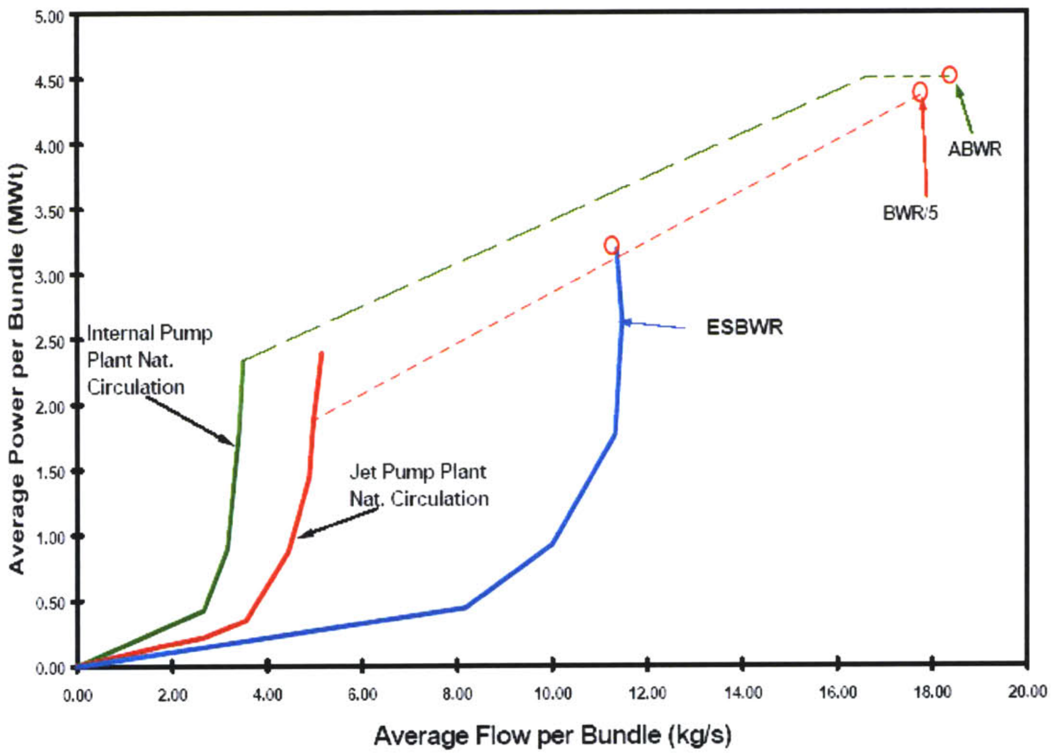


Figure 2.3 Comparison of Natural Circulation Flows[8]

As stated earlier, several vendors have sought to improve current BWR design through simplification while improving safety and reducing cost. The method of improving current designs can be done in a variety of ways. Both the ABWR and ESBWR have significantly improved BWR reactor features. This study is focusing on whether there is an advantage (in terms of safety, cost, licensing, and acceptance) in utilizing active safety improvements instead of passive safety improvements or vice versa.

2.1.1 ABWR Emergency Core Cooling System (ECCS)

The ABWR ECCS network was designed as a full three-division system in contrast to the two-division system of the BWR/6. A "division" means that all systems and components necessary to complete the safety function are contained within the division, and that a division is physically separated from other divisions to avoid any propagating failures, such as threats due to fire or flood. Thus, adding another independent, redundant division increased the defense in depth in the ABWR. As discussed earlier, the reactor pressure vessel (RPV) has no external recirculation loops or large pipe nozzles below the top of the core region. This allows for a reduced capacity ECCS while still keeping the fuel covered for the full spectrum of postulated "loss of coolant accidents" (LOCA) even assuming a single failure. Each of the three divisions has both a high and low-pressure injection pump and heat removal capability. The Reactor Core Isolation Cooling (RCIC) System includes a steam-driven, high-pressure pump. This steam-driven pump adds diversity to pumping power for even greater defense in depth. Transient response was improved by designing three available high-pressure injection systems in addition to feedwater. Furthermore, the adoption of three on-site emergency diesel-generators to support core cooling and heat removal, as well as the addition of an on-site gas turbine-generator, reduces the potential for "station blackout" (SBO). The balanced ECCS system has less reliance on the Automatic Depressurization System (ADS) function, since a single, motor driven high pressure core flooder (HPCF) can maintain core safety for any postulated pipe break The HPCF pumps provide core makeup over the entire range of system operating pressures. The RCIC System, which has been upgraded to a safety system, has the dual function of providing high pressure ECCS flow following a postulated LOCA and reactor coolant inventory control for reactor isolation transients. The low pressure ECCS for the ABWR utilizes the three residual heat removal (RHR) pumps in the post-LOCA Low Pressure Flooding (LPFL) mode and are labeled LPFL. For small LOCAs that do not depressurize the reactor system, if the high pressure makeup is unavailable, an Automatic Depressurization System (ADS) actuates to vent steam from the reactor through the safety/relief valves (SRVs) to the suppression pool, and depressurizes the reactor vessel to allow the LPFL pumps to provide core coolant makeup flow. Figure 2.4 shows the ABWR ECCS diagram. We will now discuss each ECCS system more in depth.

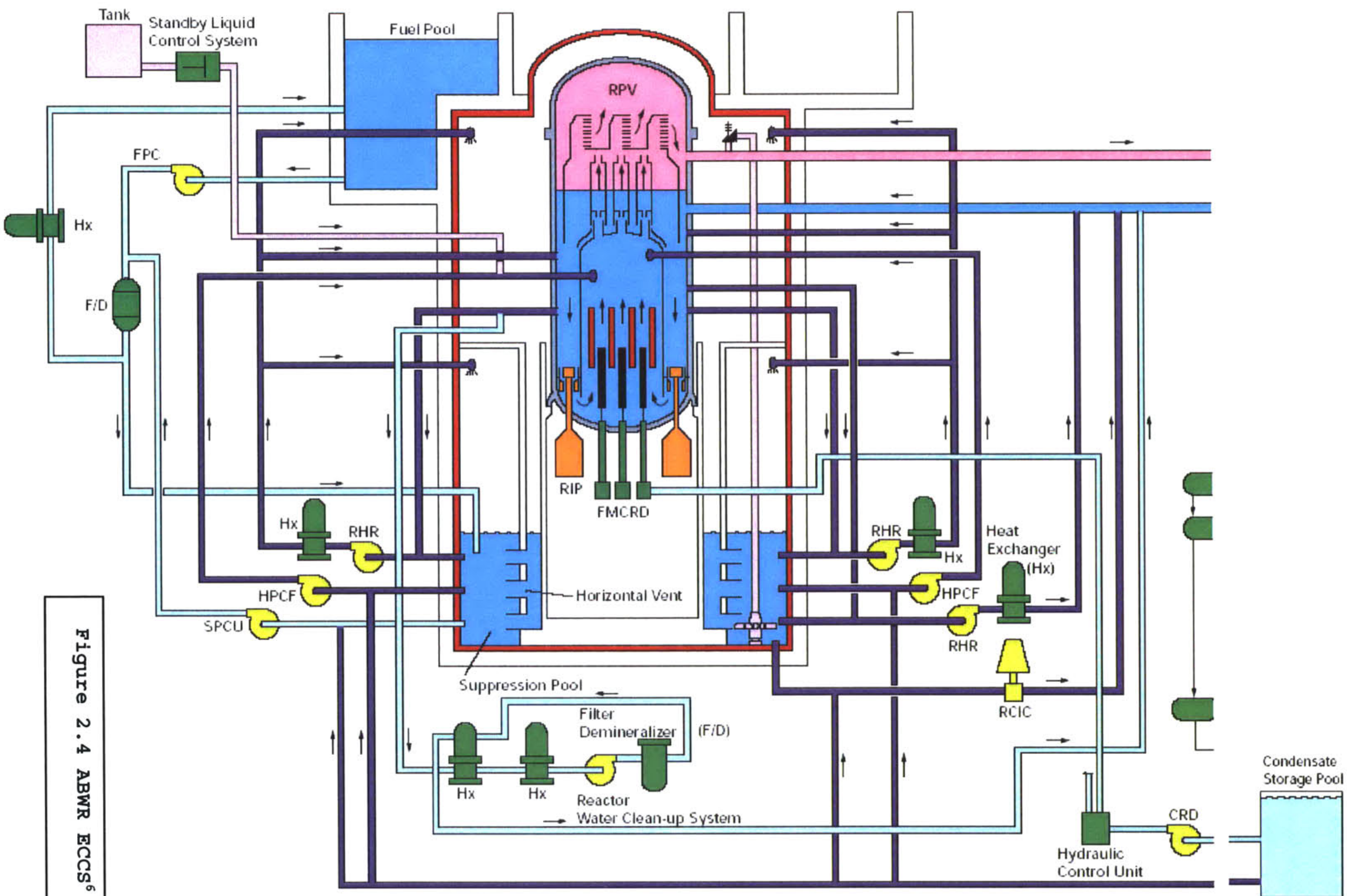


Figure 2.4 ABWR ECCS[6]

2.1.1.1 Residual Heat Removal (RHR) System

The RHR System has a dual role of providing reactor cooling for normal shutdown and providing core and containment cooling following a postulated LOCA or reactor isolation. The ABWR RHR System has been improved such that core and suppression pool cooling are achieved simultaneously since, in the core-cooling mode, the flow from the suppression pool passes through the RHR heat exchanger and the supporting heat removal systems. This system, which consists of three divisions (A, B and C), has six principal functions (in addition to test/bypass modes), each with a specific purpose outlined below. A diagram of the RHR is shown in Figure 2.5.

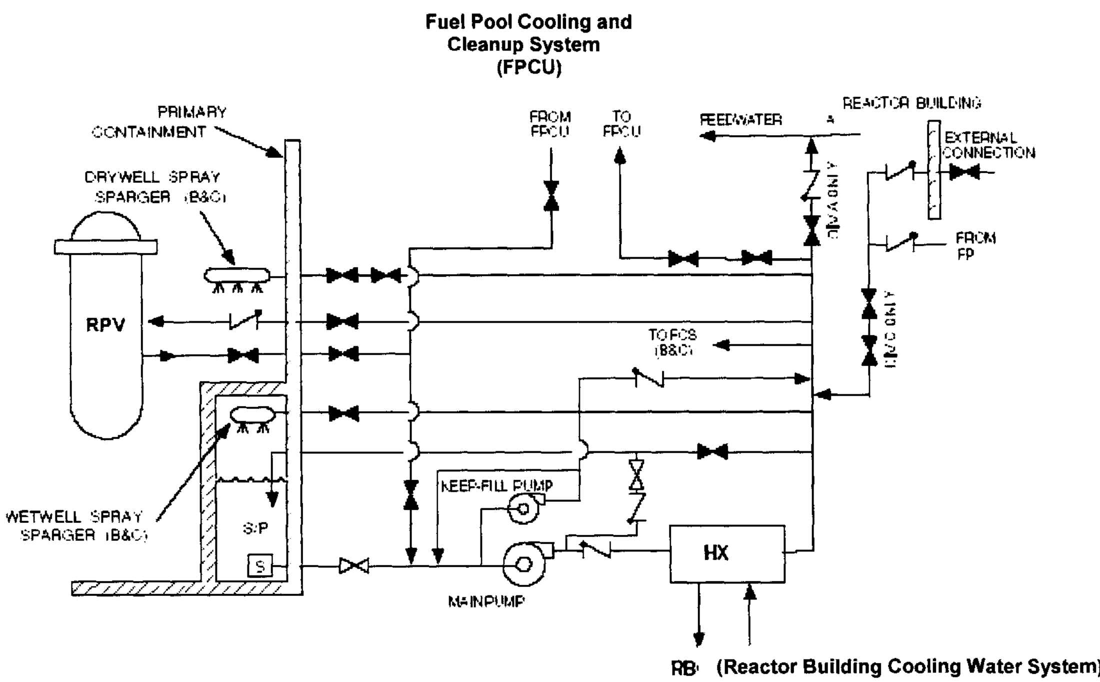


Figure 2.5 ABWR Residual Heat Removal (RHR) System[6]

i. Low Pressure Core Flooder Mode (Division A, B, and C)

The RHR System is automatically initiated when either a high drywell pressure or low reactor water level condition exists (i.e., LOCA signal). The processors use a 2-out-of-4 voting logic for RHR System initiation. Each RHR division can also be initiated manually. Following receipt of an initiation signal, the RHR System automatically initiates and operates in the LPFL mode to provide emergency makeup to the reactor vessel. The initiation signal starts the pumps, which run in the minimum flow mode until the reactor depressurizes to less than the pump's developed head pressure. A low reactor pressure signal occurs somewhat above the pump's developed head pressure which signals the injection valve to open. As the injection valve opens, the reactor pressure is contained by the testable check valve until the reactor pressure becomes less than the pump's developed head pressure at the minimum flow mode, at which time injection flow begins. This sequence satisfies the response requirements for all potential LOCA pipe breaks when the injection valve opens within 36 seconds after receiving the low reactor pressure permissive signal. The LPFL mode is accomplished by all 3 divisions of the RHR system by transferring water from the suppression pool to the RPV, via the RHR heat exchangers. The RPV injection valve in each division requires a low rector pressure permissive signal to open, and closes automatically on receipt of a high reactor vessel pressure signal.[11]

ii. Suppression Pool Cooling Mode (Division A, B, and C)

The suppression pool cooling mode of the RHR System limits the long-term post-LOCA temperature of the suppression pool, and limits the long-term peak temperatures and pressures within the wetwell and drywell regions of the containment. In this mode, the RHR System circulates water through the RHR heat exchangers and returns it directly to the suppression pool. This mode is manually initiated by control of individual system components or automatically initiated by high suppression pool temperature. The RHR pumps have sufficient net positive suction head (NPSH) available at the pump. Suction from the suppression pool is the limiting NPSH condition of all the RHR modes.[12]

iii. Shutdown cooling mode (Division A, B, and C)

In the shutdown cooling mode of operation, the RHR System removes decay heat from the reactor core, and is used to achieve and maintain a cold shutdown condition by removing decay and sensible heat from the core and reactor vessel. This mode reduces reactor pressure and temperature to cold shutdown conditions. In this mode, each division takes suction from the

RPV via its dedicated suction line, pumps the water through its respective heat exchanger tubes, and returns the cooled water to the RPV. B and C divisions discharge water back to the RPV via dedicated spargers, while division A utilizes the vessel spargers of one of the two feedwater lines. Shutdown cooling is initiated manually once the RPV has been depressurized below the system low pressure permissive.[12]

iv. Containment Spray Mode (Division B, and C)

The containment spray mode of the RHR System is available in Divisions B and C, and consists of the wetwell spray and drywell spray operating together. In this mode, the RHR System pumps suppression pool water to a single wetwell spray header and single drywell spray header through the associated RHR heat exchanger. The containment spray mode of the RHR System is initiated manually by control of individual system components. The drywell spray inlet valves can only be opened if a high drywell pressure condition exists and if the injection valves are fully closed.[12]

v. AC-Independent Water Addition (Division C)

The ACIWA mode of RHR Loop C provides a means for introducing water from Fire Protection (FP) through RHR Loop C piping and valves directly into either the RPV, drywell spray header, or wetwell spray header. The purpose is to prevent core damage or, if core damage has already occurred, to terminate melt progression when AC power is not available from either onsite or offsite sources. The ACIWA mode of RHR provides manual capability to prevent core damage when all ECCS are lost.[12]

vi. Augmented Fuel Pool Cooling and Fuel Pool Makeup (Division A, B, C)

The augmented fuel pool cooling mode of the RHR System can supplement the Fuel Pool Cooling (FPC) System by directly cooling the fuel pool by circulation of fuel pool water through the RHR heat exchanger and returning it to the fuel pool or return the cooled RHR shutdown cooling flow to the fuel pool when providing shutdown cooling during refueling.[12]

2.1.1.2 High Pressure Core Flooder System (Division B, and C)

The High Pressure Core Flooder (HPCF) System is comprised of two separate divisions. The function of the HPCF System is to provide emergency makeup water to the reactor vessel for transient or LOCA event, especially after small breaks which do not depressurize the reactor vessel. The primary source of suction is the condensate storage tank (CST) and the secondary source of supply is the suppression pool (S/P). The HPCF system is shown in Figure 2.6 below:

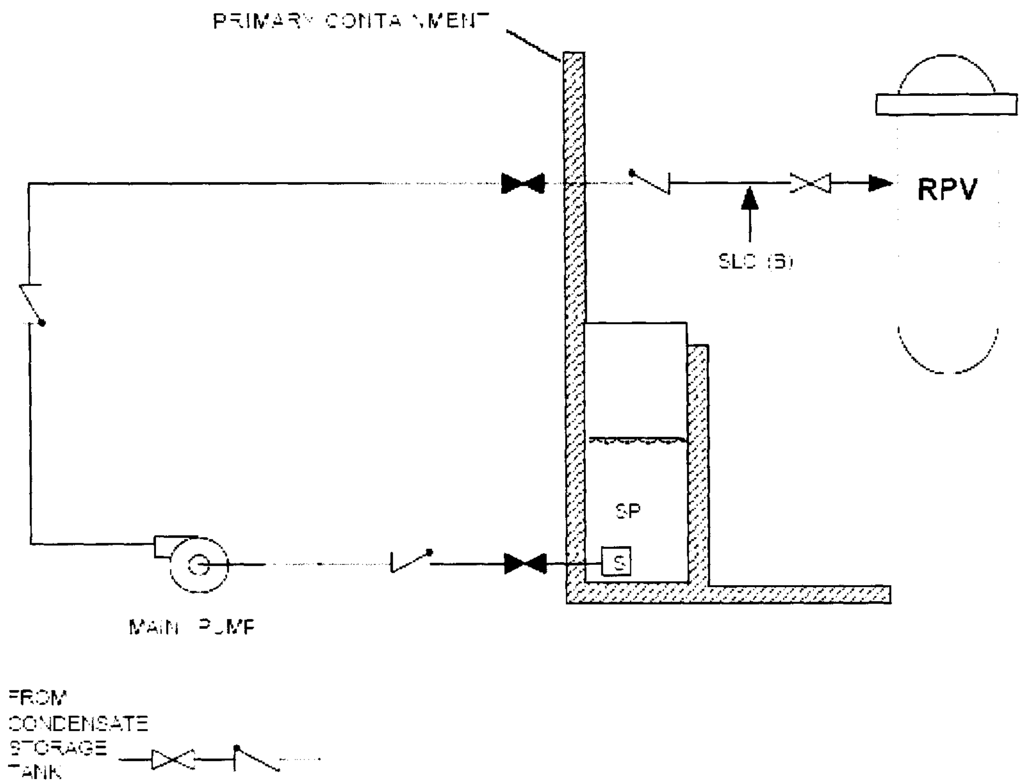


Figure 2.6 ABWR High Pressure Core Flooder (HPCF) System[7]

The HPCF System is automatically initiated when either a high drywell pressure signal or low reactor water level signal exists. Both divisions of the HPCF System are actuated at a reactor water level below the RCIC actuation level and thus provide a backup to RCIC for transients. The processors use a 2-out-of-4 voting logic for system initiation and shutdown. Manual initiation can also be performed. Following receipt of an initiation signal, the HPCF System automatically initiates and operates in the high-pressure flooder mode to provide water to the core region of the reactor. The pumps are motor-driven centrifugal pumps that provide flow as a function of reactor vessel pressure. The flow in each division is not less than a value corresponding to a straight line between a flow of 182 m^3/hr at a differential pressure of 8.12 MPa and a flow of 727 m^3/hr at a differential pressure of 0.69 MPa. The HPCF System has the capability to deliver at least 50% of these flow rates with 171°C water at the pump suction. The differential pressure values represent the difference between the reactor vessel pressure and the pressure of the air space of the source water for the pump. System flow into the reactor vessel is achieved within 16 seconds of receipt of an initiation signal and power available at the emergency busses. Pump suction is from the CST. Automatic transfer of pump suction from the CST to the S/P occurs when a low CST water level or high suppression pool water level signal exists. When a high water level signal in the reactor pressure vessel exists, the reactor vessel injection valve is automatically closed. When the low reactor water level initiation signal recurs, the injection valve automatically re-opens to reestablish HPCF flow. Emergency diesel generators power the HPCF System pump motors if auxiliary power is not available.[12]

2.1.1.3 Reactor Core Isolation Cooling (RCIC) System

The Reactor Core Isolation Cooling (RCIC) System's primary purpose is to provide makeup water to the reactor vessel when the vessel is isolated. The steam drives the RCIC turbine from the RPV which then drives the RCIC pump. This pump operates automatically in time and with sufficient coolant flow to maintain adequate water level in the reactor vessel for station blackout (loss of all AC). The RCIC steam supply to the turbine branches off one of the main steamlines inside containment upstream of the inboard MSIV and exhausts to the S/P. The primary source of RCIC pump suction is the CST. The S/P is the secondary source of RCIC pump suction and suction is transferred to this pool when a low CST water level or high S/P water level signal exists. Figure 2.7 shows the RCIC system:

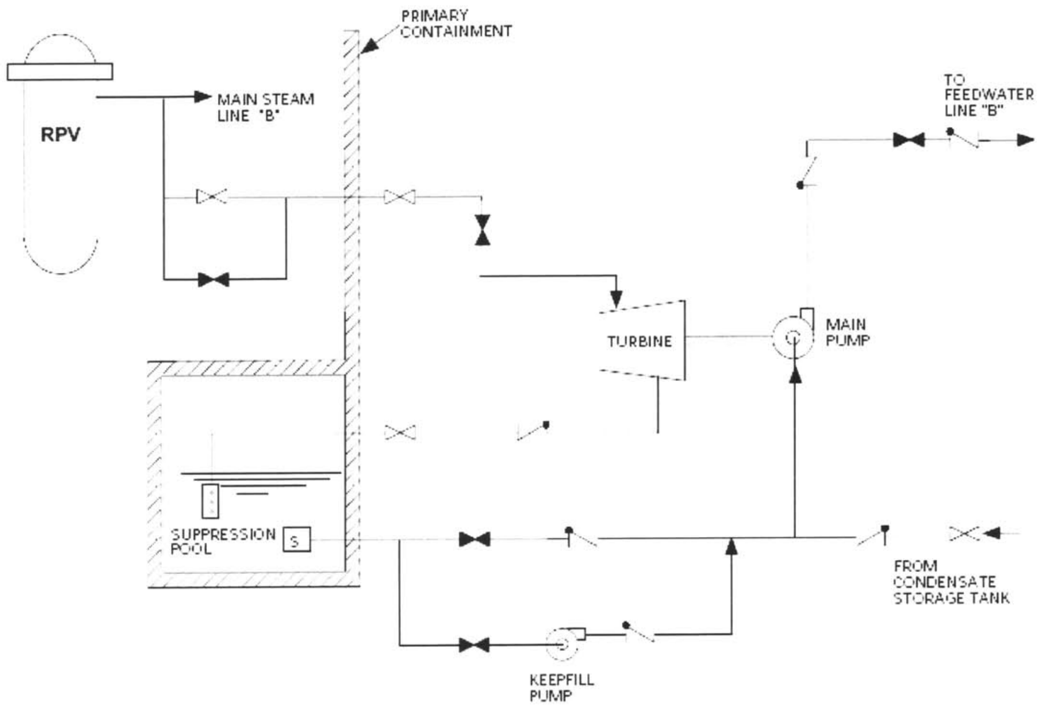


Figure 2.7 ABWR Reactor Core Isolation Cooling (RCIC) System[7]

The RCIC System is automatically initiated when either a high drywell pressure or low reactor water level condition exists. RCIC System is actuated at a reactor water level higher than the HPCF System actuation level. The processors use a 2-out-of-4 voting logic for system initiation and shutdown. Manual RCIC System can be started by local operation of components outside the main control room. The RCIC automatically shuts down when a high reactor water level condition exists. Following RCIC shutdown on high reactor water level signal, the RCIC System automatically restarts to provide RPV water makeup, if the low reactor water level initiation signal recurs. The RCIC pump delivers a flow rate of at least 182 m^3/hr against a maximum differential pressure of 8.12 MPa (between the RPV and the suction source). This flow rate is achieved within seconds of receipt of the system initiation signal. The RCIC system operates for a period of at least 2 hours under conditions of no AC power availability and no other simultaneous failures, accidents, or other design basis conditions.[12]

2.1.1.4 Automatic Depressurization System (ADS)

The Automatic Depressurization System (ADS) logic is automatically initiated after a short delay if an RPV low water level signal is present concurrently with a high drywell pressure signal. The ADS logic is also automatically initiated if only the RPV low water level signal is present. This initiation will occur after a longer delay to allow the high pressure ECCS a chance to restore the RPV water level to normal levels and thus avoid the ADS actuation. Both ADS initiation paths require an indication that at least one of the RHR or HPCF pumps is running before the initiation sequence is complete. ADS initiation is accomplished by redundant trip channels arranged in two divisionally separated logics that control two separate, solenoid-operated pneumatic pilots on each ADS SRV. Automatic initiation of the ADS is inhibited unless there is a coincident low reactor water level signal and an average power range monitors (APRMs) downscale signal. There are also main control room switches for the manual inhibit of automatic initiation of the ADS. The ADS can also be initiated manually. On a manual initiation signal, concurrent with positive indication of at least one of the RHR or HPCF pumps is running, the ADS function is initiated.[7]

2.1.2 Economic Simplified Boiling Water Reactor (ESBWR)

The ESBWR used many of the same improvements made on the ABWR but also focused on designing more passive features. For the purposes of this study, we will focus on the passive safety system upgrades and the use of natural circulation during normal operation. Most of the ESBWR passive safety systems fall under the IAEA's classification of "passive B" systems because of their minimal reliance on some active components such as motor operated valves. Later we will examine what, if any, benefits these systems offer.

Significant natural circulation flow exists in all BWRs as previously discussed. For a given core power, there is a corresponding natural circulation flow. In order to maintain sufficient flow at higher power levels using natural circulation, modifications were made to the ABWR design. The "pressure losses" encountered by the coolant as it followed its tortuous path through the core were identified and minimized. Figure 2.8 shows the typical flow of coolant through the ESBWR.

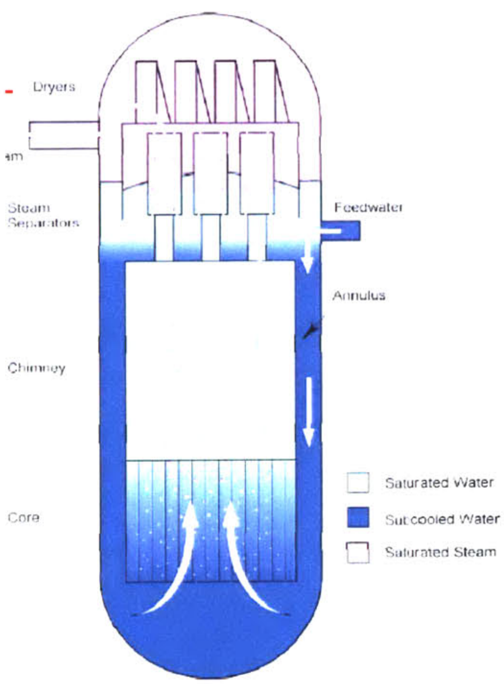


Figure 2.8 Coolant Flow Through ESBWR Vessel[8]

The following modifications were made to the ESBWR to improve natural circulation:

-Increased chimney height
-Unrestricted downcomer
-Shorter fuel/core length (~10 feet instead of usual 12 feet)
-Improved steam separators

The increased chimney height resulted in a greater buoyancy driving head while the shorter fuel, unrestricted downcomer, and improved separators minimized flow pressure losses. The downcomer in the ABWR has a very large pressure loss at the internal pump minimum flow area. Since the ESBWR has no internal pump, its downcomer flow is less restrictive. Figure 2.9 summarizes these improvements.

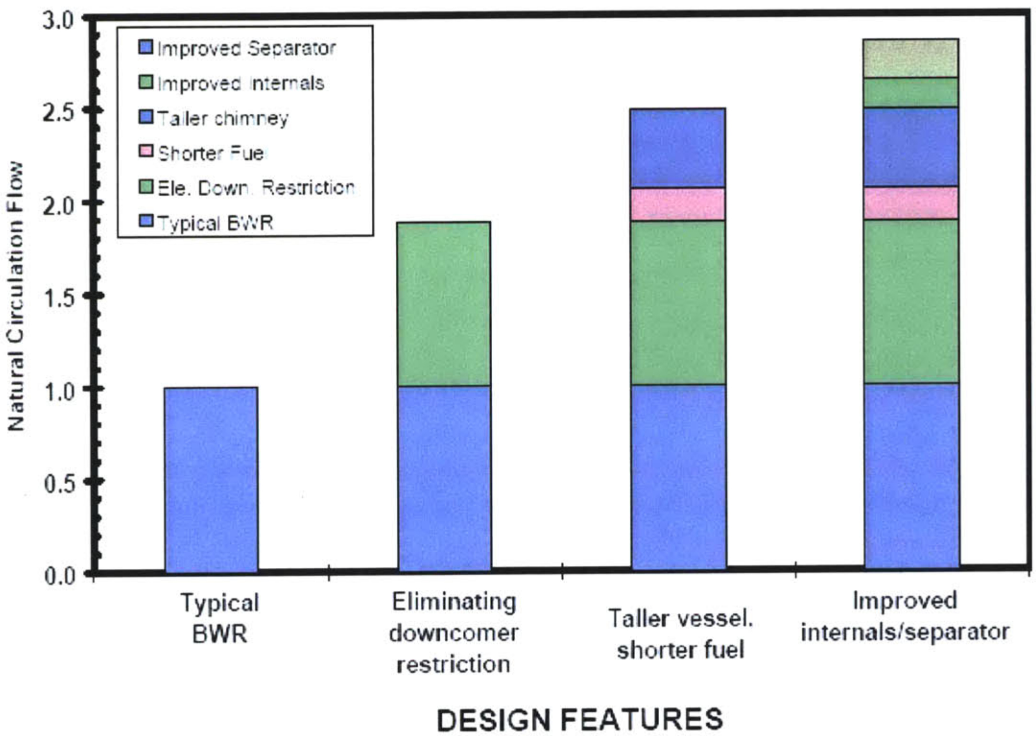


Figure 2.9 ESBWR Natural Circulation Improvements[12]

Under normal operation, the natural circulation in the ESBWR is established due to the density differences between the water in the vessel annulus (outside the shroud and chimney) and the steam/water mixture inside the shroud and chimney. The colder, higher density water in the annulus creates a higher pressure or a driving head when compared to the hotter, lower density fluid (steam/water) in the core and chimney. It's the energy produced in the core of the reactor which heats the water entering at the bottom of the core, and converts it to a steam/water mixture. In the core the subcooled water is first heated to the saturation temperature and then additional heat is added, starting the boiling process of the core coolant. As the coolant travels upward through the core, the fraction of saturated steam increases until at the exit of the core the fraction of saturated steam is about 18-weight % (18% quality). This low-density steam/water mixture travels upward through the chimney to the steam separators where centrifugal force separates the steam from the water. The separated, saturated water returns to the volume around the separators while the slightly "wet" steam travels upward to the steam dryers and eventually out the main steam nozzle and piping to the turbine. Cooler feedwater re-enters the vessel at the top of the annulus, to mix with the saturated water around the separators and subcool this water. The resulting mixture is subcooled only a few degrees below the saturation temperature. The cooler mixture then travels downward through the annulus to re-enter the core. The water therefore forms a recirculation loop within the vessel. The mass of steam leaving the vessel is matched by the mass of feedwater entering. The chimney adds height to this density difference, in effect providing additional driving head to the circulation process. A forced circulation BWR acts in the same basic manner but uses the internal or external pumps to add driving head to this recirculation flow instead of the elevation head provided by the chimney. A pump has entrance and exit losses associated with it and the pump must produce the driving head to overcome these additional losses.

Using complete natural circulation greatly simplifies the reactor design while still maintaining power/flow ratios similar to the ABWR. The taller ESBWR vessel used to stimulate natural circulation also offers a greater margin to the core becoming uncovered because of the greater initial volume of makeup water in the vessel during operation. This added margin is shown in the next chapter. The next area of focus will be the passive safety systems employed by the ESBWR.

The passive safety systems of the ESBWR can be broken up into the following systems: Isolation Condenser, Passive Containment Cooling System, and Gravity Drain Cooling System. Each of these systems has its own responsibilities. In addition, they all evolved from the SBWR and have previously been tested. Figure 2.10 shows a schematic for these passive systems.

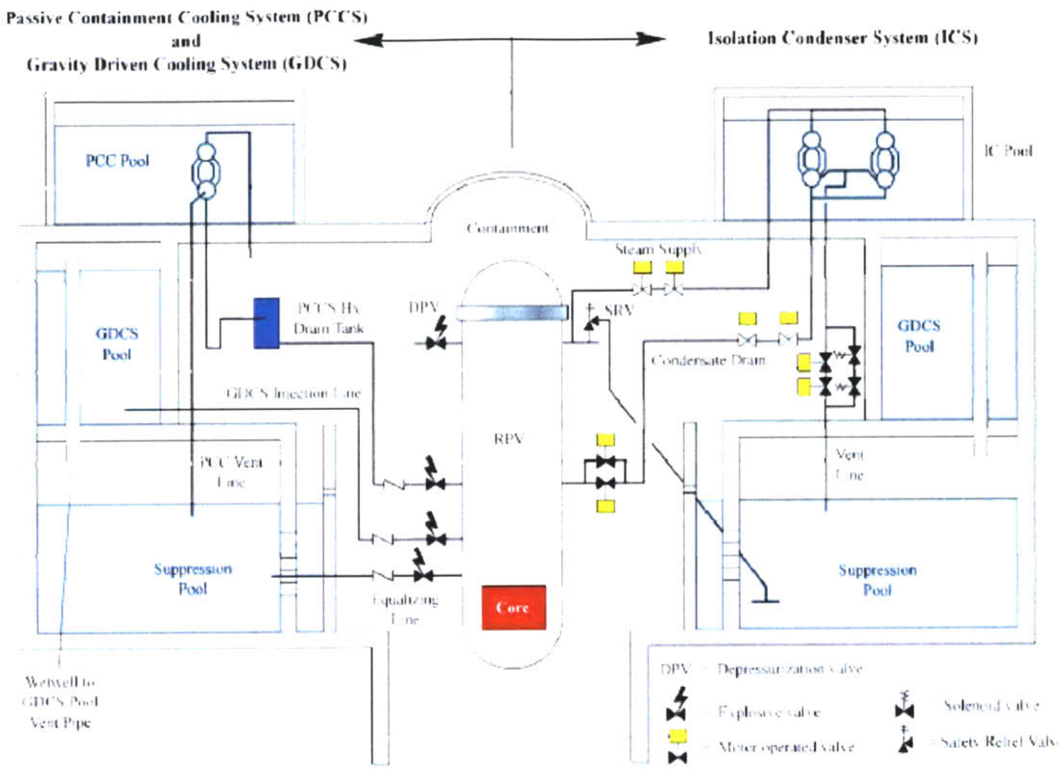


Figure 2.10 ESBWR Passive Safety Systems[8]

2.1.2.1 Gravity Drain Cooling System

The GDCS is a passive safety system which uses gravity to inject water into the reactor from the GDCS pool, an annular pressure suppression pool located at an elevation above the reactor core. It provides a simple approach to Emergency Core Cooling eliminating the need for pump or diesels, and does not need short term (three days) operator action. It requires more water in the reactor vessel above the core and additional depressurization capacity, so the reactor can be depressurized to very low pressures and gravity flow from the elevated GDCS pool can keep the core covered. The additional water can also reduce pressure rise rates for transients and add substantially more time before the core uncovers in multiple failure scenarios. Because ESBWR is a natural-circulation design, there are no large pipes attached to the vessel near or below the core elevation. Thus, the design insures full core coverage for all design basis events. A plant using the GDCS feature has the potential to be more economical to design, construct, and operate due to the reduction in safety system equipment and the resulting reduction in support systems.

The GDCS has four separate divisions, three pools, and vessel depressurization by two diverse valve designs--the SRV and the depressurization valve (DPV). The SRV is air operated while the DPV is explosive charge. The GDCS has three subsystems—short term, long term, and deluge. The short term system flow path is from the GDCS pool to the vessel through two injection lines per division. This system handles all LOCA scenarios. The squib valves open 150 seconds after the low-low vessel level signal. The long term system flow path is from the suppression pool to the vessel through one equalizing line per division. In this case, the squib valves open 30 minutes after the low-low vessel level signal. This system is primarily for protection against bottom drain line breaks. The deluge system uses GDCS water to provide corium cooling to the lower drywell. Here, the squib valves open on high concrete temperature. Figure 2.11 shows the GDCS system.

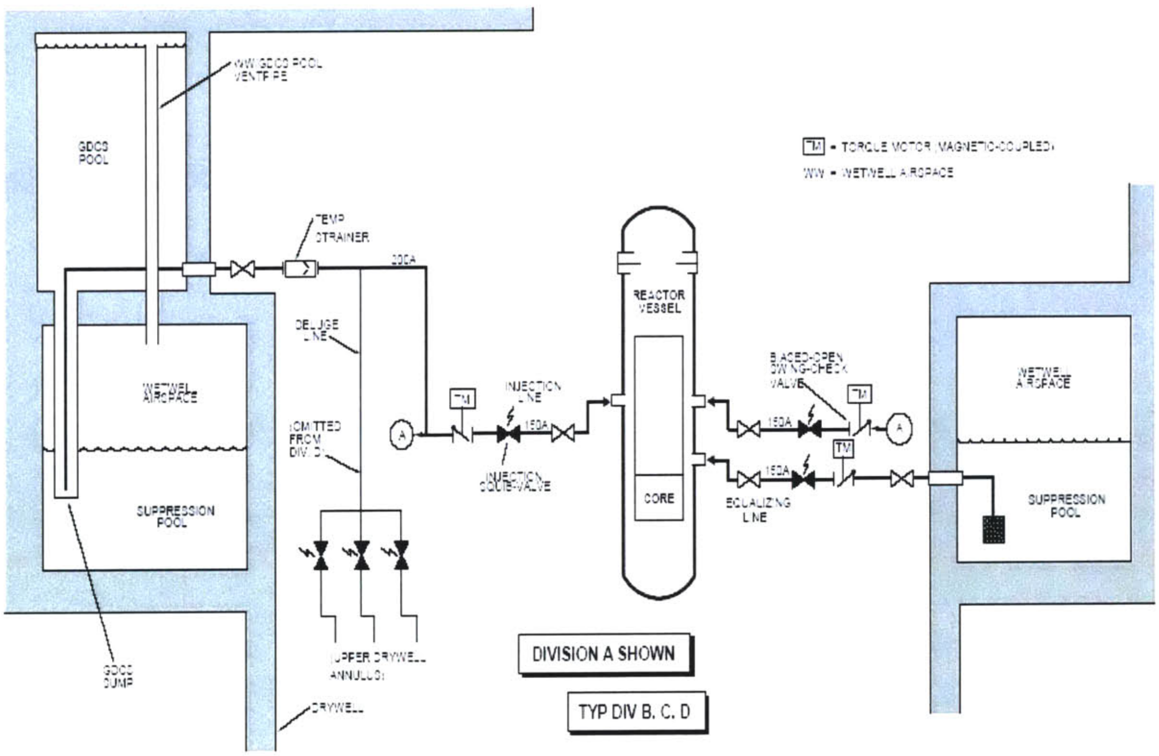


Figure 2.11 ESBWR Gravity Drain Cooling System[13]

2.1.2.2 Isolation Condenser System

The isolation condenser system (ICS) is a similar system to those used in older boiling water reactor designs. It consists of a pool located outside of the containment with a heat exchanger. The ICS transfers residual and decay heat from the reactor coolant to the water in the shell side of the heat exchanger resulting in steam generation. The steam generated in the shell side of the heat exchanger is then vented to the outside atmosphere. The system employs natural circulation as the driving head from the reactor steam side, through the isolation condenser tubes, and back to the reactor. The ICS is automatically initiated if a high reactor pressure condition is sustained for 15 seconds. The time delay prevents unnecessary system initiation during turbine trips. Also, the ICS automatically initiates on a low vessel water level to aid in reducing reactor pressure for small line breaks or when all main steam isolation valves are shut. The ICS is designed to provide core cooling regardless of whether electrical power is available which is beneficial during station blackout. It also provides decay heat removal during transients. The ESBWR ICS has four heat exchangers rated at 33.75 MWt each. Each condenser is connected through a separate loop to the reactor. Figure 2.12 shows a simplified ICS.

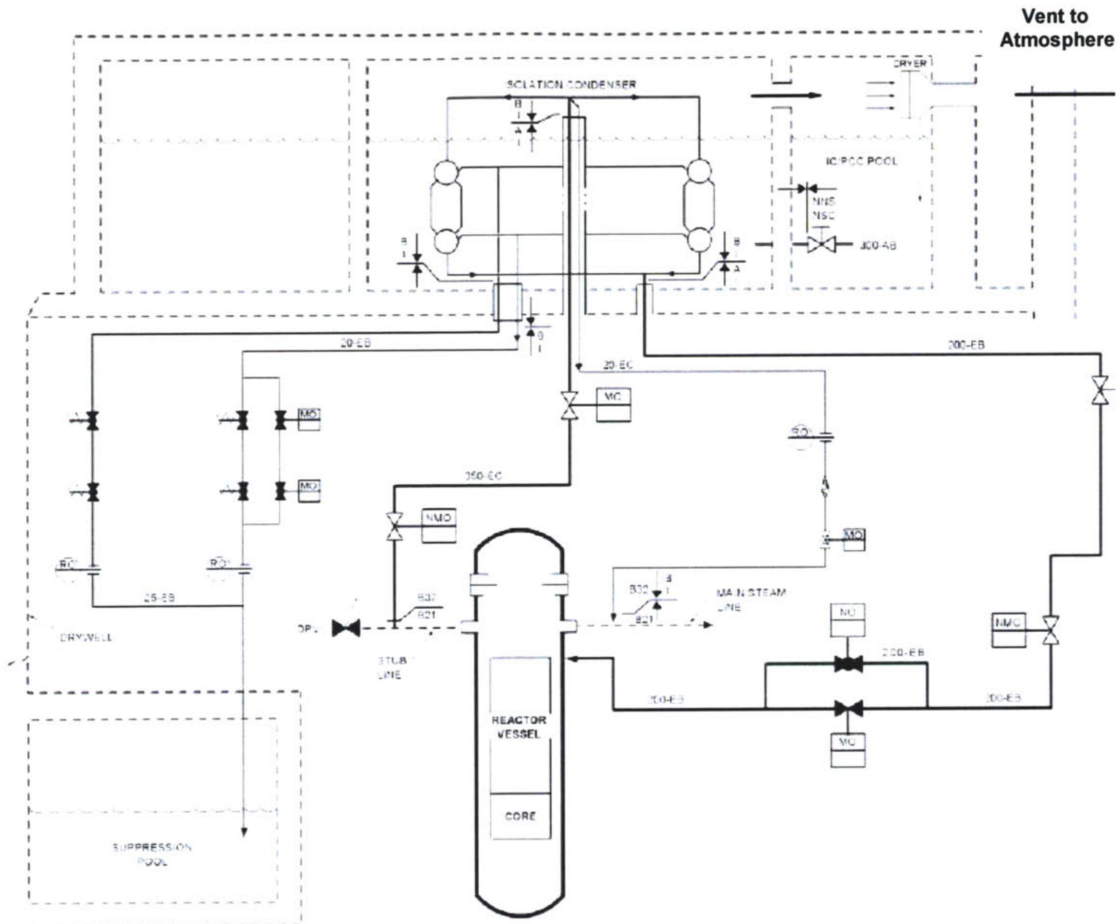


Figure 2.12 ESBWR Isolation Condenser System[13]

2.1.2.3 Passive Containment Cooling System (PCCS)

The heat transfer to the suppression pool during a LOCA accident can be removed automatically and passively for three days (72 hours) by the natural circulation water flow of the PCCS. The PCCS design includes a water filled annulus that is built into the side of suppression pool wall (also the containment wall). The heat of the pool is transfer to this "water wall" which in turn is cooled by natural circulation of the water inside the annulus. The PCCS is capable of cooling the pool this way for three days without the need for active pumps and standby diesels. Beyond 3 days, water makeup is all that is needed to continue the passive cooling functions. Containment venting is, therefore, not necessary to prevent pressure buildup or to retain containment integrity. Each heat exchanger is driven by drywell-to-wetwell pressure differential such that the steam-gas mixture seeks to find the lowest resistance pathway to restore pressure equilibrium. The heat exchanger vent lines are at less submergence than steam vents. The condensate drains to the open-top drain and holding tank which is sized to hold the condensate from initial 20 minutes of operation following a LOCA. These same tanks drain back to RPV after a time delay of ~ 30 minutes when explosive valves open. If these return valves fail to open, the condensate is not lost but returned to the lower drywell. The design pressure and temperature is 110 psig and 340°F and the 6 heat exchangers are rated at 11 MWt. Figure 2.13 shows a PCCS system.

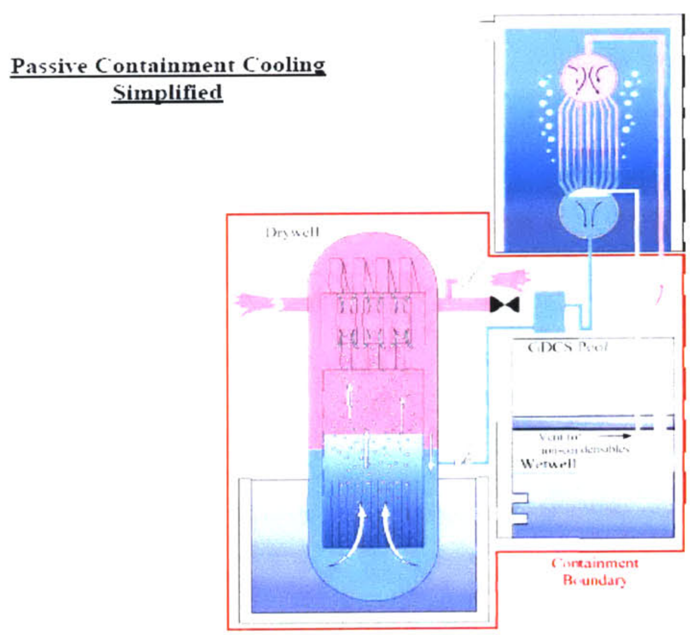


Figure 2.13 ESBWR Passive Containment Cooling System[8]

2.2 *Advanced Pressurized Water Reactor (PWR) Designs*

The PWR nuclear plant also has its origins in the U.S. Navy which continues to be the plant type of choice for all nuclear submarines and aircraft carriers. As mentioned, 69 of the 103 operating U.S. nuclear plants are of the PWR type while the remainder are BWRs. Like the BWR, the PWR has seen evolutionary design changes that have focused on simplification and enhanced safety. One recent passive design and one active design will be reviewed in detail here to contrast them against each other, and ensure that their differences are clear to the reader.

The EPR is a 1,600 MWe reactor that utilizes experience from several light water reactors worldwide to shape its design, primarily focusing on the more recent technologies of the French N4 and German KONVOI reactors. The EPR was developed in the mid 1990's by Framatome and Siemens, whose nuclear activities were combined in January 2001 to form Framatome ANP, a subsidiary of AREVA and Siemens. This collaborative effort also received assistance from French and German utilities. The extensive multi-national development effort used in its design has made it more advanced than any currently operating PWR. EPR designers chose an evolutionary course emphasizing active safety features, as active features are the standard in operating PWRs. The overall goal is to produce an economically competitive reactor while achieving a greater level of safety. Some of the more notable EPR design features are the following[14]:

- Aircraft crash resistance upgrade
- In-containment borated water storage tank
- Features to mitigate accidents beyond design base accidents (DBA)
- State-of-the-art digital control systems and control room design.
- Four trains of active safety equipment to maximize reliability and maintainability.

The four-train concept will be discussed in more depth in the next section. Table 2.4 outlines the evolutionary specifications for the EPR:

Table 2.4 EPR Specifications[15]

		EPR	N4 Framatome	KONVOI Siemens
Thermal power	MWth	4300	4250	3850
Electrical power	Mwe	~1600	1475	1365
Efficiency	%	37	34.7	35.4
Number of primary loops		4	4	4
Number of fuel assemblies		241	205	193
Design service lifetime	years	60	40	40

Around the same time of EPR design, Westinghouse was working on a new PWR that featured passive safety systems as part of the U.S. Department of Energy funded "Advanced Light Water Reactor" Program. This new reactor was known as the AP600 because of its passive safety and the fact that it generated 600MWe of electricity. The AP600 was more of a "revolutionary" design for Westinghouse since no previous PWR had been licensed that featured passive safety (although GE was simultaneously working on its SBWR, which featured passive safety). During the AP600 design program, a comprehensive test program was carried out to verify plant components, passive safety systems components, and containment behavior. When the test program was completed at the end of 1994, AP600 became the most thoroughly tested advanced reactor design ever reviewed by the U.S. NRC. The test results confirmed the exceptional behavior of the passive systems and have been instrumental in facilitating code validations. Aside from the simplified passive safety systems, the remainder of the AP600's major components are based on years of operating experience and evolutionary design from other PWRs. The AP600 received final design approval in the United States on September 3, 1998, but received little commercial success perhaps due to its low rated power (please recall that this is why GE cancelled its 600 MWe SBWR program to focus on the higher rated ESBWR). Westinghouse realized that it could significantly improve the rated power of its passive reactor by making only a few minor changes and utilizing economies of scale. Thus, the AP1000 design was born which could produce 1090 MWe. Table 2.5 outlines the major differences between the AP600 and AP1000 reactors.

Table 2.5 AP600/AP1000 Differences[16]

Feature	AP600	AP1000
Net Electric Output, MWe	600	1090
Reactor Power, MWt	1933	2993
Hot leg temperature, °F	600	615
Number of Fuel Assemblies	145	157
Type of Fuel Assembly	17 X 17	17 X 17
Active Fuel Length, ft.	12	14
Core loading, MTU	66.9	84.5
Linear Heat Rating, kw/ft	4.1	5.03
Average Power Density, kw/l	78.82	96.6
Reactor Coolant Pump Flow, gpm	51,000	65,000
Pressurizer volume, cubic ft	1600	1800

While the AP1000 containment and pressure vessel remained the same diameter as the AP600, the overall height of each increased to accommodate the increase in power. The AP1000 pressure vessel is 18 inches longer than the AP600 vessel. It should be noted that while the thermal power was increased by nearly 50%, the coolant flow was increased by only 24%. Increased heat removal capability by the flow was introduced by allowing a larger temperature rise across the core. This also led to improved power conversion efficiency.

2.2.1 Evolutionary Power Reactor (EPR)

EPR's Emergency Core Cooling system (ECCS) or Safety Injection system (SIS) comprises four trains, each of them consisting of a medium head safety injection (MHSI), an accumulator (a passive safety component), and a low head safety injection (LHSI). The RHR system is also included in this section because the SIS and RHR system are strongly correlated. With four independent, identical trains, the EPR SIS utilizes defense in depth. Injection mode is into the cold legs of the main coolant line (MCL) which is consistent with most French designs. The German PWR designs use a combined injection into both the hot and cold legs. This caused some tension in the early design phase as Framatome ANP had to prove the efficiency of the ECCS over all relevant accident sequences to the German safety authorities.

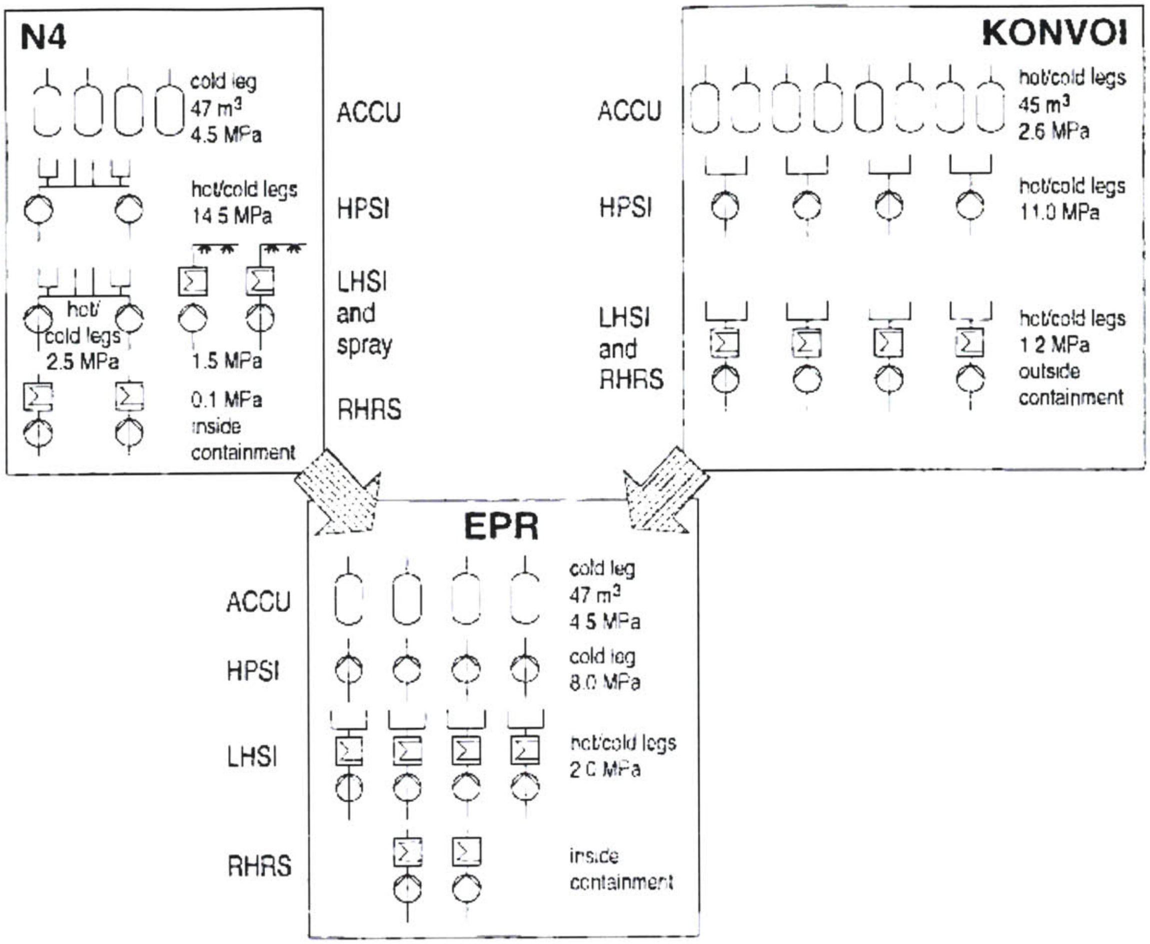
The EPR's SIS configuration is based on evolutionary design. German (KONVOI) design is characterized by a fourfold redundancy, strict separation of redundant systems (i.e. no headers), and no functional separation between the LHSI and RHR. Conversely, French (N4) design features twofold redundancy, no separation of redundancies (two trains are interconnected by headers), and functional separation of the LHSI and RHR. Each of these design approaches has its advantages: A high degree of redundancy enables the performance of preventive maintenance during operation and therefore increases plant availability while providing a limited number of redundant systems. Taking into account various backup functions is significantly beneficial for fulfillment of probabilistic safety criteria.[17]

The EPR SIS provides a fourfold redundancy as usual in the German design approach. A single train will be discussed here. High-pressure safety injection (HPSI), used for N4 and KONVOI, is replaced by a MHSI, which begins injection at 8.0 MPa into the cold leg. This is beneficial for mitigation of steam generator (SG) tube ruptures, because the potential for overfeeding of the SG and containment bypass are reduced. The SG pressure is reduced from 9.15 MPa to 6 MPa via main steam relief valves which allows the MHSI cooling to start. As the pressure continues to decrease, the next system in line is the nitrogen accumulator which is kept at a pressure of 4.5 MPa (gas and water volumes are 15 and 32 m^3 respectively) and also injects into the cold leg. Following the accumulators, the LHSI starts injection at 2.0 MPa, before complete emptying of the accumulators. LHSI pumps, in the short term, inject into the cold legs as well. In the long term (two hours after accident beginning), LHSI is switched over to combined injection into both the cold and the hot legs of main coolant line. This ensures a well-balanced pressure scaling of SIS components. Table 2.6 shows the main EPR Safety system response to accidents. Figure 2.14 shows how the EPR SIS has evolved from the French N4 and German KONVOI safety injection systems and outlines the improvements of the EPR safety system over its two predecessors.[17]

Table 2.6 Main EPR Safety System Actions[17]

Signal	Criteria
Reactor trip	Pressure < 13 MPa
ECC signal	Pressure < 11 MPa
RCP trip	LOOP or saturation at cold leg
MHSI	Pressure < 8.0 MPa and ECC signal + 30 s[a]
LHSI	Pressure < 2.0 MPa and ECC signal + 30 s[a]
Partial cooldown[b]	ECC signal
EFWS	SG level < 8 m + 50 s

[a]Delay due to diesel load step.
[b]The SGs are cooled down via the SG relief valves from 9.15 to 6 MPa with a gradient of 100 K/h.



EPR's SIS improvements over N4 SIS	EPR SIS improvements over KONVOI SIS
Fourfold redundancy	Increased accumulator pressure to 4.5 MPa
Strict separation of redundancies	Optimized accumulator water-to-nitrogen ratio
Reduced shut-off head of MHSI pumps (8.0MPa instead of 4.5 MPa)	Reduced shut-off head of MHSI pumps (8.0 MPa instead of 11.0 MPa
	Increased shut-off head of LHSI pumps (2.0 MPa instead of 1.0 MPa)
	No accumulator isolation
	IRWST instead of water tanks (inside containment)
	Reduced to 4 accumulators from 8 optimizing capacity

Figure 2.14 EPR Safety Injection System Evolution[17]

The purpose of using four identical, completely independent trains is based on the following logic. Loss of off-site power is assumed as an accident initiation. Assume one train is down for preventive maintenance. A second diesel fails to start (single failure criterion). Therefore only two MHSI pumps, two LHSI pumps and two trains of the Emergency Feed Water System (EFWS) remain available. However, when the break is located in the cold leg, the corresponding injections are not considered, thus leaving the operator with only one train available to provide long term cooling. One train is sufficient to provide all necessary safety functions for all relevant accident scenarios.[18]

These safety injection trains draw suction from the Incontainment Refueling Water Storage Tank (IRWST) which is practically an unlimited water source. The water in the tank is cooled by RHRS and/or LHSI heat exchangers. Together with the heat exchangers in the LHSI flow path, this ensures emergency core cooling without the need for a containment spray system for design basis accidents (a spray system of reduced size is provided for containment cooling in case of severe accidents). The IRWST is located inside the containment in order to avoid the suction switchover from injection to recirculation mode, which adds unreliability to the system. In case of core melt accidents, IRWST provides water for corium cooling.

The Residual Heat Removal System is combined with the Low Head Injection System. It transfers the residual heat from the reactor coolant system, via the cooling chain consisting of component cooling water system and service water system, to the ultimate heat sink, when heat removal via the steam generator is not sufficient. For residual heat removal from inside the containment after severe accidents, a dedicated containment heat removal system is provided. Its primary function is to limit the pressure increase inside the containment due to residual heat in order to ensure that during a severe accident the containment design pressure is not exceeded. Due to its high efficiency with regard to pressure reduction and its capability to maintain an adequate long-term cooling, a spray system with heat exchangers has been selected. In case of bleed the discharge of steam is done directly into the containment via a relief tank.

The steam generator emergency feedwater system consists of four separate and independent trains, each providing injection to one of the four steam generators. Each emergency feedwater pump takes suction from an emergency feedwater tank. These tanks and the systems are located in the four divisions, the safeguard buildings. The four emergency feedwater pumps are driven by electric motors which are, in an emergency power case, supplied electricity by four diesel generators. "Passive" headers can be manually opened when necessary in the long term. In order to practically eliminate the risk of core melt in case of total station blackout, two small diesel generators are also provided. They supply two emergency feedwater trains and the necessary I&C.

This system organization fulfils the principle of simplification as well as the principle of diversification, since any safety grade system function can be backed-up by another system (or a group of systems). Figure 2.15 shows a simple diagram of the EPR safety injection system.

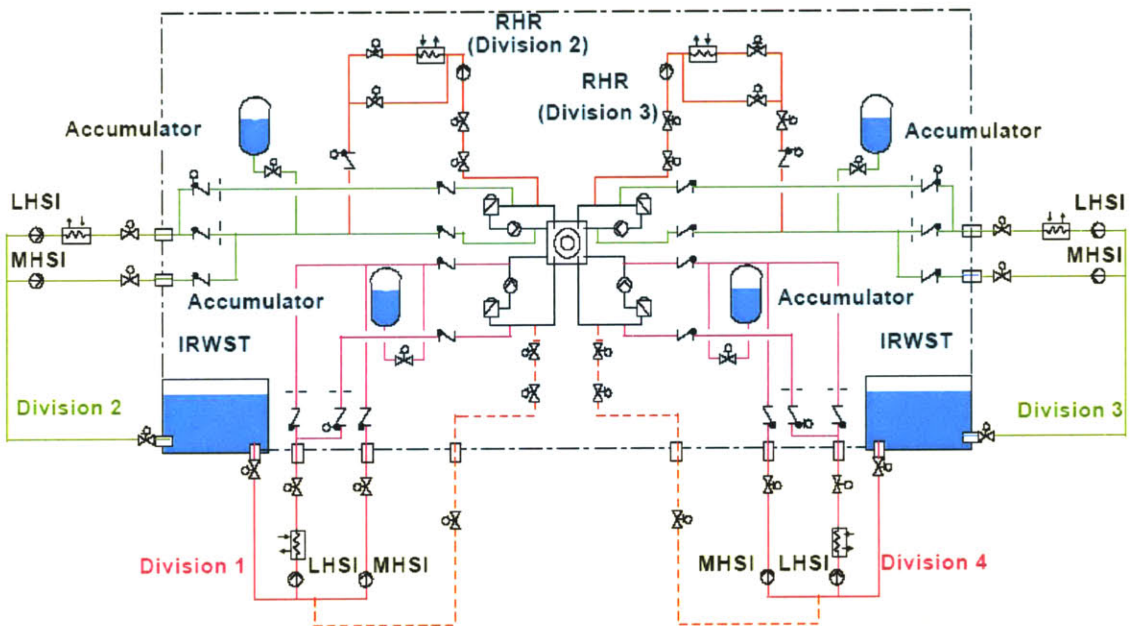


Figure 2.15 EPR Safety Injection System[18]

2.2.2 AP1000 Reactor

The safety systems for the AP1000 include passive safety injection, passive residual heat removal, and passive containment cooling. Proponents of passive systems argue that they do more than increase safety, enhance public acceptance of nuclear power, and ease licensing - they also simplify overall plant systems, equipment, and operation and maintenance. The simplification of plant systems, combined with large plant operating margins, greatly reduces the actions required by the operator in the unlikely event of an accident, a major contributor to the accident at Three Mile Island.

Simple changes in the safety-related systems from AP600 to AP1000 allow accommodation of the higher plant power without sacrificing design and safety margins. Since there are no safety-related pumps, increased flow was achieved by increasing pipe size. Additional water volumes were achieved by increasing tank sizes. These increases were made while keeping the plant footprint unchanged. This ensures that the designs of other systems are not affected by layout changes. The passive safety systems have been sized to provide increased safety margins, especially for more probable initiating events. Table 2.7 illustrates the improved margins.

Table 2.7 AP1000 Improved Safety Margins[19]

Event	Typical Plant	AP600	AP1000
Loss of Flow Margin to DNBR Limit	~1-5%	~16%	~19%
Feedline Break °C (°F) Subcooling Margin	>0 (>0)	~94 (~170)	~78 (~140)
SG Tube Rupture	Operator actions required in 10 min	Operator actions **NOT** required	Operator actions **NOT** required
Small LOCA	3" LOCA core uncovers PCT ~1500°F	< 8" LOCA **NO** core uncovery	< 8" LOCA **NO** core uncovery
Large LOCA PCT °C (°F) with uncertainty	1093-1204 (2000-2200)	913 (1676)	1162 (2124)

2.2.2.1 Passive Core Cooling System (PXS)

The passive core cooling system (PXS) protects the plant against leaks and ruptures of various sizes and locations. The PXS provides core residual heat removal, safety injection, and depressurization. The PXS is located inside the containment, and consists of the following major subsystems and associated components:

-an incontainment refueling water storage tank (IRWST)
-a passive residual heat removal heat exchanger (PRHR HX)
-two core makeup tanks (CMTs)
-an automatic depressurization system (ADS)
-two accumulators
-pH adjustment baskets
-associated piping, valves, instrumentation, and other related equipment

These PXS subsystems or components require only a one-time alignment of valves upon actuation. Once the initial actuation alignment is made, they rely solely on natural forces such as gravity and stored energy to operate. The use of active equipment or supporting systems, such as pumps, ac power sources, component cooling water or service water, is not required. The PXS is designed to mitigate design-basis events that involve a decrease in the RCS inventory such as a LOCA, or an increase or decrease in heat removal by the secondary system. For those non-LOCA events that result in an increase or decrease in heat removal by the secondary system, the PRHR HX and CMT are actuated by the protection to remove core decay heat and provide makeup and boration for reactor coolant shrinkage. For events that reduce RCS inventory, the CMTs are actuated by the protection to deliver borated water to the RCS via the DVI nozzles. As the CMTs drain down, the ADS valves are sequentially actuated to depressurize the RCS and establish the low-pressure conditions that allow injection from the accumulators, the IRWST and the containment recirculation sump.[20]

The IRWST is a large tank located above the elevation of the RCS loops that contains more than 2,234 m3 (78,900 ft3) of borated water and is designed for atmospheric pressure. It is the source of low-pressure safety injection by gravity and the heat sink for the PRHR HX, which is submerged within it. The IRWST water absorbs decay heat for more than one hour before the water begins to boil. Once boiling starts, steam passes to the containment. The steam condenses on the steel containment vessel and, after collection, drains by gravity back into the IRWST. Thus, the IRWST can provide long-term injection water by means of gravity if the RCS is depressurized. The RCS is automatically controlled to reduce pressure to about 0.83 bar (12 psig), at which point the head of water in the IRWST overcomes the low RCS pressure and the pressure loss in the injection lines. The PRHR HX and the passive containment cooling system provide indefinite decay heat removal capability with no operator action required.

The PRHR HX is connected to the RCS through an inlet line from one RCS hot-leg and an outlet line to the associated SG cold-leg plenum (RCP suction). The PRHR HX removes core decay heat by natural circulation. The PXS includes one PRHR HX. The PRHR HX protects the plant against transients that upset the normal steam generator feedwater and steam systems. It satisfies the safety criteria for loss of feedwater, feedwater line breaks, and steam line breaks.

The CMTs, which are filled with borated water during normal operation, are located at an elevation above the RCS loops, and are connected to the RCS by pressure balance lines from the cold-legs, which maintain the CMTs at the RCS pressure. The outlet line from the bottom of each CMT provides an injection path to the direct vessel injection (DVI) lines into the reactor.

The accumulators are filled with borated water that is pressurized with nitrogen gas and will inject via the DVI lines into the RCS when the RCS pressure falls below the accumulator pressure.

The PXS provides depressurization using the four stages of the ADS to permit a relatively slow, controlled RCS pressure reduction. The first three stages are connected to the top of the pressurizer and discharge through a sparger into the IRWST, and the fourth stage valves connect to the top of the RCS hot-legs and vent directly into the SG compartment. The ADS valves are actuated sequentially to depressurize the RCS to allow for gravity injection from the IRWST. The PXS is shown in Figures 2.16 and 2.17 below.

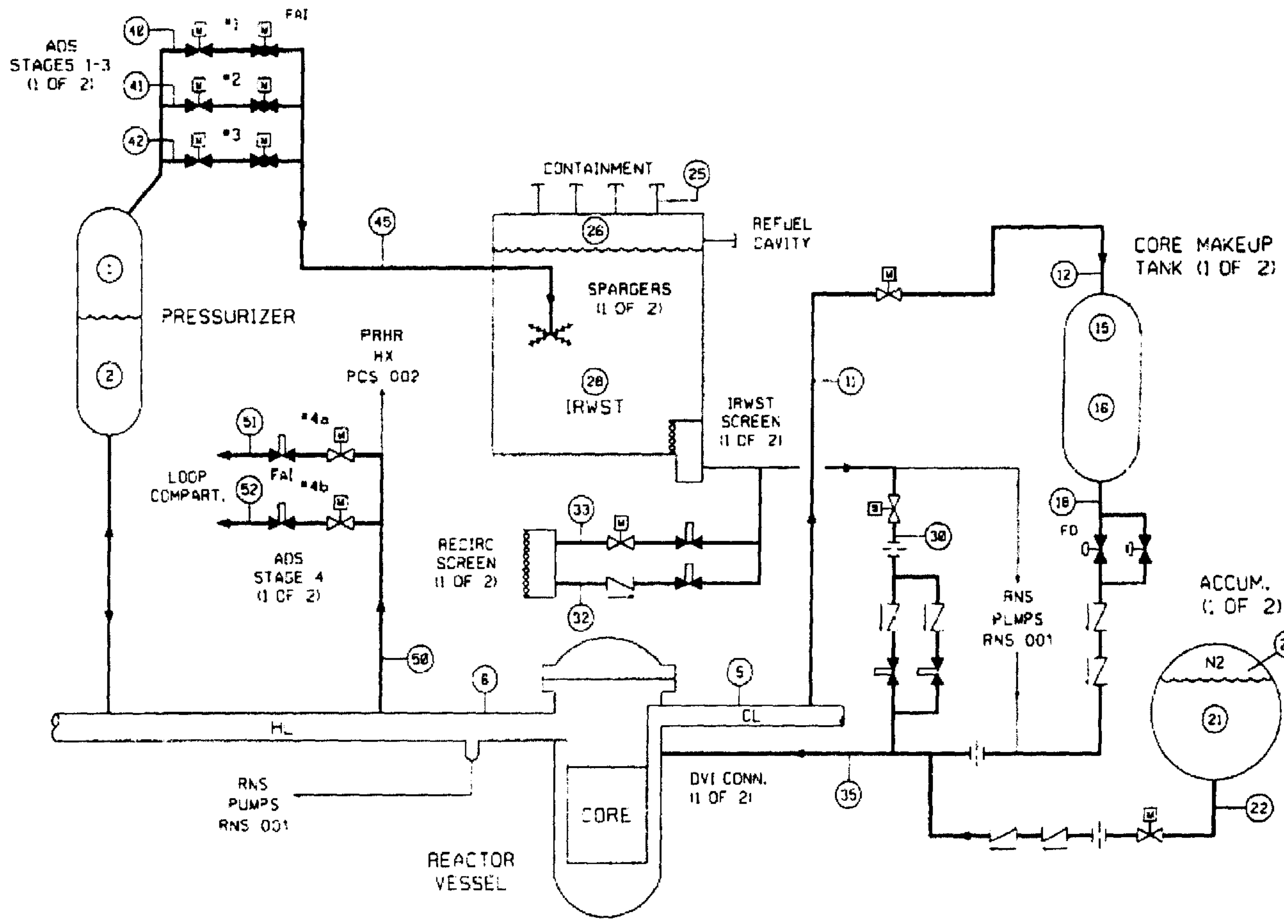


Figure 2.16 AP1000 Passive Core Cooling System[20]

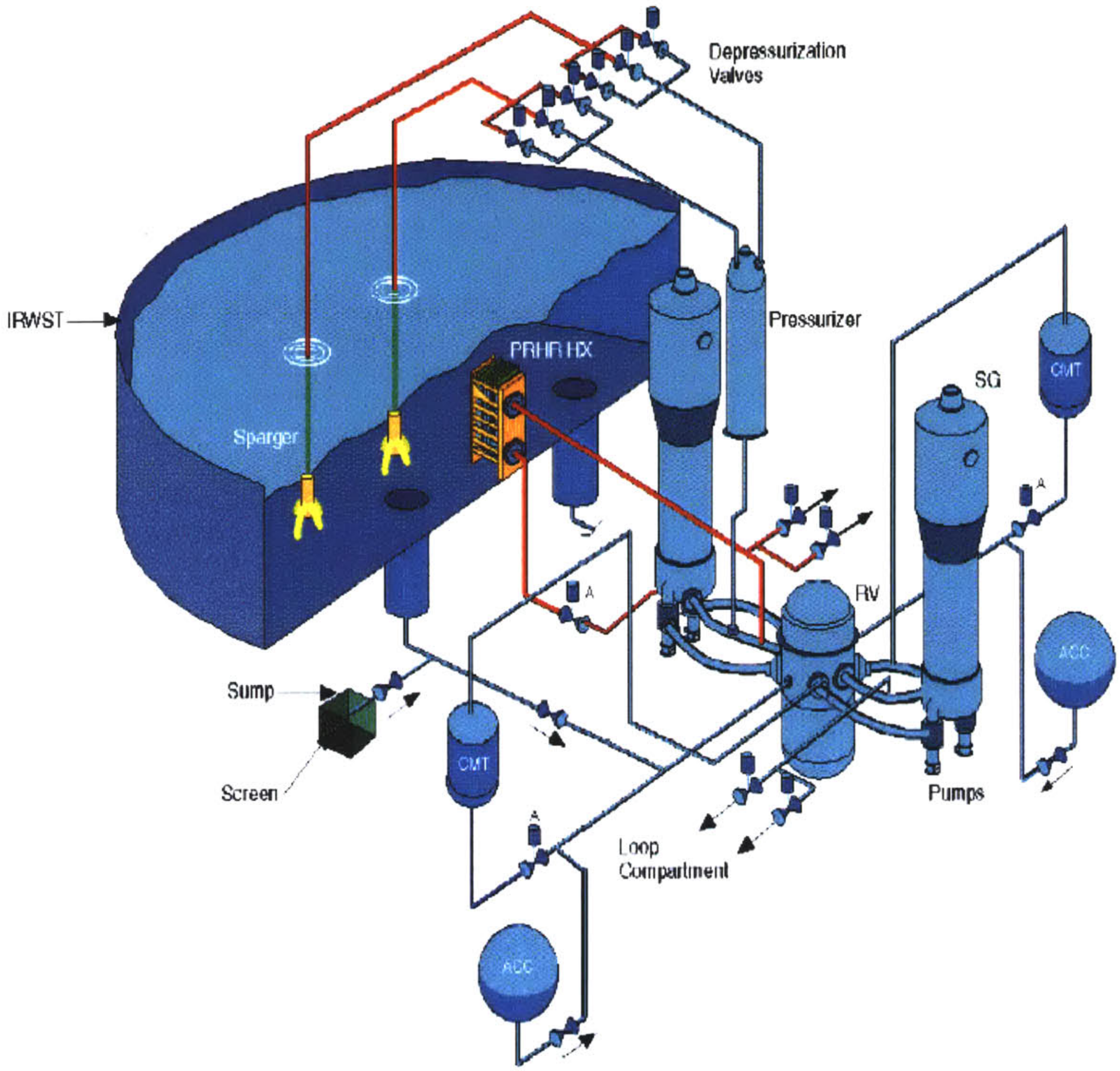


Figure 2.17 AP1000 PXS (color)[19]

2.2.2.2 Passive Containment Cooling System (PCS)

The passive containment cooling system (PCS) consists of the following components:

- a passive containment cooling water storage tank that is incorporated in the shield building structure above the containment
- an air baffle that is located between the steel containment vessel and the concrete shield building
- air inlet and exhaust paths that are incorporated in the shield building structure
- a water distribution system
- an ancillary water storage tank and two recirculation pumps for onsite storage of additional PCS cooling water

The PCS provides the safety-related ultimate heat sink for the plant. The PCS cools the containment following an accident so that design pressure is not exceeded and pressure is rapidly reduced. On actuation, the PCS delivers water to the top, external surface of the steel containment shell, which forms a film of water over the dome and sidewalls of the containment structure. Air heating leads to flow over the steel containment as it is heated, causing a chimney effect in the space between the steel and concrete shield. This airflow and cooling water evaporation removes the heat generated within the containment and expels it to the outside air. Westinghouse states that the passive containment cooling system maintains the containment pressure and temperature within the appropriate design limits for both design basis and severe accident scenarios. Figure 2.18 shows the passive containment cooling system.[20]

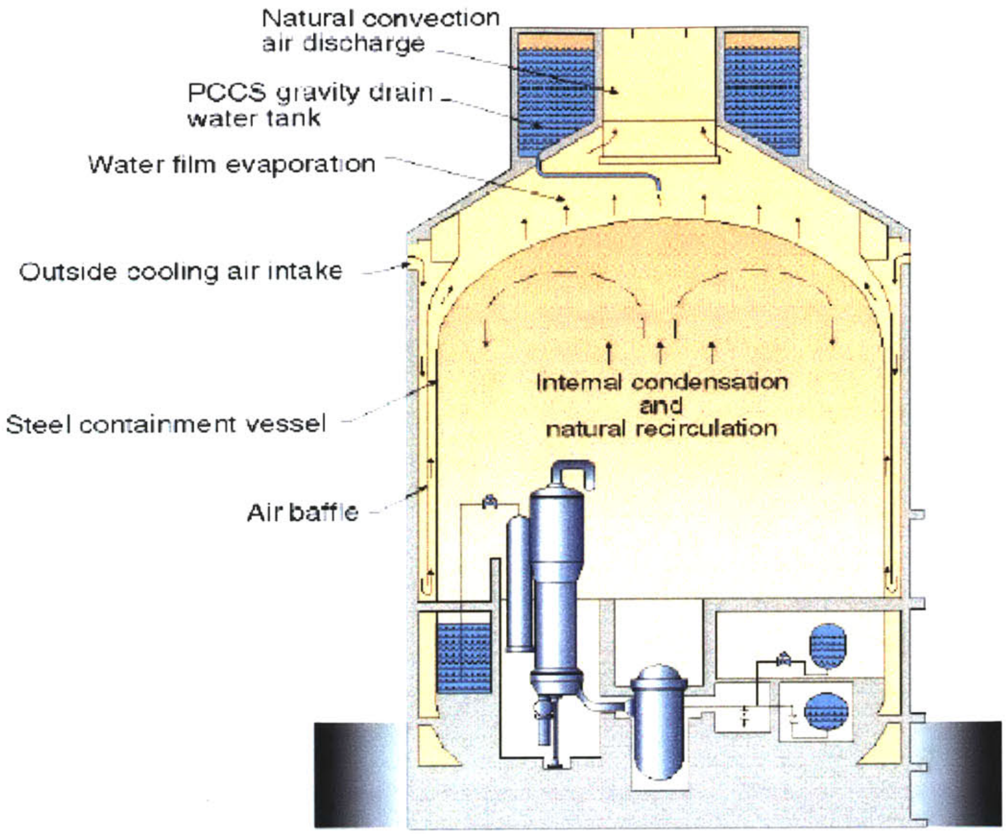


Figure 2.18 Passive Containment Cooling System[21]

The major function of the containment isolation system is to provide containment isolation to allow the normal or emergency passage of fluids through the containment boundary while preserving the integrity of the containment boundary. This prevents or limits the escape of fission products that may result from postulated accidents. The containment isolation provisions are designed so that fluid lines that penetrate the primary containment boundary are isolated in the event of an accident. The system consists of the piping, valves, and actuators that isolate the containment.

Chapter 3. Reactor Safety Comparison

3.1 General

The purpose of this chapter is to compare the selected reactors in terms of safety, specifically Core Damage Frequency (CDF). While there are other components of safety, such as occupational dose or containment failure probability, this comparison focuses solely on CDF. The reason for this is because this study focuses primarily on emergency core cooling system differences and CDF is the best measure. To determine CDF, a probabilistic risk assessment (PRA) can be performed or one can just use historical data if available. Probabilistic risk assessment is a mature methodology that can provide a quantitative assessment of the risk from accidents in nuclear power plants. It involves the development of models that delineate the response of systems and operators to accident initiating events (either external or internal to the reactor). Additional models are generated to identify the component failure modes required to cause the accident mitigating systems to fail. Each component failure mode is represented as an individual "basic event" in the systems models. Estimates of risk are obtained by propagating the failure probability and uncertainty distributions for each of the parameters through the PRA and its uncertainty models. For our comparisons here we will use reported PRA results from the vendors to determine CDF.

It is important to note that PRA is usually done by a group of individuals or a team. Two different teams are likely to get differing results when performing PRA on the same reactor. Furthermore, the nearer one gets to low probabilities (10^{-8} or so), the more sensitive the result is to minor changes in reliability/probability. Besides these limitations, PRA is a useful tool to help understand the risk of core damage for a given reactor.

The current U.S. Nuclear Regulatory risk goal for CDF is $1 \text{ X } 10^{-4}$ accidents per reactor year. All licensed reactors in the U.S. must have a CDF less than this standard. After reactor modification following TMI insights, most currently operating reactors in the U.S. have a CDF on the order of $5 \text{ X } 10^{-5}$.

3.2 ABWR vs. ESBWR

Earlier in Chapter 2, the safety systems of the GE's ABWR and ESBWR were discussed. While overall these systems each maintain an excellent level of safety, some systems handle some accidents better than others. Table 3.1 shows the overall CDF for the ABWR and ESBWR along with the major contributions to each reactor's total CDF, as calculated by the vendor.[50]

Table 3.1 CDF for ABWR and ESBWR[22]

Internal events PRA comparison

	BWR/4	BWR/6	ABWR	ESBWR
Core Damage Frequency (CDF)	$1x10^{-5}$	$2x10^{-6}$	$2x10^{-7}$	$2x10^{-7}$
Contributors to CDF				
Station Blackout	92%	80%	71%	7%
ATWS	1%	10%	<1%	<1%
LOCA	5%	5%	1%	62%
Transients	2%	5%	29%	30%
Conditional Containment Failure Probability (CCFP)	70%	40%	0.2%	0.1%
Time to release for dominant sequence	10 hr	15 hr	>24 hr	Indef.

This leads to some interesting observations. First of all, both the ABWR and ESBWR achieve a factor of 10 decrease in CDF over current operating BWRs. In fact, the ABWR and ESBWR have the same probability of core damage according to these PRA results. This means that neither one is better than the other in terms of CDF even with a slight uncertainty. Furthermore, both these advanced reactors are nearing the area of CDF sensitivity to the analysis method, since both are on the order of 10^{-7} which means that these reactors could even be safer than these current values suggest. Most recent ESBWR numbers now claim a CDF of 3×10^{-8} which yields an order of magnitude less CDF than the ABWR although both well pass the current NRC goal.[23] One BWR expert claims "the race for safety is over".[22] It should be remembered that risk from external events will add to the total risk of core damage. This includes risk from fires and seismic events.

Analyzing each of the reactors more carefully based on the different initiating events provides some more insight. The ABWR improvements, fine motion control rods and automated controls, helped reduce the anticipated transients without scram portion of CDF due to finer rod control and less chance for human error. By adding a full third division to ECCS and an on-site gas turbine generator, the ABWR also improved on LOCA, transient, and SBO risk over the BWR/6.

The ESBWR saw similar results against the BWR/6. What is intriguing is the discrepancy between the ABWR and ESBWR against each other in SBO and LOCA. By substituting a gravity fed ECCS into the reactor instead of an active one, the ESBWR LOCA contribution to CDF went up relative to the other factors. This is due to the lack of high pressure ECCS. However, the use of its isolation condensers for transients reduced SBO risk significantly. These two competing effects both affected the contribution to CDF from transients which ultimately led to about even CDF for these two reactors.

While both reactors are clearly "safe" per the NRC's guidelines, the ESBWR (passive) is more apt to handle a station blackout event than the ABWR (active). In contrast, the ABWR is much better at handling LOCA's due to its rapid, high-pressure injection ECCS availability. Table 3.2 shows the ABWR's top initiating events contributors to its overall CDF.

Table 3.2 ABWR Top Initiating Event Contributors to CDF[11]

Initiating Event	Events per year	CDF X 1E-8	Percent CDF
Station Blackout < 2 hours	1.20E-06	6.7	43%
Station Blackout 2 < X < 8 hours	4.50E-07	2.6	16%
Station Blackout > 8 hours	1.60E-08	1.7	11%
Isolation/loss of feedwater	0.18	1.7	11%
Unplanned manual reactor shutdown	1	1.2	7%

As one can see, SBO dominates (~70%) as earlier shown. Even with an added gas turbine generator, this accident is the largest contributor to CDF. Although overall SBO CDF decreased due to this addition, it did not decrease as much as other systems and thus led to an increase in percent contribution to overall CDF. SBO being the largest contributor to CDF is consistent with risk profile estimates for many other BWR PRAs that have identified SBO as one of, if not the leading, contributor to core damage frequency.

Important lessons learned from this evolutionary design in regards to safety are[22]:

- Passive safety is not necessarily any better than active. Therefore, it should be incorporated only when economic benefits can be achieved.
- Point of diminishing return for further risk reduction from internal events is being reached in the 10^{-8} range due to the presence of external risk.
- There is little benefit from adding additional trains to an active ECCS when common-mode failures dominate the risk.
- With an active ECCS, providing additional SBO protection has some merit.
- Providing passive containment heat removal diversity to active ECCS has merit.
- Increasing rod insertion reliability and FMCRDs mitigated ATWS.
- AC independent water addition system is believed by some to be the most important system for helping to prevent severe accidents.
- It could eliminate 60 percent of sensor instrumentation in the reactor safety systems without affecting plant safety.

3.3 *EPR vs. AP1000*

The EPR has submitted its final safety report to Finland safety regulators, but does not currently allow access to the document. It will most likely have a very similar breakdown as the ABWR, its active safety counterpart. The only CDF estimates given by Framatome ANP are that the EPR reduces its CDF by a factor of 10 over current operating PWRs and more specifically, gives an actual CDF estimate of 1 X 10^{-6} accidents per reactor year. This value is still an order of magnitude higher than the CDF estimate for the AP1000 given in Table 3.3 below.

Table 3.3 AP1000 Initiating Event Contributions to CDF[24]

Initiating Event	AP1000 (CDF/yr)	Operating PWRs (CDF range/yr) IPE results [NUREG-1560]
LOCAs (Total)	2.1E-07	1E-6 to 8E-5
- Large	4.5E-08	
- Spurious ADS Actuation	3.0E-08	
- Safety Injection Line Break	9.5E-08	
- Medium	1.6E-08	
- Small	1.8E-08	
- CMT Line Break	4.0E-09	
- RCS Leak	3.0E-09	
Steam Generator Tube Rupture (SGTR)	7.0E-09	9E-9 to 3E-5
Transients	8.0E-09	5E-7 to 3E-4
Loss of Offsite Power/Station Blackout	1.0E-09	1E-8 to 7E-5
Anticipated Transient Without Scram (ATWS)	5.0E-09	1E-8 to 4E-5
Interfacing System LOCA	5.0E-11	1E-9 to 8E-6
Vessel Rupture	1.0E-08	1E-7
Total	2.4E-07	4E-6 to 3E-4

The reason for the differences could be a variety of things from conservative assumptions to an actual safety advantage for the AP1000. Regardless, both reactors are very safe and well exceed NRC's standard. EPR would argue that they have many additional features to mitigate the consequences of core failure in the event that it should occur such as a "core catcher" in the event of meltdown and a reinforced containment for external threats. However since we do not have the EPR's specific data, we will focus on the AP1000 PRA.

Westinghouse's AP1000 PRA results identify 100 sequences initiated by internal events that contribute almost 100 percent of the estimated CDF from internal events. The top 5 sequences are summarized as follows[24]:

1) Event is initiated by a break in one of the two safety injection lines (a LOCA event) followed by failure of the IRWST injection line, which is not affected by the break, to remove decay heat from the core (CMT injection and RCS depressurization via the ADS system are successful). In addition to the initiating event, risk important failures appearing in this sequence are:

- plugging of the IRWST discharge line strainer in the intact line,
- common cause failure (CCF) of the two check valves in the intact IRWST discharge line
- CCF of the two explosive (squib) valves in the intact IRWST discharge line.

2) Event is initiated by a large LOCA event which is not due to spurious ADS actuation (equivalent break diameter greater than 9 inches but smaller than a vessel rupture) followed by failure of any one of the two accumulators to inject. In addition to the initiating event, risk important failures appearing in this sequence are:

- failure of any check valve in the accumulator injection lines to open, and
- plugging of any flow tuning orifice in the accumulator injection lines.

3) Event is initiated by a spurious ADS actuation event that results in a large LOCA. The RCS rapidly depressurizes and at least one of the accumulators injects, making up the RCS water loss in the short time frame. However, due to failure of either the CMT injection or the ADS actuation, the automatic IRWST injection is not actuated. In addition to the initiating event, risk important failures appearing in this sequence are:

- CCF of hardware in the PMS engineered safety feature (ESF) input logic groups (causes CMT injection actuation failure which results in failure of automatic IRWST injection actuation with no adequate time for manual actuation),
- CCF of CMT level sensors which prevents IRWST injection actuation,
- CCF of CMT injection air-operated valves to open,
- CCF of CMT injection check valves to open, and

• CCF of 2 or more fourth stage ADS explosive (squib) valves to operate.

4) Event is initiated by a break in one of the two safety injection lines (a LOCA event) followed by successful CMT injection but failure of full RCS depressurization (to allow low pressure IRWST injection). The failure that dominates the risk associated with this sequence is the CCF of ADS stage #4 explosive (squib) valves.

5) Event is a reactor vessel rupture event which leads directly to core damage.

3.4 *Passive vs. Active*

A summary of the reactors analyzed at this point is provided in Table 3.4. It shows the safety systems discussed in Chapter 2 along with the reactor's CDF discussed earlier in this Chapter.

Table 3.4 Summary of Generation III+ Reactors

<table>
<tr><th></th><th>Design</th><th>General</th><th>CDF</th><th colspan="4">Safety Systems</th></tr>
<tr><td rowspan="2">BWR</td><td>ABWR</td><td>Active</td><td>2.0 E-7</td><td>RHR</td><td>HPCF</td><td>RCIC</td><td>ADS</td></tr>
<tr><td>ESBWR</td><td>Passive</td><td>2.0 E-7</td><td>GDCS*</td><td>ICS*</td><td colspan="2">PCCS*</td></tr>
<tr><td rowspan="2">PWR</td><td>EPR</td><td>Active</td><td>1.0 E-6</td><td colspan="4">ECCS (comprised of 4 independent trains)</td></tr>
<tr><td>AP1000</td><td>Passive</td><td>2.4 E-7</td><td colspan="2">PXS*</td><td colspan="2">PCS*</td></tr>
</table>

*Classified as Passive "B" systems

Notice that similar to the ESBWR (passive), the most dominating event for the AP1000 is LOCA. Not coincidentally, we find that SBO is a very small contributor as well. The following are the most important features of the AP1000 design that contribute to the reduction in the estimated CDF associated with loss of offsite power:

• Safety-related passive systems that do not rely on ac power for operation. They rely on natural forces, such as gravity and stored energy, to perform their accident mitigation functions once actuated and started. When power is needed to actuate and start such

passive systems, dc power provided by Class 1E batteries is used.
• The PRHR is automatically actuated, without the need for any electrical power, to provide core cooling upon LOOP (Air Operated Valves (AOV) "fail safe" in the open position).

• Class 1E dc batteries with capability to support all front line passive safety-related systems for 72 hours.

• Defense-in-depth, which provides alternative means for removing decay heat from the RCS during a LOOP/SBO accident. Most current PWR plants rely on two alternative means for core cooling:

- an Auxiliary Feedwater System, with at least one turbine driven pump for SBO events, in addition to motor driven pump(s), and
- a manual "feed & bleed" capability when onsite ac power is available.

The AP1000 design provides better and more reliable defense-in-depth by relying on the following alternative means for core cooling:

- the automatically actuated non-safety-related Startup Feedwater (SFW) system when onsite ac power is available,
- the automatically actuated safety-related PRHR system, and
- an automatic with manual backup "feed & bleed" capability using systems with adequate redundancy and defense against common-cause failures throughout the RCS depressurization range for both the "feed" function (two CMTs, two accumulators, the two RNS pumps and the two IWRST gravity injection lines) and the "bleed" function (four ADS stages with two paths in each of the first three stages and four paths in the fourth stage).

• The improved reliability of the PRHR system (as compared to the AFW system used in most current PWR plants) contributes significantly to the reduced risk associated with LOOP/SBO sequences (the function of the PRHR following a LOOP/SBO event is similar to the AFW system function in operating PWRs).

- Canned reactor coolant pumps eliminate seal LOCAs, which are likely in operating PWRs during an SBO accident.

The PWR's situation is similar to the ABWR's in that passive reactors are much better at protection against station blackout while active reactor are better at combating LOCAs. However, with these advanced reactors, neither is necessarily "poor" at protection against their most dominating initiating event. The reactor safety systems are just more suited to protect against other accidents such that the *contribution* of the dominating events to CDF may be higher.

The passive systems rely on natural forces, such as gravity and stored energy, to perform their safety functions. In order for such systems to actuate and start, certain active components, such as air operated valves (AOVs) or check valves (CVs), must open. Such components do not require alternating current (ac) power for operation (to open) or for control and no support systems are needed after actuation. This reduces significantly, compared to operating nuclear power plants, the risk contribution from loss of offsite power (LOOP) and station blackout (SBO) events. In addition, because of the passive systems, several important contributions to risk in currently operating nuclear power plants have been eliminated in the AP1000 design. These risks are associated with failure of support systems (e.g., ac power and component cooling) and failure of active components (e.g., pumps and diesel generators) to start and run. Finally, the passive nature of the safety systems reduces, compared to active reactors, the reliance on operator actions to mitigate accidents. For a fair comparison to operating and evolutionary reactor designs, which use mostly active safety-related systems, the potential impact of T-H uncertainties on the performance of passive systems needs to be considered and appropriately included in the PRA models. Analyses performed by Westinghouse concluded that the AP1000 design is "robust" with respect to T-H uncertainties. However, there is much less industrial experience with some systems, such as the natural circulation systems.

The NRC has also been placing a special emphasis on PRA modeling of novel and passive features in the design as well as addressing issues related to these features, such as the issue of thermal-hydraulic (T-H) uncertainties. The issue of T-H uncertainties arises from the "passive" nature of the safety-related systems used for accident mitigation. Since passive safety systems rely on natural forces, such as gravity, to perform their functions, their driving forces are small compared to those of pumped systems. The uncertainty in the values used, as predicted by a "best-estimate" T-H analysis, can be of comparable magnitude to the predicted values themselves. Therefore, some accident sequences, with frequency high enough to impact risk but not predicted to lead to core damage by a "best-estimate" T-H analysis, may actually lead to core damage when T-H uncertainties are considered in the PRA models. T-H uncertainties and their impact on PRA models are being considered in the certification of the AP1000 design using the same approach that was used in the AP600 design certification.

Chapter 4. Safety Modeling Methodology

4.1 Introduction

Classical Probabilistic Risk Assessment (PRA) methods are utilized to evaluate the failure probability of the passive system. However, different from previous PRA's performed on active systems, the failure probabilities considered in passive systems must include the virtual components (natural circulation, gravity, etc.) in addition to the normally considered real components (valves, pumps, etc.). Real component failure data is readily available for most pumps, valves, and instrumentation due to years of operational and experimental data collected. Virtual component failure data is not as prevalent because of limited operational and experimental data on passive systems. In order to quantify these virtual component failure probabilities, and subsequently use them in conjunction with real component failure probabilities to develop a PRA on passive systems, a methodology must be developed.

ENEA, University of Pisa and Polytechnic of Milano, have outlined the basic steps in quantifying the virtual component failure probabilities of a passive system. In addition, a joint European Commission study called "Reliability Methods for Passive Safety Function" (RMPS) along with previous work from Luciano Burgazzi in this field have helped shape this methodology. The following sections outline their methodology.

4.2 Identification of the System and Parameters

The RMPS methodology starts with first identifying the passive system being analyzed and determining all of its associated T-H uncertainties. In addition, one should be aware of the specific mission of the system and also identify a specified event with which to test that system's reliability. Figure 4.1 shows the passive loop system used in the RMPS study.[25]

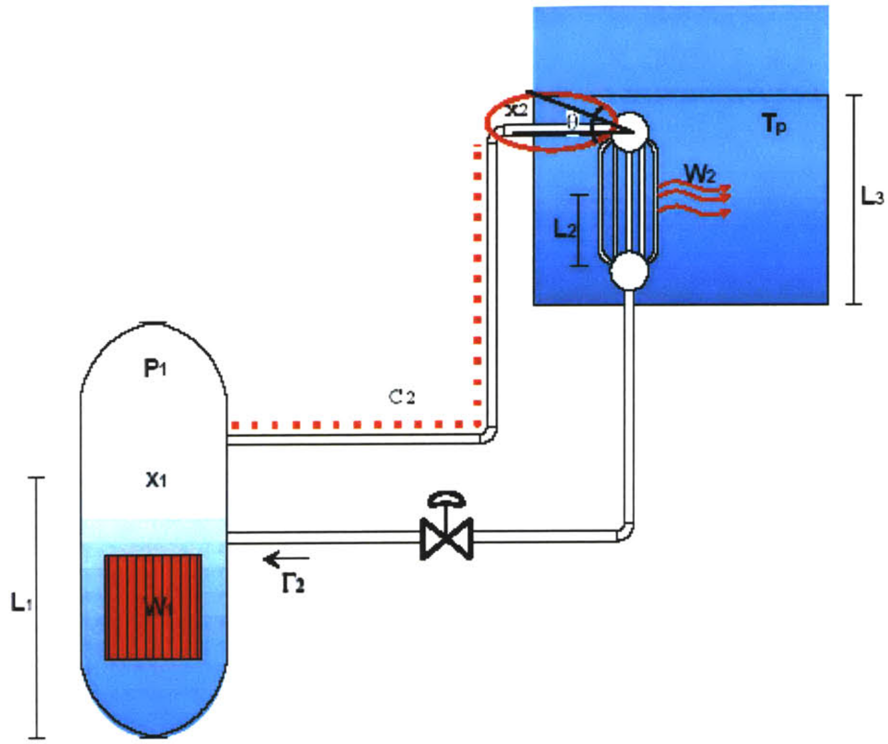


Figure 4.1 RMPS Passive Cooling System[25]

The next step is to identify the uncertain parameters that will affect the reliability of natural circulation (virtual component). The RMPS study breaks the parameters into two categories—design and critical. Design parameters act like physical links between subsystem and system during the operational condition while critical parameters refer to quantities that could represent a direct "source of failure" for the passive system, i.e. they could leave the mission unfulfilled.[25] The parameters must be independent of one another. For example, selecting RPV pressure and temperature as parameters would not meet this criteria since they are not mutually exclusive parameters. After the parameters are identified, a probability distribution is assigned to each parameter. The distribution represents the potential values that the system's parameters may be at the time of the event. The probabilities assigned to each of these values are based on engineering judgment and expert opinion. Expert judgment is important in both selecting all the important parameters and selecting all their associated probabilities for a given system. Improper assigning of parameters and probabilities are a source of error in this methodology. It is important to reach a consensus on these factors to minimize this error. Table 4.1 shows the RMPS selected parameters and corresponding probabilities for the system shown in Figure 4.1.

Table 4.1 RMPS Design and Critical Parameters[25]

DESIGN PARAMETERS

Parameter		Unit	Nominal Value	Range	Discrete Initial Values				
P_1	RPV pressure	MPa	7	0.2-9	0.2	1	3	7	9
					0.05	***0.1***	***0.15***	***0.5***	***0.2***
L_1	RPV collapsed level	m	8.7	5-12	5	7	8.7	10	12
					0.05	***0.1***	***0.5***	***0.2***	***0.15***
L_3	POOL level	m	4.3	2-5	2		4.3		5
					0.1		***0.8***		***0.1***
$T_p(0)$	POOL initial temperature	K	303	280-368	280		303		368
					0.1		***0.8***		***0.1***
-	System geometry : layout	-	-	Not assigned	-				
					1.0				

CRITICAL PARAMETERS

Critical Parameter		Discrete Values						
x_1	RPV non-condensable fraction	0.	0.01	0.1	0.2	0.5	0.8	1.
		0.719	***0.12***	***0.07***	***0.05***	***0.03***	***0.01***	***0.001***
x_2	Non-condensable fraction at the Inlet of IC piping	0.	0.01	0.1	0.2	0.5	0.8	1.
		0.71	***0.12***	***0.07***	***0.05***	***0.03***	***0.01***	***0.01***
θ	Inclination of the IC piping on the suction	0.	1.	5.	10.			
		0.5	***0.4***	***0.08***	***0.02***			
C_2	Heat Losses piping – IC Suction (kW)	0.	5.	20.	100.[4]			
		0.10	***0.7999***	***0.10***	***0.0001***			
$L_2(0)$	Initial condition liquid level - IC tubes, inner side (%)	0.	50.	100.				
		0.1	***0.1***	***0.8***				
UL	Undetected leakage (m^2)	0.	1.E-5	5.E-5	10.E-5			
		0.8899	***0.1***	***0.01***	***0.0001***			
POV	Partially opened valve in the IC discharge line (%)	1.	10.	50.	100.			
		0.001	***0.01***	***0.1***	***0.889***			

The total number of design and critical parameters is boundless for any system. The selection above represents the most important, independent factors that could contribute to the virtual component failure. In addition, there are millions of potential combinations using just the bounded set of parameters chosen above. So even after the selection of important parameters is bounded, the *combinations* of these discrete parameter values (as initial system conditions) must also be selected carefully to be statistically meaningful since it is assumed that one will not complete millions of simulations for every possible combination of the above parameters. The importance of selecting independent parameters will be shown when calculating the overall system reliability for a given event.

4.3 Define Failure Criterion

The next step in the RMPS methodology defines the failure criterion for passive system performance based on knowledge of the system mission. In order to do this, the acceptability or design limits for the system operation being modeled must be known. The failure criterion should be based on those limits that are specific to the system and connected with its mission. The RMPS study chose to define a unique failure criterion as a function of time:

$$(Z - Z_{ref})/\ Z_{ref} < (-\ 0.2) \tag{1}$$

If this equation is satisfied, then a failure has occurred. Z_{ref} is the reference case for the known failure criteria and "Z" is the value of that criteria at any given time for a given system model. The "0.2" factor illustrates how close to the reference case a Z-value must reach to be considered a failure. The value for this factor is chosen based on engineering judgment and expert opinion. The Z parameter should be based on system design limits or acceptability. The RMPS chose two possible Z quantities: thermal power exchanged across the IC and mass flow rate at the IC inlet. Using equation (1), they monitor both of these two values over the duration of the chosen event and compared them to the reference case to determine if a failure has occurred.

4.4 Build a Model and Simulate

There are two ways to build a model for the chosen system on which to perform future simulations of events. One way is to select a thermal hydraulic computer code and build a model of your system using the code. Model errors will be introduced and there is still much debate as to the limits of current computer codes for passive systems. The other alternative is to experimentally build a model of the system much like the PANDA facility has done for passive systems. This will have its own model errors and can be very costly not only to build, but to set up and run each potential event. Once a model is established, event simulations are run using various combinations of the parameters in Table 4.1 as initial system conditions. The system failure criterion is evaluated during each simulation to determine if the system accomplished its mission.

4.5 Evaluate Results

It is tedious if not impractical to run every possible combination of parameters from Table 4.1 on either a computer or physical model. However, it is important to select a representative sample from the potential combinations and this can be done through Monte Carlo analysis. Each combination simulated will have an overall system probability based on multiplying the discrete probabilities for the individual initial parameters selected. For example, if one evaluated the RMPS system to have the following initial conditions for each parameter:

(from Table 4.1)

	P1	L1	L3	Tp	x1	x2	θ	C2	L2	UL	POV
Initial Value Chosen	0.2	12	4.3	303	0	0	0	5	100	0	100
Associated Probability	0.05	0.15	0.8	0.8	0.719	0.71	0.5	0.7999	0.8	0.8899	0.889

The system probability for this combination of parameters would be determined by multiplying each of the associated probabilities together to get 6.2E-4. This is why the parameters initially selected must be independent of one another. Otherwise, you would have multiple conditional probabilities to take into account for each parameter making the calculations even more cumbersome. If the failure criterion is not reached during the simulation, then the system is "successful". All of the system probabilities (i.e. 6.2E-4) for successes are then added together to determine the system reliability. Conversely, all of the system probabilities for failures are added together to determine the system unreliability. These reliability values represent the virtual component of natural circulation that can be then entered into a full PRA tree along with the real component reliability values (pumps, valves, etc.). Thus, this methodology gives a way to quantify the reliability or unreliability of natural circulation (virtual component) including potential T-H uncertainty.

Chapter 5. Safety Model and Results

5.1 System Model Description

Since there is very limited experimental data on any of these Generation III+ designed safety systems, computer codes are often used to prove an adequate safety margin exists. The vendor CDF numbers discussed in Chapter 3 are based on computer modeling and PRA. Computer modeling is an important aid in the design process. However, just like anything else, the code has its limits. This is especially true with passive safety systems because their natural circulation processes can be greatly affected during transient conditions by a variety of T-H mechanisms in the system. These T-H mechanisms can cause delay or disruption in the predicted flow of coolant from these safety systems especially during the initial period of the transient. What is difficult, is finding a method to analyze these uncertainties. This work consisted of using the accepted methodology described in Chapter 4 to develop a simple decay heat removal model and analyze its reliability for both a passive and active system.

The first step is to choose a system to model. Reactor safety systems often work in tandem to maintain a desired safety margin for certain events. . For example, in the ESBWR during a LOCA, you will have the Gravity Drain Cooling System in operation along with the Isolation Condenser and Passive Containment Cooling Systems. It can be very tough to model each T-H uncertainty within each subsystem as the transient starts, with all systems simultaneously operating together. Thus, it is much easier to find a transient condition that only requires the use of a single system for simplicity. For this reason, the Isolation Condenser System operating under a reactor isolation transient was chosen.

While the ICS does combine with other safety systems in various transients and accidents, it is solely responsible for decay heat removal during a reactor isolation event. For overpressure protection, the Isolation Condensers have sufficient capacity to preclude actuation of the SRVs. Three out of four ICS trains remove post-reactor isolation decay heat and depressurize the reactor to safe shutdown conditions when the reactor is isolated after operation at 100% power.[26] Figure 5.1 is a simplified model diagram with the important features:

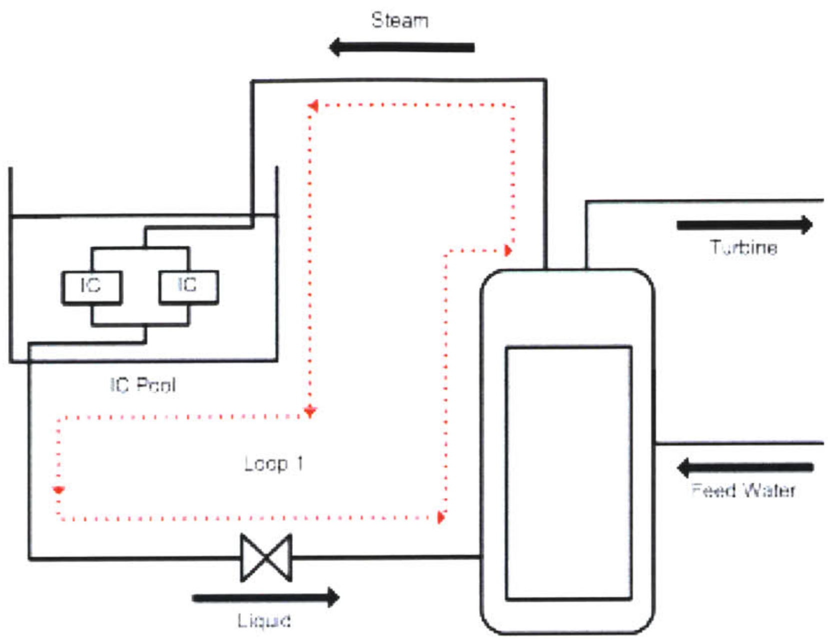


Figure 5.1 Passive Decay Heat Removal Model

This is a very simplistic model of an Isolation Condenser System lumping 3 of its 4 IC loops into one loop. This loop has the heat removal capacity of roughly 3 IC loops in the ESBWR. It does not have the venting path for non-condensable gases from the isolation condensers to the suppression pool nor the other auxiliary connecting systems and bypass valves that the real isolation condenser system has. While the model is simple, it is not without merit. It has the key features which are the heat exchanger and condensate line return valve (IC isolation valve), which is the valve that initiates the passive system when opened. The isolation condensers are located high above the core to facilitate the natural circulation process. Think of the model as a simple passive loop heat removal system that could be used in either a PWR or BWR. A comparable active system would replace the natural circulation process with a pump. Figure 5.2 shows a comparable active safety system for this simplified model.

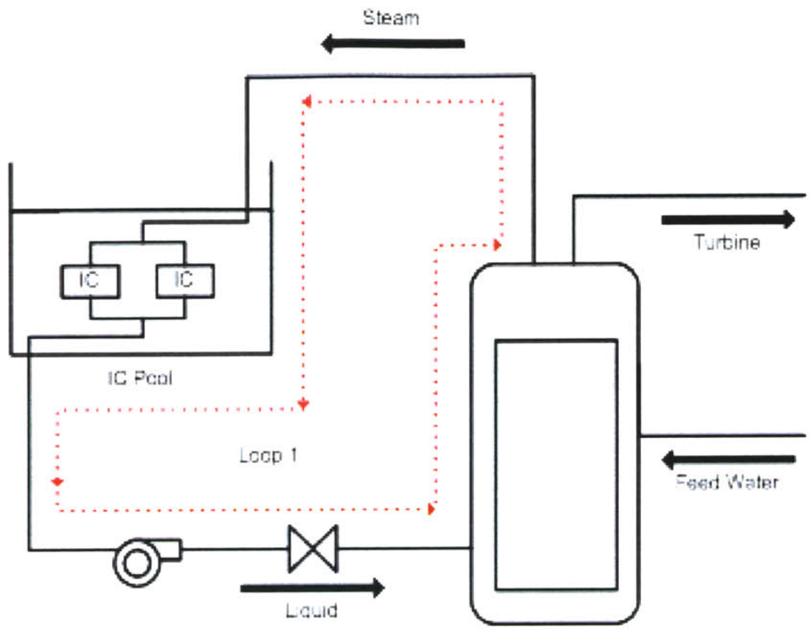


Figure 5.2 Active Decay Heat Removal Model

The most comparable active system in utility and function to the Isolation Condenser of the ESBWR is the RCIC system in the ABWR discussed in Chapter 2. A steam turbine drives the RCIC pump through auxiliary piping upstream of the Main Steam Isolation Valves (MSIV) if the reactor becomes isolated. The RCIC system pumps cool, make-up water into the core for decay heat removal. Figure 5.2 uses a simple electric pump that can start or stop flow on demand of the operator instead of the turbine driven pump for simplicity. It pumps the condensed water in the loop back into the core. It is not meant to replicate the RCIC system but instead, represent a simplified active system loop comparable to the passive system loop in Figure 5.1.

While neither of these simplified models represents exact replicas of safety systems used in Generation III+ reactors, they are very similar in concept and useful in comparing passive safety to active safety under the same transient, reactor isolation. Reactor isolation can occur for a number of reasons. For this study, we will assume that there has been a steam line rupture downstream of the MSIVs which requires the operator to shut all the MSIVs and scram the reactor.

5.2 *Parameter Selection*

Besides the pump, the modeled systems are identical. Selecting the T-H parameters and associated probabilities is the next step in the methodology. Since the RMPS study had already developed important parameters and associated probabilities (Table 4.1), two parameters were chosen to analyze on the systems in Figures 5.1 and 5.2. This study chose "partially open valve in the IC discharge line (POV)" and "non-condensable gas fraction in the heat exchanger (X3)". The parameter values and probabilities for these two are shown in Table 5.1.

Table 5.1 Parameter Data Selected[25]

Parameters	Discrete Values						
[1]X3	0	0.01	0.1	0.2	0.5	0.8	1
	0.7196	***0.121***	***0.071***	***0.051***	***0.03***	***0.01***	***0.0001***
[2]POV	1	10	50	100			
	0.001	***0.01***	***0.1***	***0.889***			

[1]X3 = "Non-Condensable Gas Fraction in Heat Exchanger".
[2]POV = "Partially Opened Valve in the IC Discharge Line (%)".

The "X3" parameter is defined slightly differently than the "X1" and "X2" parameters in Table 4.1 because of the location of the non-condensable gas fraction at the start of the transient. The heat exchanger was selected as the location since this is where it is believed that most gases will collect once the transient starts and also where they will have the greatest impact on the system, preventing the steam released from the reactor to condense in its tubes. The associated probabilities are also different from those yielded by the expert opinion in Table 4.1 for "X1" and "X2" because there is less belief that this fraction will have a value of "1". It is believed, in this study, that there is only a .01% chance of having a 100% gas mixture in the heat exchanger as shown in Table 5.1. The POV parameter values and assigned probabilities are consistent with Table 4.1 from the RMPS study.

The parameters given in Tables 4.1 and 5.1 have continuous distributions but they are evaluated by expert opinion in terms of multinomial distributions after assuming their independency. This is reasonable because of the Central Limit Theorem (CLT). If there is large number of points, a multinomial distribution converges to a multivariate normal distribution like a binomial distribution converging to a normal distribution by CLT. And the independency assumption between two selected parameters (X3 and POV) yields the joint probability mass function shown in Table 5.2 with all the 28 possible combinations of paired data sets shown.

Table 5.2 Joint Probability Mass Function

No.	Paired sets (X1, POV)	Probability	No.	Paired sets (X1, POV)	Probability
1	(1, 100)	0.0000889	**15**	(0.2, 10)	0.00051
2	(1, 50)	0.00001	**16**	(0.2, 1)	0.000051
3	(1, 10)	0.000001	**17**	(0.1, 100)	0.063119
4	(1, 1)	0.0000001	**18**	(0.1, 50)	0.0071
5	(0.8, 100)	0.00889	**19**	(0.1, 10)	0.00071
6	(0.8, 50)	0.001	**20**	(0.1, 1)	0.000071
7	(0.8, 10)	0.0001	**21**	(0.01, 100)	0.107569
8	(0.8, 1)	0.00001	**22**	(0.01, 50)	0.0121
9	(0.5, 100)	0.02667	**23**	(0.01, 10)	0.00121
10	(0.5, 50)	0.003	**24**	(0.01, 1)	0.000121
11	(0.5, 10)	0.0003	**25**	(0, 100)	0.6397244
12	(0.5, 1)	0.00003	**26**	(0, 50)	0.07196
13	(0.2, 100)	0.045339	**27**	(0, 10)	0.007196
14	(0.2, 50)	0.0051	**28**	(0, 1)	0.0007196

5.3 Failure Criterion Selection

In the RMPS methodology, the failure criterion is reached if the conditions in equation (1) are met. This equation represents a failure criterion that is a 20% deviation from nominal, or reference, conditions for a particular chosen failure parameter in the general sense. For this study a specific transient, reactor isolation, is analyzed for a passive and active decay heat removal loop. The transient response from both the active and passive systems will be compared using the same failure criterion. For the Isolation Condenser System (ICS), the GE Design Control Document (DCD) states the following:

"The ICS satisfies General Design Criteria 34 as it relates to the system design being capable of removing fission product decay heat and other residual heat from the reactor core to preclude reactor coolant pressure boundary over pressurization... ...the ICS automatically limits the reactor pressure and prevents Safety Relief Valve (SRV) operation when the reactor becomes isolated following scram during power operations."[26]

Because the system is specifically designed to prevent SRV operation during the chosen transient, the failure criterion is chosen to be a certain value of steam line pressure. The specific failure value will be quantified using a similar approach as used in Chapter 4. It is important to understand that reaching this failure criterion for this particular transient will not directly cause any fuel failure in the core but it will cause the actuation of the SRVs which can cause compounding problems such as a stuck open SRV resulting in a LOCA that may lead to fuel failure. The reason this overpressure failure criterion was chosen is that it is one of the primary missions of the Isolation Condenser system in the ESBWR during a reactor isolation sequence which is consistent with the methodology in Chapter 4. The active system response to a similar transient from the same steady state initial conditions will be assessed and compared to the passive system.

A failure criterion is developed similar to that of Chapter 4:

$$(Z - Z_{ref})/ Z_{ref} < (-0.05) \qquad (2)$$

Here, "Z_{ref}" equals the SRV setpoint (8.7MPa). The factor 0.05 (5%) provides a conservative margin of error for the measured "Z" value in relation to Z_{ref} based on factors such as signal and sensor errors . Solving equation (2) for the highest acceptable measured "Z" value without failure (using the 5% margin) yields a maximum acceptable steam pressure of 8.265 MPa. For each transient simulation, if the monitored "Z" value (steam line pressure) becomes greater than 8.265 MPa, then the simulation is deemed to indicate performance failure. Otherwise, the simulation is considered a success.

5.4 Computer Modeling

Once the model and transient were selected, a computational code could be selected to best analyze the model during the transient condition. The TRACE code developed by the NRC was selected because of its thermal hydraulic analysis capabilities along with its modularity for varying system designs. First, a steady-state model was created to simulate a reactor operating at 100 percent power. Then, the code was used to run a variety of reactor isolation transients with varying T-H initial conditions while it monitored the steam line pressure. The code produced output files that were graphed in "AcGrace" (Analysis Code Graphing, Advanced Computation and Exploration of data) to determine whether the failure criterion of steam line pressure was reached. The TRACE code was run using Cygwin command codes in a bash shell. The input files for the active and passive files were created using JEdit software and are shown in Appendix A.

The models shown in Figures 5.1 and 5.2 are similar in every way with the exception of the pump which is added to the active model and provides a continuous, instantaneous flow rate upon initiation of the cooling system. The vessels used in both models are BWRs with all the same specifications including 2 channels of flow—a hot channel and a core average channel. As stated earlier, this simple cooling loop could be applied to either a BWR or PWR although BWRs have a greater affinity for natural circulation due to their longer driving buoyancy force during normal operation. Both models begin with a 100% power, steady-state flow condition using FILL and BREAK boundary conditions in the TRACE command structure to model the steam flow to the turbine and constant feed water return to the reactor. Although not designed to be an exact replica of either the ABWR or ESBWR, since much of the reactor specifications are proprietary information unknown to the researcher, many of the ESBWR known parameters were used as a basis for the vessel and steady-state thermal hydraulic specifications. The modeled passive cooling loop's isolation valve is shut during the steady-state operating conditions. Table 5.3 outlines many of the vessel and steady-state model specifications and their comparison to ESBWR specifications at 100% power outlined in the ESBWR Design Control Document.

Table 5.3 Model Vessel and Steady-State Specifications[27]

Parameter	UNITS	ESBWR	Model
Thermal Power	MWt	4500	4500
Core flow	kg/s	9034-10584	9455
Steam flow	kg/s	2433	2433
Feed flow	kg/s	2451	2426
Power density	kW/L	54	54
Operating Pressure	MPa	7.17	7.20
Pressure Drop (Core)	MPa	0.07	0.082
Core Inlet Temp	deg C	270	Core avg temp 287
Core inlet Enthalpy	KJ/Kg	1183	Core avg enthalpy 1274
Feed inlet Temp	deg C	215.5	215.5
Feed inlet Enthalpy	KJ/Kg	925	925
Fuel Assembly	Total	1132	1132
Fuel Pins Per Assembly	number	92	92
Fuel Length	m	3.7	3.7

The model core uses an axial power distribution as shown in Figure 5.3 below:

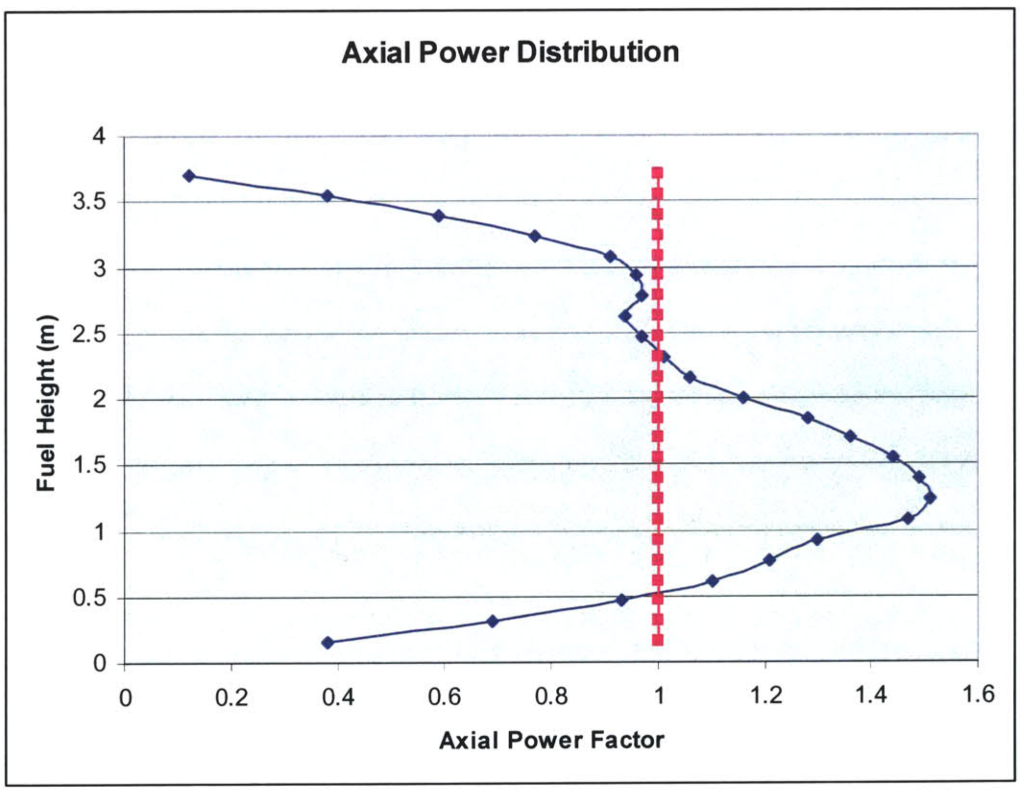


Figure 5.3 Axial Power Distribution[27]

TRACE runs the steady-state model for 50 seconds at which time a control system parameter simulates a reactor scram and the closure of the main steam isolation valve to the turbine which stops all steam flow to the turbine and returns feed flow to the reactor. This simulation is the same as a simultaneous closure of all MSIVs in an operating reactor following a scram. In a real reactor, these valves could shut accidentally or by the operator (in the case of a steam line rupture accident downstream of these valves). Once all of these valves are closed, the reactor is considered isolated without a heat sink. The scram instantly decreases the reactor power to the decay heat production level of roughly 6% of its original thermal value. This value continues to decrease non-linearly over time. TRACE has built-in tables and functions to model this and Figure 5.4 shows the shutdown reactor power level vs. time that was used by the code during the simulation.

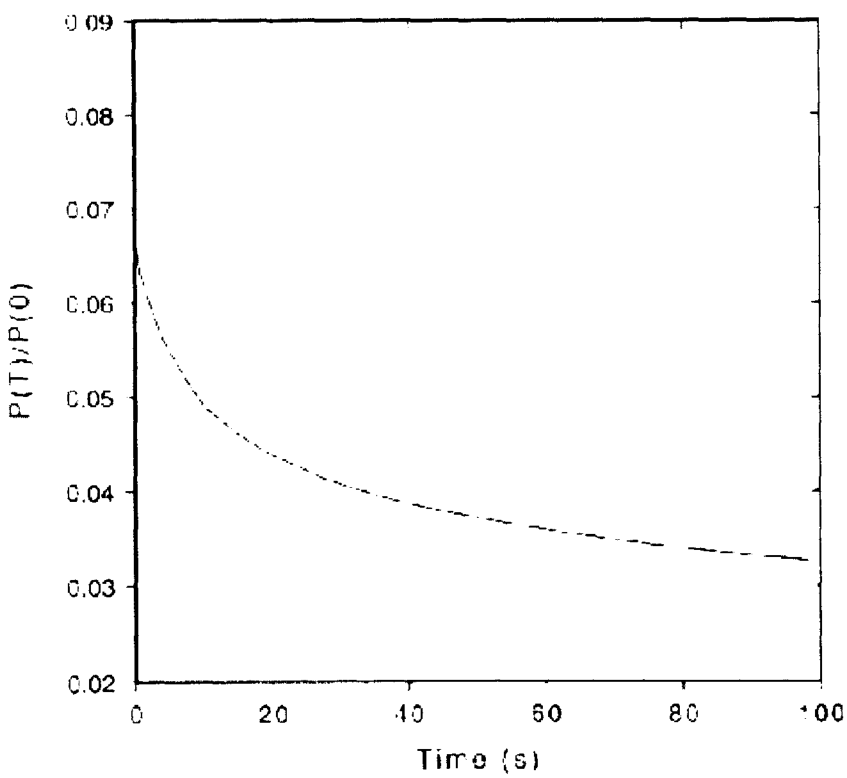


Figure 5.4 Reactor Power vs. Time After Scram[28]

Note that Figure 5.4 neglects the effects of fission heat after the first few seconds of the scram and only takes into account the decay heat generated in the core. As the reactor continues to generate decay heat per Figure 5.4, the coolant builds up pressure until the modeled loop isolation valve is opened. This valve opens 3 seconds after the reactor scram and MSIV closure allowing the cooling water from the modeled loop to travel through the core then back through its heat exchanger. The valve in the model opens at a non-linear rate by using a manual input table in TRACE shown in Table 5.4 in order to best benchmark the steam pressure response of the ESBWR described later. The simulation control variables are the same for both the active and passive models in Figures 5.1 and 5.2 and a summary of these control variables is shown in Table 5.5. The heat exchanger is located higher than the center of the vessel, through usage of the TRACE code "gravity" term, to aid in the natural circulation process upon initiation. It is a vertical heat exchanger which also aids in this process with its tubes submersed in a pool of water, similar to the ESBWR Isolation Condenser System. The model uses a constant temperature boundary condition on the outside of the coolant piping at 30 degrees Celsius to simulate the pool water temperature. Under normal operation in an ESBWR Isolation Condenser System, the pool water will heat up over time and actually boil. For the purposes of this study, it is assumed that the pool water would not dramatically change temperature over the first 50 seconds of operation due to the large volume of pool water in the actual design. Thus, the boundary condition used is valid. The vertical piping connected to the heat exchanger has an added heat structure to transfer heat losses to the ambient air as the piping heats up during operation. These losses are much less significant.

Table 5.4 Modeled Loop Isolation Valve Position vs. Opening Time

Time (sec)	POV (% open)
0.0	0
0.5	30
1.0	55
1.5	75
2.0	90
2.5	100

Table 5.5 MSIV Closure Transient Sequence of Events

Time (sec)	Event(s)
-50.0	Begin Steady-State Simulation
0.0	Reactor Scram; Closure of all MSIVs (linear over 3 seconds)
3.0	MSIVs fully closed, Cooling Loop Isolation Valve begins to open
5.5	Cooling Loop Isolation Valve fully open
50.0	End Simulation

Once all these hydraulic components were in place, the passive model (Figure 5.1) was benchmarked against the actual ESBWR Isolation Condenser System performance in a similar transient (reactor isolation) to ensure its comparable response. To do this, the following three model parameters were varied using trial and error to achieve a similar result: Heat exchanger height above the core, piping diameters, and the loop isolation valve stroke time (non-linear as described in Table 5.4). The passive model flow rate determined from TRACE is a product of all these parameters. The values in Table 5.6 show the final values used, and the benchmark comparison is shown in Figures 5.5 and 5.6.

Table 5.6 Final Model Parameters Based on ESBWR Benchmarking

Height of heat exchanger above core	10.7 m
Diameter of Steam Loop Piping	0.63 m
Diameter of Cooling Water Piping	0.37 m
Loop Flow Rate	66.7 kg/s

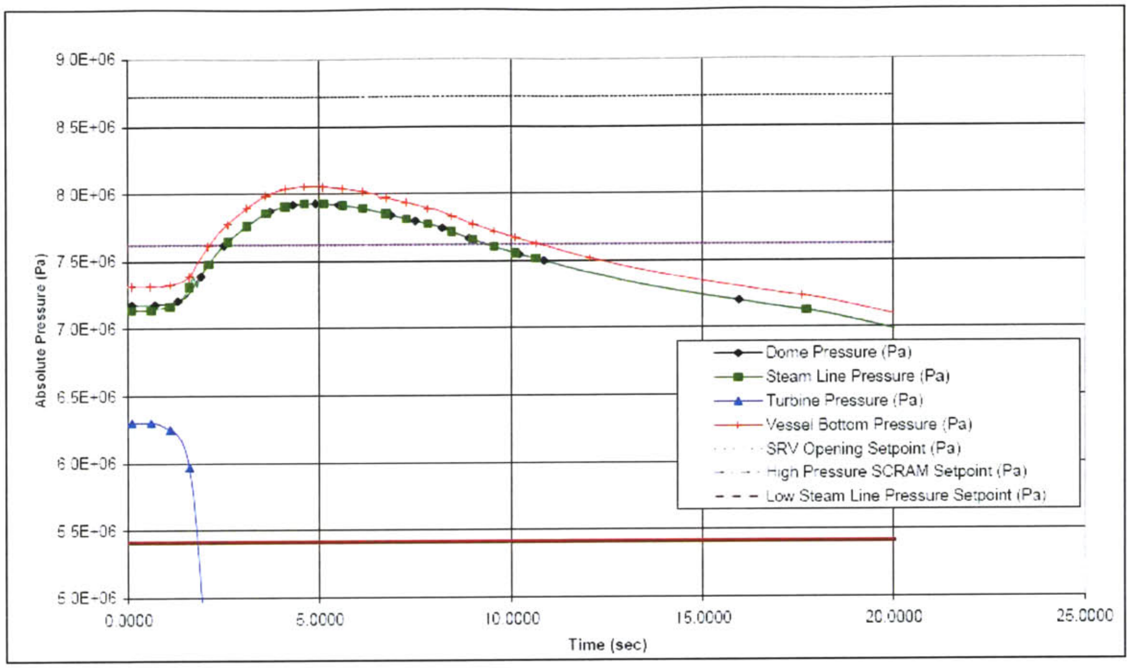


Figure 5.5 ESBWR Steam Line Pressure Response to Transient[29]

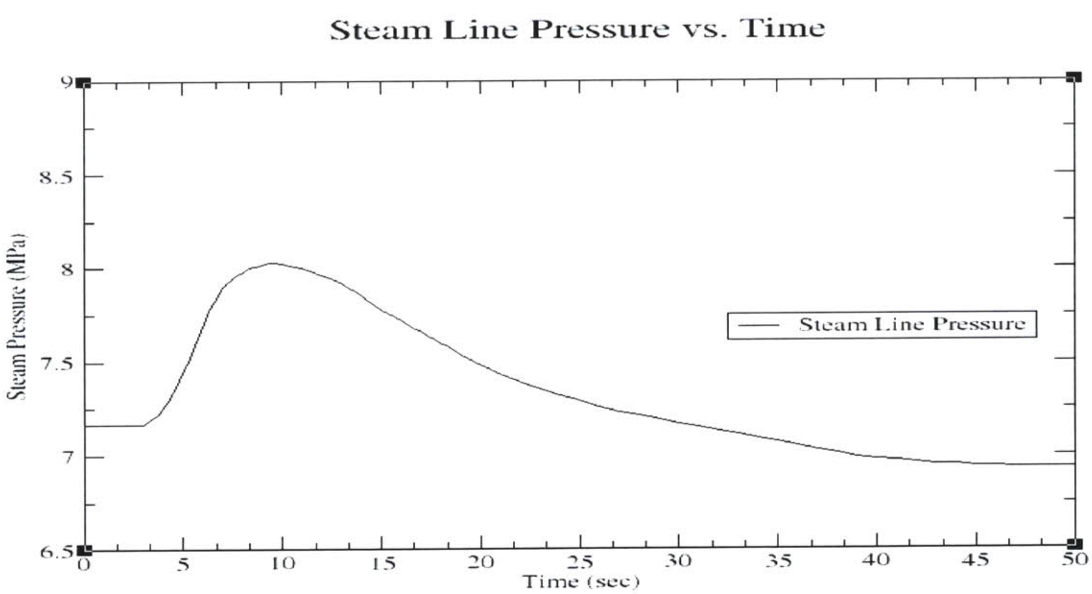


Figure 5.6 TRACE Model Steam Line Pressure Response to Transient

The ESBWR transient shown in Figure 5.5 is from Chapter 15 of its Design Control Document which simulated the same closure of all MSIV's and the Isolation Condenser transient response.

The TRACE model nominal case response is shown in Figure 5.6 and is very comparable. Thus, the key failure criterion, steam line pressure, follows the same trend in the model including the maximum pressure reached, ~8 MPa. This validates the failure criterion.

It must be stressed again that the passive TRACE model is not intended to be an exact replica of the ESBWR core or its associated Isolation Condenser System. The known parameters from the ESBWR design were merely used and benchmarked to verify model acceptability. Unknowns such as actual volumetric flow rates, height specifications, and valve timing diagrams along with the absence of associated systems (i.e. vent piping to suppression tanks) makes the loop model a lumped, simplified version of the isolation condenser system. Its one loop has roughly the same the heat removal capacity of 3 of 4 ESBWR isolation condenser loops based on the benchmarking that was done. The specific transient in the ESBWR DCD had some slight variations as the transient in this study. First, the DCD transient did not start IC flow until 15 seconds after the scram. However, the TRACE model did not include neutronic feedback which helps shutdown the reactor during this transient. Because of this, there are slight variations in the core flow response as illustrated in Figures 5.7 and 5.8. Also note that the decay heat curve, represented by the "Simulated Thermal Power" curve in Figure 5.7, is slightly different from the one used by the TRACE code represented in Figure 5.4. The "Total Power" curve in Figure 5.7 represents the fission power that the TRACE model does not take into account.

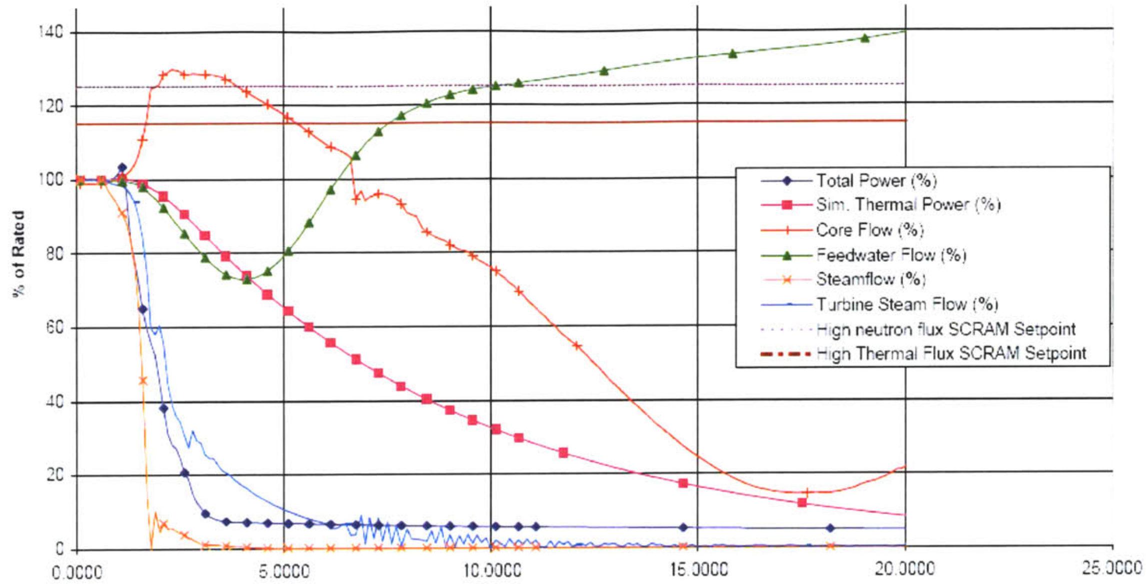


Figure 5.7 ESBWR Transient Core Flow

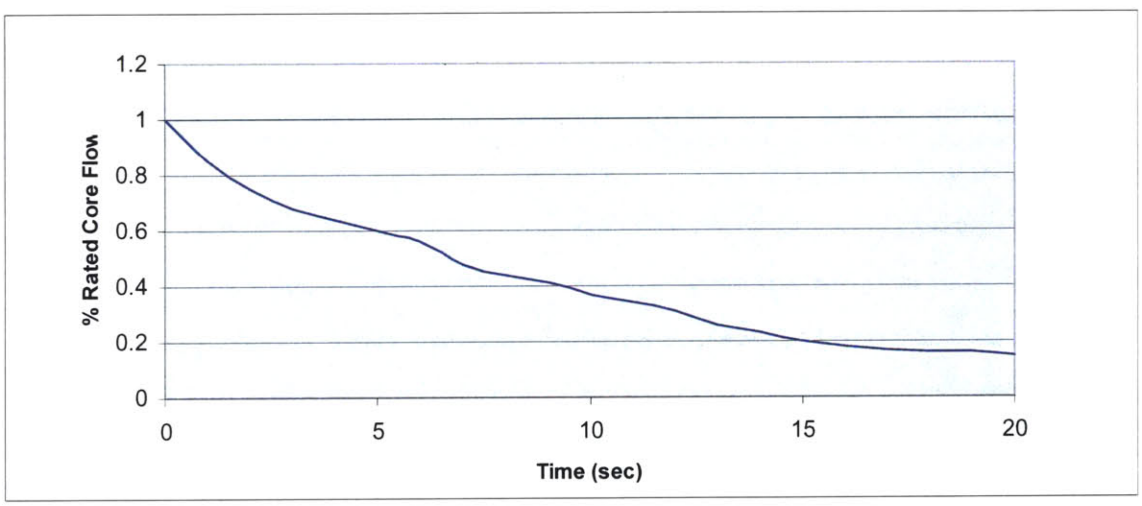


Figure 5.8 TRACE Model Transient Core Flow

The active system TRACE model only differs from the passive model in that the maximum flow rate achieved in the passive model shown in Table 5.7 is instantaneously and continuously achieved in the active model. This obviously assumes that the pump starts and produces rated flow every time the decay heat removal loop initiates, which does not always happen in reality. This assumption will be accounted for in the results section using experimental pump reliability data. Thus the model alone is simply comparing how the two T-H uncertainties selected (POV and non-condensable gas fraction) affect the operation of a simple decay heat removal cooling loop of both natural circulation (passive) and instantaneous (active) flow. The active model is not meant to be an exact replica of an active Generation III+ system because in the ABWR RCIC system and EPR core cooling systems, the make up water comes from a separate tank unlike this model which instead pumps the condensed steam from the loop back into the core after it passes through the heat exchanger.

5.5 Evaluation and Results

Each model was run 28 times using the paired sets of parameters from Table 5.2, and the steam line pressure failure criterion from equation (2) was monitored and recorded every 0.33 seconds over a 50 second period. Lowering this time (0.33 seconds) increases the computing time required to complete each simulation because more data must be recorded by TRACE. The recording periodicity of 0.33 seconds was sufficient enough to not miss any significant "gaps" in between recorded data. And since the goal of this project was to investigate how T-H uncertainties affect the *initial* transient, 50 seconds of total monitoring is sufficient.

The simulation was considered a failure if the maximum pressure reached or exceeded 8.265 MPa at any time during the transient. As a reminder, the reason for this failure setpoint was that the ESBWR system was designed to prevent a steam relief valve from lifting during this transient and equation (2) assumed a 5% error margin to the 8.7MPa setpoint. Most of the transient cases run followed a similar shape to the benchmark cases with flatter or steeper curves depending on the parameters used. If a simulation successfully maintained pressure below 8.265 MPa, then the simulation was deemed a "success". Otherwise, it was considered a failure. The results from each of the 28 paired sets of T-H parameters are shown in Table 5.7:

Table 5.7 Safety Simulation Results

No.	Paired sets (X1, POV)	Probability	Passive Model	Active Model
1	(1, 100)	0.0000889	FAILURE	FAILURE
2	(1, 50)	0.00001	FAILURE	FAILURE
3	(1, 10)	0.000001	FAILURE	FAILURE
4	(1, 1)	0.0000001	FAILURE	FAILURE
5	(0.8, 100)	0.00889	FAILURE	FAILURE
6	(0.8, 50)	0.001	FAILURE	FAILURE
7	(0.8, 10)	0.0001	FAILURE	FAILURE
8	(0.8, 1)	0.00001	FAILURE	FAILURE
9	(0.5, 100)	0.02667	FAILURE	SUCCESS
10	(0.5, 50)	0.003	FAILURE	FAILURE
11	(0.5, 10)	0.0003	FAILURE	FAILURE
12	(0.5, 1)	0.00003	FAILURE	FAILURE
13	(0.2, 100)	0.045339	SUCCESS	SUCCESS
14	(0.2, 50)	0.0051	FAILURE	FAILURE
15	(0.2, 10)	0.00051	FAILURE	FAILURE
16	(0.2, 1)	0.000051	FAILURE	FAILURE
17	(0.1, 100)	0.063119	SUCCESS	SUCCESS
18	(0.1, 50)	0.0071	FAILURE	SUCCESS
19	(0.1, 10)	0.00071	FAILURE	FAILURE
20	(0.1, 1)	0.000071	FAILURE	FAILURE
21	(0.01, 100)	0.107569	SUCCESS	SUCCESS
22	(0.01, 50)	0.0121	FAILURE	SUCCESS
23	(0.01, 10)	0.00121	FAILURE	FAILURE
24	(0.01, 1)	0.000121	FAILURE	FAILURE
25	(0, 100)	0.6397244	SUCCESS	SUCCESS
26	(0, 50)	0.07196	FAILURE	SUCCESS
27	(0, 10)	0.007196	FAILURE	FAILURE
28	(0, 1)	0.0007196	FAILURE	FAILURE

The highlighted values represent simulations of "successful" events while all others represent system failures. There is a corresponding probability for each of the 28 paired set shown in the middle column of Table 5.7. By summing up all the probabilities corresponding to a "successful" event, each model's probability of success can be calculated. The results from this summation of probabilities for both the passive and active models are summarized in Table 5.8.

Table 5.8 Model Success Probabilities

Passive Model Probability of Success	85.58%
Active Model Probability of Success	97.36%

There are a few conclusions that can be drawn from these results. The first one is that active systems handle potential T-H uncertainties better than passive systems with the same rated flow. This conclusion takes into account an important assumption of instantaneous flow for the active model as soon as the loop isolation valve opens which is the most optimistic case. In other words, the probability of success for the active model in Table 5.8 is an upper bound or best case scenario. Second, both safety systems modeled had very high overall probabilities of success regardless of the T-H uncertainties imposed (X3 and POV). Structural failures like pipe breaks or valve leaks would yield the same failure rate contributions for either system assuming the same types of piping and valves are used which they were in this model. The last major reliability factor that must be accounted for is the pump in the active system. It is not 100% reliable as the simulation assumes. Using pump reliability data for various surveillance testing intervals (STI) ranging from 1 month to 12 months, the overall active system reliability can be determined by multiplying those pump reliability numbers by the 0.9736 success rate given that the pump starts (from Table 5.8). Because the design basis requires 3 of 4 loops to operate and the model lumps these loops together for simplicity, pump reliability data for three pumps in series is used in Table 5.9. The overall active results including pump reliability are shown in Table 5.9 next to the overall passive system case for comparison. The shaded columns represent the higher reliability system for a given STI. Notice how the active system is only more reliable when the pumps are tested at least every five months. Otherwise, passive systems are more reliable even when the T-H uncertainties of X3 and POV are considered. Also, remember that the active system values are a best case scenario because of assumed instantaneous flow, given that the pump starts. If the pump does not start, the active system is assumed to fail because there will be minimal flow.

Table 5.9 Overall Success Probabilities[30]

STI (months)	Pump Reliability	Active System Reliability	Passive System Reliability
1	0.970	**0.9444**	0.8558
2	0.949	**0.9239**	0.8558
3	0.927	**0.9025**	0.8558
4	0.906	**0.8821**	0.8558
5	0.886	**0.8626**	0.8558
6	0.866	0.8431	**0.8558**
7	0.847	0.8246	**0.8558**
8	0.827	0.8052	**0.8558**
9	0.809	0.7876	**0.8558**
10	0.791	0.7701	**0.8558**
11	0.773	0.7526	**0.8558**
12	0.755	0.7351	**0.8558**

Modeling T-H uncertainties properly is an important factor in determining an accurate CDF from a PRA. This simulation proposes a method to help model these factors accurately. Based on the results from this model, it is clear that active systems of similar design provide a greater margin of safety when faced with these uncertainties *assuming* the pump is tested at least every five months. The question remains as to whether this advantage (shown in Table 5.9) is significant enough to make up for other potential disadvantages (such as cost) that active systems may have compared to passive systems.

Chapter 6. Economic Model and Results

6.1 Overview

The MIT study, The Future of Nuclear Power[30], used a cost model to compare nuclear power to other energy alternatives. Using that cost model, the study varied different parameters and considered various carbon taxes to see what it would take to make nuclear power cost competitive in the deregulated market. Using the same cost model, comparisons can be made between reactors with passive safety systems and those with active ones. One of the potential benefits from passive safety systems is reduced operating and maintenance (O&M) costs due to fewer components. One of the potential disadvantages is the longer lead time necessary for licensing reactors with new passive systems and first time construction considerations. Finally the cost of capital itself should be considered to determine what design may achieve an advantage in this area.

The economic model computes real levelized annual cost (LAC) of electricity production to assess economic competitiveness. This cost is simply the constant dollar (2002 dollars used) price of electricity that would be necessary over the economic life of the plant to cover all expenses including operating expenses, loan repayments, and taxes. A simple spreadsheet was used to calculate this cost and the base assumptions are shown in Table 6.1.

Table 6.1 Base Cost Assumptions (2002 dollars)[31]

Overnight Cost	$2000/kWe
O&M Cost	1.5 cents/kWh (includes fuel)
O&M real escalation rate	1.0%/year
Construction Period	5 years
Capacity Factor	85%
Financing:	
Equity	15% nominal
Debt	8% nominal
Inflation	3%
Income Tax Rate	38%
Equity Fraction	50%
Debt Fraction	50%
Weighted Average Cost of Capital (WACC)*	6.8%
Project Economic Life	40 years
Levelized Annual Cost (LAC)	**6.7 cents/kWe-hr**

*real WACC after taxes

The base factors yield a levelized annual cost (in 2002 real dollars) 6.7 cents/kWe-hr per the MIT cost model used in their study. A more detailed breakdown of the spreadsheet used in this study follows.

6.2 *Economics Model Methodology*

The MIT Future of Nuclear Power economics model uses a discounted annual cash flow analysis using nominal dollars for tax calculations and then converts these amounts to constant real dollars using the assumed 3% inflation rate. Once levelized using this inflation rate, these costs can be converted to an equal annual payment over the lifetime of the plant which is done by the spreadsheet to get the LAC.

The capital investment of the plant can be calculated in real dollars once the length of construction time is known and cost of capital is determined. The total construction cost, C_{TOT}, is as follows:

$$C_{TOT} = \sum X_j \,(1 + r_{eff})^{-n}$$

where $X_n = F_n C_o(1 + i)^n$

$r_{eff} = (D^* r_d) + (E^* r_e)$

X_n = total outlay (nominal dollars) in year "n"

n = years of construction including final licensing and testing

C_o = Overnight Cost

F_n = Fraction of overnight cost allocated to year "n"

r_{eff} = effective interest rate

r_d and r_e = nominal cost of debt and nominal cost of equity

D and E = Debt fraction and Equity fraction of initial investment

i = general rate of inflation assumed

One can see how the time component can be a major factor considering the effective interest rate. The "cost of capital" (r_{eff}) for this project also shows its importance in conjunction with the time period (n) that it is applied. The revenue stream is based off the sale of electricity which is simply the quantity of electricity produced multiplied the price of electricity.

$$R_n = Q * p_n$$

where $Q = (L/1000) * (CF) * 8760$ hrs/year

$p_n = p_o (1 + i)^n$

Q = quantity of electricity produced

CF = plant capacity factor

L = plant net capacity

p_n = price of electricity in year "n"

n = number of years

Now that the revenue stream is clear, it is time to outline the cost stream which can be broken down into fixed and variable operating expenses. It is assumed that most of these expenses increase at the rate of inflation every year except in where a "real" escalation rate is used as shown in Table 6.1 for O&M expenses. The total operating expenses are calculated summing the operating, fuel, waste, O&M, and decommissioning costs as shown below:

$$C_n\,(\text{op}) + C_n\,(\text{fuel}) + C_n\,(\text{waste}) + C_n\,(\text{fixed O\&M}) + C_n\,(\text{variable O\&M}) + C_n\,(\text{decom}) = C_{n,\,\text{total}}$$

The taxes, T_n, for any given year "n" are calculated using the following equation:

$$T_n = \tau\,[R_n - C_n\,(\text{op}) - C_n\,(\text{incremental}) - D_n - I_n]$$

where D_n = annual asset depreciation, I_n = annual interest payments to creditors, τ = tax rate, and C_n (incremental) = incremental capital expenditures. These taxes add to the cost stream for the year. The final cash flow concern is the investor return based on the debt to equity fraction and promised returns. The spreadsheet then converts the annual cash flows to constant real dollars and determines a LAC for the project based on its lifetime.

6.3 Economic Analysis

The next step is to vary the O&M cost (not the O&M escalation rate), construction time, and cost of capital to see what effect it has on the LAC. A way to see which of these three factors has the most effect on LAC of nuclear energy is by analyzing what change in each parameter will result in the same change in LAC. This approach is shown in Table 6.2. It is well known that the capital cost of the nuclear plant is where most of the expense lies, however the opinion is mixed as to which reactor would be cheaper to build in terms of overnight cost (as will be shown in Chapter 7). Passive systems require taller structures but less internal components. Due to lack of data, it is unclear whether either will have a significant advantage in overnight capital costs.

Table 6.2 Cost Effects

Parameter Changed	Base Case	Base LAC	New Case	New LAC
O&M cost	1.5 cents/kWeh	6.7 cents/kWe-hr	1.3 cents/kWeh	6.5 cents/kWe-hr
Construction Time	5 years	6.7 cents/kWe-hr	4 years	6.5 cents/kWe-hr
Real WACC after taxes	6.80%	6.7 cents/kWe-hr	6.35%	6.5 cents/kWe-hr

As one can see, lowering O&M costs by 2 mills/kWe yields a 0.2 cent/kWe-hr decrease in the LAC which is the same decrease in LAC seen when the construction time is reduced one year or when the WACC decreases to 6.35%. Going from 6.7 to 6.5 cents/kWe-hr is a modest 3% decrease in LAC. Comparatively, the plant can achieve this decrease in cost by decreasing O&M costs 13% (from 1.5 to 1.3 cents/kWeh), reducing WACC by 6.6% (from 6.80% to 6.35%), or finishing construction in year 4 instead of year 5. A sensitivity analysis of all three parameters and their affect on % change in LAC is shown in Figure 6.1. The % change of base case LAC (6.7 cents/kWe-hr) was determined for a 5%, 10%, 15%, and 20% change of each parameter except for construction/licensing delays. For this delay parameter, the % change in LAC was calculated for every year that the construction/licensing was completed ahead of schedule (base case is set at 5 years total). All three are plotted in Figure 6.1.

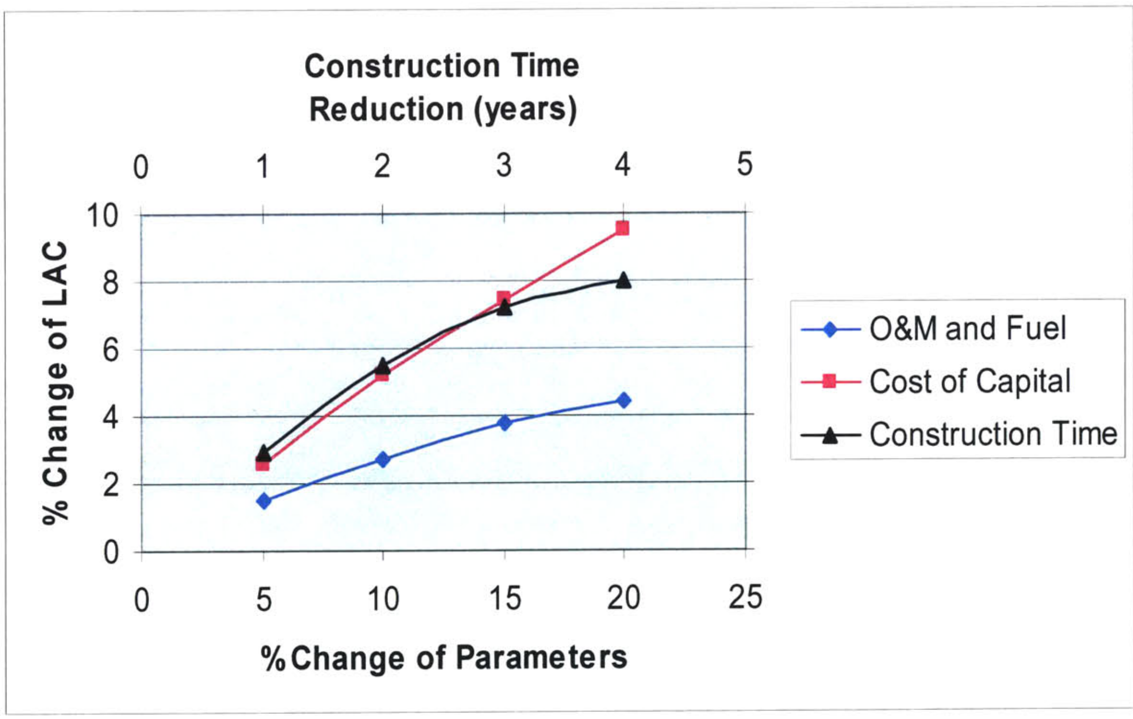


Figure 6.1 Sensitivity of Levelized Cost

Out of the three choices, it appears that cost of capital (WACC) has the most impact on the LAC. Decreasing construction and licensing time by one year initially causes the same economic benefits as decreasing the cost of capital by 5%. As the total construction time becomes less and less, so does the economic benefit to the LAC of electricity.

The question remains as to whether any of these new goals for these parameters can be met easier with a reactor with passive safety systems over one with active ones. If a reactor with passive safety systems takes one year longer to license and build than one with active safety systems, it will require a decrease in other areas (O&M costs for example) to offset the cost disadvantage of taking one year longer, if it wants to remain competitive in a deregulated market. The above examples give an idea of what it will take to meet these lower cost goals.

An interesting question surrounds the cost of capital for the new reactor. Will reactors with passive safety systems obtain a lower cost of capital because investors believe they are safer and less prone to being shutdown for liability concerns? Or will they obtain a higher cost of capital since there is little experimental data on passive systems and the investors want to hedge that risk? Because WACC is such a sensitive factor in the overall cost of nuclear energy, the differences in investor opinion between active and passive safety models are important.

Passive safety promises smaller O&M costs due to fewer parts and equipment requiring less maintenance. The problem with this promise is that it is only a promise until proven over time after a reactor with passive safety systems is built and operated. Figure 6.1 shows how large the promise of lower O&M will need to be to have the same impact as other factors. Also unknown will be the total construction and licensing time since a reactor has not been built in quite some time in the U.S. While the base case assumed five years , it could just as easily be more than that which will cause a higher LAC and create a negative impact on electricity cost.

The next chapter focuses on the various expert opinions of passive systems including the three parameters modeled here in this chapter. This will hopefully provide insight as to the current perception of passive safety from various professional affiliations.

Chapter 7. Survey on Attitudes Towards Passive Safety

7.1 *Overview*

A survey was conducted among nuclear energy experts of various affiliations to determine their views and opinions on the safety, cost, and licensing of reactors with passive safety systems, especially in comparison to reactors with active safety systems. The surveys were conducted via face-to-face or phone interviews. A total of 31 experts were contacted representing seven nuclear affiliation categories. The categorization was formed based on the role of the represented party in the nuclear industry—regulators, vendors, utilities, academia, consultants, and both pro- and anti-nuclear non-profit groups. The survey is not meant to be a scientific sample representative of the US nuclear energy enterprise, with proportional representation of either the institutions involved or the personnel of the various segments of the enterprise. Rather it is meant to explore the range of opinions within the enterprise, with some representation of all its important segments. Therefore the experts were chosen to be at the managerial level in their institutions, and come from several institutions in each category of affiliation. Table 7.1 provides the total number of people surveyed in each category of affiliation along with the specific institutions represented. All institutions are represented by one respondent unless otherwise indicated in parenthesis.

Table 7.1 Survey Overview

GROUP	Total Surveyed	Companies represented
Utilities	6	Exelon, Entergy, Dominion, Duke, Southern California Edison, Constellation
Vendors	6	General Electric (2), Westinghouse (2), Framatome ANP (2)
Consultants	5	Business America, Performance Improved Intl., INL, DOE, Sandia Natl. Lab
Academia	6	MIT (3), University of Wisconsin (2), UCLA
Regulators	4	Nuclear Regulatory Commission (4)
Pro-Groups	2	EPRI (2)
Anti-Groups	2	Union of Concerned Scientists, NRDC

A total of 10 questions were included in the survey. Participants were asked to express their agreement or disagreement with statements on a 1 to 5 scale, with a 1 meaning "strongly disagree" and a 5 meaning "strongly agree." Respondents were also allowed to answer "no opinion" if they felt they did not wish to comment on a particular question. In addition, they could add specific comments after each question to amplify their numeric response.

The first nine questions were statements about safety, cost, or licensing of systems, with the tenth question being an overall feeling on the preference of passive safety systems compared to active ones. The ten questions asked are:

1. In general, reactors with passive safety systems achieve a lower "core damage frequency" (CDF) than ones with active safety systems.
2. Reactors with passive safety systems are licensed (start to finish) ______ years earlier/later than ones with active safety systems.
3. Reactors with passive safety systems can achieve higher capacity factors than ones with active safety systems.
4. Reactors with passive safety systems are more profitable for utilities than ones with active safety systems.
5. Current probabilistic risk assessment methods are adequate to quantify for passive safety systems.
6. Reactors with passive safety systems are more accepted by the public and interest groups than ones with active safety systems.
7. Reactors with passive safety systems have a lower initial <u>capital</u> cost than ones with active safety systems.
8. Reactors with passive safety systems have a lower <u>operating and maintenance</u> (O&M) cost than ones with active safety systems.
9. Reactors with passive safety systems have lower <u>personnel required</u> than ones with active safety systems.
10. If all things (safety, cost, licensing etc.) were equal, I would prefer a reactor with passive safety systems over one with active safety systems.

Questions 1, 5 and 6 represent the "safety" category
Question 2 represents the "licensing" category
Questions 3, 4, 7, 8 and 9 represent the "cost" category
Question 10 represents the "overall" category

The questions (or more accurately the statements) were set up this way to provide consistency for scoring each in the same way. With the exception of question 2 on licensing, a score above 3.0 on a question represents a favorable opinion of passive safety systems. The higher the score above 3.0, the more favorable the response is towards passive safety systems. Conversely, a score below 3.0 represents a negative opinion of passive systems and in most cases, a preference for active systems.

The next sections will present a break down the results of the survey by affiliation, category, and specific question asked.

7.2 Affiliation Breakdown

7.2.1 Utilities

The job of a utility is to provide continuous uninterrupted power to its constituents. Obviously it would prefer to do this and the lowest possible cost in order to get a larger market size (if the plant is not a regulated market) or profit (if the plant is in a regulated market). Now that the industry is moving towards deregulation, utilities are much more interested in choosing the most cost effective means of producing the electricity. However, safety is just as important factor to consider when evaluating the overall cost since the utility would lose income if the plant is idled to resolve incidents and also is liable for any safety mishap that occurs. With the new streamlined regulatory process, utilities are less concerned about the licensing time of a particular plant design (more of a vendor concern) and more concerned about receiving their early site permit to build a new plant.

Several personnel associated with various utilities were given the aforementioned survey and their results are summarized in Table 7.2.

Table 7.2 Utility Results

Survey Question

	1	2	3	4	5	6	7	8	9	10
Utilities	4.00	1.5-YR (Later)	3.00	4.00	3.00	4.67	2.33	5.00	4.00	4.00

It is clear from the results that the utilities favor passive plant systems. One of the interesting things to note is how unanimously and strongly they feel that reactors with passive safety systems will yield less "operation and maintenance" (O&M) costs over the life of the plant (question #8). This was mainly due to less moving parts (especially pumps) which require periodic maintenance.

Conversely, they feel the opposite is true for the initial capital cost (question #7). Some utilities cited that because these systems were new, they may create longer construction lead times and higher overnight costs. In addition, most see a larger "$/kW" overnight cost because the maximum output of many reactors with passive systems is perceived to be smaller than ones with their active counterparts. Many cited the AP1000 as too small to fully take advantage of economies of scale. One mentioned that in order to take advantage of using a single rotor turbine generator and longer refueling/higher burn-up cycles, a reactor with at least 1000 MWe output was necessary. The fact that ESBWR has moved to the 1500 MWe size has in fact been a factor in increased interest in the US among utilities anxious to maximize the power generated from their plants. But given that the survey was conducted mostly in the summer and fall of 2005, this new rating of the ESBWR may not have been well appreciated by those surveyed.

Another result that stands out is question #6 which shows that utilities feel reactors with passive systems will be more accepted by public interest groups. Some of the specific comments on that question were that passive systems had "better packaging" and were "less complicated." Furthermore, the utility group feels that reactors with passive safety systems will achieve equal capacity factors as those with active systems because the "maintenance done on the safety systems is not the limiting factor during the shutdown." Overall, utilities seem to prefer reactors with passive safety systems as also indicated in question 10.

7.2.2 Vendors

Vendors would be expected to be more concerned with the licensing process and the desirability of the reactors they design. To be fair, we surveyed various companies comprised of both the active and passive safety system designers. It is no surprise that some of the more positive reviews of passive systems came from those companies whose newer designs utilized this technology. In turn, some of the negative responses came from those vendors who designed comparable reactors with active safety systems. Still, the survey results yield some consensus views in a couple of areas as shown in Table 7.3.

Table 7.3 Vendor Results

Survey Question

	1	2	3	4	5	6	7	8	9	10
Vendors	3.67	1.33-YR (Later)	3.67	4.00	3.00	4.33	3.00	5.00	4.67	3.67

Similar to utilities, vendors unanimously believe that passive systems require less O&M costs than active systems, and most agree that they require less total personnel at the plant (question #9). It is also important to see that the perceived licensing time of a reactor with passive safety systems is 1.33 years longer (not shorter) than one with active systems. The main reason for this cited in the survey by the vendors was due to the "novelty of passive systems to regulators." In other words, because this technology is relatively new, it may take regulators longer to study and approve its design. This belief is common among most groups as will be discussed later. Although not as strong a preference, vendors agree with utilities and prefer reactors with passive safety systems overall (question #10).

7.2.3 Consultants

The consultants interviewed do mostly energy consulting for utilities although some have also worked for vendors. They bring a broader scope of background to the survey in the sense that many have worked with multiple utilities, vendors, regulators, and non-profit groups to solve various energy issues. Their results are shown in Table 7.4.

Table 7.4 Consultant Results

Survey Question

	1	2	3	4	5	6	7	8	9	10
Consultants	4.00	1-YR (Later)	4.00	4.33	2.00	4.33	3.00	5.00	4.50	5.00

As can be seen, passive systems score high across the board with the exception of questions #5 and #7, the former being a question on the adequacy of current "probabilistic risk analysis" (PRA) methods for reactors with passive safety systems. While this question has scored low in other groups (including the ones already covered), it is particularly noticeable here since all other marks are favorable for passive systems. Some of the specific concerns from consultants about current PRA modeling are:

(1) There needs to be more system/component reliability testing on new applications and more failure rate data collection.

(2) There also needs to be an assessment of human performance within the context of these new passive systems.

In question #7, many consultants argued that there is an "expectation" that passive systems could be less capital intensive than active systems in the long run, but since no new plant has been built in the U.S. in about 15 years, most see the capital cost of a nuclear plant being the same regardless of its safety systems.

7.2.4 Academia

Various professors at MIT and other prominent nuclear engineering schools were surveyed in order to get their perspective of the desirability of passive systems. Their opinion is important due to the fact that they generally have done extensive research in some of these areas being assessed. In addition, the academicians are not obviously biased towards the products of one company, or the attitudes of industry versus those of the regulator bodies. Also, academia often sees the technology as it is developed, before it is adopted in a particular form, since the academic experts provide much of the preliminary research for many vendors, utilities, and the regulators. The results are given in Table 7.5.

Table 7.5 Academia Results

Survey Question

	1	2	3	4	5	6	7	8	9	10
Academia	4.33	2-YR (Later)	4.00	4.00	2.33	3.67	3.00	4.33	3.67	4.00

Professors generally score reactors with passive safety systems as more favorable with the exception of acceptable PRA methods for these systems. They also see a much longer licensing time for passive systems than previous groups. The highest scores were achieved on questions #8 (O&M cost) and #1, which show that the academic experts believe reactors with passive systems achieve a lower "core damage frequency" than those with active systems. They specifically cite increased "inherent" safety and much improved performance in loss of electric power accidents to energize the pumps. The specific worry about PRA stems from a combination of larger thermal-hydraulic uncertainties due to lack of sufficient experimental data. Overall, the academic experts are also more favorable towards passive systems.

7.2.5 Regulators

Regulators are obviously an important component of the U.S. nuclear enterprise. Their mission is to protect the public health and safety, and the environment, from the effects of radiation from nuclear reactors, materials, and waste facilities. Thus, the regulators control the licensing of all new designs and ensure their safety before granting them acceptance certificates or permits. It is not surprising that this group refused to answer "no opinion" to some of the questions, as they are to remain neutral in many areas (see "NO" for "no opinion" in question #4 on profitability). The results are given in Table 7.6.

Table 7.6 Regulator Results

Survey Question

	1	2	3	4	5	6	7	8	9	10
Regulators	4.33	0.5-YR (Later)	3.67	NO	2.67	3.00	3.67	4.00	4.00	3.00

It is not surprising that the regulators feel that licensing of reactors with passive systems will be very close to those with active systems. They cite that they have already seen most of the passive designs now (i.e. the AP600, AP1000, and most recently ESBWR) and thus, it is no longer a limiting factor. A more limiting factor on licensing is the sheer number of new applications for plant uprates, new design certification, and site certification and what might materialize for construction. This has occurred at a time the experience base within NRC has suffered due to retirement of many of the experts in various disciplines. While the regulators do not strongly state an overall preference for either type of reactor, they do show a favorable impression of the passive systems, by affirming that they will cost less and achieve a lower CDF (question #1). The reason they cite for a lower CDF is the diversity of the passive safety systems to eliminate common mode failures often associated with repetitive active safety system trains. The regulators also cite a reduction in the human error component of reliability with passive systems. These specific questions will also be discussed in later phases of the work.

7.2.6 Non-Profit Groups

Non-profit groups provide valuable independent opinions, and at times in-depth studies, of the nuclear industry in a variety of areas. These groups can have a profound impact on public opinion and consequently the future of the industry. While many groups claim no biases, historical data shows otherwise for most of them. It is important to include both biases, pro-industry and anti-industry, to look for common concerns or assurances within the groups. For this study, the groups were simply broken up into "pro-nuclear" and "anti-nuclear" groups based on the group's historical stance on nuclear power. The results are shown in Table 7.7.

Table 7.7 Non-Profit Results

Survey Question

	1	2	3	4	5	6	7	8	9	10
Pro-Groups	4.00	2-YR (Later)	3.00	3.50	2.00	4.00	3.00	4.00	3.50	4.50
Anti-Groups	3.00	3-YR (Later)	3.00	4.00	1.50	3.00	3.00	3.50	2.50	3.00

It is interesting to see that the pro-nuclear groups generally prefer reactors with passive safety systems and cite better CDF, profitability, and cost. Question #6 directly indicates that they are more favorable towards those reactors with passive systems. Conversely, the anti-nuclear groups do not show a clear preference towards either reactor. They also believe that the passive systems would require longer licensing time, perhaps the longest seen in this survey, citing that these systems are relatively untested. Furthermore, both groups believe that utilities see the passive plants as more profitable (question #4) although they seem to believe they would yield slightly less cost if any (questions #7-9). Both groups add to the prevailing opinion that more work needs to be done in PRA of passive safety systems. Lack of experimental data was specifically mentioned as it was by other groups.

7.3 Breakdown by Question Category

We will now lump the questions together into the following categories:

Safety—questions 1, 5, and 6

Licensing—question 2

Cost—questions 3, 4, 7, 8, and 9

Preference—question 10

Averaging the results of each of the categories for each expert affiliation group yields (in rank order with respect to favoring passive systems), we get the results shown in Table 7.8.

Table 7.8 Category Results

	SAFETY		LICENSING		COST		PREFERENCE
Utilities	3.89	**Regulators**	0.50 YRS	**Consultants**	4.17	**Consultants**	5.00
Vendors	3.67	**Consultants**	1.00 YRS	**Vendors**	3.67	**Pro Groups**	4.50
Consultants	3.44	**Vendors**	1.33 YRS	**Regulators**	3.84	**Utilities**	4.00
Academia	3.44	**Utilities**	1.50 YRS	**Academia**	3.80	**Academia**	4.00
Regulators	3.33	**Academia**	2.00 YRS	**Utilities**	3.67	**Vendors**	3.67
Pro Groups	3.33	**Pro Groups**	2.00 YRS	**Pro Groups**	3.40	**Regulators**	3.00
Anti Groups	2.50	**Anti Groups**	3.00 YRS	**Anti Groups**	3.20	**Anti Groups**	3.00
Average	3.37	**Average**	1.62 YRS	**Average**	3.68	**Average**	3.88

This shows that utilities hold the most favorable opinion of the passive systems with regards to safety while consultants and vendors were most favorable in cost. The regulators felt that the licensing was not much different between the two the types of systems while both non-profit groups saw a significant lag in licensing time for reactors with passive systems. Note also the average for each category at the bottom of the column. This shows that with the exception of licensing (which most groups believe takes 1.62 years longer on average), reactors with passive safety systems are preferred to those with active systems in all areas, with cost receiving more favorable feedback (3.73) than safety (3.37). By averaging all but the licensing "category" scores above for a particular group, we can get an overall score for each group (licensing does not fit the 5.0 scale model like the other 3 categories' scores do). By doing it this way, cost will not be weighted more than safety even though it had more questions pertaining to its category. Those "overall" results are shown in Table 7.9.

Table 7.9 Overall Results In the Order of Favoring Passive Systems

	OVERALL
Consultants	4.20
Utilities	3.85
Academia	3.75
Pro Groups	3.74
Vendors	3.67
Regulators	3.39
Anti Groups	2.90

Thus, consultants perceive reactors with passive safety as the more favorable alternative when safety, cost, and personal general preference are taken into account. Anti-nuclear groups are the only group that scored passive systems below a 3.0. Every other group shows favorable assessments on reactors with passive safety systems. Nevertheless, all groups also believe that the licensing would take anywhere from 0.5 to 3 years longer (refer to Table 7.7) although the regulators themselves believe very close to equal licensing times.

7.4 *Question Breakdown*

Now let's look at the overall average for each question to see any general trends or concerns amongst the groups. This will help identify specific shortfalls, if any, in the future and determine any general stereotypes that currently exist. The question-by-question averages were obtained by averaging the affiliation group average scores. This way, a group with more survey participants was not more heavily weighted than the other groups. The average scores for each question are given in Table 7.10 (note the overall average in at the bottom).

Table 7.10 Question Results

Survey Question

	1	2	3	4	5	6	7	8	9	10
Regulators	4.33	0.5-YR (L)	3.67	NO	2.67	3.00	3.67	4.00	4.00	3.00
Utilities	4.00	1.5-YR (L)	3.00	4.00	3.00	4.67	2.33	5.00	4.00	4.00
Vendors	3.67	1.33-YR (L)	3.67	4.00	3.00	4.33	3.00	5.00	4.67	3.67
Consultants	4.00	1-YR (L)	4.00	4.33	2.00	4.33	3.00	5.00	4.50	5.00
Pro Groups	4.00	2-YR (L)	3.00	3.50	2.00	4.00	3.00	4.00	3.50	4.50
Anti Groups	3.00	3-YR (L)	3.00	4.00	1.50	3.00	3.00	3.50	2.50	3.00
Academia	4.33	2-YR (L)	4.00	4.00	2.33	3.67	3.00	4.33	3.67	4.00
Average	3.90	1.62-YR (L)	3.48	3.97	2.36	3.86	3.00	4.40	3.83	3.88

The question on which passive systems fared the best was achieving a lower operating and maintenance cost (question #8). That question received an overall average of 4.40. This is important because cost is one of the largest barriers for nuclear power, although not the operating part of the cost. The second best was question #4 (3.97 average) which stated that reactors with passive systems were viewed as more profitable by utilities. The third highest was that reactors with passive safety systems can achieve a lower CDF than ones with active systems (3.90 average). This is important to both utilities and vendors. Utilities must think about liability issues while the vendors need their design approved by the regulators before they can sell them. The safer the design, the more licensable and marketable the reactor will be. All questions scored above 3.0 showing a favorable bias towards passive systems with the exception of questions #5 (on PRA) and #7 (on capital cost). Question #5 inquired about the acceptability of

PRA for passive safety systems. The number one concern was lack of experimental data. Other concerns voiced were that common mode production and maintenance failures have not been fully identified yet. In addition, utilities worry about the human error factors such as input assumptions and detecting out-of-specification conditions/configurations. Some groups cited that event trees need to be expanded more to encompass all possible thermal hydraulic uncertainties. Overall, this study clearly indicates the perception that reactors with passive safety systems are superior to those with active systems in terms of cost, safety, and personal preference but inferior in licensing time.

Chapter 8. The Hybrid Approach of Passive and Active Systems

The NRC reviews all new designs submitted without any bias towards a particular type. Recent U.S. policy has given a variety of benefits to new nuclear plants including production tax credits, loan guarantees, and "standby support" for potential licensing delays (these were outlined in Chapter 1). These benefits are to help jumpstart the new nuclear reactor order in general and are not catered to a specific reactor type. Congress could have offered these benefits only to a certain type of reactor (active or passive) had it felt that one design was truly superior to the other. This type of lever could significantly affect the other market forces within the electricity deregulated market. At this point, the reactor design decision is basically a market decision for utilities since all designs currently receive the same benefits with the exception of the ESBWR and EPR which have not completed their full licensing processes yet. The ESBWR should likely finish within the next year while the EPR has just started the process. Some of the government benefits mentioned only apply for the first few "new" reactors and thus, time is of the essence in making a plant selection by utilities. With the ABWR and AP1000 already completing their certification, the utilities would still have to decide between active and passive safety systems even today. Which will they choose and why? And will that be the best decision for the public?

Cost and safety will be important factors in the decision. Without having any experience for passive systems, decisions will have to be made on projections and computational models for both cost and safety. The safety calculations and general opinion of passive safety will in turn affect the cost of capital required to build the plant. The safer the plant design is perceived, the less risky the investment and therefore, the less is the cost of capital. Thus, if investors believe in passive systems' promised safety and cost reduction models and lower their cost of capital compared to that of a reactor with active safety systems, the capital providers can also have a large impact on which ALWR is desired by the utility. In addition, the utility wants to make as large a profit as possible so these models are just as important to them directly. Obviously operational cost projections (to include cost of capital) will be important, but so will safety and risk projections. The utility surely does not want to have a high risk liability on their hands.

Passive systems promise less expensive plants, and if they prove to be as reliable as the current active plants, they can be a more competitive energy source. They also could be less susceptible to human error, thus avoiding some accident initiators and reducing the risk of severe accidents for the utilities and insurance companies. Expert opinion seems to be on their side as shown in Chapter 7. Gravity is a force that the experts believe to be reliable. The major disadvantage is the lack of operational and experimental data. There have been many tests done at facilities like PANDA which test similarly designed passive systems, but most of the studies to prove passive safety have been done using computational models. And with the dearth of experimental data, there is limited ability to verify these computer models for accuracy. Second, some of the computer codes were not designed to model natural circulation transients with a high degree of accuracy. Finally, since flow is dependent on natural forces (not forced by a pump), thermal hydraulic uncertainties in the system can have a larger effect on the flow and heat transfer characteristics of the coolant, and thus the system performance. From a liability standpoint, having a "button" to automatically start the coolant flow necessary to protect the core (i.e. a pump) can provide added peace of mind. Of course, this is an additional cost and may eliminate any of the cost advantages gained from its original elimination.

So the policy debate ends where nuclear safety debates often end. How safe is safe enough? All the safety systems used in the four Generation III+ reactors discussed far surpass the NRC CDF safety goal of 1×10^{-4} as discussed in Chapter 3. Both types of reactor provide a much lower risk of core damage than the 103 currently in operation in the U.S. today. Active systems in the 103 reactors in operation provide years of experimental data that support the ALWRs with active safety systems although the ALWR active systems are newer and more diverse. The passive systems do provide potential advantages. The problem is in proving these advantages right now. Therefore, early passive systems will be providing this pricing and safety data currently lacking and will help prove these projections and models.

An intermediate alternative may be the design that Toshiba is currently working on known as the AB1600. It combines many of the features of the ABWR and ESBWR thus attempting to maximize the net benefit of both active and passive safety systems. The issue is can the reactor combine both features while still keeping costs low. The AB1600 would improve countermeasures for severe accidents (SA) and the economics of the ABWR by introducing "hybrid" active/passive safety systems and simplifying overall plant systems. Achieving simplification of reactor system is primarily accomplished by reducing the number of fuel bundles and control rods by adopting a larger bundle, which is 1.2 times as large as the current ABWR fuel. The AB1600 incorporates passive systems such as PCCS, GDCS, and the isolation condenser along with two, active ECCS divisions to make up the overall safety system. The maximum power output of 4500 MWt is based on the maximum power without changing the RPV diameter from the current ABWR. Because reactor internal pump (RIP) motor power is increased from the current ABWR and simplification of the fuel characteristics, the number of RIP can be reduced from 10 to 8. The current target of the AB1600's first commercial operation is set at the late 2010's. An overview of the design changes is outlined in Table 8.1 below.

Table 8.1 AB1600 Comparison of key parameters[32]

Parameter	BWR/6	ABWR	ESBWR	AB1600
Power (MWt)	3293	3926	4500	4500
Power (MWe)	1290	1350	1550	1600
Vessel Height (m)	21.8	21.1	27.7	23.1
Vessel Diameter (m)	6.4	7.1	7.1	7.1
Fuel Bundles (number)	800	872	1132	600
Number of CRDs	193	205	269	137
Power Density (kW/l)	54.2	51	54.3	58.5
Number of RIPs	N/A	10	0	8

The AB1600 uses a passive containment cooling system (PCCS) similar to the one already discussed to cool the primary containment directly during a severe accident. In addition, the AB1600 has a gravity driven core cooling system (GDCS) which together with the PCCS provide the recycling needed for core cooling capability after severe accidents. The GDCS and the PCCS also can keep the core water coverage and achieve in-vessel retention (IVR). The condensate water by PCCS is returned to the GDCS pool that is installed in the drywell. The GDCS can continue to inject water into the reactor pressure vessel (RPV) until the PCCS pool is empty. The 2m extension of RPV height over the ABWR and introduction of the isolation condenser (IC) can maintain the core coverage at the time of a LOCA and eliminate the need for a high pressure core flooder system (HPCF).[32]

By introducing these passive safety systems, the composition of the emergency core cooling system (ECCS) / heat removal system can be reduced to two divisions configuration from three divisions' configuration. Also, the trains of reactor building closed cooling water and reactor seawater can be reduced to two divisions from three. This configuration change contributes to improvement in economy by attaining amount-of-resources reduction in not only main systems but also related systems. A further reduction in cost is achieved by simplifying the amount of resources such as instruments/control cables, remote-control valves and pipes of the remaining active systems and non-safety related components. Each ECCS division has two low pressure flooder (LPFL) pumps and one emergency gas turbine generator (GTG). The LPFL pumps are also used as the residual heat removal (RHR) pumps. Furthermore, the configuration of PCV and layout concept of will be optimized and is considered for withstanding airplane crash.[32] The design goal of the AB1600 is to achieve 30% power generation cost reduction and a 20% capital cost reduction from recent ABWR.[32] No comparison is made to GE's ESBWR. Thus, the AB1600 has the possibility attaining both an economical and safety goal by simplification of system and utilizing a "hybrid" active/passive safety system.

Chapter 9. Concluding Remarks and Recommendations for Future Work

9.1 General Conclusions

Generation III reactors, which have increased reliance on passive systems, will be the next generation of reactors built in the U.S. Currently, active safety systems are utilized in 100% of the operating reactors (Generation II) in the country. Reactors with passive systems have a lot of promise, but limited experience. The current thermal hydraulic and risk assessment computer models may not be sufficiently tuned to accurately calculate the reliability of these systems. Thermal hydraulic uncertainty during transients is very complex and makes it difficult to quantify the functional failure rates. In our work, we used a somewhat simplified system to illustrate a general observation. When considering just the T-H uncertainties, it was no surprise that the active system showed higher reliability in this study. However, after adding the pump failure data, the two systems were much closer in their reliability.

A generalized conclusion could be that while the sources of inadequate performance could be different, the passive and active systems may turn out to have comparable reliability. The active systems gain reliability by periodic testing of the active components. Therefore, more frequent testing will boost their reliability. Our example showed the active system is more reliable if the pumps are tested at least every five months, but that the passive system is more reliable if the pumps are tested at a lesser frequency. Vendor calculations show that the core damage frequency of the passive systems is well below the safety goals set by the NRC such that even if their computations are somewhat off based about the uncertainties, the system's performance should still be well above that implied by the safety goals.

More passive system experimental data and/or field experience would be helpful to the confidence in their performance. By gradual phasing in of the new types of reactors, such as building only one or two of these reactor types may yield the answers to the uncertainties, and if by chance problems develop, only one or two reactors would have to be modified. Another way to ease the use of passive safety ECCS into newer reactors would be to combine presence of active and passive safety systems in one reactor design (like the AB1600). This way, experimental data on passive systems can be gathered while still maintaining the familiar and reliable active systems in case unforeseen problems develop.

The cost savings and losses of passive systems are still unclear since no such nuclear reactors have been built and even for the active systems, the foreign data is not easy to translate to the U.S. Our survey shows that most experts feel the O&M cost will be reduced for passive systems. However, the model for the levelized annual cost (LAC) of electricity shows that a 13% decrease in O&M costs only yields a 3% decrease in the LAC for nuclear power. The model also showed that a one year lag time can cost a 3% increase in LAC such that potential O&M gains may be offset by lag times that may be required to certify the newer, unknown passive systems. The capital costs won't be known until a reactor is finally built again in the U.S. Vendor data have overnight costs as low as $1200/kWe for the ESBWR[33] and other Generation III+ reactors claim they can get close to $1500/kWe (the model used in our calculations assumes $2000/kWe). The vendor estimates are likely to be optimistic since these new reactors will be the first ones built in over 15 years. For this reason, and the policy breaks outlined in Chapter 1 for any new ALWR, it is uncertain whether there will be much advantage gained by either type in terms of capital costs.

An important factor in the overall cost of electricity produced from one of the new reactors will be the cost of money it achieves when financing the project. Investors who are in favor of a particular reactor type may offer lower rates for that type of reactor. The survey shows that expert opinion in all groups seems to favor passive systems. It is unclear as to the extent this opinion will have on the cost of money. But the important effects of a lower financing cost were proven in the model. This effect outweighs any O&M and time lag (carrying cost) savings on a percentage-wise saving basis if it can be achieved.

9.2 Recommendations for Future Work

Future work should include surveys of potential investors to determine what factor, if any, reactor safety system type has on the financing of the project. Expanding the survey (both in terms of questions and expert affiliations) would be desirable to add confidence to the results. In addition, other safety systems, such as the Gravity Drain Coolant System or Passive Core Containment Cooling System should be modeled and analyzed during transients using a similar method as performed here for the stuck valve event. Also, full PRA's should be reviewed to determine the level of uncertainty already included in the models, and to verify vendor data shown in Chapter 3.

To more completely compare active and passive systems, common mode failures and human failure rates should be taken into account along with the thermal hydraulic uncertainty. Such considerations can be examined within the framework of the full PRAs for these systems.

9.3 Concluding Remarks

This is an exciting time in the nuclear industry, with many new reactor orders being so near. Current operators are more comfortable with active systems and would require some retraining if passive systems are implemented. Still, introducing more passive systems is the right thing to do if there are quantifiable safety and cost benefits which make nuclear power more competitive. The ABWR is already operating in Japan and Taiwan. Experimental data is available. The EPR is currently under construction in Finland and France and will be operational before anything new will be built in the United States. The NRC scrutinized the AP1000 design and determined it to be adequately safe. There is enough confidence in the safety of all proposed systems to allow building a few of them in the near future. The certified designs should be subjected to periods of examination to verify the reliability of the passive systems embedded in the designs. From potential annual maintenance cost reductions to safety system response, more data can be obtained to continue to move towards future designs like using passive systems in gas cooled cores. The initial step is the hardest.

Overall, any of the four Generation III+ designs are on the market once licensed. This study has shown that both models have high reliability, but both are subject to functional failures at low probability. The thermal hydraulic uncertainty factors in passive systems should not be ignored although that overall contribution to system failure when compared to an active system may not amount to much difference. A full PRA using properly modeled T-H uncertainties and human errors would be needed to more completely evaluate the differences in passive and active systems.

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Appendix A. TRACE Steady-state Input File

```
free format
*
*************
* main data *
*************
*
*     numtcr      ieos      inopt      nmat      id2o
        1          0          1          0          0
Model of Reactor Core
*
*
*****************
* namelist data *
*****************
*
 &inopts
  cpuflg=1,
  dtstrt=-1.0,
  iadded=10,
  noair=0,
  usesjc=3,
  npower=1,
  nhtstr=4,
  igas=1
 &end
*
***************
* Model Flags *
***************
*
*      dstep      timet
         0         0.0
*     stdyst      transi      ncomp      njun      ipak
         0          1          11          5          1
*      epso       epss
      1.0E-3     1.0E-3
*     oitmax      sitmax      isolut      ncontr      nccfl
        10         10          0          0          0
*      ntsv       ntcb       ntcf       ntrp       ntcp
         1          0          0          0          0
*
************************
* component-number data *
*************************
```

```
*
* iorder*       1       11      26      41      51s
* iorder*     170      171     172     173     174s
* iorder*     184e
*
*
************************************************
* Starting Signal Variable Section of Model    *
************************************************
*
*      idsv      isvn      ilcn      icn1      icn2
          1         0         0         0         0
************************************************
* Finished Signal Variable Section of Model    *
************************************************
*
*
*
*
*******  type        num      userid         component name
pipe                  1         1              Loop 1 Hot leg
*     ncells    nodes      jun1      jun2      epsw
          2         0         1        52       0.0
*     nsides
          0
*      ichf     iconc      iacc      ipow    npipes
          0         0         0         0         1
*     radin        th     houtl     houtv     toutl
        0.0       0.0       0.0       0.0       0.0
*     toutv      pwin     pwoff     rpwmx     pwscl
        0.0       0.0       0.0       0.0       0.0
* dx   *     1.4733     1.4733e
* vol  *    0.58123    0.58123e
* fa   *    0.39451    0.39451    0.39451e
* fric *        0.0        0.0       0.0e
* grav *        0.0        0.0       0.0e
* hd   *    0.70874    0.70874    0.70874e
* nff  *         -1         -1        -1e
* alp  *        0.0       0.0e
* vl   *        0.0        0.0       0.0e
* vv   *        0.0        0.0       0.0e
* tl   *      550.0     550.0e
* tv   *      550.0     550.0e
* p    *      7.0E6     7.0E6e
* pa   *        0.0       0.0e
*
```

```
*
*d: Primary System Pressure
*******  type        num      userid            component name
break                11         1          System Pressure
*      jun1       ibty       isat       ioff     adjpress
       53         0          1          0         0
*      dxin       volin      alpin      tin       pin
     1.4733     0.58123      0.0       550.0     7.0E6
*      pain       concin     rbmx       poff      belv
       0.0        0.0        0.0        0.0       0.0
*
*
*d: Vessel
*******  type        num      userid            component name
vessel               26         1          $26$ 3-d vessel
*      nasx       nrsx       ntsx       ncsr      ivssbf
        7          2          4          2          0
*      idcu       idcl       idcr       icru      icrl
        6          2          1          5          2
*      icrr       ilcsp      iucsp      iuhp      iconc
        1          0          0          0          0
*      igeom      nvent      nvvtb      nsgrid
        0          0          0          0
*      shelv      epsw
       27.7       0.0
*  z   *      4.7       8.7       12.7      16.7s
*  z   *      19.7      22.7      27.7e
*  r   *      2.3       3.5e
*  t   *   90.00021   180.0004   270.0006   360.0008e
*      lisrl      lisrc      lisrf      ljuns     zfrac
        6          1          3          1
        6          5          3          41
* level 1
*
*  cfzlyt *     0.0       0.0       0.0       0.0s
*  cfzlyt *     0.0       0.0       0.0       0.0e
*  cfzlz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3s
*  cfzlz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3e
*  cfzlxr *     0.0       0.0       0.0       0.0s
*  cfzlxr *     0.0       0.0       0.0       0.0e
*  cfzvyt *     0.0       0.0       0.0       0.0s
*  cfzvyt *     0.0       0.0       0.0       0.0e
*  cfzvz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3s
*  cfzvz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3e
*  cfzvxr *     0.0       0.0       0.0       0.0s
*  cfzvxr *     0.0       0.0       0.0       0.0e
```

```
*   frvol *  0.1800935  0.1800935  0.1800935  0.1800935s
*   frvol * 0.02116456 0.02116456 0.02116456 0.02116456e
*  frfayt *  0.1414256  0.1414256  0.1414256  0.1414256s
*  frfayt * 0.02681191 0.02681191 0.02681191 0.02681191e
*  frfaz  *  0.4728711  0.4728711  0.4728711  0.4728711s
*  frfaz  * 0.08696042 0.08696042 0.08696042 0.08696042e
*  frfaxr *  0.1250877  0.1250877  0.1250877  0.1250877s
*  frfaxr *      0.0        0.0        0.0        0.0e
*    hdyt *      0.74       0.74       0.74       0.74s
*    hdyt *      0.82       0.82       0.82       0.82e
*    hdz  *      0.74       0.74       0.74       0.74s
*    hdz  *      0.82       0.82       0.82       0.82e
*    hdxr *      0.74       0.74       0.74       0.74s
*    hdxr *      0.82       0.82       0.82       0.82e
*   alpn  *      0.0        0.0        0.0        0.0s
*   alpn  *      0.0        0.0        0.0        0.0e
*   vvnyt *      0.0        0.0        0.0        0.0s
*   vvnyt *      0.0        0.0        0.0        0.0e
*   vvnz  *      0.0        0.0        0.0        0.0s
*   vvnz  *      0.0        0.0        0.0        0.0e
*   vvnxr *      0.0        0.0        0.0        0.0s
*   vvnxr *      0.0        0.0        0.0        0.0e
*   vlnyt *      0.0        0.0        0.0        0.0s
*   vlnyt *      0.0        0.0        0.0        0.0e
*   vlnz  *      0.0        0.0        0.0        0.0s
*   vlnz  *      0.0        0.0        0.0        0.0e
*   vlnxr *      0.0        0.0        0.0        0.0s
*   vlnxr *      0.0        0.0        0.0        0.0e
*     tvn *    550.0      550.0      550.0      550.0s
*     tvn *    550.0      550.0      550.0      550.0e
*     tln *    550.0      550.0      550.0      550.0s
*     tln *    550.0      550.0      550.0      550.0e
*      pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*      pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*     pan *      0.0        0.0        0.0        0.0s
*     pan *      0.0        0.0        0.0        0.0e
* level 2
*
*  cfzlyt *      0.0        0.0        0.0        0.0s
*  cfzlyt *      0.0        0.0        0.0        0.0e
*  cfzlz  *  0.013025   0.013025   0.013025   0.013025s
*  cfzlz  *      0.0        0.0        0.0        0.0e
*  cfzlxr *      0.0        0.0        0.0        0.0s
*  cfzlxr *      0.0        0.0        0.0        0.0e
*  cfzvyt *      0.0        0.0        0.0        0.0s
*  cfzvyt *      0.0        0.0        0.0        0.0e
```

```
* cfzvz *   0.013025   0.013025   0.013025   0.013025s
* cfzvz *   0.0   0.0   0.0   0.0e
* cfzvxr *   0.0   0.0   0.0   0.0s
* cfzvxr *   0.0   0.0   0.0   0.0e
* frvol *   0.1517568   0.1517568   0.1517568   0.1517568s
* frvol *   0.03891449   0.03891449   0.03891449   0.03891449e
* frfayt *   0.1500133   0.1500133   0.1500133   0.1500133s
* frfayt *   0.04108   0.04108   0.04108   0.04108e
* frfaz *   0.1780657   0.1780657   0.1780657   0.1780657s
* frfaz *   0.1293782   0.1293782   0.1293782   0.1293782e
* frfaxr *   0.1250111   0.1250111   0.1250111   0.1250111s
* frfaxr *   0.0   0.0   0.0   0.0e
* hdyt *   0.23   0.23   0.23   0.23s
* hdyt *   0.41   0.41   0.41   0.41e
* hdz *   0.013   0.013   0.013   0.013s
* hdz *   0.41   0.41   0.41   0.41e
* hdxr *   0.23   0.23   0.23   0.23s
* hdxr *   0.41   0.41   0.41   0.41e
* alpn *   0.0   0.0   0.0   0.0s
* alpn *   0.0   0.0   0.0   0.0e
* vvnyt *   0.0   0.0   0.0   0.0s
* vvnyt *   0.0   0.0   0.0   0.0e
* vvnz *   0.0   0.0   0.0   0.0s
* vvnz *   0.0   0.0   0.0   0.0e
* vvnxr *   0.0   0.0   0.0   0.0s
* vvnxr *   0.0   0.0   0.0   0.0e
* vlnyt *   0.0   0.0   0.0   0.0s
* vlnyt *   0.0   0.0   0.0   0.0e
* vlnz *   0.0   0.0   0.0   0.0s
* vlnz *   0.0   0.0   0.0   0.0e
* vlnxr *   0.0   0.0   0.0   0.0s
* vlnxr *   0.0   0.0   0.0   0.0e
* tvn *   550.0   550.0   550.0   550.0s
* tvn *   550.0   550.0   550.0   550.0e
* tln *   550.0   550.0   550.0   550.0s
* tln *   550.0   550.0   550.0   550.0e
* pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7s
* pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7e
* pan *   0.0   0.0   0.0   0.0s
* pan *   0.0   0.0   0.0   0.0e
* level 3
*
* cfzlyt *   0.0   0.0   0.0   0.0s
* cfzlyt *   0.0   0.0   0.0   0.0e
* cfzlz *   0.0   0.0   0.0   0.0s
* cfzlz *   0.0   0.0   0.0   0.0e
```

```
* cfzlxr *     0.0        0.0        0.0        0.0s
* cfzlxr *     0.0        0.0        0.0        0.0e
* cfzvyt *     0.0        0.0        0.0        0.0s
* cfzvyt *     0.0        0.0        0.0        0.0e
* cfzvz  *     0.0        0.0        0.0        0.0s
* cfzvz  *     0.0        0.0        0.0        0.0e
* cfzvxr *     0.0        0.0        0.0        0.0s
* cfzvxr *     0.0        0.0        0.0        0.0e
*  frvol * 0.08435715 0.08435715 0.08435715 0.08435715s
*  frvol * 0.04328887 0.04328887 0.04328887 0.04328887e
* frfayt * 0.09995437 0.09995437 0.09995437 0.09995437s
* frfayt * 0.04484076 0.04484076 0.04484076 0.04484076e
* frfaz  *  0.2779249  0.2779249  0.2779249  0.2779249s
* frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
* frfaxr *     0.0        0.0        0.0        0.0s
* frfaxr *     0.0        0.0        0.0        0.0e
*   hdyt *    0.013      0.013      0.013      0.013s
*   hdyt *    0.178      0.178      0.178      0.178e
*   hdz  *    0.013      0.013      0.013      0.013s
*   hdz  *    0.178      0.178      0.178      0.178e
*   hdxr *    0.013      0.013      0.013      0.013s
*   hdxr *    0.178      0.178      0.178      0.178e
*  alpn  *     0.0        0.0        0.0        0.0s
*  alpn  *     0.0        0.0        0.0        0.0e
*  vvnyt *     0.0        0.0        0.0        0.0s
*  vvnyt *     0.0        0.0        0.0        0.0e
*  vvnz  *     0.0        0.0        0.0        0.0s
*  vvnz  *     0.0        0.0        0.0        0.0e
*  vvnxr *     0.0        0.0        0.0        0.0s
*  vvnxr *     0.0        0.0        0.0        0.0e
*  vlnyt *     0.0        0.0        0.0        0.0s
*  vlnyt *     0.0        0.0        0.0        0.0e
*  vlnz  *     0.0        0.0        0.0        0.0s
*  vlnz  *     0.0        0.0        0.0        0.0e
*  vlnxr *     0.0        0.0        0.0        0.0s
*  vlnxr *     0.0        0.0        0.0        0.0e
*    tvn *    550.0      550.0      550.0      550.0s
*    tvn *    550.0      550.0      550.0      550.0e
*    tln *    550.0      550.0      550.0      550.0s
*    tln *    550.0      550.0      550.0      550.0e
*     pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *     0.0        0.0        0.0        0.0s
*    pan *     0.0        0.0        0.0        0.0e
* level 4
*
```

```
* cfzlyt *    0.0     0.0     0.0     0.0s
* cfzlyt *    0.0     0.0     0.0     0.0e
* cfzlz  *    0.0     0.0     0.0     0.0s
* cfzlz  *    0.0     0.0     0.0     0.0e
* cfzlxr *    0.0     0.0     0.0     0.0s
* cfzlxr *    0.0     0.0     0.0     0.0e
* cfzvyt *    0.0     0.0     0.0     0.0s
* cfzvyt *    0.0     0.0     0.0     0.0e
* cfzvz  *    0.0     0.0     0.0     0.0s
* cfzvz  *    0.0     0.0     0.0     0.0e
* cfzvxr *    0.0     0.0     0.0     0.0s
* cfzvxr *    0.0     0.0     0.0     0.0e
*  frvol * 0.08436409 0.08436409 0.08436409 0.08436409s
*  frvol * 0.04329244 0.04329244 0.04329244 0.04329244e
* frfayt * 0.09996261 0.09996261 0.09996261 0.09996261s
* frfayt * 0.04484445 0.04484445 0.04484445 0.04484445e
* frfaz  *  0.2779249  0.2779249  0.2779249  0.2779249s
* frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
* frfaxr *    0.0     0.0     0.0     0.0s
* frfaxr *    0.0     0.0     0.0     0.0e
*   hdyt *    0.013   0.013   0.013   0.013s
*   hdyt *    0.178   0.178   0.178   0.178e
*   hdz  *    0.013   0.013   0.013   0.013s
*   hdz  *    0.178   0.178   0.178   0.178e
*   hdxr *    0.013   0.013   0.013   0.013s
*   hdxr *    0.178   0.178   0.178   0.178e
*  alpn  *    0.0     0.0     0.0     0.0s
*  alpn  *    0.0     0.0     0.0     0.0e
*  vvnyt *    0.0     0.0     0.0     0.0s
*  vvnyt *    0.0     0.0     0.0     0.0e
*  vvnz  *    0.0     0.0     0.0     0.0s
*  vvnz  *    0.0     0.0     0.0     0.0e
*  vvnxr *    0.0     0.0     0.0     0.0s
*  vvnxr *    0.0     0.0     0.0     0.0e
*  vlnyt *    0.0     0.0     0.0     0.0s
*  vlnyt *    0.0     0.0     0.0     0.0e
*  vlnz  *    0.0     0.0     0.0     0.0s
*  vlnz  *    0.0     0.0     0.0     0.0e
*  vlnxr *    0.0     0.0     0.0     0.0s
*  vlnxr *    0.0     0.0     0.0     0.0e
*    tvn *    550.0   550.0   550.0   550.0s
*    tvn *    550.0   550.0   550.0   550.0e
*    tln *    550.0   550.0   550.0   550.0s
*    tln *    550.0   550.0   550.0   550.0e
*     pn *  1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*     pn *  1.5513E7  1.5513E7  1.5513E7  1.5513E7e
```

```
*    pan *      0.0        0.0        0.0        0.0s
*    pan *      0.0        0.0        0.0        0.0e
* level 5
*
* cfzlyt *      0.0        0.0        0.0        0.0s
* cfzlyt *      0.0        0.0        0.0        0.0e
* cfzlz  *   5.138E-3   5.138E-3   5.138E-3   5.138E-3s
* cfzlz  *      0.0        0.0        0.0        0.0e
* cfzlxr *      0.0        0.0        0.0        0.0s
* cfzlxr *      0.0        0.0        0.0        0.0e
* cfzvyt *      0.0        0.0        0.0        0.0s
* cfzvyt *      0.0        0.0        0.0        0.0e
* cfzvz  *   5.138E-3   5.138E-3   5.138E-3   5.138E-3s
* cfzvz  *      0.0        0.0        0.0        0.0e
* cfzvxr *      0.0        0.0        0.0        0.0s
* cfzvxr *      0.0        0.0        0.0        0.0e
*  frvol *  0.1124762  0.1124762  0.1124762  0.1124762s
*  frvol * 0.05771849 0.05771849 0.05771849 0.05771849e
* frfayt *  0.1332725  0.1332725  0.1332725  0.1332725s
* frfayt * 0.05978768 0.05978768 0.05978768 0.05978768e
* frfaz  *  0.1780657  0.1780657  0.1780657  0.1780657s
* frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
* frfaxr *      0.0        0.0        0.0        0.0s
* frfaxr *      0.0        0.0        0.0        0.0e
*   hdyt *    0.013      0.013      0.013      0.013s
*   hdyt *    0.178      0.178      0.178      0.178e
*   hdz  *    0.013      0.013      0.013      0.013s
*   hdz  *    0.178      0.178      0.178      0.178e
*   hdxr *    0.013      0.013      0.013      0.013s
*   hdxr *    0.178      0.178      0.178      0.178e
*  alpn  *      0.0        0.0        0.0        0.0s
*  alpn  *      0.0        0.0        0.0        0.0e
*  vvnyt *      0.0        0.0        0.0        0.0s
*  vvnyt *      0.0        0.0        0.0        0.0e
*  vvnz  *      0.0        0.0        0.0        0.0s
*  vvnz  *      0.0        0.0        0.0        0.0e
*  vvnxr *      0.0        0.0        0.0        0.0s
*  vvnxr *      0.0        0.0        0.0        0.0e
*  vlnyt *      0.0        0.0        0.0        0.0s
*  vlnyt *      0.0        0.0        0.0        0.0e
*  vlnz  *      0.0        0.0        0.0        0.0s
*  vlnz  *      0.0        0.0        0.0        0.0e
*  vlnxr *      0.0        0.0        0.0        0.0s
*  vlnxr *      0.0        0.0        0.0        0.0e
*    tvn *    550.0      550.0      550.0      550.0s
*    tvn *    550.0      550.0      550.0      550.0e
```

```
*    tln *     550.0      550.0      550.0      550.0s
*    tln *     550.0      550.0      550.0      550.0e
*     pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *      0.0        0.0        0.0       0.0s
*    pan *      0.0        0.0        0.0       0.0e
* level 6
*
* cfzlyt *      0.0        0.0        0.0       0.0s
* cfzlyt *      0.0        0.0        0.0       0.0e
* cfzlz  *      1.0        1.0        1.0       1.0s
* cfzlz  *      1.0        1.0        1.0       1.0e
* cfzlxr *      0.0        0.0        0.0       0.0s
* cfzlxr *      0.0        0.0        0.0       0.0e
* cfzvyt *      0.0        0.0        0.0       0.0s
* cfzvyt *      0.0        0.0        0.0       0.0e
* cfzvz  *      1.0        1.0        1.0       1.0s
* cfzvz  *      1.0        1.0        1.0       1.0e
* cfzvxr *      0.0        0.0        0.0       0.0s
* cfzvxr *      0.0        0.0        0.0       0.0e
*  frvol *  0.9478957  0.9478957  0.9478957  0.9478957s
*  frvol *  0.1919029  0.1919029  0.1919029  0.1919029e
* frfayt *  0.7093623  0.7093623  0.7093623  0.7093623s
* frfayt * 0.08965547 0.08965547 0.08965547 0.08965547e
* frfaz  * 0.05128291 0.05128291 0.05128291 0.05128291s
* frfaz  *      0.0        0.0        0.0       0.0e
* frfaxr *      0.0        0.0        0.0       0.0s
* frfaxr *      0.0        0.0        0.0       0.0e
*   hdyt *     0.23       0.23       0.23      0.23s
*   hdyt *    0.178      0.178      0.178     0.178e
*   hdz  *     0.23       0.23       0.23      0.23s
*   hdz  *    0.178      0.178      0.178     0.178e
*   hdxr *     0.23       0.23       0.23      0.23s
*   hdxr *    0.178      0.178      0.178     0.178e
*  alpn  *      0.0        0.0        0.0       0.0s
*  alpn  *      0.0        0.0        0.0       0.0e
*  vvnyt *      0.0        0.0        0.0       0.0s
*  vvnyt *      0.0        0.0        0.0       0.0e
*  vvnz  *      0.0        0.0        0.0       0.0s
*  vvnz  *      0.0        0.0        0.0       0.0e
*  vvnxr *      0.0        0.0        0.0       0.0s
*  vvnxr *      0.0        0.0        0.0       0.0e
*  vlnyt *      0.0        0.0        0.0       0.0s
*  vlnyt *      0.0        0.0        0.0       0.0e
*  vlnz  *      0.0        0.0        0.0       0.0s
*  vlnz  *      0.0        0.0        0.0       0.0e
```

```
*   vlnxr *      0.0        0.0        0.0       0.0s
*   vlnxr *      0.0        0.0        0.0       0.0e
*     tvn *    550.0      550.0      550.0     550.0s
*     tvn *    550.0      550.0      550.0     550.0e
*     tln *    550.0      550.0      550.0     550.0s
*     tln *    550.0      550.0      550.0     550.0e
*      pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*      pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*     pan *      0.0        0.0        0.0       0.0s
*     pan *      0.0        0.0        0.0       0.0e
* level 7
*
*  cfzlyt *      0.0        0.0        0.0       0.0s
*  cfzlyt *      0.0        0.0        0.0       0.0e
*  cfzlz  *      0.0        0.0        0.0       0.0s
*  cfzlz  *      0.0        0.0        0.0       0.0e
*  cfzlxr *      0.0        0.0        0.0       0.0s
*  cfzlxr *      0.0        0.0        0.0       0.0e
*  cfzvyt *      0.0        0.0        0.0       0.0s
*  cfzvyt *      0.0        0.0        0.0       0.0e
*  cfzvz  *      0.0        0.0        0.0       0.0s
*  cfzvz  *      0.0        0.0        0.0       0.0e
*  cfzvxr *      0.0        0.0        0.0       0.0s
*  cfzvxr *      0.0        0.0        0.0       0.0e
*   frvol *  0.1925958  0.1925958  0.1925958  0.1925958s
*   frvol *  0.0360128  0.0360128  0.0360128  0.0360128e
*  frfayt *  0.2282058  0.2282058  0.2282058  0.2282058s
*  frfayt * 0.02091093 0.02091093 0.02091093 0.02091093e
*  frfaz  *      0.0        0.0        0.0       0.0s
*  frfaz  *      0.0        0.0        0.0       0.0e
*  frfaxr *  0.1426287  0.1426287  0.1426287  0.1426287s
*  frfaxr *      0.0        0.0        0.0       0.0e
*    hdyt *     0.35       0.35       0.35      0.35s
*    hdyt *     1.69       1.69       1.69      1.69e
*    hdz  *     0.35       0.35       0.35      0.35s
*    hdz  *     1.69       1.69       1.69      1.69e
*    hdxr *     0.35       0.35       0.35      0.35s
*    hdxr *     1.69       1.69       1.69      1.69e
*   alpn  *      0.0        0.0        0.0       0.0s
*   alpn  *      0.0        0.0        0.0       0.0e
*   vvnyt *      0.0        0.0        0.0       0.0s
*   vvnyt *      0.0        0.0        0.0       0.0e
*   vvnz  *      0.0        0.0        0.0       0.0s
*   vvnz  *      0.0        0.0        0.0       0.0e
*   vvnxr *      0.0        0.0        0.0       0.0s
*   vvnxr *      0.0        0.0        0.0       0.0e
```

```
*   vlnyt *     0.0      0.0      0.0      0.0s
*   vlnyt *     0.0      0.0      0.0      0.0e
*   vlnz  *     0.0      0.0      0.0      0.0s
*   vlnz  *     0.0      0.0      0.0      0.0e
*   vlnxr *     0.0      0.0      0.0      0.0s
*   vlnxr *     0.0      0.0      0.0      0.0e
*    tvn *    550.0    550.0    550.0    550.0s
*    tvn *    550.0    550.0    550.0    550.0e
*    tln *    550.0    550.0    550.0    550.0s
*    tln *    550.0    550.0    550.0    550.0e
*     pn *  1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*     pn *  1.5513E7  1.5513E7  1.5513E7  1.5513E7e
*    pan *     0.0      0.0      0.0      0.0s
*    pan *     0.0      0.0      0.0      0.0e
*
*
******* type        num      userid          component name
pipe              41         1   $41$ int-loop c-leg vssl c6
*     ncells      nodes      jun1       jun2       epsw
        2          0         51         41        0.0
*     nsides
        0
*       ichf      iconc       iacc       ipow       npipes
        0          0          0          0          1
*      radin        th        houtl      houtv       toutl
       0.0         0.0        0.0        0.0        0.0
*      toutv       pwin       pwoff      rpwmx       pwscl
       0.0         0.0        0.0        0.0        0.0
* dx    *     1.4733    1.4733e
* vol   *    0.58123    0.58123e
* fa    *    0.39451    0.39451    0.39451e
* fric  *      0.0       0.0       0.0e
* grav  *      0.0       0.0       0.0e
* hd    *    0.70874    0.70874    0.70874e
* nff   *       1         1        -1e
* alp   *      0.0       0.0e
* vl    *      0.0       0.0       0.0e
* vv    *      0.0       0.0       0.0e
* tl    *    550.0     550.0e
* tv    *    550.0     550.0e
* p     *  1.5513E7   1.5513E7e
* pa    *      0.0       0.0e
*
*
*d: Inlet flow from the cold leg.
******* type        num      userid          component name
```

```
fill             51          1          Vessel Inlet Flow
*     jun1       ifty        ioff
      51         2           0
*     twtold     rfmx        concin      felv
      0.0        1.0E20      0.0         0.0
*     dxin       volin       alpin       vlin       tlin
      1.4733     0.58123     0.0         0.0        488.75
*     pin        pain        flowin      vvin       tvin
      7.0E6      0.0         2450.0      0.0        550.0
*
*
*d: MSIV
******* type          num        userid             component name
valve            184         1                      unnamed
*     ncells     nodes       jun1        jun2       epsw
      2          0           52          53         0.0
*     nsides
      0
*     ichf       iconc       ivty        ivps       nvtb2
      1          0           0           2          0
*     ivtr       ivsv        nvtb1       nvsv       nvrf
      0          0           0           0          0
*     ivtrov     ivtyov
      0          0
*     rvmx       rvov        fminov      fmaxov
      0.2        0.0         0.0         1.0
*     radin      th          houtl       houtv      toutl
      0.0        0.0         0.0         0.0        0.0
*     toutv      avlve       hvlve       favlve     xpos
      0.0        0.39451     0.70874     1.0        1.0
* dx   *     1.4733     1.4733e
* vol  *     0.58123    0.58123e
* fa   *     0.39451    0.39451    0.39451e
* fric *     0.0        0.0        0.0e
* grav *     0.0        0.0        0.0e
* hd   *     0.70874    0.70874    0.70874e
* nff  *     -1         1          1e
* alp  *     0.0        0.0e
* vl   *     0.0        0.0        0.0e
* vv   *     0.0        0.0        0.0e
* tl   *     558.979    558.979e
* tv   *     558.979    558.979e
* p    *     7.0E6      7.0E6e
* pa   *     0.0        0.0e
*
*
```

```
*******************************************
* Starting Heat Structure Section of Model *
*******************************************
*
*******  type        num       userid          component name
htstr              170          0   $140$ reactor-core fuel rods
*     nzhstr       ittc        hscyl        ichf
        3           0           1            1
*     nopowr       plane       liqlev       iaxcnd
        0           3           1            0
*      nmwrx        nfci        nfcil        hdri        hdro
        1           1           1          0.0         0.0
*      nhot        nodes        irftr       nzmax       irftr2
        0           8           0          100          0
*    dtxht(1)    dtxht(2)      dznht       hgapo
       4.0         50.0       5.0E-3      6000.0
*
*  idbcin *        0          0          0e
*  idbcon *        2          2          2e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
* hcomon2  *        26         1          1          3e
* hcomon2  *        26         1          1          4e
* hcomon2  *        26         1          1          5e
* dhtstrz *     1.2141      1.2142      1.2141e
*   rdx *      9843.0e
* radrd *       0.0     2.0E-3     3.0E-3     4.0E-3   4.6427E-3s
* radrd *   4.7422E-3     5.05E-3   5.3594E-3e
* matrd *          1          1          1          1s
* matrd *          3          2          2e
*   nfax *         5          5          5e
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0e
* fpuo2 *       0.0e
*   ftd *      0.945e
*  gmix *        1.0         0.0         0.0         0.0s
*  gmix *        0.0         0.0         0.0e
*  gmles *       0.0e
*  pgapt *      1.0E7e
*  plvol *       0.0 e
*  pslen *       0.0 e
```

```
*   clenn *        0.0 e
*  burn *     1.54E4     1.54E4     1.54E4e
*
*******  type          num        userid             component name
htstr              171          0   $140$ reactor-core fuel rods
*      nzhstr         ittc        hscyl         ichf
         3           0            1            1
*      nopowr        plane       liqlev       iaxcnd
         0           3            1            0
*      nmwrx         nfci        nfcil        hdri         hdro
         1           1            1         0.0          0.0
*       nhot        nodes        irftr        nzmax       irftr2
         0           8            0          100           0
*    dtxht(1)     dtxht(2)       dznht       hgapo
       4.0         50.0        5.0E-3      6000.0
*
*  idbcin *        0         0          0e
*  idbcon *         2         2          2e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
* hcomon2  *        26         1          2          3e
* hcomon2  *        26         1          2          4e
* hcomon2  *        26         1          2          5e
* dhtstrz *    1.2141     1.2142     1.2141e
*   rdx *      9843.0e
* radrd *       0.0     2.0E-3     3.0E-3     4.0E-3   4.6427E-3s
* radrd *  4.7422E-3     5.05E-3  5.3594E-3e
* matrd *          1          1          1          1s
* matrd *          3          2          2e
*   nfax *         5          5          5e
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0e
* fpuo2 *        0.0e
*    ftd *      0.945e
*  gmix *        1.0        0.0        0.0        0.0s
*  gmix *        0.0        0.0        0.0e
*   gmles *        0.0e
*   pgapt *       1.0E7e
*   plvol *        0.0 e
*   pslen *        0.0 e
*   clenn *        0.0 e
```

```
* burn *     1.54E4     1.54E4     1.54E4e
*
******* type          num       userid             component name
htstr                172          0   $140$ reactor-core fuel rods
*     nzhstr        ittc       hscyl       ichf
        3           0          1          1
*     nopowr        plane      liqlev      iaxcnd
        0           3          1          0
*      nmwrx       nfci       nfcil       hdri       hdro
        1           1          1       0.0        0.0
*       nhot       nodes       irftr       nzmax      irftr2
        0           8          0        100          0
*    dtxht(1)    dtxht(2)      dznht       hgapo
       4.0        50.0       5.0E-3      6000.0
*
* idbcin *        0         0          0e
* idbcon *        2         2          2e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
* hcomon2  *        26         1          3          3e
* hcomon2  *        26         1          3          4e
* hcomon2  *        26         1          3          5e
* dhtstrz *     1.2141     1.2142     1.2141e
*   rdx *      9843.0e
* radrd *        0.0     2.0E-3     3.0E-3     4.0E-3   4.6427E-3s
* radrd *   4.7422E-3     5.05E-3   5.3594E-3e
* matrd *          1          1          1          1s
* matrd *          3          2          2e
*    nfax *        5          5          5e
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0e
* fpuo2 *        0.0e
*    ftd *      0.945e
*   gmix *        1.0        0.0        0.0        0.0s
*   gmix *        0.0        0.0        0.0e
*   gmles *        0.0e
*   pgapt *       1.0E7e
*   plvol *        0.0 e
*   pslen *        0.0 e
*   clenn *        0.0 e
* burn *     1.54E4     1.54E4     1.54E4e
```

```
*
*******  type          num        userid            component name
htstr               173          0   $140$ reactor-core fuel rods
*       nzhstr       ittc       hscyl        ichf
          3          0          1           1
*      nopowr        plane      liqlev       iaxcnd
          0          3          1           0
*      nmwrx        nfci       nfcil        hdri        hdro
          1          1          1        0.0         0.0
*       nhot        nodes       irftr       nzmax       irftr2
          0          8          0         100          0
*    dtxht(1)     dtxht(2)      dznht       hgapo
        4.0        50.0       5.0E-3      6000.0
*
*  idbcin *        0          0         0e
*  idbcon *         2          2         2e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
* hcomon2  *        26          1          4          3e
* hcomon2  *        26          1          4          4e
* hcomon2  *        26          1          4          5e
* dhtstrz *     1.2141      1.2142      1.2141e
*   rdx *      9843.0e
* radrd *       0.0      2.0E-3     3.0E-3     4.0E-3   4.6427E-3s
* radrd *   4.7422E-3     5.05E-3   5.3594E-3e
* matrd *          1          1          1          1s
* matrd *          3          2          2e
*    nfax *        5          5          5e
*    rftn *      550.0      550.0      550.0      550.0s
*    rftn *      550.0      550.0      550.0      550.0s
*    rftn *      550.0      550.0      550.0      550.0s
*    rftn *      550.0      550.0      550.0      550.0s
*    rftn *      550.0      550.0      550.0      550.0s
*    rftn *      550.0      550.0      550.0      550.0e
* fpuo2 *        0.0e
*   ftd *      0.945e
*  gmix *        1.0        0.0        0.0        0.0s
*  gmix *        0.0        0.0        0.0e
*   gmles *        0.0e
*   pgapt *      1.0E7e
*   plvol *        0.0 e
*   pslen *        0.0 e
*   clenn *        0.0 e
*  burn *     1.54E4      1.54E4      1.54E4e
*******************************************
```

```
* Finished Heat Structure Section of Model *
*******************************************
*
*
*
*
****************************************
*   Starting Power Components      *
****************************************
*
******* type        num      userid            component name
power              174          1  Power Comp for old ht str 140
*     numpwr     chanpow
        4          0
* htnum *      170        171        172        173e
*     irpwty       ndgx        ndhx        nrts        nhist
        5          0          0         10          0
*     izpwtr      izpwsv      nzpwtb      nzpwsv      nzpwrf
        0          1          1          0          0
*     ipwrad      ipwdep     promheat     decaheat     wtbypass
        0          0        0.0         0.0         0.0
*     nzpwz       nzpwi      nfbpwt       nrpwr       nrpwi
        0          0          0           1           0
*     react       tneut      rpwoff      rrpwmx      rpwscl
       0.0         0.0        0.0       1.0E20        1.0
*     rpowri      zpwin      zpwoff      rzpwmx
      4.5E9        0.0        0.0         0.0
*     extsou       pldr       pdrat      fucrac
       0.0         0.0       1.334        1.0
* rdpwr *    1.2109     1.2371     1.2703     1.3201     1.3823s
* rdpwr *      0.0        0.0        0.0e
* cpowr *      1.0        1.0        1.0        1.0e
* zpwtb1*      0.0s
* zpwtb1*    0.93748s
* zpwtb1*    1.20535s
* zpwtb1*    0.83715e
****************************************
*   Finished Power Components      *
****************************************
*
*
*
end
*
****************
* Timestep Data *
```

```
*****************
*     dtmin     dtmax     tend     rtwfp
      0.05      1.0       50.0     10.0
*     edint     gfint     dmpint   sedint
      12.0      0.5       12.0     12.0
*
*     endflag
      -1.0
```

Appendix B. TRACE Passive Model Restart File

```
free format
*
*************
* main data *
*************
*
*     numtcr     ieos     inopt     nmat     id2o
        1         0         1         0         0
Model of Reactor Core
*
*
*****************
* namelist data *
*****************
*
 &inopts
  cpuflg=1,
  dtstrt=-1.0,
  iadded=10,
  noair=0,
  usesjc=3,
  npower=1,
  nhtstr=5,
  igas=1
 &end
*
***************
* Model Flags *
***************
*
*     dstep     timet
        0        0.0
*     stdyst    transi    ncomp     njun     ipak
        0         1        16        10        1
*      epso      epss
     1.0E-3    1.0E-3
*     oitmax    sitmax    isolut    ncontr    nccfl
       10        10         0         0         0
*      ntsv      ntcb      ntcf      ntrp      ntcp
        1         0         0         0         0
*
*************************
* component-number data *
*************************
```

```
*
* iorder*       1       11      26      41      51s
* iorder*     170      171     172     173     174s
* iorder*     184      194     214     254     264s
* iorder*     274e
*
*
************************************************
* Starting Signal Variable Section of Model   *
************************************************
*
*     idsv     isvn     ilcn     icn1     icn2
        1        0        0        0        0
************************************************
* Finished Signal Variable Section of Model   *
************************************************
*
*
*
*
*******  type       num     userid          component name
pipe               1         1          Loop 1 Hot leg
*     ncells     nodes     jun1     jun2     epsw
        2          0         1       52      0.0
*     nsides
        0
*     ichf      iconc     iacc     ipow     npipes
        0          0         0        0        1
*     radin      th      houtl    houtv    toutl
       0.0        0.0      0.0      0.0      0.0
*     toutv      pwin     pwoff    rpwmx    pwscl
       0.0        0.0      0.0      0.0      0.0
* dx   *    1.4733    1.4733e
* vol  *    0.58123   0.58123e
* fa   *    0.39451   0.39451   0.39451e
* fric *      0.0       0.0       0.0e
* grav *      0.0       0.0       0.0e
* hd   *    0.70874   0.70874   0.70874e
* nff  *      -1        -1        -1e
* alp  *      0.0       0.0e
* vl   *      0.0       0.0       0.0e
* vv   *      0.0       0.0       0.0e
* tl   *    550.0     550.0e
* tv   *    550.0     550.0e
* p    *    7.0E6     7.0E6e
* pa   *      0.0       0.0e
```

```
*
*
*d: Primary System Pressure
*******  type        num      userid           component name
break              11          1          System Pressure
*      jun1       ibty       isat       ioff    adjpress
       53         0          1          0        0
*      dxin       volin      alpin      tin        pin
     1.4733     0.58123      0.0      550.0      7.0E6
*      pain      concin      rbmx      poff       belv
       0.0        0.0      100.0       0.0        0.0
*
*
*d: Vessel
*******  type        num      userid           component name
vessel             26          1          $26$ 3-d vessel
*      nasx       nrsx       ntsx       ncsr      ivssbf
        7          2          4          4         0
*      idcu       idcl       idcr       icru       icrl
        6          2          1          5          2
*      icrr       ilcsp      iucsp      iuhp       iconc
        1          0          0          0          0
*      igeom       nvent      nvvtb      nsgrid
        0          0          0          0
*      shelv       epsw
       27.7        0.0
*  z   *     4.7       8.7       12.7      16.7s
*  z   *     19.7      22.7      27.7e
*  r   *     2.3       3.5e
*  t   *  90.00021   180.0004   270.0006   360.0008e
*      lisrl      lisrc      lisrf      ljuns      zfrac
        6          1          3          1
        6          1          3         62
        6          5          3         41
        6          5          3         61
* level 1
*
* cfzlyt *     0.0       0.0       0.0       0.0s
* cfzlyt *     0.0       0.0       0.0       0.0e
* cfzlz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3s
* cfzlz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3e
* cfzlxr *     0.0       0.0       0.0       0.0s
* cfzlxr *     0.0       0.0       0.0       0.0e
* cfzvyt *     0.0       0.0       0.0       0.0s
* cfzvyt *     0.0       0.0       0.0       0.0e
* cfzvz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3s
```

```
* cfzvz  *    3.7E-3     3.7E-3     3.7E-3     3.7E-3e
* cfzvxr *    0.0        0.0        0.0        0.0s
* cfzvxr *    0.0        0.0        0.0        0.0e
*  frvol *  0.1800935  0.1800935  0.1800935  0.1800935s
*  frvol * 0.02116456 0.02116456 0.02116456 0.02116456e
* frfayt *  0.1414256  0.1414256  0.1414256  0.1414256s
* frfayt * 0.02681191 0.02681191 0.02681191 0.02681191e
* frfaz  *  0.4728711  0.4728711  0.4728711  0.4728711s
* frfaz  * 0.08696042 0.08696042 0.08696042 0.08696042e
* frfaxr *  0.1250877  0.1250877  0.1250877  0.1250877s
* frfaxr *    0.0        0.0        0.0        0.0e
*   hdyt *    0.74       0.74       0.74       0.74s
*   hdyt *    0.82       0.82       0.82       0.82e
*   hdz  *    0.74       0.74       0.74       0.74s
*   hdz  *    0.82       0.82       0.82       0.82e
*   hdxr *    0.74       0.74       0.74       0.74s
*   hdxr *    0.82       0.82       0.82       0.82e
*  alpn  *    0.0        0.0        0.0        0.0s
*  alpn  *    0.0        0.0        0.0        0.0e
*  vvnyt *    0.0        0.0        0.0        0.0s
*  vvnyt *    0.0        0.0        0.0        0.0e
*  vvnz  *    0.0        0.0        0.0        0.0s
*  vvnz  *    0.0        0.0        0.0        0.0e
*  vvnxr *    0.0        0.0        0.0        0.0s
*  vvnxr *    0.0        0.0        0.0        0.0e
*  vlnyt *    0.0        0.0        0.0        0.0s
*  vlnyt *    0.0        0.0        0.0        0.0e
*  vlnz  *    0.0        0.0        0.0        0.0s
*  vlnz  *    0.0        0.0        0.0        0.0e
*  vlnxr *    0.0        0.0        0.0        0.0s
*  vlnxr *    0.0        0.0        0.0        0.0e
*    tvn *    550.0      550.0      550.0      550.0s
*    tvn *    550.0      550.0      550.0      550.0e
*    tln *    550.0      550.0      550.0      550.0s
*    tln *    550.0      550.0      550.0      550.0e
*     pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn *  1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *    0.0        0.0        0.0        0.0s
*    pan *    0.0        0.0        0.0        0.0e
* level 2
*
* cfzlyt *    0.0        0.0        0.0        0.0s
* cfzlyt *    0.0        0.0        0.0        0.0e
* cfzlz  *  0.013025   0.013025   0.013025   0.013025s
* cfzlz  *    0.0        0.0        0.0        0.0e
* cfzlxr *    0.0        0.0        0.0        0.0s
```

```
* cfzlxr *    0.0       0.0       0.0       0.0e
* cfzvyt *    0.0       0.0       0.0       0.0s
* cfzvyt *    0.0       0.0       0.0       0.0e
* cfzvz  *  0.013025  0.013025  0.013025  0.013025s
* cfzvz  *    0.0       0.0       0.0       0.0e
* cfzvxr *    0.0       0.0       0.0       0.0s
* cfzvxr *    0.0       0.0       0.0       0.0e
*  frvol * 0.1517568  0.1517568  0.1517568  0.1517568s
*  frvol * 0.03891449 0.03891449 0.03891449 0.03891449e
* frfayt * 0.1500133  0.1500133  0.1500133  0.1500133s
* frfayt *  0.04108    0.04108    0.04108    0.04108e
* frfaz  * 0.1780657  0.1780657  0.1780657  0.1780657s
* frfaz  * 0.1293782  0.1293782  0.1293782  0.1293782e
* frfaxr * 0.1250111  0.1250111  0.1250111  0.1250111s
* frfaxr *    0.0       0.0       0.0       0.0e
*   hdyt *    0.23      0.23      0.23      0.23s
*   hdyt *    0.41      0.41      0.41      0.41e
*   hdz  *   0.013     0.013     0.013     0.013s
*   hdz  *    0.41      0.41      0.41      0.41e
*   hdxr *    0.23      0.23      0.23      0.23s
*   hdxr *    0.41      0.41      0.41      0.41e
*  alpn  *    0.0       0.0       0.0       0.0s
*  alpn  *    0.0       0.0       0.0       0.0e
*  vvnyt *    0.0       0.0       0.0       0.0s
*  vvnyt *    0.0       0.0       0.0       0.0e
*  vvnz  *    0.0       0.0       0.0       0.0s
*  vvnz  *    0.0       0.0       0.0       0.0e
*  vvnxr *    0.0       0.0       0.0       0.0s
*  vvnxr *    0.0       0.0       0.0       0.0e
*  vlnyt *    0.0       0.0       0.0       0.0s
*  vlnyt *    0.0       0.0       0.0       0.0e
*  vlnz  *    0.0       0.0       0.0       0.0s
*  vlnz  *    0.0       0.0       0.0       0.0e
*  vlnxr *    0.0       0.0       0.0       0.0s
*  vlnxr *    0.0       0.0       0.0       0.0e
*    tvn *   550.0     550.0     550.0     550.0s
*    tvn *   550.0     550.0     550.0     550.0e
*    tln *   550.0     550.0     550.0     550.0s
*    tln *   550.0     550.0     550.0     550.0e
*     pn * 1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn * 1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *    0.0       0.0       0.0       0.0s
*    pan *    0.0       0.0       0.0       0.0e
* level 3
*
* cfzlyt *    0.0       0.0       0.0       0.0s
```

```
* cfzlyt *   0.0   0.0   0.0   0.0e
* cfzlz  *   0.0   0.0   0.0   0.0s
* cfzlz  *   0.0   0.0   0.0   0.0e
* cfzlxr *   0.0   0.0   0.0   0.0s
* cfzlxr *   0.0   0.0   0.0   0.0e
* cfzvyt *   0.0   0.0   0.0   0.0s
* cfzvyt *   0.0   0.0   0.0   0.0e
* cfzvz  *   0.0   0.0   0.0   0.0s
* cfzvz  *   0.0   0.0   0.0   0.0e
* cfzvxr *   0.0   0.0   0.0   0.0s
* cfzvxr *   0.0   0.0   0.0   0.0e
*  frvol * 0.08435715 0.08435715 0.08435715 0.08435715s
*  frvol * 0.04328887 0.04328887 0.04328887 0.04328887e
* frfayt * 0.09995437 0.09995437 0.09995437 0.09995437s
* frfayt * 0.04484076 0.04484076 0.04484076 0.04484076e
* frfaz  *  0.2779249  0.2779249  0.2779249  0.2779249s
* frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
* frfaxr *   0.0   0.0   0.0   0.0s
* frfaxr *   0.0   0.0   0.0   0.0e
*   hdyt *   0.013   0.013   0.013   0.013s
*   hdyt *   0.178   0.178   0.178   0.178e
*   hdz  *   0.013   0.013   0.013   0.013s
*   hdz  *   0.178   0.178   0.178   0.178e
*   hdxr *   0.013   0.013   0.013   0.013s
*   hdxr *   0.178   0.178   0.178   0.178e
*  alpn  *   0.0   0.0   0.0   0.0s
*  alpn  *   0.0   0.0   0.0   0.0e
*  vvnyt *   0.0   0.0   0.0   0.0s
*  vvnyt *   0.0   0.0   0.0   0.0e
*  vvnz  *   0.0   0.0   0.0   0.0s
*  vvnz  *   0.0   0.0   0.0   0.0e
*  vvnxr *   0.0   0.0   0.0   0.0s
*  vvnxr *   0.0   0.0   0.0   0.0e
*  vlnyt *   0.0   0.0   0.0   0.0s
*  vlnyt *   0.0   0.0   0.0   0.0e
*  vlnz  *   0.0   0.0   0.0   0.0s
*  vlnz  *   0.0   0.0   0.0   0.0e
*  vlnxr *   0.0   0.0   0.0   0.0s
*  vlnxr *   0.0   0.0   0.0   0.0e
*    tvn *   550.0   550.0   550.0   550.0s
*    tvn *   550.0   550.0   550.0   550.0e
*    tln *   550.0   550.0   550.0   550.0s
*    tln *   550.0   550.0   550.0   550.0e
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *   0.0   0.0   0.0   0.0s
```

```
*    pan *       0.0        0.0        0.0        0.0e
* level 4
*
*  cfzlyt *      0.0        0.0        0.0        0.0s
*  cfzlyt *      0.0        0.0        0.0        0.0e
*  cfzlz  *      0.0        0.0        0.0        0.0s
*  cfzlz  *      0.0        0.0        0.0        0.0e
*  cfzlxr *      0.0        0.0        0.0        0.0s
*  cfzlxr *      0.0        0.0        0.0        0.0e
*  cfzvyt *      0.0        0.0        0.0        0.0s
*  cfzvyt *      0.0        0.0        0.0        0.0e
*  cfzvz  *      0.0        0.0        0.0        0.0s
*  cfzvz  *      0.0        0.0        0.0        0.0e
*  cfzvxr *      0.0        0.0        0.0        0.0s
*  cfzvxr *      0.0        0.0        0.0        0.0e
*   frvol * 0.08436409 0.08436409 0.08436409 0.08436409s
*   frvol * 0.04329244 0.04329244 0.04329244 0.04329244e
*  frfayt * 0.09996261 0.09996261 0.09996261 0.09996261s
*  frfayt * 0.04484445 0.04484445 0.04484445 0.04484445e
*  frfaz  *  0.2779249  0.2779249  0.2779249  0.2779249s
*  frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
*  frfaxr *      0.0        0.0        0.0        0.0s
*  frfaxr *      0.0        0.0        0.0        0.0e
*    hdyt *     0.013      0.013      0.013      0.013s
*    hdyt *     0.178      0.178      0.178      0.178e
*    hdz  *     0.013      0.013      0.013      0.013s
*    hdz  *     0.178      0.178      0.178      0.178e
*    hdxr *     0.013      0.013      0.013      0.013s
*    hdxr *     0.178      0.178      0.178      0.178e
*   alpn  *      0.0        0.0        0.0        0.0s
*   alpn  *      0.0        0.0        0.0        0.0e
*   vvnyt *      0.0        0.0        0.0        0.0s
*   vvnyt *      0.0        0.0        0.0        0.0e
*   vvnz  *      0.0        0.0        0.0        0.0s
*   vvnz  *      0.0        0.0        0.0        0.0e
*   vvnxr *      0.0        0.0        0.0        0.0s
*   vvnxr *      0.0        0.0        0.0        0.0e
*   vlnyt *      0.0        0.0        0.0        0.0s
*   vlnyt *      0.0        0.0        0.0        0.0e
*   vlnz  *      0.0        0.0        0.0        0.0s
*   vlnz  *      0.0        0.0        0.0        0.0e
*   vlnxr *      0.0        0.0        0.0        0.0s
*   vlnxr *      0.0        0.0        0.0        0.0e
*     tvn *     550.0      550.0      550.0      550.0s
*     tvn *     550.0      550.0      550.0      550.0e
*     tln *     550.0      550.0      550.0      550.0s
```

```
*    tln *      550.0       550.0       550.0       550.0e
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *       0.0         0.0         0.0         0.0s
*    pan *       0.0         0.0         0.0         0.0e
* level 5
*
*  cfzlyt *      0.0         0.0         0.0         0.0s
*  cfzlyt *      0.0         0.0         0.0         0.0e
*  cfzlz  *   5.138E-3   5.138E-3   5.138E-3   5.138E-3s
*  cfzlz  *      0.0         0.0         0.0         0.0e
*  cfzlxr *      0.0         0.0         0.0         0.0s
*  cfzlxr *      0.0         0.0         0.0         0.0e
*  cfzvyt *      0.0         0.0         0.0         0.0s
*  cfzvyt *      0.0         0.0         0.0         0.0e
*  cfzvz  *   5.138E-3   5.138E-3   5.138E-3   5.138E-3s
*  cfzvz  *      0.0         0.0         0.0         0.0e
*  cfzvxr *      0.0         0.0         0.0         0.0s
*  cfzvxr *      0.0         0.0         0.0         0.0e
*   frvol *  0.1124762   0.1124762   0.1124762   0.1124762s
*   frvol * 0.05771849  0.05771849  0.05771849  0.05771849e
*  frfayt *  0.1332725   0.1332725   0.1332725   0.1332725s
*  frfayt * 0.05978768  0.05978768  0.05978768  0.05978768e
*  frfaz  *  0.1780657   0.1780657   0.1780657   0.1780657s
*  frfaz  *  0.1426204   0.1426204   0.1426204   0.1426204e
*  frfaxr *      0.0         0.0         0.0         0.0s
*  frfaxr *      0.0         0.0         0.0         0.0e
*    hdyt *    0.013       0.013       0.013       0.013s
*    hdyt *    0.178       0.178       0.178       0.178e
*    hdz  *    0.013       0.013       0.013       0.013s
*    hdz  *    0.178       0.178       0.178       0.178e
*    hdxr *    0.013       0.013       0.013       0.013s
*    hdxr *    0.178       0.178       0.178       0.178e
*   alpn  *      0.0         0.0         0.0         0.0s
*   alpn  *      0.0         0.0         0.0         0.0e
*   vvnyt *      0.0         0.0         0.0         0.0s
*   vvnyt *      0.0         0.0         0.0         0.0e
*   vvnz  *      0.0         0.0         0.0         0.0s
*   vvnz  *      0.0         0.0         0.0         0.0e
*   vvnxr *      0.0         0.0         0.0         0.0s
*   vvnxr *      0.0         0.0         0.0         0.0e
*   vlnyt *      0.0         0.0         0.0         0.0s
*   vlnyt *      0.0         0.0         0.0         0.0e
*   vlnz  *      0.0         0.0         0.0         0.0s
*   vlnz  *      0.0         0.0         0.0         0.0e
*   vlnxr *      0.0         0.0         0.0         0.0s
```

```
*   vlnxr *     0.0       0.0       0.0       0.0e
*    tvn *     550.0     550.0     550.0     550.0s
*    tvn *     550.0     550.0     550.0     550.0e
*    tln *     550.0     550.0     550.0     550.0s
*    tln *     550.0     550.0     550.0     550.0e
*     pn *   1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*     pn *   1.5513E7  1.5513E7  1.5513E7  1.5513E7e
*    pan *      0.0       0.0       0.0       0.0s
*    pan *      0.0       0.0       0.0       0.0e
* level 6
*
* cfzlyt *      0.0       0.0       0.0       0.0s
* cfzlyt *      0.0       0.0       0.0       0.0e
* cfzlz  *      1.0       1.0       1.0       1.0s
* cfzlz  *      1.0       1.0       1.0       1.0e
* cfzlxr *      0.0       0.0       0.0       0.0s
* cfzlxr *      0.0       0.0       0.0       0.0e
* cfzvyt *      0.0       0.0       0.0       0.0s
* cfzvyt *      0.0       0.0       0.0       0.0e
* cfzvz  *      1.0       1.0       1.0       1.0s
* cfzvz  *      1.0       1.0       1.0       1.0e
* cfzvxr *      0.0       0.0       0.0       0.0s
* cfzvxr *      0.0       0.0       0.0       0.0e
*  frvol *  0.9478957  0.9478957  0.9478957  0.9478957s
*  frvol *  0.1919029  0.1919029  0.1919029  0.1919029e
* frfayt *  0.7093623  0.7093623  0.7093623  0.7093623s
* frfayt * 0.08965547 0.08965547 0.08965547 0.08965547e
* frfaz  * 0.05128291 0.05128291 0.05128291 0.05128291s
* frfaz  *      0.0       0.0       0.0       0.0e
* frfaxr *      0.0       0.0       0.0       0.0s
* frfaxr *      0.0       0.0       0.0       0.0e
*   hdyt *     0.23      0.23      0.23      0.23s
*   hdyt *     0.178     0.178     0.178     0.178e
*   hdz  *     0.23      0.23      0.23      0.23s
*   hdz  *     0.178     0.178     0.178     0.178e
*   hdxr *     0.23      0.23      0.23      0.23s
*   hdxr *     0.178     0.178     0.178     0.178e
*  alpn  *      0.0       0.0       0.0       0.0s
*  alpn  *      0.0       0.0       0.0       0.0e
*  vvnyt *      0.0       0.0       0.0       0.0s
*  vvnyt *      0.0       0.0       0.0       0.0e
*  vvnz  *      0.0       0.0       0.0       0.0s
*  vvnz  *      0.0       0.0       0.0       0.0e
*  vvnxr *      0.0       0.0       0.0       0.0s
*  vvnxr *      0.0       0.0       0.0       0.0e
*  vlnyt *      0.0       0.0       0.0       0.0s
```

```
*   vlnyt *     0.0      0.0      0.0      0.0e
*   vlnz  *     0.0      0.0      0.0      0.0s
*   vlnz  *     0.0      0.0      0.0      0.0e
*   vlnxr *     0.0      0.0      0.0      0.0s
*   vlnxr *     0.0      0.0      0.0      0.0e
*     tvn *   550.0    550.0    550.0    550.0s
*     tvn *   550.0    550.0    550.0    550.0e
*     tln *   550.0    550.0    550.0    550.0s
*     tln *   550.0    550.0    550.0    550.0e
*      pn *  1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*      pn *  1.5513E7  1.5513E7  1.5513E7  1.5513E7e
*     pan *     0.0      0.0      0.0      0.0s
*     pan *     0.0      0.0      0.0      0.0e
* level 7
*
*  cfzlyt *     0.0      0.0      0.0      0.0s
*  cfzlyt *     0.0      0.0      0.0      0.0e
*  cfzlz  *     0.0      0.0      0.0      0.0s
*  cfzlz  *     0.0      0.0      0.0      0.0e
*  cfzlxr *     0.0      0.0      0.0      0.0s
*  cfzlxr *     0.0      0.0      0.0      0.0e
*  cfzvyt *     0.0      0.0      0.0      0.0s
*  cfzvyt *     0.0      0.0      0.0      0.0e
*  cfzvz  *     0.0      0.0      0.0      0.0s
*  cfzvz  *     0.0      0.0      0.0      0.0e
*  cfzvxr *     0.0      0.0      0.0      0.0s
*  cfzvxr *     0.0      0.0      0.0      0.0e
*   frvol *  0.1925958  0.1925958  0.1925958  0.1925958s
*   frvol *  0.0360128  0.0360128  0.0360128  0.0360128e
*  frfayt *  0.2282058  0.2282058  0.2282058  0.2282058s
*  frfayt * 0.02091093 0.02091093 0.02091093 0.02091093e
*  frfaz  *     0.0      0.0      0.0      0.0s
*  frfaz  *     0.0      0.0      0.0      0.0e
*  frfaxr *  0.1426287  0.1426287  0.1426287  0.1426287s
*  frfaxr *     0.0      0.0      0.0      0.0e
*    hdyt *    0.35     0.35     0.35     0.35s
*    hdyt *    1.69     1.69     1.69     1.69e
*    hdz  *    0.35     0.35     0.35     0.35s
*    hdz  *    1.69     1.69     1.69     1.69e
*    hdxr *    0.35     0.35     0.35     0.35s
*    hdxr *    1.69     1.69     1.69     1.69e
*   alpn  *     0.0      0.0      0.0      0.0s
*   alpn  *     0.0      0.0      0.0      0.0e
*   vvnyt *     0.0      0.0      0.0      0.0s
*   vvnyt *     0.0      0.0      0.0      0.0e
*   vvnz  *     0.0      0.0      0.0      0.0s
```

```
*   vvnz  *       0.0       0.0       0.0       0.0e
*   vvnxr *       0.0       0.0       0.0       0.0s
*   vvnxr *       0.0       0.0       0.0       0.0e
*   vlnyt *       0.0       0.0       0.0       0.0s
*   vlnyt *       0.0       0.0       0.0       0.0e
*   vlnz  *       0.0       0.0       0.0       0.0s
*   vlnz  *       0.0       0.0       0.0       0.0e
*   vlnxr *       0.0       0.0       0.0       0.0s
*   vlnxr *       0.0       0.0       0.0       0.0e
*    tvn *      550.0     550.0     550.0     550.0s
*    tvn *      550.0     550.0     550.0     550.0e
*    tln *      550.0     550.0     550.0     550.0s
*    tln *      550.0     550.0     550.0     550.0e
*     pn *   1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*     pn *   1.5513E7  1.5513E7  1.5513E7  1.5513E7e
*    pan *      0.0       0.0       0.0       0.0s
*    pan *      0.0       0.0       0.0       0.0e
*
*
*******  type        num      userid           component name
pipe               41          1   $41$ int-loop c-leg vssl c6
*    ncells      nodes       jun1       jun2       epsw
        2          0         51         41        0.0
*    nsides
        0
*      ichf      iconc        iacc       ipow     npipes
        0          0          0          0          1
*     radin         th       houtl      houtv      toutl
       0.0        0.0        0.0        0.0        0.0
*     toutv       pwin       pwoff      rpwmx      pwscl
       0.0        0.0        0.0        0.0        0.0
* dx    *     1.4733    1.4733e
* vol   *    0.58123    0.58123e
* fa    *    0.39451    0.39451   0.39451e
* fric  *       0.0       0.0       0.0e
* grav  *       0.0       0.0       0.0e
* hd    *    0.70874    0.70874   0.70874e
* nff   *         1         1       -1e
* alp   *       0.0       0.0e
* vl    *       0.0       0.0       0.0e
* vv    *       0.0       0.0       0.0e
* tl    *     550.0     550.0e
* tv    *     550.0     550.0e
* p     *   1.5513E7  1.5513E7e
* pa    *       0.0       0.0e
*
```

```
*
*d: Inlet flow from the cold leg.
******* type        num      userid           component name
fill              51         1          Vessel Inlet Flow
*      jun1       ifty       ioff
       51         2          0
*     twtold      rfmx       concin      felv
       0.0       1.0E20       0.0        0.0
*      dxin       volin      alpin       vlin        tlin
      1.4733     0.58123      0.0         0.0        488.75
*       pin        pain      flowin      vvin        tvin
      7.0E6        0.0      2450.0        0.0        550.0
*
*
*d: MSIV
******* type        num      userid           component name
valve             184        1                  unnamed
*     ncells      nodes      jun1        jun2        epsw
        2          0          52          53         0.0
*     nsides
        0
*      ichf       iconc      ivty        ivps        nvtb2
        1          0          0           2           0
*      ivtr       ivsv       nvtb1       nvsv        nvrf
        0          0          0           0           0
*     ivtrov      ivtyov
        0          0
*      rvmx        rvov      fminov      fmaxov
       0.2         0.0        0.0         1.0
*     radin        th        houtl       houtv       toutl
       0.0         0.0        0.0         0.0         0.0
*     toutv       avlve      hvlve       favlve       xpos
       0.0       0.39451    0.70874       1.0          1.0
* dx   *     1.4733     1.4733e
* vol  *    0.58123     0.58123e
* fa   *   0.39451    0.39451    0.39451e
* fric *       0.0       0.0        0.0e
* grav *       0.0       0.0        0.0e
* hd   *   0.70874    0.70874    0.70874e
* nff  *       -1          1          1e
* alp  *       0.0       0.0e
* vl   *       0.0       0.0        0.0e
* vv   *       0.0       0.0        0.0e
* tl   *   558.979    558.979e
* tv   *   558.979    558.979e
* p    *     7.0E6      7.0E6e
```

```
* pa   *        0.0       0.0e
*
*
*******  type         num      userid             component name
pipe               194          1                   unnamed
*     ncells        nodes       jun1       jun2       epsw
        2           0         62         59        0.0
*     nsides
        0
*       ichf       iconc        iacc        ipow      npipes
        1           0           0          0          1
*      radin          th        houtl       houtv       toutl
       0.0         0.0         0.0         0.0         0.0
*      toutv        pwin       pwoff       rpwmx        pwscl
       0.0         0.0         0.0         0.0         0.0
* dx   *       5.33      5.33e
* vol  *    5.853551    5.853551e
* fa   *    1.098227   1.098227   1.098227e
* fric *       0.0       0.0       0.0e
* grav *        1.0       1.0      -1.0e
* hd   *     1.1825     1.1825     1.1825e
* nff  *         1          1          1e
* alp  *       0.0       0.0e
* vl   *       0.0       0.0       0.0e
* vv   *       0.0       0.0       0.0e
* tl   *    558.979    558.979e
* tv   *    558.979    558.979e
* p    *     7.0E6      7.0E6e
* pa   *       0.0       0.0e
*
*
*******  type         num      userid             component name
valve              214          1                   unnamed
*     ncells        nodes       jun1       jun2       epsw
        2           0         58         61        0.0
*     nsides
        0
*       ichf       iconc        ivty        ivps      nvtb2
        1           0           1          2          0
*       ivtr        ivsv       nvtb1        nvsv       nvrf
        0           1           1          0          0
*     ivtrov      ivtyov
        0           0
*       rvmx        rvov      fminov      fmaxov
       0.2         0.0         0.0         1.0
*      radin          th        houtl       houtv       toutl
```

```
       0.0        0.0        0.0        0.0        0.0
*      toutv      avlve      hvlve      favlve     xpos
       0.0     1.098227    1.1825       0.0        0.0
* dx   *     0.15      0.15e
* vol  *   0.1178097  0.1178097e
* fa   *   0.7853982  0.7853982  0.7853982e
* fric *     0.0       0.0       0.0e
* grav *     0.0       0.0       0.0e
* hd   *     1.0       1.0       1.0e
* nff  *     1         1         1e
* alp  *     0.0       0.0e
* vl   *     0.0       0.0       0.0e
* vv   *     0.0       0.0       0.0e
* tl   *    300.0     300.0e
* tv   *    300.0     300.0e
* p    *    7.0E6     7.0E6e
* pa   *     0.0       0.0e
* vtb1 *     0.0       0.0e
*
*
******* type        num      userid          component name
pipe           254         1                 unnamed
*     ncells     nodes      jun1      jun2      epsw
        2          0        60        58        0.0
*     nsides
        0
*      ichf      iconc      iacc      ipow      npipes
        1          0         0         0         1
*      radin      th        houtl     houtv      toutl
       0.0        0.0        0.0       0.0        0.0
*      toutv      pwin      pwoff     rpwmx      pwscl
       0.0        0.0        0.0       0.0        0.0
* dx   *     5.33      5.33e
* vol  *   5.853551   5.853551e
* fa   *   1.098227   1.098227  0.7853982e
* fric *     0.0       0.0       0.0e
* grav *     1.0      -1.0       0.0e
* hd   *   1.1825     1.1825     1.0e
* nff  *     1         1         1e
* alp  *     0.0       0.0e
* vl   *     0.0       0.0       0.0e
* vv   *     0.0       0.0       0.0e
* tl   *    300.0     300.0e
* tv   *    300.0     300.0e
* p    *    7.0E6     7.0E6e
* pa   *     0.0       0.0e
```

```
*
*
*******  type        num      userid            component name
pipe              264          1                  unnamed
*     ncells      nodes      jun1      jun2      epsw
         2          0        60        59       0.0
*     nsides
         0
*      ichf       iconc       iacc       ipow      npipes
         1          0          0          0         1
*      radin        th        houtl      houtv      toutl
        0.0        0.0        0.0        0.0        0.0
*      toutv       pwin       pwoff      rpwmx      pwscl
        0.0        0.0        0.0        0.0        0.0
* dx    *       1.0      1.0e
* vol   *    1.098227   1.098227e
* fa    *    1.098227   1.098227   1.098227e
* fric  *       0.0       0.0       0.0e
* grav  *      -1.0       0.0       1.0e
* hd    *     1.1825     1.1825    1.1825e
* nff   *        1         1         1e
* alp   *       0.0       0.0e
* vl    *       0.0       0.0       0.0e
* vv    *       0.0       0.0       0.0e
* tl    *    558.979    558.979e
* tv    *    558.979    558.979e
* p     *      7.0E6     7.0E6e
* pa    *       0.0       0.0e
*
*
*******************************************
* Starting Heat Structure Section of Model *
*******************************************
*
*******  type        num      userid            component name
htstr             170          0    $140$ reactor-core fuel rods
*     nzhstr       ittc      hscyl      ichf
         3          0          1          1
*     nopowr       plane      liqlev     iaxcnd
         0          3          1          0
*      nmwrx       nfci       nfcil      hdri       hdro
         1          1          1        0.0        0.0
*      nhot       nodes      irftr      nzmax     irftr2
         0          8          0        100          0
*    dtxht(1)    dtxht(2)     dznht      hgapo
        4.0        50.0      5.0E-3     6000.0
```

```
*
* idbcin *     0      0      0e
* idbcon *     2      2      2e
*qflxbco1 *    0.0e
*qflxbco1 *    0.0e
*qflxbco1 *    0.0e
* hcomon2 *    26     1      1      3e
* hcomon2 *    26     1      1      4e
* hcomon2 *    26     1      1      5e
* dhtstrz *  1.2141   1.2142   1.2141e
*  rdx *   9843.0e
* radrd *    0.0    2.0E-3    3.0E-3    4.0E-3  4.6427E-3s
* radrd *  4.7422E-3    5.05E-3  5.3594E-3e
* matrd *      1      1      1      1s
* matrd *      3      2      2e
*   nfax *     5      5      5e
*   rftn *   550.0    550.0    550.0    550.0s
*   rftn *   550.0    550.0    550.0    550.0s
*   rftn *   550.0    550.0    550.0    550.0s
*   rftn *   550.0    550.0    550.0    550.0s
*   rftn *   550.0    550.0    550.0    550.0s
*   rftn *   550.0    550.0    550.0    550.0e
* fpuo2 *    0.0e
*  ftd *   0.945e
* gmix *     1.0      0.0      0.0      0.0s
* gmix *     0.0      0.0      0.0e
*  gmles *     0.0e
*  pgapt *   1.0E7e
*  plvol *     0.0 e
*  pslen *     0.0 e
*  clenn *     0.0 e
* burn *   1.54E4    1.54E4    1.54E4e
*
*******  type        num      userid           component name
htstr            171          0   $140$ reactor-core fuel rods
*      nzhstr      ittc      hscyl      ichf
          3         0         1         1
*      nopowr      plane      liqlev      iaxcnd
          0         3         1         0
*      nmwrx      nfci      nfcil      hdri      hdro
          1         1         1       0.0       0.0
*      nhot      nodes      irftr      nzmax      irftr2
          0         8         0       100         0
*    dtxht(1)    dtxht(2)     dznht      hgapo
        4.0        50.0      5.0E-3      6000.0
*
```

```
 *  idbcin *       0        0        0e
 *  idbcon *       2        2        2e
 *qflxbco1  *      0.0e
 *qflxbco1  *      0.0e
 *qflxbco1  *      0.0e
 * hcomon2  *       26        1        2        3e
 * hcomon2  *       26        1        2        4e
 * hcomon2  *       26        1        2        5e
 * dhtstrz *     1.2141    1.2142    1.2141e
 *   rdx *     9843.0e
 * radrd *      0.0     2.0E-3    3.0E-3    4.0E-3   4.6427E-3s
 * radrd *   4.7422E-3    5.05E-3   5.3594E-3e
 * matrd *         1         1         1         1s
 * matrd *         3         2         2e
 *    nfax *       5         5         5e
 *    rftn *     550.0     550.0     550.0     550.0s
 *    rftn *     550.0     550.0     550.0     550.0s
 *    rftn *     550.0     550.0     550.0     550.0s
 *    rftn *     550.0     550.0     550.0     550.0s
 *    rftn *     550.0     550.0     550.0     550.0s
 *    rftn *     550.0     550.0     550.0     550.0e
 * fpuo2 *      0.0e
 *   ftd *     0.945e
 *  gmix *      1.0       0.0       0.0       0.0s
 *  gmix *      0.0       0.0       0.0e
 *   gmles *      0.0e
 *   pgapt *     1.0E7e
 *   plvol *      0.0 e
 *   pslen *      0.0 e
 *   clenn *      0.0 e
 *  burn *    1.54E4    1.54E4    1.54E4e
 *
*******  type        num       userid           component name
htstr              172          0  $140$ reactor-core fuel rods
*      nzhstr       ittc       hscyl       ichf
           3          0          1          1
*      nopowr       plane       liqlev      iaxcnd
           0          3          1          0
*       nmwrx        nfci        nfcil       hdri        hdro
           1          1          1        0.0        0.0
*        nhot        nodes       irftr       nzmax      irftr2
           0          8          0         100          0
*     dtxht(1)    dtxht(2)      dznht      hgapo
         4.0       50.0       5.0E-3      6000.0
*
* idbcin *         0          0          0e
```

```
 *  idbcon *        2         2         2e
 *qflxbco1  *       0.0e
 *qflxbco1  *       0.0e
 *qflxbco1  *       0.0e
 * hcomon2  *        26        1         3        3e
 * hcomon2  *        26        1         3        4e
 * hcomon2  *        26        1         3        5e
 * dhtstrz *    1.2141     1.2142     1.2141e
 *   rdx *     9843.0e
 * radrd *       0.0     2.0E-3    3.0E-3    4.0E-3   4.6427E-3s
 * radrd *   4.7422E-3    5.05E-3  5.3594E-3e
 * matrd *         1         1         1         1s
 * matrd *         3         2         2e
 *    nfax *       5         5         5e
 *    rftn *     550.0      550.0      550.0      550.0s
 *    rftn *     550.0      550.0      550.0      550.0s
 *    rftn *     550.0      550.0      550.0      550.0s
 *    rftn *     550.0      550.0      550.0      550.0s
 *    rftn *     550.0      550.0      550.0      550.0s
 *    rftn *     550.0      550.0      550.0      550.0e
 * fpuo2 *       0.0e
 *   ftd *     0.945e
 *  gmix *       1.0        0.0        0.0        0.0s
 *  gmix *       0.0        0.0        0.0e
 *   gmles *       0.0e
 *   pgapt *     1.0E7e
 *   plvol *       0.0 e
 *   pslen *       0.0 e
 *   clenn *       0.0 e
 *  burn *     1.54E4     1.54E4     1.54E4e
 *
 *******  type         num       userid            component name
 htstr                173          0   $140$ reactor-core fuel rods
 *      nzhstr        ittc       hscyl        ichf
          3           0           1            1
 *      nopowr        plane       liqlev       iaxcnd
          0           3           1            0
 *      nmwrx        nfci        nfcil        hdri         hdro
          1           1           1         0.0          0.0
 *       nhot        nodes       irftr        nzmax        irftr2
          0           8           0          100           0
 *    dtxht(1)     dtxht(2)      dznht        hgapo
         4.0         50.0       5.0E-3       6000.0
 *
 *  idbcin *        0         0         0e
 *  idbcon *        2         2         2e
```

```
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
* hcomon2  *       26       1       4       3e
* hcomon2  *       26       1       4       4e
* hcomon2  *       26       1       4       5e
* dhtstrz *    1.2141    1.2142    1.2141e
*   rdx *     9843.0e
* radrd *      0.0     2.0E-3    3.0E-3    4.0E-3   4.6427E-3s
* radrd *  4.7422E-3    5.05E-3   5.3594E-3e
* matrd *        1        1        1        1s
* matrd *        3        2        2e
*   nfax *       5        5        5e
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0e
* fpuo2 *      0.0e
*   ftd *     0.945e
*  gmix *      1.0       0.0       0.0       0.0s
*  gmix *      0.0       0.0       0.0e
*   gmles *      0.0e
*   pgapt *     1.0E7e
*   plvol *      0.0 e
*   pslen *      0.0 e
*   clenn *      0.0 e
*  burn *     1.54E4     1.54E4     1.54E4e
*
*******  type        num       userid            component name
htstr              274          0                   unnamed
*      nzhstr        ittc       hscyl        ichf
        2          0          1          1
*      nopowr       plane       liqlev       iaxcnd
        1          3          0          0
*      nmwrx       nfci       nfcil       hdri       hdro
        0          0          0       0.0        0.0
*      nhot       nodes       irftr       nzmax       irftr2
        0          2          0        100          0
*    dtxht(1)    dtxht(2)      dznht       hgapo
        2.0        10.0      1.0E-3      6300.0
*
*  idbcin *        2        2e
*  idbcon *        5        5e
* hcomon1  *       264        1        0        0e
```

```
* hcomon1  *       264        2        0        0e
* tsurfo2  *     300.0e
* tsurfo2  *     300.0e
* dhtstrz *      1.0       1.0e
*   rdx *       1.0e
* radrd *    0.59125    0.69125e
* matrd *         6e
*    nfax *         1         1e
*    rftn *      300.0     300.0     300.0     300.0e
******************************************
* Finished Heat Structure Section of Model *
******************************************
*
*
*
*
***************************************
*    Starting Power Components        *
***************************************
*
*******   type        num       userid            component name
power               174            1  Power Comp for old ht str 140
*      numpwr     chanpow
         4          0
* htnum *       170        171        172        173e
*      irpwty        ndgx        ndhx        nrts        nhist
         5          0          0          10          0
*      izpwtr      izpwsv      nzpwtb      nzpwsv      nzpwrf
         0          1          1          0          0
*      ipwrad      ipwdep     promheat    decaheat    wtbypass
         0          0         0.0         0.0         0.0
*      nzpwz       nzpwi       nfbpwt      nrpwr       nrpwi
         0          0          0          1          0
*      react       tneut       rpwoff      rrpwmx      rpwscl
        0.0         0.0         0.0       1.0E20        1.0
*      rpowri      zpwin       zpwoff      rzpwmx
       4.5E9        0.0         0.0         0.0
*      extsou      pldr        pdrat       fucrac
        0.0         0.0        1.334        1.0
* rdpwr *     1.2109     1.2371     1.2703     1.3201     1.3823s
* rdpwr *       0.0        0.0        0.0e
* cpowr *       1.0        1.0        1.0        1.0e
* zpwtb1*      0.0s
* zpwtb1*    0.93748s
* zpwtb1*    1.20535s
* zpwtb1*    0.83715e
```

```
****************************************
*    Finished Power Components         *
****************************************
*
*
*
end
*
*****************
* Timestep Data *
*****************
*      dtmin      dtmax      tend      rtwfp
       0.05       1.0        50.0      10.0
*      edint      gfint      dmpint    sedint
       12.0       0.5        12.0      12.0
*
*     endflag
       -1.0
```

```
free format
*
*************
* main data *
*************
*
*     numtcr     ieos     inopt     nmat     id2o
         1        0        1         0        0
Model of Reactor Core
*
*
*****************
* namelist data *
*****************
*
 &inopts
  cpuflg=1,
  dtstrt=-1.0,
  iadded=10,
  noair=0,
  usesjc=3,
  npower=1,
  nhtstr=5,
  igas=1
 &end
*
***************
* Model Flags *
***************
*
*      dstep      timet
         0        0.0
*     stdyst     transi     ncomp     njun     ipak
         0          1         17        11        1
*      epso       epss
      1.0E-3     1.0E-3
*     oitmax     sitmax     isolut     ncontr     nccfl
        10         10         0          0         0
*      ntsv       ntcb       ntcf       ntrp      ntcp
         1          0          0          0         0
*
*************************
* component-number data *
*************************
```

```
*
* iorder*     1      11     26     41     51s
* iorder*    170     171    172    173    174s
* iorder*    184     194    214    254    264s
* iorder*    274     284e
*
*
************************************************
* Starting Signal Variable Section of Model    *
************************************************
*
*     idsv     isvn     ilcn     icn1     icn2
       1        0        0        0        0
************************************************
* Finished Signal Variable Section of Model    *
************************************************
*
*
*
*
******* type       num     userid          component name
pipe               1        1          Loop 1 Hot leg
*    ncells     nodes     jun1     jun2     epsw
       2         0         1        52       0.0
*    nsides
       0
*     ichf      iconc     iacc     ipow     npipes
       0         0         0        0         1
*     radin       th      houtl     houtv     toutl
       0.0        0.0      0.0       0.0       0.0
*     toutv      pwin     pwoff     rpwmx      pwscl
       0.0        0.0      0.0       0.0       0.0
* dx   *    1.4733    1.4733e
* vol  *    0.58123   0.58123e
* fa   *   0.39451   0.39451   0.39451e
* fric *     0.0       0.0       0.0e
* grav *     0.0       0.0       0.0e
* hd   *   0.70874   0.70874   0.70874e
* nff  *     -1        -1        -1e
* alp  *     0.0      0.0e
* vl   *     0.0       0.0       0.0e
* vv   *     0.0       0.0       0.0e
* tl   *    550.0    550.0e
* tv   *    550.0    550.0e
* p    *    7.0E6    7.0E6e
* pa   *     0.0      0.0e
```

```
*
*
*d: Primary System Pressure
*******  type        num      userid            component name
break               11        1           System Pressure
*      jun1       ibty       isat       ioff     adjpress
        53          0          1          0          0
*      dxin       volin       alpin        tin         pin
     1.4733     0.58123       0.0        550.0       7.0E6
*      pain      concin       rbmx        poff        belv
       0.0         0.0       100.0        0.0         0.0
*
*
*d: Vessel
*******  type        num      userid            component name
vessel              26        1           $26$ 3-d vessel
*      nasx       nrsx       ntsx       ncsr      ivssbf
        7          2          4          4          0
*      idcu       idcl       idcr       icru       icrl
        6          2          1          5          2
*      icrr       ilcsp      iucsp      iuhp       iconc
        1          0          0          0          0
*      igeom      nvent      nvvtb      nsgrid
        0          0          0          0
*      shelv      epsw
       27.7       0.0
*  z   *     4.7       8.7      12.7      16.7s
*  z   *     19.7      22.7      27.7e
*  r   *     2.3       3.5e
*  t   *  90.00021  180.0004  270.0006  360.0008e
*      lisrl      lisrc      lisrf      ljuns      zfrac
        6          1          3          1
        6          1          3          62
        6          5          3          41
        6          5          3          61
* level 1
*
*  cfzlyt *     0.0       0.0       0.0       0.0s
*  cfzlyt *     0.0       0.0       0.0       0.0e
*  cfzlz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3s
*  cfzlz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3e
*  cfzlxr *     0.0       0.0       0.0       0.0s
*  cfzlxr *     0.0       0.0       0.0       0.0e
*  cfzvyt *     0.0       0.0       0.0       0.0s
*  cfzvyt *     0.0       0.0       0.0       0.0e
*  cfzvz  *   3.7E-3    3.7E-3    3.7E-3    3.7E-3s
```

```
* cfzvz *    3.7E-3    3.7E-3    3.7E-3    3.7E-3e
* cfzvxr *     0.0     0.0     0.0     0.0s
* cfzvxr *     0.0     0.0     0.0     0.0e
*  frvol *  0.1800935  0.1800935  0.1800935  0.1800935s
*  frvol * 0.02116456 0.02116456 0.02116456 0.02116456e
* frfayt *  0.1414256  0.1414256  0.1414256  0.1414256s
* frfayt * 0.02681191 0.02681191 0.02681191 0.02681191e
* frfaz  *  0.4728711  0.4728711  0.4728711  0.4728711s
* frfaz  * 0.08696042 0.08696042 0.08696042 0.08696042e
* frfaxr *  0.1250877  0.1250877  0.1250877  0.1250877s
* frfaxr *     0.0     0.0     0.0     0.0e
*   hdyt *    0.74    0.74    0.74    0.74s
*   hdyt *    0.82    0.82    0.82    0.82e
*   hdz  *    0.74    0.74    0.74    0.74s
*   hdz  *    0.82    0.82    0.82    0.82e
*   hdxr *    0.74    0.74    0.74    0.74s
*   hdxr *    0.82    0.82    0.82    0.82e
*  alpn  *     0.0     0.0     0.0     0.0s
*  alpn  *     0.0     0.0     0.0     0.0e
*  vvnyt *     0.0     0.0     0.0     0.0s
*  vvnyt *     0.0     0.0     0.0     0.0e
*  vvnz  *     0.0     0.0     0.0     0.0s
*  vvnz  *     0.0     0.0     0.0     0.0e
*  vvnxr *     0.0     0.0     0.0     0.0s
*  vvnxr *     0.0     0.0     0.0     0.0e
*  vlnyt *     0.0     0.0     0.0     0.0s
*  vlnyt *     0.0     0.0     0.0     0.0e
*  vlnz  *     0.0     0.0     0.0     0.0s
*  vlnz  *     0.0     0.0     0.0     0.0e
*  vlnxr *     0.0     0.0     0.0     0.0s
*  vlnxr *     0.0     0.0     0.0     0.0e
*    tvn *   550.0   550.0   550.0   550.0s
*    tvn *   550.0   550.0   550.0   550.0e
*    tln *   550.0   550.0   550.0   550.0s
*    tln *   550.0   550.0   550.0   550.0e
*     pn * 1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*     pn * 1.5513E7  1.5513E7  1.5513E7  1.5513E7e
*    pan *     0.0     0.0     0.0     0.0s
*    pan *     0.0     0.0     0.0     0.0e
* level 2
*
* cfzlyt *     0.0     0.0     0.0     0.0s
* cfzlyt *     0.0     0.0     0.0     0.0e
* cfzlz  *  0.013025  0.013025  0.013025  0.013025s
* cfzlz  *     0.0     0.0     0.0     0.0e
* cfzlxr *     0.0     0.0     0.0     0.0s
```

```
* cfzlxr *    0.0        0.0        0.0        0.0e
* cfzvyt *    0.0        0.0        0.0        0.0s
* cfzvyt *    0.0        0.0        0.0        0.0e
* cfzvz  *  0.013025   0.013025   0.013025   0.013025s
* cfzvz  *    0.0        0.0        0.0        0.0e
* cfzvxr *    0.0        0.0        0.0        0.0s
* cfzvxr *    0.0        0.0        0.0        0.0e
*  frvol * 0.1517568  0.1517568  0.1517568  0.1517568s
*  frvol * 0.03891449 0.03891449 0.03891449 0.03891449e
* frfayt * 0.1500133  0.1500133  0.1500133  0.1500133s
* frfayt *  0.04108    0.04108    0.04108    0.04108e
* frfaz  * 0.1780657  0.1780657  0.1780657  0.1780657s
* frfaz  * 0.1293782  0.1293782  0.1293782  0.1293782e
* frfaxr * 0.1250111  0.1250111  0.1250111  0.1250111s
* frfaxr *    0.0        0.0        0.0        0.0e
*   hdyt *    0.23       0.23       0.23       0.23s
*   hdyt *    0.41       0.41       0.41       0.41e
*   hdz  *   0.013      0.013      0.013      0.013s
*   hdz  *    0.41       0.41       0.41       0.41e
*   hdxr *    0.23       0.23       0.23       0.23s
*   hdxr *    0.41       0.41       0.41       0.41e
*  alpn  *    0.0        0.0        0.0        0.0s
*  alpn  *    0.0        0.0        0.0        0.0e
*  vvnyt *    0.0        0.0        0.0        0.0s
*  vvnyt *    0.0        0.0        0.0        0.0e
*  vvnz  *    0.0        0.0        0.0        0.0s
*  vvnz  *    0.0        0.0        0.0        0.0e
*  vvnxr *    0.0        0.0        0.0        0.0s
*  vvnxr *    0.0        0.0        0.0        0.0e
*  vlnyt *    0.0        0.0        0.0        0.0s
*  vlnyt *    0.0        0.0        0.0        0.0e
*  vlnz  *    0.0        0.0        0.0        0.0s
*  vlnz  *    0.0        0.0        0.0        0.0e
*  vlnxr *    0.0        0.0        0.0        0.0s
*  vlnxr *    0.0        0.0        0.0        0.0e
*    tvn *   550.0      550.0      550.0      550.0s
*    tvn *   550.0      550.0      550.0      550.0e
*    tln *   550.0      550.0      550.0      550.0s
*    tln *   550.0      550.0      550.0      550.0e
*     pn * 1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn * 1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *    0.0        0.0        0.0        0.0s
*    pan *    0.0        0.0        0.0        0.0e
* level 3
*
* cfzlyt *    0.0        0.0        0.0        0.0s
```

```
* cfzlyt *    0.0    0.0    0.0    0.0e
* cfzlz  *    0.0    0.0    0.0    0.0s
* cfzlz  *    0.0    0.0    0.0    0.0e
* cfzlxr *    0.0    0.0    0.0    0.0s
* cfzlxr *    0.0    0.0    0.0    0.0e
* cfzvyt *    0.0    0.0    0.0    0.0s
* cfzvyt *    0.0    0.0    0.0    0.0e
* cfzvz  *    0.0    0.0    0.0    0.0s
* cfzvz  *    0.0    0.0    0.0    0.0e
* cfzvxr *    0.0    0.0    0.0    0.0s
* cfzvxr *    0.0    0.0    0.0    0.0e
*  frvol * 0.08435715 0.08435715 0.08435715 0.08435715s
*  frvol * 0.04328887 0.04328887 0.04328887 0.04328887e
* frfayt * 0.09995437 0.09995437 0.09995437 0.09995437s
* frfayt * 0.04484076 0.04484076 0.04484076 0.04484076e
* frfaz  *  0.2779249  0.2779249  0.2779249  0.2779249s
* frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
* frfaxr *    0.0    0.0    0.0    0.0s
* frfaxr *    0.0    0.0    0.0    0.0e
*   hdyt *    0.013    0.013    0.013    0.013s
*   hdyt *    0.178    0.178    0.178    0.178e
*   hdz  *    0.013    0.013    0.013    0.013s
*   hdz  *    0.178    0.178    0.178    0.178e
*   hdxr *    0.013    0.013    0.013    0.013s
*   hdxr *    0.178    0.178    0.178    0.178e
*  alpn  *    0.0    0.0    0.0    0.0s
*  alpn  *    0.0    0.0    0.0    0.0e
*  vvnyt *    0.0    0.0    0.0    0.0s
*  vvnyt *    0.0    0.0    0.0    0.0e
*  vvnz  *    0.0    0.0    0.0    0.0s
*  vvnz  *    0.0    0.0    0.0    0.0e
*  vvnxr *    0.0    0.0    0.0    0.0s
*  vvnxr *    0.0    0.0    0.0    0.0e
*  vlnyt *    0.0    0.0    0.0    0.0s
*  vlnyt *    0.0    0.0    0.0    0.0e
*  vlnz  *    0.0    0.0    0.0    0.0s
*  vlnz  *    0.0    0.0    0.0    0.0e
*  vlnxr *    0.0    0.0    0.0    0.0s
*  vlnxr *    0.0    0.0    0.0    0.0e
*    tvn *    550.0    550.0    550.0    550.0s
*    tvn *    550.0    550.0    550.0    550.0e
*    tln *    550.0    550.0    550.0    550.0s
*    tln *    550.0    550.0    550.0    550.0e
*     pn * 1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*     pn * 1.5513E7  1.5513E7  1.5513E7  1.5513E7e
*    pan *    0.0    0.0    0.0    0.0s
```

```
*    pan *      0.0        0.0        0.0        0.0e
* level 4
*
* cfzlyt *      0.0        0.0        0.0        0.0s
* cfzlyt *      0.0        0.0        0.0        0.0e
* cfzlz  *      0.0        0.0        0.0        0.0s
* cfzlz  *      0.0        0.0        0.0        0.0e
* cfzlxr *      0.0        0.0        0.0        0.0s
* cfzlxr *      0.0        0.0        0.0        0.0e
* cfzvyt *      0.0        0.0        0.0        0.0s
* cfzvyt *      0.0        0.0        0.0        0.0e
* cfzvz  *      0.0        0.0        0.0        0.0s
* cfzvz  *      0.0        0.0        0.0        0.0e
* cfzvxr *      0.0        0.0        0.0        0.0s
* cfzvxr *      0.0        0.0        0.0        0.0e
*  frvol * 0.08436409 0.08436409 0.08436409 0.08436409s
*  frvol * 0.04329244 0.04329244 0.04329244 0.04329244e
* frfayt * 0.09996261 0.09996261 0.09996261 0.09996261s
* frfayt * 0.04484445 0.04484445 0.04484445 0.04484445e
* frfaz  *  0.2779249  0.2779249  0.2779249  0.2779249s
* frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
* frfaxr *      0.0        0.0        0.0        0.0s
* frfaxr *      0.0        0.0        0.0        0.0e
*   hdyt *    0.013      0.013      0.013      0.013s
*   hdyt *    0.178      0.178      0.178      0.178e
*   hdz  *    0.013      0.013      0.013      0.013s
*   hdz  *    0.178      0.178      0.178      0.178e
*   hdxr *    0.013      0.013      0.013      0.013s
*   hdxr *    0.178      0.178      0.178      0.178e
*  alpn  *      0.0        0.0        0.0        0.0s
*  alpn  *      0.0        0.0        0.0        0.0e
*  vvnyt *      0.0        0.0        0.0        0.0s
*  vvnyt *      0.0        0.0        0.0        0.0e
*  vvnz  *      0.0        0.0        0.0        0.0s
*  vvnz  *      0.0        0.0        0.0        0.0e
*  vvnxr *      0.0        0.0        0.0        0.0s
*  vvnxr *      0.0        0.0        0.0        0.0e
*  vlnyt *      0.0        0.0        0.0        0.0s
*  vlnyt *      0.0        0.0        0.0        0.0e
*  vlnz  *      0.0        0.0        0.0        0.0s
*  vlnz  *      0.0        0.0        0.0        0.0e
*  vlnxr *      0.0        0.0        0.0        0.0s
*  vlnxr *      0.0        0.0        0.0        0.0e
*    tvn *    550.0      550.0      550.0      550.0s
*    tvn *    550.0      550.0      550.0      550.0e
*    tln *    550.0      550.0      550.0      550.0s
```

```
*    tln *      550.0      550.0      550.0      550.0e
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *       0.0        0.0        0.0        0.0s
*    pan *       0.0        0.0        0.0        0.0e
* level 5
*
* cfzlyt *       0.0        0.0        0.0        0.0s
* cfzlyt *       0.0        0.0        0.0        0.0e
* cfzlz  *   5.138E-3   5.138E-3   5.138E-3   5.138E-3s
* cfzlz  *       0.0        0.0        0.0        0.0e
* cfzlxr *       0.0        0.0        0.0        0.0s
* cfzlxr *       0.0        0.0        0.0        0.0e
* cfzvyt *       0.0        0.0        0.0        0.0s
* cfzvyt *       0.0        0.0        0.0        0.0e
* cfzvz  *   5.138E-3   5.138E-3   5.138E-3   5.138E-3s
* cfzvz  *       0.0        0.0        0.0        0.0e
* cfzvxr *       0.0        0.0        0.0        0.0s
* cfzvxr *       0.0        0.0        0.0        0.0e
*  frvol *  0.1124762  0.1124762  0.1124762  0.1124762s
*  frvol * 0.05771849 0.05771849 0.05771849 0.05771849e
* frfayt *  0.1332725  0.1332725  0.1332725  0.1332725s
* frfayt * 0.05978768 0.05978768 0.05978768 0.05978768e
* frfaz  *  0.1780657  0.1780657  0.1780657  0.1780657s
* frfaz  *  0.1426204  0.1426204  0.1426204  0.1426204e
* frfaxr *       0.0        0.0        0.0        0.0s
* frfaxr *       0.0        0.0        0.0        0.0e
*   hdyt *     0.013      0.013      0.013      0.013s
*   hdyt *     0.178      0.178      0.178      0.178e
*   hdz  *     0.013      0.013      0.013      0.013s
*   hdz  *     0.178      0.178      0.178      0.178e
*   hdxr *     0.013      0.013      0.013      0.013s
*   hdxr *     0.178      0.178      0.178      0.178e
*   alpn *       0.0        0.0        0.0        0.0s
*   alpn *       0.0        0.0        0.0        0.0e
*  vvnyt *       0.0        0.0        0.0        0.0s
*  vvnyt *       0.0        0.0        0.0        0.0e
*  vvnz  *       0.0        0.0        0.0        0.0s
*  vvnz  *       0.0        0.0        0.0        0.0e
*  vvnxr *       0.0        0.0        0.0        0.0s
*  vvnxr *       0.0        0.0        0.0        0.0e
*  vlnyt *       0.0        0.0        0.0        0.0s
*  vlnyt *       0.0        0.0        0.0        0.0e
*  vlnz  *       0.0        0.0        0.0        0.0s
*  vlnz  *       0.0        0.0        0.0        0.0e
*  vlnxr *       0.0        0.0        0.0        0.0s
```

```
*   vlnxr *      0.0        0.0        0.0        0.0e
*    tvn *     550.0      550.0      550.0      550.0s
*    tvn *     550.0      550.0      550.0      550.0e
*    tln *     550.0      550.0      550.0      550.0s
*    tln *     550.0      550.0      550.0      550.0e
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7s
*     pn *   1.5513E7   1.5513E7   1.5513E7   1.5513E7e
*    pan *      0.0        0.0        0.0        0.0s
*    pan *      0.0        0.0        0.0        0.0e
* level 6
*
* cfzlyt *      0.0        0.0        0.0        0.0s
* cfzlyt *      0.0        0.0        0.0        0.0e
* cfzlz  *      1.0        1.0        1.0        1.0s
* cfzlz  *      1.0        1.0        1.0        1.0e
* cfzlxr *      0.0        0.0        0.0        0.0s
* cfzlxr *      0.0        0.0        0.0        0.0e
* cfzvyt *      0.0        0.0        0.0        0.0s
* cfzvyt *      0.0        0.0        0.0        0.0e
* cfzvz  *      1.0        1.0        1.0        1.0s
* cfzvz  *      1.0        1.0        1.0        1.0e
* cfzvxr *      0.0        0.0        0.0        0.0s
* cfzvxr *      0.0        0.0        0.0        0.0e
*  frvol *  0.9478957  0.9478957  0.9478957  0.9478957s
*  frvol *  0.1919029  0.1919029  0.1919029  0.1919029e
* frfayt *  0.7093623  0.7093623  0.7093623  0.7093623s
* frfayt * 0.08965547 0.08965547 0.08965547 0.08965547e
* frfaz  * 0.05128291 0.05128291 0.05128291 0.05128291s
* frfaz  *      0.0        0.0        0.0        0.0e
* frfaxr *      0.0        0.0        0.0        0.0s
* frfaxr *      0.0        0.0        0.0        0.0e
*   hdyt *     0.23       0.23       0.23       0.23s
*   hdyt *     0.178      0.178      0.178      0.178e
*   hdz  *     0.23       0.23       0.23       0.23s
*   hdz  *     0.178      0.178      0.178      0.178e
*   hdxr *     0.23       0.23       0.23       0.23s
*   hdxr *     0.178      0.178      0.178      0.178e
*  alpn  *      0.0        0.0        0.0        0.0s
*  alpn  *      0.0        0.0        0.0        0.0e
*  vvnyt *      0.0        0.0        0.0        0.0s
*  vvnyt *      0.0        0.0        0.0        0.0e
*  vvnz  *      0.0        0.0        0.0        0.0s
*  vvnz  *      0.0        0.0        0.0        0.0e
*  vvnxr *      0.0        0.0        0.0        0.0s
*  vvnxr *      0.0        0.0        0.0        0.0e
*  vlnyt *      0.0        0.0        0.0        0.0s
```

```
*   vlnyt *     0.0      0.0      0.0      0.0e
*   vlnz  *     0.0      0.0      0.0      0.0s
*   vlnz  *     0.0      0.0      0.0      0.0e
*   vlnxr *     0.0      0.0      0.0      0.0s
*   vlnxr *     0.0      0.0      0.0      0.0e
*     tvn *   550.0    550.0    550.0    550.0s
*     tvn *   550.0    550.0    550.0    550.0e
*     tln *   550.0    550.0    550.0    550.0s
*     tln *   550.0    550.0    550.0    550.0e
*      pn * 1.5513E7 1.5513E7 1.5513E7 1.5513E7s
*      pn * 1.5513E7 1.5513E7 1.5513E7 1.5513E7e
*     pan *     0.0      0.0      0.0      0.0s
*     pan *     0.0      0.0      0.0      0.0e
* level 7
*
* cfzlyt *     0.0      0.0      0.0      0.0s
* cfzlyt *     0.0      0.0      0.0      0.0e
* cfzlz  *     0.0      0.0      0.0      0.0s
* cfzlz  *     0.0      0.0      0.0      0.0e
* cfzlxr *     0.0      0.0      0.0      0.0s
* cfzlxr *     0.0      0.0      0.0      0.0e
* cfzvyt *     0.0      0.0      0.0      0.0s
* cfzvyt *     0.0      0.0      0.0      0.0e
* cfzvz  *     0.0      0.0      0.0      0.0s
* cfzvz  *     0.0      0.0      0.0      0.0e
* cfzvxr *     0.0      0.0      0.0      0.0s
* cfzvxr *     0.0      0.0      0.0      0.0e
*  frvol * 0.1925958 0.1925958 0.1925958 0.1925958s
*  frvol * 0.0360128 0.0360128 0.0360128 0.0360128e
* frfayt * 0.2282058 0.2282058 0.2282058 0.2282058s
* frfayt * 0.02091093 0.02091093 0.02091093 0.02091093e
* frfaz  *     0.0      0.0      0.0      0.0s
* frfaz  *     0.0      0.0      0.0      0.0e
* frfaxr * 0.1426287 0.1426287 0.1426287 0.1426287s
* frfaxr *     0.0      0.0      0.0      0.0e
*   hdyt *     0.35     0.35     0.35     0.35s
*   hdyt *     1.69     1.69     1.69     1.69e
*   hdz  *     0.35     0.35     0.35     0.35s
*   hdz  *     1.69     1.69     1.69     1.69e
*   hdxr *     0.35     0.35     0.35     0.35s
*   hdxr *     1.69     1.69     1.69     1.69e
*   alpn *     0.0      0.0      0.0      0.0s
*   alpn *     0.0      0.0      0.0      0.0e
*  vvnyt *     0.0      0.0      0.0      0.0s
*  vvnyt *     0.0      0.0      0.0      0.0e
*  vvnz  *     0.0      0.0      0.0      0.0s
```

```
*   vvnz  *       0.0       0.0       0.0       0.0e
*   vvnxr *       0.0       0.0       0.0       0.0s
*   vvnxr *       0.0       0.0       0.0       0.0e
*   vlnyt *       0.0       0.0       0.0       0.0s
*   vlnyt *       0.0       0.0       0.0       0.0e
*   vlnz  *       0.0       0.0       0.0       0.0s
*   vlnz  *       0.0       0.0       0.0       0.0e
*   vlnxr *       0.0       0.0       0.0       0.0s
*   vlnxr *       0.0       0.0       0.0       0.0e
*    tvn *      550.0     550.0     550.0     550.0s
*    tvn *      550.0     550.0     550.0     550.0e
*    tln *      550.0     550.0     550.0     550.0s
*    tln *      550.0     550.0     550.0     550.0e
*     pn *   1.5513E7  1.5513E7  1.5513E7  1.5513E7s
*     pn *   1.5513E7  1.5513E7  1.5513E7  1.5513E7e
*    pan *      0.0       0.0       0.0       0.0s
*    pan *      0.0       0.0       0.0       0.0e
*
*
*******  type        num      userid          component name
pipe                41          1   $41$ int-loop c-leg vssl c6
*     ncells      nodes      jun1      jun2      epsw
         2          0         51        41        0.0
*     nsides
         0
*       ichf      iconc       iacc       ipow      npipes
         0          0          0          0          1
*      radin        th       houtl      houtv      toutl
        0.0        0.0        0.0        0.0        0.0
*      toutv      pwin       pwoff      rpwmx      pwscl
        0.0        0.0        0.0        0.0        0.0
* dx    *     1.4733    1.4733e
* vol   *    0.58123    0.58123e
* fa    *    0.39451    0.39451    0.39451e
* fric  *       0.0       0.0       0.0e
* grav  *       0.0       0.0       0.0e
* hd    *    0.70874    0.70874    0.70874e
* nff   *         1         1        -1e
* alp   *       0.0       0.0e
* vl    *       0.0       0.0       0.0e
* vv    *       0.0       0.0       0.0e
* tl    *     550.0     550.0e
* tv    *     550.0     550.0e
* p     *   1.5513E7  1.5513E7e
* pa    *       0.0       0.0e
*
```

```
*
*d: Inlet flow from the cold leg.
*******  type        num      userid          component name
fill              51        1        Vessel Inlet Flow
*      jun1       ifty       ioff
        51        2        0
*    twtold      rfmx      concin       felv
        0.0     1.0E20       0.0        0.0
*      dxin      volin      alpin       vlin        tlin
     1.4733    0.58123        0.0        0.0      488.75
*       pin       pain      flowin       vvin        tvin
      7.0E6        0.0     2450.0        0.0       550.0
*
*
*d: MSIV
*******  type        num      userid          component name
valve             184        1                unnamed
*    ncells      nodes      jun1       jun2       epsw
        2          0         52         53        0.0
*    nsides
        0
*      ichf      iconc       ivty       ivps       nvtb2
      · 1          0          0          2          0
*      ivtr       ivsv      nvtb1       nvsv       nvrf
        0          0          0          0          0
*    ivtrov     ivtyov
        0          0
*      rvmx       rvov     fminov     fmaxov
       0.2        0.0        0.0        1.0
*     radin         th      houtl      houtv      toutl
       0.0        0.0        0.0        0.0        0.0
*     toutv      avlve      hvlve      favlve      xpos
       0.0    0.39451    0.70874        1.0        1.0
* dx   *     1.4733    1.4733e
* vol  *    0.58123   0.58123e
* fa   *    0.39451   0.39451   0.39451e
* fric *        0.0       0.0       0.0e
* grav *        0.0       0.0       0.0e
* hd   *    0.70874   0.70874   0.70874e
* nff  *         -1         1        1e
* alp  *        0.0      0.0e
* vl   *        0.0       0.0       0.0e
* vv   *        0.0       0.0       0.0e
* tl   *    558.979  558.979e
* tv   *    558.979  558.979e
* p    *      7.0E6     7.0E6e
```

```
* pa   *        0.0       0.0e
*
*
******* type        num      userid           component name
pipe              194         1                unnamed
*    ncells      nodes      jun1      jun2      epsw
        2          0         62         59        0.0
*    nsides
        0
*      ichf       iconc        iacc       ipow      npipes
        1          0          0          0          1
*     radin         th       houtl       houtv      toutl
       0.0         0.0        0.0         0.0        0.0
*     toutv        pwin       pwoff      rpwmx       pwscl
       0.0         0.0        0.0         0.0        0.0
* dx   *       5.33      5.33e
* vol  *    5.853551   5.853551e
* fa   *    1.098227   1.098227   1.098227e
* fric  *       0.0       0.0       0.0e
* grav  *       1.0       1.0      -1.0e
* hd   *     1.1825     1.1825     1.1825e
* nff  *         1         1         1e
* alp  *        0.0       0.0e
* vl   *        0.0       0.0       0.0e
* vv   *        0.0       0.0       0.0e
* tl   *    558.979    558.979e
* tv   *    558.979    558.979e
* p    *      7.0E6      7.0E6e
* pa   *        0.0       0.0e
*
*
******* type        num      userid           component name
valve             214         1                unnamed
*    ncells      nodes      jun1      jun2      epsw
        2          0         63         61        0.0
*    nsides
        0
*      ichf       iconc       ivty       ivps      nvtb2
        1          0          1          2          0
*      ivtr       ivsv       nvtb1      nvsv       nvrf
        0          1          1          0          0
*    ivtrov     ivtyov
        0          0
*      rvmx        rvov      fminov      fmaxov
       0.2         0.0        0.0         1.0
*     radin         th       houtl       houtv      toutl
```

```
       0.0        0.0        0.0        0.0        0.0
*      toutv      avlve      hvlve      favlve      xpos
       0.0    1.098227     1.1825       0.0        0.0
* dx   *     0.15      0.15e
* vol  *   0.1178097   0.1178097e
* fa   *   1.098227   0.7853982   0.7853982e
* fric  *      0.0        0.0        0.0e
* grav  *      0.0        0.0        0.0e
* hd   *     1.1825       1.0        1.0e
* nff  *       1          1          1e
* alp  *      0.0        0.0e
* vl   *      0.0        0.0        0.0e
* vv   *      0.0        0.0        0.0e
* tl   *     300.0      300.0e
* tv   *     300.0      300.0e
* p    *     7.0E6      7.0E6e
* pa   *      0.0        0.0e
* vtb1  *     0.0        0.0e
*
*
*******  type        num       userid          component name
pipe              254          1                unnamed
*     ncells      nodes      jun1      jun2      epsw
         2          0         60        64       0.0
*     nsides
         0
*      ichf      iconc       iacc      ipow      npipes
         1          0          0         0         1
*      radin        th       houtl      houtv      toutl
       0.0        0.0        0.0        0.0        0.0
*      toutv      pwin      pwoff      rpwmx      pwscl
       0.0        0.0        0.0        0.0        0.0
* dx   *     5.33      5.33e
* vol  *   5.853551   5.853551e
* fa   *   1.098227   1.098227   1.098227e
* fric  *      0.0        0.0        0.0e
* grav  *      1.0       -1.0        0.0e
* hd   *     1.1825     1.1825     1.1825e
* nff  *       1          1          1e
* alp  *      0.0        0.0e
* vl   *      0.0        0.0        0.0e
* vv   *      0.0        0.0        0.0e
* tl   *     300.0      300.0e
* tv   *     300.0      300.0e
* p    *     7.0E6      7.0E6e
* pa   *      0.0        0.0e
```

```
*
*
*******  type          num       userid            component name
pipe               264          1                 unnamed
*     ncells      nodes      jun1      jun2      epsw
        2          0        60         59        0.0
*     nsides
        0
*       ichf      iconc       iacc       ipow      npipes
        1          0          0          0         1
*      radin        th       houtl      houtv      toutl
       0.0        0.0        0.0        0.0        0.0
*      toutv       pwin      pwoff      rpwmx      pwscl
       0.0        0.0        0.0        0.0        0.0
* dx   *      1.0       1.0e
* vol  *   1.098227   1.098227e
* fa   *  1.098227   1.098227   1.098227e
* fric *      0.0       0.0       0.0e
* grav *     -1.0       0.0       1.0e
* hd   *    1.1825     1.1825     1.1825e
* nff  *       1          1         1e
* alp  *      0.0       0.0e
* vl   *      0.0       0.0       0.0e
* vv   *      0.0       0.0       0.0e
* tl   *   558.979    558.979e
* tv   *   558.979    558.979e
* p    *     7.0E6     7.0E6e
* pa   *      0.0       0.0e
*
*
*******  type          num       userid            component name
pump               284          1                 unnamed
*     ncells      nodes      jun1      jun2      epsw
        0          0        64         63        0.0
*       ichf      iconc     ipmpty       irp       ipm
        1          0        11          0         0
*      icbvl      icbvv
        1          1
*      vllim      vvlim
       66.0       66.0
* dx   *   f 0.0000e+00e
* vol  *   f 0.0000e+00e
* fa   * f   1.098227e
* fric * f       0.0e
* grav * f       0.0e
* hd   * f     1.1825e
```

```
* nff   *  f          1e
* alp   *    f 0.0000e+00e
* vl    *  f        0.0e
* vv    *  f        0.0e
* tl    *   f 0.0000e+00e
* tv    *    f 0.0000e+00e
* p     *    f 0.0000e+00e
* pa    *    f 0.0000e+00e
*
*
*******************************************
* Starting Heat Structure Section of Model *
*******************************************
*
*******  type         num       userid            component name
htstr                 170          0   $140$ reactor-core fuel rods
*      nzhstr        ittc       hscyl        ichf
          3           0          1           1
*      nopowr        plane      liqlev       iaxcnd
          0           3          1           0
*      nmwrx        nfci       nfcil       hdri        hdro
          1           1          1         0.0         0.0
*      nhot        nodes       irftr       nzmax      irftr2
          0           8          0         100          0
*    dtxht(1)     dtxht(2)      dznht       hgapo
        4.0         50.0       5.0E-3      6000.0
*
*  idbcin *         0          0          0e
*  idbcon *         2          2          2e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
*qflxbco1  *       0.0e
* hcomon2  *        26          1          1         3e
* hcomon2  *        26          1          1         4e
* hcomon2  *        26          1          1         5e
* dhtstrz *     1.2141     1.2142     1.2141e
*   rdx *      9843.0e
* radrd *       0.0     2.0E-3     3.0E-3     4.0E-3   4.6427E-3s
* radrd *   4.7422E-3     5.05E-3   5.3594E-3e
* matrd *         1          1          1          1s
* matrd *         3          2          2e
*   nfax *        5          5          5e
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0s
*   rftn *      550.0       550.0       550.0       550.0s
```

```
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0e
* fpuo2 *      0.0e
*  ftd *     0.945e
*  gmix *      1.0      0.0      0.0      0.0s
*  gmix *      0.0      0.0      0.0e
*   gmles *      0.0e
*   pgapt *     1.0E7e
*   plvol *      0.0 e
*   pslen *      0.0 e
*   clenn *      0.0 e
*  burn *    1.54E4    1.54E4    1.54E4e
*
*******  type        num      userid            component name
htstr              171         0   $140$ reactor-core fuel rods
*      nzhstr       ittc       hscyl       ichf
         3          0          1          1
*      nopowr       plane      liqlev      iaxcnd
         0          3          1          0
*      nmwrx       nfci       nfcil       hdri        hdro
         1          1          1         0.0         0.0
*       nhot       nodes       irftr       nzmax      irftr2
         0          8          0         100          0
*    dtxht(1)    dtxht(2)      dznht       hgapo
        4.0        50.0      5.0E-3      6000.0
*
*  idbcin *       0        0        0e
*  idbcon *       2        2        2e
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
* hcomon2  *       26        1        2        3e
* hcomon2  *       26        1        2        4e
* hcomon2  *       26        1        2        5e
* dhtstrz *    1.2141    1.2142    1.2141e
*   rdx *     9843.0e
* radrd *      0.0    2.0E-3    3.0E-3    4.0E-3   4.6427E-3s
* radrd *  4.7422E-3     5.05E-3  5.3594E-3e
* matrd *         1         1         1        1s
* matrd *         3         2        2e
*   nfax *        5         5        5e
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
*   rftn *     550.0     550.0     550.0     550.0s
```

```
*   rftn *      550.0      550.0      550.0      550.0e
* fpuo2 *        0.0e
*   ftd *     0.945e
*  gmix *       1.0       0.0       0.0       0.0s
*  gmix *       0.0       0.0       0.0e
*   gmles *       0.0e
*   pgapt *      1.0E7e
*   plvol *       0.0 e
*   pslen *       0.0 e
*   clenn *       0.0 e
*  burn *     1.54E4     1.54E4     1.54E4e
*
*******  type          num       userid              component name
htstr               172          0   $140$ reactor-core fuel rods
*      nzhstr        ittc       hscyl        ichf
         3           0           1           1
*      nopowr        plane       liqlev       iaxcnd
         0           3           1           0
*       nmwrx        nfci        nfcil        hdri        hdro
         1           1           1         0.0         0.0
*        nhot       nodes        irftr       nzmax       irftr2
         0           8           0         100           0
*    dtxht(1)    dtxht(2)       dznht       hgapo
       4.0        50.0       5.0E-3      6000.0
*
*  idbcin *       0         0         0e
*  idbcon *        2         2         2e
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
* hcomon2  *       26         1         3         3e
* hcomon2  *       26         1         3         4e
* hcomon2  *       26         1         3         5e
* dhtstrz *    1.2141      1.2142      1.2141e
*   rdx *     9843.0e
* radrd *       0.0     2.0E-3     3.0E-3     4.0E-3   4.6427E-3s
* radrd *   4.7422E-3    5.05E-3   5.3594E-3e
* matrd *         1          1          1          1s
* matrd *         3          2          2e
*    nfax *        5          5          5e
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0e
```

```
* fpuo2 *      0.0e
*   ftd *    0.945e
*  gmix *      1.0      0.0      0.0      0.0s
*  gmix *      0.0      0.0      0.0e
*   gmles *      0.0e
*   pgapt *     1.0E7e
*   plvol *      0.0 e
*   pslen *      0.0 e
*   clenn *      0.0 e
*  burn *    1.54E4    1.54E4    1.54E4e
*
*******  type        num      userid           component name
htstr               173          0   $140$ reactor-core fuel rods
*      nzhstr        ittc       hscyl       ichf
          3           0           1           1
*      nopowr        plane      liqlev      iaxcnd
          0           3           1           0
*       nmwrx        nfci       nfcil       hdri       hdro
          1           1           1         0.0        0.0
*        nhot       nodes       irftr      nzmax      irftr2
          0           8           0         100          0
*     dtxht(1)    dtxht(2)      dznht      hgapo
        4.0        50.0       5.0E-3     6000.0
*
*  idbcin *       0        0        0e
*  idbcon *       2        2        2e
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
*qflxbco1  *      0.0e
* hcomon2  *       26        1        4        3e
* hcomon2  *       26        1        4        4e
* hcomon2  *       26        1        4        5e
* dhtstrz *    1.2141     1.2142     1.2141e
*   rdx *     9843.0e
* radrd *       0.0     2.0E-3     3.0E-3     4.0E-3   4.6427E-3s
* radrd *   4.7422E-3    5.05E-3   5.3594E-3e
* matrd *         1         1         1        1s
* matrd *         3         2         2e
*    nfax *       5         5         5e
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0s
*    rftn *     550.0      550.0      550.0      550.0e
* fpuo2 *      0.0e
```

```
*   ftd *      0.945e
*  gmix *       1.0       0.0       0.0       0.0s
*  gmix *       0.0       0.0       0.0e
*   gmles *       0.0e
*   pgapt *      1.0E7e
*   plvol *       0.0 e
*   pslen *       0.0 e
*   clenn *       0.0 e
*  burn *     1.54E4     1.54E4     1.54E4e
*
*******   type        num      userid            component name
htstr              274         0                    unnamed
*      nzhstr       ittc      hscyl       ichf
         2          0          1          1
*      nopowr       plane      liqlev      iaxcnd
         1          3          0          0
*       nmwrx       nfci      nfcil       hdri       hdro
         0          0          0        0.0        0.0
*        nhot       nodes      irftr      nzmax     irftr2
         0          2          0        100         0
*    dtxht(1)    dtxht(2)     dznht      hgapo
        2.0        10.0      1.0E-3     6300.0
*
*  idbcin *        2        2e
*  idbcon *        5        5e
* hcomon1  *        264        1        0        0e
* hcomon1  *        264        2        0        0e
* tsurfo2  *     300.0e
* tsurfo2  *     300.0e
* dhtstrz *       1.0       1.0e
*   rdx *       1.0e
* radrd *    0.59125    0.69125e
* matrd *        6e
*   nfax *        1        1e
*   rftn *     300.0     300.0     300.0     300.0e
********************************************
* Finished Heat Structure Section of Model *
********************************************
*
*
*
*
*****************************************
*    Starting Power Components         *
*****************************************
*
```

```
*******  type       num      userid          component name
power            174          1  Power Comp for old ht str 140
*     numpwr     chanpow
        4          0
* htnum *      170      171      172      173e
*     irpwty      ndgx       ndhx       nrts       nhist
        5          0          0        10          0
*     izpwtr      izpwsv      nzpwtb      nzpwsv      nzpwrf
        0          1          1          0          0
*     ipwrad      ipwdep     promheat    decaheat     wtbypass
        0          0        0.0        0.0         0.0
*      nzpwz      nzpwi      nfbpwt      nrpwr      nrpwi
        0          0          0          1          0
*      react      tneut      rpwoff      rrpwmx      rpwscl
       0.0        0.0        0.0      1.0E20        1.0
*     rpowri      zpwin      zpwoff      rzpwmx
      4.5E9        0.0        0.0        0.0
*     extsou       pldr       pdrat      fucrac
       0.0        0.0      1.334        1.0
* rdpwr *    1.2109     1.2371     1.2703     1.3201     1.3823s
* rdpwr *      0.0        0.0       0.0e
* cpowr *      1.0        1.0       1.0       1.0e
* zpwtb1*      0.0s
* zpwtb1*    0.93748s
* zpwtb1*    1.20535s
* zpwtb1*    0.83715e
****************************************
*    Finished Power Components        *
****************************************
*
*
*
end
*
*****************
* Timestep Data *
*****************
*      dtmin      dtmax      tend      rtwfp
       0.05       1.0       50.0       10.0
*      edint      gfint      dmpint     sedint
       12.0       0.5       12.0       12.0
*
*     endflag
      -1.0
```