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System Study: Residual Heat Removal 1998–2022

December 2023

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ABSTRACT

This report presents an unreliability evaluation of the residual heat removal (RHR) system in two modes of operation (low-pressure injection in response to a large loss-of-coolant accident and in response to post-trip shutdown cooling) at 93 U.S. commercial operating nuclear reactors. New Standardized Plant Analysis Risk (SPAR) models with the most recent SPAR parameter update results were used in this report. Demand, run hour, and failure data from 1998–2022 for selected components were obtained from the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS), formerly the INPO Consolidated Events Database. The unreliability results are trended for the most recent 10-year period while yearly estimates for system unreliability are provided for the entire active period. No statistically significant increasing or decreasing trends were identified in the RHR results.

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ACRONYMS

AOV	air-operated valve
BW	Babcock and Wilcox
BWR	boiling water reactor
CCF	common-cause failure
CE	Combustion Engineering
DHR	decay heat removal
FTOC	fail to open/close
FTOP	fail to operate
FTR	fail to run (normally running equipment)
FTR>1H	fail to run more than 1 hour (standby equipment)
FTR<1H	fail to run less than 1 hour (after start, standby equipment)
FTS	fail to start
GE	General Electric
GTG	gas turbine generator
HPCI	high-pressure coolant injection
HTG	hydro turbine generator
HTX	heat exchanger
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
IRIS	Industry Reporting and Information System
LOHT	loss of heat transfer
LLOCA	large loss-of-coolant accident
LPI	low-pressure injection
MDP	motor-driven pump
MOV	motor-operated valve
MSPI	Mitigating Systems Performance Index
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RCS	reactor coolant system
RHR	residual heat removal
ROP	Reactor Oversight Process
SDC	shutdown cooling

SO	spurious operation
SPAR	standardized plant analysis risk
SPC	suppression pool cooling
SSU	safety system unavailability
UA	unavailability (maintenance or state of another component)
WE	Westinghouse Electric

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System Study:
Residual Heat Removal
1998–2022

1. INTRODUCTION

The residual heat removal (RHR) system is typically a multiple use system with modes of operation for low-pressure injection (LPI), shutdown cooling (SDC), suppression pool or containment sump cooling, and containment spray. Some plants have dedicated systems to accomplish one or more of these modes. This report presents an unreliability evaluation of the RHR system over time in two operation modes—LPI in response to a large loss-of-coolant accident (LLOCA) and post-trip SDC—at 93 U.S. commercial operating nuclear reactors.

Demand, run hour, and failure data from calendar year 1998–2022 for selected components in the RHR system were obtained from the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS), formerly the INPO Consolidated Events Database (ICES) and the Equipment Performance and Information Exchange Database (EPIX). Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process (ROP) Safety System Unavailability (SSU) database (1998–2001) and the Mitigating Systems Performance Index (MSPI) database (2002–2022). The system unreliability results are trended for the most recent 10-year period while yearly estimates for system unreliability are provided for the entire active period.

This report does not attempt to estimate basic event values for use in a probabilistic risk assessment (PRA). Suggested values for such use are presented in the 2020 SPAR parameter update including INL/EXT-21-65055, *Industry Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants: 2020 Update* [1], which is the most recent update to NUREG/CR-6928 [2], and INL/EXT-21-62940, *CCF Parameter Estimations, 2020 Update* [3], for common-cause failure (CCF) parameters.

New SPAR models (versions of 8.80 or above, as indicated in Table 1) that utilize the 2020 SPAR parameter update results [1, 3] were used in this report. In previous system studies, which can be found at the Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov/), older SPAR models (versions of 8.1 to 8.2) with the *2010 Component Reliability Update* [4] for basic event data were used for the 2011 through 2020 system study updates. For comparison purposes, it is necessary to use the same set of SPAR models and basic event data in the analysis while the only variables subject to change are yearly demand, run hour, failure, and unavailability data for selected components in the system. However, more recent SPAR models must be used to replace outdated models periodically so that the system study reflects the current plant and system configurations as well as the more representative baseline data for the industry performance. With the 2020 SPAR parameter and model updates concluded in 2022, it was a good time to revamp the system study with the more current models for the 2022 update.

All models include failures due to unavailability while in test or maintenance. Human actions and recovery events in the models are set to "Ignore" in the study for the results to represent the mechanical part of the system. An overview of the trending methods, glossary of terms, and abbreviations can be found in the *Overview and Reference* document [5] on the NRC web page (https://nrcoe.inl.gov).

The remainder of this section describes the RHR design classes for the LPI and SDC modes, respectively. Section 2 summarizes the main findings from the study. Section 3 presents the baseline RHR LPI and SDC unreliability results using basic event values from the 2020 SPAR parameter update.

Section 4 shows the trend results for RHR LPI and SDC unreliability using system-specific data as listed in Section 6. Section 5 provides the basic event group importance information using the baseline results from Section 3. Section 7 presents a high-level generic description of the RHR system.

1.1 Low-Pressure Injection Mode

Table 1 shows the definitions of the RHR LPI design classes. For each plant, the corresponding Standardized Plant Analysis Risk (SPAR) model was used in the calculations. The LPI mode represents the use of the system as it is normally lined up during power operations. The RHR system in LPI mode is an automatically initiated event.

The RHR system can be categorized by the number of redundant LPI pumps and plant vendor design for the LPI mode. Table 3 summarizes the plant RHR LPI classes and the SPAR model versions used in this study.

This report calculated two variations of the LPI mode model for the RHR system. The RHR LPI start-only model is the RHR LPI SPAR model modified by setting all fail-to-run basic events to zero (“False”), setting all human error and recovery events to “Ignore,” all room cooling events to “False,” and all pump cooling events to “False.” The RHR LPI 8-hour mission model includes all basic events in the RHR LPI SPAR model while setting all human error and recovery events to “Ignore.”

Table 1. RHR LPI class definitions.

RHR LPI Class	Description	Number of Plants
2 pumps; BW	Two RHR pump Babcock and Wilcox (BW) Design	2
2 pumps; CE	Two RHR pump Combustion Engineering (CE) Design	8
2 pumps; GE	Two RHR pump General Electric (GE) Design	9
2 pumps; WE	Two RHR pump Westinghouse (WE) Design	44
3 pumps; BW	Three RHR pump Babcock and Wilcox Design	3
3 pumps; GE	Three RHR pump General Electric Design	3
3 pumps; WE	Three RHR pump Westinghouse Design	2
4 pumps; CE	Four RHR pump Combustion Engineering Design	3
4 pumps; GE	Four RHR pump General Electric Design	19
Total		93

1.2 Shutdown Cooling Mode

Table 2 shows the definitions of the RHR SDC design classes used in this report. For each plant, the corresponding SPAR model (version model indicated in Table 3) was used in the calculations.

The SDC mode represents the most challenging (more risk significant at pressurized water reactors [PWRs] than in boiling water reactors [BWRs]) use of the equipment since the heat exchangers are required to function and valves must be repositioned to initiate the cooldown function. The RHR system in the SDC mode is a manually initiated event. Each fault tree modeling the RHR SDC mode includes a human action basic event to model the initiation. This basic event often comes out as the most important basic event in the model. To evaluate the system in more detail, the human action to initiate SDC was set to “Ignore” in the fault tree.

The RHR system can also be categorized by the heat sink method for the SDC mode, which is the most significant difference noted between systems at plants. The direct heat sink takes sensible heat from the reactor coolant system (RCS) and transfers it directly to the ultimate heat sink (a variation of a service water system either dedicated or shared with other safety systems). The indirect heat sink transfers sensible heat to a closed cooling water system, which in turn transfers the heat to the ultimate heat sink. Table 3 includes the plant RHR SDC along with the RHR LPI classes and the SPAR model versions used in this study.

Two variations of the SDC mode for the RHR system are calculated. The RHR SDC start-only model is the RHR SDC SPAR model modified by setting all fail-to-run basic events to zero ("False"), setting all human error and recovery events to "Ignore," setting all room cooling events to "False," and setting all pump cooling events to "False." The RHR SDC 24-hour mission variation includes all basic events in the RHR SDC SPAR model while setting all human error and recovery events to "Ignore."

Table 2. RHR SDC class definitions.

RHR SDC Class	Description	Number of Plants
Direct-multiple	Direct heat sink, uses multiple suction paths	5
Direct-single	Direct heat sink, uses a single suction path	26
Indirect-multiple	Indirect heat sink, uses multiple suction paths	21
Indirect-single	Indirect heat sink, uses a single suction path	29
No suction modeled	Models do not include the suction path valves (model suppression pool cooling only)	3
Single use	Plants with a single-use SDC system	9
Total		93

Table 3. RHR design class summary.

Plant	SPAR ID	SPAR Version	LPI Class	SDC Class
Arkansas 1	ANO1	8.80	2 pumps; BW	Direct-Single
Arkansas 2	ANO2	8.81	2 pumps; CE	Direct-Single
Beaver Valley 1	BVS1	8.80	2 pumps; WE	Single Use
Beaver Valley 2	BVS2	8.80	2 pumps; WE	Single Use
Braidwood 1 & 2	BRWD	8.81	2 pumps; WE	Indirect-Multiple
Browns Ferry 1	BRF1	8.80	4 pumps; GE	Direct-Single
Browns Ferry 2	BRF2	8.80	4 pumps; GE	Direct-Single
Browns Ferry 3	BRF3	8.80	4 pumps; GE	Direct-Single
Brunswick 1	BRU1	8.80	4 pumps; GE	Direct-Single
Brunswick 2	BRU2	8.80	4 pumps; GE	Direct-Single
Byron 1 & 2	BYRN	8.81	2 pumps; WE	Indirect-Multiple
Callaway	CALL	8.80	2 pumps; WE	Indirect-Multiple
Calvert Cliffs 1	CCF1	8.80	2 pumps; CE	Indirect-Single
Calvert Cliffs 2	CCF2	8.80	2 pumps; CE	Indirect-Single
Catawba 1 & 2	CATA	8.81	2 pumps; WE	Indirect-Single
Clinton 1	CLNT	8.80	2 pumps; GE	Direct-Single
Columbia 2	COLM	8.80	2 pumps; GE	Direct-Single

Table 3. (continued).

Plant	SPAR ID	SPAR Version	LPI Class	SDC Class
Comanche Peak 1 & 2	COPK	8.81	2 pumps; WE	Indirect-Multiple
Cook 1 & 2	COOK	8.81	2 pumps; WE	Indirect-Single
Cooper	COOP	8.80	4 pumps; GE	Direct-Single
Davis-Besse	DAVB	8.81	2 pumps; BW	Indirect-Single
Diablo Canyon 1 & 2	DCAN	8.81	2 pumps; WE	Indirect-Single
Dresden 2 & 3	DRES	8.81	3 pumps; GE	Single Use
Farley 1 & 2	FARL	8.81	2 pumps; WE	Indirect-Multiple
Fermi 2	FERM	8.80	4 pumps; GE	Direct-Single
FitzPatrick	FITZ	8.80	4 pumps; GE	No suction modeled
Ginna	GINA	8.80	2 pumps; WE	Indirect-Single
Grand Gulf	GGUL	8.80	2 pumps; GE	Direct-Single
Harris	HARR	8.81	2 pumps; WE	Indirect-Multiple
Hatch 1 & 2	HATC	8.82	4 pumps; GE	Direct-Single
Hope Creek	HOPE	8.80	2 pumps; GE	Direct-Single
LaSalle 1 & 2	LSAL	8.81	2 pumps; GE	Direct-Single
Limerick 1	LIM1	8.80	4 pumps; GE	Direct-Single
Limerick 2	LIM2	8.82	4 pumps; GE	Direct-Single
McGuire 1 & 2	MCGU	8.80	2 pumps; WE	Indirect-Single
Millstone 2	MIL2	8.80	2 pumps; CE	Indirect-Single
Millstone 3	MIL3	8.80	2 pumps; WE	Indirect-Multiple
Monticello	MONT	8.81	4 pumps; GE	Direct-Single
Nine Mile Pt. 1	NMP1	8.80	3 pumps; GE	Single Use
Nine Mile Pt. 2	NMP2	8.80	2 pumps; GE	Direct-Single
North Anna 1 & 2	NANN	8.80	2 pumps; WE	Single Use
Oconee 1, 2 & 3	OCON	8.80	3 pumps; BW	Indirect-Single
Palisades	PALI	8.80	2 pumps; CE	Indirect-Single
Palo Verde 1, 2 & 3	PVNG	8.80	4 pumps; CE	Direct-Multiple
Peach Bottom 2	PBT2	8.80	4 pumps; GE	Direct-Single
Peach Bottom 3	PBT3	8.80	4 pumps; GE	Direct-Single
Perry	PERY	8.80	2 pumps; GE	Indirect-Single
Point Beach 1 & 2	PBCH	8.80	2 pumps; WE	Indirect-Single
Prairie Island 1 & 2	PRAI	8.80	2 pumps; WE	Direct-Multiple

Table 3. (continued).

Plant	SPAR ID	SPAR Version	LPI Class	SDC Class
Quad Cities 1 & 2	QCTY	8.80	4 pumps; GE	Direct-Single
River Bend	RIVB	8.80	2 pumps; GE	Direct-Single
Robinson 2	ROBN	8.80	2 pumps; WE	Indirect-Single
Salem 1 & 2	SALM	8.80	2 pumps; WE	Indirect-Single
Seabrook	SBRK	8.80	2 pumps; WE	Indirect-Multiple
Sequoyah 1 & 2	SEQH	8.80	2 pumps; WE	Indirect-Single
South Texas 1 & 2	STEX	8.80	3 pumps; WE	Indirect-Multiple
St. Lucie 1	STL1	8.80	2 pumps; CE	Indirect-Multiple
St. Lucie 2	STL2	8.80	2 pumps; CE	Indirect-Multiple
Summer	SUMM	8.80	2 pumps; WE	Indirect-Multiple
Surry 1&2	SURY	8.80	2 pumps; WE	Single Use
Susquehanna 1	SUS1	8.82	4 pumps; GE	No suction modeled
Susquehanna 2	SUS2	8.80	4 pumps; GE	No suction modeled
Turkey Point 3 & 4	TKPT	8.80	2 pumps; WE	Indirect-Single
Vogtle 1 & 2	VOGT	8.80	2 pumps; WE	Indirect-Multiple
Waterford 3	WTRF	8.80	2 pumps; CE	Indirect-Multiple
Watts Bar 1&2	WB12	8.80	2 pumps; WE	Indirect-Single
Wolf Creek	WOLF	8.80	2 pumps; WE	Indirect-Multiple

2. SUMMARY OF FINDINGS

The results of this RHR system unreliability study are summarized in this section. Of particular interest is any statistically significant[a] increasing trend. In this update, for the most recent 10-year period, **statistically significant decreasing trends** were identified in the industry-wide estimates of **RHR LPI start-only unreliability and RHR SDC start-only unreliability**; **a highly statistically significant decreasing trend** was identified in the industry-wide estimate of **RHR LPI 8-hour mission unreliability**; and **no statistically significant trend** was identified in the industry-wide estimates of **RHR SDC 24-hour mission unreliability**.

The industry-wide RHR start-only and 8-hour (or 24-hour for SDC) mission basic event group importances were evaluated for LPI and SDC. For both **start-only and 8-hour mission** (or 24-hour mission for SDC), **the leading contributor to RHR LPI unreliability** is the **RHR MDP** group of basic events followed by the **Room Cooling, Injection, Suction, Heat Sink,** and **Special** groups, and **the leading contributor to RHR SDC unreliability** is the **Suction** group of basic events followed by the **Injection, RHR MDP, Heat Sink,** and **AC Power** groups.

For those plants with a single suction source, the Suction group importance increases significantly. For those plants that have multiple suction sources, the importance of other groups such as AC Power, Injection, Heat Sink, and Pump increases as the Suction group importance decreases (see Figure 20 vs. Figure 21). The distinction between the heat sink types (direct versus indirect) is small due to the standby nature of most of the direct heat sink systems and the normally operating nature of the indirect heat sink systems.

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a Statistically significant is defined in terms of the "p-value." A p-value is a probability indicating whether to accept or reject the null hypothesis that there is no trend in the data. P-values less than or equal to 0.05 indicate that we are 95% confident that there is a trend in the data (reject the null hypothesis of no trend). By convention, we use the "Michelin Guide" scale: p-value < 0.05 (statistically significant); p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

3. INDUSTRY-WIDE UNRELIABILITY

3.1 Low-Pressure Injection Mode

The RHR LPI mode fault trees (which can be labeled as "LPI" or "LCI" as indicated in Table 14) from the SPAR models were evaluated for each of the 93 U.S. commercial operating pressurized water nuclear power plants with an RHR system.

This study estimates the industry-wide unreliability of the RHR system for two variations, a start-only model and an 8-hour mission model. The uncertainty distributions for RHR show both plant design variability and parameter uncertainty while using industry-wide component failure data from the 2020 SPAR parameter update.[b] Table 4 shows the percentiles and mean of the aggregated sample data (Latin hypercube, 1,000 samples for each model) collected from the uncertainty calculations of the RHR fault trees in the SPAR models. In Figure 1 and Figure 2, the 5th and 95th percentiles and mean point estimates are shown for each RHR class and the industry.

In Figure 1 and Figure 2, the class distribution width is affected by differences in the plant modeling and parameter uncertainty used in the models. Because the width is affected by the plant modeling, the width is also affected by the number of unique plant models in a class. For those classes with very few plants that share a design, the distribution width can be very small.

Table 4. Industry-wide RHR LPI mode unreliability values.

Model	RHR Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-only	Industry	7.58E-06	8.67E-05	5.25E-04	2.08E-03
	2 pumps; BW	3.80E-05	2.07E-04	3.86E-04	1.23E-03
	2 pumps; CE	2.04E-05	3.55E-04	2.37E-03	1.06E-02
	2 pumps; GE	4.18E-06	1.13E-04	3.21E-04	1.30E-03
	2 pumps; WE	1.95E-05	8.97E-05	1.95E-04	7.72E-04
	3 pumps; BW	5.09E-06	3.25E-05	1.95E-04	3.73E-04
	3 pumps; GE	4.47E-06	6.04E-04	1.68E-03	2.97E-03
	3 pumps; WE	3.26E-06	1.50E-05	2.17E-05	6.20E-05
	4 pumps; CE	1.16E-05	5.58E-05	6.79E-05	1.68E-04
	4 pumps; GE	4.09E-06	5.72E-05	2.36E-04	1.15E-03
8-hour Mission	Industry	8.09E-06	9.39E-05	5.39E-04	2.16E-03
	2 pumps; BW	3.74E-05	2.16E-04	3.90E-04	1.20E-03
	2 pumps; CE	2.32E-05	3.55E-04	2.37E-03	1.06E-02
	2 pumps; GE	4.66E-06	1.17E-04	3.22E-04	1.32E-03
	2 pumps; WE	2.22E-05	9.48E-05	1.99E-04	7.71E-04
	3 pumps; BW	5.91E-06	3.39E-05	9.89E-05	3.83E-04
	3 pumps; GE	4.87E-06	6.25E-04	1.65E-03	2.98E-03
	3 pumps; WE	3.41E-06	1.52E-05	2.19E-05	6.35E-05
	4 pumps; CE	1.23E-04	4.76E-04	9.62E-04	3.31E-03
	4 pumps; GE	4.39E-06	5.84E-05	2.37E-04	1.16E-03

b In using industry-wide component failure data, individual plant-specific performance does not appear in the distribution of results.

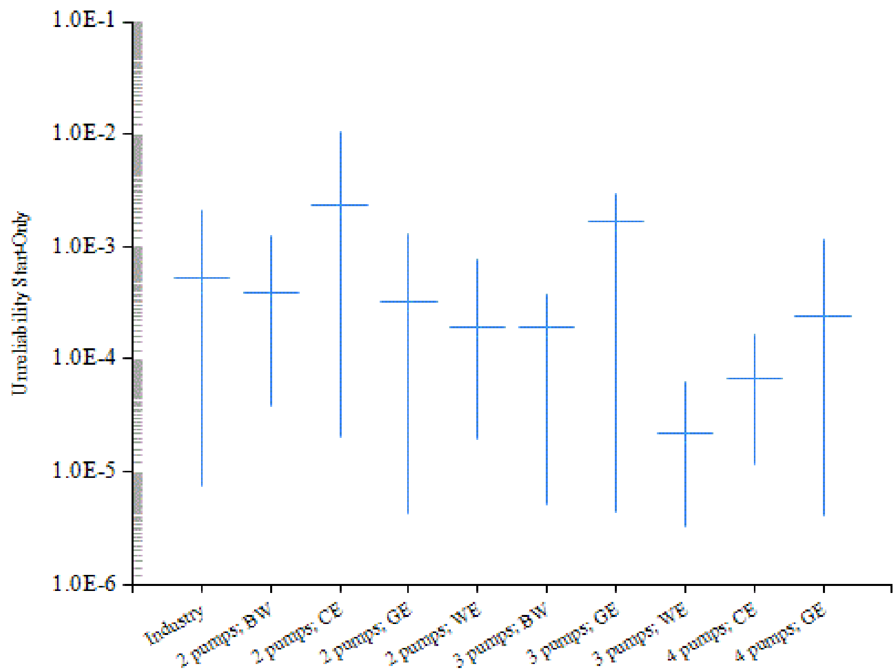

Figure 1. RHR LPI mode start-only unreliability for class and industry-wide groupings.

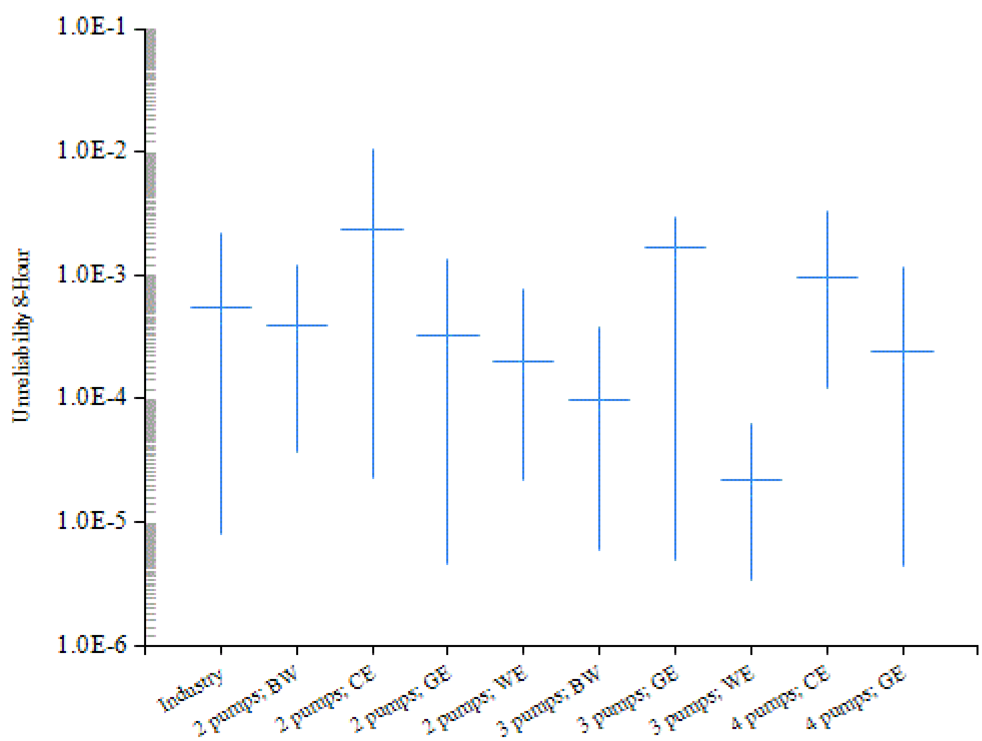

Figure 2. RHR LPI mode 8-hour mission unreliability for class and industry-wide groupings.

3.2 Shutdown Cooling Mode

The RHR SDC mode fault trees (which can be labeled as “RHR,” “SDC,” or “DHR,” as indicated in Table 14) from the SPAR models were evaluated for each of the 93 U.S. commercial operating pressurized water nuclear power plants with an RHR system.

The industry-wide unreliability of the RHR system has been estimated for two variations, a start-only model and a 24-hour mission model. The uncertainty distributions for RHR show both plant design variability and parameter uncertainty while using industry-wide component failure data from the 2020 SPAR parameter update.[c]

Table 5 shows the percentiles and mean of the aggregated sample data (Latin hypercube, 1,000 samples for each model) collected from the uncertainty calculations of the RHR fault trees in the SPAR models. In Figure 3 and Figure 4, the 5th and 95th percentiles and mean point estimates are shown for each RHR class and for the industry.

In Figure 3 and Figure 4, the class distribution width is affected by differences in the plant modeling and parameter uncertainty used in the models. Because the width is affected by the plant modeling, the width is also affected by the number of different plant models in a class. For those classes with very few plants that share a design, the width can be very small.

Table 5. Industry-wide RHR SDC mode unreliability values.

Model	RHR Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-only	Industry	2.45E-04	2.40E-03	3.77E-03	1.18E-02
	Direct-Multiple	7.06E-04	2.57E-03	3.45E-03	9.26E-03
	Direct-Single	4.34E-04	1.88E-03	2.28E-03	5.29E-03
	Indirect-Multiple	2.03E-04	2.24E-03	3.66E-03	1.16E-02
	Indirect-Single	9.81E-04	3.64E-03	5.15E-03	1.43E-02
	No suction modeled	1.86E-05	2.04E-04	4.45E-04	1.68E-03
	Single Use	4.43E-04	4.49E-03	7.33E-03	2.57E-02
24-hour Mission	Industry	2.52E-04	2.42E-03	3.79E-03	1.17E-02
	Direct-Multiple	6.99E-04	2.72E-03	3.59E-03	9.70E-03
	Direct-Single	4.36E-04	1.89E-03	2.28E-03	5.28E-03
	Indirect-Multiple	2.15E-04	2.25E-03	3.67E-03	1.15E-02
	Indirect-Single	9.99E-04	3.65E-03	5.17E-03	1.42E-02
	No suction modeled	2.13E-05	2.03E-04	4.44E-04	1.68E-03
	Single Use	4.51E-04	4.51E-03	7.47E-03	2.64E-02

c By using industry-wide component failure data, individual plant performance is not included in the distribution of results.

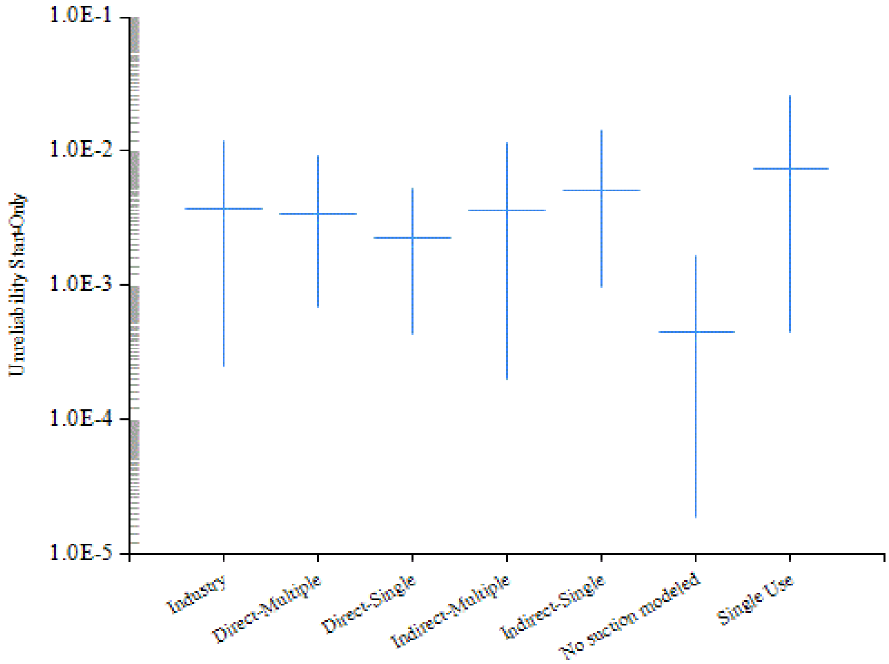

Figure 3. RHR SDC mode start-only unreliability for class and industry-wide groupings.

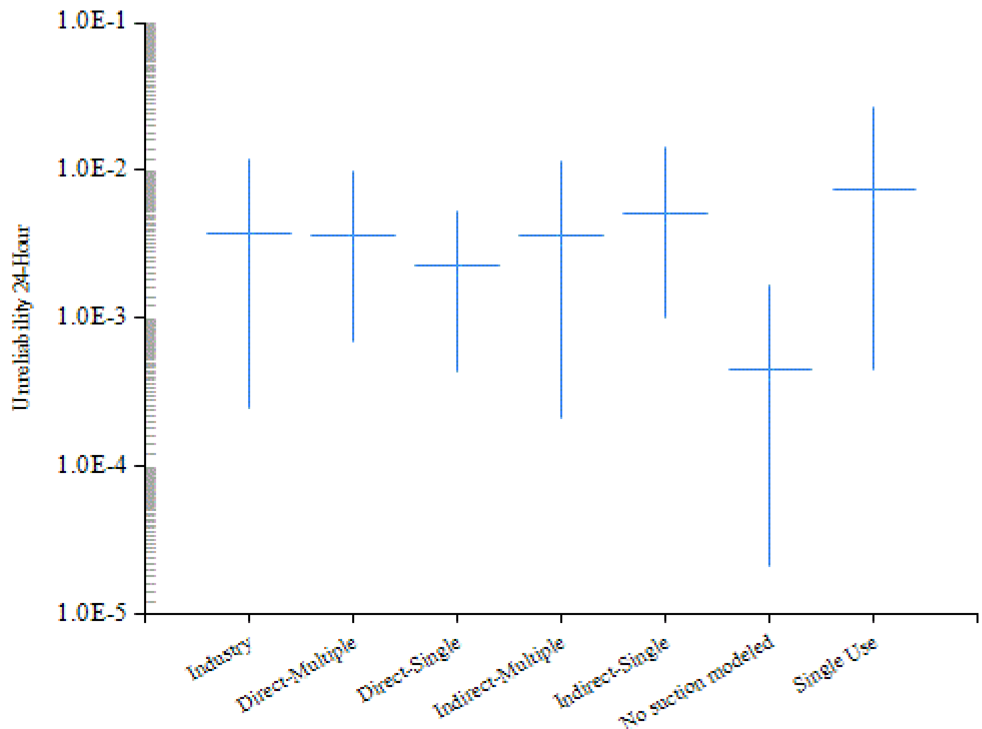

Figure 4. RHR SDC mode 24-hour mission unreliability for class and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly failure and demand or run-time data from 1998–2022 were obtained from IRIS for the RHR system. RHR train maintenance unavailability data for trending are from the same period as reported in the ROP program and IRIS. The component basic event uncertainty was calculated for the RHR system components using the trending methods described in Sections 1 and 2 of Reference [5]. These data were loaded into the RHR system fault tree in each SPAR model (see Table 3).

The trend charts show the results of varying component reliability data over time and updating generic, relatively flat prior distributions (or constrained noninformative distributions, refer to Section 2 of Reference [5]) using data for each year. In addition, the calculated industry-wide system reliability from this update (the "industry" values in Table 5) is shown as "SPAR/ICES" in the charts for comparison. Section 4 of Reference [5] provides a more detailed discussion of the trending methods. The regression method is indicated in the lower left-hand corner of the trend figures.

4.1 Low-Pressure Injection Mode

The components that were varied in the RHR LPI mode model are:

- RHR MDP start, run, and test and maintenance
- RHR heat exchanger heat transfer and test and maintenance
- Suction and injection valves fail to open or close.

Figure 5 shows the trend in the RHR LPI mode start-only unreliability. Table 7 shows the data points for Figure 5. **A statistically significant decreasing trend** was identified in the industry-wide estimates of **RHR LPI start-only unreliability** for the most recent 10-year period.

Figure 6 shows the trend in the 8-hour mission unreliability. Table 8 shows the data points for Figure 6. **A highly statistically significant decreasing trend** was identified in the industry-wide estimate of **RHR LPI 8-hour mission unreliability** for the most recent 10-year period.

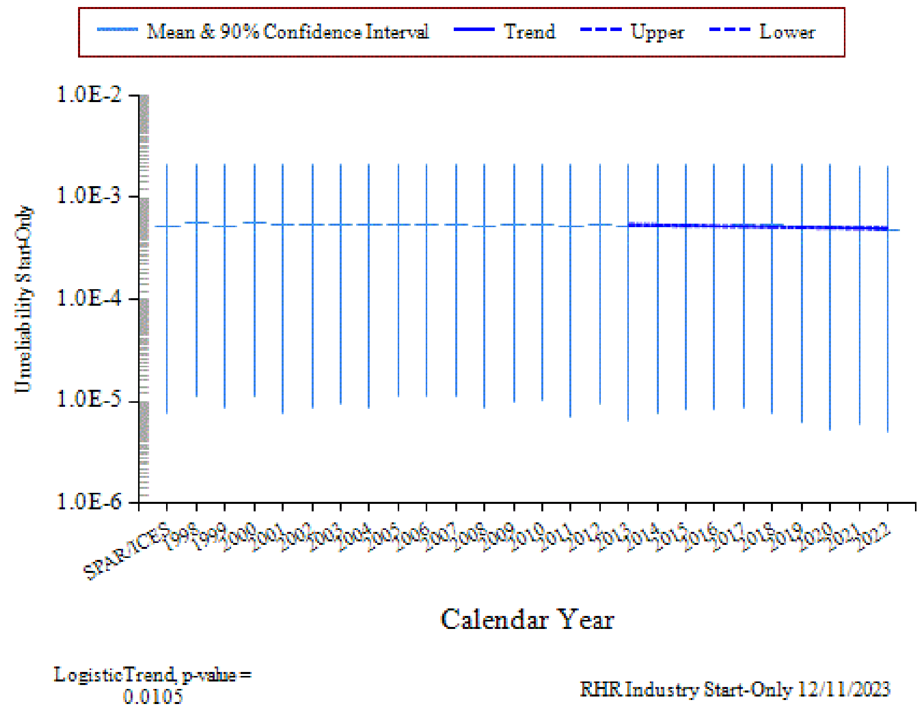

Figure 5. Trend of RHR system LPI mode start-only unreliability.

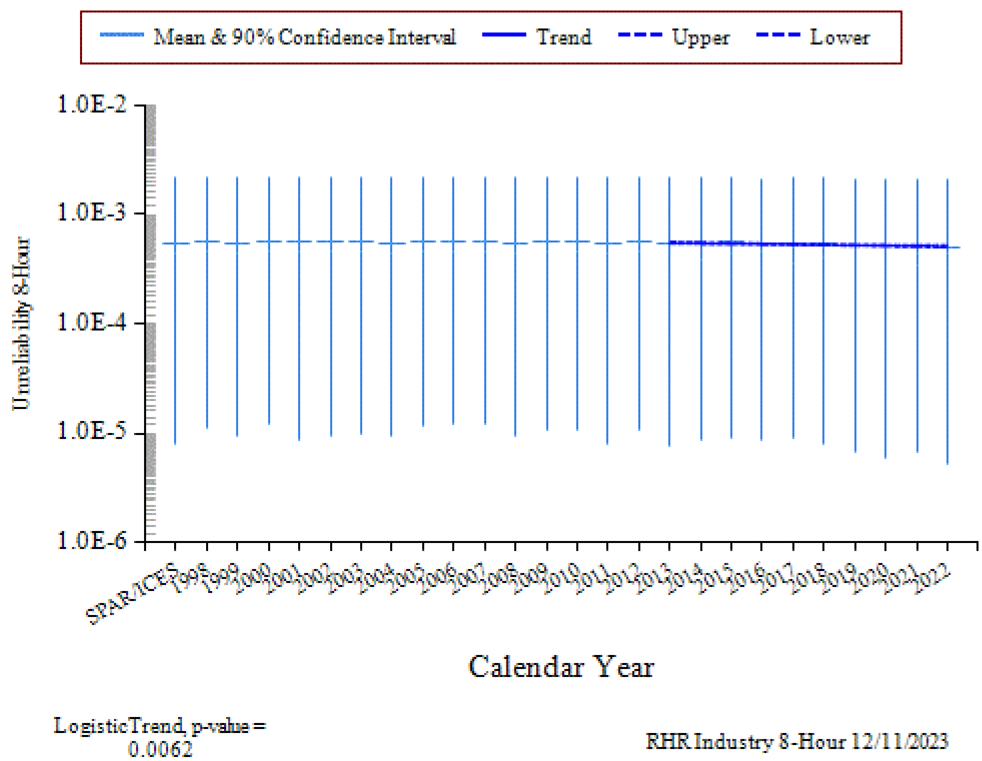

Figure 6. Trend of RHR system LPI mode 8-hour mission unreliability.

4.2 Shutdown Cooling Mode

The components varied in the RHR SDC mode model are:

- RHR motor-driven pump start, run, and test and maintenance
- RHR heat exchanger heat transfer and test and maintenance
- Suction and injection valves fail to open or close.

Figure 7 shows the trend in the RHR SDC mode start-only unreliability. Table 9 shows the data points for Figure 7. **A statistically significant decreasing trend was identified** in the industry-wide estimates of **RHR SDC start-only unreliability** for the most recent 10-year period.

Figure 8 shows the trend in the RHR SDC mode 24-hour mission unreliability. Table 10 shows the data points for Figure 8. **No statistically significant trend was identified** in the industry-wide estimates of **RHR SDC 24-hour mission unreliability** for the most recent 10-year period.

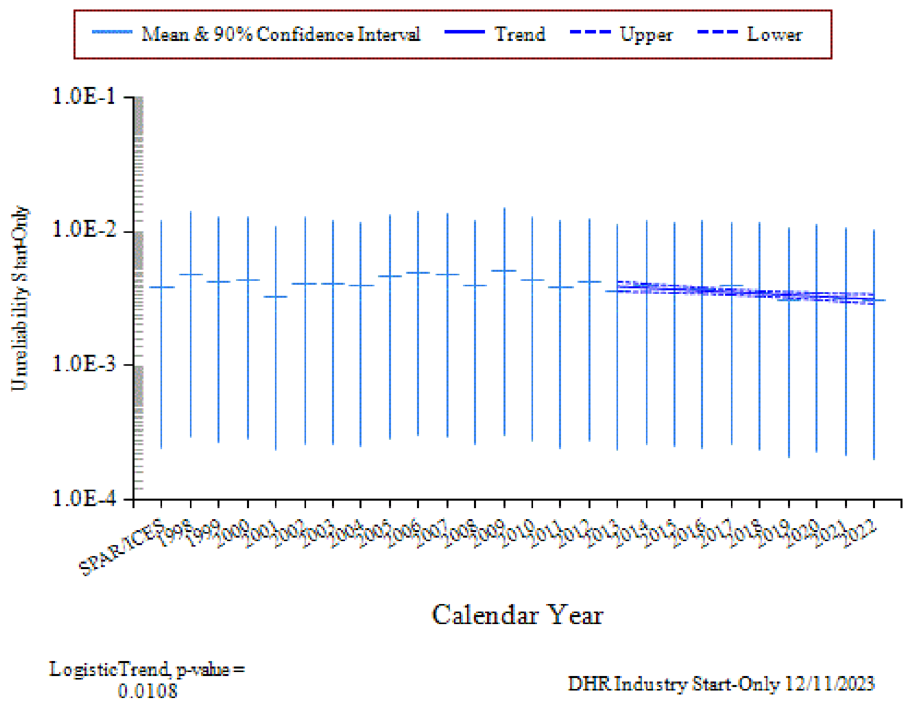

Figure 7. Trend of RHR system SDC mode start-only unreliability.

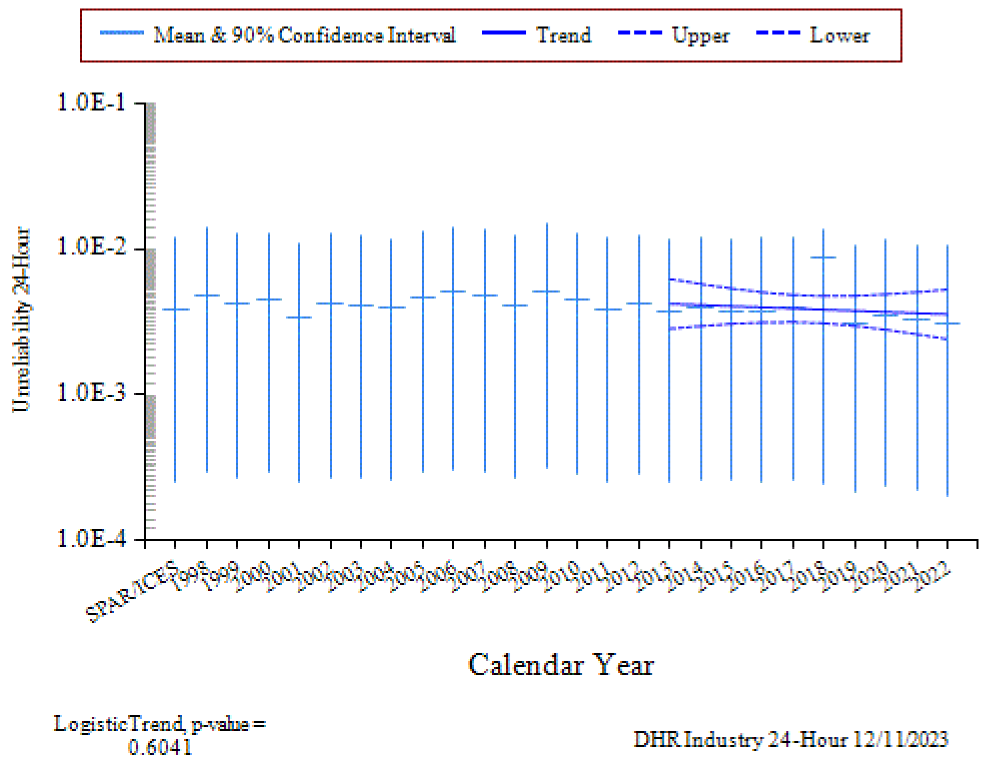

Figure 8. Trend of RHR system SDC mode 24-hour mission unreliability.

5. BASIC EVENT GROUP IMPORTANCES

The RHR basic event group Fussell-Vesely importances were calculated for each plant using the industry-wide data from the 2020 SPAR parameter update. These basic event group importances were then averaged across all plants to represent an industry-wide basic event group importance. Table 6 shows the SPAR model RHR importance groups and their descriptions.

Table 6. RHR model basic event importance group descriptions.

Group	Description
AC Power	The ac buses and circuit breakers that supply power to the RHR pumps
CCW	Closed cooling water system, including an intermediate cooling system that transfers the heat to the ultimate heat sink
Cooling	Cooling support components: service water or component cooling pumps, valves, and heat exchangers
DC Power	The batteries and battery chargers that supply power to the pump control circuitry
EPS	RHR dependency on the emergency power system
Heat Sink	The pumps, valves, strainers and other equipment associated with the ultimate heat sink
HTX	The first heat exchanger in the system to transfer heat from the RCS to the next level of heat removal
Injection	The flow path equipment to direct the SDC water to the RCS loop
Instrument Air	Instrument air support to the RHR model
Instrumentation	All basic events related to instrumentation and control
MDP	The motor-driven pumps that provide the recirculation flow from the RCS loop back to the RCS
Min Flow	The minimum flow valves around the RHR heat exchangers to control the cooldown rate
Pump Cooling	Cooling provided to the shutdown cooling pumps
Room Cooling	Cooling provided to the room of the RHR pumps
Special	Various events used in the models that are not directly associated with the RHR system
Suction	Valves in the suction section of the SDC system that are required to change position to redirect the suction to the RCS loop

5.1 Low-Pressure Injection Mode

The industry-wide RHR start-only and 8-hour mission basic event group importances for the LPI mode are shown in Figure 9. For both **start-only and 8-hour mission**, the leading contributor to RHR LPI unreliability is the **RHR MDP** group of basic events followed by the **Room Cooling, Injection, Suction, Heat Sink,** and **Special** groups.

For more discussion on the RHR MDPs and the RHR motor-operated and air-operated valves (MOVs and AOVs), see the component reliability studies at the NRC Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov).

The basic event group importances were also averaged across plants of the same RHR class to represent basic event group importances for different RHR classes. The RHR class-specific start-only and 8-hour mission basic event group importances for LPI mode are shown in Figure 10–Figure 18.

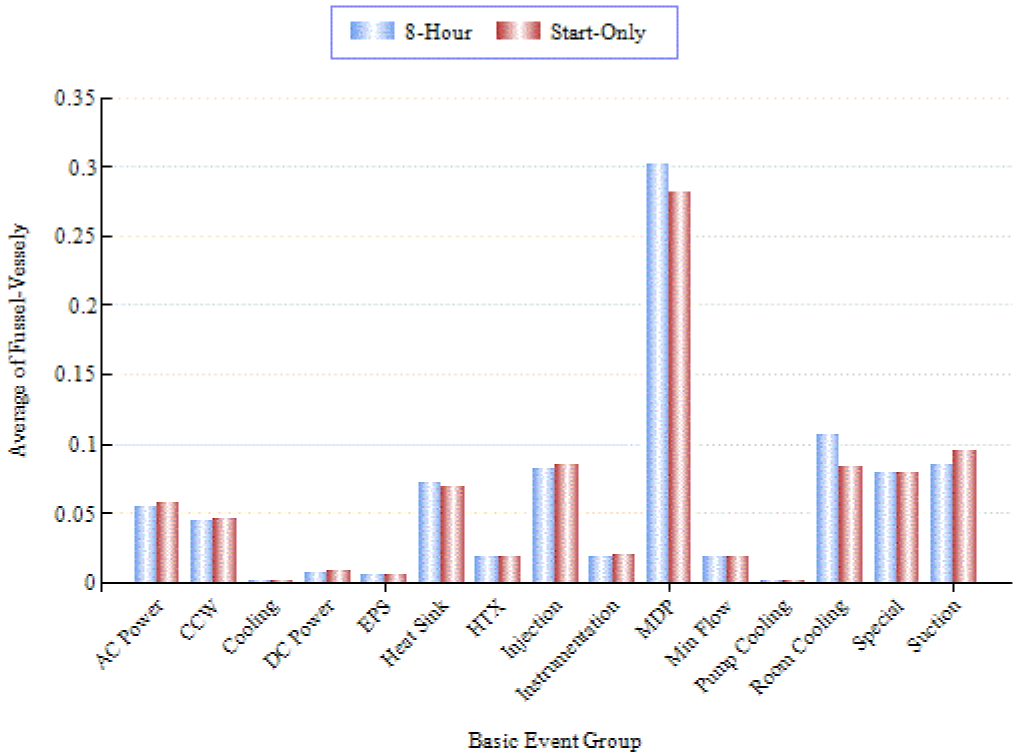

Figure 9. RHR LPI mode industry-wide basic event group importances.

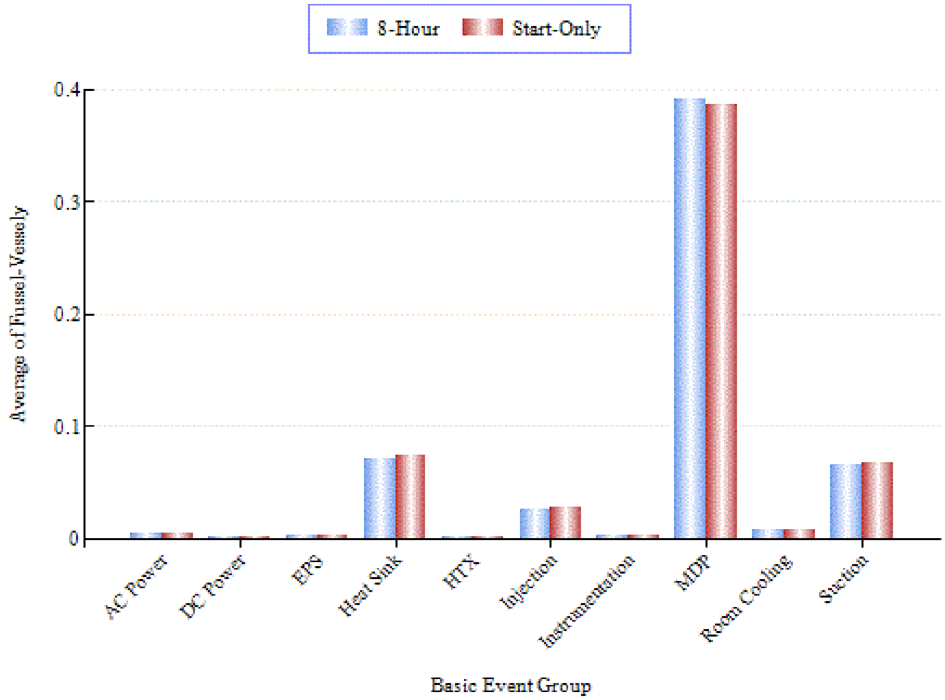

Figure 10. RHR LPI mode two pump BW basic event group importances.

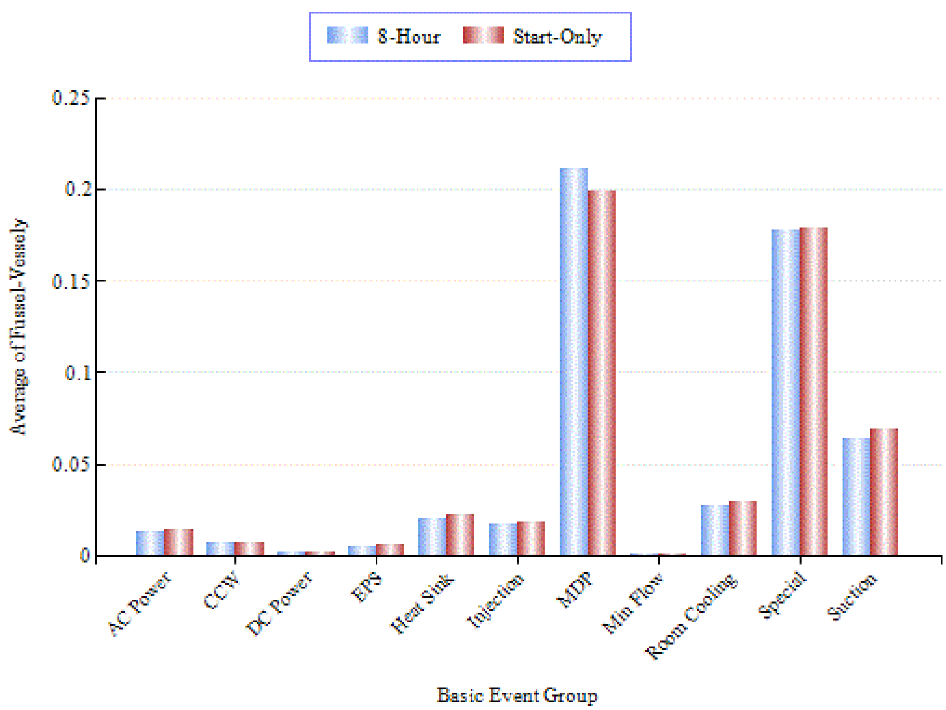

Figure 11. RHR LPI mode two pumps CE basic event group importances.

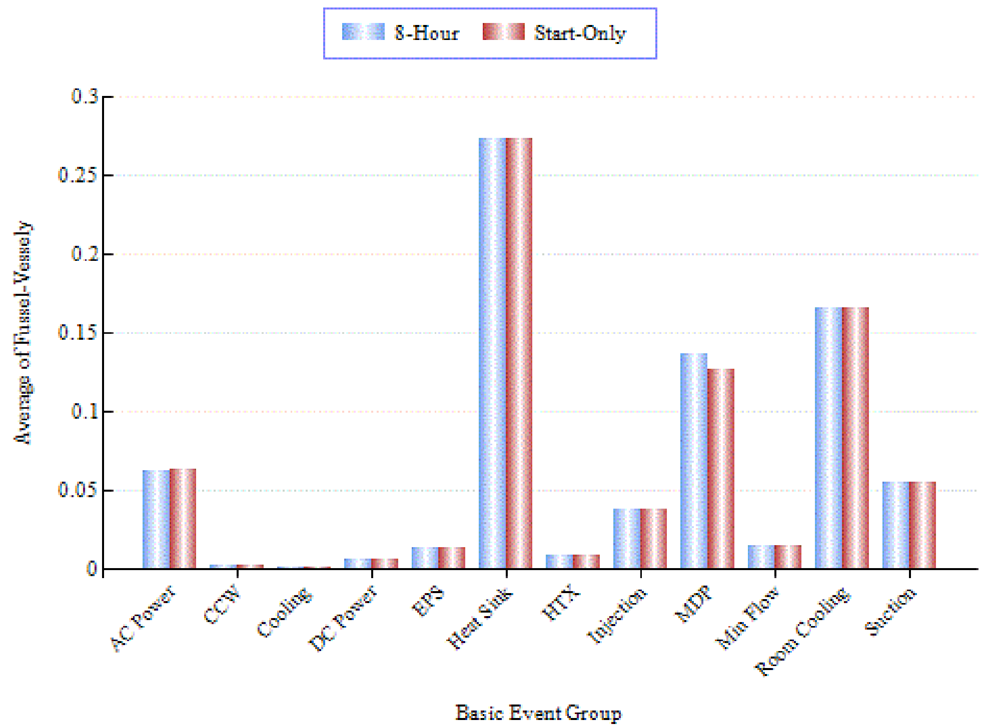

Figure 12. RHR LPI mode two pumps GE basic event group importances.

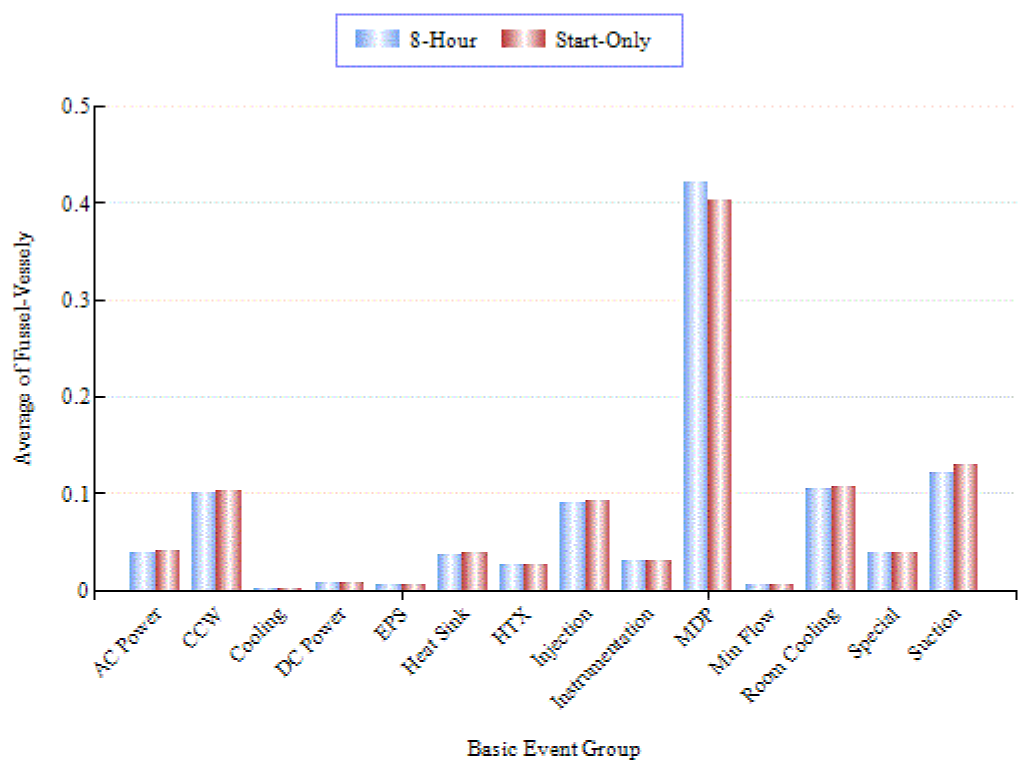

Figure 13. RHR LPI mode two pumps WE basic event group importances.

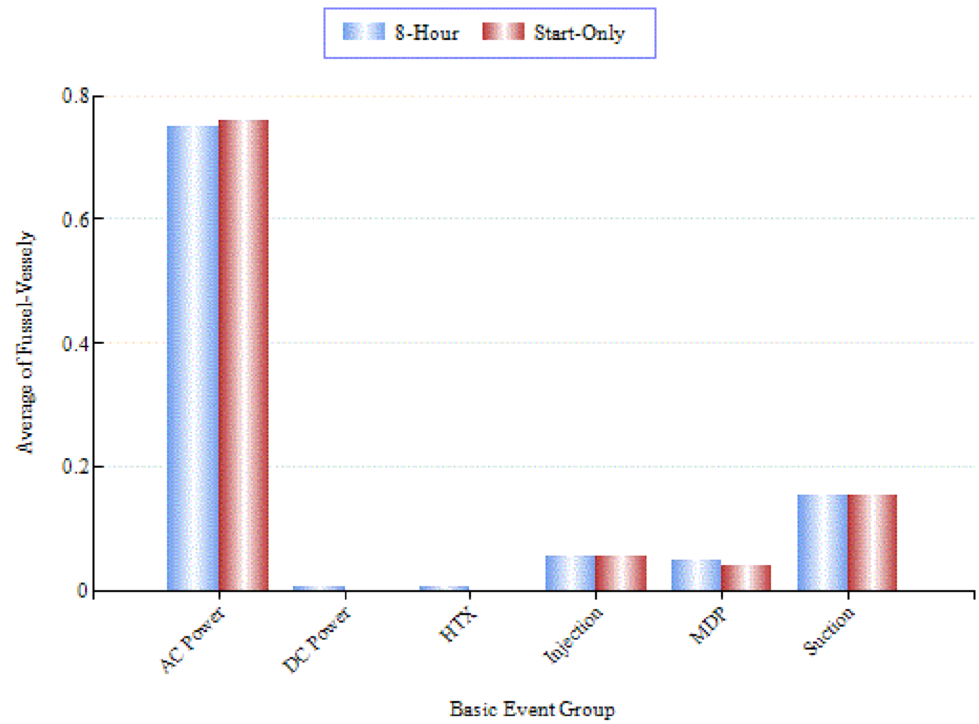

Figure 14. RHR LPI mode three pumps BW basic event group importances.

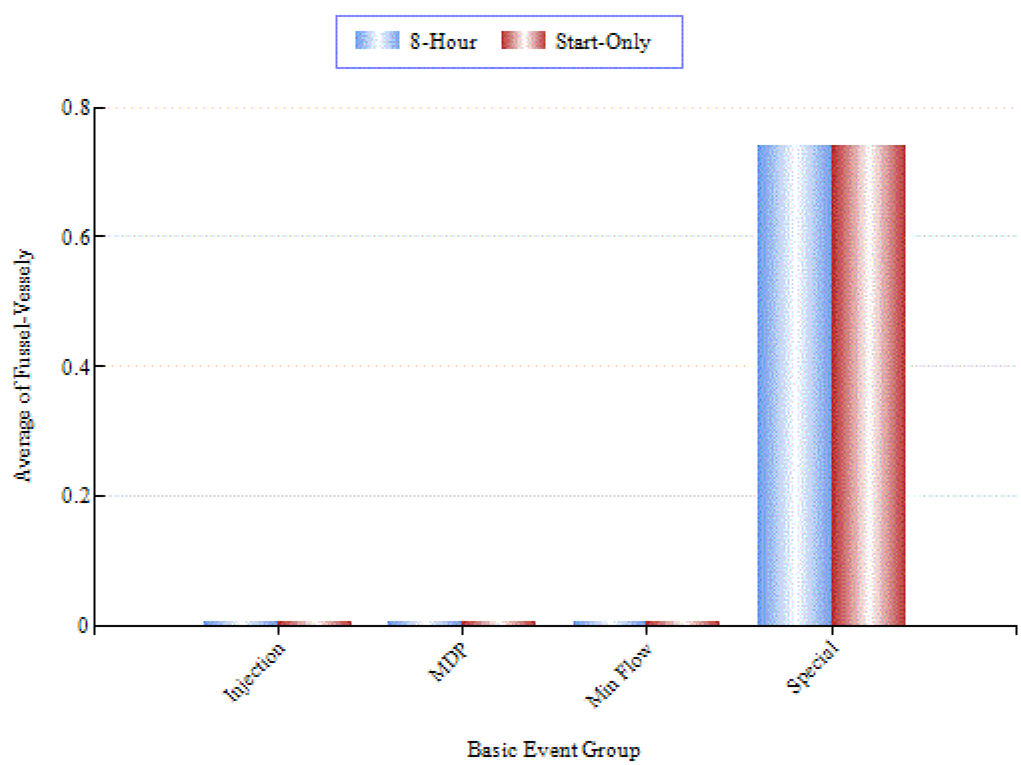

Figure 15. RHR LPI mode three pumps GE basic event group importances.

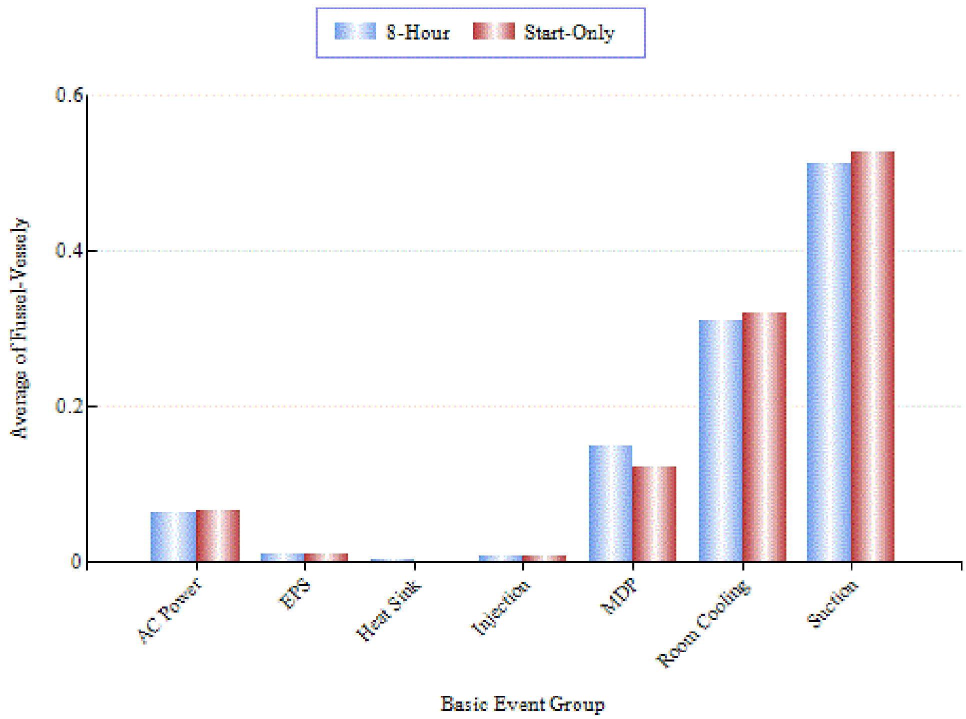

Figure 16. RHR LPI mode three pumps WE basic event group importances.

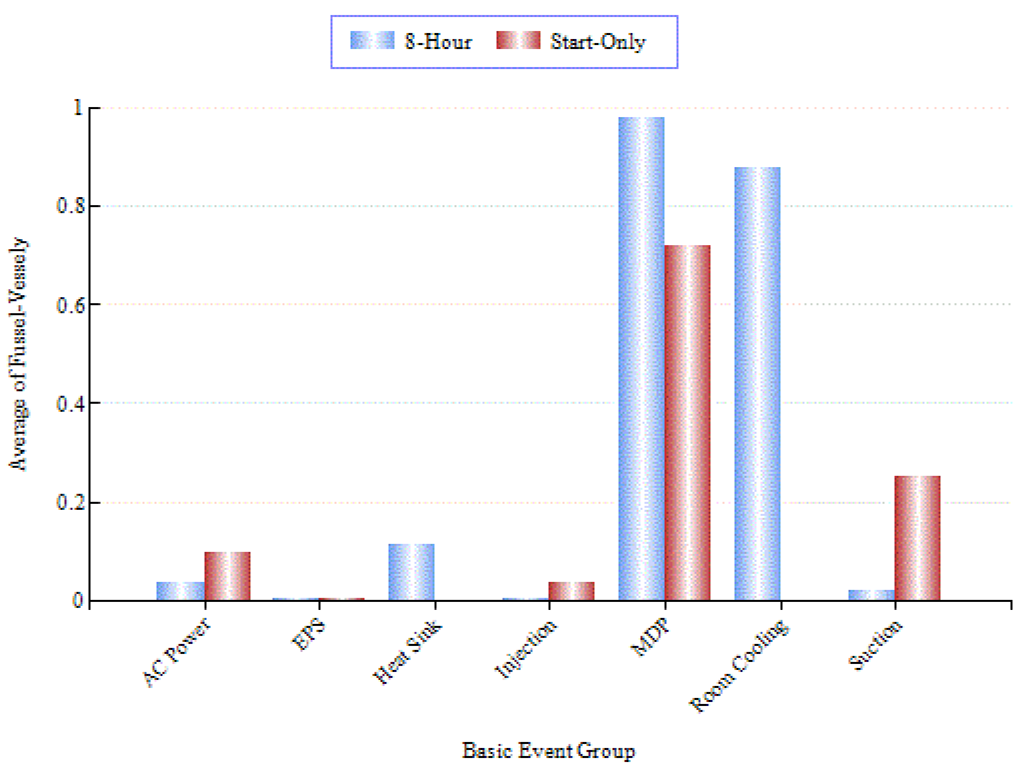

Figure 17. RHR LPI mode four pumps CE basic event group importances.

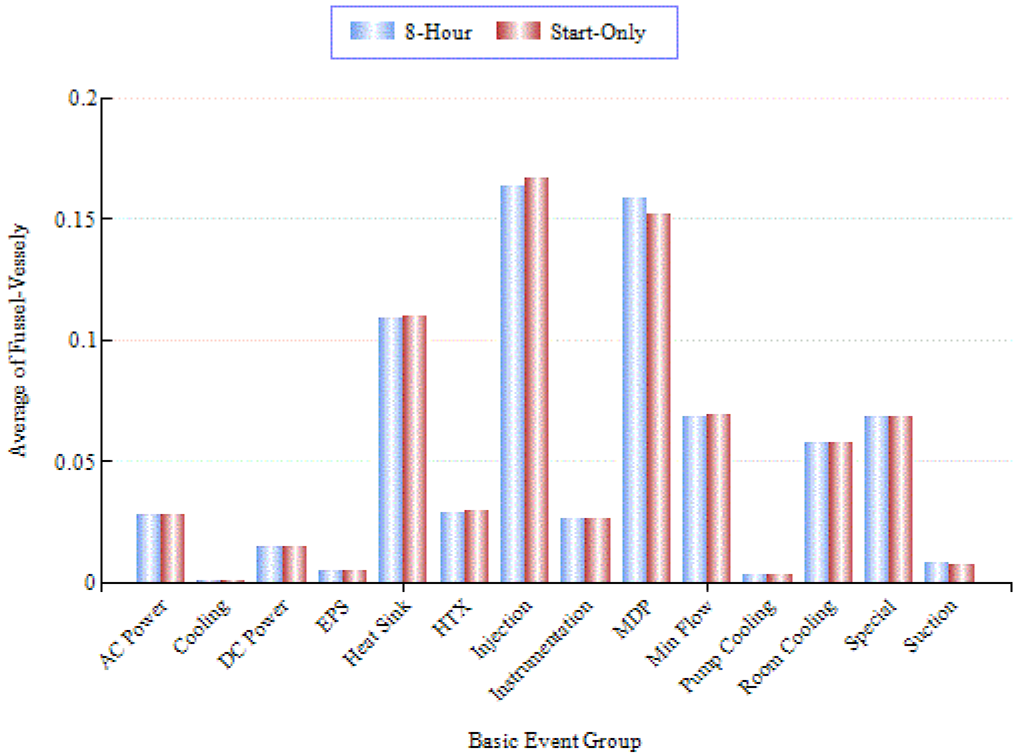

Figure 18. RHR LPI mode four pumps GE basic event group importances.

5.2 Shutdown Cooling Mode

The industry-wide RHR start-only and 24-hour mission basic event group importances for SDC mode are shown in Figure 19. For both **start-only and 24-hour mission**, the leading contributor to **RHR SDC unreliability** is the **Suction** group of basic events followed by the **Injection, RHR MDP, Heat Sink,** and **AC Power** groups.

For more discussion on the RHR MOVs and AOVs, see the MOV and AOV component reliability studies at the NRC Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov).

The basic event group importances were also averaged across plants of the same RHR class to represent basic event group importances for different RHR classes. The RHR class-specific start-only and 24-hour mission basic event group importances for the SDC mode are shown in Figure 20–Figure 26.

For those plants with a single suction source, the Suction group importance increases significantly. For those plants that have multiple suction sources, the importance of other groups such as AC Power, Injection, Heat Sink, and Pump increases as the Suction group importance decreases (see Figure 20 vs. Figure 21). The distinction between the heat sink types (direct versus indirect) is small due to the standby nature of most of the direct heat sink systems and the normal operating nature of the indirect heat sink systems.

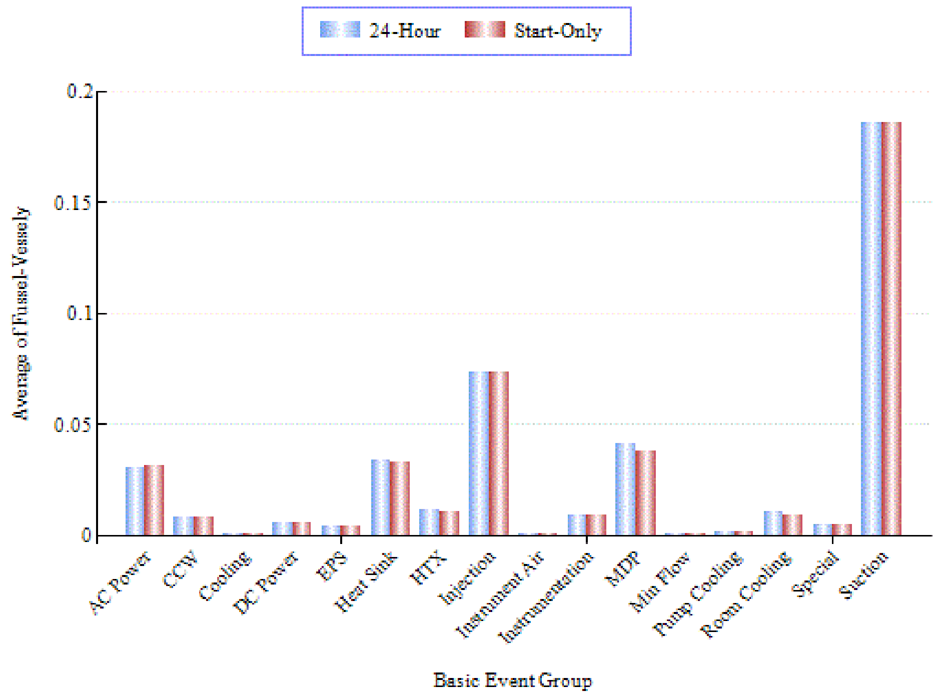

Figure 19. RHR SDC mode industry-wide basic event group importances.

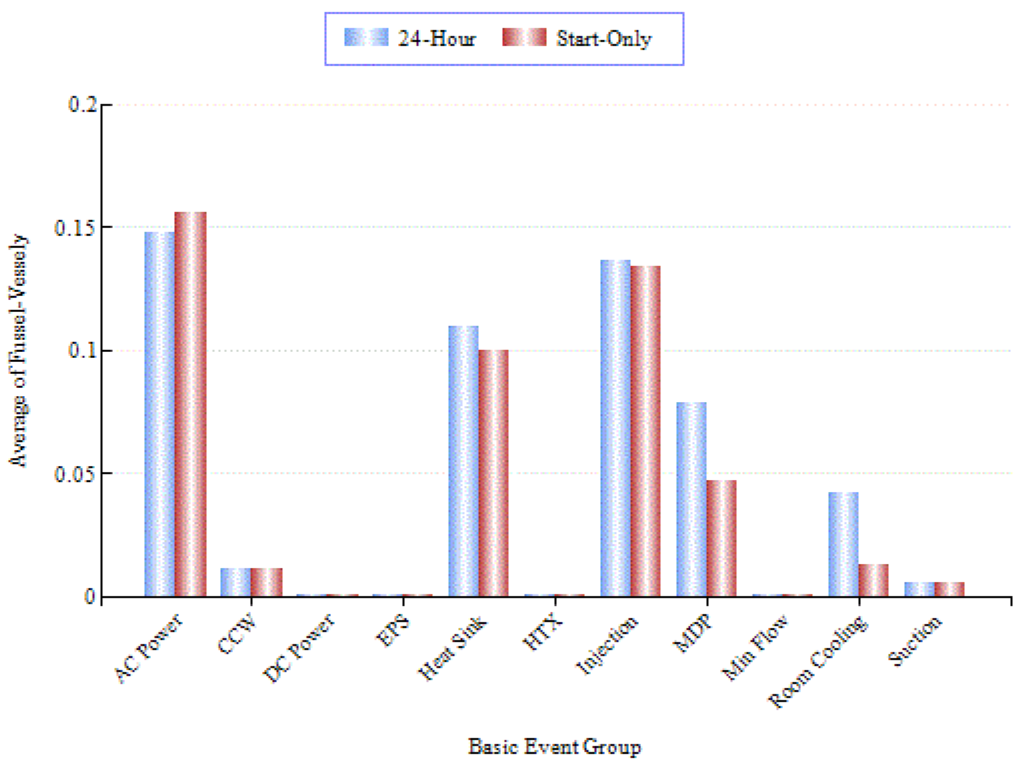

Figure 20. RHR SDC mode direct heat sink, multiple suction path basic event group importances.

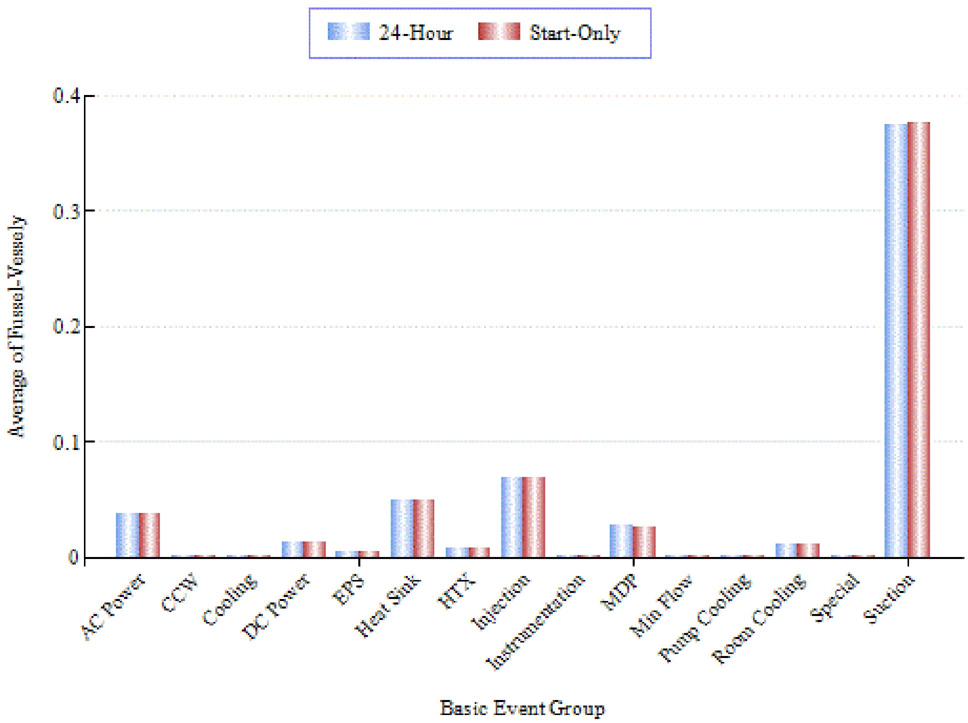

Figure 21. RHR SDC mode direct heat sink, single suction path basic event group importances.

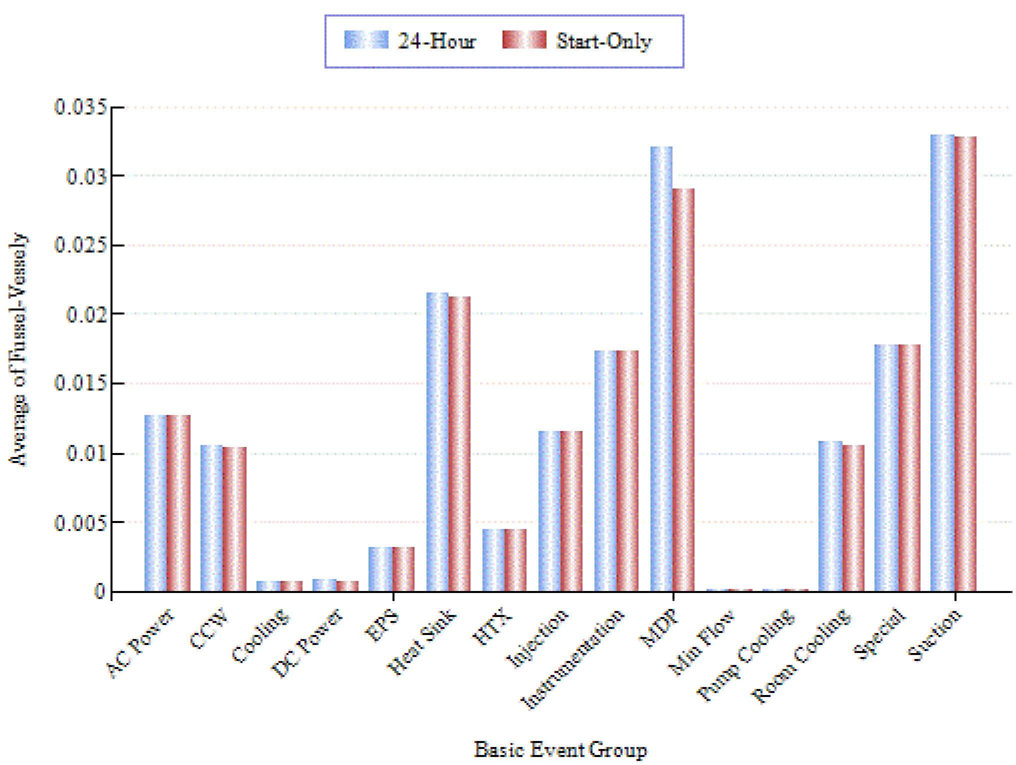

Figure 22. RHR SDC mode indirect heat sink, multiple suction paths basic event group importances.

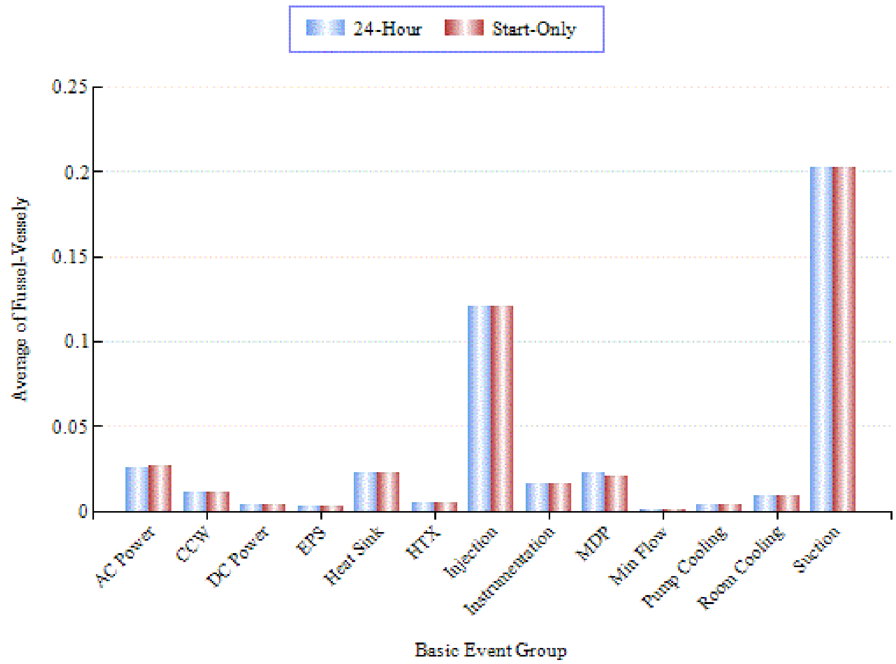

Figure 23. RHR SDC mode indirect heat sink, single suction path basic event group importances.

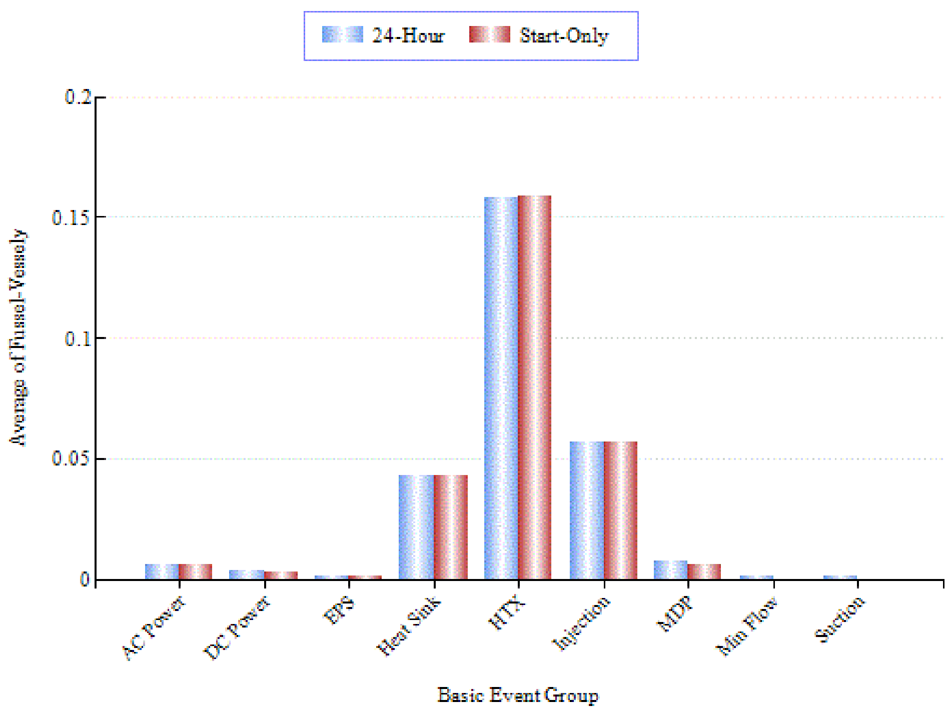

Figure 24. RHR SDC mode no suction modeled basic event group importances.

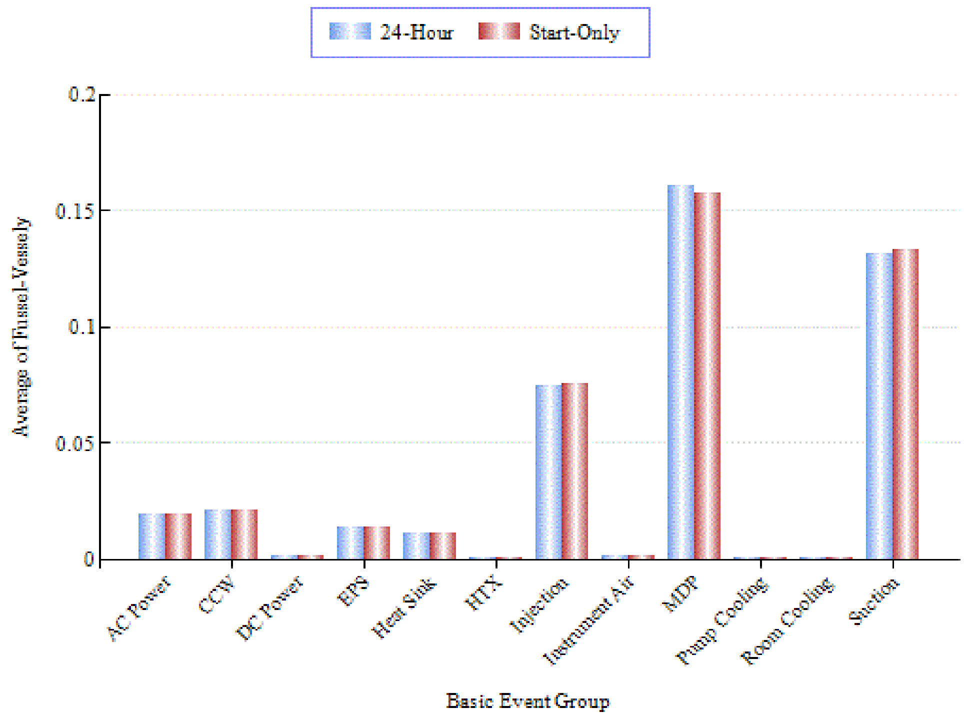

Figure 25. RHR SDC mode single use SDC system basic event group importances.

6. DATA TABLES

Table 7. Plot data for Figure 5, RHR LPI mode start-only unreliability trend.

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	7.58E-06	5.25E-04	2.08E-03
1998	--	--	--	1.10E-05	5.52E-04	2.11E-03
1999	--	--	--	8.54E-06	5.28E-04	2.08E-03
2000	--	--	--	1.10E-05	5.52E-04	2.12E-03
2001	--	--	--	7.79E-06	5.34E-04	2.11E-03
2002	--	--	--	8.72E-06	5.37E-04	2.08E-03
2003	--	--	--	9.24E-06	5.41E-04	2.09E-03
2004	--	--	--	8.78E-06	5.35E-04	2.10E-03
2005	--	--	--	1.10E-05	5.48E-04	2.10E-03
2006	--	--	--	1.12E-05	5.49E-04	2.11E-03
2007	--	--	--	1.12E-05	5.49E-04	2.10E-03
2008	--	--	--	8.59E-06	5.29E-04	2.06E-03
2009	--	--	--	1.00E-05	5.48E-04	2.11E-03
2010	--	--	--	1.02E-05	5.45E-04	2.10E-03
2011	--	--	--	7.13E-06	5.16E-04	2.05E-03
2012	--	--	--	9.38E-06	5.40E-04	2.09E-03
2013	5.21E-04	5.37E-04	5.53E-04	6.57E-06	5.21E-04	2.05E-03
2014	5.19E-04	5.32E-04	5.46E-04	7.57E-06	5.26E-04	2.07E-03
2015	5.17E-04	5.28E-04	5.39E-04	8.41E-06	5.40E-04	2.08E-03
2016	5.14E-04	5.23E-04	5.33E-04	8.27E-06	5.19E-04	2.05E-03
2017	5.10E-04	5.19E-04	5.27E-04	8.55E-06	5.30E-04	2.06E-03
2018	5.06E-04	5.14E-04	5.23E-04	7.58E-06	5.33E-04	2.07E-03
2019	5.01E-04	5.10E-04	5.19E-04	6.27E-06	5.14E-04	2.05E-03
2020	4.95E-04	5.06E-04	5.16E-04	5.33E-06	5.07E-04	2.04E-03
2021	4.89E-04	5.01E-04	5.14E-04	5.98E-06	4.98E-04	2.01E-03
2022	4.82E-04	4.97E-04	5.12E-04	4.93E-06	4.82E-04	2.00E-03

Table 8. Plot data for Figure 6, RHR LPI mode 8-hour mission unreliability trend.

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	8.09E-06	5.39E-04	2.16E-03
1998	--	--	--	1.14E-05	5.64E-04	2.18E-03
1999	--	--	--	9.30E-06	5.44E-04	2.16E-03
2000	--	--	--	1.21E-05	5.70E-04	2.21E-03
2001	--	--	--	8.67E-06	5.55E-04	2.19E-03
2002	--	--	--	9.48E-06	5.53E-04	2.17E-03
2003	--	--	--	1.00E-05	5.57E-04	2.19E-03
2004	--	--	--	9.28E-06	5.43E-04	2.14E-03
2005	--	--	--	1.16E-05	5.62E-04	2.18E-03
2006	--	--	--	1.21E-05	5.64E-04	2.19E-03
2007	--	--	--	1.19E-05	5.63E-04	2.18E-03
2008	--	--	--	9.33E-06	5.44E-04	2.14E-03
2009	--	--	--	1.08E-05	5.62E-04	2.20E-03
2010	--	--	--	1.08E-05	5.59E-04	2.19E-03
2011	--	--	--	7.83E-06	5.32E-04	2.13E-03
2012	--	--	--	1.09E-05	5.60E-04	2.19E-03
2013	5.37E-04	5.52E-04	5.66E-04	7.56E-06	5.37E-04	2.13E-03
2014	5.35E-04	5.47E-04	5.59E-04	8.50E-06	5.42E-04	2.16E-03
2015	5.32E-04	5.42E-04	5.53E-04	9.14E-06	5.54E-04	2.15E-03
2016	5.29E-04	5.38E-04	5.46E-04	8.73E-06	5.32E-04	2.12E-03
2017	5.26E-04	5.33E-04	5.41E-04	9.00E-06	5.42E-04	2.14E-03
2018	5.21E-04	5.29E-04	5.36E-04	8.09E-06	5.47E-04	2.15E-03
2019	5.16E-04	5.24E-04	5.33E-04	6.76E-06	5.26E-04	2.11E-03
2020	5.10E-04	5.20E-04	5.30E-04	5.92E-06	5.21E-04	2.11E-03
2021	5.04E-04	5.15E-04	5.27E-04	6.84E-06	5.13E-04	2.08E-03
2022	4.98E-04	5.11E-04	5.25E-04	5.23E-06	4.98E-04	2.06E-03

Table 9. Plot data for Figure 7, RHR SDC mode start-only unreliability trend.

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	2.45E-04	3.77E-03	1.18E-02
1998	--	--	--	2.93E-04	4.76E-03	1.41E-02
1999	--	--	--	2.65E-04	4.18E-03	1.28E-02
2000	--	--	--	2.84E-04	4.39E-03	1.27E-02
2001	--	--	--	2.38E-04	3.30E-03	1.09E-02
2002	--	--	--	2.63E-04	4.11E-03	1.27E-02
2003	--	--	--	2.63E-04	4.07E-03	1.21E-02
2004	--	--	--	2.55E-04	3.90E-03	1.17E-02
2005	--	--	--	2.90E-04	4.63E-03	1.31E-02
2006	--	--	--	3.04E-04	4.99E-03	1.39E-02
2007	--	--	--	2.96E-04	4.80E-03	1.36E-02
2008	--	--	--	2.61E-04	4.00E-03	1.21E-02
2009	--	--	--	3.04E-04	5.09E-03	1.47E-02
2010	--	--	--	2.78E-04	4.39E-03	1.27E-02
2011	--	--	--	2.43E-04	3.81E-03	1.20E-02
2012	--	--	--	2.73E-04	4.16E-03	1.21E-02
2013	3.59E-03	3.90E-03	4.23E-03	2.36E-04	3.62E-03	1.14E-02
2014	3.55E-03	3.80E-03	4.08E-03	2.56E-04	3.89E-03	1.19E-02
2015	3.50E-03	3.72E-03	3.94E-03	2.51E-04	3.67E-03	1.16E-02
2016	3.45E-03	3.63E-03	3.81E-03	2.44E-04	3.73E-03	1.18E-02
2017	3.39E-03	3.54E-03	3.71E-03	2.59E-04	3.99E-03	1.17E-02
2018	3.31E-03	3.46E-03	3.62E-03	2.36E-04	3.50E-03	1.16E-02
2019	3.21E-03	3.38E-03	3.55E-03	2.09E-04	3.05E-03	1.04E-02
2020	3.11E-03	3.30E-03	3.50E-03	2.31E-04	3.44E-03	1.13E-02
2021	3.00E-03	3.22E-03	3.46E-03	2.17E-04	3.20E-03	1.05E-02
2022	2.90E-03	3.15E-03	3.42E-03	1.99E-04	3.07E-03	1.03E-02

Table 10. Plot data for Figure 8, RHR SDC mode 24-hour mission unreliability trend.

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	2.52E-04	3.79E-03	1.17E-02
1998	--	--	--	2.95E-04	4.78E-03	1.41E-02
1999	--	--	--	2.72E-04	4.22E-03	1.28E-02
2000	--	--	--	2.93E-04	4.43E-03	1.27E-02
2001	--	--	--	2.50E-04	3.35E-03	1.10E-02
2002	--	--	--	2.72E-04	4.16E-03	1.27E-02
2003	--	--	--	2.72E-04	4.11E-03	1.22E-02
2004	--	--	--	2.56E-04	3.91E-03	1.17E-02
2005	--	--	--	2.94E-04	4.65E-03	1.30E-02
2006	--	--	--	3.09E-04	5.04E-03	1.39E-02
2007	--	--	--	2.98E-04	4.84E-03	1.36E-02
2008	--	--	--	2.68E-04	4.04E-03	1.22E-02
2009	--	--	--	3.10E-04	5.13E-03	1.48E-02
2010	--	--	--	2.84E-04	4.41E-03	1.27E-02
2011	--	--	--	2.52E-04	3.86E-03	1.21E-02
2012	--	--	--	2.87E-04	4.23E-03	1.23E-02
2013	2.83E-03	4.20E-03	6.21E-03	2.48E-04	3.68E-03	1.15E-02
2014	2.95E-03	4.12E-03	5.75E-03	2.61E-04	3.91E-03	1.19E-02
2015	3.06E-03	4.05E-03	5.35E-03	2.59E-04	3.71E-03	1.17E-02
2016	3.13E-03	3.97E-03	5.04E-03	2.49E-04	3.75E-03	1.18E-02
2017	3.15E-03	3.90E-03	4.83E-03	2.59E-04	4.01E-03	1.18E-02
2018	3.09E-03	3.83E-03	4.74E-03	2.42E-04	8.65E-03	1.34E-02
2019	2.96E-03	3.76E-03	4.77E-03	2.15E-04	3.08E-03	1.05E-02
2020	2.79E-03	3.69E-03	4.88E-03	2.36E-04	3.47E-03	1.14E-02
2021	2.59E-03	3.62E-03	5.05E-03	2.25E-04	3.23E-03	1.06E-02
2022	2.40E-03	3.55E-03	5.26E-03	2.03E-04	3.09E-03	1.04E-02

Table 11. Basic event reliability trending data.

Failure Mode	Component [a]	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOC	AOV	1998	4	916	2.01E-03	4.83	2.40E+03	Beta
FTOC	AOV	1999	3	1,088	1.49E-03	3.83	2.58E+03	Beta
FTOC	AOV	2000	1	824	7.92E-04	1.83	2.31E+03	Beta
FTOC	AOV	2001	0	942	3.42E-04	0.83	2.43E+03	Beta
FTOC	AOV	2002	3	1,010	1.53E-03	3.83	2.50E+03	Beta
FTOC	AOV	2003	1	993	7.37E-04	1.83	2.48E+03	Beta
FTOC	AOV	2004	0	893	3.49E-04	0.83	2.38E+03	Beta
FTOC	AOV	2005	1	763	8.13E-04	1.83	2.25E+03	Beta
FTOC	AOV	2006	2	711	1.29E-03	2.83	2.20E+03	Beta
FTOC	AOV	2007	2	727	1.28E-03	2.83	2.22E+03	Beta
FTOC	AOV	2008	1	722	8.28E-04	1.83	2.21E+03	Beta
FTOC	AOV	2009	4	760	2.15E-03	4.83	2.25E+03	Beta
FTOC	AOV	2010	1	713	8.31E-04	1.83	2.20E+03	Beta
FTOC	AOV	2011	2	734	1.27E-03	2.83	2.22E+03	Beta
FTOC	AOV	2012	0	716	3.77E-04	0.83	2.21E+03	Beta
FTOC	AOV	2013	1	726	8.27E-04	1.83	2.21E+03	Beta
FTOC	AOV	2014	1	705	8.34E-04	1.83	2.19E+03	Beta
FTOC	AOV	2015	1	743	8.20E-04	1.83	2.23E+03	Beta
FTOC	AOV	2016	1	738	8.22E-04	1.83	2.23E+03	Beta
FTOC	AOV	2017	0	751	3.71E-04	0.83	2.24E+03	Beta
FTOC	AOV	2018	2	753	1.26E-03	2.83	2.24E+03	Beta
FTOC	AOV	2019	0	752	3.71E-04	0.83	2.24E+03	Beta
FTOC	AOV	2020	2	752	1.26E-03	2.83	2.24E+03	Beta
FTOC	AOV	2021	0	756	3.70E-04	0.83	2.25E+03	Beta
FTOC	AOV	2022	0	759	3.70E-04	0.83	2.25E+03	Beta
FTOP	AOV	1998	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	1999	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2000	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2001	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2002	1	2,409,000	2.36E-07	2.26	9.58E+06	Gamma
FTOP	AOV	2003	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
FTOP	AOV	2004	0	2,409,000	1.32E-07	1.26	9.58E+06	Gamma
FTOP	AOV	2005	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2006	0	2,400,240	1.32E-07	1.26	9.57E+06	Gamma
FTOP	AOV	2007	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2008	1	2,391,480	2.36E-07	2.26	9.56E+06	Gamma
FTOP	AOV	2009	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2010	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2011	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma

Table 11. (continued).

Failure Mode	Component a	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	AOV	2012	2	2,391,480	3.41E-07	3.26	9.56E+06	Gamma
FTOP	AOV	2013	0	2,391,480	1.32E-07	1.26	9.56E+06	Gamma
FTOP	AOV	2014	1	2,391,480	2.36E-07	2.26	9.56E+06	Gamma
FTOP	AOV	2015	1	2,426,520	2.36E-07	2.26	9.60E+06	Gamma
FTOP	AOV	2016	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
FTOP	AOV	2017	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
FTOP	AOV	2018	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
FTOP	AOV	2019	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
FTOP	AOV	2020	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
FTOP	AOV	2021	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
FTOP	AOV	2022	0	2,426,520	1.31E-07	1.26	9.60E+06	Gamma
SO	AOV	1998	1	2,391,480	1.09E-07	1.86	1.71E+07	Gamma
SO	AOV	1999	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2000	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2001	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2002	0	2,409,000	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2003	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2004	0	2,409,000	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2005	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2006	0	2,400,240	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2007	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2008	2	2,391,480	1.67E-07	2.86	1.71E+07	Gamma
SO	AOV	2009	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2010	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2011	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2012	1	2,391,480	1.09E-07	1.86	1.71E+07	Gamma
SO	AOV	2013	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2014	0	2,391,480	5.03E-08	0.86	1.71E+07	Gamma
SO	AOV	2015	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2016	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2017	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2018	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2019	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2020	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2021	0	2,426,520	5.02E-08	0.86	1.71E+07	Gamma
SO	AOV	2022	1	2,426,520	1.09E-07	1.86	1.71E+07	Gamma
LOHT	HTX	1998	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	1999	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2000	2	3,360	3.71E-07	10.5	2.83E+07	Gamma

Table 11. (continued).

Failure Mode	Component [a]	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
LOHT	HTX	2001	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2002	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2003	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2004	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2005	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2006	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2007	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2008	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2009	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2010	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2011	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2012	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2013	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2014	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2015	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2016	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2017	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2018	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2019	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2020	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2021	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
LOHT	HTX	2022	0	3,360	3.00E-07	8.5	2.83E+07	Gamma
FTR>1H	MDP	1998	0	111,414	2.93E-06	0.51	1.74E+05	Gamma
FTR>1H	MDP	1999	1	72,648	1.11E-05	1.51	1.36E+05	Gamma
FTR>1H	MDP	2000	1	56,258	1.27E-05	1.51	1.19E+05	Gamma
FTR>1H	MDP	2001	2	63,163	1.99E-05	2.51	1.26E+05	Gamma
FTR>1H	MDP	2002	2	51,207	2.20E-05	2.51	1.14E+05	Gamma
FTR>1H	MDP	2003	2	57,718	2.08E-05	2.51	1.21E+05	Gamma
FTR>1H	MDP	2004	0	45,533	4.71E-06	0.51	1.08E+05	Gamma
FTR>1H	MDP	2005	1	54,026	1.29E-05	1.51	1.17E+05	Gamma
FTR>1H	MDP	2006	2	51,555	2.19E-05	2.51	1.14E+05	Gamma
FTR>1H	MDP	2007	1	49,847	1.34E-05	1.51	1.13E+05	Gamma
FTR>1H	MDP	2008	2	54,050	2.15E-05	2.51	1.17E+05	Gamma
FTR>1H	MDP	2009	1	51,956	1.32E-05	1.51	1.15E+05	Gamma
FTR>1H	MDP	2010	1	51,017	1.33E-05	1.51	1.14E+05	Gamma
FTR>1H	MDP	2011	2	56,469	2.10E-05	2.51	1.19E+05	Gamma
FTR>1H	MDP	2012	3	59,850	2.86E-05	3.51	1.23E+05	Gamma
FTR>1H	MDP	2013	3	56,041	2.95E-05	3.51	1.19E+05	Gamma
FTR>1H	MDP	2014	0	52,903	4.41E-06	0.51	1.16E+05	Gamma

Table 11. (continued).

Failure Mode	Component [a]	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR>1H	MDP	2015	2	53,206	2.16E-05	2.51	1.16E+05	Gamma
FTR>1H	MDP	2016	1	57,468	1.26E-05	1.51	1.20E+05	Gamma
FTR>1H	MDP	2017	0	55,854	4.30E-06	0.51	1.19E+05	Gamma
FTR>1H	MDP	2018	1	55,817	1.27E-05	1.51	1.19E+05	Gamma
FTR>1H	MDP	2019	1	51,403	1.32E-05	1.51	1.14E+05	Gamma
FTR>1H	MDP	2020	1	53,194	1.30E-05	1.51	1.16E+05	Gamma
FTR>1H	MDP	2021	1	51,093	1.33E-05	1.51	1.14E+05	Gamma
FTR>1H	MDP	2022	0	56,002	4.30E-06	0.51	1.19E+05	Gamma
FTR<1H	MDP	1998	0	4,624	5.28E-05	0.58	1.10E+04	Gamma
FTR<1H	MDP	1999	1	4,811	1.42E-04	1.58	1.12E+04	Gamma
FTR<1H	MDP	2000	2	4,530	2.37E-04	2.58	1.09E+04	Gamma
FTR<1H	MDP	2001	1	4,602	1.44E-04	1.58	1.09E+04	Gamma
FTR<1H	MDP	2002	0	4,881	5.16E-05	0.58	1.12E+04	Gamma
FTR<1H	MDP	2003	0	4,936	5.13E-05	0.58	1.13E+04	Gamma
FTR<1H	MDP	2004	0	5,029	5.09E-05	0.58	1.14E+04	Gamma
FTR<1H	MDP	2005	0	5,377	4.94E-05	0.58	1.17E+04	Gamma
FTR<1H	MDP	2006	0	5,111	5.06E-05	0.58	1.15E+04	Gamma
FTR<1H	MDP	2007	0	5,235	5.00E-05	0.58	1.16E+04	Gamma
FTR<1H	MDP	2008	0	5,301	4.97E-05	0.58	1.16E+04	Gamma
FTR<1H	MDP	2009	0	5,225	5.01E-05	0.58	1.16E+04	Gamma
FTR<1H	MDP	2010	0	5,198	5.02E-05	0.58	1.15E+04	Gamma
FTR<1H	MDP	2011	0	5,153	5.04E-05	0.58	1.15E+04	Gamma
FTR<1H	MDP	2012	2	5,211	2.23E-04	2.58	1.16E+04	Gamma
FTR<1H	MDP	2013	0	5,221	5.01E-05	0.58	1.16E+04	Gamma
FTR<1H	MDP	2014	2	5,059	2.26E-04	2.58	1.14E+04	Gamma
FTR<1H	MDP	2015	0	5,039	5.09E-05	0.58	1.14E+04	Gamma
FTR<1H	MDP	2016	0	5,084	5.07E-05	0.58	1.14E+04	Gamma
FTR<1H	MDP	2017	0	4,913	5.15E-05	0.58	1.13E+04	Gamma
FTR<1H	MDP	2018	0	4,810	5.19E-05	0.58	1.11E+04	Gamma
FTR<1H	MDP	2019	0	4,709	5.24E-05	0.58	1.10E+04	Gamma
FTR<1H	MDP	2020	0	4,702	5.24E-05	0.58	1.10E+04	Gamma
FTR<1H	MDP	2021	1	4,757	1.42E-04	1.58	1.11E+04	Gamma
FTR<1H	MDP	2022	0	4,810	5.19E-05	0.58	1.12E+04	Gamma
FTS	MDP	1998	5	4,624	8.68E-04	7.07	8.14E+03	Beta
FTS	MDP	1999	2	4,811	4.88E-04	4.07	8.33E+03	Beta
FTS	MDP	2000	6	4,530	1.00E-03	8.07	8.04E+03	Beta
FTS	MDP	2001	7	4,602	1.12E-03	9.07	8.11E+03	Beta
FTS	MDP	2002	3	4,881	6.03E-04	5.07	8.40E+03	Beta
FTS	MDP	2003	4	4,936	7.18E-04	6.07	8.45E+03	Beta

Table 11. (continued).

Failure Mode	Component [a]	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTS	MDP	2004	4	5,029	7.10E-04	6.07	8.54E+03	Beta
FTS	MDP	2005	5	5,377	7.95E-04	7.07	8.89E+03	Beta
FTS	MDP	2006	4	5,111	7.03E-04	6.07	8.63E+03	Beta
FTS	MDP	2007	5	5,235	8.07E-04	7.07	8.75E+03	Beta
FTS	MDP	2008	3	5,301	5.75E-04	5.07	8.82E+03	Beta
FTS	MDP	2009	1	5,225	3.51E-04	3.07	8.74E+03	Beta
FTS	MDP	2010	4	5,198	6.96E-04	6.07	8.71E+03	Beta
FTS	MDP	2011	1	5,153	3.54E-04	3.07	8.67E+03	Beta
FTS	MDP	2012	3	5,211	5.81E-04	5.07	8.73E+03	Beta
FTS	MDP	2013	1	5,221	3.51E-04	3.07	8.74E+03	Beta
FTS	MDP	2014	1	5,059	3.58E-04	3.07	8.58E+03	Beta
FTS	MDP	2015	6	5,039	9.43E-04	8.07	8.55E+03	Beta
FTS	MDP	2016	4	5,084	7.05E-04	6.07	8.60E+03	Beta
FTS	MDP	2017	3	4,913	6.01E-04	5.07	8.43E+03	Beta
FTS	MDP	2018	6	4,810	9.69E-04	8.07	8.32E+03	Beta
FTS	MDP	2019	5	4,709	8.59E-04	7.07	8.22E+03	Beta
FTS	MDP	2020	0	4,702	2.52E-04	2.07	8.22E+03	Beta
FTS	MDP	2021	2	4,757	4.92E-04	4.07	8.27E+03	Beta
FTS	MDP	2022	0	4,810	2.48E-04	2.07	8.33E+03	Beta
FTOC	MOV	1998	15	12,533	1.07E-03	17.43	1.63E+04	Beta
FTOC	MOV	1999	12	14,395	7.93E-04	14.43	1.82E+04	Beta
FTOC	MOV	2000	14	13,070	9.74E-04	16.43	1.69E+04	Beta
FTOC	MOV	2001	4	14,636	3.49E-04	6.43	1.84E+04	Beta
FTOC	MOV	2002	10	13,467	7.20E-04	12.43	1.73E+04	Beta
FTOC	MOV	2003	11	13,259	7.87E-04	13.43	1.70E+04	Beta
FTOC	MOV	2004	10	12,594	7.58E-04	12.43	1.64E+04	Beta
FTOC	MOV	2005	15	11,520	1.14E-03	17.43	1.53E+04	Beta
FTOC	MOV	2006	16	10,067	1.33E-03	18.43	1.39E+04	Beta
FTOC	MOV	2007	14	9,867	1.20E-03	16.43	1.37E+04	Beta
FTOC	MOV	2008	8	9,958	7.58E-04	10.43	1.37E+04	Beta
FTOC	MOV	2009	15	9,991	1.26E-03	17.43	1.38E+04	Beta
FTOC	MOV	2010	11	9,988	9.74E-04	13.43	1.38E+04	Beta
FTOC	MOV	2011	6	10,129	6.05E-04	8.43	1.39E+04	Beta
FTOC	MOV	2012	10	10,075	8.96E-04	12.43	1.39E+04	Beta
FTOC	MOV	2013	5	10,029	5.37E-04	7.43	1.38E+04	Beta
FTOC	MOV	2014	7	10,165	6.75E-04	9.43	1.40E+04	Beta
FTOC	MOV	2015	5	10,055	5.36E-04	7.43	1.39E+04	Beta
FTOC	MOV	2016	6	10,041	6.09E-04	8.43	1.38E+04	Beta
FTOC	MOV	2017	9	10,098	8.22E-04	11.43	1.39E+04	Beta

Table 11. (continued).

Failure Mode	Component a	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOC	MOV	2018	3	10,123	3.90E-04	5.43	1.39E+04	Beta
FTOC	MOV	2019	1	10,084	2.47E-04	3.43	1.39E+04	Beta
FTOC	MOV	2020	3	10,108	3.90E-04	5.43	1.39E+04	Beta
FTOC	MOV	2021	3	10,092	3.91E-04	5.43	1.39E+04	Beta
FTOC	MOV	2022	2	10,096	3.19E-04	4.43	1.39E+04	Beta
FTOP	MOV	1998	1	16,039,560	4.61E-08	1.8	3.90E+07	Gamma
FTOP	MOV	1999	8	16,179,720	2.25E-07	8.8	3.92E+07	Gamma
FTOP	MOV	2000	1	16,179,720	4.59E-08	1.8	3.92E+07	Gamma
FTOP	MOV	2001	2	16,179,720	7.14E-08	2.8	3.92E+07	Gamma
FTOP	MOV	2002	0	16,188,480	2.04E-08	0.8	3.92E+07	Gamma
FTOP	MOV	2003	2	16,206,000	7.14E-08	2.8	3.92E+07	Gamma
FTOP	MOV	2004	0	16,179,720	2.04E-08	0.8	3.92E+07	Gamma
FTOP	MOV	2005	0	16,188,480	2.04E-08	0.8	3.92E+07	Gamma
FTOP	MOV	2006	1	16,188,480	4.59E-08	1.8	3.92E+07	Gamma
FTOP	MOV	2007	1	16,179,720	4.59E-08	1.8	3.92E+07	Gamma
FTOP	MOV	2008	0	16,179,720	2.04E-08	0.8	3.92E+07	Gamma
FTOP	MOV	2009	1	16,179,720	4.59E-08	1.8	3.92E+07	Gamma
FTOP	MOV	2010	0	16,249,800	2.03E-08	0.8	3.92E+07	Gamma
FTOP	MOV	2011	0	16,460,040	2.02E-08	0.8	3.95E+07	Gamma
FTOP	MOV	2012	1	16,276,080	4.58E-08	1.8	3.93E+07	Gamma
FTOP	MOV	2013	2	16,258,560	7.13E-08	2.8	3.93E+07	Gamma
FTOP	MOV	2014	0	16,293,600	2.03E-08	0.8	3.93E+07	Gamma
FTOP	MOV	2015	0	16,451,280	2.02E-08	0.8	3.95E+07	Gamma
FTOP	MOV	2016	0	16,451,280	2.02E-08	0.8	3.95E+07	Gamma
FTOP	MOV	2017	0	16,363,680	2.03E-08	0.8	3.94E+07	Gamma
FTOP	MOV	2018	0	16,591,440	2.02E-08	0.8	3.96E+07	Gamma
FTOP	MOV	2019	2	16,416,240	7.10E-08	2.8	3.94E+07	Gamma
FTOP	MOV	2020	0	16,425,000	2.02E-08	0.8	3.94E+07	Gamma
FTOP	MOV	2021	0	16,389,960	2.03E-08	0.8	3.94E+07	Gamma
FTOP	MOV	2022	0	16,389,960	2.03E-08	0.8	3.94E+07	Gamma
SO	MOV	1998	2	16,039,560	2.64E-08	43.5	1.65E+09	Gamma
SO	MOV	1999	0	16,179,720	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2000	2	16,179,720	2.64E-08	43.5	1.65E+09	Gamma
SO	MOV	2001	0	16,179,720	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2002	0	16,188,480	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2003	1	16,206,000	2.58E-08	42.5	1.65E+09	Gamma
SO	MOV	2004	0	16,179,720	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2005	0	16,188,480	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2006	0	16,188,480	2.52E-08	41.5	1.65E+09	Gamma

Table 11. (continued).

Failure Mode	Component [a]	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	MOV	2007	1	16,179,720	2.58E-08	42.5	1.65E+09	Gamma
SO	MOV	2008	0	16,179,720	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2009	0	16,179,720	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2010	0	16,249,800	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2011	0	16,460,040	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2012	0	16,276,080	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2013	1	16,258,560	2.58E-08	42.5	1.65E+09	Gamma
SO	MOV	2014	1	16,293,600	2.58E-08	42.5	1.65E+09	Gamma
SO	MOV	2015	2	16,451,280	2.64E-08	43.5	1.65E+09	Gamma
SO	MOV	2016	0	16,451,280	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2017	0	16,363,680	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2018	0	16,591,440	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2019	0	16,416,240	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2020	0	16,425,000	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2021	0	16,389,960	2.52E-08	41.5	1.65E+09	Gamma
SO	MOV	2022	0	16,389,960	2.52E-08	41.5	1.65E+09	Gamma

[a] AOV = air-operated valve
HTX = heat exchanger
LOHT = loss of heat transfer
MDP = motor-driven pump
MOV = motor-operated valve.

Table 12. Basic event unavailability (UA) trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	HDR	2002	65.50999	99,780	6.55E-04	0.58	8.83E+02	Beta
UA	HDR	2003	74.87	116,710	4.49E-04	0.44	9.73E+02	Beta
UA	HDR	2004	89.83	130,034	5.94E-04	0.28	4.73E+02	Beta
UA	HDR	2005	58.15	133,104	3.69E-04	0.68	1.83E+03	Beta
UA	HDR	2006	71.01	128,734	5.05E-04	0.26	5.16E+02	Beta
UA	HDR	2007	76.46	129,191	4.99E-04	0.36	7.19E+02	Beta
UA	HDR	2008	126.52	134,841	8.17E-04	0.23	2.81E+02	Beta
UA	HDR	2009	39.06	126,568	2.82E-04	0.28	1.01E+03	Beta
UA	HDR	2010	41.96	117,219	2.90E-04	0.3	1.02E+03	Beta
UA	HDR	2011	125.89	124,993	8.09E-04	0.28	3.49E+02	Beta
UA	HDR	2012	110.39	113,692	1.05E-03	0.17	1.60E+02	Beta
UA	HDR	2013	199.94	121,526	1.40E-03	0.19	1.33E+02	Beta
UA	HDR	2014	128.12	121,838	1.15E-03	0.17	1.51E+02	Beta
UA	HDR	2015	63.4	117,481	5.03E-04	0.45	8.99E+02	Beta
UA	HDR	2016	143.32	121,760	1.14E-03	0.21	1.85E+02	Beta
UA	HDR	2017	114.88	119,345	9.09E-04	0.38	4.22E+02	Beta
UA	HDR	2018	18.49	115,317	1.09E-04	0.34	3.13E+03	Beta
UA	HDR	2019	22.28	125,420	1.32E-04	0.35	2.64E+03	Beta
UA	HDR	2020	44.42	101,979	4.71E-04	0.2	4.26E+02	Beta
UA	HDR	2021	100.92	82,687	9.76E-04	0.17	1.70E+02	Beta
UA	HDR	2022	76.51	60,846	1.18E-03	0.2	1.68E+02	Beta
UA	HTX	2002	81.17	67,910	1.17E-03	0.81	6.91E+02	Beta
UA	HTX	2003	76.37	65,155	1.15E-03	1.83	1.59E+03	Beta
UA	HTX	2004	92.61	64,551	1.35E-03	0.91	6.71E+02	Beta
UA	HTX	2005	131.19	66,989	1.98E-03	1.37	6.90E+02	Beta
UA	HTX	2006	129.23	63,643	1.93E-03	1.49	7.71E+02	Beta
UA	HTX	2007	101.47	63,978	1.52E-03	0.97	6.38E+02	Beta
UA	HTX	2008	202.29	68,462	3.00E-03	0.75	2.48E+02	Beta
UA	HTX	2009	191.61	63,561	2.85E-03	0.98	3.45E+02	Beta
UA	HTX	2010	81.8	64,938	1.19E-03	0.58	4.88E+02	Beta
UA	HTX	2011	69.02	66,804	1.02E-03	0.64	6.32E+02	Beta
UA	HTX	2012	164.42	57,594	2.51E-03	0.73	2.91E+02	Beta
UA	HTX	2013	99.44	65,388	1.50E-03	0.36	2.40E+02	Beta
UA	HTX	2014	238.16	62,876	3.62E-03	0.82	2.25E+02	Beta
UA	HTX	2015	191.66	62,816	2.86E-03	1.14	3.98E+02	Beta
UA	HTX	2016	98.06	68,307	1.45E-03	1.67	1.14E+03	Beta
UA	HTX	2017	174.33	64,723	2.64E-03	0.98	3.71E+02	Beta
UA	HTX	2018	117.17	52,180	1.72E-03	0.75	4.32E+02	Beta
UA	HTX	2019	79.51	51,258	1.60E-03	0.33	2.06E+02	Beta
UA	HTX	2020	400.84	49,368	7.88E-03	0.89	1.12E+02	Beta

Table 12. (continued).

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	HTX	2021	169.67	51,670	3.32E-03	1.28	3.84E+02	Beta
UA	HTX	2022	0.32	40,596	6.13E-06	0.33	5.44E+04	Beta
UA	MDP	2002	8884.24	1,593,597	5.63E-03	1.68	2.97E+02	Beta
UA	MDP	2003	9772.959	1,720,085	5.50E-03	1.57	2.83E+02	Beta
UA	MDP	2004	9175.799	1,822,984	4.94E-03	1.83	3.70E+02	Beta
UA	MDP	2005	9058.934	1,798,788	4.98E-03	1.8	3.60E+02	Beta
UA	MDP	2006	8793.487	1,806,084	4.64E-03	1.41	3.04E+02	Beta
UA	MDP	2007	8816.43	1,828,663	4.79E-03	1.68	3.50E+02	Beta
UA	MDP	2008	8992.06	1,816,831	4.86E-03	1.75	3.58E+02	Beta
UA	MDP	2009	10340.6	1,788,238	5.57E-03	1.86	3.32E+02	Beta
UA	MDP	2010	10231.1	1,812,125	5.55E-03	2.11	3.78E+02	Beta
UA	MDP	2011	9073.84	1,751,567	5.05E-03	1.59	3.14E+02	Beta
UA	MDP	2012	9931.96	1,703,781	5.46E-03	1.88	3.43E+02	Beta
UA	MDP	2013	9644.48	1,725,621	4.94E-03	1.16	2.33E+02	Beta
UA	MDP	2014	10050	1,758,886	5.37E-03	1.84	3.40E+02	Beta
UA	MDP	2015	8554.99	1,737,119	4.80E-03	1.62	3.37E+02	Beta
UA	MDP	2016	7783.67	1,716,086	4.45E-03	2.47	5.53E+02	Beta
UA	MDP	2017	7963.6	1,682,602	4.69E-03	1.22	2.58E+02	Beta
UA	MDP	2018	7889.57	1,670,807	4.59E-03	1.34	2.90E+02	Beta
UA	MDP	2019	7014.12	1,662,682	4.03E-03	1.32	3.27E+02	Beta
UA	MDP	2020	6374.34	1,619,358	3.67E-03	1.44	3.92E+02	Beta
UA	MDP	2021	5142.74	1,573,136	3.07E-03	1.47	4.77E+02	Beta
UA	MDP	2022	5738.38	1,538,823	3.65E-03	1.61	4.39E+02	Beta

[a] HDR = header.

Table 13. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTOC	Fail to open/close
FTOP	Fail to operate
FTR	Fail to run (normally running equipment)
FTR>1H	Fail to run more than 1 hour (standby equipment)
FTR<1H	Fail to run less than 1 hour (after start; standby equipment)
FTS	Fail to start
LOHT	Loss of heat transfer
SO	Spurious operation
UA	Unavailability (maintenance or state of another component)

7. SYSTEM DESCRIPTION

Being a multipurpose system, RHR provides many important functional configurations generally known as modes of operation. The different modes of RHR operation can include:

- Low-pressure coolant/safety injection
- SDC
- Suppression pool cooling (SPC) or containment sump recirculation
- Containment spray
- Fuel pool cooling.

The fundamental differences between plants can be summarized as having dedicated SDC systems, using an intermediate closed cooling system or a direct heat sink source of cooling to the RHR heat exchangers, having different numbers of pumps (from two to four), and having either a single-path loop suction valve configuration with two valves or multiple paths. The RHR configurations at each plant are provided in Table 14. Figure 27 shows a generic depiction of an RHR system.

7.1 Low-Pressure Injection Mode

The RHR system LPI mode is primarily designed to mitigate loss-of-coolant accidents (large and medium). During the injection phase of operation following a large LOCA, the RHR operates as an open-loop system and provides a rapid injection of coolant to the primary system to ensure reactor shutdown and adequate core cooling. LPI operation is initiated automatically.

Considering the above process, LPI operation requires:

- Opening discharge valves (AOV or MOV)
- Starting and running one or more RHR pumps.

Either offsite or onsite emergency power may be used to operate RHR pumps and valves.

7.2 Shutdown Cooling Mode

For the SDC mode of the RHR system, the flow path is different from LPI and SPC or containment sump recirculation in that the suction source is the reactor via the reactor recirculation line or hot leg. From the recirculation line or the hot legs, water flows through two motor-operated isolation valves in series, the first being located inside containment while the second is outside containment. This is then followed by individual suction isolation valves for each train, then to the suction of each pump.

The RHR system in SDC mode removes fission product decay heat from the reactor core and sensible heat from RCS components during system cooldowns and at cold shutdown. The design pressure limits for the RHR system are lower than the RCS, so the system is isolated from the RCS during power operation. During RCS cooldowns to cold shutdown, the RHR system remains isolated until RCS temperature and pressure are below interlock setpoints.

SDC is not automatic. The RHR system is cold relative to the RCS, so RHR components must undergo a heatup process prior to use. RHR heat transfer (RCS cooldown) is controlled through a heat exchanger cooling water valve adjustment.

Considering the above process, SDC operation requires:

- Opening suction and discharge valves (AOV or MOV)

Table 14. (continued).

- Starting and running one or more RHR pumps
- Establishing cooling water flow to the RHR heat exchanger
- Isolating the heat exchanger bypass
- Flow control through minimum flow valves
- Flow control of cooling water.

Either offsite or onsite emergency power may be used to operate RHR pumps and valves.

Two basic types of heat sinks are used at U.S. commercial operating nuclear reactors. The first is referred to as a direct heat sink and the second as an indirect heat sink:

- **Direct Heat Sink**—The direct heat sink generally uses a standby service water system to provide the heat sink for SDC. In some plants, this is a dedicated RHR service water system; in other plants, the emergency service water system is used. Either way, since the system is in standby, the pumps must be started to provide cooling
- **Indirect Heat Sink**—The plants with an indirect heat sink use a closed cooling water system, such as the reactor building closed cooling water system, as the first heat removal provider. The heat is ultimately removed by a normally running service water system. The main purpose of this intermediate cooling water system is to provide a barrier to the release of radioactive liquid to the environment.

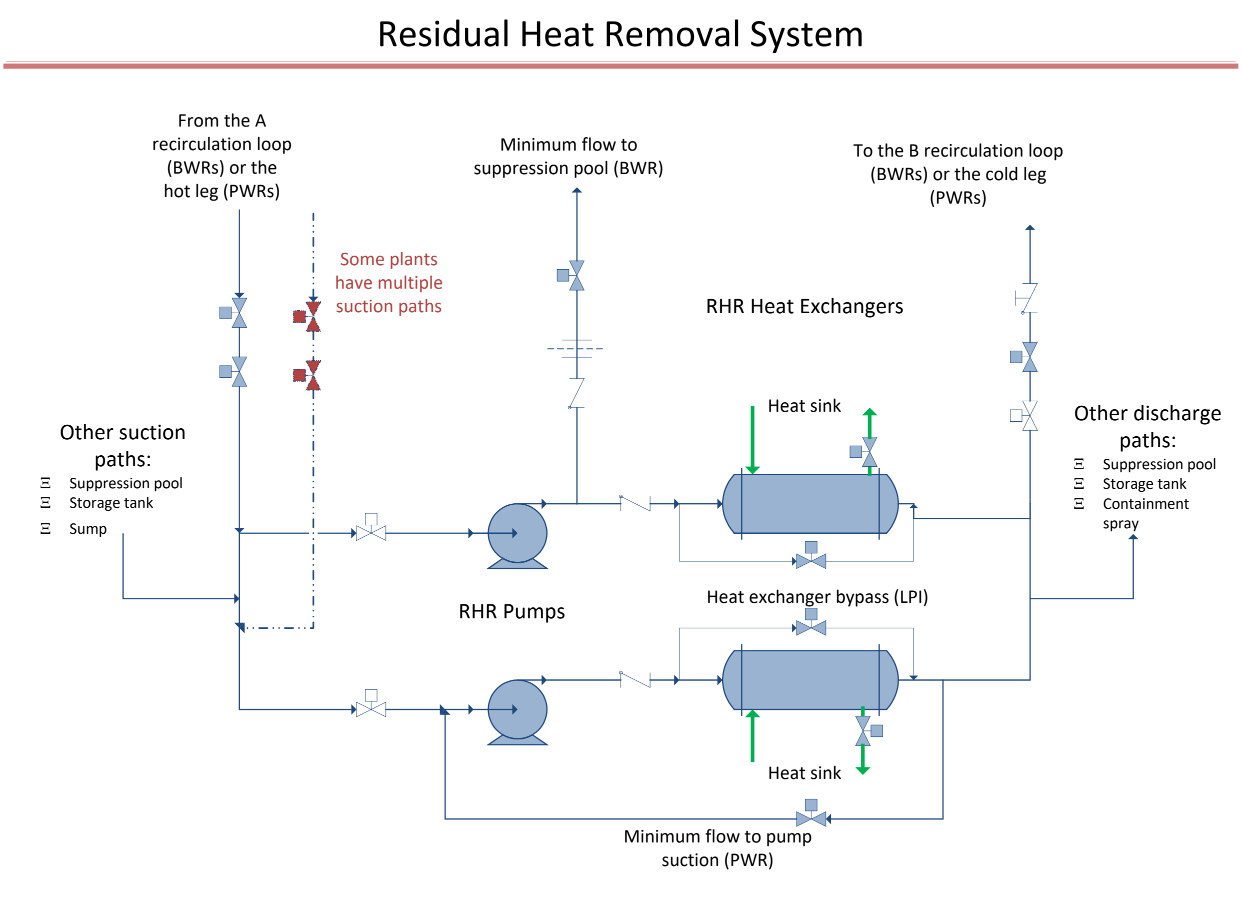

Figure 26. Generic depiction of the RHR system.

Table 14. Listing of the RHR design classes.[a]

Plant	Vendor	LPI Tree	SDC Tree[b]	BWR Contain-ment	BWR Design	PWR Loops	LPI Class	SDC Class
Arkansas 1	BW	LPI	DHR			2	2 pumps; BW	Direct-Single
Arkansas 2	CE	LPI	SDC			2	2 pumps; CE	Direct-Single
Beaver Valley 1	WE	LPI	RHR			3	2 pumps; WE	Single Use
Beaver Valley 2	WE	LPI	RHR			3	2 pumps; WE	Single Use
Braidwood 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Braidwood 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Browns Ferry 1	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Browns Ferry 2	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Browns Ferry 3	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Brunswick 1	GE	LCI	SDC	MARK I(C)	B-CLASS 4		4 pumps; GE	Direct-Single
Brunswick 2	GE	LCI	SDC	MARK I(C)	B-CLASS 4		4 pumps; GE	Direct-Single
Byron 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Byron 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Callaway	WE	LPI	RHR		SNUPPS	4	2 pumps; WE	Indirect-Multiple
Calvert Cliffs 1	CE	LPI	SDC			2	2 pumps; CE	Indirect-Single
Calvert Cliffs 2	CE	LPI	SDC			2	2 pumps; CE	Indirect-Single
Catawba 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Catawba 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Clinton 1	GE	LCI	SDC	MARK III(C)	B-CLASS 6		2 pumps; GE	Direct-Single
Columbia 2	GE	LCI	SDC	MARK II	B-CLASS 5		2 pumps; GE	Direct-Single
Comanche Peak 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Comanche Peak 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Cook 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Cook 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single

Table 14. (continued).

Plant	Vendor	LPI Tree	SDC Tree[b]	BWR Contain-ment	BWR Design	PWR Loops	LPI Class	SDC Class
Cooper	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Davis-Besse	BW	LPI	DHR			2	2 pumps; BW	Indirect-Single
Diablo Canyon 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Diablo Canyon 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Dresden 2	GE	LCI	SDC	MARK I	B-CLASS 3		3 pumps; GE	Single Use
Dresden 3	GE	LCI	SDC	MARK I	B-CLASS 3		3 pumps; GE	Single Use
Farley 1	WE	LPI	RHR			3	2 pumps; WE	Indirect-Multiple
Farley 2	WE	LPI	RHR			3	2 pumps; WE	Indirect-Multiple
Fermi 2	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
FitzPatrick	GE	LCI	SPC	MARK I	B-CLASS 4		4 pumps; GE	No suction modeled
Ginna	WE	LPI	RHR			2	2 pumps; WE	Indirect-Single
Grand Gulf	GE	LCI	SDC	MARK III(C)	B-CLASS 6		2 pumps; GE	Direct-Single
Harris	WE	LPI	RHR			3	2 pumps; WE	Indirect-Multiple
Hatch 1	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Hatch 2	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Hope Creek	GE	LCI	SDC	MARK I	B-CLASS 4		2 pumps; GE	Direct-Single
La Salle 1	GE	LCI	SDC	MARK II(C)	B-CLASS 5		2 pumps; GE	Direct-Single
La Salle 2	GE	LCI	SDC	MARK II(C)	B-CLASS 5		2 pumps; GE	Direct-Single
Limerick 1	GE	LCI	SDC	MARK II(C)	B-CLASS 4		4 pumps; GE	Direct-Single
Limerick 2	GE	LCI	SDC	MARK II(C)	B-CLASS 4		4 pumps; GE	Direct-Single
McGuire 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
McGuire 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Millstone 2	CE	LPI	SDC			2	2 pumps; CE	Indirect-Single
Millstone 3	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Monticello	GE	LCI	SDC	MARK I	B-CLASS 3		4 pumps; GE	Direct-Single

Table 14. (continued).

Plant	Vendor	LPI Tree	SDC Tree[b]	BWR Contain-ment	BWR Design	PWR Loops	LPI Class	SDC Class
Nine Mile Pt. 1	GE	LCS	SDC	MARK I	B-CLASS 2		3 pumps; GE	Single Use
Nine Mile Pt. 2	GE	LCI	SDC	MARK II(C)	B-CLASS 5		2 pumps; GE	Direct-Single
North Anna 1	WE	LPI	RHR			3	2 pumps; WE	Single Use
North Anna 2	WE	LPI	RHR			3	2 pumps; WE	Single Use
Oconee 1	BW	LPI	DHR			2	3 pumps; BW	Indirect-Single
Oconee 2	BW	LPI	DHR			2	3 pumps; BW	Indirect-Single
Oconee 3	BW	LPI	DHR			2	3 pumps; BW	Indirect-Single
Palisades	CE	LPI	SDC			2	2 pumps; CE	Indirect-Single
Palo Verde 1	CE	LPI	SDC		SYSTEM 80	2	4 pumps; CE	Direct-Multiple
Palo Verde 2	CE	LPI	SDC		SYSTEM 80	2	4 pumps; CE	Direct-Multiple
Palo Verde 3	CE	LPI	SDC		SYSTEM 80	2	4 pumps; CE	Direct-Multiple
Peach Bottom 2	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Peach Bottom 3	GE	LCI	SDC	MARK I	B-CLASS 4		4 pumps; GE	Direct-Single
Perry	GE	LCI	SDC	MARK III	B-CLASS 6		2 pumps; GE	Indirect-Single
Point Beach 1	WE	LPI	RHR			2	2 pumps; WE	Indirect-Single
Point Beach 2	WE	LPI	RHR			2	2 pumps; WE	Indirect-Single
Prairie Island 1	WE	LPI	RHR			2	2 pumps; WE	Direct-Multiple
Prairie Island 2	WE	LPI	RHR			2	2 pumps; WE	Direct-Multiple
Quad Cities 1	GE	LCI	SDC	MARK I	B-CLASS 3		4 pumps; GE	Direct-Single
Quad Cities 2	GE	LCI	SDC	MARK I	B-CLASS 3		4 pumps; GE	Direct-Single
River Bend	GE	LCI	SDC	MARK III	B-CLASS 6		2 pumps; GE	Direct-Single
Robinson 2	WE	LPI	RHR			3	2 pumps; WE	Indirect-Single
Salem 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Salem 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Seabrook	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple

Table 14. (continued).

Plant	Vendor	LPI Tree	SDC Tree[b]	BWR Contain-ment	BWR Design	PWR Loops	LPI Class	SDC Class
Sequoyah 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Sequoyah 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
South Texas 1	WE	LPI	RHR			4	3 pumps; WE	Indirect-Multiple
South Texas 2	WE	LPI	RHR			4	3 pumps; WE	Indirect-Multiple
St. Lucie 1	CE	LPI	SDC			2	2 pumps; CE	Indirect-Multiple
St. Lucie 2	CE	LPI	SDC		2HL/4CL	2	2 pumps; CE	Indirect-Multiple
Summer	WE	LPI	RHR			3	2 pumps; WE	Indirect-Multiple
Surry 1	WE	LPI	RHR			3	2 pumps; WE	Single Use
Surry 2	WE	LPI	RHR			3	2 pumps; WE	Single Use
Susquehanna 1	GE	LCI	SPC	MARK II(C)	B-CLASS 4		4 pumps; GE	No suction modeled
Susquehanna 2	GE	LCI	SPC	MARK II(C)	B-CLASS 4		4 pumps; GE	No suction modeled
Turkey Point 3	WE	LPI	RHR			3	2 pumps; WE	Indirect-Single
Turkey Point 4	WE	LPI	RHR			3	2 pumps; WE	Indirect-Single
Vogtle 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Vogtle 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Multiple
Waterford 3	CE	LPI	SDC		2HL/4CL	2	2 pumps; CE	Indirect-Multiple
Watts Bar 1	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Watts Bar 2	WE	LPI	RHR			4	2 pumps; WE	Indirect-Single
Wolf Creek	WE	LPI	RHR		SNUPPS	4	2 pumps; WE	Indirect-Multiple

[a] Nuclear Regulatory Commission, *Overview and Comparison of U.S. Commercial Nuclear Reactors*, NUREG/CR-5640, SAIC-89/1541, September 1990.

[b] DHR = decay heat removal.

8. REFERENCES

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