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System Study: Residual Heat Removal 1998–2014

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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 post-trip shutdown-cooling) at 104 U.S. commercial nuclear power plants. Demand, run hours, and failure data from fiscal year 1998 through 2014 for selected components were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). 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 trends were identified in the RHR results. A highly statistically significant decreasing trend was observed for the RHR injection mode start-only unreliability. Statistically significant decreasing trends were observed for RHR shutdown cooling mode start-only unreliability and RHR shutdown cooling model 24-hour unreliability.

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FIGURES

TABLES

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
FTR>1H	fail to run more than one hour (standby)
FTR<1H	fail to run less than one hour
FTS	fail to start
FY	fiscal year
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
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
PRA	probabilistic risk assessment
RCS	reactor coolant system
RHR	residual heat removal
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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1. INTRODUCTION

The residual heat removal (RHR) system is typically a multiple use system with modes of operation for low-pressure injection, shutdown cooling, suppression pool or containment sump cooling, and/or containment spray. Some plants have dedicated systems to accomplish one or more of these modes. This report presents an unreliability evaluation over time of the RHR system in two modes of operation—low-pressure injection (LPI) in response to a large loss-of-coolant accident (LLOCA) and post-trip shutdown-cooling (SDC)—at 104 U.S. commercial nuclear power plants.

Demand, run hours, and failure data from fiscal year (FY)-98 through FY-14 for selected components in the RHR system were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process Safety System Unavailability (SSU) database (FY-98 through FY-01) and the Mitigating Systems Performance Index (MSPI) database (FY-02 through FY-14). Common-cause failure (CCF) data used in the models are from the 2010 update to the CCF database. 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 2010 Component Reliability Update (Reference 1), which is an update to Reference 2 (NUREG/CR-6928). Baseline RHR unreliability results using basic event values from that report are summarized in Section 3. Trend results for RHR (using system-specific data) are presented in Section 4. Similar to previous system study updates, Section 5 contains importance information (using the baseline results from Section 3), and Section 7 describes the RHR system.

All models include failures due to unavailability while in test or maintenance. Human error has not been included in the SPAR model logic. Human actions for various recovery actions are included. An overview of the trending methods, glossary of terms, and abbreviations can be found in the Overview and Reference document on the Reactor Operational Experience Results and Databases web page.

1.1 Low-Pressure Injection Mode

Table 1 shows the definitions of the design classes used in the low-pressure injection mode of operation sections of this report. For each plant the corresponding SPAR model (version model indicated in Table 3 was used in the calculations. The low-pressure injection mode represents the use of the system as it is normally lined up during power operations. The RHR system in low-pressure injection mode is an automatically initiated event.

The RHR is categorized by the number of redundant low-pressure injection pumps and the plant vendor design as the most significant differences noted between systems at plants for the low-pressure injection mode. Table 3 summarizes the plants and their LPI classes.

Two versions of the low-pressure injection mode models for the RHR system are calculated. The RHR start-only model is the SPAR RHR low-pressure injection mode model modified by setting all fail-to-run basic events to zero (False), setting all recovery events to False, all room cooling events to False, and all pump cooling events to False. The 8-hour mission model includes all basic events in the SPAR RHR low-pressure injection mode model.

Table 1. RHR low-pressure injection class definitions.

RHR Injection Class	Description	Number of Plants
2 pumps; BW	Two RHR pump Babcock and Wilcox (BW) Design	4
2 pumps; CE	Two RHR pump Combustion Engineering (CE) Design	11
2 pumps; GE	Two RHR pump General Electric (GE) Design	9
2 pumps; WE	Two RHR pump Westinghouse (WE) Design	46
3 pumps; BW	Three RHR pump Babcock and Wilcox Design	3
3 pumps; GE	Three RHR pump General Electric Design	4
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	22
Total		104

1.2 Shutdown Cooling Mode

Table 2 shows the definitions of the design classes used in the shutdown-cooling mode of operation sections of this report. For each plant the corresponding Standardized Plant Analysis Risk (SPAR) model (version model indicated in Table 3) was used in the calculations.

The shutdown-cooling mode represents the most challenging (more risk-significant at PWRs than in 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 shutdown cooling mode is a manually initiated event. Each fault tree modeling the shutdown-cooling mode of RHR includes a human action basic event to model the initiation. This basic event always comes out as the most important basic event in the model. To evaluate the system in more detail, the human action to initiate shutdown cooling was trimmed from the fault tree.

The RHR shutdown-cooling mode is categorized by the heat sink method in this report as 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 summarizes the plants and their classes.

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

Table 2. RHR shutdown cooling mode design class definitions.

RHR Shutdown Cooling Design 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	29
Indirect-Multiple	Indirect heat sink, uses multiple suction paths	24
Indirect-Single	Indirect heat sink, uses a single suction path	31
No suction modeled	Models do not include the suction path valves (model suppression pool cooling only)	4
Single Train	Only one train is used in the model	1
Single Use	Plants with a single-use SDC system	10
Total		104

Table 3. RHR design class summary.

Plant	Version	Injection Class	Shutdown Cooling Class
Arkansas 1	8.19	2 pumps; BW	Direct-Single
Arkansas 2	8.21	2 pumps; CE	Direct-Single
Beaver Valley 1	8.22	2 pumps; WE	Single Use
Beaver Valley 2	8.23	2 pumps; WE	Single Use
Braidwood 1	8.21	2 pumps; WE	Indirect-Multiple
Braidwood 2	8.21	2 pumps; WE	Indirect-Multiple
Browns Ferry 1	8.22	4 pumps; GE	Direct-Single
Browns Ferry 2	8.22	4 pumps; GE	Direct-Single
Browns Ferry 3	8.18	4 pumps; GE	Direct-Single
Brunswick 1	8.20	4 pumps; GE	Direct-Single
Brunswick 2	8.20	4 pumps; GE	Direct-Single
Byron 1	8.21	2 pumps; WE	Indirect-Multiple
Byron 2	8.21	2 pumps; WE	Indirect-Multiple
Callaway	8.21	2 pumps; WE	Indirect-Multiple
Calvert Cliffs 1	8.22	2 pumps; CE	Indirect-Single
Calvert Cliffs 2	8.21	2 pumps; CE	Indirect-Single
Catawba 1	8.20	2 pumps; WE	Indirect-Single
Catawba 2	8.20	2 pumps; WE	Indirect-Single
Clinton 1	8.17	2 pumps; GE	Direct-Single
Columbia 2	8.16	2 pumps; GE	Direct-Single
Comanche Peak 1	8.21	2 pumps; WE	Indirect-Multiple
Comanche Peak 2	8.21	2 pumps; WE	Indirect-Multiple
Cook 1	8.20	2 pumps; WE	Indirect-Single
Cook 2	8.20	2 pumps; WE	Indirect-Single
Cooper	8.22	4 pumps; GE	Direct-Single
Crystal River 3	8.16	2 pumps; BW	Direct-Single
Davis-Besse	8.19	2 pumps; BW	Indirect-Single
Diablo Canyon 1	8.19	2 pumps; WE	Indirect-Single
Diablo Canyon 2	8.19	2 pumps; WE	Indirect-Single
Dresden 2	8.18	3 pumps; GE	Single Use
Dresden 3	8.18	3 pumps; GE	Single Use
Duane Arnold	8.22	4 pumps; GE	Direct-Single
Farley 1	8.18	2 pumps; WE	Indirect-Multiple
Farley 2	8.18	2 pumps; WE	Indirect-Multiple
Fermi 2	8.20	4 pumps; GE	Direct-Single
FitzPatrick	8.17	4 pumps; GE	No suction modeled
Fort Calhoun	8.20	2 pumps; CE	Indirect-Single
Ginna	8.23	2 pumps; WE	Indirect-Single
Grand Gulf	8.22	2 pumps; GE	Direct-Single
Harris	8.23	2 pumps; WE	Indirect-Multiple
Hatch 1	8.20	4 pumps; GE	Direct-Single
Hatch 2	8.20	4 pumps; GE	Direct-Single
Hope Creek	8.18	2 pumps; GE	Direct-Single
Indian Point 2	8.19	2 pumps; WE	Indirect-Single
Indian Point 3	8.20	2 pumps; WE	Indirect-Single
Kewaunee	8.20	2 pumps; WE	Indirect-Multiple
La Salle 1	8.21	2 pumps; GE	Direct-Single
La Salle 2	8.21	2 pumps; GE	Direct-Single
Limerick 1	8.20	4 pumps; GE	Direct-Single
Limerick 2	8.19	4 pumps; GE	Direct-Single
McGuire 1	8.20	2 pumps; WE	Indirect-Single
McGuire 2	8.20	2 pumps; WE	Indirect-Single
Millstone 2	8.17	2 pumps; CE	Indirect-Single
Millstone 3	8.20	2 pumps; WE	Indirect-Multiple
Monticello	8.20	4 pumps; GE	Direct-Single
Nine Mile Pt. 1	8.21	3 pumps; GE	Single Use
Nine Mile Pt. 2	8.17	2 pumps; GE	Direct-Single
North Anna 1	8.20	2 pumps; WE	Single Use
North Anna 2	8.20	2 pumps; WE	Single Use
Oconee 1	8.19	3 pumps; BW	Indirect-Single
Oconee 2	8.19	3 pumps; BW	Indirect-Single
Oconee 3	8.19	3 pumps; BW	Indirect-Single
Oyster Creek	8.22	3 pumps; GE	Single Use
Palisades	8.20	2 pumps; CE	Indirect-Single
Palo Verde 1	8.20	4 pumps; CE	Direct-Multiple
Palo Verde 2	8.20	4 pumps; CE	Direct-Multiple
Palo Verde 3	8.20	4 pumps; CE	Direct-Multiple
Peach Bottom 2	8.25	4 pumps; GE	Direct-Single
Peach Bottom 3	8.21	4 pumps; GE	Direct-Single
Perry	8.19	2 pumps; GE	Indirect-Single
Pilgrim	8.21	4 pumps; GE	No suction modeled
Point Beach 1	8.20	2 pumps; WE	Indirect-Single
Point Beach 2	8.20	2 pumps; WE	Indirect-Single
Prairie Island 1	8.19	2 pumps; WE	Direct-Multiple
Prairie Island 2	8.19	2 pumps; WE	Direct-Multiple
Quad Cities 1	8.18	4 pumps; GE	Direct-Single
Quad Cities 2	8.18	4 pumps; GE	Direct-Single
River Bend	8.20	2 pumps; GE	Direct-Single
Robinson 2	8.17	2 pumps; WE	Indirect-Single
Salem 1	8.20	2 pumps; WE	Indirect-Single
Salem 2	8.20	2 pumps; WE	Indirect-Single
San Onofre 2	8.22	2 pumps; CE	Indirect-Multiple
San Onofre 3	8.22	2 pumps; CE	Indirect-Multiple
Seabrook	8.20	2 pumps; WE	Indirect-Multiple
Sequoyah 1	8.16	2 pumps; WE	Indirect-Single
Sequoyah 2	8.16	2 pumps; WE	Indirect-Single
South Texas 1	8.17	3 pumps; WE	Indirect-Multiple
South Texas 2	8.17	3 pumps; WE	Indirect-Multiple

Table 3. (continued).

Plant	Version	Injection Class	Shutdown Cooling Class
St. Lucie 1	8.19	2 pumps; CE	Indirect-Multiple
St. Lucie 2	8.19	2 pumps; CE	Indirect-Multiple
Summer	8.23	2 pumps; WE	Indirect-Multiple
Surry 1	8.19	2 pumps; WE	Single Use
Surry 2	8.15	2 pumps; WE	Single Use
Susquehanna 1	8.23	4 pumps; GE	No suction modeled
Susquehanna 2	8.21	4 pumps; GE	No suction modeled
Three Mile Isl 1	8.20	2 pumps; BW	Single Train
Turkey Point 3	8.20	2 pumps; WE	Indirect-Single
Turkey Point 4	8.20	2 pumps; WE	Indirect-Single
Vermont Yankee	8.19	4 pumps; GE	Direct-Single
Vogtle 1	8.21	2 pumps; WE	Indirect-Multiple
Vogtle 2	8.21	2 pumps; WE	Indirect-Multiple
Waterford 3	8.16	2 pumps; CE	Indirect-Multiple
Watts Bar 1	8.16	2 pumps; WE	Indirect-Single
Wolf Creek	8.20	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 the existence of any statistically significant[a] increasing trends. In this update no statistically significant increasing trends were identified in the RHR unreliability trend results.

2.1 Increasing Trends

2.1.1 Extremely Statistically Significant

- None.

2.1.2 Highly Statistically Significant

- None

2.1.3 Statistically Significant

- None.

2.2 Decreasing Trends

2.2.1 Extremely Statistically Significant

- None

2.2.2 Highly Statistically Significant

- Start-only RHR injection mode unreliability (Figure 5) was found to be decreasing.

2.2.3 Statistically Significant

- Start-only RHR shutdown cooling mode unreliability (Figure 7) was found to be decreasing.
- RHR shutdown cooling mode unreliability (Figure 8) for a 24-hour mission was found to be decreasing.

2.3 Importance Measure Results

The industry-wide RHR low-pressure injection mode start-only and 8-hour basic event group importances were evaluated and are shown in Figure 9. In both cases, the leading contributors to RHR LPI system unreliability are the RHR motor-driven pumps followed by the injection flow path. Section 5 shows importance charts for each RHR LPI class.

The industry-wide RHR shutdown-cooling mode start-only and 24-hour basic event group importances were evaluated and are shown in Figure 19. In both cases, the leading contributor to RHR SDC system unreliability in the shutdown-cooling mode is the human action to reposition the valves in the suction flow path followed by random failures of the injection flow path. The suction was the third most important segment. Section 5 shows importance charts for each RHR SDC class. For those plants with a single suction source, the suction segment importance increases significantly. For those plants that have

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 of 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).

multiple suction sources, the pump importance increases since the suction segment importance decreases. The distinction between the heat sink types (direct versus indirect) is not very large. This is due to the standby nature of most of the direct heat sink systems and the normally operating nature of the indirect heat sink systems.

3. INDUSTRY-WIDE UNRELIABILITY

3.1 Low-Pressure Injection Mode

The RHR low-pressure injection mode fault trees (not all SPAR models label the appropriate fault tree as 'LPI', Table 14 lists the fault tree that was evaluated for this report) from the SPAR models were evaluated for each of the 104 operating U.S. commercial pressurized water nuclear power plants with an RHR system.

The industry-wide unreliability of the RHR system has been estimated for two modes of operation. A start-only model and an 8-hour mission model were evaluated. The uncertainty distributions for RHR show both plant design variability and parameter uncertainty while using industry-wide component failure data (FY-98 through FY-10).[a] Table 4 shows the percentiles and mean of the aggregated sample data (Latin hypercube, 1000 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 for the industry.

In Figure 1 and Figure 2, the width of the distribution for a class is affected by the differences in the plant modeling and the 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 4. Industry-wide unreliability values.

Model	RHR Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-only	Industry	7.08E−06	4.95E−05	2.60E−04	8.57E−04
	2 pumps; BW	3.08E−05	1.77E−04	3.42E−04	1.09E−03
	2 pumps; CE	1.59E−05	5.74E−05	9.27E−04	5.77E−03
	2 pumps; GE	7.19E−06	6.77E−05	1.54E−04	5.56E−04
	2 pumps; WE	8.94E−06	4.23E−05	1.42E−04	8.55E−04
	3 pumps; BW	1.43E−05	6.49E−05	1.23E−04	4.00E−04
	3 pumps; GE	3.00E−07	4.03E−05	6.70E−05	1.89E−04
	3 pumps; WE	1.55E−06	8.02E−06	1.01E−05	2.70E−05
	4 pumps; CE	2.05E−05	7.06E−05	8.73E−05	2.09E−04
	4 pumps; GE	7.06E−06	5.18E−05	2.83E−04	8.34E−04
8-hour Mission	Industry	1.07E−05	6.85E−05	3.07E−04	8.96E−04
	2 pumps; BW	4.52E−05	1.94E−04	3.64E−04	1.13E−03
	2 pumps; CE	2.57E−05	8.57E−05	9.92E−04	6.07E−03
	2 pumps; GE	8.53E−06	1.02E−04	2.16E−04	7.32E−04
	2 pumps; WE	1.64E−05	5.80E−05	1.50E−04	8.62E−04
	3 pumps; BW	2.74E−05	1.27E−04	1.88E−04	5.65E−04
	3 pumps; GE	1.89E−06	4.27E−05	6.98E−05	1.89E−04
	3 pumps; WE	4.80E−06	1.38E−05	1.60E−05	3.41E−05
	4 pumps; CE	4.53E−05	1.43E−04	5.09E−04	5.56E−04
	4 pumps; GE	7.93E−06	6.84E−05	3.55E−04	1.39E−03

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

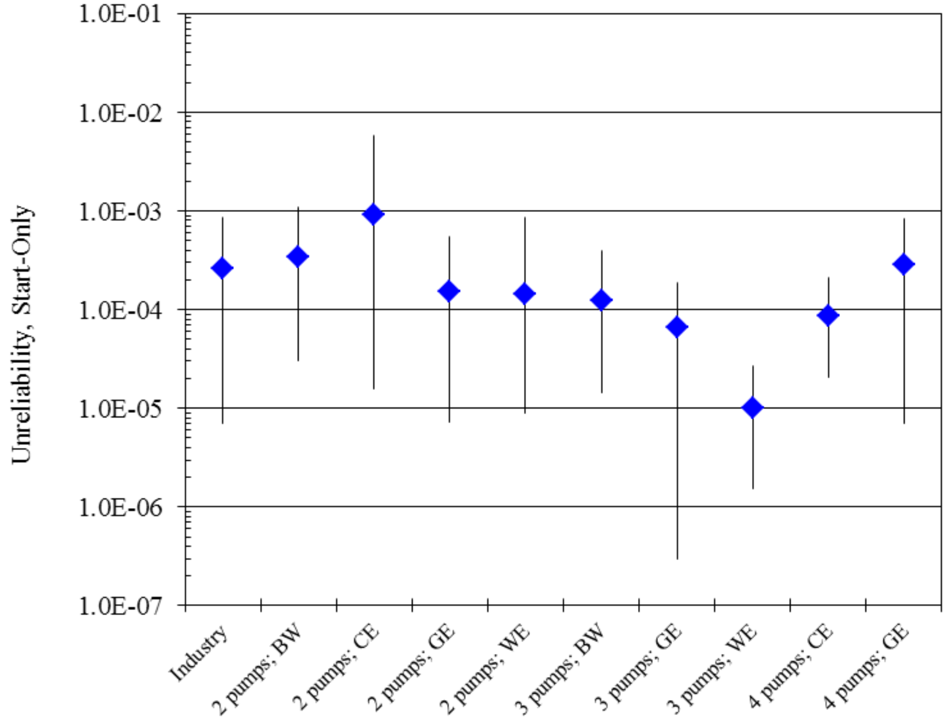

Figure 1. RHR low-pressure injection mode start-only mission unreliability for class and industry-wide groupings.

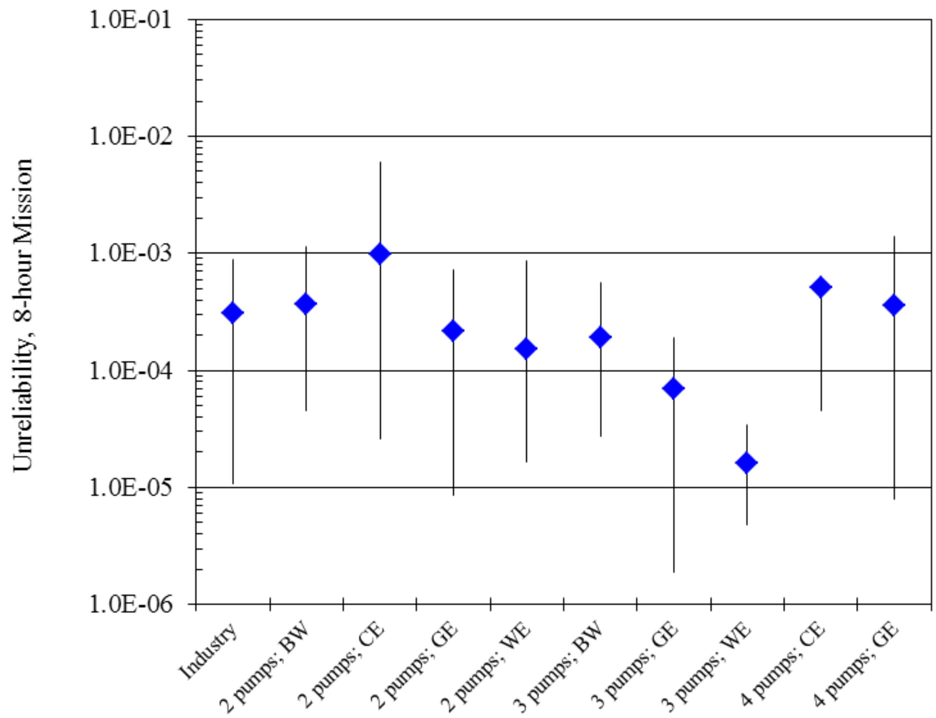

Figure 2. RHR low-pressure injection mode 8-hour mission unreliability for class and industry-wide groupings.

3.2 Shutdown Cooling Mode

The RHR shutdown cooling mode fault trees (not all SPAR models label the appropriate fault tree as 'RHR', Table 14 lists the fault tree that was evaluated for this report) from the SPAR models were evaluated for each of the 104 operating U.S. commercial pressurized water nuclear power plants with an RHR system.

The industry-wide unreliability of the RHR system has been estimated for two modes of operation. A start-only model and a 24-hour mission model were evaluated. The uncertainty distributions for RHR show both plant design variability and parameter uncertainty while using industry-wide component failure data (FY-98 through FY-10).[a] Table 5 shows the percentiles and mean of the aggregated sample data (Latin hypercube, 1000 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 width of the distribution for a class is affected by the differences in the plant modeling and the 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 shutdown cooling mode unreliability values.

Model	RHR Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-only	Industry	1.80E−04	2.81E−03	4.39E−03	1.39E−02
	Direct-Single	4.08E−04	2.38E−03	3.03E−03	7.71E−03
	Direct-Multiple	5.15E−04	2.02E−03	2.99E−03	8.67E−03
	No Suction Modeled	2.82E−06	1.38E−04	4.07E−04	1.73E−03
	Indirect-Single	1.13E−03	4.04E−03	5.68E−03	1.39E−02
	Indirect-Multiple	1.20E−04	1.57E−03	2.72E−03	9.06E−03
	Single Use	7.45E−04	7.82E−03	9.81E−03	2.41E−02
	Single Train	9.67E−03	1.79E−02	1.93E−02	3.47E−02
24-hour Mission	Industry	2.23E−04	2.93E−03	4.57E−03	1.44E−02
	Direct-Single	4.22E−04	2.44E−03	3.11E−03	7.78E−03
	Direct-Multiple	6.84E−04	2.33E−03	3.56E−03	9.40E−03
	No Suction Modeled	1.37E−05	1.79E−04	4.35E−04	1.74E−03
	Indirect-Single	1.19E−03	4.18E−03	5.84E−03	1.41E−02
	Indirect-Multiple	1.64E−04	1.69E−03	2.81E−03	9.16E−03
	Single Use	7.64E−04	8.28E−03	1.04E−02	2.59E−02
	Single Train	1.02E−02	1.84E−02	1.97E−02	3.41E−02

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

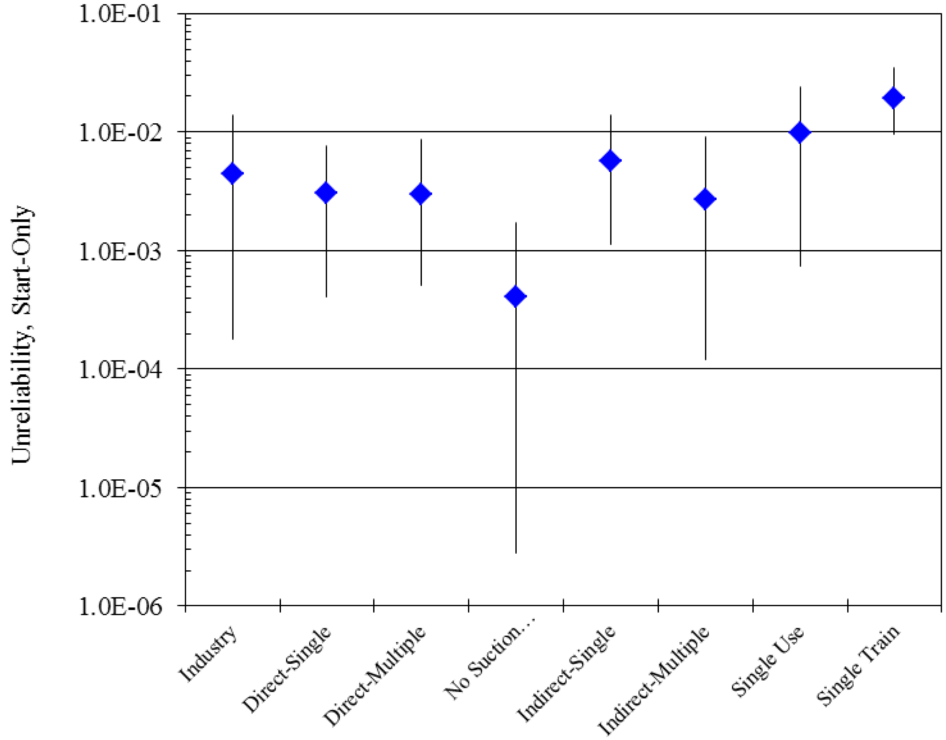

Figure 3. RHR shutdown cooling mode start-only mission unreliability for class and industry-wide groupings.

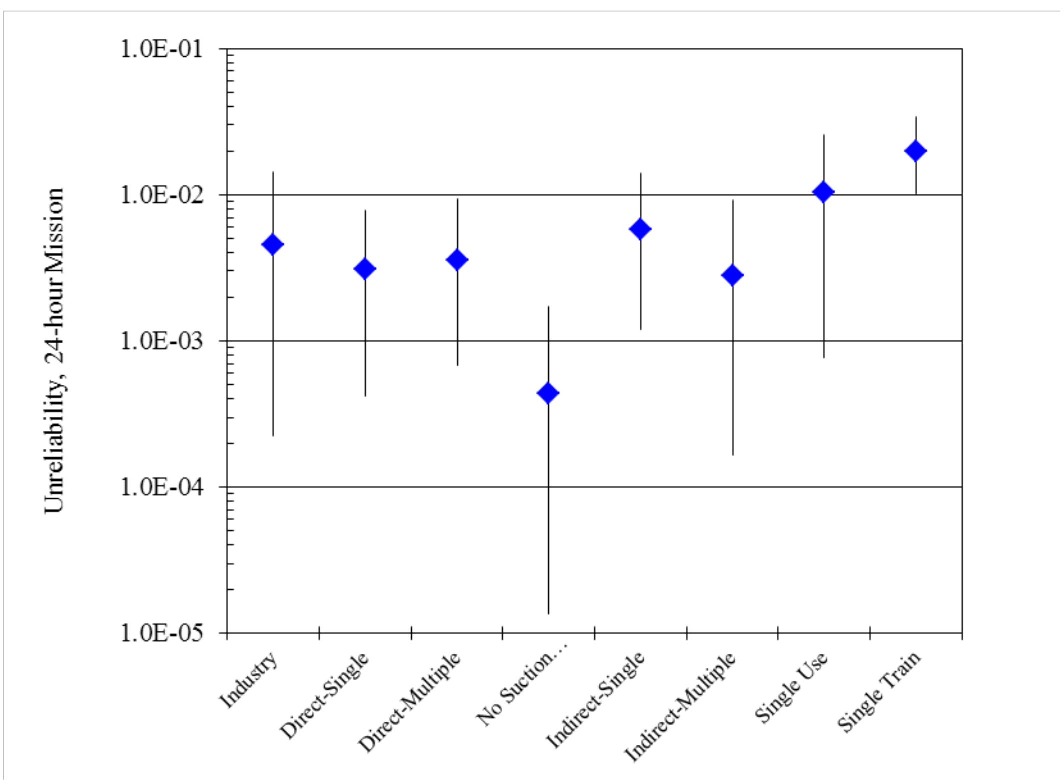

Figure 4. RHR shutdown cooling mode 24-hour mission unreliability for class and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly (FY-98 through FY-14) failure and demand or run time data were obtained from ICES for the RHR system. RHR train maintenance unavailability data for trending are from the same time period, as reported in the ROP and ICES. The component basic event uncertainty was calculated for the RHR system components using the trending methods described in Section 1 and 2 of the Overview and Reference document. 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 using data for each year. In addition, the calculated industry-wide system reliability from this update is shown. Section 4 of the Overview and Reference link on the System Studies main web page provides more detailed discussion of the trending methods. In the lower left-hand corner of the trend figures, the regression method is reported.

4.1 Low-Pressure Injection Mode

The components that were varied in the RHR (injection 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 5 shows the trend in the RHR (injection mode) start-only model unreliability. Table 7 shows the data points for Figure 5. There is no statistically significant trend within the industry-wide estimates of RHR (injection mode) system start-only mission on a per fiscal year. Figure 6 shows the trend in the 8-hour mission unreliability. No statistically significant trend within the industry-wide estimate of RHR (injection mode) system unreliability (8-hour mission) on a per fiscal year basis was identified. Table 8 shows the data points for Figure 6.

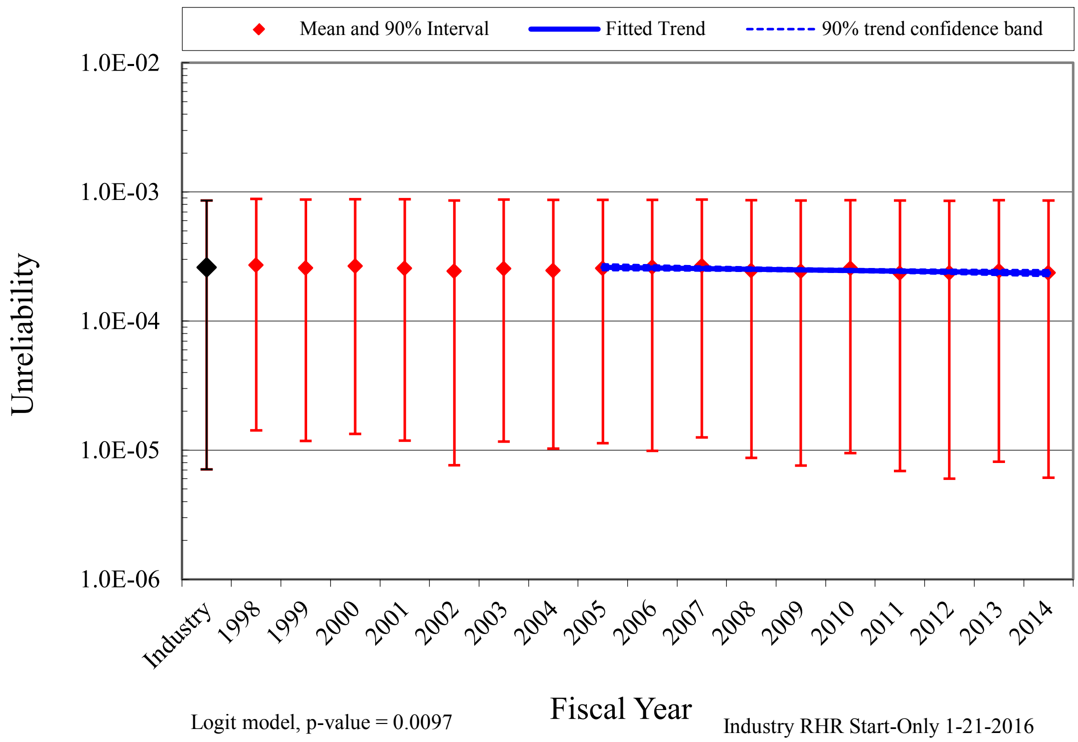

Figure 5. Trend of RHR (injection mode) system unreliability (start-only model), as a function of fiscal year.

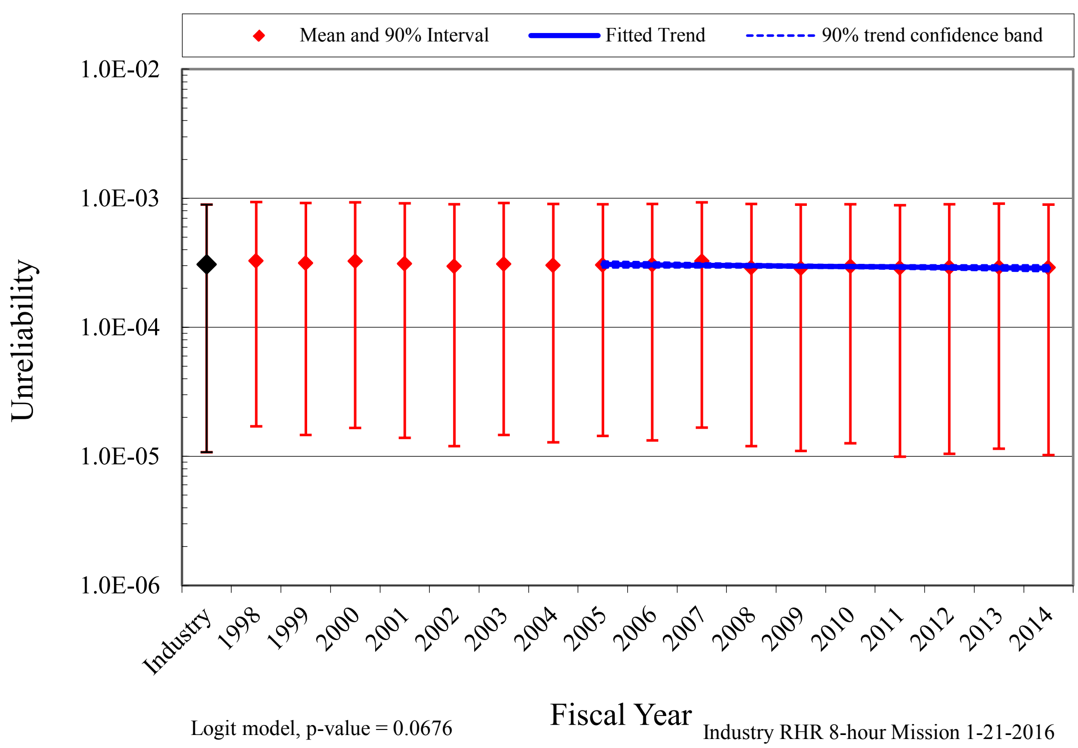

Figure 6. Trend of RHR (injection mode) system unreliability (8-hour model), as a function of fiscal year.

4.2 Shutdown Cooling Mode

The components that were varied in the shutdown-cooling mode of the RHR 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 shutdown-cooling mode RHR start-only model unreliability. Table 9 shows the data points for Figure 7. No statistically significant trends within the industry-wide estimates of the shutdown-cooling mode RHR system start-only mission on a per fiscal year basis were identified. Figure 8 shows the trend in the 24-hour mission unreliability. No statistically significant trend within the industry-wide estimates of RHR system unreliability (24-hour mission) on a per fiscal year basis was identified. Table 10 shows the data points for Figure 8.

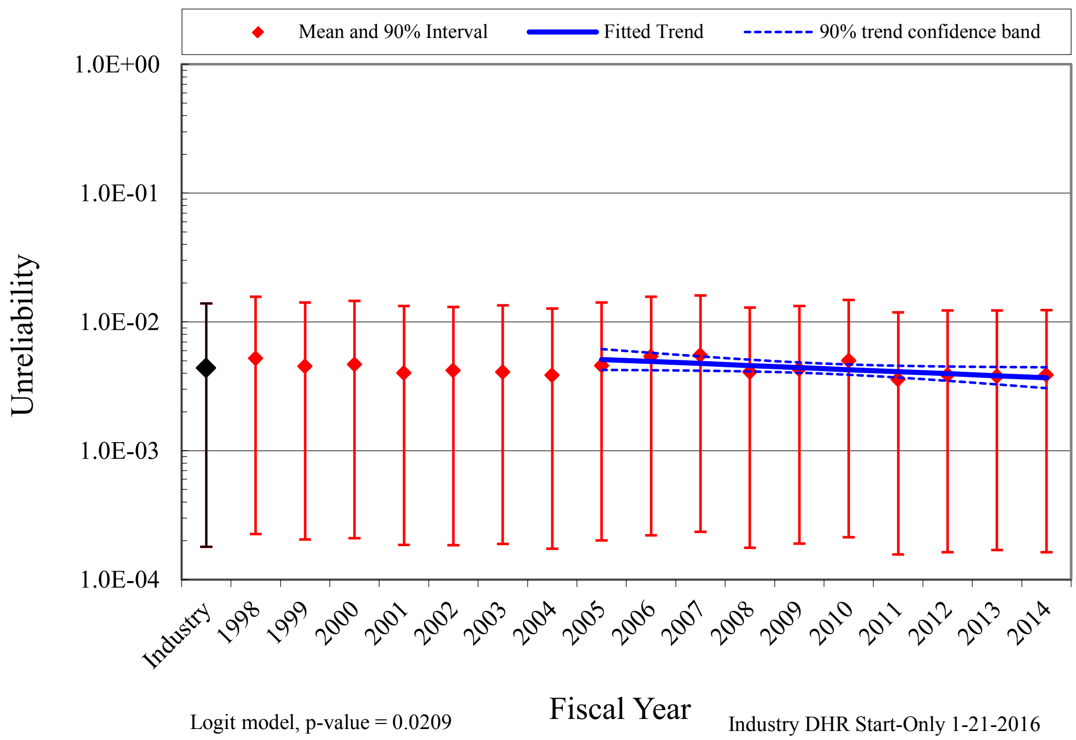

Figure 7. Trend of RHR shutdown cooling mode system unreliability (start-only model), as a function of fiscal year.

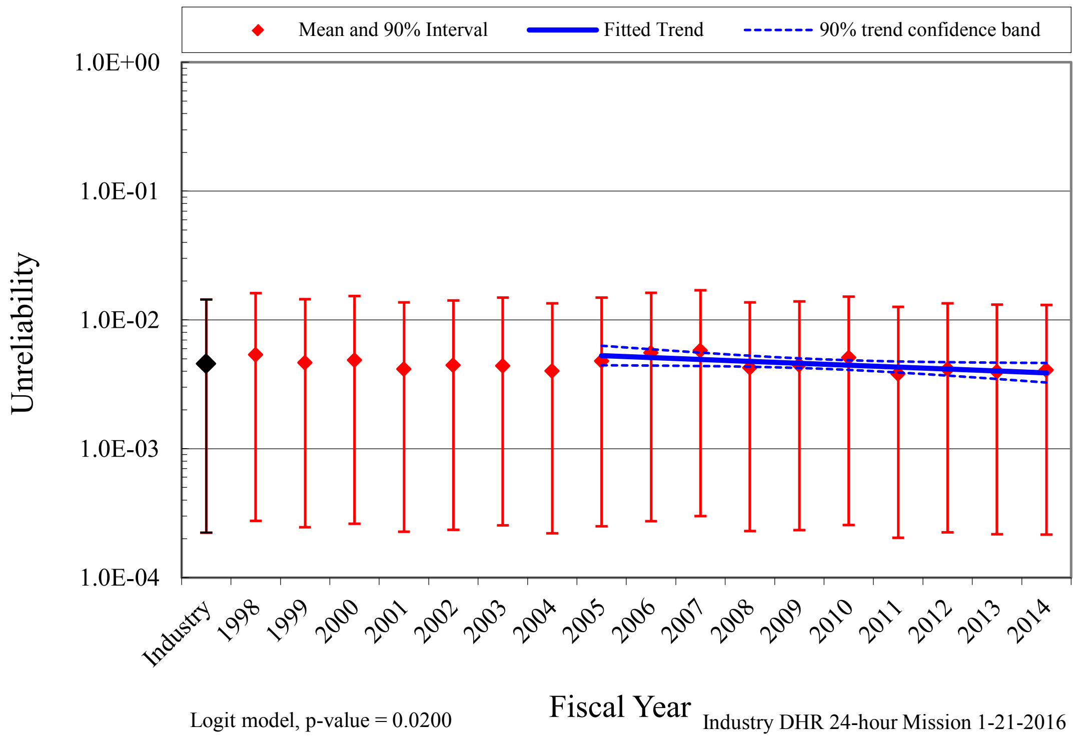

Figure 8. Trend of RHR shutdown cooling mode system unreliability (24-hour model), as a function of fiscal year.

5. BASIC EVENT GROUP IMPORTANCES

The RHR basic event group Fussell-Vesely importances were calculated for each plant using the industry-wide data (1998–2010). 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. An intermediate cooling system that transfers the heat to the ultimate heat sink.
DC Power	The batteries and battery chargers that supply power to the pump control circuitry.
EPS	RHR dependency on the emergency power system.
HA Start RHR	Human action to start the pumps and re-align any valves.
Heat Sink	The pumps, valves, strainers and other equipment associated with the ultimate heat sink.
Human Action	Other human actions for recovery of equipment.
Injection	The flow path equipment, to direct the shutdown cooling water to the RCS loop.
Instrument Air	Instrument air support to the RHR model.
Min Flow	The minimum flow valves around the RHR heat exchangers. These are used to control the cooldown rate.
Pump Cooling	Cooling provided to the shutdown cooling pumps.
RHR HTX	The first heat exchanger in the system to transfer heat from the RCS to the next level of heat removal.
RHR MDP	The motor-driven pumps that provide the recirculation flow from the RCS loop back to the RCS.
Room Cooling	Cooling provided to the room the shutdown cooling pumps are located in.
Special	Various events used in the models that are not directly associated with the RHR system.
Suction	Valves in the suction section of the shutdown cooling system. These valves 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 basic event group importances for low-pressure-injection mode are shown in Figure 9. In both cases, the leading contributors to RHR LPI system unreliability are the RHR motor-driven pumps followed by the injection flow path. For more discussion on the RHR motor-driven pumps and the RHR motor-operated and air-operated valves (MOVs and AOVs), see the component reliability studies at NRC Reactor Operational Experience Results and Databases.

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

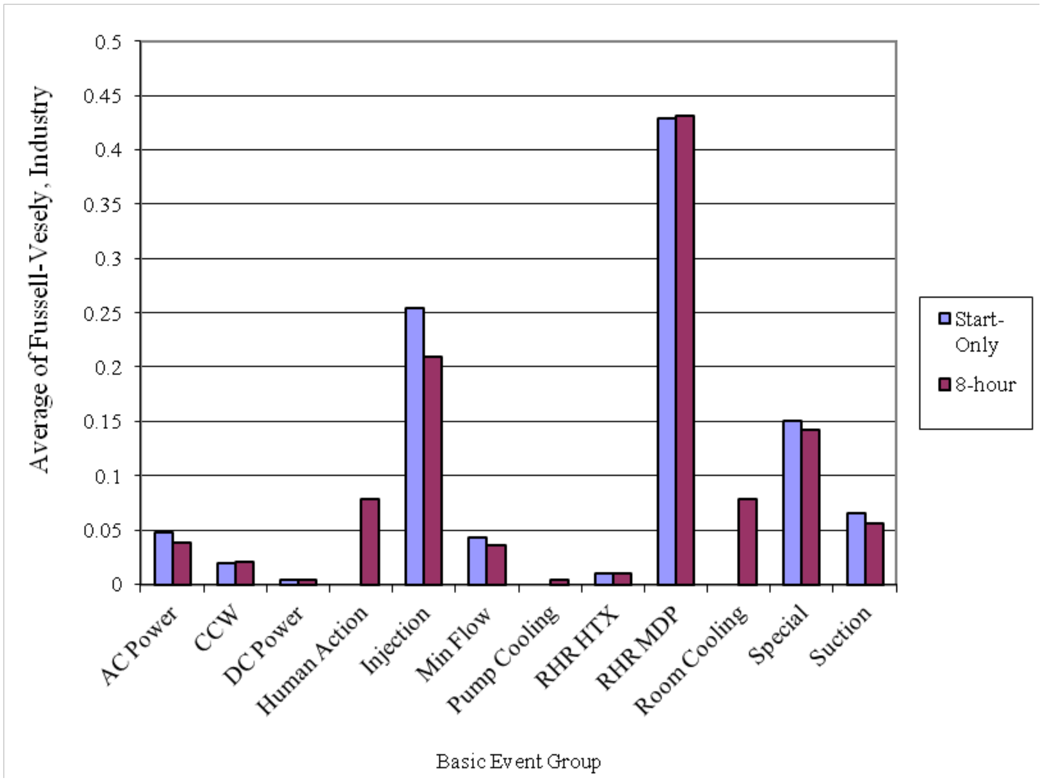

Figure 9. RHR (injection mode) industry-wide basic event group importances.

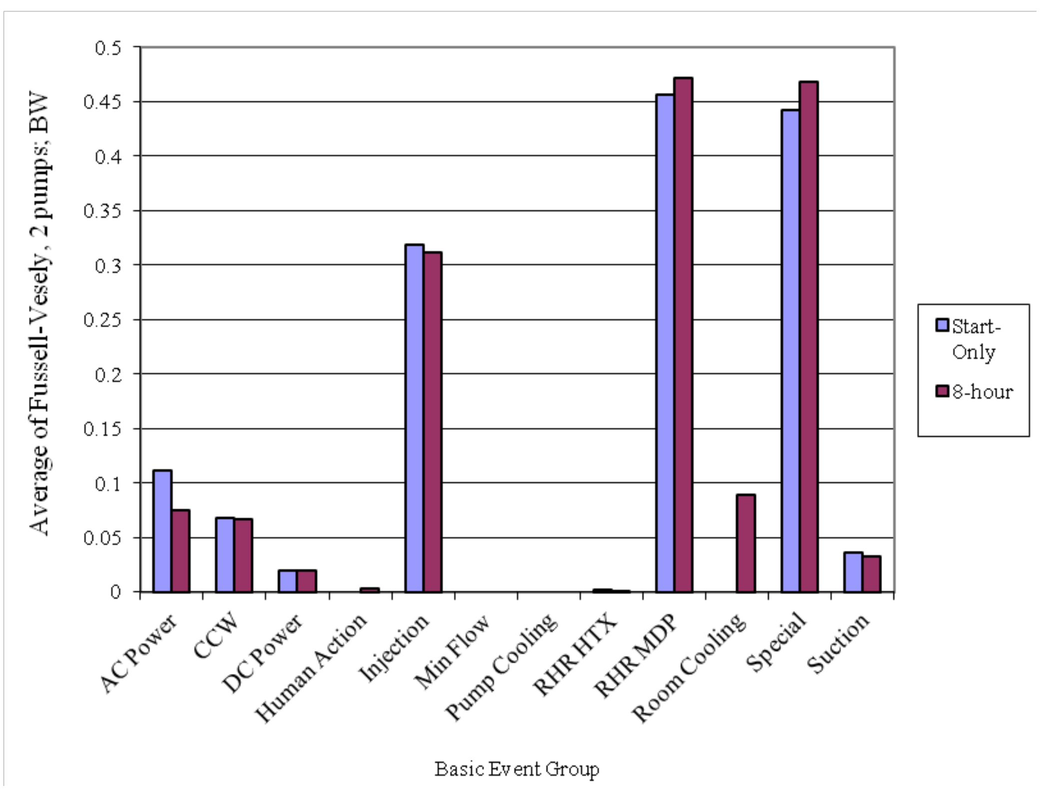

Figure 10. RHR (injection mode) two pump BW basic event group importances.

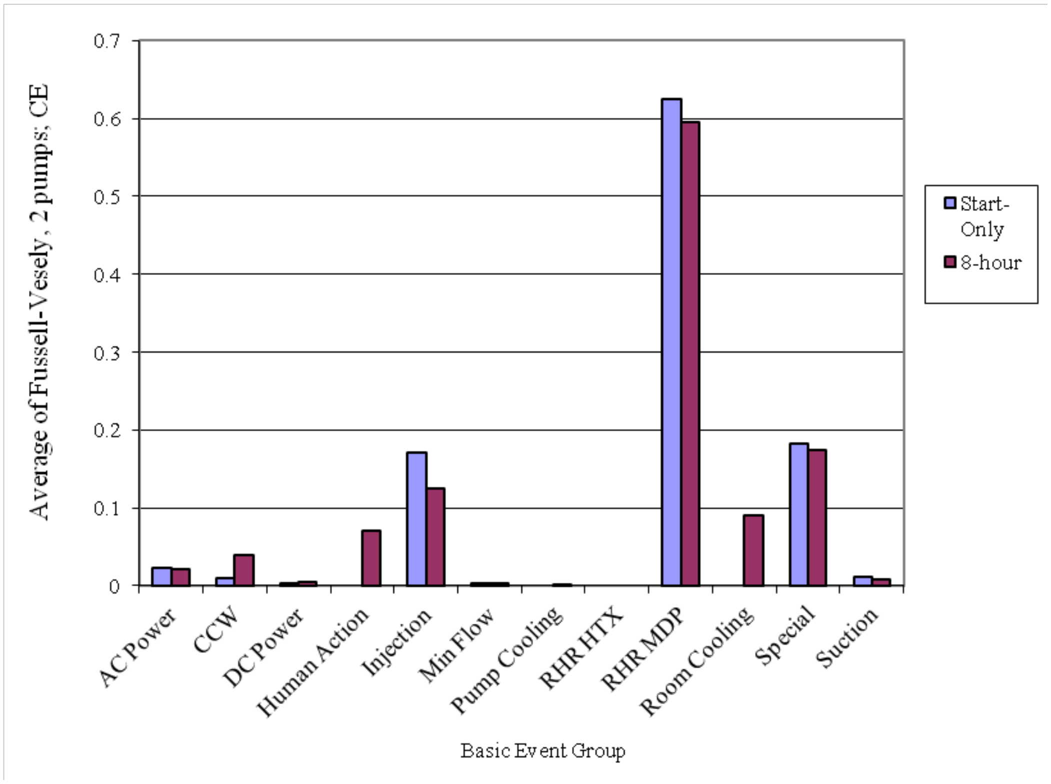

Figure 11. RHR (injection mode) two pumps CE basic event group importances.

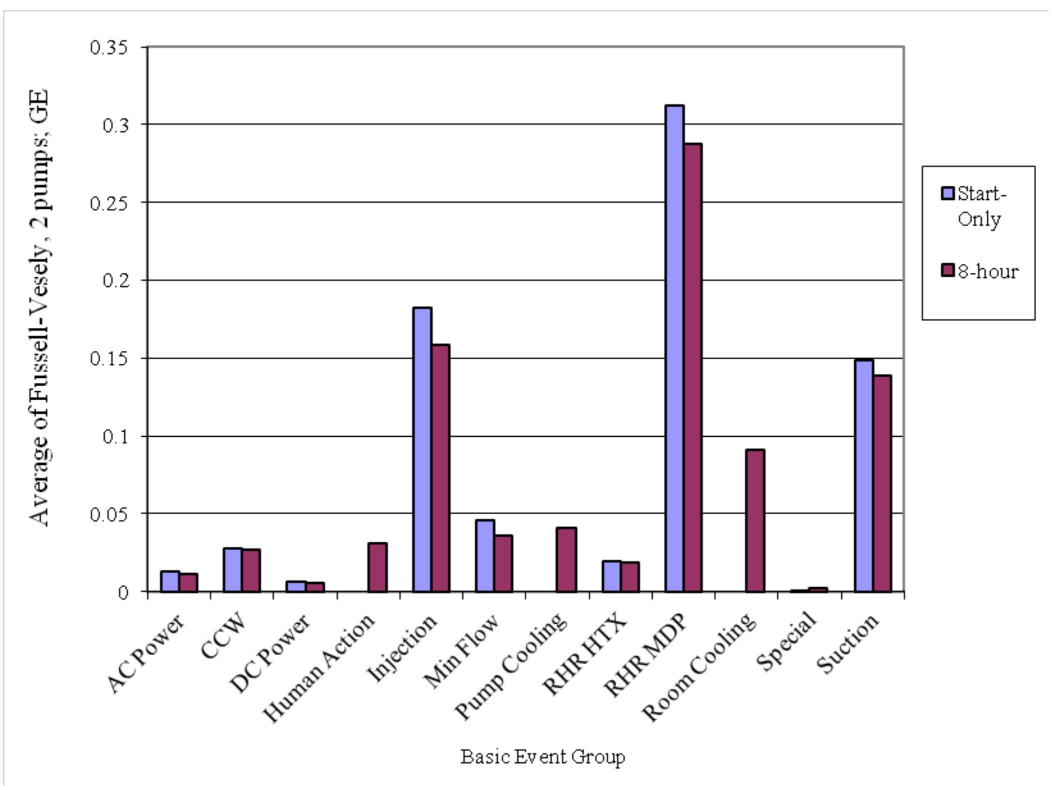

Figure 12. RHR (injection mode) two pumps GE basic event group importances.

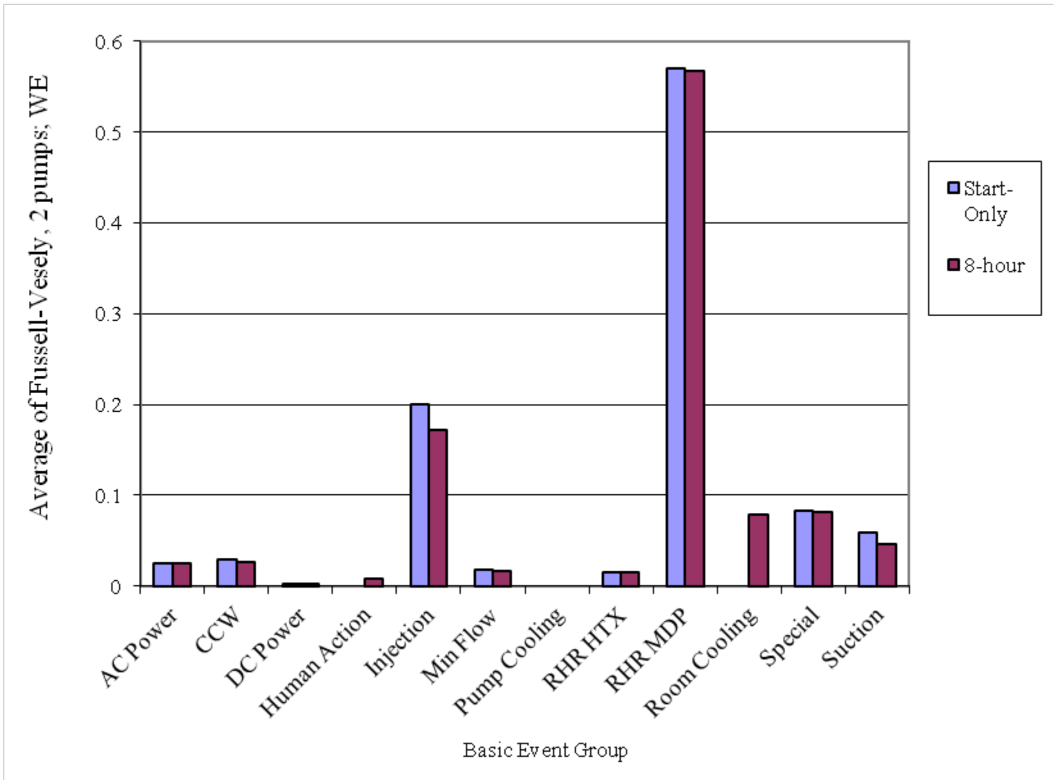

Figure 13. RHR (injection mode) two pumps WE basic event group importances.

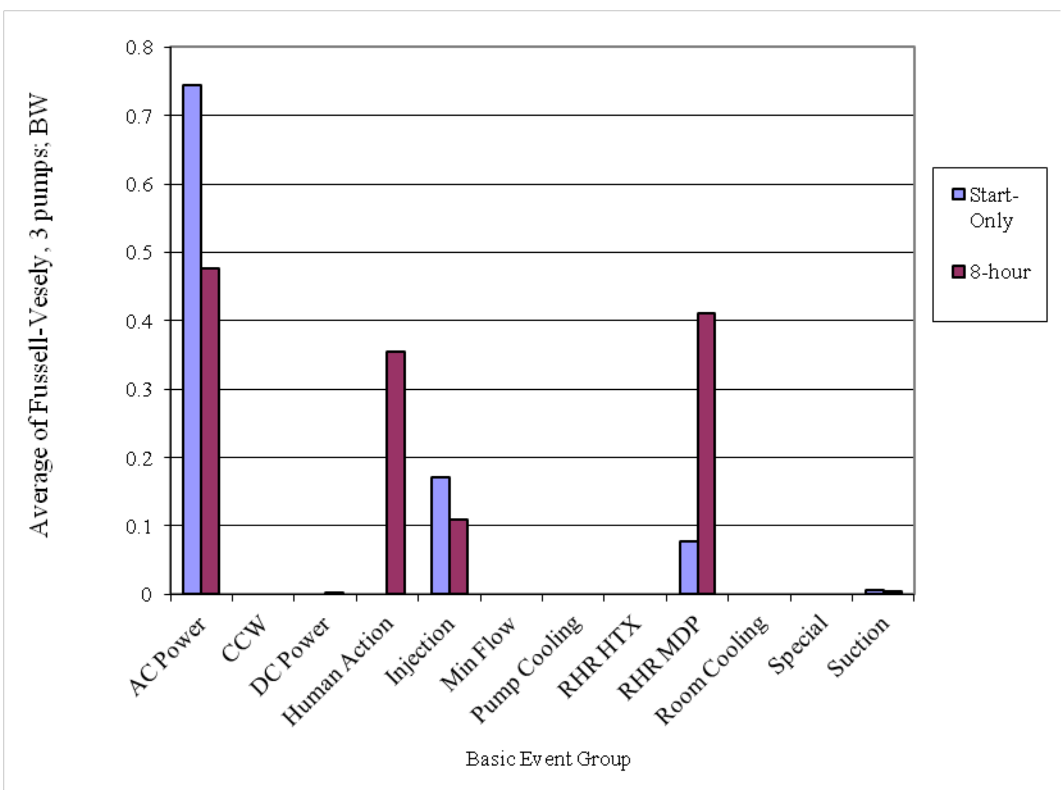

Figure 14. RHR (injection mode) three pumps BW basic event group importances.

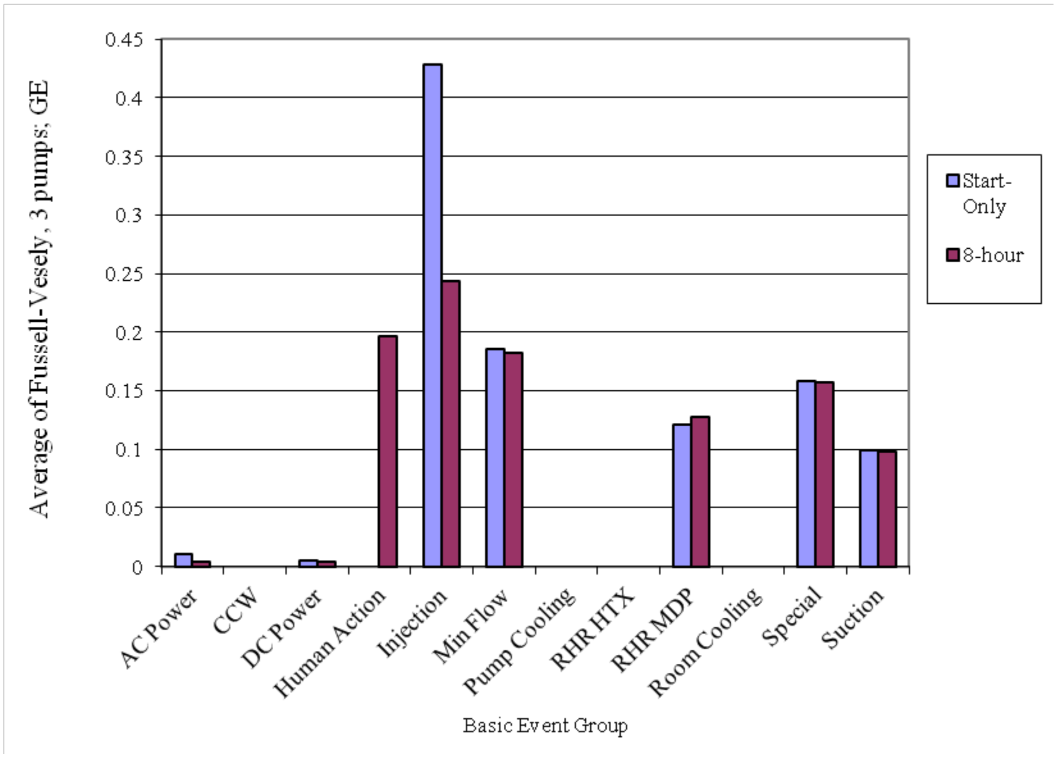

Figure 15. RHR (injection mode) three pumps GE basic event group importances.

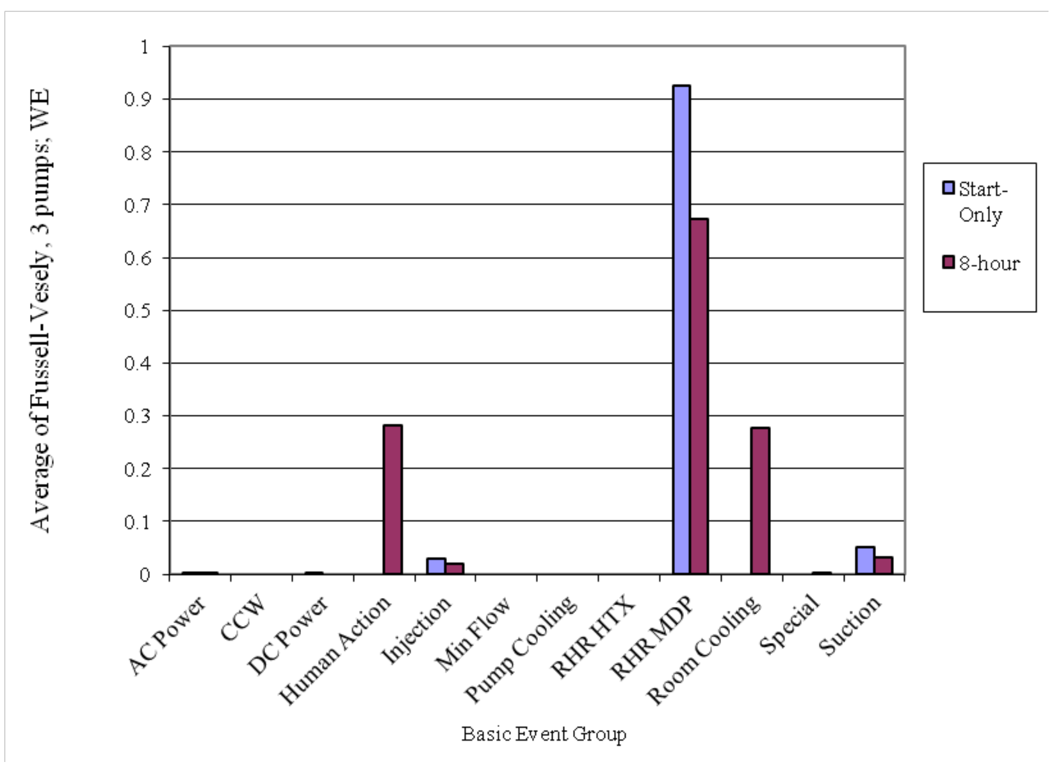

Figure 16. RHR (injection mode) three pumps WE basic event group importances.

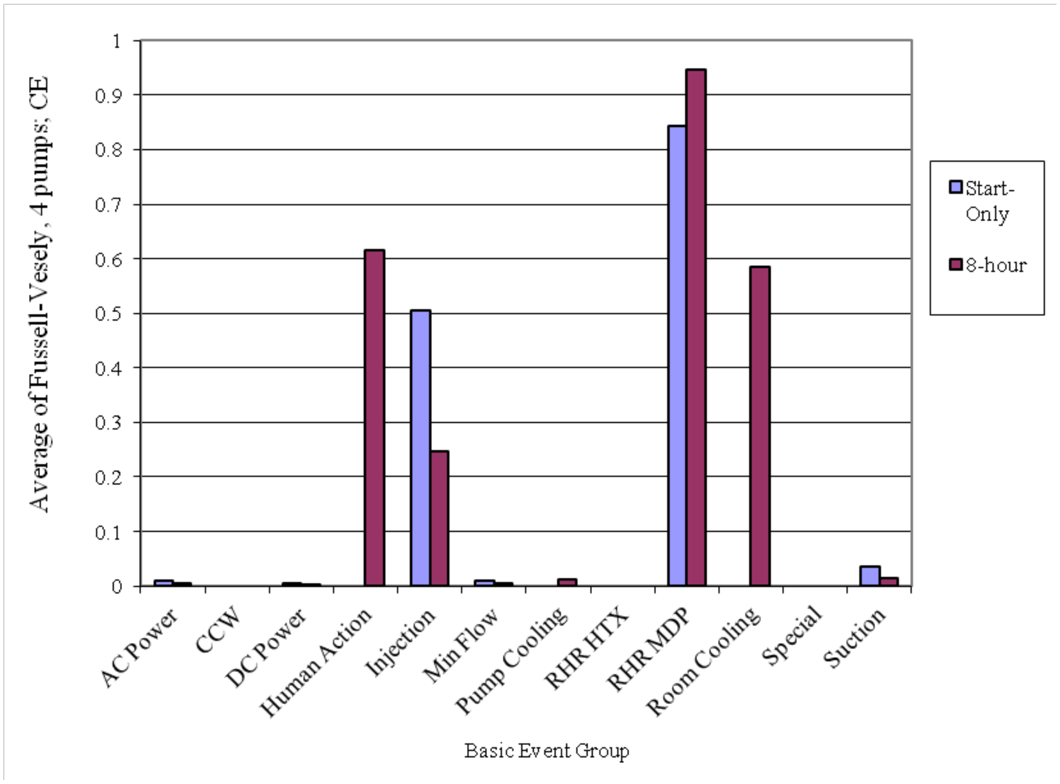

Figure 17. RHR (injection mode) four pumps CE basic event group importances.

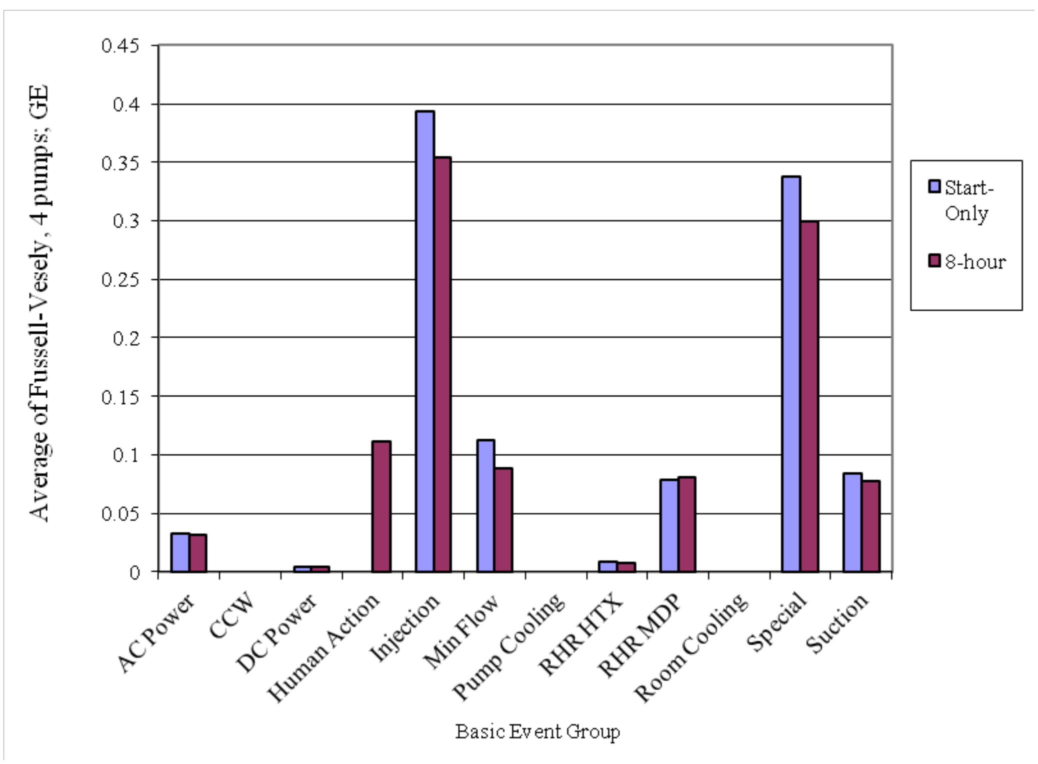

Figure 18. RHR (injection mode) four pumps GE basic event group importances.

5.2 Shutdown Cooling Mode

The industry-wide RHR start-only and 24-hour basic event group importances for shutdown cooling mode are shown in Figure 19. In both cases, the leading contributor to RHR system unreliability is the realignment of the RHR suction flowpath followed by random failures of the injection flow path. For more discussion on the RHR MOVs and AOVs, see the MOV and AOV component reliability studies at NRC Reactor Operational Experience Results and Databases.

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

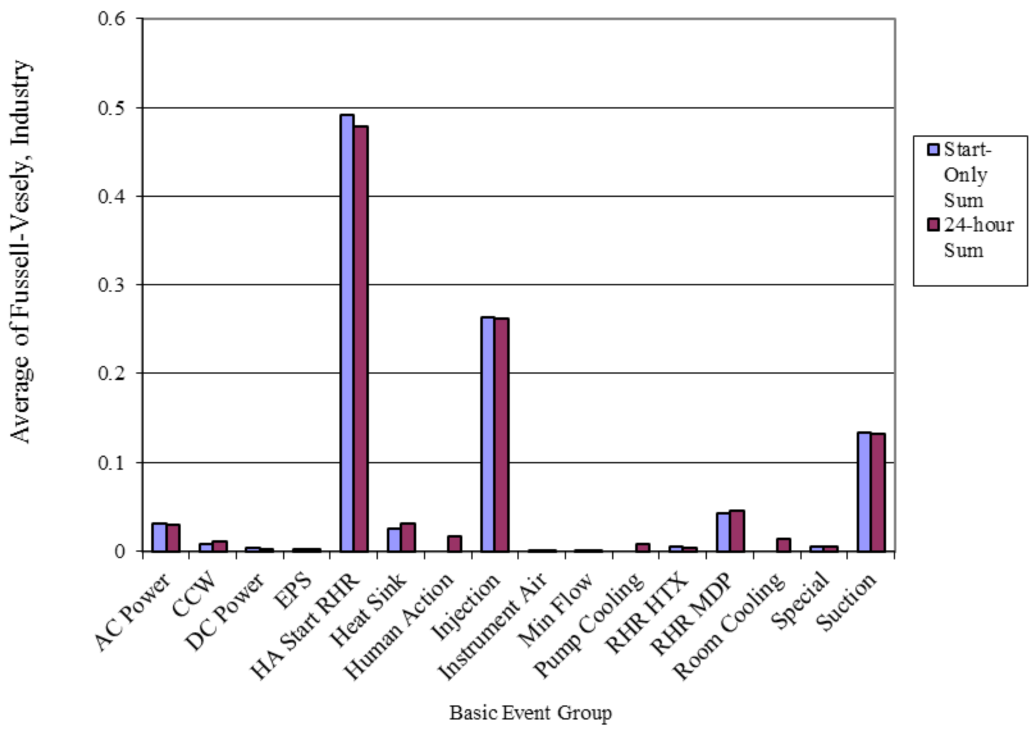

Figure 19. RHR shutdown cooling mode industry-wide basic event group importances.

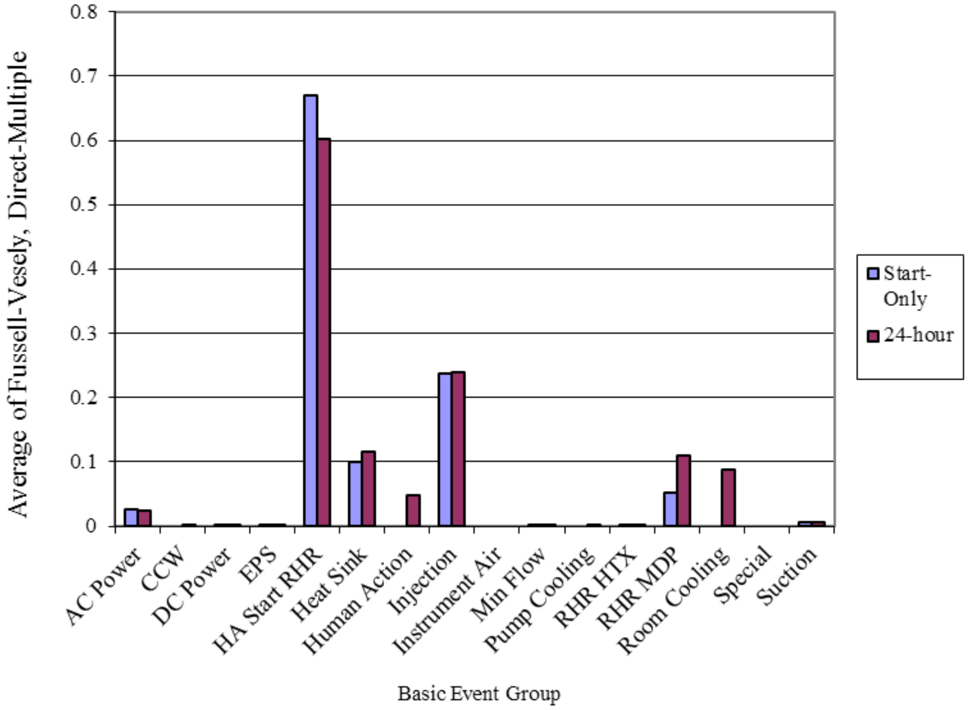

Figure 20. RHR shutdown cooling mode direct heat sink, multiple suction path basic event group importances.

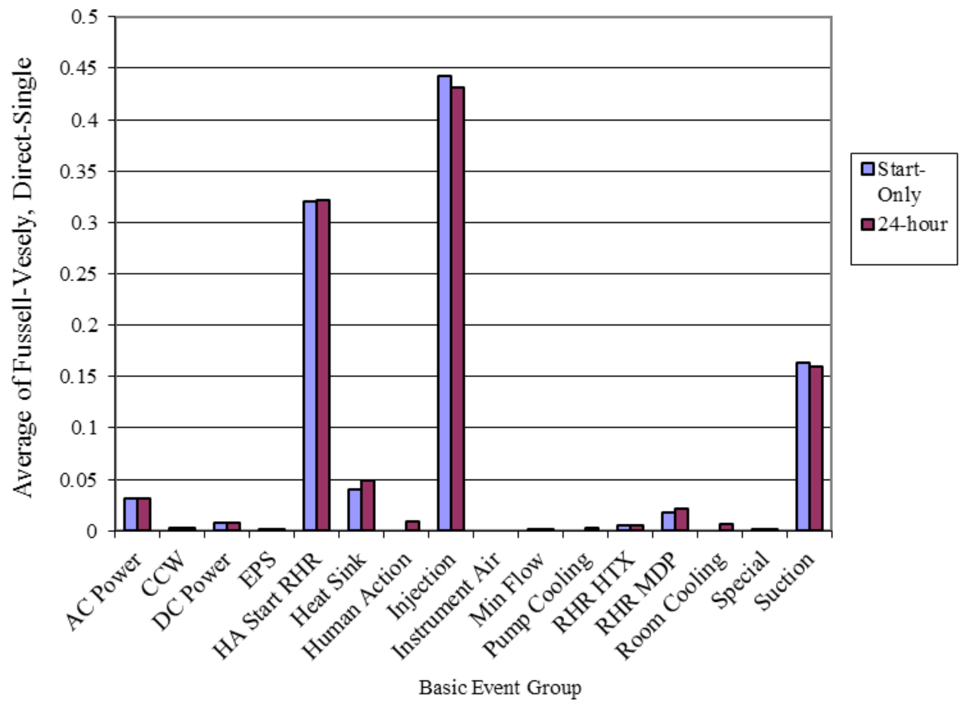

Figure 21. RHR shutdown cooling mode direct heat sink, single suction path basic event group importances.

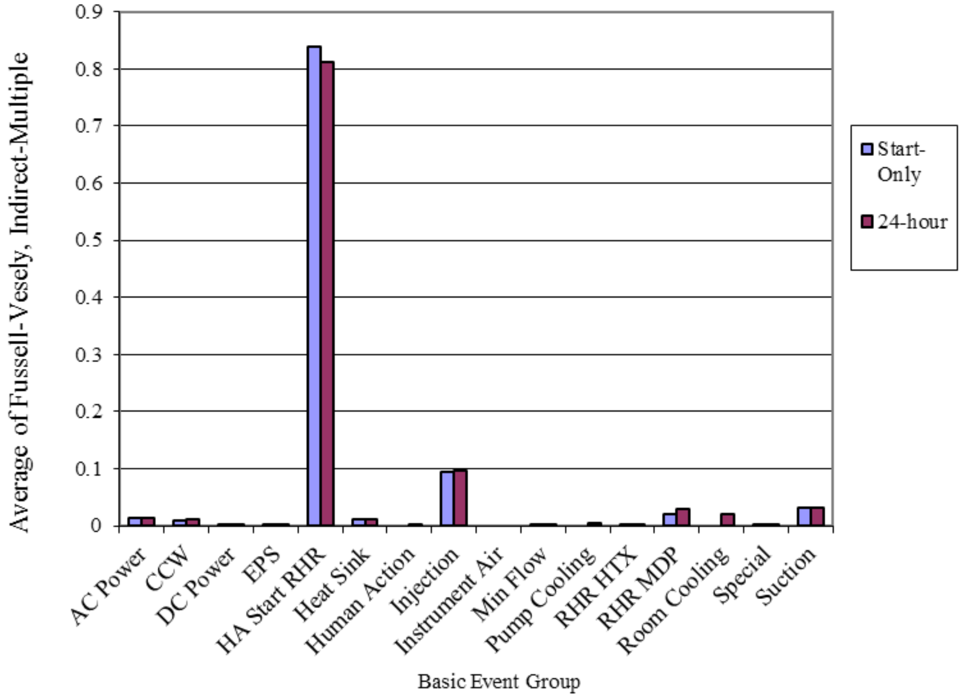

Figure 22. RHR shutdown cooling mode indirect heat sink, multiple suction paths basic event group importances.

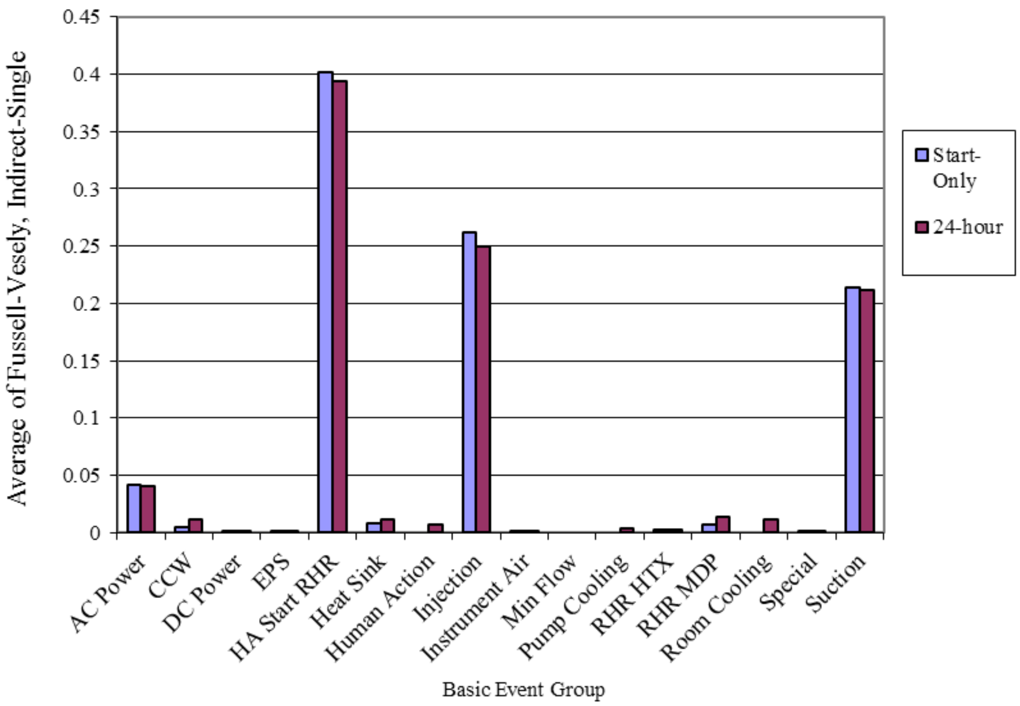

Figure 23. RHR shutdown cooling mode indirect heat sink, single suction path basic event group importances.

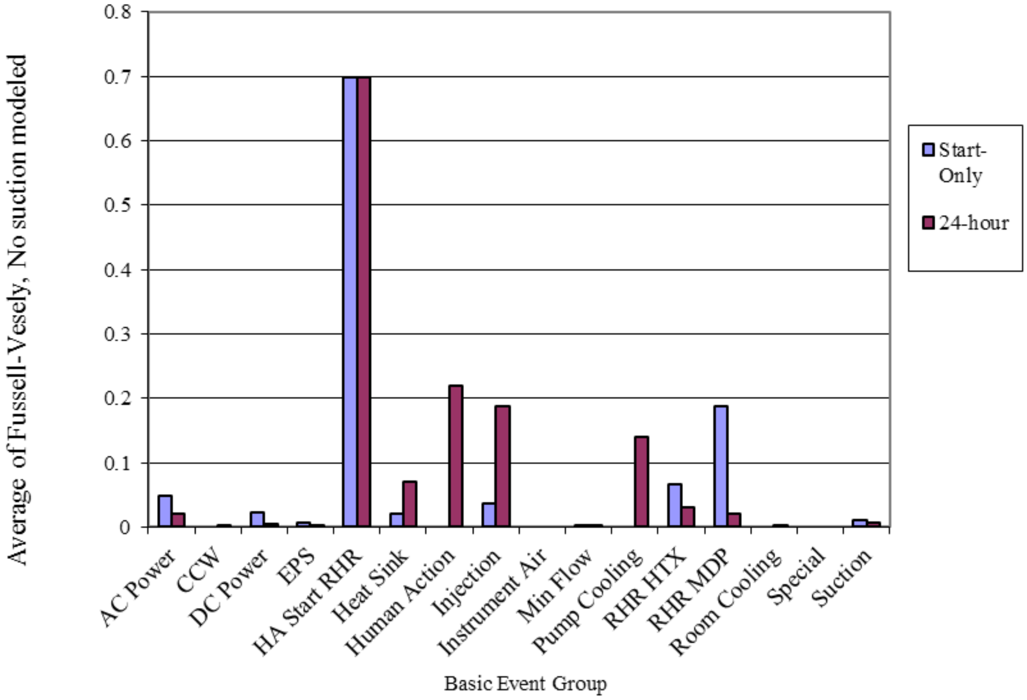

Figure 24. RHR shutdown cooling mode no suction modeled basic event group importances.

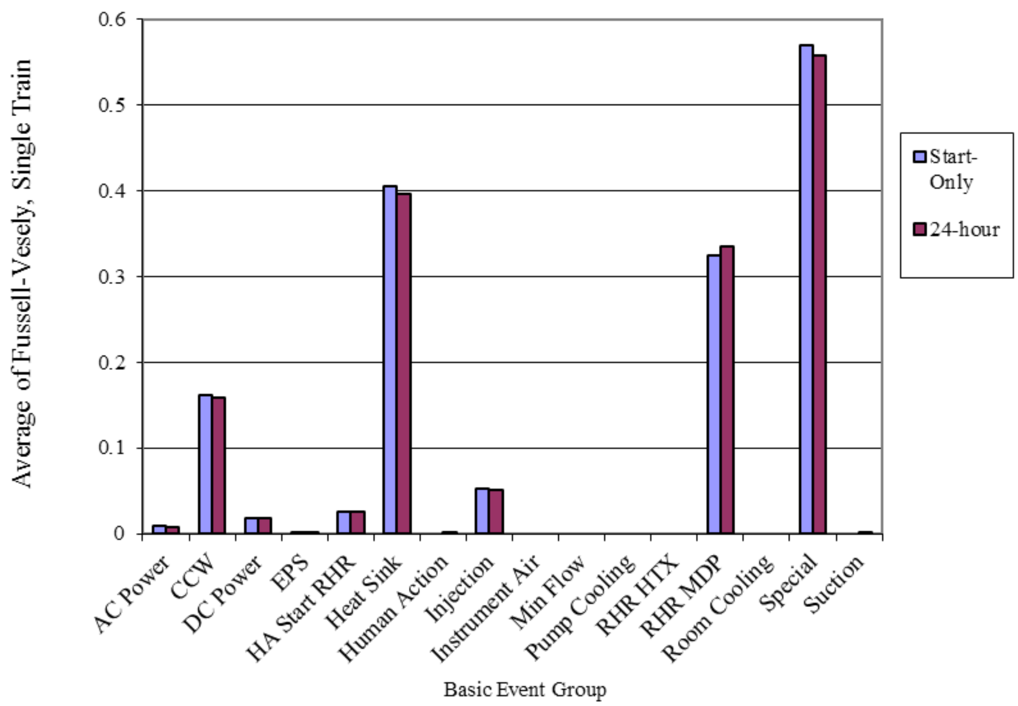

Figure 25. RHR shutdown cooling mode single train basic event group importances.

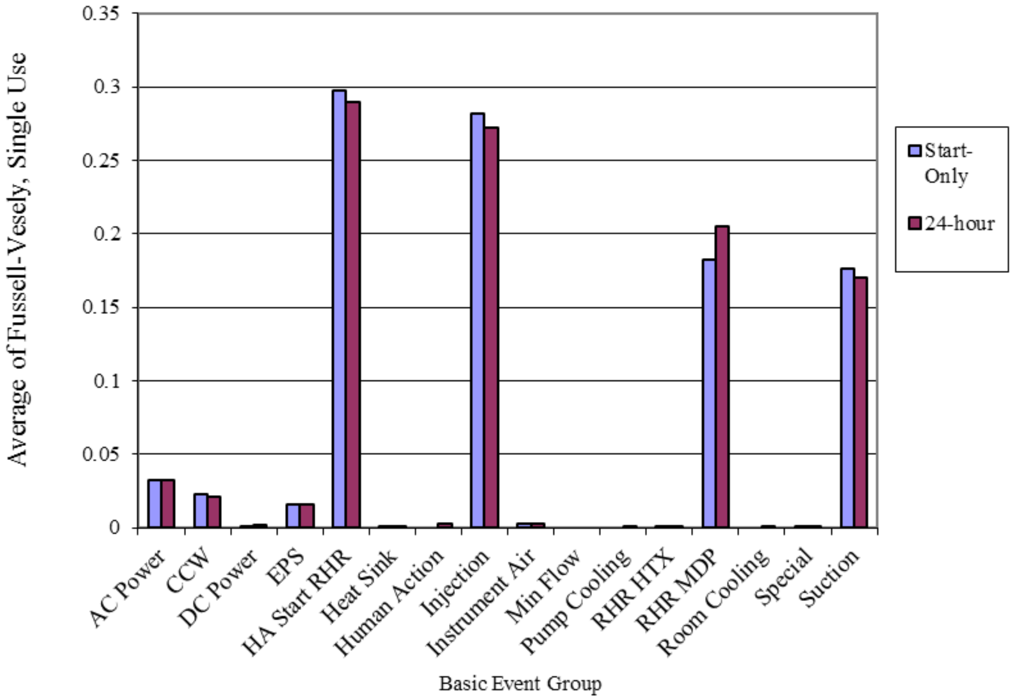

Figure 26. RHR shutdown cooling mode single use SDC system basic event group importances.

6. DATA TABLES

Table 7. Plot data for RHR low-pressure injection mode start-only trend, Figure 5.

	Regression Curve Data Points			Annual Estimate Data Points		
FY/Source	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
Industry				7.08E−06	8.57E−04	2.60E−04
1998				1.42E-05	8.83E-04	2.71E-04
1999				1.18E-05	8.73E-04	2.57E-04
2000				1.34E-05	8.80E-04	2.65E-04
2001				1.19E-05	8.77E-04	2.56E-04
2002				7.66E-06	8.59E-04	2.43E-04
2003				1.16E-05	8.72E-04	2.54E-04
2004				1.03E-05	8.68E-04	2.46E-04
2005	2.61E-04	2.48E-04	2.75E-04	1.14E-05	8.69E-04	2.55E-04
2006	2.58E-04	2.47E-04	2.69E-04	9.87E-06	8.70E-04	2.62E-04
2007	2.55E-04	2.46E-04	2.64E-04	1.25E-05	8.75E-04	2.68E-04
2008	2.52E-04	2.45E-04	2.60E-04	8.73E-06	8.65E-04	2.46E-04
2009	2.49E-04	2.43E-04	2.56E-04	7.58E-06	8.60E-04	2.43E-04
2010	2.46E-04	2.40E-04	2.53E-04	9.47E-06	8.64E-04	2.55E-04
2011	2.44E-04	2.37E-04	2.51E-04	6.89E-06	8.57E-04	2.35E-04
2012	2.41E-04	2.32E-04	2.49E-04	6.02E-06	8.55E-04	2.36E-04
2013	2.38E-04	2.28E-04	2.48E-04	8.15E-06	8.66E-04	2.43E-04
2014	2.35E-04	2.23E-04	2.47E-04	6.11E-06	8.56E-04	2.37E-04

Table 8. Plot data for RHR low-pressure injection mode 8-hour trend, Figure 6.

	Regression Curve Data Points			Annual Estimate Data Points		
FY/Source	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
Industry				1.07E−05	8.96E−04	3.07E−04
1998				1.71E-05	9.37E-04	3.27E-04
1999				1.46E-05	9.21E-04	3.13E-04
2000				1.66E-05	9.31E-04	3.24E-04
2001				1.39E-05	9.14E-04	3.10E-04
2002				1.20E-05	8.97E-04	2.97E-04
2003				1.46E-05	9.19E-04	3.08E-04
2004				1.29E-05	9.05E-04	3.01E-04
2005	3.07E-04	2.91E-04	3.23E-04	1.44E-05	9.01E-04	3.03E-04
2006	3.04E-04	2.91E-04	3.18E-04	1.33E-05	9.01E-04	3.05E-04
2007	3.02E-04	2.91E-04	3.13E-04	1.66E-05	9.32E-04	3.25E-04
2008	3.00E-04	2.91E-04	3.09E-04	1.20E-05	9.03E-04	2.90E-04
2009	2.98E-04	2.90E-04	3.05E-04	1.10E-05	8.91E-04	2.87E-04
2010	2.95E-04	2.88E-04	3.03E-04	1.26E-05	8.97E-04	2.97E-04
2011	2.93E-04	2.85E-04	3.02E-04	9.96E-06	8.85E-04	2.87E-04
2012	2.91E-04	2.81E-04	3.02E-04	1.05E-05	8.97E-04	2.91E-04
2013	2.89E-04	2.76E-04	3.02E-04	1.14E-05	9.08E-04	2.92E-04
2014	2.87E-04	2.72E-04	3.02E-04	1.02E-05	8.93E-04	2.90E-04

Table 9. Plot data for RHR shutdown cooling mode start-only trend, Figure 7.

	Regression Curve Data Points			Annual Estimate Data Points		
FY/Source	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
Industry				1.80E−04	1.39E−02	4.39E−03
1998				2.25E-04	1.57E-02	5.22E-03
1999				2.04E-04	1.42E-02	4.51E-03
2000				2.10E-04	1.46E-02	4.68E-03
2001				1.86E-04	1.33E-02	4.00E-03
2002				1.85E-04	1.31E-02	4.18E-03
2003				1.89E-04	1.34E-02	4.08E-03
2004				1.74E-04	1.27E-02	3.85E-03
2005	5.11E-03	4.24E-03	6.15E-03	2.01E-04	1.41E-02	4.57E-03
2006	4.93E-03	4.22E-03	5.76E-03	2.21E-04	1.57E-02	5.39E-03
2007	4.75E-03	4.18E-03	5.40E-03	2.35E-04	1.61E-02	5.50E-03
2008	4.58E-03	4.13E-03	5.09E-03	1.77E-04	1.29E-02	4.07E-03
2009	4.42E-03	4.03E-03	4.85E-03	1.90E-04	1.33E-02	4.29E-03
2010	4.26E-03	3.89E-03	4.68E-03	2.13E-04	1.48E-02	4.99E-03
2011	4.11E-03	3.70E-03	4.57E-03	1.57E-04	1.19E-02	3.57E-03
2012	3.97E-03	3.49E-03	4.51E-03	1.63E-04	1.23E-02	3.86E-03
2013	3.83E-03	3.27E-03	4.47E-03	1.70E-04	1.23E-02	3.77E-03
2014	3.69E-03	3.06E-03	4.45E-03	1.63E-04	1.23E-02	3.88E-03

Table 10. Plot data for RHR shutdown cooling mode 24-hour trend, Figure 8.

	Regression Curve Data Points			Annual Estimate Data Points		
FY/Source	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
Industry				2.23E−04	1.44E−02	4.57E−03
1998				2.76E-04	1.61E-02	5.37E-03
1999				2.46E-04	1.45E-02	4.64E-03
2000				2.61E-04	1.53E-02	4.87E-03
2001				2.27E-04	1.37E-02	4.14E-03
2002				2.35E-04	1.41E-02	4.44E-03
2003				2.54E-04	1.49E-02	4.40E-03
2004				2.20E-04	1.34E-02	4.02E-03
2005	5.30E-03	4.45E-03	6.30E-03	2.50E-04	1.49E-02	4.77E-03
2006	5.12E-03	4.42E-03	5.92E-03	2.74E-04	1.62E-02	5.55E-03
2007	4.95E-03	4.39E-03	5.57E-03	2.99E-04	1.70E-02	5.75E-03
2008	4.78E-03	4.33E-03	5.27E-03	2.29E-04	1.37E-02	4.24E-03
2009	4.62E-03	4.24E-03	5.03E-03	2.33E-04	1.39E-02	4.46E-03
2010	4.46E-03	4.09E-03	4.87E-03	2.56E-04	1.51E-02	5.10E-03
2011	4.31E-03	3.91E-03	4.76E-03	2.04E-04	1.26E-02	3.80E-03
2012	4.17E-03	3.70E-03	4.70E-03	2.25E-04	1.35E-02	4.13E-03
2013	4.03E-03	3.48E-03	4.66E-03	2.17E-04	1.31E-02	3.96E-03
2014	3.89E-03	3.27E-03	4.63E-03	2.16E-04	1.31E-02	4.07E-03

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	1	868	1.04E-03	2.112	2035	Beta
FTOC	AOV	1999	1	1031	9.60E-04	2.112	2198	Beta
FTOC	AOV	2000	0	878	5.43E-04	1.112	2046	Beta
FTOC	AOV	2001	0	961	5.22E-04	1.112	2129	Beta
FTOC	AOV	2002	1	988	9.79E-04	2.112	2155	Beta
FTOC	AOV	2003	1	973	9.86E-04	2.112	2140	Beta
FTOC	AOV	2004	0	923	5.31E-04	1.112	2091	Beta
FTOC	AOV	2005	0	838	5.54E-04	1.112	2006	Beta
FTOC	AOV	2006	2	717	1.65E-03	3.112	1883	Beta
FTOC	AOV	2007	1	737	1.11E-03	2.112	1904	Beta
FTOC	AOV	2008	0	729	5.86E-04	1.112	1897	Beta
FTOC	AOV	2009	1	726	1.11E-03	2.112	1893	Beta
FTOC	AOV	2010	1	756	1.10E-03	2.112	1923	Beta
FTOC	AOV	2011	0	738	5.83E-04	1.112	1906	Beta
FTOC	AOV	2012	0	721	5.88E-04	1.112	1889	Beta
FTOC	AOV	2013	0	734	5.84E-04	1.112	1902	Beta
FTOC	AOV	2014	0	716	5.90E-04	1.112	1884	Beta
FTOC	MOV	1998	17	11377	1.41E-03	19.046	13483	Beta
FTOC	MOV	1999	14	13631	1.02E-03	16.046	15740	Beta
FTOC	MOV	2000	16	13538	1.15E-03	18.046	15645	Beta
FTOC	MOV	2001	10	13831	7.55E-04	12.046	15944	Beta
FTOC	MOV	2002	12	13953	8.74E-04	14.046	16064	Beta
FTOC	MOV	2003	10	13762	7.58E-04	12.046	15875	Beta
FTOC	MOV	2004	8	12774	6.74E-04	10.046	14889	Beta
FTOC	MOV	2005	14	12252	1.12E-03	16.046	14361	Beta
FTOC	MOV	2006	16	9955	1.49E-03	18.046	12062	Beta
FTOC	MOV	2007	17	9901	1.58E-03	19.046	12007	Beta
FTOC	MOV	2008	8	9946	8.32E-04	10.046	12061	Beta
FTOC	MOV	2009	9	9741	9.31E-04	11.046	11855	Beta
FTOC	MOV	2010	14	10024	1.32E-03	16.046	12133	Beta
FTOC	MOV	2011	5	10053	5.79E-04	7.046	12171	Beta
FTOC	MOV	2012	7	9992	7.47E-04	9.046	12108	Beta
FTOC	MOV	2013	6	10041	6.61E-04	8.046	12158	Beta
FTOC	MOV	2014	7	9957	7.49E-04	9.046	12073	Beta
FTOP	AOV	1998	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	1999	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2000	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2001	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2002	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2003	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2004	0	1314000	2.02E-07	1.421	7033000	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	2005	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2006	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2007	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2008	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2009	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2010	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2011	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2012	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2013	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	AOV	2014	0	1314000	2.02E-07	1.421	7033000	Gamma
FTOP	MOV	1998	1	15741720	6.50E-08	2.458	37791720	Gamma
FTOP	MOV	1999	3	15881880	1.18E-07	4.458	37931880	Gamma
FTOP	MOV	2000	6	15881880	1.97E-07	7.458	37931880	Gamma
FTOP	MOV	2001	1	15881880	6.48E-08	2.458	37931880	Gamma
FTOP	MOV	2002	0	15881880	3.84E-08	1.458	37931880	Gamma
FTOP	MOV	2003	2	15916920	9.11E-08	3.458	37966920	Gamma
FTOP	MOV	2004	0	15890640	3.84E-08	1.458	37940640	Gamma
FTOP	MOV	2005	0	15890640	3.84E-08	1.458	37940640	Gamma
FTOP	MOV	2006	1	15890640	6.48E-08	2.458	37940640	Gamma
FTOP	MOV	2007	1	15881880	6.48E-08	2.458	37931880	Gamma
FTOP	MOV	2008	0	15873120	3.84E-08	1.458	37923120	Gamma
FTOP	MOV	2009	0	15873120	3.84E-08	1.458	37923120	Gamma
FTOP	MOV	2010	1	15873120	6.48E-08	2.458	37923120	Gamma
FTOP	MOV	2011	0	16109640	3.82E-08	1.458	38159640	Gamma
FTOP	MOV	2012	1	15951960	6.47E-08	2.458	38001960	Gamma
FTOP	MOV	2013	2	15951960	9.10E-08	3.458	38001960	Gamma
FTOP	MOV	2014	0	15925680	3.84E-08	1.458	37975680	Gamma
FTR<1H	MDP	1998	0	4537	9.42E-05	1.820	19327	Gamma
FTR<1H	MDP	1999	1	4690	1.45E-04	2.820	19480	Gamma
FTR<1H	MDP	2000	2	4703	1.96E-04	3.820	19493	Gamma
FTR<1H	MDP	2001	0	4570	9.40E-05	1.820	19360	Gamma
FTR<1H	MDP	2002	1	4765	1.44E-04	2.820	19555	Gamma
FTR<1H	MDP	2003	0	5182	9.11E-05	1.820	19972	Gamma
FTR<1H	MDP	2004	0	5124	9.14E-05	1.820	19914	Gamma
FTR<1H	MDP	2005	0	5414	9.01E-05	1.820	20204	Gamma
FTR<1H	MDP	2006	0	4987	9.20E-05	1.820	19777	Gamma
FTR<1H	MDP	2007	0	5232	9.09E-05	1.820	20022	Gamma
FTR<1H	MDP	2008	0	5082	9.16E-05	1.820	19872	Gamma
FTR<1H	MDP	2009	0	5143	9.13E-05	1.820	19933	Gamma
FTR<1H	MDP	2010	0	5253	9.08E-05	1.820	20043	Gamma
FTR<1H	MDP	2011	0	4979	9.21E-05	1.820	19769	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	2012	1	5077	1.42E-04	2.820	19867	Gamma
FTR<1H	MDP	2013	1	5253	1.41E-04	2.820	20043	Gamma
FTR<1H	MDP	2014	2	4903	1.94E-04	3.820	19693	Gamma
FTR>1H	MDP	1998	1	101829	1.01E-05	1.781	176839	Gamma
FTR>1H	MDP	1999	0	80909	5.01E-06	0.781	155919	Gamma
FTR>1H	MDP	2000	1	54515	1.38E-05	1.781	129525	Gamma
FTR>1H	MDP	2001	0	64853	5.58E-06	0.781	139864	Gamma
FTR>1H	MDP	2002	3	53175	2.95E-05	3.781	128185	Gamma
FTR>1H	MDP	2003	6	62061	4.95E-05	6.781	137072	Gamma
FTR>1H	MDP	2004	2	46351	2.29E-05	2.781	121361	Gamma
FTR>1H	MDP	2005	1	53193	1.39E-05	1.781	128203	Gamma
FTR>1H	MDP	2006	0	43873	6.57E-06	0.781	118883	Gamma
FTR>1H	MDP	2007	3	47807	3.08E-05	3.781	122817	Gamma
FTR>1H	MDP	2008	2	47863	2.26E-05	2.781	122873	Gamma
FTR>1H	MDP	2009	1	44270	1.49E-05	1.781	119280	Gamma
FTR>1H	MDP	2010	0	48434	6.33E-06	0.781	123444	Gamma
FTR>1H	MDP	2011	2	48201	2.26E-05	2.781	123211	Gamma
FTR>1H	MDP	2012	4	54123	3.70E-05	4.781	129133	Gamma
FTR>1H	MDP	2013	2	51875	2.19E-05	2.781	126885	Gamma
FTR>1H	MDP	2014	1	45574	1.48E-05	1.781	120584	Gamma
FTS	MDP	1998	6	4537	1.21E-03	7.948	6585	Beta
FTS	MDP	1999	5	4690	1.03E-03	6.948	6739	Beta
FTS	MDP	2000	6	4703	1.18E-03	7.948	6751	Beta
FTS	MDP	2001	6	4570	1.20E-03	7.948	6618	Beta
FTS	MDP	2002	2	4765	5.79E-04	3.948	6817	Beta
FTS	MDP	2003	6	5182	1.10E-03	7.948	7230	Beta
FTS	MDP	2004	5	5124	9.68E-04	6.948	7173	Beta
FTS	MDP	2005	5	5414	9.30E-04	6.948	7463	Beta
FTS	MDP	2006	3	4987	7.03E-04	4.948	7038	Beta
FTS	MDP	2007	5	5232	9.53E-04	6.948	7281	Beta
FTS	MDP	2008	3	5082	6.93E-04	4.948	7133	Beta
FTS	MDP	2009	2	5143	5.48E-04	3.948	7195	Beta
FTS	MDP	2010	3	5253	6.77E-04	4.948	7304	Beta
FTS	MDP	2011	2	4979	5.61E-04	3.948	7031	Beta
FTS	MDP	2012	1	5077	4.13E-04	2.948	7130	Beta
FTS	MDP	2013	3	5253	6.77E-04	4.948	7304	Beta
FTS	MDP	2014	1	4903	4.24E-04	2.948	6956	Beta
LOHT	HTX	1998	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	1999	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2000	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2001	2	0	5.86E-07	18.500	31564650	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	2002	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2003	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2004	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2005	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2006	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2007	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2008	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2009	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2010	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2011	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2012	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2013	0	0	5.23E-07	16.500	31564650	Gamma
LOHT	HTX	2014	0	0	5.23E-07	16.500	31564650	Gamma
SO	AOV	1998	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	1999	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2000	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2001	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2002	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2003	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2004	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2005	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2006	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2007	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2008	1	1314000	2.57E-07	1.680	6525000	Gamma
SO	AOV	2009	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2010	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2011	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2012	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	AOV	2013	1	1314000	2.57E-07	1.680	6525000	Gamma
SO	AOV	2014	0	1314000	1.04E-07	0.680	6525000	Gamma
SO	MOV	1998	3	15741720	1.10E-07	3.570	32581720	Gamma
SO	MOV	1999	0	15881880	1.74E-08	0.570	32721880	Gamma
SO	MOV	2000	2	15881880	7.85E-08	2.570	32721880	Gamma
SO	MOV	2001	0	15881880	1.74E-08	0.570	32721880	Gamma
SO	MOV	2002	0	15881880	1.74E-08	0.570	32721880	Gamma
SO	MOV	2003	1	15916920	4.79E-08	1.570	32756920	Gamma
SO	MOV	2004	0	15890640	1.74E-08	0.570	32730640	Gamma
SO	MOV	2005	0	15890640	1.74E-08	0.570	32730640	Gamma
SO	MOV	2006	0	15890640	1.74E-08	0.570	32730640	Gamma
SO	MOV	2007	1	15881880	4.80E-08	1.570	32721880	Gamma
SO	MOV	2008	0	15873120	1.74E-08	0.570	32713120	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	2009	0	15873120	1.74E-08	0.570	32713120	Gamma
SO	MOV	2010	0	15873120	1.74E-08	0.570	32713120	Gamma
SO	MOV	2011	0	16109640	1.73E-08	0.570	32949640	Gamma
SO	MOV	2012	0	15951960	1.74E-08	0.570	32791960	Gamma
SO	MOV	2013	1	15951960	4.79E-08	1.570	32791960	Gamma
SO	MOV	2014	0	15925680	1.74E-08	0.570	32765680	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 UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	HDR	2002	46.210	76298	6.50E-04	0.313	480.8	Beta
UA	HDR	2003	82.450	104108	5.42E-04	0.391	721.6	Beta
UA	HDR	2004	97.290	135846	6.22E-04	0.239	384.1	Beta
UA	HDR	2005	57.280	127718	3.90E-04	0.647	1656.7	Beta
UA	HDR	2006	61.720	128166	4.63E-04	0.209	450.8	Beta
UA	HDR	2007	87.360	132783	5.22E-04	0.386	738.8	Beta
UA	HDR	2008	72.520	131153	4.88E-04	0.289	592.6	Beta
UA	HDR	2009	83.740	130048	6.13E-04	0.171	279.6	Beta
UA	HDR	2010	50.700	121815	3.35E-04	0.358	1067.4	Beta
UA	HDR	2011	69.600	118160	4.94E-04	0.245	496.0	Beta
UA	HDR	2012	148.650	117699	1.15E-03	0.202	175.3	Beta
UA	HDR	2013	157.450	119651	1.26E-03	0.187	148.2	Beta
UA	HDR	2014	133.460	119441	1.19E-03	0.177	148.6	Beta
UA	HTX	2002	25.270	50600	4.87E-04	0.485	995.0	Beta
UA	HTX	2003	76.800	64793	1.17E-03	0.564	479.4	Beta
UA	HTX	2004	121.880	68060	1.78E-03	0.882	493.4	Beta
UA	HTX	2005	89.070	63664	1.32E-03	0.613	462.4	Beta
UA	HTX	2006	138.760	63550	2.13E-03	1.647	771.7	Beta
UA	HTX	2007	131.920	66979	1.98E-03	1.244	627.7	Beta
UA	HTX	2008	183.640	65370	2.73E-03	0.678	247.5	Beta
UA	HTX	2009	175.170	65542	2.60E-03	0.843	323.4	Beta
UA	HTX	2010	124.630	66029	1.84E-03	0.739	400.5	Beta
UA	HTX	2011	86.640	64211	1.29E-03	1.315	1014.8	Beta
UA	HTX	2012	153.060	59810	2.37E-03	0.746	313.3	Beta
UA	HTX	2013	265.530	62692	3.90E-03	0.722	184.4	Beta
UA	HTX	2014	222.370	62876	3.38E-03	0.840	247.7	Beta
UA	MDP	2002	6757.020	1181635	5.77E-03	1.440	248.2	Beta
UA	MDP	2003	9903.722	1694959	5.80E-03	1.479	253.4	Beta
UA	MDP	2004	8834.132	1823048	4.78E-03	1.669	347.6	Beta
UA	MDP	2005	9412.642	1786052	5.13E-03	2.002	388.7	Beta
UA	MDP	2006	8511.063	1823976	4.54E-03	1.467	321.4	Beta
UA	MDP	2007	8779.190	1812695	4.67E-03	1.392	296.5	Beta
UA	MDP	2008	9328.030	1816209	5.11E-03	2.092	407.3	Beta
UA	MDP	2009	10380.670	1816116	5.45E-03	1.829	333.5	Beta
UA	MDP	2010	10181.760	1788704	5.48E-03	1.904	345.3	Beta
UA	MDP	2011	9126.340	1756809	5.09E-03	1.857	362.9	Beta
UA	MDP	2012	9675.660	1733064	5.23E-03	1.597	303.9	Beta
UA	MDP	2013	9731.110	1702603	5.24E-03	1.438	273.1	Beta
UA	MDP	2014	10079.140	1748918	5.30E-03	1.224	229.8	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
FTR>1H	Fail to run more than one hour (standby)
FTR<1H	Fail to run less than one hour
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
- Shutdown Cooling
- Suppression Pool Cooling (SPC) or Containment Sump Recirculation
- Containment Spray
- Fuel Pool Cooling.

The fundamental differences between plants can be summarized as some plants have dedicated shutdown-cooling systems, plants either use an intermediate closed cooling system or use a direct heat sink source of cooling to the RHR heat exchangers, plants have differing number of pumps (from 2 to 4), and the loop suction valve configuration is a single path with two valves or there are multiple paths. The RHR configurations at each plant are shown in Table 14. Figure 27 shows a generic depiction of a RHR system.

7.1 Low Pressure Injection Mode

The low-pressure injection (LPI) mode of the RHR system is primarily designed to mitigate the 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 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 by heat exchanger cooling water valve adjustment.

Considering the above process, SDC operation requires

- Opening suction and discharge valves (AOV or MOV)

- 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 nuclear power plants. The first is referred to here as a direct heat sink and the second is referred to here as an intermediate heat sink:

Direct Heat Sink—The direct heat sink generally uses a standby service water system to provide the heat sink for shutdown cooling. In some plants this is a dedicated residual heat removal 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 the intermediate cooling water system is to provide a barrier to the release of radioactive liquid to the environment.

Residual Heat Removal System

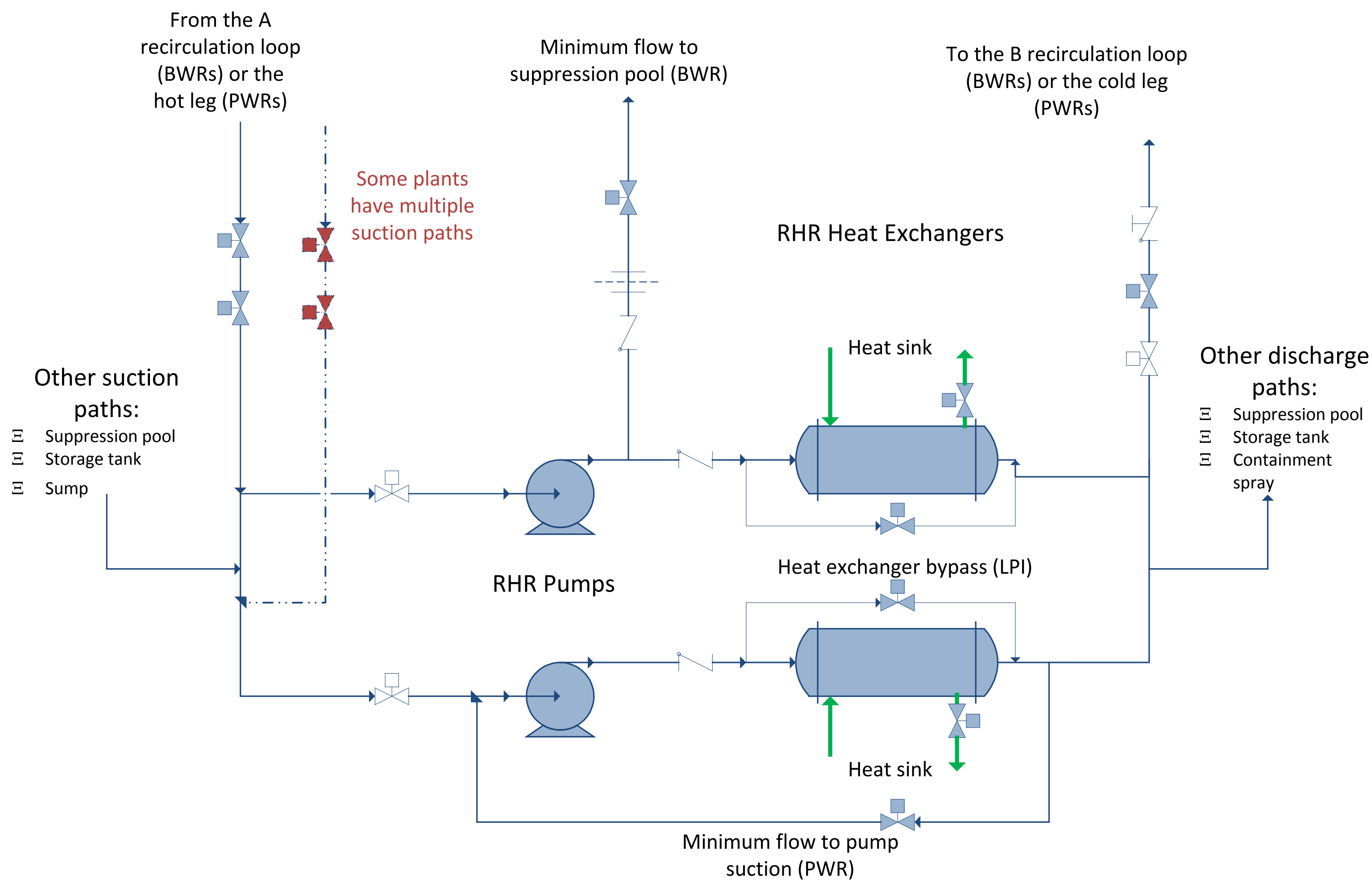

Figure 27. Generic depiction of the RHR system.

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

Plant	Vendor	LPI Tree	SDC Tree[b]	BWR Containment	BWR Design	PWR Loops	Shutdown Cooling Class	Injection Class
Arkansas 1	BW	LPI	DHR			2	Direct-Single	2 pumps; BW
Arkansas 2	CE	LPI	SDC			2	Direct-Single	2 pumps; CE
Beaver Valley 1	WE	LPI	RHR			3	Single Use	2 pumps; WE
Beaver Valley 2	WE	LPI	RHR			3	Single Use	2 pumps; WE
Braidwood 1	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Braidwood 2	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Browns Ferry 1	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Browns Ferry 2	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Browns Ferry 3	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Brunswick 1	GE	LCI	SDC	MARK I(C)	B-CLASS 4		Direct-Single	4 pumps; GE
Brunswick 2	GE	LCI	SDC	MARK I(C)	B-CLASS 4		Direct-Single	4 pumps; GE
Byron 1	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Byron 2	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Callaway	WE	LPI	RHR		SNUPPS	4	Indirect-Multiple	2 pumps; WE
Calvert Cliffs 1	CE	LPI	SDC			2	Indirect-Single	2 pumps; CE
Calvert Cliffs 2	CE	LPI	SDC			2	Indirect-Single	2 pumps; CE
Catawba 1	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Catawba 2	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Clinton 1	GE	LCI	SDC	MARK III(C)	B-CLASS 6		Direct-Single	2 pumps; GE
Columbia 2	GE	LCI	SDC	MARK II	B-CLASS 5		Direct-Single	2 pumps; GE
Comanche Peak 1	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Comanche Peak 2	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Cook 1	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Cook 2	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Cooper	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Crystal River 3	BW	LPI	DHR			2	Direct-Single	2 pumps; BW
Davis-Besse	BW	LPI	DHR			2	Indirect-Single	2 pumps; BW
Diablo Canyon 1	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Diablo Canyon 2	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Dresden 2	GE	LCI	SDC	MARK I	B-CLASS 3		Single Use	3 pumps; GE
Dresden 3	GE	LCI	SDC	MARK I	B-CLASS 3		Single Use	3 pumps; GE
Duane Arnold	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Farley 1	WE	LPI	RHR			3	Indirect-Multiple	2 pumps; WE
Farley 2	WE	LPI	RHR			3	Indirect-Multiple	2 pumps; WE
Fermi 2	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
FitzPatrick	GE	LCI	SPC	MARK I	B-CLASS 4		No suction modeled	4 pumps; GE
Fort Calhoun	CE	LPI	SDC			2	Indirect-Single	2 pumps; CE
Ginna	WE	LPI	RHR			2	Indirect-Single	2 pumps; WE
Grand Gulf	GE	LCI	SDC	MARK III(C)	B-CLASS 6		Direct-Single	2 pumps; GE
Harris	WE	LPI	RHR			3	Indirect-Multiple	2 pumps; WE
Hatch 1	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Hatch 2	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Hope Creek	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	2 pumps; GE
Indian Point 2	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE

Table 14. (continued).

Plant	Vendor	LPI Tree	SDC Tree[b]	BWR Containment	BWR Design	PWR Loops	Shutdown Cooling Class	Injection Class
Indian Point 3	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Kewaunee	WE	LPI	RHR			2	Indirect-Multiple	2 pumps; WE
La Salle 1	GE	LCI	SDC	MARK II(C)	B-CLASS 5		Direct-Single	2 pumps; GE
La Salle 2	GE	LCI	SDC	MARK II(C)	B-CLASS 5		Direct-Single	2 pumps; GE
Limerick 1	GE	LCI	SDC	MARK II(C)	B-CLASS 4		Direct-Single	4 pumps; GE
Limerick 2	GE	LCI	SDC	MARK II(C)	B-CLASS 4		Direct-Single	4 pumps; GE
McGuire 1	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
McGuire 2	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Millstone 2	CE	LPI	SDC			2	Indirect-Single	2 pumps; CE
Millstone 3	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Monticello	GE	LCI	SDC	MARK I	B-CLASS 3		Direct-Single	4 pumps; GE
Nine Mile Pt. 1	GE	LCS	SDC	MARK I	B-CLASS 2		Single Use	3 pumps; GE
Nine Mile Pt. 2	GE	LCI	SDC	MARK II(C)	B-CLASS 5		Direct-Single	2 pumps; GE
North Anna 1	WE	LPI	RHR			3	Single Use	2 pumps; WE
North Anna 2	WE	LPI	RHR			3	Single Use	2 pumps; WE
Oconee 1	BW	LPI	DHR			2	Indirect-Single	3 pumps; BW
Oconee 2	BW	LPI	DHR			2	Indirect-Single	3 pumps; BW
Oconee 3	BW	LPI	DHR			2	Indirect-Single	3 pumps; BW
Oyster Creek	GE	LCI	SDC	MARK I	B-CLASS 2		Single Use	3 pumps; GE
Palisades	CE	LPI	SDC			2	Indirect-Single	2 pumps; CE
Palo Verde 1	CE	LPI	SDC		SYSTEM 80	2	Direct-Multiple	4 pumps; CE
Palo Verde 2	CE	LPI	SDC		SYSTEM 80	2	Direct-Multiple	4 pumps; CE
Palo Verde 3	CE	LPI	SDC		SYSTEM 80	2	Direct-Multiple	4 pumps; CE
Peach Bottom 2	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Peach Bottom 3	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Perry	GE	LCI	SDC	MARK III	B-CLASS 6		Indirect-Single	2 pumps; GE
Pilgrim	GE	LCI	SPC	MARK I	B-CLASS 3		No suction modeled	4 pumps; GE
Point Beach 1	WE	LPI	RHR			2	Indirect-Single	2 pumps; WE
Point Beach 2	WE	LPI	RHR			2	Indirect-Single	2 pumps; WE
Prairie Island 1	WE	LPI	RHR			2	Direct-Multiple	2 pumps; WE
Prairie Island 2	WE	LPI	RHR			2	Direct-Multiple	2 pumps; WE
Quad Cities 1	GE	LCI	SDC	MARK I	B-CLASS 3		Direct-Single	4 pumps; GE
Quad Cities 2	GE	LCI	SDC	MARK I	B-CLASS 3		Direct-Single	4 pumps; GE
River Bend	GE	LCI	SDC	MARK III	B-CLASS 6		Direct-Single	2 pumps; GE
Robinson 2	WE	LPI	RHR			3	Indirect-Single	2 pumps; WE
Salem 1	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Salem 2	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
San Onofre 2	CE	LPI	SDC			2	Indirect-Multiple	2 pumps; CE
San Onofre 3	CE	LPI	SDC			2	Indirect-Multiple	2 pumps; CE
Seabrook	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Sequoyah 1	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Sequoyah 2	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
South Texas 1	WE	LPI	RHR			4	Indirect-Multiple	3 pumps; WE
South Texas 2	WE	LPI	RHR			4	Indirect-Multiple	3 pumps; WE
St. Lucie 1	CE	LPI	SDC			2	Indirect-Multiple	2 pumps; CE

Table 14. (continued).

Plant	Vendor	LPI Tree	SDC Tree[b]	BWR Containment	BWR Design	PWR Loops	Shutdown Cooling Class	Injection Class
St. Lucie 2	CE	LPI	SDC		2HL/4CL	2	Indirect-Multiple	2 pumps; CE
Summer	WE	LPI	RHR			3	Indirect-Multiple	2 pumps; WE
Surry 1	WE	LPI	RHR			3	Single Use	2 pumps; WE
Surry 2	WE	LPI	RHR			3	Single Use	2 pumps; WE
Susquehanna 1	GE	LCI	SPC	MARK II(C)	B-CLASS 4		No suction modeled	4 pumps; GE
Susquehanna 2	GE	LCI	SPC	MARK II(C)	B-CLASS 4		No suction modeled	4 pumps; GE
Three Mile Isl 1	BW	LPI	DHR			2	Single Train	2 pumps; BW
Turkey Point 3	WE	LPI	RHR			3	Indirect-Single	2 pumps; WE
Turkey Point 4	WE	LPI	RHR			3	Indirect-Single	2 pumps; WE
Vermont Yankee	GE	LCI	SDC	MARK I	B-CLASS 4		Direct-Single	4 pumps; GE
Vogtle 1	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Vogtle 2	WE	LPI	RHR			4	Indirect-Multiple	2 pumps; WE
Waterford 3	CE	LPI	SDC		2HL/4CL	2	Indirect-Multiple	2 pumps; CE
Watts Bar 1	WE	LPI	RHR			4	Indirect-Single	2 pumps; WE
Wolf Creek	WE	LPI	RHR		SNUPPS	4	Indirect-Multiple	2 pumps; WE

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

b. DHR = decay heat removal.

8. REFERENCES

1. Nuclear Regulatory Commission, *Component Reliability Data Sheets Update 2010*, January 2012, http://nrcoe.inl.gov/resultsdb/publicdocs/AvgPerf/ComponentReliabilityDataSheets2010.pdf

2. S.A. Eide et al., *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants*, Nuclear Regulatory Commission, NUREG/CR-6928, February 2007.