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System Study: High-Pressure Safety Injection 1998–2022

December 2023

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ABSTRACT

This report presents an unreliability evaluation of the high-pressure safety injection system (HPSI) at 62 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 hours, and failure data from calendar years 1998–2022 for selected components were obtained from the Institute of Nuclear Power Operations Industry Reporting and Information System. 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. Highly statistically significant increasing trends were identified in both the HPSI system start-only unreliability and 8-hour mission unreliability.

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ACRONYMS

AFW	auxiliary feedwater
BWST	borated water storage tank
CCF	common-cause failure
CVC	chemical volume control
ECCS	emergency core cooling system
EPIX	Equipment Performance and Information Exchange
ESFAS	engineered safety features actuation system
FTOC	fail to open/close
FTOP	fail to operate
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
HPSI	high-pressure safety injection
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
IRIS	Industry Reporting and Information System
LOCA	loss-of-coolant accident
LOOP	loss-of-offsite power
MDP	motor-driven pump
MFW	main feedwater
MSPI	Mitigating Systems Performance Index
MUT	makeup tank
NPSH	net positive suction head
NRC	Nuclear Regulatory Commission
PORV	power-operated relief valve
PRA	probabilistic risk assessment
PZR	pressurizer
RCP	reactor coolant pump
RCS	reactor coolant system
ROP	Reactor Oversight Process
RWST	refueling water storage tank
SGTRs	steam generator tube ruptures
SI	safety injection

SLOCA	small loss-of-coolant accident
SPAR	Standardized Plant Analysis Risk
SSU	safety system unavailability
UA	unavailability (maintenance or state of another component)
VCT	volume control tank

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1. INTRODUCTION

This report presents an unreliability evaluation of the high-pressure safety injection (HPSI) system at 62 U.S. commercial operating nuclear reactors listed in Table 1. For each reactor (or plant), the corresponding Standardized Plant Analysis Risk (SPAR) model was used in the yearly calculations. Demand, run hour, and failure data from calendar year 1998–2022 for selected components in the HPSI 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.

The HPSI classes were categorized by the number of pump trains (no specification on pump type) used in the SPAR models. Class 2 HPSI includes configurations that effectively result in a success criterion of one of two pumps. Class 3 HPSI includes configurations that effectively result in a success criterion of one of three pumps. HPSI designs effectively resulting in a success criterion of one of four or more are included in Class 4. Table 1 summarizes the plants, their HPSI classes, and the SPAR model versions used in this study.

The HPSI model is evaluated using the small loss-of-coolant accident (SLOCA) flag set in the SPAR model. The SLOCA flag set assumes all support systems are available and that the HPSI system is required to perform to mitigate the effects of the SLOCA initiating event. All models include failures due to unavailability while in test or maintenance. Human error 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 are in the *Overview and Reference* document [5] on the NRC web page (https://nrcoe.inl.gov).

Two variations of the HPSI system model are implemented and calculated. The HPSI start-only model is the HPSI SPAR model modified by setting all fail-to-run basic events to zero ("False"), all human error and recovery events to "Ignore," and all cooling basic events to "False." The 8-hour mission model sets all human error and recovery events to "Ignore."

Section 2 of this report summarizes the main findings from the study. Section 3 presents the baseline HPSI unreliability results using basic event values from the 2020 SPAR parameter update. Section 4 shows the trend results for HPSI 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 HPSI system.

Table 1. HPSI design class summary.

Class	Plant	SPAR ID	SPAR Version
Class 2	Arkansas 1	ANO1	8.8
Class 2	Harris	HARR	8.81
Class 2	Palisades	PALI	8.8
Class 2	Palo Verde 1, 2 & 3	PVNG	8.8
Class 2	Point Beach 1 & 2	PBCH	8.8
Class 2	Prairie Island 1 & 2	PRAI	8.8
Class 2	St. Lucie 1	STL1	8.8
Class 2	St. Lucie 2	STL2	8.8
Class 2	Summer	SUMM	8.8
Class 3	Arkansas 2	ANO2	8.81
Class 3	Beaver Valley 1	BVS1	8.8
Class 3	Beaver Valley 2	BVS2	8.8
Class 3	Calvert Cliffs 1	CCF1	8.8
Class 3	Calvert Cliffs 2	CCF2	8.8
Class 3	Farley 1 & 2	FARL	8.81
Class 3	Ginna	GINA	8.8
Class 3	Millstone 2	MIL2	8.8
Class 3	North Anna 1 & 2	NANN	8.8
Class 3	Oconee 1, 2 & 3	OCON	8.8
Class 3	Robinson 2	ROBN	8.8
Class 3	South Texas 1 & 2	STEX	8.8
Class 3	Surry 1&2	SURY	8.8
Class 3	Waterford 3	WTRF	8.8
Class 4	Braidwood 1 & 2	BRWD	8.81

Class	Plant	SPAR ID	SPAR Version
Class 4	Byron 1 & 2	BYRN	8.81
Class 4	Callaway	CALL	8.8
Class 4	Catawba 1 & 2	CATA	8.81
Class 4	Comanche Peak 1 & 2	COPK	8.81
Class 4	Cook 1 & 2	COOK	8.81
Class 4	Davis-Besse	DAVB	8.81
Class 4	Diablo Canyon 1 & 2	DCAN	8.81
Class 4	McGuire 1 & 2	MCGU	8.8
Class 4	Millstone 3	MIL3	8.8
Class 4	Salem 1 & 2	SALM	8.8
Class 4	Seabrook	SBRK	8.8
Class 4	Sequoyah 1 & 2	SEQH	8.8
Class 4	Turkey Point 3 & 4	TKPT	8.8
Class 4	Vogtle 1 & 2	VOGT	8.8
Class 4	Watts Bar 1&2	WB12	8.8
Class 4	Wolf Creek	WOLF	8.8

2. SUMMARY OF FINDINGS

The results of this HPSI system unreliability study are summarized in this section. Of particular interest is any statistically significant[a] increasing trends. In this update, **highly statistically significant decreasing trends** were identified in both the **HPSI system start-only unreliability** and **8-hour mission unreliability** for the most recent 10-year period.

The industry-wide HPSI start-only and 8-hour mission basic event group importance were evaluated. For both **start-only and 8-hour mission**, **the leading contributor to HPSI system unreliability** is the **Suction** group of basic events followed by the **HPSI Pump** and **Cooling** groups.

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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

The HPSI fault trees from the SPAR models were evaluated for each of the 62 U.S. commercial operating pressurized water reactor nuclear power plants with an HPSI system.

The industry-wide unreliability of the HPSI system has been estimated for two variations. A start-only model and an 8-hour mission model were evaluated. The uncertainty distributions for HPSI show both plant design variability and parameter uncertainty while using industry-wide component failure data as in the 2020 SPAR parameter update.[b] Table 2 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 HPSI 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 class and for the industry.

Table 2. Industry-wide unreliability values.

Model	HPSI Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-only	Industry	1.29E-06	2.60E-05	1.44E-04	7.54E-04
	Class 2	1.16E-05	7.55E-05	3.11E-04	1.58E-03
	Class 3	3.49E-06	2.76E-05	9.91E-05	2.98E-04
	Class 4	6.50E-07	1.09E-05	9.13E-05	3.84E-04
8-hour Mission	Industry	1.33E-06	2.77E-05	1.46E-04	7.65E-04
	Class 2	1.43E-05	8.38E-05	3.20E-04	1.60E-03
	Class 3	4.14E-06	2.92E-05	1.00E-04	2.98E-04
	Class 4	6.66E-07	1.08E-05	9.11E-05	3.64E-04

In Figure 1 and Figure 2, the width of the distribution for a class is affected by the differences in the plant modeling and parameter uncertainty used in the models. Because the width is affected by 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.

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

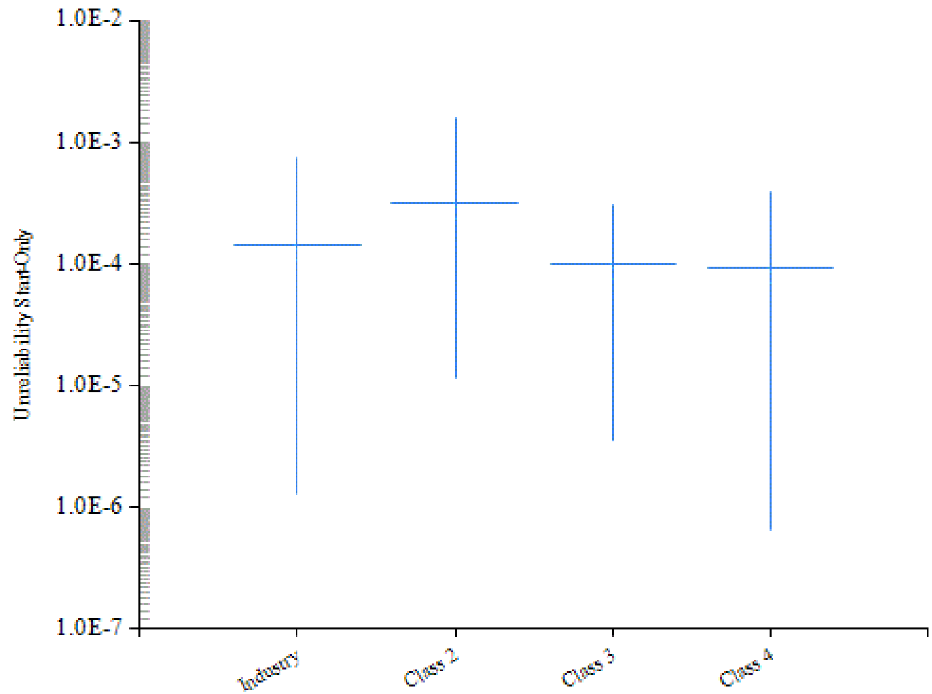

Figure 1. HPSI start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

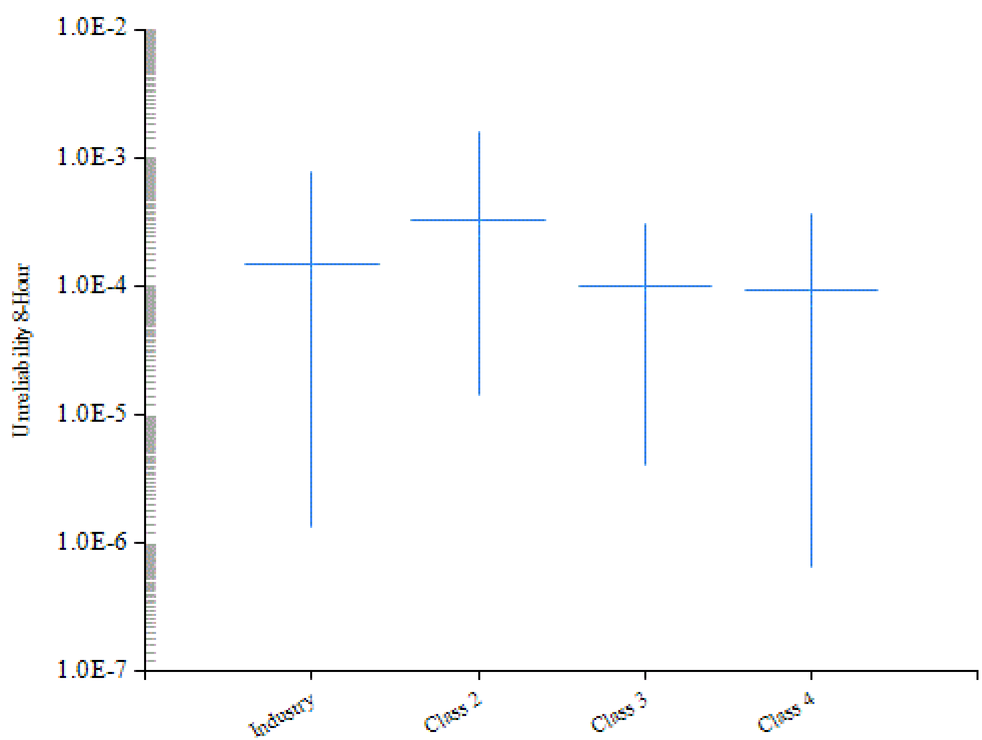

Figure 2. HPSI 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly failure and demand or run-time data from 1998–2022 were obtained from IRIS for the HPSI system. HPSI 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 HPSI system components using the trending methods described in Sections 1 and 2 of Reference [5]. Tables 6 and 7 show the yearly data values for each HPSI system-specific component and failure mode combination that were varied in the model. These data were loaded into the HPSI system fault tree in each SPAR model with a HPSI system (see Table 1).

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 (the "industry" values in Table 2) 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.

The components that were varied in the HPSI model are:

- HPSI motor-driven pump (MDP) start, run, and test and maintenance
- Chemical volume control (CVC) system MDP start, run, and test and maintenance
- Injection valves fail to open.

Figure 3 shows the trend in the HPSI start-only model unreliability. Table 4 shows the data points for Figure 3. **A highly statistically significant decreasing trend** was identified within the industry-wide estimates of **HPSI system start-only unreliability** for the most recent 10-year period.

Figure 4 shows the trend in the 8-hour mission unreliability. Table 5 shows the data points for Figure 4. **A highly statistically significant decreasing trend** was identified within the industry-wide estimates of **HPSI system 8-hour mission unreliability** for the most recent 10-year period.

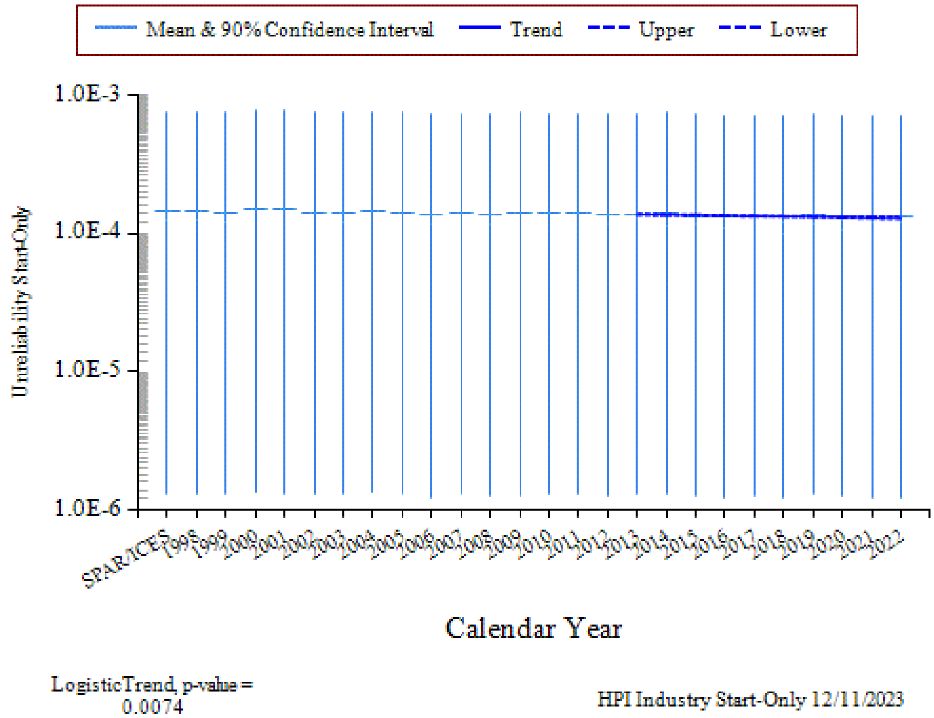

Figure 3. Trend of HPSI system start-only unreliability.

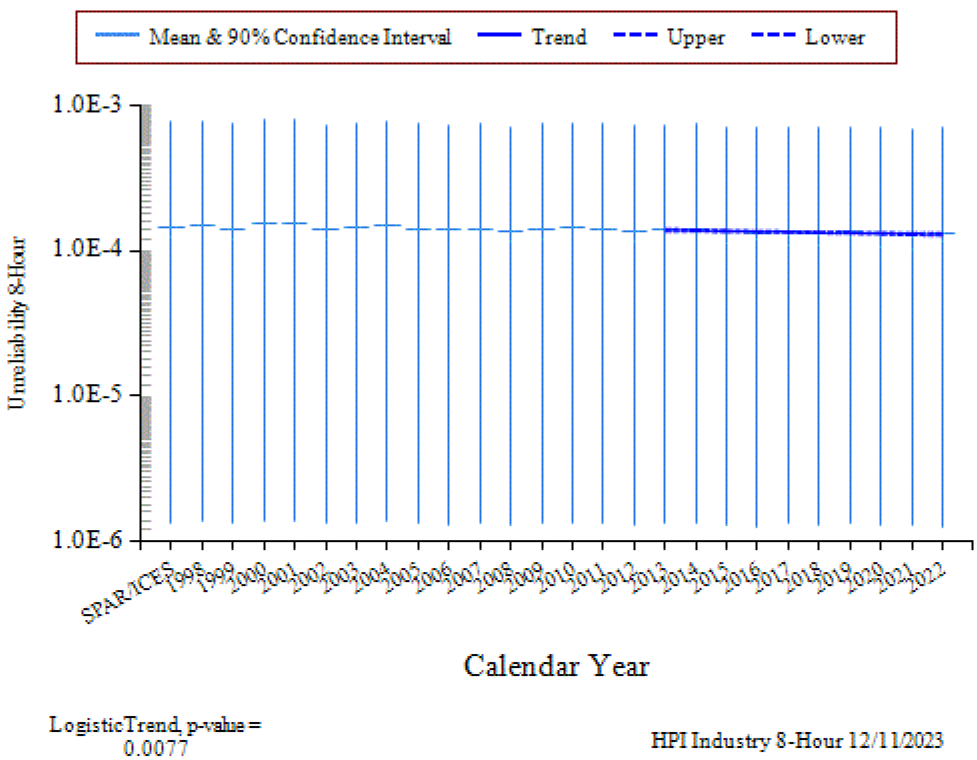

Figure 4. Trend of HPSI system 8-hour mission unreliability.

5. BASIC EVENT GROUP IMPORTANCES

The HPSI basic event group Fussell-Vesely importances were calculated for the start-only and 8-hour mission models 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.

The industry-wide HPSI start-only and 8-hour mission basic event group importances were evaluated and shown in Figure 5. For both **start-only and 8-hour mission**, **the leading contributor to HPSI system unreliability** is the **Suction** group of basic events followed by the **HPSI Pump** and **Cooling** groups.

For more discussion on the HPSI MDPs, see the MDP component reliability studies at the NRC Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov). Table 3 shows the SPAR model HPSI importance groups and their descriptions.

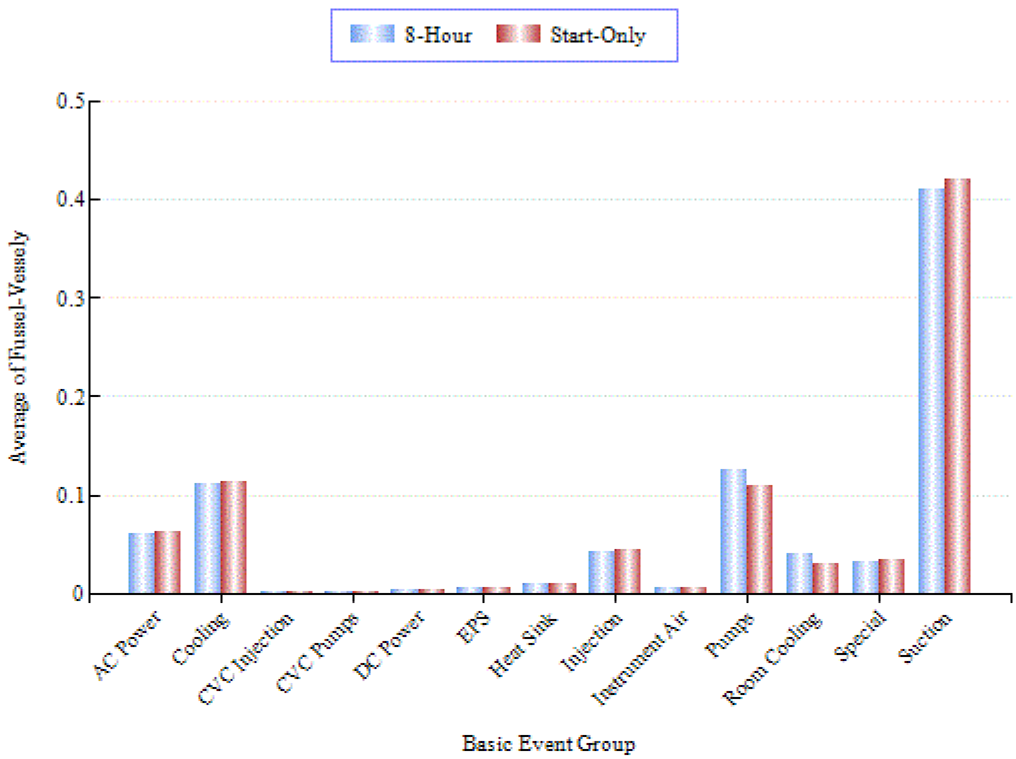

Figure 5. HPSI industry-wide basic event group importances.

Table 3. HPSI model basic event importance group descriptions.

Group	Description
AC Power	The ac buses and circuit breakers that supply power to the HPSI pumps
Cooling	The pumps, valves, and heat exchangers that provide heat removal to the HPSI MDP and the HPSI room
CVC Injection	The motor-operated valves and check valves in the HPSI injection path
CVC Pumps	All basic events associated with the CVC (charging; normally running) MDPs, including the start, run, common-cause, and test and maintenance
DC Power	The batteries and battery chargers that supply power to the HPSI MDP control circuitry
EPS	HPSI dependency on the emergency power system
Heat Sink	The pumps, valves, strainers, and other equipment associated with the ultimate heat sink
Injection	The motor-operated valves and check valves in the HPSI injection path
Instrument Air	Instrument air support to the HPSI model
Pumps	All basic events associated with the HPSI (generally lower head than CVC pumps; standby) MDPs, including the start, run, common-cause, and test and maintenance
Room Cooling	All basic events associated with the pump room cooling
Special	Various events used in the models that are not directly associated with the HPSI system
Suction	The motor-operated valves and air-operated valves in the tank suction path, including tank failure

The basic event group importances were also averaged across plants of the same HPSI class to represent basic event group importances for different HPSI classes. The HPSI class-specific start-only and 8-hour mission basic event group importances are shown in Figure 6–Figure 8. The leading contributor to Class 2 HPSI system unreliability is the HPSI Pump group, while the leading contributor to Class 3 and Class 4 HPSI system unreliability is the **Suction** group.

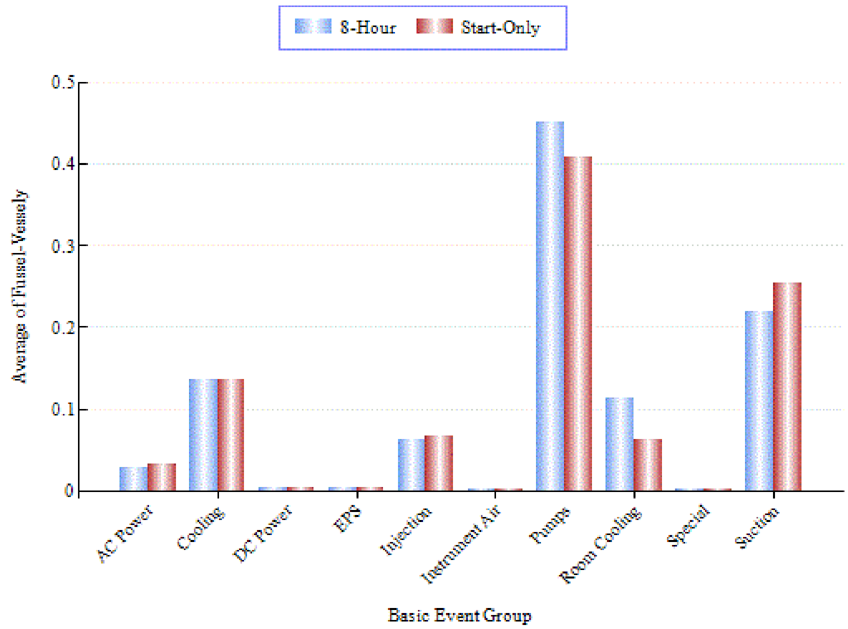

Figure 6. HPSI Class 2 basic event group importances.

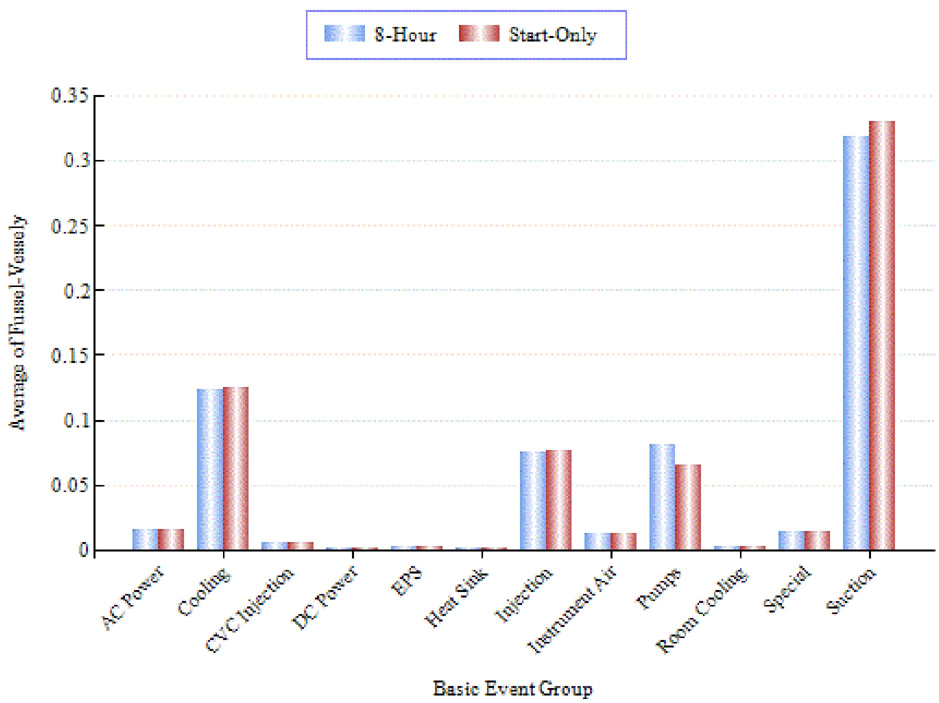

Figure 7. HPSI Class 3 basic event group importances.

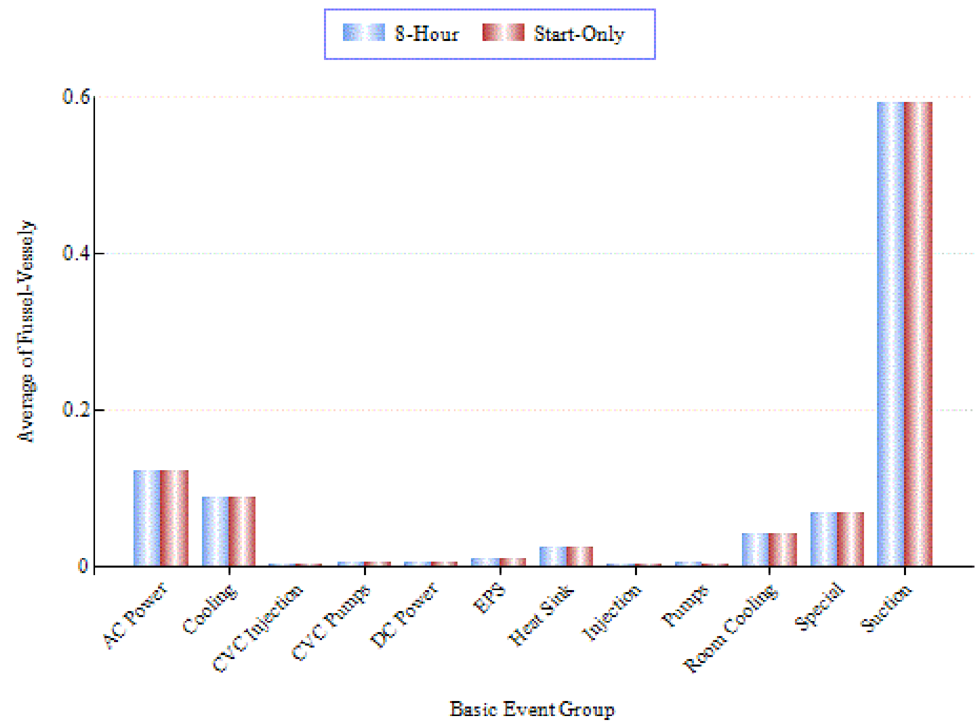

Figure 8. HPSI Class 4 basic event group importances.

6. DATA TABLES

Table 4. Plot data for Figure 3, HPSI 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	--	--	--	1.29E-06	1.44E-04	7.54E-04
1998	--	--	--	1.30E-06	1.45E-04	7.58E-04
1999	--	--	--	1.29E-06	1.40E-04	7.39E-04
2000	--	--	--	1.34E-06	1.51E-04	7.79E-04
2001	--	--	--	1.30E-06	1.51E-04	7.81E-04
2002	--	--	--	1.29E-06	1.39E-04	7.37E-04
2003	--	--	--	1.30E-06	1.40E-04	7.44E-04
2004	--	--	--	1.32E-06	1.44E-04	7.53E-04
2005	--	--	--	1.30E-06	1.39E-04	7.35E-04
2006	--	--	--	1.22E-06	1.36E-04	7.24E-04
2007	--	--	--	1.31E-06	1.38E-04	7.30E-04
2008	--	--	--	1.27E-06	1.35E-04	7.18E-04
2009	--	--	--	1.26E-06	1.38E-04	7.37E-04
2010	--	--	--	1.31E-06	1.41E-04	7.35E-04
2011	--	--	--	1.28E-06	1.38E-04	7.28E-04
2012	--	--	--	1.27E-06	1.36E-04	7.25E-04
2013	1.34E-04	1.37E-04	1.40E-04	1.29E-06	1.37E-04	7.32E-04
2014	1.33E-04	1.36E-04	1.38E-04	1.29E-06	1.40E-04	7.41E-04
2015	1.33E-04	1.35E-04	1.37E-04	1.26E-06	1.33E-04	7.13E-04
2016	1.32E-04	1.34E-04	1.36E-04	1.23E-06	1.30E-04	7.04E-04
2017	1.31E-04	1.33E-04	1.35E-04	1.27E-06	1.33E-04	7.11E-04
2018	1.30E-04	1.32E-04	1.34E-04	1.22E-06	1.30E-04	7.01E-04
2019	1.29E-04	1.31E-04	1.33E-04	1.29E-06	1.34E-04	7.15E-04
2020	1.28E-04	1.30E-04	1.32E-04	1.25E-06	1.30E-04	7.03E-04
2021	1.27E-04	1.29E-04	1.32E-04	1.21E-06	1.28E-04	6.96E-04
2022	1.25E-04	1.28E-04	1.31E-04	1.20E-06	1.29E-04	7.01E-04

Table 5. Plot data for Figure 4, HPSI 8-hour mission unreliability trend.

Year/Source	Regression Curve Data Points			Plot Trend Error Bar Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	1.33E-06	1.46E-04	7.65E-04
1998	--	--	--	1.36E-06	1.47E-04	7.69E-04
1999	--	--	--	1.33E-06	1.41E-04	7.36E-04
2000	--	--	--	1.37E-06	1.53E-04	7.88E-04
2001	--	--	--	1.37E-06	1.53E-04	7.92E-04
2002	--	--	--	1.34E-06	1.41E-04	7.35E-04
2003	--	--	--	1.35E-06	1.43E-04	7.43E-04
2004	--	--	--	1.37E-06	1.47E-04	7.70E-04
2005	--	--	--	1.34E-06	1.41E-04	7.47E-04
2006	--	--	--	1.30E-06	1.38E-04	7.35E-04
2007	--	--	--	1.36E-06	1.41E-04	7.46E-04
2008	--	--	--	1.31E-06	1.37E-04	7.12E-04
2009	--	--	--	1.34E-06	1.40E-04	7.50E-04
2010	--	--	--	1.35E-06	1.42E-04	7.50E-04
2011	--	--	--	1.33E-06	1.40E-04	7.42E-04
2012	--	--	--	1.31E-06	1.37E-04	7.21E-04
2013	1.35E-04	1.39E-04	1.42E-04	1.34E-06	1.39E-04	7.32E-04
2014	1.35E-04	1.37E-04	1.40E-04	1.35E-06	1.42E-04	7.52E-04
2015	1.34E-04	1.36E-04	1.39E-04	1.29E-06	1.34E-04	7.08E-04
2016	1.33E-04	1.35E-04	1.37E-04	1.27E-06	1.32E-04	7.00E-04
2017	1.33E-04	1.34E-04	1.36E-04	1.32E-06	1.35E-04	7.08E-04
2018	1.32E-04	1.33E-04	1.35E-04	1.28E-06	1.32E-04	6.96E-04
2019	1.31E-04	1.32E-04	1.34E-04	1.32E-06	1.35E-04	7.10E-04
2020	1.29E-04	1.31E-04	1.34E-04	1.31E-06	1.32E-04	7.00E-04
2021	1.28E-04	1.31E-04	1.33E-04	1.29E-06	1.30E-04	6.90E-04
2022	1.26E-04	1.30E-04	1.33E-04	1.26E-06	1.30E-04	6.96E-04

Table 6. Basic event reliability trending data.

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOC	AOV	1998	0	670	3.85E-04	0.83	2.16E+03	Beta
FTOC	AOV	1999	0	469	4.25E-04	0.83	1.96E+03	Beta
FTOC	AOV	2000	0	447	4.29E-04	0.83	1.94E+03	Beta
FTOC	AOV	2001	0	317	4.60E-04	0.83	1.81E+03	Beta
FTOC	AOV	2002	0	426	4.34E-04	0.83	1.92E+03	Beta
FTOC	AOV	2003	2	345	1.54E-03	2.83	1.83E+03	Beta
FTOC	AOV	2004	0	312	4.62E-04	0.83	1.80E+03	Beta
FTOC	AOV	2005	0	307	4.63E-04	0.83	1.80E+03	Beta
FTOC	AOV	2006	1	275	1.04E-03	1.83	1.76E+03	Beta
FTOC	AOV	2007	0	272	4.72E-04	0.83	1.76E+03	Beta
FTOC	AOV	2008	1	272	1.04E-03	1.83	1.76E+03	Beta
FTOC	AOV	2009	0	272	4.72E-04	0.83	1.76E+03	Beta
FTOC	AOV	2010	0	272	4.72E-04	0.83	1.76E+03	Beta
FTOC	AOV	2011	3	272	2.17E-03	3.83	1.76E+03	Beta
FTOC	AOV	2012	0	272	4.72E-04	0.83	1.76E+03	Beta
FTOC	AOV	2013	0	272	4.72E-04	0.83	1.76E+03	Beta
FTOC	AOV	2014	1	272	1.04E-03	1.83	1.76E+03	Beta
FTOC	AOV	2015	0	315	4.61E-04	0.83	1.80E+03	Beta
FTOC	AOV	2016	0	309	4.62E-04	0.83	1.80E+03	Beta
FTOC	AOV	2017	0	309	4.62E-04	0.83	1.80E+03	Beta
FTOC	AOV	2018	0	309	4.62E-04	0.83	1.80E+03	Beta
FTOC	AOV	2019	0	309	4.62E-04	0.83	1.80E+03	Beta
FTOC	AOV	2020	0	309	4.62E-04	0.83	1.80E+03	Beta
FTOC	AOV	2021	0	309	4.62E-04	0.83	1.80E+03	Beta
FTOC	AOV	2022	0	309	4.62E-04	0.83	1.80E+03	Beta
FTOP	AOV	1998	0	648,240	1.61E-07	1.26	7.82E+06	Gamma
FTOP	AOV	1999	0	648,240	1.61E-07	1.26	7.82E+06	Gamma
FTOP	AOV	2000	1	692,040	2.87E-07	2.26	7.86E+06	Gamma
FTOP	AOV	2001	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2002	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2003	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2004	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2005	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2006	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2007	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2008	0	692,040	1.60E-07	1.26	7.86E+06	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	AOV	2009	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2010	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2011	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2012	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2013	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2014	0	692,040	1.60E-07	1.26	7.86E+06	Gamma
FTOP	AOV	2015	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2016	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2017	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2018	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2019	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2020	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2021	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
FTOP	AOV	2022	0	718,320	1.60E-07	1.26	7.89E+06	Gamma
SO	AOV	1998	0	648,240	5.60E-08	0.86	1.53E+07	Gamma
SO	AOV	1999	0	648,240	5.60E-08	0.86	1.53E+07	Gamma
SO	AOV	2000	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2001	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2002	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2003	1	692,040	1.21E-07	1.86	1.54E+07	Gamma
SO	AOV	2004	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2005	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2006	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
SO	AOV	2007	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2008	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2009	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2010	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2011	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2012	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2013	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2014	0	692,040	5.58E-08	0.86	1.54E+07	Gamma
SO	AOV	2015	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
SO	AOV	2016	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
SO	AOV	2017	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
SO	AOV	2018	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
SO	AOV	2019	0	718,320	5.57E-08	0.86	1.54E+07	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	AOV	2020	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
SO	AOV	2021	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
SO	AOV	2022	0	718,320	5.57E-08	0.86	1.54E+07	Gamma
FTR>1H	MDP	1998	2	142,845	1.22E-05	2.51	2.06E+05	Gamma
FTR>1H	MDP	1999	1	120,277	8.25E-06	1.51	1.83E+05	Gamma
FTR>1H	MDP	2000	1	108,063	8.84E-06	1.51	1.71E+05	Gamma
FTR>1H	MDP	2001	1	98,316	9.37E-06	1.51	1.61E+05	Gamma
FTR>1H	MDP	2002	2	98,002	1.56E-05	2.51	1.61E+05	Gamma
FTR>1H	MDP	2003	2	121,668	1.36E-05	2.51	1.85E+05	Gamma
FTR>1H	MDP	2004	4	139,291	2.23E-05	4.51	2.02E+05	Gamma
FTR>1H	MDP	2005	0	137,960	2.54E-06	0.51	2.01E+05	Gamma
FTR>1H	MDP	2006	1	124,853	8.05E-06	1.51	1.88E+05	Gamma
FTR>1H	MDP	2007	1	117,844	8.36E-06	1.51	1.81E+05	Gamma
FTR>1H	MDP	2008	1	122,541	8.15E-06	1.51	1.85E+05	Gamma
FTR>1H	MDP	2009	0	122,490	2.76E-06	0.51	1.85E+05	Gamma
FTR>1H	MDP	2010	0	115,874	2.86E-06	0.51	1.79E+05	Gamma
FTR>1H	MDP	2011	1	113,853	8.55E-06	1.51	1.77E+05	Gamma
FTR>1H	MDP	2012	0	111,156	2.94E-06	0.51	1.74E+05	Gamma
FTR>1H	MDP	2013	2	106,549	1.48E-05	2.51	1.69E+05	Gamma
FTR>1H	MDP	2014	2	110,910	1.44E-05	2.51	1.74E+05	Gamma
FTR>1H	MDP	2015	0	111,433	2.93E-06	0.51	1.74E+05	Gamma
FTR>1H	MDP	2016	0	109,963	2.96E-06	0.51	1.73E+05	Gamma
FTR>1H	MDP	2017	2	117,098	1.40E-05	2.51	1.80E+05	Gamma
FTR>1H	MDP	2018	1	119,176	8.30E-06	1.51	1.82E+05	Gamma
FTR>1H	MDP	2019	0	116,655	2.85E-06	0.51	1.80E+05	Gamma
FTR>1H	MDP	2020	1	119,913	8.27E-06	1.51	1.83E+05	Gamma
FTR>1H	MDP	2021	0	120,197	2.79E-06	0.51	1.83E+05	Gamma
FTR>1H	MDP	2022	0	115,506	2.86E-06	0.51	1.78E+05	Gamma
FTR<1H	MDP	1998	0	2,977	6.21E-05	0.58	9.32E+03	Gamma
FTR<1H	MDP	1999	0	3,432	5.92E-05	0.58	9.77E+03	Gamma
FTR<1H	MDP	2000	0	3,237	6.05E-05	0.58	9.58E+03	Gamma
FTR<1H	MDP	2001	0	3,171	6.09E-05	0.58	9.51E+03	Gamma
FTR<1H	MDP	2002	0	3,024	6.18E-05	0.58	9.36E+03	Gamma
FTR<1H	MDP	2003	0	3,361	5.97E-05	0.58	9.70E+03	Gamma
FTR<1H	MDP	2004	0	3,317	6.00E-05	0.58	9.66E+03	Gamma
FTR<1H	MDP	2005	0	3,296	6.01E-05	0.58	9.64E+03	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR<1H	MDP	2006	0	3,578	5.84E-05	0.58	9.92E+03	Gamma
FTR<1H	MDP	2007	1	3,061	1.68E-04	1.58	9.40E+03	Gamma
FTR<1H	MDP	2008	0	3,429	5.93E-05	0.58	9.77E+03	Gamma
FTR<1H	MDP	2009	1	3,302	1.64E-04	1.58	9.64E+03	Gamma
FTR<1H	MDP	2010	0	3,116	6.12E-05	0.58	9.46E+03	Gamma
FTR<1H	MDP	2011	0	3,126	6.12E-05	0.58	9.47E+03	Gamma
FTR<1H	MDP	2012	0	3,020	6.19E-05	0.58	9.36E+03	Gamma
FTR<1H	MDP	2013	0	3,014	6.19E-05	0.58	9.35E+03	Gamma
FTR<1H	MDP	2014	0	2,963	6.22E-05	0.58	9.30E+03	Gamma
FTR<1H	MDP	2015	0	2,952	6.23E-05	0.58	9.29E+03	Gamma
FTR<1H	MDP	2016	0	2,952	6.23E-05	0.58	9.29E+03	Gamma
FTR<1H	MDP	2017	0	3,128	6.12E-05	0.58	9.47E+03	Gamma
FTR<1H	MDP	2018	0	3,146	6.10E-05	0.58	9.49E+03	Gamma
FTR<1H	MDP	2019	0	2,991	6.20E-05	0.58	9.33E+03	Gamma
FTR<1H	MDP	2020	0	3,161	6.09E-05	0.58	9.50E+03	Gamma
FTR<1H	MDP	2021	1	3,162	1.66E-04	1.58	9.50E+03	Gamma
FTR<1H	MDP	2022	0	3,030	6.18E-05	0.58	9.37E+03	Gamma
FTS	MDP	1998	2	2,977	6.26E-04	4.07	6.49E+03	Beta
FTS	MDP	1999	2	3,432	5.85E-04	4.07	6.95E+03	Beta
FTS	MDP	2000	5	3,237	1.05E-03	7.07	6.75E+03	Beta
FTS	MDP	2001	4	3,171	9.07E-04	6.07	6.69E+03	Beta
FTS	MDP	2002	3	3,024	7.74E-04	5.07	6.54E+03	Beta
FTS	MDP	2003	4	3,361	8.82E-04	6.07	6.88E+03	Beta
FTS	MDP	2004	5	3,317	1.03E-03	7.07	6.83E+03	Beta
FTS	MDP	2005	4	3,296	8.90E-04	6.07	6.81E+03	Beta
FTS	MDP	2006	0	3,578	2.92E-04	2.07	7.10E+03	Beta
FTS	MDP	2007	4	3,061	9.22E-04	6.07	6.58E+03	Beta
FTS	MDP	2008	5	3,429	1.02E-03	7.07	6.94E+03	Beta
FTS	MDP	2009	1	3,302	4.50E-04	3.07	6.82E+03	Beta
FTS	MDP	2010	6	3,116	1.22E-03	8.07	6.63E+03	Beta
FTS	MDP	2011	2	3,126	6.12E-04	4.07	6.64E+03	Beta
FTS	MDP	2012	2	3,020	6.22E-04	4.07	6.54E+03	Beta
FTS	MDP	2013	3	3,014	7.76E-04	5.07	6.53E+03	Beta
FTS	MDP	2014	2	2,963	6.28E-04	4.07	6.48E+03	Beta
FTS	MDP	2015	1	2,952	4.74E-04	3.07	6.47E+03	Beta
FTS	MDP	2016	1	2,952	4.74E-04	3.07	6.47E+03	Beta

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTS	MDP	2017	4	3,128	9.13E-04	6.07	6.64E+03	Beta
FTS	MDP	2018	1	3,146	4.60E-04	3.07	6.66E+03	Beta
FTS	MDP	2019	4	2,991	9.32E-04	6.07	6.51E+03	Beta
FTS	MDP	2020	4	3,161	9.08E-04	6.07	6.68E+03	Beta
FTS	MDP	2021	1	3,162	4.59E-04	3.07	6.68E+03	Beta
FTS	MDP	2022	0	3,030	3.16E-04	2.07	6.55E+03	Beta
FTOC	MOV	1998	6	5,590	8.98E-04	8.43	9.38E+03	Beta
FTOC	MOV	1999	2	5,757	4.63E-04	4.43	9.56E+03	Beta
FTOC	MOV	2000	7	5,539	1.01E-03	9.43	9.33E+03	Beta
FTOC	MOV	2001	4	5,257	7.10E-04	6.43	9.05E+03	Beta
FTOC	MOV	2002	2	5,348	4.84E-04	4.43	9.15E+03	Beta
FTOC	MOV	2003	3	5,373	5.92E-04	5.43	9.17E+03	Beta
FTOC	MOV	2004	5	5,424	8.05E-04	7.43	9.22E+03	Beta
FTOC	MOV	2005	4	5,188	7.15E-04	6.43	8.98E+03	Beta
FTOC	MOV	2006	3	4,885	6.25E-04	5.43	8.68E+03	Beta
FTOC	MOV	2007	3	4,795	6.32E-04	5.43	8.59E+03	Beta
FTOC	MOV	2008	0	5,002	2.76E-04	2.43	8.80E+03	Beta
FTOC	MOV	2009	4	4,954	7.34E-04	6.43	8.75E+03	Beta
FTOC	MOV	2010	3	4,761	6.34E-04	5.43	8.56E+03	Beta
FTOC	MOV	2011	3	4,853	6.27E-04	5.43	8.65E+03	Beta
FTOC	MOV	2012	2	4,912	5.08E-04	4.43	8.71E+03	Beta
FTOC	MOV	2013	2	4,795	5.15E-04	4.43	8.59E+03	Beta
FTOC	MOV	2014	5	4,816	8.62E-04	7.43	8.61E+03	Beta
FTOC	MOV	2015	1	4,859	3.96E-04	3.43	8.66E+03	Beta
FTOC	MOV	2016	0	4,775	2.83E-04	2.43	8.58E+03	Beta
FTOC	MOV	2017	0	4,877	2.80E-04	2.43	8.68E+03	Beta
FTOC	MOV	2018	0	4,764	2.84E-04	2.43	8.56E+03	Beta
FTOC	MOV	2019	1	4,688	4.04E-04	3.43	8.49E+03	Beta
FTOC	MOV	2020	0	4,867	2.80E-04	2.43	8.67E+03	Beta
FTOC	MOV	2021	0	4,749	2.84E-04	2.43	8.55E+03	Beta
FTOC	MOV	2022	1	4,783	3.99E-04	3.43	8.58E+03	Beta
FTOP	MOV	1998	0	8,830,080	2.51E-08	0.8	3.18E+07	Gamma
FTOP	MOV	1999	0	8,830,080	2.51E-08	0.8	3.18E+07	Gamma
FTOP	MOV	2000	0	8,830,080	2.51E-08	0.8	3.18E+07	Gamma
FTOP	MOV	2001	1	8,830,080	5.65E-08	1.8	3.18E+07	Gamma
FTOP	MOV	2002	1	8,812,560	5.65E-08	1.8	3.18E+07	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	MOV	2003	0	8,812,560	2.51E-08	0.8	3.18E+07	Gamma
FTOP	MOV	2004	0	8,812,560	2.51E-08	0.8	3.18E+07	Gamma
FTOP	MOV	2005	0	8,847,600	2.51E-08	0.8	3.18E+07	Gamma
FTOP	MOV	2006	0	8,873,880	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2007	0	8,865,120	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2008	0	8,865,120	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2009	0	8,882,640	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2010	0	8,873,880	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2011	1	8,996,520	5.62E-08	1.8	3.20E+07	Gamma
FTOP	MOV	2012	1	8,873,880	5.64E-08	1.8	3.19E+07	Gamma
FTOP	MOV	2013	0	8,908,920	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2014	0	8,873,880	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2015	0	8,935,200	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2016	0	8,996,520	2.49E-08	0.8	3.20E+07	Gamma
FTOP	MOV	2017	0	9,057,840	2.49E-08	0.8	3.21E+07	Gamma
FTOP	MOV	2018	1	9,075,360	5.61E-08	1.8	3.21E+07	Gamma
FTOP	MOV	2019	0	8,935,200	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2020	0	8,970,240	2.50E-08	0.8	3.20E+07	Gamma
FTOP	MOV	2021	0	8,926,440	2.50E-08	0.8	3.19E+07	Gamma
FTOP	MOV	2022	0	8,926,440	2.50E-08	0.8	3.19E+07	Gamma
SO	MOV	1998	0	8,830,080	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	1999	0	8,830,080	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2000	0	8,830,080	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2001	0	8,830,080	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2002	0	8,812,560	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2003	0	8,812,560	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2004	0	8,812,560	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2005	0	8,847,600	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2006	0	8,873,880	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2007	0	8,865,120	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2008	0	8,865,120	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2009	0	8,882,640	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2010	0	8,873,880	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2011	0	8,996,520	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2012	0	8,873,880	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2013	0	8,908,920	2.53E-08	41.5	1.64E+09	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	MOV	2014	0	8,873,880	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2015	0	8,935,200	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2016	0	8,996,520	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2017	0	9,057,840	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2018	0	9,075,360	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2019	0	8,935,200	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2020	0	8,970,240	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2021	0	8,926,440	2.53E-08	41.5	1.64E+09	Gamma
SO	MOV	2022	0	8,926,440	2.53E-08	41.5	1.64E+09	Gamma

Table 7. Basic event unavailability (UA) trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	MDP	1998	6282.77	1,394,450	4.23E-03	1.11	2.62E+02	Beta
UA	MDP	1999	7124.01	1,462,526	4.48E-03	1.58	3.51E+02	Beta
UA	MDP	2000	7947.34	1,497,199	5.02E-03	2.07	4.09E+02	Beta
UA	MDP	2001	8488.82	1,544,955	5.51E-03	0.98	1.77E+02	Beta
UA	MDP	2002	6180.7	1,587,234	3.84E-03	1.35	3.50E+02	Beta
UA	MDP	2003	6400.178	1,549,554	3.81E-03	1.43	3.73E+02	Beta
UA	MDP	2004	6481.596	1,611,202	3.83E-03	1.84	4.79E+02	Beta
UA	MDP	2005	4769.727	1,584,007	3.08E-03	1.35	4.36E+02	Beta
UA	MDP	2006	5512.531	1,579,742	3.35E-03	0.99	2.96E+02	Beta
UA	MDP	2007	4587.91	1,622,723	2.91E-03	1.35	4.61E+02	Beta
UA	MDP	2008	4830.12	1,583,020	3.07E-03	0.84	2.74E+02	Beta
UA	MDP	2009	5262.83	1,566,514	3.39E-03	1.64	4.83E+02	Beta
UA	MDP	2010	5183.31	1,596,046	3.33E-03	1.29	3.85E+02	Beta
UA	MDP	2011	5225.45	1,543,817	3.35E-03	1.19	3.55E+02	Beta
UA	MDP	2012	5160.15	1,502,828	3.20E-03	1.32	4.09E+02	Beta
UA	MDP	2013	5563.05	1,521,929	3.36E-03	1.39	4.12E+02	Beta
UA	MDP	2014	4540.99	1,531,624	2.97E-03	0.99	3.32E+02	Beta
UA	MDP	2015	4595.8	1,531,552	2.94E-03	1.44	4.86E+02	Beta
UA	MDP	2016	4032.75	1,539,576	2.69E-03	1.41	5.24E+02	Beta
UA	MDP	2017	4057.73	1,506,527	2.64E-03	1.51	5.69E+02	Beta
UA	MDP	2018	3796.75	1,517,218	2.52E-03	0.87	3.43E+02	Beta
UA	MDP	2019	3705	1,513,656	2.48E-03	0.86	3.47E+02	Beta
UA	MDP	2020	3039.09	1,476,475	1.97E-03	1.14	5.77E+02	Beta
UA	MDP	2021	2853.91	1,440,698	1.81E-03	1.07	5.90E+02	Beta
UA	MDP	2022	3141.62	1,435,616	2.08E-03	1.08	5.17E+02	Beta

Table 8. Failure mode acronyms.

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

7. SYSTEM DESCRIPTION

The HPSI system is part of the Emergency Core Cooling System (ECCS) that performs emergency coolant injection and recirculation functions to maintain reactor core coolant inventory and adequate decay heat removal following a loss-of-coolant accident (LOCA). The coolant injection function is performed during a relatively short-term period subsequent to a LOCA, followed by realignment to a recirculation mode of operation to maintain long-term, post-LOCA core cooling. In addition to the above, reactors equipped with pressurizer (PZR) power-operated relief valves (PORVs) could use the PORVs and HPSI to remove decay heat from the reactor in the event of the loss of the Main Feedwater (MFW) and Auxiliary Feedwater (AFW) systems.

The HPSI system actuates automatically on low PZR pressure, high containment pressure, or when steam line pressure or flow anomalies are detected. Therefore, in addition to a LOCA, other events will lead to HPSI actuation. Some examples of such events are steam generator tube ruptures (SGTRs), reactor coolant system (RCS) overcooling events from steam line breaks (e.g., stuck open main steam safety valves), or RCS depressurization events (e.g., stuck open PZR spray valves). The HPSI SPAR models were analyzed using the SLOCA initiator flag.

The HPSI systems in this study have been grouped into three different design classes, as shown in Table 1. The criteria that determined this grouping was the number of charging pumps, intermediate-head, and high-head safety injection trains available for automatic actuation used in the SPAR models. Each system typically consists of at least two independent divisions. The divisions consist of several different combinations of MDP trains. Because of the diversity in system design, operation, and response to plant transients, a detailed discussion of each plant-specific system is impractical. A general description is provided for the two major designs utilizing high-head or intermediate-head functional schemes. Differences among the other types of system design classes are also discussed. Table 9 summarizes the plants and their assigned classes.

SPAR HPSI modeling incorporates the plant-to-plant design and operational differences indicated in Table 9. All ac emergency power sources, either automatically started and aligned to essential buses given a loss-of-offsite power or manually started and aligned within approximately 30 minutes, are included in the HPSI SPAR fault trees along with dependencies, such as room cooling, service water cooling, and dc power.

The HPSI system is typically not in service during normal plant operations except for the charging pumps. It is considered part of the ECCS and is used to restore primary coolant volume during LOCAs, depressurization events, and overcooling events. However, the HPSI systems have wide variation from vendor to vendor and from plant to plant. In some B&W and Westinghouse plants, the normal makeup pumps are also the HPSI pumps, and therefore, a portion of the HPSI system is in service during normal modes of plant operation. The Combustion Engineering and other Westinghouse designs commonly use a charging system for normal makeup that is separate from the safety injection pumps, which are used only during emergency or abnormal situations. However, even in these designs the makeup and safety injection systems are interrelated because they share common valves, water sources, piping runs, and other equipment. Consequently, the safety injection systems can be either intermediate-head capacity (approximately 1,400 psi) or high-head capacity (approximately 2,200 psi) depending on whether they are used for normal charging (high-head) or not (intermediate-head). These differences in system pressure and postulated break size determine how the HPSI system is used during emergencies.

The HPSI system is typically started automatically by the engineered safety features actuation system (ESFAS) or equivalent, depending on plant design and terminology. Generally, the ESFAS automatic start signal set points include a low RCS pressure or a high reactor building (i.e., containment) pressure signal. There can be additional start signals, but these two are typical.

Table 9. HPSI design class summary.

Class	Plant	Total	CVC Pumps	HPSI Pumps
Class 2	Arkansas 1	2		2
Class 2	Harris	3		3[a]
Class 2	Palisades	2		2
Class 2	Palo Verde 1	2		2
Class 2	Palo Verde 2	2		2
Class 2	Palo Verde 3	2		2
Class 2	Point Beach 1	2		2
Class 2	Point Beach 2	2		2
Class 2	Prairie Island 1	2		2
Class 2	Prairie Island 2	2		2
Class 2	St. Lucie 1	2		2
Class 2	St. Lucie 2	2		2
Class 2	Summer	2		2
Class 3	Arkansas 2	3		3
Class 3	Beaver Valley 1	3		3
Class 3	Beaver Valley 2	3		3
Class 3	Calvert Cliffs 1	3		3
Class 3	Calvert Cliffs 2	3		3
Class 3	Farley 1	3	3	
Class 3	Farley 2	3	3	
Class 3	Ginna	3		3
Class 3	Millstone 2	3		3
Class 3	North Anna 1	3		3
Class 3	North Anna 2	3		3
Class 3	Oconee 1	3		3
Class 3	Oconee 2	3		3
Class 3	Oconee 3	3		3
Class 3	Robinson 2	3		3
Class 3	South Texas 1	3		3
Class 3	South Texas 2	3		3
Class 3	Surry 1	3		3
Class 3	Surry 2	3		3
Class 3	Waterford 3	3		3
Class 4	Braidwood 1	4	2	2
Class 4	Braidwood 2	4	2	2
Class 4	Byron 1	4	2	2
Class 4	Byron 2	4	2	2
Class 4	Callaway	4	2	2

Table 9. (continued).

Class	Plant	Total	CVC Pumps	HPSI Pumps
Class 4	Catawba 1	4	2	2
Class 4	Catawba 2	4	2	2
Class 4	Comanche Peak 1	4	2	2
Class 4	Comanche Peak 2	4	2	2
Class 4	Cook 1	4	2	2
Class 4	Cook 2	4	2	2
Class 4	Davis-Besse	4	2	2
Class 4	Diablo Canyon 1	4	2	2
Class 4	Diablo Canyon 2	4	2	2
Class 4	McGuire 1	4	2	2
Class 4	McGuire 2	4	2	2
Class 4	Millstone 3	4	2	2
Class 4	Salem 1	4	2	2
Class 4	Salem 2	4	2	2
Class 4	Seabrook	4	2	2
Class 4	Sequoyah 1	4	2	2
Class 4	Sequoyah 2	4	2	2
Class 4	Turkey Point 3	4		4
Class 4	Turkey Point 4	4		4
Class 4	Vogtle 1	4	2	2
Class 4	Vogtle 1	4	2	2
Class 4	Watts Bar 1	4	2	2
Class 4	Watts Bar 1	4	2	2
Class 4	Wolf Creek	4	2	2

[a] At Harris, the third pump takes 8 hours to install.

As mentioned before, in some PWRs, the normally running charging pumps are used to perform the HPSI function. In these plants, during normal operations, the charging-pump or makeup pump takes suction from the volume control tank (VCT) or makeup tank (MUT). The level in this tank is maintained from letdown received from the purification loop of the RCS, reactor coolant pump (RCP) seal return, charging/makeup pump recirculation, and other minor sources. Borated water is occasionally added to the VCT/MUT depending on losses in the system, such as RCS leakage or operational requirements to borate or de-borate. During emergency operation, the suction of the charging/makeup pumps is changed. Several valves reposition automatically upon receipt of a safety injection signal. This allows a large reserve tank to supply borated water to the suction of the charging/safety injection pumps. This large tank is commonly called the refueling water storage tank (RWST) or borated water storage tank (BWST). The water in this tank has a high boron concentration, generally 2,400 ppm. The tank volume varies from about 245,000 to as high as 450,000 gallons but is often in the 338,000–425,000-gallon range. Once the valves have repositioned, the head from the RWST/BWST seats the VCT/MUT outlet check valve, and the highly borated water is then supplied to the safety injection (SI) pumps.

During emergency situations, when the water in the RWST/BWST is depleted, water is available to the HPSI pumps from the reactor building or containment building sump. This water may be directly available to the SI pumps via piping and valves, or it may require a low-pressure stage pump to provide sufficient net positive suction head (NPSH) to the SI and charging/makeup pumps. This source of water becomes extremely important during emergencies that require a prolonged time for injection before being terminated and possibly exhausting the RWST/BWST water capacity. In this case, the HPSI system is used in the "recirculation mode."

The above discussion mainly applies to designs where the charging/makeup pumps are used in normal operation and also the HPSI pumps during emergencies. These pumps require low-pressure pumps to provide NPSH from the reactor building or containment building sump, for example. Oconee 1, 2, and 3 utilize this design.

The following descriptions apply to those designs that incorporate separate SI pumps and charging/makeup pumps. For these designs, the charging/makeup pumps still operate as mentioned above. That is, during normal operation the charging pumps take suction from the VCT/MUT. However, upon receipt of a SI signal, the pumps take suction from the RWST and the valves between the VCT/MUT and the charging pump suction close (typically, there are two valves). However, the dedicated SI pumps can only take water from the RWST/BWST and not the VCT/MUT as the charging/make-up pumps can. These SI pumps are intermediate-head. As such, they require the charging/make-up pumps to be in operation until the RCS press decreases to the pressure where the intermediate-head pumps can inject water on their own. At this point, the charging/make-up pumps can be turned off or left on to help inject a greater volume of water. Braidwood 1 and 2 are examples of this design. The final plant design contains only intermediate-head SI pumps that are used for HPSI. These pumps take suction from the RWST/BWST for injection and are aligned to take suction directly from the reactor building or containment build sump during "recirculation mode." Waterford is an example of this design.

In the plants equipped with charging/make-up pumps and dedicated SI pumps, the charging/make-up pumps typically supply make-up or cooling water to plant equipment as well during normal operation, for example, supply to the RCP seal. This normally requires 8–10 gpm per RCP. Another function is PZR-level control. This system senses PZR level and opens or closes the PZR-level control valve allowing more or less make-up to maintain the selected PZR-level set point. Most of the flow from the charging/make-up pumps is returned to the VCT/MUT via recirculation piping and valves during normal system operation. Once an ECCS signal is received or the operator manually repositions valves to their emergency position, the discharge of the charging/make-up pumps redirects. The flow from the SI and the charging/make-up pumps to the RCP seals is reduced. The charging/make-up pump recirculation back to the VCT/MUT is also automatically terminated in order to maximize SI flow into the RCS. There are generally three or four injection nozzles to the RCS for HPSI. These nozzles, located in the cold legs[c] of the RCS have instrumented piping connected to them from the charging/make-up pumps and SI pumps, depending on the design. Some of the devices and instrumentation on the discharge piping include, but are not limited to injection/isolation valves, flow-balancing orifices, flow crossover piping, and nozzle and total flow indicators.

Figure 9 shows a simplified generic HPSI system diagram. Note that the Residual Heat Removal system, which is part of the ECCS system along with the HPSI system is included in the diagram (within the dotted line) for illustration purpose only.

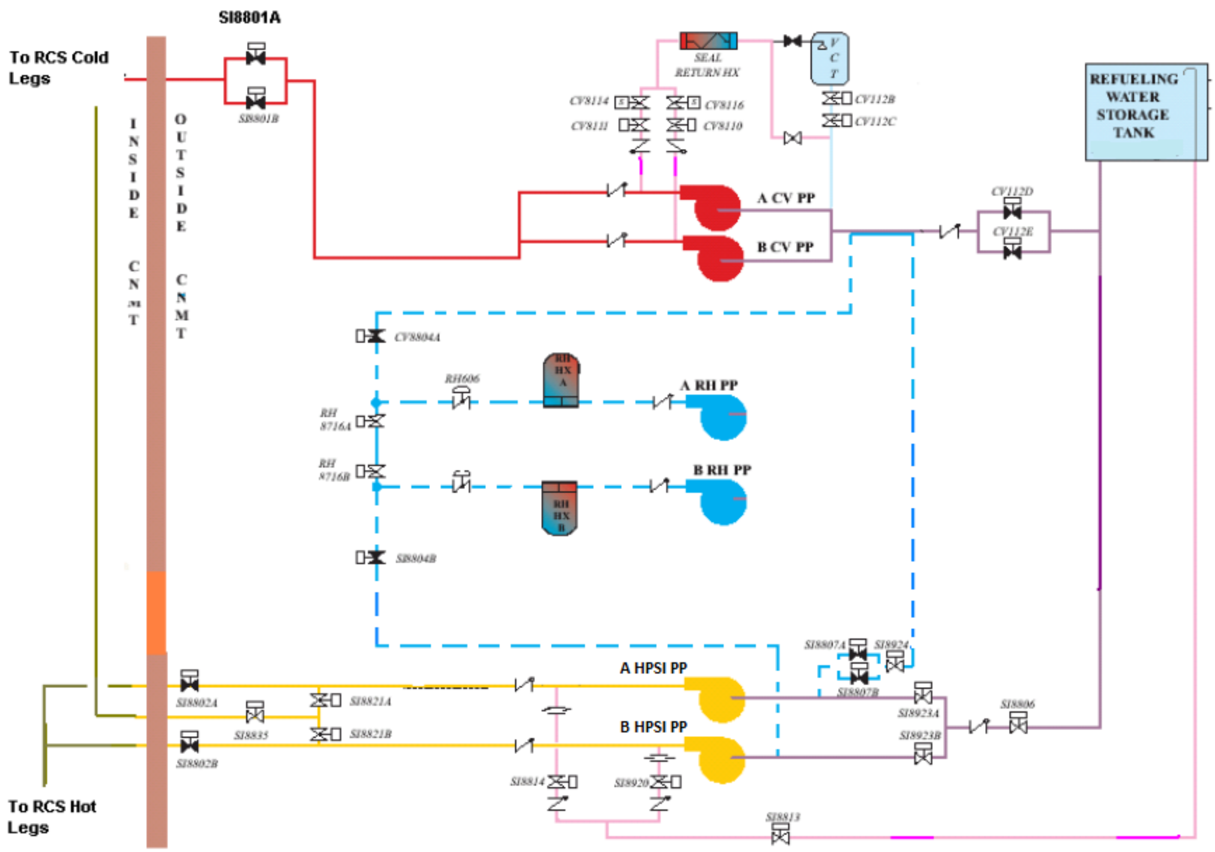

Figure 9. Simplified generic HPSI system diagram.

c Some designs also have injection nozzles in the hot legs.

8. REFERENCES

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