

System Study: High-Pressure Safety Injection 1998–2016

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ABSTRACT

This report presents an unreliability evaluation of the high-pressure safety injection system (HPSI) at 69 U.S. commercial nuclear power plants. Demand, run hours, and failure data from calendar years 1998 through 2016 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 HPSI results. A statistically significant decreasing trend was identified for HPSI start-only unreliability.

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ACRONYMS

AFW	auxiliary feedwater
BWST	borated water storage tank
CCF	common-cause failure
CY	calendar year
ECCS	emergency core cooling system
EPIX	Equipment Performance and Information Exchange
ESFAS	engineered safety features actuation system
FY	fiscal year
HPSI	high-pressure safety injection
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
LOCA	loss-of-coolant accident
MFW	main feedwater
MSPI	Mitigating Systems Performance Index
MUT	make-up tank
NPSH	net positive suction head
PORV	power-operated relief valve
PRA	probabilistic risk assessment
PZR	pressurizer
RCP	reactor coolant pump
RCS	reactor coolant system
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
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 69 U.S. commercial nuclear power plants listed in Table 1. For each plant, the corresponding Standardized Plant Analysis Risk (SPAR) model (version model indicated in Table 1) was used in the yearly calculations. Different from previous year's updates, this year's results are based on calendar year (CY) instead of fiscal year (FY). Demand, run hours, and failure data from 1998 through 2016 for selected components in the HPSI 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 (1998 through 2001) and the Mitigating Systems Performance Index (MSPI) database (2002 through 2016). 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 HPSI unreliability results using basic event values from that report are summarized in Section 3.^a Trend results for HPSI (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 HPSI.

The HPSI classes were categorized by 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 and their classes.

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 has not been included in the SPAR model logic. 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.

Two modes of the models for the HPSI system are calculated. The HPSI start-only model is the HPSI SPAR model modified by setting all fail-to-run basic events to zero (False), setting all recovery events to False, and setting all cooling basic events to False. The 8-hour mission model includes all basic events in the HPSI SPAR model.

^a Note that the 2015 Component Reliability Update (Reference 3) is now available to report more current estimated basic event values for use in a PRA. Estimates from the 2015 Update will be used in the next system study.

Table 1. HPSI design class summary.

Class	Plant	Version
Class 2	Kewaunee	8.20
Class 2	Palisades	8.20
Class 2	Palo Verde 1	8.20
Class 2	Palo Verde 2	8.20
Class 2	Palo Verde 3	8.20
Class 2	Point Beach 1	8.20
Class 2	Point Beach 2	8.20
Class 2	Prairie Island 1	8.19
Class 2	Prairie Island 2	8.19
Class 2	St. Lucie 1	8.19
Class 2	St. Lucie 2	8.19
Class 2	Summer	8.23
Class 3	Arkansas 1	8.19
Class 3	Arkansas 2	8.21
Class 3	Beaver Valley 1	8.22
Class 3	Beaver Valley 2	8.23
Class 3	Calvert Cliffs 1	8.22
Class 3	Calvert Cliffs 2	8.21
Class 3	Crystal River 3	8.16
Class 3	Farley 1	8.18
Class 3	Farley 2	8.18
Class 3	Fort Calhoun	8.20
Class 3	Ginna	8.23
Class 3	Harris	8.23
Class 3	Indian Point 2	8.19
Class 3	Indian Point 3	8.20
Class 3	Millstone 2	8.17
Class 3	North Anna 1	8.20
Class 3	North Anna 2	8.20
Class 3	Oconee 1	8.19
Class 3	Oconee 2	8.19
Class 3	Oconee 3	8.19
Class 3	Robinson 2	8.17
Class 3	San Onofre 2	8.22
Class 3	San Onofre 3	8.22

Class	Plant	Version
Class 3	South Texas 1	8.17
Class 3	South Texas 2	8.17
Class 3	Surry 1	8.19
Class 3	Surry 2	8.15
Class 3	Three Mile Isl 1	8.20
Class 3	Waterford 3	8.16
Class 4	Braidwood 1	8.21
Class 4	Braidwood 2	8.21
Class 4	Byron 1	8.21
Class 4	Byron 2	8.21
Class 4	Callaway	8.21
Class 4	Catawba 1	8.20
Class 4	Catawba 2	8.20
Class 4	Comanche Peak 1	8.21
Class 4	Comanche Peak 2	8.21
Class 4	Cook 1	8.20
Class 4	Cook 2	8.20
Class 4	Davis-Besse	8.19
Class 4	Diablo Canyon 1	8.19
Class 4	Diablo Canyon 2	8.19
Class 4	McGuire 1	8.20
Class 4	McGuire 2	8.20
Class 4	Millstone 3	8.20
Class 4	Salem 1	8.20
Class 4	Salem 2	8.20
Class 4	Seabrook	8.20
Class 4	Sequoyah 1	8.16
Class 4	Sequoyah 2	8.16
Class 4	Turkey Point 3	8.20
Class 4	Turkey Point 4	8.20
Class 4	Vogtle 1	8.21
Class 4	Vogtle 2	8.21
Class 4	Watts Bar 1	8.16
Class 4	Wolf Creek	8.20

2. SUMMARY OF FINDINGS

The results of this HPSI 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 HPSI unreliability results. A decreasing trend in start only unreliability was identified as a statistically significant decreasing trend.

The industry-wide HPSI start-only and 8-hour basic event group importance was evaluated and is shown in Figure 5. In the 8-hour case, the leading contributor to HPSI system unreliability is the suction, followed by the HPI pumps, cooling support, and the injection flow path. In the start-only case, the leading contributor to HPSI system unreliability is the suction, followed by the HPI pumps, the injection flow path, and AC power.

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).

3. INDUSTRY-WIDE UNRELIABILITY

The HPSI fault trees from the SPAR models were evaluated for each of the 69 operating U.S. commercial pressurized water reactor nuclear power plants with an HPSI system.

The industry-wide unreliability of the HPSI 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 HPSI show both plant design variability and parameter uncertainty while using industry-wide component failure data (1998–2010).^a Table 2 shows the percentiles and mean of the aggregated sample data (Latin hypercube, 1000 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	2.24E-08	1.17E-05	4.33E-05	1.08E-04
	Class 2	7.56E-06	4.10E-05	5.47E-05	1.35E-04
	Class 3	1.11E-06	1.97E-05	7.45E-05	1.23E-04
	Class 4	7.57E-09	4.45E-07	7.29E-06	4.09E-05
8-hour Mission	Industry	7.83E-08	2.02E-05	6.44E-05	1.36E-04
	Class 2	1.21E-05	5.16E-05	6.77E-05	1.62E-04
	Class 3	3.91E-06	2.87E-05	1.12E-04	1.46E-04
	Class 4	2.56E-08	1.86E-06	1.65E-05	9.00E-05

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.

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

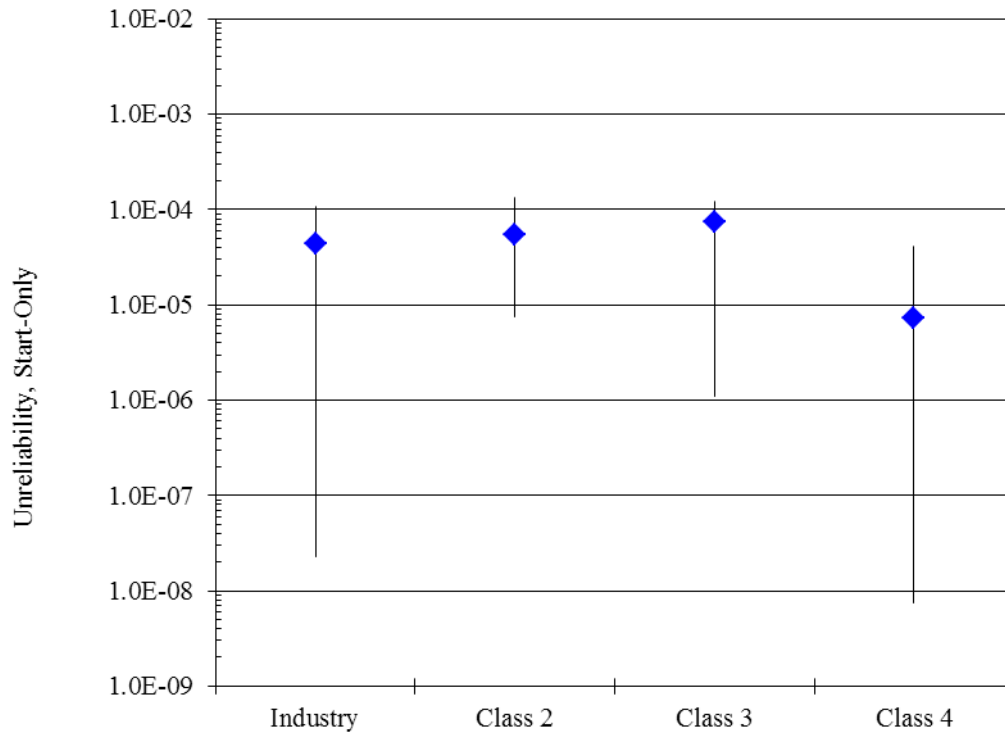


Figure 1. HPSI start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

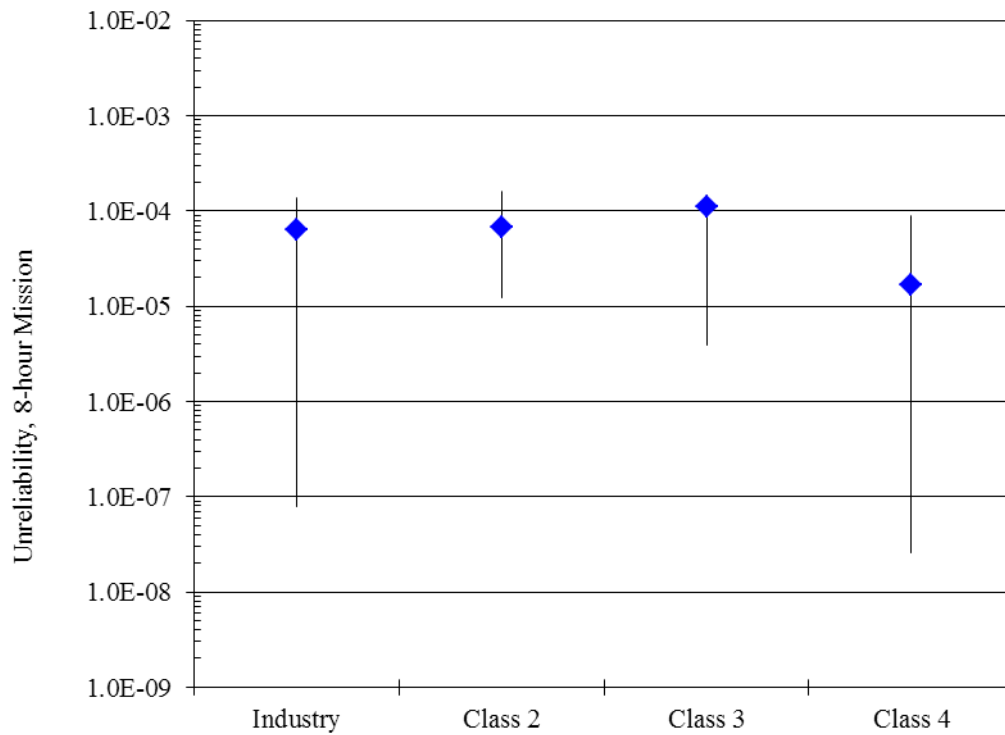


Figure 2. HPSI 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly (from 1998 through 2016) failure and demand or run time data were obtained from ICES for the HPSI system. HPSI 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 HPSI system components using the trending methods described in Section 1 and 2 of the [Overview and Reference document](#). Tables 6 and 7 show the yearly data values for each HPSI system specific component and failure mode combination that was 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 using data for each year. In addition, for comparison, the calculated industry-wide system reliability from this update (SPAR/EPIX) 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.

The components that were varied in the HPSI model are

- HPSI motor-driven pump start, run, and test and maintenance.
- CVC motor-driven pump start, run, and test and maintenance.
- Injection valves fail-to-open.

Figure 3 shows the trend in the HPSI start-only model unreliability. The decreasing trend in start-only unreliability is statistically significant^a. Table 4 shows the data points for Figure 3. Figure 4 shows the trend in the 8-hour mission unreliability. The Figure 4 trend is not statistically significant. Table 5 shows the data points for Figure 4.

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).

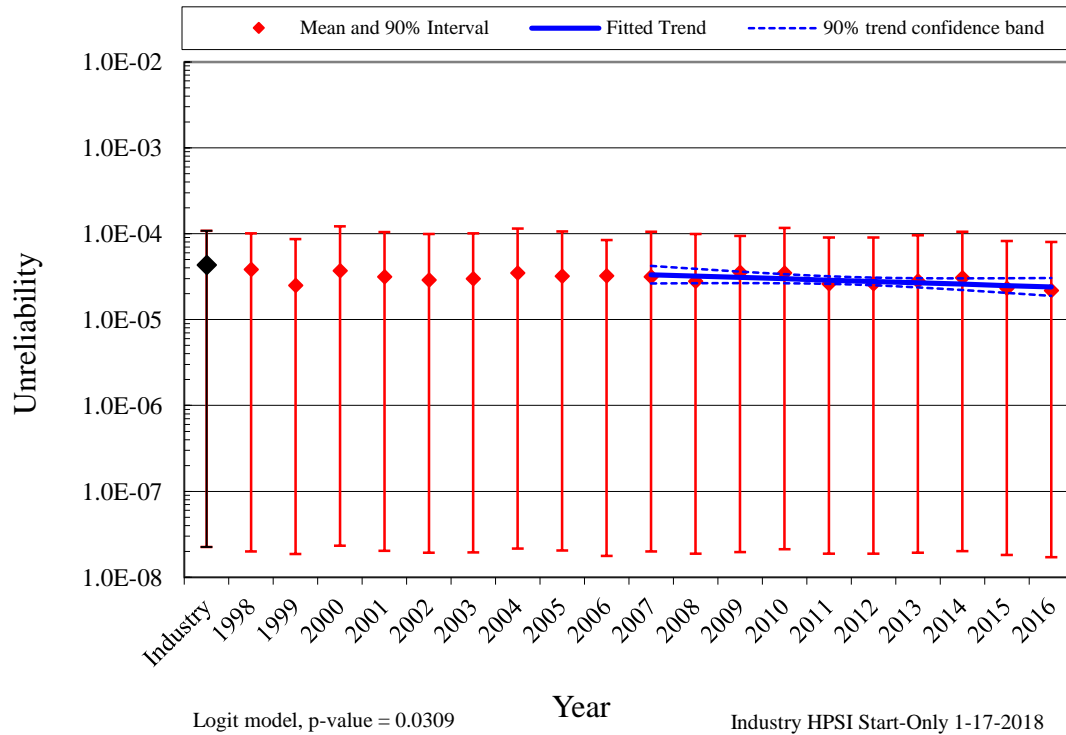


Figure 3. Trend of HPSI system unreliability (start-only model), as a function of year.

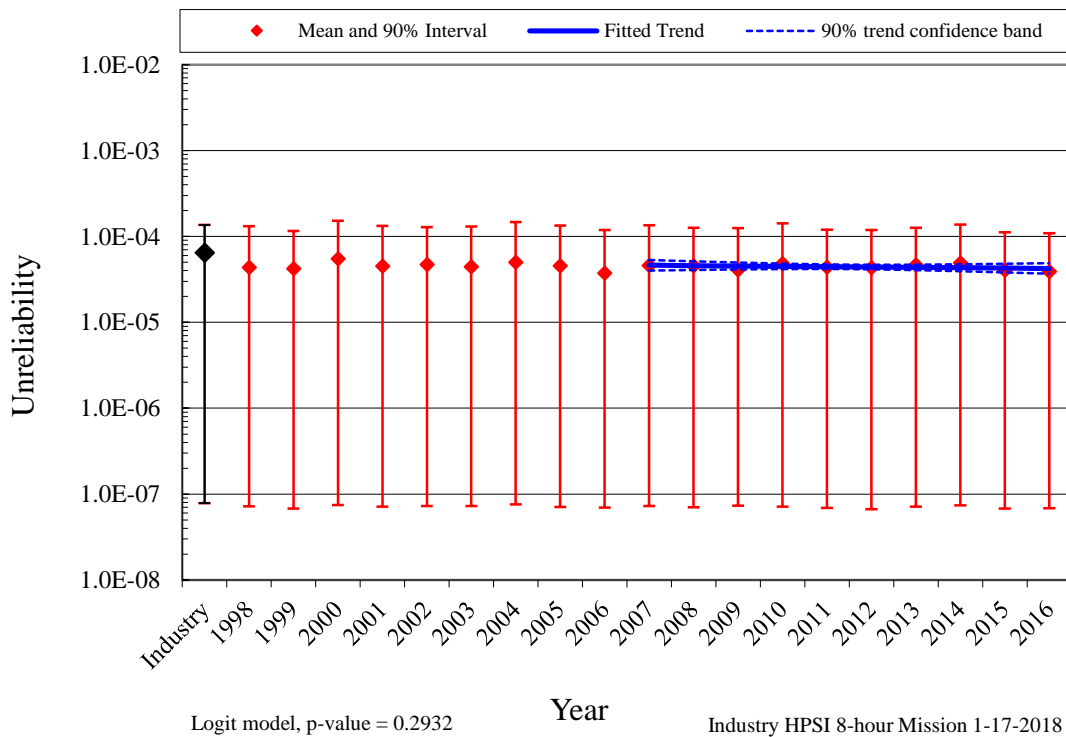


Figure 4. Trend of HPSI system unreliability (8-hour model), as a function of year.

5. BASIC EVENT GROUP IMPORTANCES

The HPSI basic event group Fussell-Vesely importances were calculated for the start-only and 8-hour modes 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. The industry-wide HPSI start-only and 8-hour basic event group importances are shown in Figure 5. In the 8-hour case, the leading contributor to HPSI system unreliability is the suction, followed by the HPI pumps, cooling support, and the injection flow path. In the start-only case, the leading contributor to HPSI system unreliability is the suction, followed by the HPI pumps, the injection flow path, and AC power. For more discussion on the HPSI motor-driven pumps, see the motor-driven pump component reliability studies at NRC Reactor Operational Experience Results and Databases. Table 3 shows the SPAR model HPSI importance groups and their descriptions.

The basic event group importances were also averaged across plants of the same HPSI class to represent class basic event group importances. The class HPSI start-only and 8-hour basic event group importances are shown in Figure 6 through Figure 8.

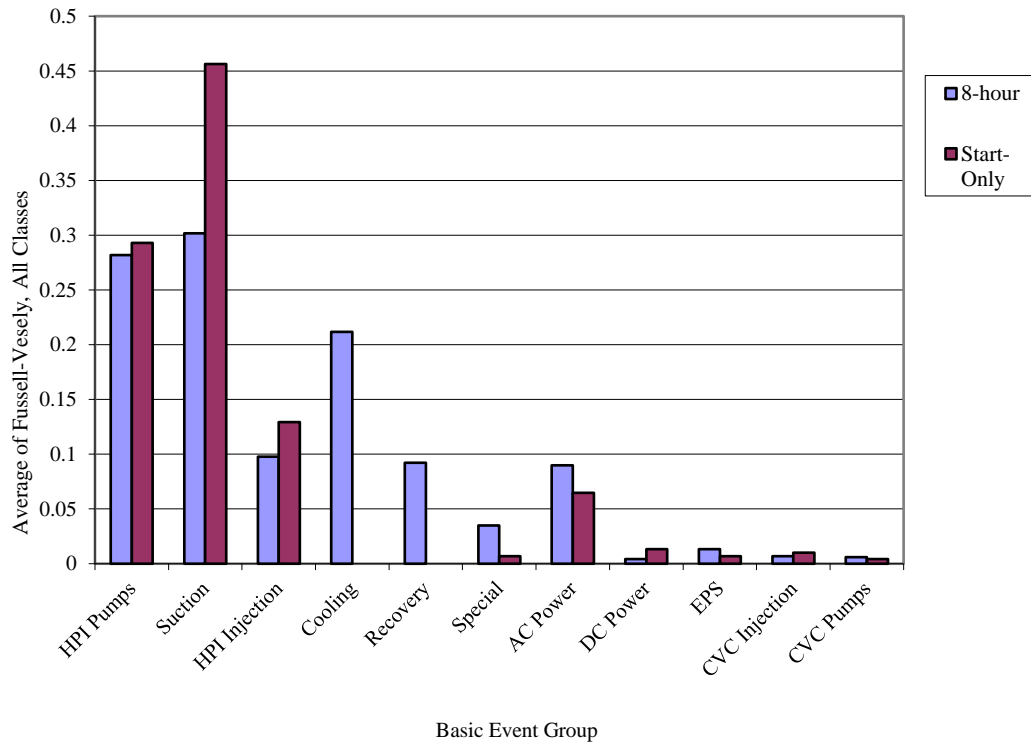


Figure 5. HPSI industry-wide basic event group importances.

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 motor-driven pump 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) motor-driven pumps. The start, run, common-cause, and test and maintenance are included in the group of basic events.
DC Power	The batteries and battery chargers that supply power to the HPSI motor-driven pump control circuitry.
EPS	HPSI dependency on the emergency power system.
HPI Injection	The motor-operated valves and check valves in the HPSI injection path.
HPI Pumps	All basic events associated with the HPSI (generally lower head; standby) motor-driven pumps. The start, run, common-cause, and test and maintenance are included in the group of basic events.
Recovery	Recovery of pump fail to start.
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. Includes the failure of the tank.

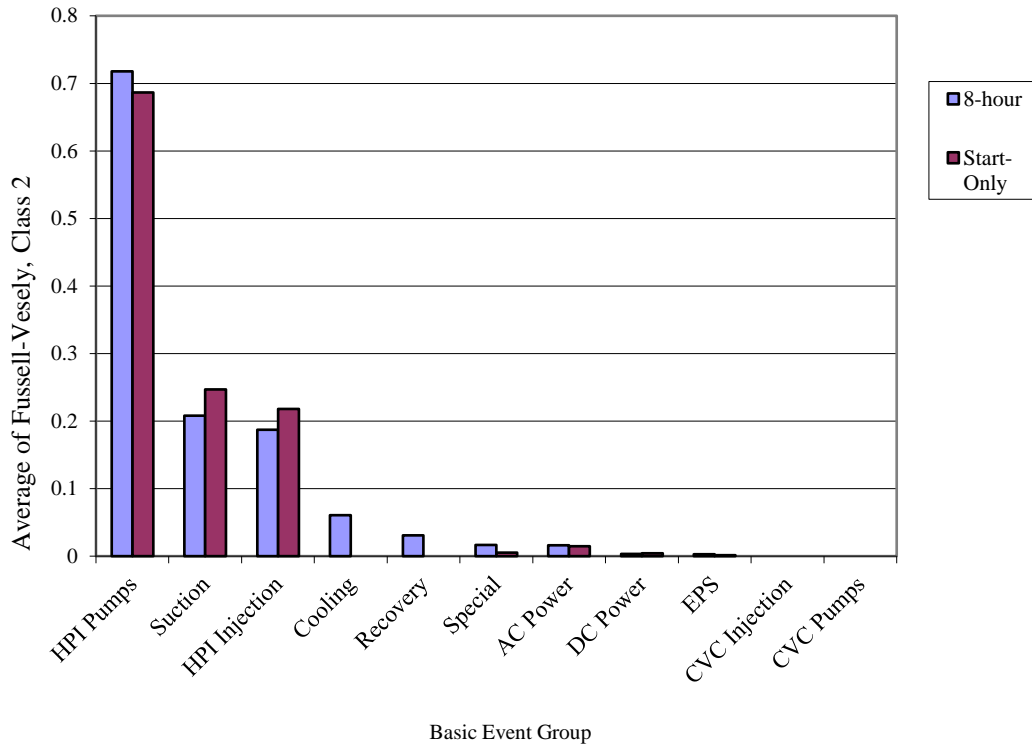


Figure 6. HPSI Class 2 basic event group importances.

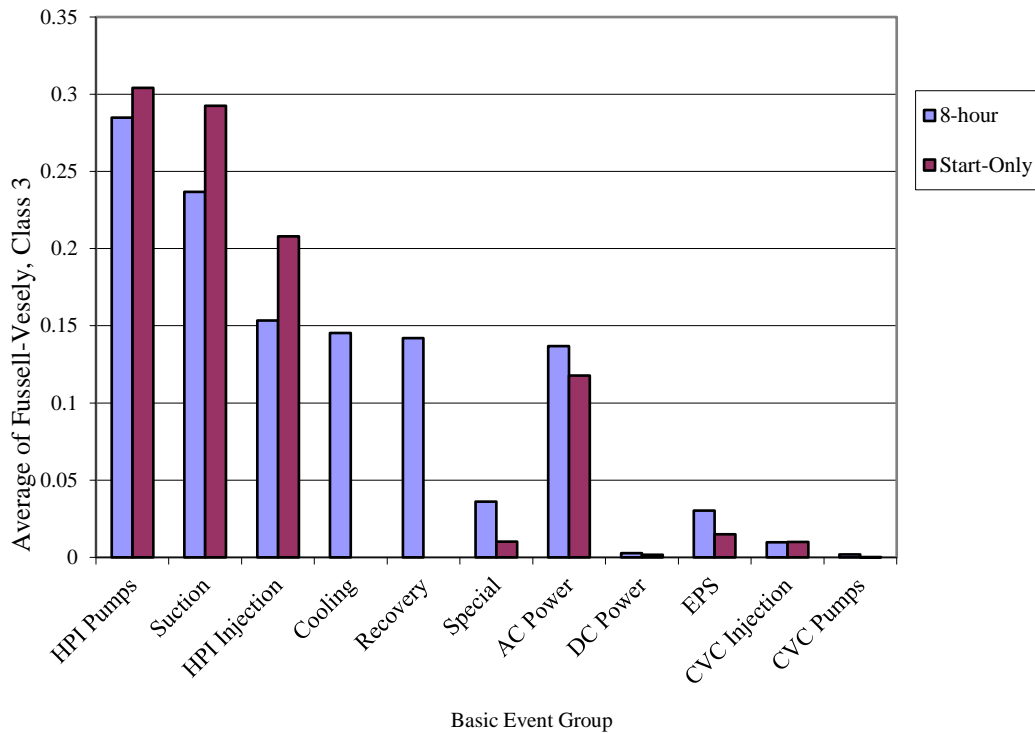


Figure 7. HPSI Class 3 basic event group importances.

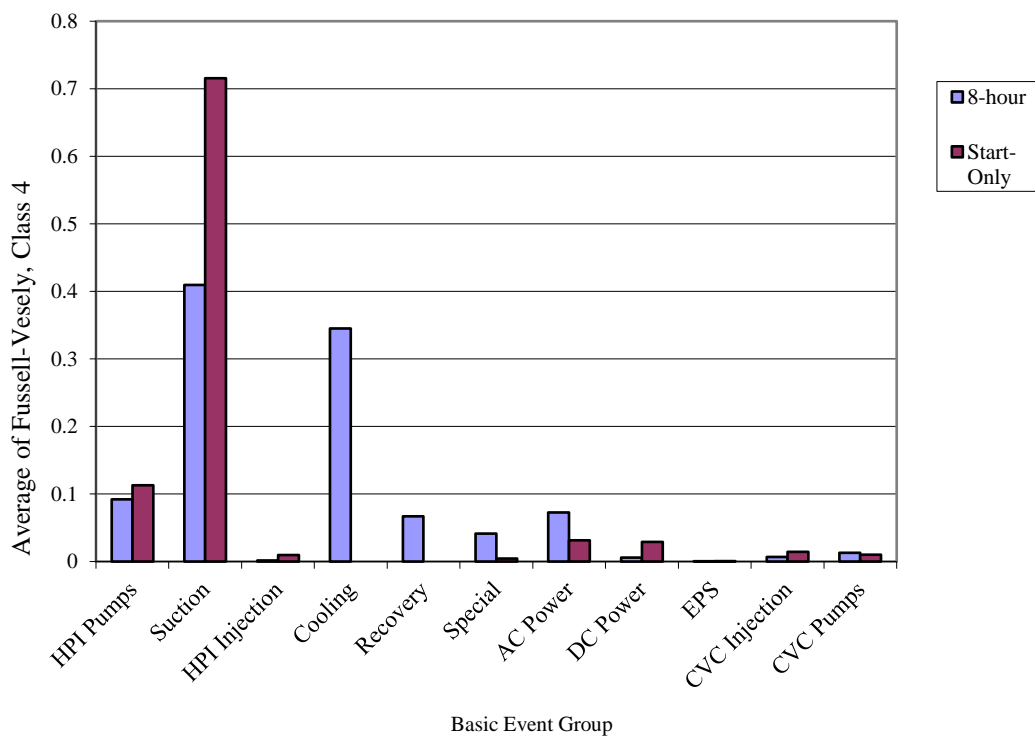


Figure 8. HPSI Class 4 basic event group importances.

6. DATA TABLES

Table 4. Plot data for HPSI start-only trend, Figure 3.

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ EPIX				2.24E-08	1.08E-04	4.33E-05
1998				1.99E-08	1.01E-04	3.82E-05
1999				1.87E-08	8.64E-05	2.49E-05
2000				2.32E-08	1.22E-04	3.71E-05
2001				2.03E-08	1.05E-04	3.14E-05
2002				1.93E-08	9.90E-05	2.90E-05
2003				1.95E-08	1.01E-04	3.01E-05
2004				2.15E-08	1.15E-04	3.49E-05
2005				2.04E-08	1.07E-04	3.20E-05
2006				1.77E-08	8.46E-05	3.24E-05
2007	3.33E-05	2.63E-05	4.22E-05	1.99E-08	1.05E-04	3.15E-05
2008	3.21E-05	2.65E-05	3.90E-05	1.88E-08	9.89E-05	2.79E-05
2009	3.10E-05	2.65E-05	3.62E-05	1.96E-08	9.41E-05	3.56E-05
2010	2.99E-05	2.64E-05	3.38E-05	2.13E-08	1.16E-04	3.49E-05
2011	2.88E-05	2.60E-05	3.19E-05	1.88E-08	8.99E-05	2.61E-05
2012	2.78E-05	2.51E-05	3.08E-05	1.88E-08	9.03E-05	2.62E-05
2013	2.68E-05	2.37E-05	3.03E-05	1.94E-08	9.61E-05	2.82E-05
2014	2.58E-05	2.21E-05	3.02E-05	2.02E-08	1.06E-04	3.08E-05
2015	2.49E-05	2.05E-05	3.02E-05	1.81E-08	8.23E-05	2.32E-05
2016	2.40E-05	1.90E-05	3.04E-05	1.72E-08	8.00E-05	2.18E-05

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

Year/Source	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ EPIX				7.83E-08	1.36E-04	6.44E-05
1998				7.23E-08	1.32E-04	4.37E-05
1999				6.78E-08	1.15E-04	4.21E-05
2000				7.43E-08	1.52E-04	5.48E-05
2001				7.15E-08	1.33E-04	4.53E-05
2002				7.24E-08	1.28E-04	4.73E-05
2003				7.24E-08	1.30E-04	4.43E-05
2004				7.61E-08	1.47E-04	5.02E-05
2005				7.07E-08	1.33E-04	4.54E-05
2006				6.98E-08	1.18E-04	3.73E-05
2007	4.61E-05	3.99E-05	5.33E-05	7.25E-08	1.35E-04	4.61E-05
2008	4.57E-05	4.06E-05	5.15E-05	7.01E-08	1.26E-04	4.57E-05
2009	4.53E-05	4.12E-05	4.98E-05	7.35E-08	1.25E-04	4.08E-05
2010	4.48E-05	4.16E-05	4.83E-05	7.12E-08	1.42E-04	4.84E-05
2011	4.44E-05	4.17E-05	4.73E-05	6.88E-08	1.20E-04	4.39E-05
2012	4.40E-05	4.13E-05	4.68E-05	6.66E-08	1.19E-04	4.35E-05
2013	4.36E-05	4.04E-05	4.70E-05	7.12E-08	1.26E-04	4.66E-05
2014	4.32E-05	3.92E-05	4.75E-05	7.37E-08	1.37E-04	4.91E-05
2015	4.27E-05	3.79E-05	4.81E-05	6.81E-08	1.12E-04	4.04E-05
2016	4.23E-05	3.66E-05	4.89E-05	6.82E-08	1.09E-04	3.90E-05

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	348.8	7.33E-04	1.112	1517	Beta
FTOC	AOV	1999	0	382.6	7.17E-04	1.112	1551	Beta
FTOC	AOV	2000	0	353.3	7.30E-04	1.112	1521	Beta
FTOC	AOV	2001	0	290.1	7.62E-04	1.112	1458	Beta
FTOC	AOV	2002	0	358.7	7.28E-04	1.112	1527	Beta
FTOC	AOV	2003	2	318.2	2.09E-03	3.112	1484	Beta
FTOC	AOV	2004	0	284.9	7.65E-04	1.112	1453	Beta
FTOC	AOV	2005	0	285.3	7.65E-04	1.112	1453	Beta
FTOC	AOV	2006	1	271.1	1.47E-03	2.112	1438	Beta
FTOC	AOV	2007	0	264.4	7.76E-04	1.112	1432	Beta
FTOC	AOV	2008	1	263.1	1.47E-03	2.112	1430	Beta
FTOC	AOV	2009	0	263.4	7.76E-04	1.112	1431	Beta
FTOC	AOV	2010	0	263.1	7.76E-04	1.112	1431	Beta
FTOC	AOV	2011	3	264.1	2.87E-03	4.112	1429	Beta
FTOC	AOV	2012	0	263.1	7.76E-04	1.112	1431	Beta
FTOC	AOV	2013	0	262.4	7.77E-04	1.112	1430	Beta
FTOC	AOV	2014	1	263.4	1.47E-03	2.112	1430	Beta
FTOC	AOV	2015	0	263.4	7.76E-04	1.112	1431	Beta
FTOC	AOV	2016	0	263.4	7.76E-04	1.112	1431	Beta
FTOC	MOV	1998	5	5,460.9	9.29E-04	7.046	7579	Beta
FTOC	MOV	1999	2	5,655.7	5.20E-04	4.046	7777	Beta
FTOC	MOV	2000	7	5,438.6	1.20E-03	9.046	7555	Beta
FTOC	MOV	2001	4	5,239.1	8.21E-04	6.046	7358	Beta
FTOC	MOV	2002	2	5,322.2	5.43E-04	4.046	7443	Beta
FTOC	MOV	2003	3	5,315.6	6.78E-04	5.046	7436	Beta
FTOC	MOV	2004	5	5,421.3	9.34E-04	7.046	7539	Beta
FTOC	MOV	2005	4	5,172.3	8.29E-04	6.046	7291	Beta
FTOC	MOV	2006	3	4,887.6	7.20E-04	5.046	7008	Beta
FTOC	MOV	2007	3	4,802.6	7.28E-04	5.046	6923	Beta
FTOC	MOV	2008	0	5,008.4	2.87E-04	2.046	7131	Beta
FTOC	MOV	2009	4	4,963.3	8.53E-04	6.046	7082	Beta
FTOC	MOV	2010	3	4,768.4	7.32E-04	5.046	6888	Beta
FTOC	MOV	2011	2	4,858.8	5.79E-04	4.046	6980	Beta
FTOC	MOV	2012	2	4,913.4	5.75E-04	4.046	7034	Beta
FTOC	MOV	2013	2	4,790.0	5.85E-04	4.046	6911	Beta
FTOC	MOV	2014	5	4,820.2	1.01E-03	7.046	6938	Beta
FTOC	MOV	2015	1	4,832.7	4.38E-04	3.046	6955	Beta
FTOC	MOV	2016	0	4,747.9	2.98E-04	2.046	6871	Beta
FTOP	AOV	1998	0	586,920.0	2.25E-07	1.421	6305920	Gamma
FTOP	AOV	1999	0	586,920.0	2.25E-07	1.421	6305920	Gamma
FTOP	AOV	2000	1	630,720.0	3.81E-07	2.421	6349720	Gamma
FTOP	AOV	2001	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2002	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2003	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2004	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2005	0	630,720.0	2.24E-07	1.421	6349720	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	AOV	2006	0	657,000.0	2.23E-07	1.421	6376000	Gamma
FTOP	AOV	2007	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2008	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2009	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2010	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2011	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2012	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2013	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2014	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2015	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	AOV	2016	0	630,720.0	2.24E-07	1.421	6349720	Gamma
FTOP	MOV	1998	0	8,383,320.0	4.79E-08	1.458	30433320	Gamma
FTOP	MOV	1999	0	8,383,320.0	4.79E-08	1.458	30433320	Gamma
FTOP	MOV	2000	0	8,383,320.0	4.79E-08	1.458	30433320	Gamma
FTOP	MOV	2001	1	8,383,320.0	8.08E-08	2.458	30433320	Gamma
FTOP	MOV	2002	1	8,365,800.0	8.08E-08	2.458	30415800	Gamma
FTOP	MOV	2003	0	8,365,800.0	4.79E-08	1.458	30415800	Gamma
FTOP	MOV	2004	0	8,365,800.0	4.79E-08	1.458	30415800	Gamma
FTOP	MOV	2005	0	8,400,840.0	4.79E-08	1.458	30450840	Gamma
FTOP	MOV	2006	0	8,427,120.0	4.78E-08	1.458	30477120	Gamma
FTOP	MOV	2007	0	8,418,360.0	4.79E-08	1.458	30468360	Gamma
FTOP	MOV	2008	0	8,418,360.0	4.79E-08	1.458	30468360	Gamma
FTOP	MOV	2009	0	8,435,880.0	4.78E-08	1.458	30485880	Gamma
FTOP	MOV	2010	0	8,427,120.0	4.78E-08	1.458	30477120	Gamma
FTOP	MOV	2011	1	8,549,760.0	8.03E-08	2.458	30599760	Gamma
FTOP	MOV	2012	1	8,427,120.0	8.07E-08	2.458	30477120	Gamma
FTOP	MOV	2013	0	8,462,160.0	4.78E-08	1.458	30512160	Gamma
FTOP	MOV	2014	0	8,427,120.0	4.78E-08	1.458	30477120	Gamma
FTOP	MOV	2015	0	8,427,120.0	4.78E-08	1.458	30477120	Gamma
FTOP	MOV	2016	0	8,427,120.0	4.78E-08	1.458	30477120	Gamma
FTR<1H	MDP	1998	0	2,899.2	1.03E-04	1.82	17689	Gamma
FTR<1H	MDP	1999	0	3,288.1	1.01E-04	1.82	18078	Gamma
FTR<1H	MDP	2000	0	3,215.0	1.01E-04	1.82	18005	Gamma
FTR<1H	MDP	2001	0	3,186.2	1.01E-04	1.82	17976	Gamma
FTR<1H	MDP	2002	0	3,022.6	1.02E-04	1.82	17813	Gamma
FTR<1H	MDP	2003	0	3,171.9	1.01E-04	1.82	17962	Gamma
FTR<1H	MDP	2004	0	2,961.2	1.03E-04	1.82	17751	Gamma
FTR<1H	MDP	2005	0	2,945.7	1.03E-04	1.82	17736	Gamma
FTR<1H	MDP	2006	0	3,209.3	1.01E-04	1.82	17999	Gamma
FTR<1H	MDP	2007	1	2,709.4	1.61E-04	2.82	17499	Gamma
FTR<1H	MDP	2008	0	3,121.0	1.02E-04	1.82	17911	Gamma
FTR<1H	MDP	2009	1	3,036.6	1.58E-04	2.82	17827	Gamma
FTR<1H	MDP	2010	0	2,855.8	1.03E-04	1.82	17646	Gamma
FTR<1H	MDP	2011	0	2,856.6	1.03E-04	1.82	17647	Gamma
FTR<1H	MDP	2012	0	2,756.9	1.04E-04	1.82	17547	Gamma
FTR<1H	MDP	2013	0	2,737.6	1.04E-04	1.82	17528	Gamma
FTR<1H	MDP	2014	0	2,682.3	1.04E-04	1.82	17472	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	2015	0	2,658.6	1.04E-04	1.82	17449	Gamma
FTR<1H	MDP	2016	0	2,653.2	1.04E-04	1.82	17443	Gamma
FTR>1H	MDP	1998	2	135,659.1	1.32E-05	2.781	210669	Gamma
FTR>1H	MDP	1999	0	111,509.9	4.19E-06	0.781	186520	Gamma
FTR>1H	MDP	2000	1	105,703.1	9.86E-06	1.781	180713	Gamma
FTR>1H	MDP	2001	1	99,084.7	1.02E-05	1.781	174095	Gamma
FTR>1H	MDP	2002	2	102,978.6	1.56E-05	2.781	177989	Gamma
FTR>1H	MDP	2003	2	111,553.8	1.49E-05	2.781	186564	Gamma
FTR>1H	MDP	2004	4	116,208.6	2.50E-05	4.781	191219	Gamma
FTR>1H	MDP	2005	0	117,432.1	4.06E-06	0.781	192442	Gamma
FTR>1H	MDP	2006	1	116,565.8	9.30E-06	1.781	191576	Gamma
FTR>1H	MDP	2007	1	122,238.2	9.03E-06	1.781	197248	Gamma
FTR>1H	MDP	2008	1	119,206.1	9.17E-06	1.781	194216	Gamma
FTR>1H	MDP	2009	0	112,640.0	4.16E-06	0.781	187650	Gamma
FTR>1H	MDP	2010	0	110,992.9	4.20E-06	0.781	186003	Gamma
FTR>1H	MDP	2011	1	102,319.5	1.00E-05	1.781	177330	Gamma
FTR>1H	MDP	2012	0	102,898.1	4.39E-06	0.781	177908	Gamma
FTR>1H	MDP	2013	2	93,482.4	1.65E-05	2.781	168492	Gamma
FTR>1H	MDP	2014	2	89,014.4	1.70E-05	2.781	164024	Gamma
FTR>1H	MDP	2015	0	89,426.5	4.75E-06	0.781	164437	Gamma
FTR>1H	MDP	2016	0	86,690.6	4.83E-06	0.781	161701	Gamma
FTS	MDP	1998	2	2,899.2	7.97E-04	3.948	4951	Beta
FTS	MDP	1999	2	3,288.1	7.39E-04	3.948	5340	Beta
FTS	MDP	2000	5	3,215.0	1.32E-03	6.948	5264	Beta
FTS	MDP	2001	4	3,186.2	1.13E-03	5.948	5236	Beta
FTS	MDP	2002	4	3,022.6	1.17E-03	5.948	5073	Beta
FTS	MDP	2003	4	3,171.9	1.14E-03	5.948	5222	Beta
FTS	MDP	2004	5	2,961.2	1.38E-03	6.948	5010	Beta
FTS	MDP	2005	4	2,945.7	1.19E-03	5.948	4996	Beta
FTS	MDP	2006	0	3,209.3	3.70E-04	1.948	5263	Beta
FTS	MDP	2007	4	2,709.4	1.25E-03	5.948	4759	Beta
FTS	MDP	2008	5	3,121.0	1.34E-03	6.948	5170	Beta
FTS	MDP	2009	1	3,036.6	5.79E-04	2.948	5090	Beta
FTS	MDP	2010	6	2,855.8	1.62E-03	7.948	4904	Beta
FTS	MDP	2011	2	2,856.6	8.04E-04	3.948	4909	Beta
FTS	MDP	2012	2	2,756.9	8.20E-04	3.948	4809	Beta
FTS	MDP	2013	3	2,737.6	1.03E-03	4.948	4789	Beta
FTS	MDP	2014	2	2,682.3	8.33E-04	3.948	4734	Beta
FTS	MDP	2015	1	2,658.6	6.25E-04	2.948	4712	Beta
FTS	MDP	2016	1	2,653.2	6.26E-04	2.948	4706	Beta
SO	AOV	1998	0	586,920.0	1.17E-07	0.6801	5797920	Gamma
SO	AOV	1999	0	586,920.0	1.17E-07	0.6801	5797920	Gamma
SO	AOV	2000	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2001	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2002	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2003	1	630,720.0	2.88E-07	1.6801	5841720	Gamma
SO	AOV	2004	0	630,720.0	1.16E-07	0.6801	5841720	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	AOV	2005	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2006	0	657,000.0	1.16E-07	0.6801	5868000	Gamma
SO	AOV	2007	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2008	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2009	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2010	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2011	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2012	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2013	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2014	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2015	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	AOV	2016	0	630,720.0	1.16E-07	0.6801	5841720	Gamma
SO	MOV	1998	0	8,383,320.0	2.26E-08	0.5703	25223320	Gamma
SO	MOV	1999	0	8,383,320.0	2.26E-08	0.5703	25223320	Gamma
SO	MOV	2000	0	8,383,320.0	2.26E-08	0.5703	25223320	Gamma
SO	MOV	2001	0	8,383,320.0	2.26E-08	0.5703	25223320	Gamma
SO	MOV	2002	0	8,365,800.0	2.26E-08	0.5703	25205800	Gamma
SO	MOV	2003	0	8,365,800.0	2.26E-08	0.5703	25205800	Gamma
SO	MOV	2004	0	8,365,800.0	2.26E-08	0.5703	25205800	Gamma
SO	MOV	2005	0	8,400,840.0	2.26E-08	0.5703	25240840	Gamma
SO	MOV	2006	0	8,427,120.0	2.26E-08	0.5703	25267120	Gamma
SO	MOV	2007	0	8,418,360.0	2.26E-08	0.5703	25258360	Gamma
SO	MOV	2008	0	8,418,360.0	2.26E-08	0.5703	25258360	Gamma
SO	MOV	2009	0	8,435,880.0	2.26E-08	0.5703	25275880	Gamma
SO	MOV	2010	0	8,427,120.0	2.26E-08	0.5703	25267120	Gamma
SO	MOV	2011	0	8,549,760.0	2.25E-08	0.5703	25389760	Gamma
SO	MOV	2012	0	8,427,120.0	2.26E-08	0.5703	25267120	Gamma
SO	MOV	2013	0	8,462,160.0	2.25E-08	0.5703	25302160	Gamma
SO	MOV	2014	0	8,427,120.0	2.26E-08	0.5703	25267120	Gamma
SO	MOV	2015	0	8,427,120.0	2.26E-08	0.5703	25267120	Gamma
SO	MOV	2016	0	8,427,120.0	2.26E-08	0.5703	25267120	Gamma

Table 7. Basic event UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	MDP	1998	6283	1394450	4.23E-03	1.114	262.5	Beta
UA	MDP	1999	7124	1462526	4.54E-03	1.639	359.1	Beta
UA	MDP	2000	7947	1497199	5.02E-03	2.068	409.5	Beta
UA	MDP	2001	8489	1544955	5.51E-03	0.982	177.1	Beta
UA	MDP	2002	6181	1587234	3.84E-03	1.352	350.3	Beta
UA	MDP	2003	6400	1549554	3.81E-03	1.427	373.4	Beta
UA	MDP	2004	6482	1611202	3.83E-03	1.843	479.3	Beta
UA	MDP	2005	4770	1584007	3.08E-03	1.348	436.0	Beta
UA	MDP	2006	5513	1579742	3.35E-03	0.994	295.6	Beta
UA	MDP	2007	4588	1622723	2.91E-03	1.347	460.9	Beta
UA	MDP	2008	4830	1583020	3.07E-03	0.845	274.4	Beta
UA	MDP	2009	5263	1566514	3.39E-03	1.642	483.3	Beta
UA	MDP	2010	5183	1596046	3.33E-03	1.287	385.3	Beta
UA	MDP	2011	5225	1543817	3.35E-03	1.191	354.9	Beta
UA	MDP	2012	5160	1502828	3.20E-03	1.316	409.3	Beta
UA	MDP	2013	5563	1521929	3.46E-03	1.492	429.8	Beta
UA	MDP	2014	4541	1531624	2.97E-03	0.992	332.4	Beta
UA	MDP	2015	4572	1531552	2.93E-03	1.421	483.5	Beta
UA	MDP	2016	4017	1539576	2.68E-03	1.404	522.3	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 one hour
FTR<1H	Fail to Run less than one hour (after start)
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 after LOCA initiation, followed by realignment to a recirculation mode of operation to maintain long-term, post-LOCA core cooling. In addition to the above, reactors which are 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), RCS overcooling events resulting 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 analyzed have been grouped into three different design classes as shown in Table 1. The criteria used to determine 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 a number of different combinations of motor-driven pump trains. Because of the diversity in system design, operation, and response to plant transients, a detailed discussion of the each plant-specific system is not practical. 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 modeling of the HPSI incorporates the plant-to-plant design and operational differences indicated in Table 9. All ac emergency power sources that either are automatically started and aligned to essential buses given a LOOP or can be manually started and aligned within approximately 30 minutes are included in the HPSI SPAR fault trees. Included in the HPSI SPAR fault trees are 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 plants, B&W in particular and some Westinghouse designs, the normal make-up 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 make-up that is separate from the safety injection pumps, which are used only during emergency or abnormal situations. However, even in these designs the make-up and safety injection systems are inter-related because they share common valves, water sources, piping runs, and other equipment. Consequently, the safety injection systems can be either intermediate-head capacity (approximately 1400 psi), or high-head capacity (approximately 2200 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 it 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 reactor coolant system 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	Harris	3		3 ^a
Class 2	Kewaunee	2		2
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 1	3		3
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	Crystal River 3	3		3
Class 3	Farley 1	3	3	
Class 3	Farley 2	3	3	
Class 3	Fort Calhoun	3		3
Class 3	Ginna	3		3
Class 3	Indian Point 2	3		3
Class 3	Indian Point 3	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	San Onofre 2	3		3
Class 3	San Onofre 3	3		3

Class	Plant	Total	CVC Pumps	HPSI Pumps
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	Three Mile Island 1	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
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 2	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/make-up pump takes suction from the volume control tank (VCT)/make-up tank (MUT). The level in this tank is maintained from letdown received from the purification loop of the reactor coolant system (RCS), reactor coolant pump (RCP) seal return, charging/make-up pump recirculation, and other minor sources. Borated water is added to the VCT/MUT occasionally 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/make-up 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 2400 ppm boron. The tank volume varies from about 245,000 to as high as 450,000 gallons but is often in the 338,000 to 425,000 gallon range. Once the valves have repositioned, the head from the RWST/BWST seats the VCT/MUT outlet check valve, and thereby the highly borated water is 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/make-up 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/make-up pumps used in normal operation are also the HPSI pumps during emergencies. These pumps require the 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 applies to those designs that incorporate separate SI pumps and charging/make-up pumps. For these designs, the charging/make-up pumps operate the same as mentioned above. That is, during normal operation the charging pumps take suction from the VCT/MUT. However, upon receipt of a safety injection 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 like the charging/make-up pumps. These SI pumps are intermediate head. The intermediate-head SI pumps will require the charging/make-up pumps to be in operation until the RCS pressure decreases to the pressure where the intermediate-head pumps can inject water. 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 an example 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 building sump during “recirculation mode.” Waterford is an example of this design.

In the plants equipped with charging/make-up pumps and dedicated SI pumps, typically, during normal operation, the charging/make-up pumps supply make-up or cooling water to plant equipment. One is the RCP seal supply. This normally requires 8 to 10 gpm per reactor coolant pump. Another function is pressurizer level control. This system senses pressurizer level and opens or closes the pressurizer level control valve allowing more or less make-up to maintain the selected pressurizer 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 is redirected. There are generally three or four injection nozzles to the RCS for HPSI. These nozzles, located in the cold legs 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 is not limited to injection/isolation valves, flow-balancing orifices, flow crossover piping, and nozzle and total flow indicators. 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.

8. REFERENCES

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