System Study: High-Pressure Coolant Injection 1998–2018

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ABSTRACT

This report presents an unreliability evaluation of the high-pressure coolant injection system (HPCI) at 25 U.S. commercial boiling water reactors. Demand, run hours, and failure data from 1998 through 2018 for selected components were obtained from the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS), formerly the INPO Consolidated Events Database (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 or decreasing trends were identified in the HPCI results.

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ACRONYMS

BWR   boiling water reactor

CCF   common-cause failure
CST   condensate storage tank

EPIX   Equipment Performance and Information Exchange

FTOC   fail to open/close
FTOP   fail to operate
FTR>1H   fail to run more than one hour (standby)
FTR<1H   fail to run less than one hour (after start)
FTS   fail to start

HPCI   high-pressure coolant injection

ICES   INPO Consolidated Events Database
INPO   Institute of Nuclear Power Operations
IRIS   Industry Reporting and Information System

MOV   motor-operated valve
MSPI   Mitigating Systems Performance Index

NRC   Nuclear Regulatory Commission

PRA   probabilistic risk assessment

ROP   Reactor Oversight Process
RPV   reactor pressure vessel

SPAR   standardized plant analysis risk
SSU   safety system unavailability

UA   unavailability (maintenance or state of another component)

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1. INTRODUCTION

This report presents an unreliability evaluation of the high-pressure coolant injection (HPCI) systems at the 25 U.S. commercial boiling water reactors (BWRs) 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. Demand, run hours, and failure data from 1998 through 2018 for selected components in the HPCI 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 through 2001) and the Mitigating Systems Performance Index (MSPI) database (2002 through 2018). 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 2015 Component Reliability Update [1], which is an update to NUREG/CR-6928 [2] and the 2010 Component Reliability Update [3]. Baseline HPCI unreliability results using basic event values from the 2010 Component Reliability Update[a] are summarized in Section 3. Trend results for HPCI (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 HPCI.

The HPCI model is evaluated using the transient flag set in the SPAR model. The transient flag set assumes all support systems are available and that the HPCI system is required to perform to mitigate the effects of the transient 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 False in the study for the results to represent the mechanical part of the system 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 paper Overview and Reference [4] on the Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov/resultsdb/).

Two modes of the models for the HPCI system are calculated. The HPCI start-only model is the HPCI SPAR model modified by setting all fail-to-run basic events to zero (False), setting all human error and recovery events to False, setting the suction transfer to the torus to False, and setting all cooling basic events to False. The 8-hour mission model sets all human error and recovery events to False.

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[a] In order to keep the SPAR models and BE data static so that the only variable in the analysis was the demand, run hours, failure, and unavailability data for selected components in the HPCI system, the same versions of SPAR models as those in the 2016 system study were used in this study. Those versions of SPAR models used data from the 2010 Component Reliability Update.

Table 1. BWR plants with a HPCI system selected for the study.

Plant	Version
Browns Ferry 1	8.22
Browns Ferry 2	8.22
Browns Ferry 3	8.18
Brunswick 1	8.20
Brunswick 2	8.20
Cooper	8.22
Dresden 2	8.18
Dresden 3	8.18
Duane Arnold	8.22
Fermi 2	8.20
FitzPatrick	8.17
Hatch 1	8.20
Hatch 2	8.20
Hope Creek	8.18
Limerick 1	8.20
Limerick 2	8.19
Monticello	8.20
Peach Bottom 2	8.25
Peach Bottom 3	8.21
Pilgrim	8.21
Quad Cities 1	8.18
Quad Cities 2	8.18
Susquehanna 1	8.23
Susquehanna 2	8.21
Vermont Yankee	8.19

2. SUMMARY OF FINDINGS

The results of this HPCI 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 or decreasing trends were identified** in the HPCI unreliability trend results.

The industry-wide HPCI start-only and 8-hour basic event group importances were evaluated and are shown in Figure 3:

- In the ***Start-Only*** case—the leading contributor to HPCI system unreliability is the **HPCI TDP** group of basic events followed by the Injection group.

- In the ***8-Hour*** case— the leading contributor to HPCI system unreliability is also the **HPCI TDP** group of basic events followed by the Injection group.

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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 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 HPCI fault trees from the SPAR models were evaluated for each of the 25 operating U.S. commercial boiling water nuclear power plants with a HPCI system.

The industry-wide unreliability of the HPCI system has been estimated for two modes of operation. A failure to start (start-only) model and an 8-hour mission model were evaluated. The uncertainty distributions for HPCI show both plant design variability and parameter uncertainty from the 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 HPCI fault trees in the SPAR models. The lower and upper bounds are based directly on the samples (Latin hypercube) from the uncertainty calculations in the SPAR models. For the industry-level results, the SPAR samples were combined into one large sample in order to determine the industry-level bounds, mean, and median.

Table 2. Industry-wide unreliability values.

Model	Lower (5%)	Median	Mean	Upper (95%)
Start-Only	1.49E-02	3.18E-02	3.71E-02	7.79E-02
8-hour Mission	2.35E-02	4.65E-02	5.17E-02	9.75E-02

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

4. INDUSTRY-WIDE TRENDS

The yearly (1998–2018) failure and demand or run time data were obtained from ICES for the HPCI system. HPCI train maintenance unavailability data for trending are from the same time period, as reported in the ROP program and ICES. The component basic event uncertainty was calculated for the HPCI system components using the trending methods described in Section 1 and 2 of the Overview and Reference document [4]. Tables 6 and 7 show the yearly data values for each HPCI system specific component and failure mode combination that was varied in the model. These data were loaded into the HPCI system fault tree in each SPAR model with a HPCI 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 this update (current SPAR/ ICES) is shown. Section 4 of the Overview and Reference document 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 HPCI model are:

- HPCI turbine-driven pump start, run, and test and maintenance.

- HPCI motor-operated valve, fail to operate.

Figure 1 shows the trend in the start-only model unreliability. Table 4 shows the data points for Figure 1. **No statistically significant trend was identified** within the industry-wide estimates of HPCI system unreliability (start-only) on a per fiscal year basis.

Figure 2 shows the trend in the 8-hour mission unreliability. Table 5 shows the data points for Figure 2. **No statistically significant trend was identified** within the industry-wide estimates of HPCI system unreliability (8-hour mission) on a per fiscal year basis.
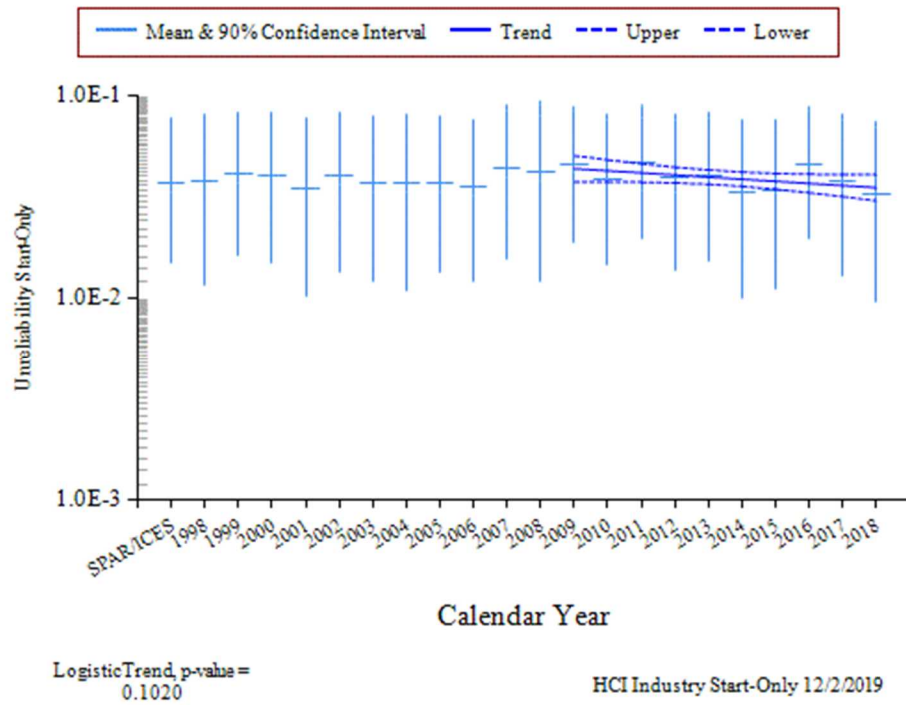
Figure 1. Trend of HPCI system unreliability (start-only model), as a function of fiscal year.
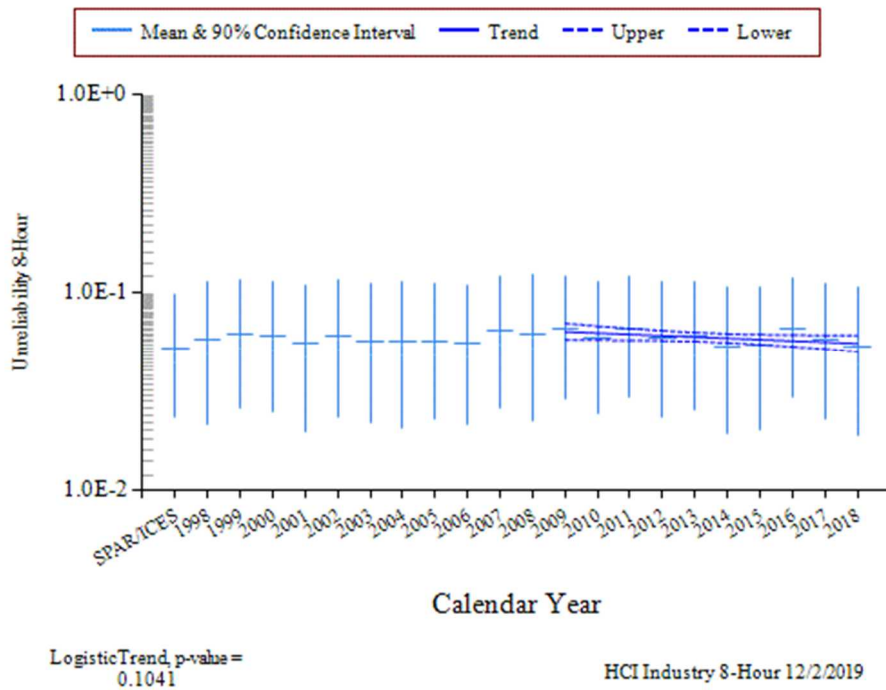
Figure 2. Trend of HPCI system unreliability (8-hour model), as a function of fiscal year.

5. BASIC EVENT GROUP IMPORTANCES

The HPCI 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 HPCI start-only and 8-hour basic event group importances are shown in Figure 3:

- In the *Start-Only* case—the leading contributor to HPCI system unreliability is the **HPCI TDP** group of basic events followed by the Injection group.

- In the *8-Hour* case— the leading contributor to HPCI system unreliability is also the **HPCI TDP** group of basic events followed by the Injection group.

For more discussion on the HPCI turbine-driven pumps, see the turbine-driven pump component reliability study at the NRC Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov/resultsdb/). Table 3 shows the SPAR model HPCI importance groups and their descriptions.
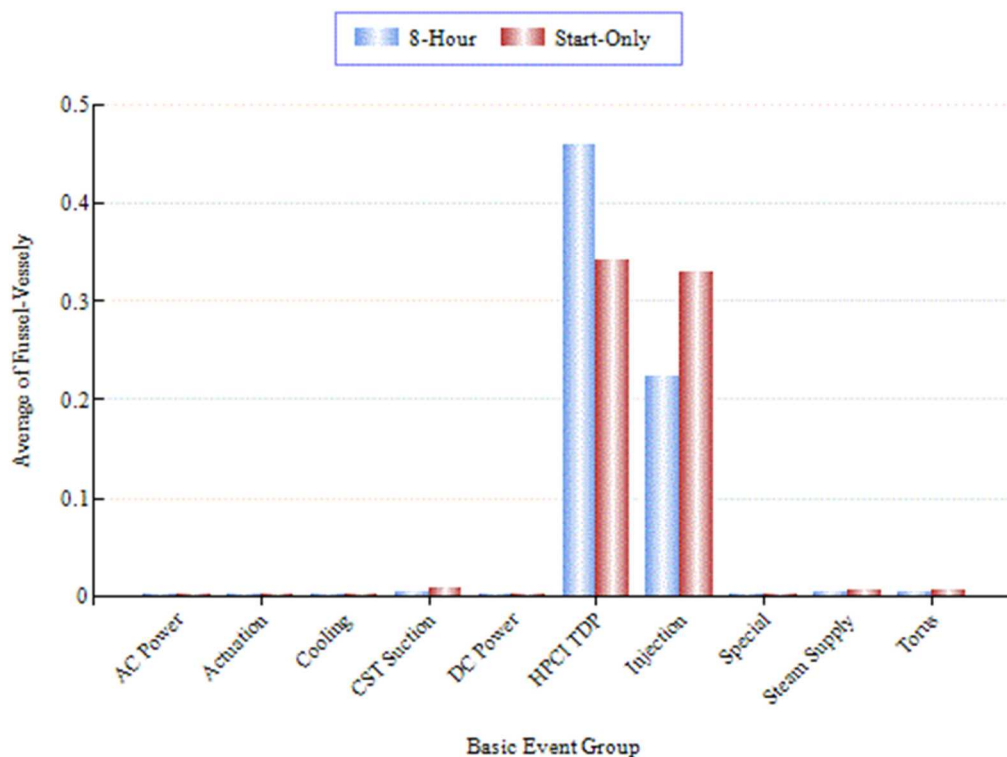
Figure 3. HPCI basic event group importances.

Table 3. HPCI model basic event importance group descriptions.

Group	Description
AC Power	The ac buses and circuit breakers that supply power to the service water pumps and the HPCI motor-operated valves.
Actuation	ESF actuation circuitry.
Cooling	The pumps, valves, and heat exchangers that provide heat removal to the HPCI turbine-driven pump.
CST Suction	Suction path and condensate storage tank.
DC Power	The batteries and battery chargers that supply power to the HPCI turbine-driven pump control circuitry.
EPS	HPCI dependency on the emergency power system.
HPCI TDP	All basic events associated with the turbine-driven pumps. The start, run, common-cause, and test and maintenance are included in the group of basic events.
Injection	The motor-operated valves and check valves in the HPCI injection path.
Steam Supply	The steam supply valves to the HPCI turbine.
Torus	The suppression pool motor-operated valves, check valves, and strainers required when a need to transfer to the suppression pool (torus) occurs.

6. DATA TABLES

Table 4. Plot data for HPCI start-only trend, Figure 1.

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	1.49E-02	3.71E-02	7.79E-02
1998	--	--	--	1.16E-02	3.74E-02	8.04E-02
1999	--	--	--	1.63E-02	4.12E-02	8.29E-02
2000	--	--	--	1.50E-02	4.04E-02	8.25E-02
2001	--	--	--	1.03E-02	3.50E-02	7.76E-02
2002	--	--	--	1.35E-02	3.98E-02	8.29E-02
2003	--	--	--	1.21E-02	3.70E-02	7.93E-02
2004	--	--	--	1.09E-02	3.69E-02	8.04E-02
2005	--	--	--	1.36E-02	3.70E-02	7.82E-02
2006	--	--	--	1.21E-02	3.51E-02	7.61E-02
2007	--	--	--	1.57E-02	4.40E-02	8.87E-02
2008	--	--	--	1.21E-02	4.21E-02	9.41E-02
2009	3.75E-02	4.35E-02	5.04E-02	1.89E-02	4.59E-02	8.84E-02
2010	3.75E-02	4.25E-02	4.81E-02	1.46E-02	3.89E-02	8.02E-02
2011	3.74E-02	4.15E-02	4.61E-02	1.94E-02	4.64E-02	8.87E-02
2012	3.71E-02	4.05E-02	4.43E-02	1.36E-02	3.90E-02	8.11E-02
2013	3.65E-02	3.96E-02	4.29E-02	1.53E-02	4.05E-02	8.23E-02
2014	3.56E-02	3.86E-02	4.19E-02	1.01E-02	3.34E-02	7.50E-02
2015	3.45E-02	3.77E-02	4.13E-02	1.10E-02	3.38E-02	7.49E-02
2016	3.31E-02	3.68E-02	4.09E-02	1.95E-02	4.54E-02	8.70E-02
2017	3.17E-02	3.60E-02	4.08E-02	1.29E-02	3.80E-02	8.02E-02
2018	3.03E-02	3.51E-02	4.07E-02	9.58E-03	3.27E-02	7.42E-02

Table 5. Plot data for HPCI 8-hour trend, Figure 2.

Year/Source	Regression Curve Data Points			Plot Trend Error Bar Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	2.35E-02	5.17E-02	9.75E-02
1998	--	--	--	2.12E-02	5.75E-02	1.12E-01
1999	--	--	--	2.62E-02	6.12E-02	1.15E-01
2000	--	--	--	2.49E-02	6.04E-02	1.15E-01
2001	--	--	--	1.98E-02	5.51E-02	1.10E-01
2002	--	--	--	2.35E-02	5.98E-02	1.15E-01
2003	--	--	--	2.18E-02	5.71E-02	1.11E-01
2004	--	--	--	2.07E-02	5.69E-02	1.12E-01
2005	--	--	--	2.30E-02	5.71E-02	1.10E-01
2006	--	--	--	2.15E-02	5.53E-02	1.08E-01
2007	--	--	--	2.58E-02	6.39E-02	1.21E-01
2008	--	--	--	2.22E-02	6.20E-02	1.24E-01
2009	5.77E-02	6.35E-02	6.98E-02	2.90E-02	6.58E-02	1.20E-01
2010	5.76E-02	6.25E-02	6.78E-02	2.43E-02	5.89E-02	1.13E-01
2011	5.75E-02	6.16E-02	6.59E-02	2.97E-02	6.63E-02	1.21E-01
2012	5.72E-02	6.06E-02	6.42E-02	2.35E-02	5.91E-02	1.13E-01
2013	5.67E-02	5.97E-02	6.29E-02	2.52E-02	6.05E-02	1.14E-01
2014	5.58E-02	5.88E-02	6.20E-02	1.94E-02	5.36E-02	1.07E-01
2015	5.46E-02	5.79E-02	6.14E-02	2.03E-02	5.40E-02	1.07E-01
2016	5.32E-02	5.70E-02	6.11E-02	2.96E-02	6.53E-02	1.19E-01
2017	5.18E-02	5.62E-02	6.09E-02	2.27E-02	5.81E-02	1.12E-01
2018	5.02E-02	5.53E-02	6.09E-02	1.89E-02	5.29E-02	1.06E-01

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	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	1999	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2000	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2001	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2002	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2003	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2004	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2005	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2006	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2007	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2008	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2009	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2010	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2011	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2012	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2013	0	62	9.03E-04	1.11	1.23E+03	Beta
FTOC	AOV	2014	0	79	8.91E-04	1.11	1.25E+03	Beta
FTOC	AOV	2015	0	83	8.88E-04	1.11	1.25E+03	Beta
FTOC	AOV	2016	0	83	8.88E-04	1.11	1.25E+03	Beta
FTOC	AOV	2017	0	83	8.88E-04	1.11	1.25E+03	Beta
FTOC	AOV	2018	0	83	8.88E-04	1.11	1.25E+03	Beta
FTOP	AOV	1998	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	1999	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2000	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2001	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2002	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2003	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2004	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2005	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2006	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2007	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2008	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2009	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2010	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2011	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2012	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2013	0	43,800	2.47E-07	1.42	5.76E+06	Gamma
FTOP	AOV	2014	0	52,560	2.46E-07	1.42	5.77E+06	Gamma
FTOP	AOV	2015	0	52,560	2.46E-07	1.42	5.77E+06	Gamma
FTOP	AOV	2016	0	52,560	2.46E-07	1.42	5.77E+06	Gamma
FTOP	AOV	2017	0	52,560	2.46E-07	1.42	5.77E+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	2018	0	52,560	2.46E-07	1.42	5.77E+06	Gamma
SO	AOV	1998	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	1999	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2000	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2001	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2002	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2003	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2004	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2005	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2006	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2007	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2008	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2009	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2010	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2011	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2012	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2013	0	43,800	1.29E-07	0.68	5.25E+06	Gamma
SO	AOV	2014	0	52,560	1.29E-07	0.68	5.26E+06	Gamma
SO	AOV	2015	0	52,560	1.29E-07	0.68	5.26E+06	Gamma
SO	AOV	2016	0	52,560	1.29E-07	0.68	5.26E+06	Gamma
SO	AOV	2017	0	52,560	1.29E-07	0.68	5.26E+06	Gamma
SO	AOV	2018	0	52,560	1.29E-07	0.68	5.26E+06	Gamma
FTOC	MOV	1998	5	2,110	1.66E-03	7.05	4.23E+03	Beta
FTOC	MOV	1999	1	1,970	7.44E-04	3.05	4.09E+03	Beta
FTOC	MOV	2000	1	2,019	7.35E-04	3.05	4.14E+03	Beta
FTOC	MOV	2001	4	1,996	1.47E-03	6.05	4.11E+03	Beta
FTOC	MOV	2002	1	1,944	7.49E-04	3.05	4.07E+03	Beta
FTOC	MOV	2003	1	2,097	7.21E-04	3.05	4.22E+03	Beta
FTOC	MOV	2004	2	1,984	9.85E-04	4.05	4.10E+03	Beta
FTOC	MOV	2005	4	1,989	1.47E-03	6.05	4.11E+03	Beta
FTOC	MOV	2006	1	1,996	7.39E-04	3.05	4.12E+03	Beta
FTOC	MOV	2007	8	2,036	2.41E-03	10.05	4.15E+03	Beta
FTOC	MOV	2008	4	2,033	1.45E-03	6.05	4.15E+03	Beta
FTOC	MOV	2009	4	2,046	1.45E-03	6.05	4.16E+03	Beta
FTOC	MOV	2010	1	2,013	7.36E-04	3.05	4.13E+03	Beta
FTOC	MOV	2011	0	1,958	5.01E-04	2.05	4.08E+03	Beta
FTOC	MOV	2012	3	1,984	1.23E-03	5.05	4.10E+03	Beta
FTOC	MOV	2013	1	1,984	7.41E-04	3.05	4.11E+03	Beta
FTOC	MOV	2014	1	1,954	7.47E-04	3.05	4.08E+03	Beta
FTOC	MOV	2015	1	1,934	7.51E-04	3.05	4.06E+03	Beta
FTOC	MOV	2016	1	1,965	7.45E-04	3.05	4.09E+03	Beta
FTOC	MOV	2017	1	1,969	7.44E-04	3.05	4.09E+03	Beta

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
FTOC	MOV	2018	0	1,836	5.16E-04	2.05	3.96E+03	Beta
FTOP	MOV	1998	0	2,137,440	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	1999	0	2,128,680	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2000	0	2,128,680	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2001	0	2,128,680	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2002	0	2,128,680	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2003	0	2,128,680	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2004	0	2,137,440	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2005	0	2,137,440	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2006	0	2,137,440	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2007	1	2,137,440	1.02E-07	2.46	2.42E+07	Gamma
FTOP	MOV	2008	0	2,137,440	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2009	0	2,154,960	6.02E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2010	0	2,207,520	6.01E-08	1.46	2.43E+07	Gamma
FTOP	MOV	2011	0	2,146,200	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2012	0	2,190,000	6.01E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2013	1	2,146,200	1.02E-07	2.46	2.42E+07	Gamma
FTOP	MOV	2014	0	2,146,200	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2015	1	2,163,720	1.02E-07	2.46	2.42E+07	Gamma
FTOP	MOV	2016	0	2,111,160	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2017	0	2,111,160	6.03E-08	1.46	2.42E+07	Gamma
FTOP	MOV	2018	0	2,111,160	6.03E-08	1.46	2.42E+07	Gamma
SO	MOV	1998	0	2,137,440	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	1999	0	2,128,680	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2000	1	2,128,680	8.28E-08	1.57	1.90E+07	Gamma
SO	MOV	2001	0	2,128,680	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2002	0	2,128,680	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2003	1	2,128,680	8.28E-08	1.57	1.90E+07	Gamma
SO	MOV	2004	0	2,137,440	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2005	0	2,137,440	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2006	0	2,137,440	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2007	1	2,137,440	8.27E-08	1.57	1.90E+07	Gamma
SO	MOV	2008	0	2,137,440	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2009	0	2,154,960	3.00E-08	0.57	1.90E+07	Gamma
SO	MOV	2010	1	2,207,520	8.24E-08	1.57	1.90E+07	Gamma
SO	MOV	2011	0	2,146,200	3.00E-08	0.57	1.90E+07	Gamma
SO	MOV	2012	0	2,190,000	3.00E-08	0.57	1.90E+07	Gamma
SO	MOV	2013	0	2,146,200	3.00E-08	0.57	1.90E+07	Gamma
SO	MOV	2014	1	2,146,200	8.27E-08	1.57	1.90E+07	Gamma
SO	MOV	2015	0	2,163,720	3.00E-08	0.57	1.90E+07	Gamma
SO	MOV	2016	0	2,111,160	3.01E-08	0.57	1.90E+07	Gamma
SO	MOV	2017	0	2,111,160	3.01E-08	0.57	1.90E+07	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	MOV	2018	0	2,111,160	3.01E-08	0.57	1.90E+07	Gamma
FTR>1H	TDP	1998	0	37	1.55E-03	12.5	8.07E+03	Gamma
FTR>1H	TDP	1999	0	52	1.55E-03	12.5	8.08E+03	Gamma
FTR>1H	TDP	2000	1	35	1.67E-03	13.5	8.06E+03	Gamma
FTR>1H	TDP	2001	0	38	1.55E-03	12.5	8.07E+03	Gamma
FTR>1H	TDP	2002	0	23	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2003	0	23	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2004	1	32	1.68E-03	13.5	8.06E+03	Gamma
FTR>1H	TDP	2005	0	25	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2006	0	18	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2007	0	18	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2008	1	22	1.68E-03	13.5	8.05E+03	Gamma
FTR>1H	TDP	2009	0	116	1.53E-03	12.5	8.14E+03	Gamma
FTR>1H	TDP	2010	1	57	1.67E-03	13.5	8.09E+03	Gamma
FTR>1H	TDP	2011	2	28	1.80E-03	14.5	8.06E+03	Gamma
FTR>1H	TDP	2012	0	19	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2013	1	33	1.67E-03	13.5	8.06E+03	Gamma
FTR>1H	TDP	2014	0	19	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2015	0	22	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2016	1	30	1.68E-03	13.5	8.06E+03	Gamma
FTR>1H	TDP	2017	0	18	1.55E-03	12.5	8.05E+03	Gamma
FTR>1H	TDP	2018	0	18	1.55E-03	12.5	8.05E+03	Gamma
FTR<1H	TDP	1998	0	219	2.21E-03	0.96	4.35E+02	Gamma
FTR<1H	TDP	1999	0	211	2.25E-03	0.96	4.28E+02	Gamma
FTR<1H	TDP	2000	1	201	4.70E-03	1.96	4.17E+02	Gamma
FTR<1H	TDP	2001	0	190	2.37E-03	0.96	4.06E+02	Gamma
FTR<1H	TDP	2002	0	185	2.40E-03	0.96	4.02E+02	Gamma
FTR<1H	TDP	2003	2	192	7.25E-03	2.96	4.09E+02	Gamma
FTR<1H	TDP	2004	0	189	2.38E-03	0.96	4.05E+02	Gamma
FTR<1H	TDP	2005	0	194	2.35E-03	0.96	4.10E+02	Gamma
FTR<1H	TDP	2006	0	205	2.28E-03	0.96	4.21E+02	Gamma
FTR<1H	TDP	2007	3	197	9.58E-03	3.96	4.14E+02	Gamma
FTR<1H	TDP	2008	1	196	4.75E-03	1.96	4.13E+02	Gamma
FTR<1H	TDP	2009	1	198	4.74E-03	1.96	4.14E+02	Gamma
FTR<1H	TDP	2010	0	195	2.34E-03	0.96	4.11E+02	Gamma
FTR<1H	TDP	2011	0	196	2.33E-03	0.96	4.13E+02	Gamma
FTR<1H	TDP	2012	0	190	2.36E-03	0.96	4.07E+02	Gamma
FTR<1H	TDP	2013	0	186	2.39E-03	0.96	4.03E+02	Gamma
FTR<1H	TDP	2014	0	175	2.46E-03	0.96	3.92E+02	Gamma
FTR<1H	TDP	2015	1	177	4.98E-03	1.96	3.94E+02	Gamma
FTR<1H	TDP	2016	2	193	7.23E-03	2.96	4.10E+02	Gamma
FTR<1H	TDP	2017	0	182	2.41E-03	0.96	3.99E+02	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR<1H	TDP	2018	0	172	2.47E-03	0.96	3.89E+02	Gamma
FTS	TDP	1998	0	219	2.59E-03	0.94	3.63E+02	Beta
FTS	TDP	1999	3	211	1.11E-02	3.94	3.52E+02	Beta
FTS	TDP	2000	3	201	1.14E-02	3.94	3.42E+02	Beta
FTS	TDP	2001	1	190	5.80E-03	1.94	3.33E+02	Beta
FTS	TDP	2002	2	185	8.91E-03	2.94	3.27E+02	Beta
FTS	TDP	2003	1	192	5.76E-03	1.94	3.35E+02	Beta
FTS	TDP	2004	1	189	5.82E-03	1.94	3.32E+02	Beta
FTS	TDP	2005	2	194	8.69E-03	2.94	3.36E+02	Beta
FTS	TDP	2006	2	205	8.41E-03	2.94	3.47E+02	Beta
FTS	TDP	2007	2	197	8.60E-03	2.94	3.39E+02	Beta
FTS	TDP	2008	2	196	8.62E-03	2.94	3.39E+02	Beta
FTS	TDP	2009	4	198	1.44E-02	4.94	3.38E+02	Beta
FTS	TDP	2010	2	195	8.66E-03	2.94	3.37E+02	Beta
FTS	TDP	2011	4	196	1.45E-02	4.94	3.36E+02	Beta
FTS	TDP	2012	1	190	5.79E-03	1.94	3.33E+02	Beta
FTS	TDP	2013	3	186	1.19E-02	3.94	3.27E+02	Beta
FTS	TDP	2014	0	175	2.94E-03	0.94	3.19E+02	Beta
FTS	TDP	2015	0	177	2.92E-03	0.94	3.21E+02	Beta
FTS	TDP	2016	4	193	1.46E-02	4.94	3.33E+02	Beta
FTS	TDP	2017	1	182	5.93E-03	1.94	3.25E+02	Beta
FTS	TDP	2018	1	172	6.12E-03	1.94	3.15E+02	Beta

Table 7. Basic event UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	TDP	1998	2,417	182,188	1.42E-02	1.72	119.62	Beta
UA	TDP	1999	2,264	195,033	1.16E-02	2.4	204.79	Beta
UA	TDP	2000	2,047	196,240	1.04E-02	1.56	148.15	Beta
UA	TDP	2001	1,735	195,742	9.03E-03	0.96	104.86	Beta
UA	TDP	2002	2,403	199,989	1.21E-02	1.39	113.05	Beta
UA	TDP	2003	2,378	194,267	1.23E-02	1.76	141.1	Beta
UA	TDP	2004	2,240	196,465	1.16E-02	1.12	95.13	Beta
UA	TDP	2005	1,627	195,610	8.34E-03	2.12	251.76	Beta
UA	TDP	2006	1,535	197,941	7.81E-03	1.91	243.38	Beta
UA	TDP	2007	2,758	196,270	1.42E-02	1.24	86.39	Beta
UA	TDP	2008	2,718	199,399	1.36E-02	0.58	42.2	Beta
UA	TDP	2009	2,342	193,544	1.20E-02	1.74	143.03	Beta
UA	TDP	2010	2,263	197,083	1.14E-02	2.5	216.3	Beta
UA	TDP	2011	2,682	192,786	1.40E-02	2.3	161.99	Beta
UA	TDP	2012	2,632	192,525	1.35E-02	2.04	148.48	Beta
UA	TDP	2013	1,925	193,672	1.00E-02	1.78	175.74	Beta
UA	TDP	2014	2,198	196,708	1.12E-02	2.12	186.94	Beta
UA	TDP	2015	2,234	189,557	1.16E-02	2.89	245.08	Beta
UA	TDP	2016	2,416	192,415	1.25E-02	2.84	225.2	Beta
UA	TDP	2017	2,500	192,345	1.31E-02	2.04	153.86	Beta
UA	TDP	2018	1,475	188,839	7.86E-03	1.36	171.46	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 HPCI system is a single-train system that provides a reliable source of high-pressure coolant for cases where there is a loss of normal core coolant inventory. Figure 4 provides a simplified schematic diagram of the system.

The HPCI system consists of a steam turbine-driven pump, valves, and valve operators, and associated piping, including that from the normal and alternate pump suction sources and the pump discharge up to the penetration of the main feedwater line. For this study, the part of the main feedwater line from the check valve upstream of the HPCI connection to the reactor vessel, including the check valve, was considered part of the HPCI system. The steam turbine-driven pump includes all steam piping from the main steam line penetration to the turbine, and turbine exhaust piping to the suppression pool, valves and valve operators, gland sealing steam, and the turbine auxiliary oil system.

The HPCI system is actuated by either a low reactor water level or a high drywell pressure. Initially the system operates in an open loop mode, taking suction from the condensate storage tank (CST) and injecting water into the reactor pressure vessel (RPV) via one of the main feedwater lines. When the level in the CST reaches a low-level set point, the HPCI pump suction is aligned to the suppression pool. To maintain RPV level after the initial recovery, the HPCI system is placed in manual control, which may involve controlling turbine speed, diverting flow through minimum-flow or test lines, cycling the injection motor-operated valve (MOV), or complete stop-start cycles.

The HPCI system is also manually used to help control RPV pressure following a transient. Although this is not part of the ECCS design function, it is employed in this manner in PRAs. However, only a small percentage PRAs that employ this function model the pressure control operation. In this mode, the turbine-driven pump is operated manually with the injection valve closed and the full-flow test-line MOV open. Turbine operation with the injection line isolated and the test line open allows the turbine to draw steam from the RPV, thereby reducing RPV pressure. Operation of the system in the pressure control mode may also occur with intermittent injection of coolant to the RPV. As steam is being drawn off the RPV, the RPV water inventory is reduced, resulting in the need for vessel water level restoration. When level restoration is required, the injection valve is opened and the test-line MOV is closed. Upon restoration of RPV water inventory, the system is returned to the pressure control line-up. This cycling between injection and pressure control can be repeated as necessary.
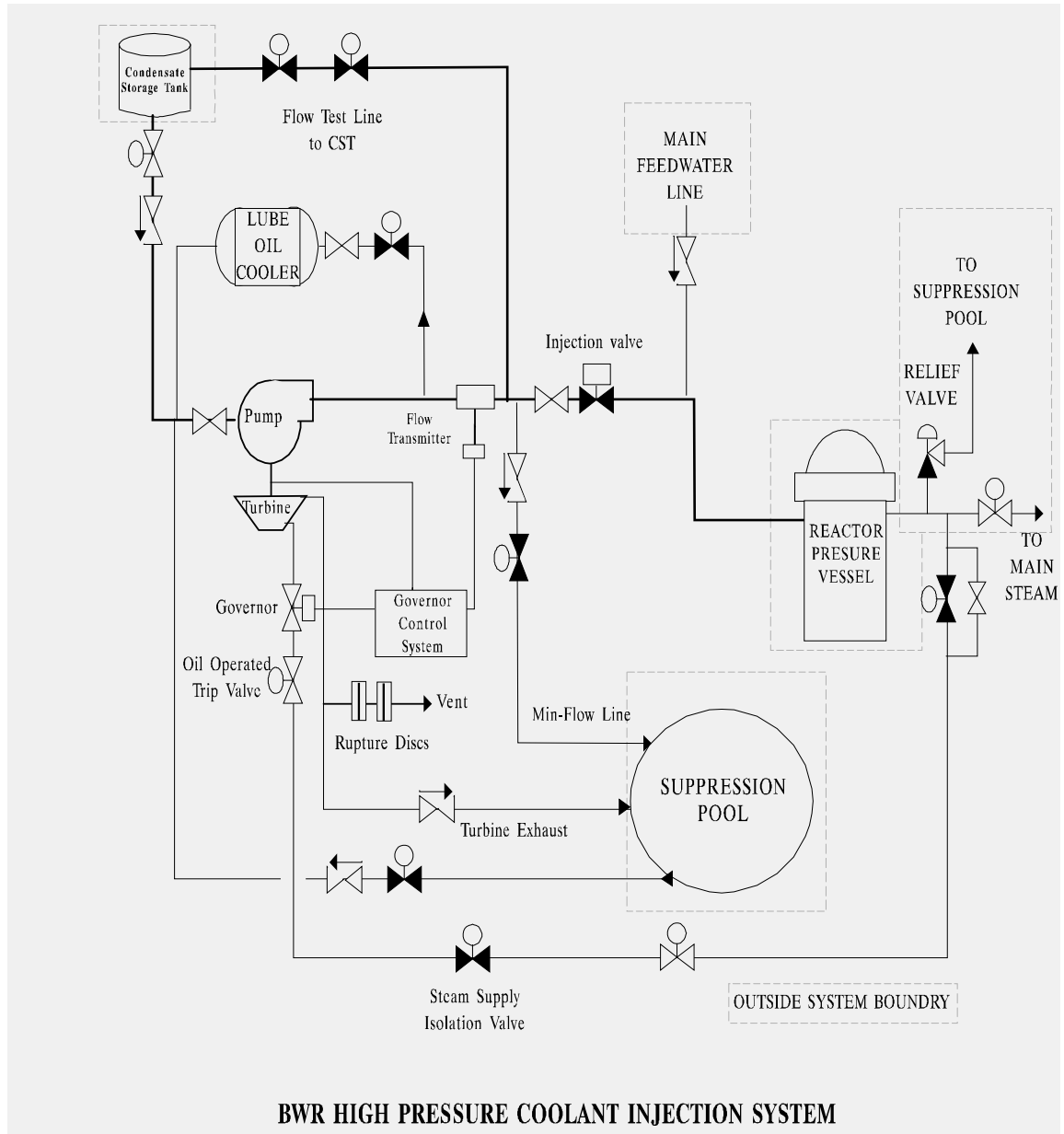
BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

Figure 4. HPCI system diagram.

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