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Reliability Study Update: High-Pressure Coolant Injection (HPCI) System, 1987–1998 (DRAFT)

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EXECUTIVE SUMMARY

This report presents a performance evaluation of the High-Pressure Coolant Injection (HPCI) systems at 24 United States commercial boiling-water reactors (BWRs). The evaluation is based on the operating experience from 1987 through 1998, as reported in Licensee Event Reports (LERs). This report updates a previous analysis of the HPCI system for the same twenty-four BWRs based on the operating experience from 1987 through 1993. The primary objectives of the study are to: (1) estimate the system unreliability based on 1987–1998 operating experience; (2) compare these estimates with the assumptions, models, and data used in probabilistic risk assessments and individual plant evaluations (PRA/IPEs); (3) determine if there are trends and patterns in the HPCI system operating experience; (4) provide an engineering analysis of the factors affecting HPCI system unreliability; and (5) determine if the HPCI system unreliability from this updated study is changing in comparison to the original study results based on the 1987–1993 operating experience.

This study used as its source data the operating experience from 1987 through 1998 as reported in LERs. The Sequence Coding and Search System (SCSS) database was used to identify LERs that reported unplanned demands and inoperabilities of the HPCI system. The full text of each LER was reviewed from a risk and reliability perspective by at least two engineers with commercial nuclear power plant experience.

The HPCI system unreliability was estimated using a fault tree model to associate event occurrences with broadly defined failure modes such as failure to start or failure to run. The probabilities for the failure modes were calculated by reviewing the failure information, categorizing each event by failure mode, and estimating the corresponding number of demands (both successes and failures). Sixteen plant risk reports (i.e., PRAs, IPEs, and NUREGs) were used for comparison to the HPCI reliability results calculated in this study. These reports document HPCI system information for twenty-four BWR plants.

Major Findings–Reliability Analysis

HPCI system unreliability based on the 1987–1998 operating experience has increased slightly compared to the earlier estimate presented in the original report. The unreliability estimated based on original 1987–1993 operating experience and the1987–1998 operating experience are 5.6E-2 and 6.6E-2, respectively. The small increase in the HPCI system reliability estimate based on the 1987–1998 operating experience is primarily due to modeling failure of the injection valve to reopen in the unreliability calculation. This failure mode was not included in the system unreliability estimate calculated in the original report.

The major findings from the update analysis are summarized below.

Overall unreliability. The industry-wide unreliability of the HPCI system calculated from the 1987–1998 operating experience is 6.6E-02 per demand. If the probability of operator recovery from failure is ignored, the industry-wide mean is 8.1E-02. The unreliability estimates are based on failures that occurred during unplanned demands, and cyclic and quarterly surveillance tests.

Failure of the injection valve to reopen (cycling the injection valve for subsequent reactor pressure vessel water level control) and failure to start of the system other than the injection valve are the leading contributors to HPCI system unreliability, 33% and 26%, respectively.

Plant-specific results. Individual plant results vary from about 5.5E-02 to 9.1E-02, or less than a factor of two. The estimates of HPCI system unreliability using operating experience from LERs and fault tree analyses are plotted in Figure ES-1. The differences among plants are very small meaning the differences are not risk significant. Details are provided in Section 3.2 of the report.

Comparisons to PRA/IPEs. A second fault tree was developed to compare HPCI system unreliabilities based on PRA/IPE data and data from the 1987–1998 operating experience. The industry-wide average of HPCI system unreliability calculated using data (e.g., component failure probabilities, maintenance unavailability) extracted from PRA/IPEs is about a factor of three

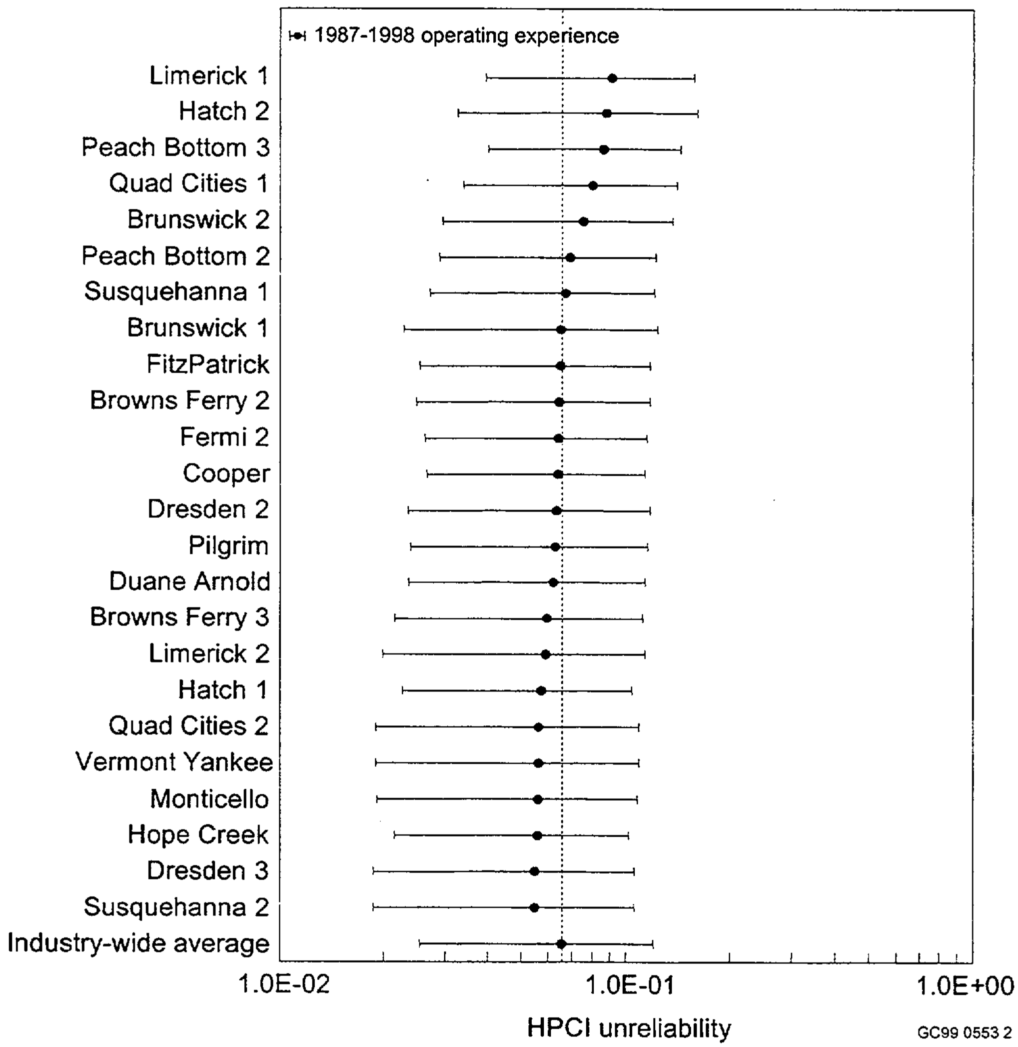


Figure ES-1. Plant-specific estimates of HPCI system unreliability.

lower than the industry-wide estimate based on the 1987–1998 experience. However, this comparison is based on data from the original IPE submittals. A plot of these estimates is shown in Figure ES-2. Section 3.3 provides the results and insights for comparison with PRA/IPE results.

The leading contributors to HPCI system unreliability based on the fault tree developed for comparison to PRA/IPEs and using the 1987–1998 experience are the failure of the injection valve to reopen (cycling the injection valve for subsequent for reactor pressure vessel water level control) and failure to run of the injection system, 55% and 42%, respectively.

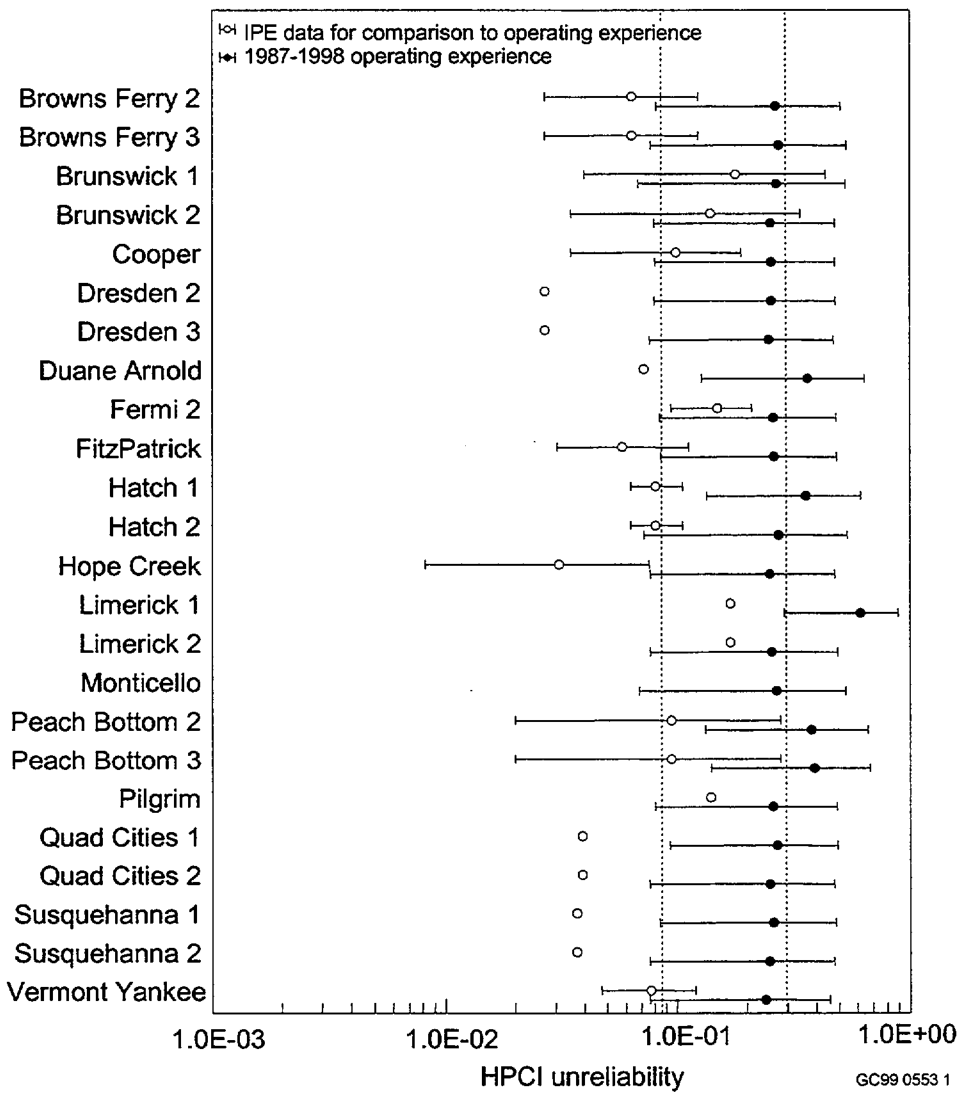


Figure ES-2. Plant-specific estimates of HPCI system unreliability for a PRA comparison based on the 1987–1998 operating experience and compared to estimates calculated using component failure probabilities found in the PRA/IPEs. (The dashed lines represent the corresponding industry-wide averages.)

Unreliability trend. Estimates of HPCI system unreliability on a per calendar year basis identified no statistically significant decreasing trend within the industry estimates. Figure ES-3 displays the trend by calendar year of the unreliability calculated from the 1987–1998 experience.

Unplanned demand trend. Trends were identified in the frequency of HPCI unplanned demands (Figure ES-4). When modeled as a function of calendar year, the unplanned demand frequency exhibited a highly statistically significant decreasing trend.

Failure trend. The frequency of failure events observed by all detection methods was analyzed to determine trends. These detection methods include unplanned demands, cyclic and quarterly surveillance tests, as well as other detection methods, such as weekly tests and inspections. When modeled as a function of calendar year, a highly statistically significant decreasing trend was identified. The frequency of all HPCI system failures decreased by about a factor of four during the 1987–1998 period. Based on the end point of the trend line (calendar year 1998), this frequency is equivalent to an expectation across the industry (24 plants) of about nine HPCI system failures per year. The fitted frequency is plotted against calendar year in Figure ES-5.

Section 4.1 provides details of these and other trends identified using the analysis of the 1987–1998 operating experience.

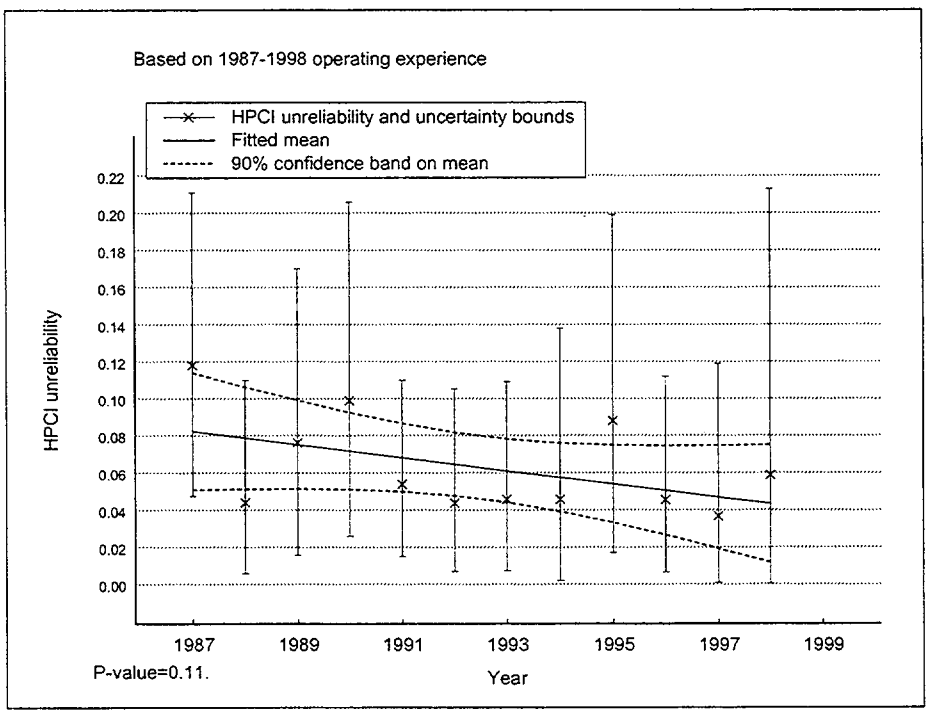


Figure ES-3. Trend of HPCI system unreliability, as a function of calendar year. The decreasing trend is not statistically significant.

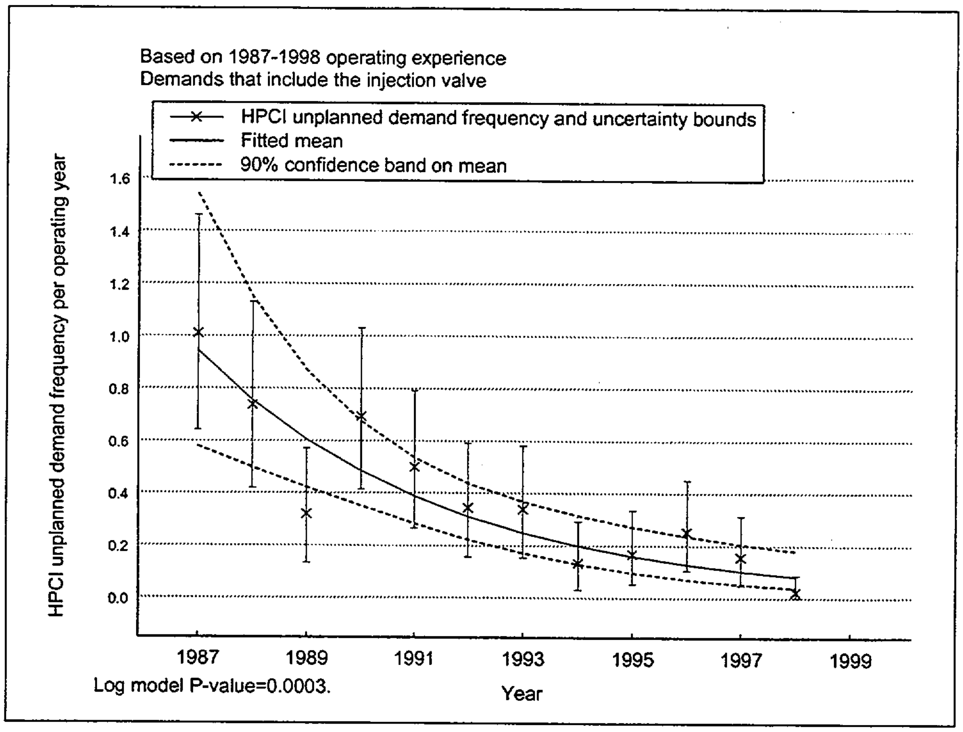


Figure ES-4. Frequency (events per operating year) of unplanned demands, as a function of calendar year. The decreasing trend is highly statistically significant.

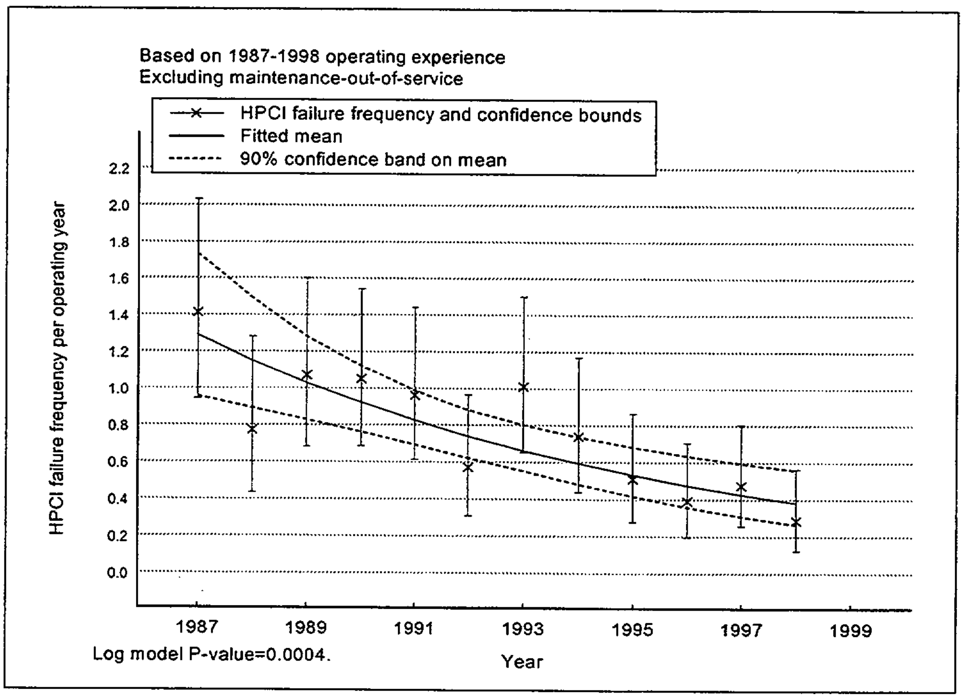


Figure ES-5. Frequency (events per operating year) of failures, as a function of calendar year. The decreasing trend is highly statistically significant.

Major Findings–Engineering Analysis

The HPCI system failures were reviewed several ways to identify the factors affecting overall system unreliability and the effectiveness of surveillance tests to detect these failures. The forty-six system failures used in the unreliability calculation were reviewed for insights into the cause of failure, component failed, and the HPCI system mode of failure. In addition, the remaining 116 failures were used to assist in developing insights into the reliability performance of the HPCI system.

Section 4.3 provides details on the insights derived from the HPCI system failures.

Major contributor to system unreliability. As presented earlier, the leading contributor to HPCI system unreliability is the failure of the injection valve to reopen for subsequent reactor pressure vessel water level control. Based on the limited unplanned demand data (79 demands), there is a 0.6% probability of the injection valve failing to initially open compared to 20% probability that the injection valve will fail to reopen if needed later during plant recovery. The failure probability of the injection valve to reopen is based on only two failure events from the 1987–1998 operating experience.

Effectiveness of various detection methods. Overall, testing of various types and frequencies was the most effective method in detecting failures. Testing identified about half of the HPCI system failures. Although quarterly and cyclic surveillance testing as required by plant technical specifications resulted in 28% of the HPCI system failures, approximately 24% of the HPCI system failures were discovered by other routine tests and checks (e.g., weekly and monthly tests, post maintenance tests, etc.).

The HPCI system injection valve is tested quarterly; however, the quarterly testing of this valve is done in an environment that does not produce the same stresses on the valve that the valve would encounter in an accident environment. In addition, the injection valve is not cycled repeatedly during the quarterly test.

Leading component failures. Two component groups contributed about 62% of all HPCI system failures: instrumentation and control (electronic) components and valves, 35% and 27%, respectively.

Leading causes of failure. Seven out of ten failures of the HPCI system observed in the 1987–1998 experience were attributed to hardware-related problems. Personnel errors caused 17% of all HPCI system failures. However, 70% of these failures were immediately identified, meaning that the failures were of the nature where plant personnel were able to respond to the failures immediately after they occur.

FOREWORD

This report provides information relevant to high-pressure coolant injection (HPCI) system performance in response to normal operational transients and summarizes the event data used in the analysis. The results, findings, conclusions, and information contained in this and similar system reliability studies conducted by the Office for Nuclear Regulatory Research are intended to support several risk-informed regulatory activities. This includes providing information about relevant operating experience that can be used to enhance plant inspections of risk-important systems and information used to support staff technical reviews of proposed license amendments, including risk-informed applications. In the future, this work will be used in the development of risk-based performance indicators that will be based to a large extent on plant-specific system and equipment performance.

Findings and conclusions from the performance analysis of the HPCI systems at 24 United States commercial boiling-water reactors based on 1987–1998 operating experience are presented in the Executive Summary. The results of the risk-based analysis and engineering analysis are summarized at the beginning of Sections 3 and 4. This report provides an industry-wide perspective on the reliability of HPCI systems, and how both industry (generic) and plant-specific performance compares with reliability estimates from probabilistic risk assessments (PRAs) and individual plant examinations (IPEs). This report also provides an indication of how performance varies between plants and the measurable magnitude of that variation. The dominant contributors are identified along with information on important failure modes and causes. A tabulation of failures, demands, and estimated failure rates for key system equipment is also included.

The report provides a mechanism for identifying individual licensee event reports (LERs) that are the source of the tabulated failure, demand, and failure-rate estimates. For convenience, the risk-important information that would be useful in support of risk-informed regulatory activities involving the HPCI system is summarized in Table P-1. Users of this information are cautioned to be aware of the uncertainty in quantitative results when drawing inferences about industry performance trends and plant-specific variations in performance.

The application of results to plant-specific applications may require a more detailed review of the relevant LERs to determine specific aspects of the events associated with the dominant contributors that are applicable to a specific plant design and operational characteristics. Factors such as type of equipment, configuration variations, operating environment and conditions, and test and maintenance practices would need to be considered in light of specific information provided in the LERs cited in this report. This review is needed to determine if generic experiences described in the report are applicable to the design and operational features of the system at a specific plant. This is especially important for dominant failure modes associated with the starting reliability of pumps and the running reliability of pumps in general. In addition, it may be appropriate to obtain and review more recent LERs to bring plant-specific insights on performance and the potentially important dominant contributors to a more current state. A search of the LER database can be conducted through the NRC's Sequence Coding and Search System (SCSS) to identify the system failures and demands that occurred after the period covered by this report. SCSS contains the full text LERs and is accessible by NRC staff from the SCSS home page (http://scss.ornl.gov/). Nuclear industry organizations and the general public can obtain information from the SCSS on a cost recovery basis by contacting the Oak Ridge National Laboratory.

The Office of Nuclear Regulatory Research plans to periodically update the information in this report as additional data becomes available.

Thomas L. King, Director
Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research

Table P-1. Summary of risk-important information specific to HPCI system unreliability.

Plant-specific failure data with LER references (failure mode, method of detection, cause, component, and LER reference)	Table A-2[a]
Plant-specific demand data with LER references	Table A-3[a]
Failure events used to estimate system unreliability (event summary, failure mode, and LER reference)	Table A-5
System failure mode data, probability information, and system unreliability estimates	Table 3
Dominant contributors to HPCI system unreliability	Section 3.2.1
Plant-specific estimates of HPCI system unreliability	Figure 5
Causal factors affecting dominant contributors to HPCI system reliability (affected subsystems and components, failure modes, and failure causes)	Section 4.3

a. Other documents such as logs, reports, and inspection reports that contain information about plant-specific experience (e.g., maintenance, operation, or surveillance testing) should be reviewed during plant inspections to supplement the information contained in this report. These sources will provide updated information on plant operating experience including failure events and demands captured in plant logs that are not reportable in LERs, such as single train failures during tests.

ACKNOWLEDGMENTS

ACRONYMS

ASEP	Accident Sequence Evaluation Program
ASME	American Society of Mechanical Engineers
ASP	accident sequence precursor
BWR	boiling-water reactor
CCDP	conditional core damage probability
CCF	common cause failure
CCP	centrifugal charging pump
CRD	control rod drive
CFR	Code of Federal Regulations
CL	cold water leg
CST	condensate storage tank
DRAA	Division of Risk Analysis and Applications (NRC)
ECCS	emergency core cooling systems
EOC	error of commission
ESF	engineered safety feature
ESFAS	engineered safety feature actuation system
FRFRO	failure to recover from FRO
FRFTRI	failure to recover from FTRI
FRFTSI	failure to recover from FTSI
FRO	failure of the injection valve to reopen
FTRI	failure to run other than suction transfer
FTRT	failure to run suction transfer
FTSI	failure to start other than the injection valve
FTSV	failure to start injection valve
HVAC	heating, ventilating, and air conditioning

HPCI	high-pressure coolant injection
INEEL	Idaho National Environmental and Engineering Laboratory
IPE	individual plant examination
LER	Licensee Event Report
LOCA	loss-of-coolant accident
MCC	motor control center
MOOS	maintenance-out-of-service
MOV	motor-operated valve
NPRDS	Nuclear Plant Reliability Data System
NRC	U.S. Nuclear Regulatory Commission
NSSS	nuclear steam supply system
ORNL	Oak Ridge National Laboratory
PRA	probabilistic risk assessment
RCIC	reactor core isolation cooling system
RES	Office of Nuclear Regulatory Research
RPV	reactor pressure vessel
SAS	SAS Institute, Inc.'s commercial software package
SCSS	Sequence Coding and Search System (LER database maintained at ORNL)
SRV	safety relief valve
TDP	turbine-driven pump

TERMINOLOGY

Cyclic surveillance test— The plant technical specifications require a simulation of the automatic start of the HPCI system with a periodicity of once a fuel cycle, and at least once every 18 months (referred to as cyclic tests). This test typically simulates the automatic actuation of system components. However, the injection valve is not tested under the same conditions that the valve would experience during an unplanned demand (flow to the vessel).

Demand— An event that initiates either the system or component of the system to perform its safety function as a result of an actual valid or invalid (spurious) initiation signal. Types of demands used to estimate failure probabilities are unplanned demands and demands from cyclic and quarterly surveillance.

Dependent failure—Two events are statistically dependent if the $\text{Prob}(A \cap B) = \text{Prob}(A)\ \text{Prob}(B|A) = \text{Prob}(B)\ \text{Prob}(A|B) \neq \text{Prob}(A)\ \text{Prob}(B)$.

Error of commission (EOC)—A failure of the HPCI system as a result of being purposely or inappropriately rendered inoperable by operator action when the system was needed to inject to the RPV.

Failure frequency—The number of failures divided by operating time (in operating years).

Failure—An inoperability in which the capability of the HPCI system to supply water to the RPV was lost when a demand for HPCI existed. For estimating HPCI unreliability, a subset of the failures was used (that is, only those that occurred during unplanned demands and cyclic and quarterly surveillance tests).

Failure to run (FTR)—Any failure to complete the mission after a successful start of the HPCI pump. This includes obvious cases of failure to continue running, and also cases when the pump started and supplied water to the RPV, tripped off for a valid reason, and then could not be restarted.

Failure to start (FTS)—Failure of the HPCI system to start on a valid demand signal.

Fault— A condition where the system would have been able to perform sufficiently well even though the system was declared not operable as defined by plant technical specifications.

Independent failure—Two or more events are statistically independent if $\text{Prob}(A \cap B) = \text{Prob}(A)\ \text{Prob}(B)$.

Inoperability—An event affecting the HPCI system such that it did not meet the operability requirements of plant technical specifications and therefore was required to be reported in an LER. Inoperability events include failures and faults.

Long-term mission—The elapsed clock time from the first demand caused by an accident condition typically postulated in PRA/IPEs (e.g., loss-of-coolant, main steam line break inside containment) until plant conditions are such that the system is no longer required. The long-term mission time is typically 24 hours.

Maintenance out-of-service (MOOS)—A failure occurring during an unplanned demand that is attributed to a maintenance activity.

Maintenance unavailability—Probability that a system is out of service for maintenance at any instant in time.

Operating conditions—Conditions in which technical specifications require HPCI operability, typically while the plant is in Modes 1 (power operations), 2 (start-up), and 3 (hot shutdown).

Operating experience—A term used to represent the industry operating experience (demands, failures, and faults) as reported in LERs. It is also referred to as operational data, operating data or industry experience.

Operating year— A unit of measure expressed as the time the plant is in an operating state. Any plant shutdowns exceeding twenty-four hours are excluded from the operating time. On the average, boiling-water reactors operate about 70% during a calendar year.

PRA/IPE—A term used to represent the data sources (PRAs, IPEs, and NUREG reports) that describe plant-specific system modeling and risk assessment, rather than a simple focus on operating data.

P-value—The probability that the assumed model or hypothesis is statistically rejected. In this study, a model was rejected if the p-value is less than 0.05.

Recovery—An act that enables the HPCI system to be recovered from a failure without maintenance intervention. Generally, recovery of the HPCI system was only considered in the unplanned demand events. Each failure reported during an unplanned demand was evaluated to determine whether recovery of the system by operator actions had occurred. Typically, a failure was recovered if the operator was able to reposition a switch, open a valve, or close a beaker to restore the HPCI system failure. Events that required replacing components were not considered as recoveries. Also, for redundant systems, it may not be necessary to recover the failed train/piping segment immediately if the other redundant system succeeded. The LERs were further analyzed to determine those failures that may have been recovered if attempted.

Quarterly surveillance test demands— In addition to the cyclic surveillance tests, ASME standard Section XI requires a surveillance test of the injection pump every three months. These quarterly tests are used to estimate the failure mode probabilities that involve the components being tested.

Reliability—The probability of a component or system to perform a required function under stated conditions for a stated period of time. Typically computed as one minus the unreliability.

Short-term mission—The elapsed clock time from the first demand caused by a transient condition that includes a reactor trip until plant conditions are such that the system is no longer required. The short-term mission time is typically a few minutes after system initiation up to several hours.

Unreliability—Probability that the HPCI system will not fulfill its required mission. This includes the unavailability contribution of the system being out of service for maintenance, as well as failures to start or run.

Unplanned demand— A manual or automatic initiation of the system or component that was not part of a pre-planned evolution, such as maintenance or testing. The automatic initiation of the system or component can be caused by either an actual valid or invalid (spurious) initiation signal. Unplanned demands typically are the result of an actual low reactor pressure vessel water level conditions (manual or automatic actuation signal) or a spurious low level indication from the reactor pressure vessel level instrumentation. An inadvertent opening of the suppression pool suction valve is considered an unplanned demand for that valve. Spurious signals or inadvertent initiation signals that occurred during the performance of a surveillance test, or generated during maintenance activities on the HPCI system were not classified as unplanned demands.

Unplanned demand frequency—The number of unplanned demands divided by operating time (in operating years).

Reliability Study Update: High-Pressure Coolant Injection (HPCI) System, 1987–1998 (DRAFT)

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission's (NRC) Office of Nuclear Regulatory Research has, in cooperation with other NRC offices, undertaken efforts to monitor and report on the functional reliability of risk-important systems in boiling-water reactor (BWR) and pressurized-water reactor nuclear power plants. The final reports in the NUREG/CR-5500 series have been issued on the reliability of 10 risk-important systems based on U.S. operating experience.

Objectives. The purpose of this report is to update the results of functional reliability of the high-pressure coolant injection (HPCI) system in BWRs. The objectives of this update are to:

- Estimate unreliability based on U.S. operating experience from 1987 through 1998;
- Compare the results with the assumptions, models, and failure probabilities used in probabilistic risk assessments and individual plant examinations (PRA/IPEs);
- Determine if trends and patterns are present in the HPCI system operating experience;
- Provide an engineering analysis of the factors affecting HPCI system unreliability; and
- Determine if the HPCI system unreliability from this updated study is changing in comparison to the original study.

Approach. The approach used in the update to the HPCI system reliability study is identical to that used in the original study as documented in NUREG/CR-5500, Vol. 4, *Reliability Study: High-Pressure Coolant Injection System, 1987–1993* (Ref. 1). This approach provides estimates for the evaluation of HPCI system unreliability for two cases.

First, the HPCI system unreliability was estimated for the HPCI system in performing its routine mission. The estimate was based on data from unplanned demands from the 1987–1998 operating experience and system functional tests that best simulate system response to a low reactor vessel water level transient. The data from these sources are considered to best represent the plant conditions during accident conditions. Data from component malfunctions that did not result in a loss of safety function of the system were not included in the reliability analysis. A fault tree model was developed to estimate HPCI system unreliability based on actual failures found in the 1987–1998 operating experience.

Second, data from the 1987–1998 operating experience are used to compare the estimates and associated assumptions as found in the PRA/IPEs. In order to make this comparison, a second fault tree model was developed for the HPCI system in performing the longer term "accident mitigation" mission postulated in PRA/IPEs. This PRA/IPE comparison model includes operating modes not experienced in the routine mission, such as suction transfer from the condensate storage tank to the suppression pool. The PRA/IPE comparison model is used to provide a template for mapping relevant PRA/IPE component failures probabilities into an HPCI system model. The mapping provides a relational structure for comparing PRA/IPE results to the estimates derived from the 1987–1998 operating experience. The estimates produced from the PRA/IPE comparison model does not completely reflect unreliability estimates based on the routine mission or assumed in the PRA/IPEs. However, the PRA/IPE comparison model does provides a baseline for making comparisons to the HPCI unreliability estimates assumed in plant-specific PRA/IPEs.

Report content. This report is arranged as follows.

- Section 1 provides the introduction.

- Section 2 describes the scope of the study; outlines the HPCI system boundaries; briefly describes the data collection and analysis methods; discusses the rationale for classifying failures as recoverable; and provides the breakdown of failure and demand counts used in estimating HPCI system unreliability.

- Section 3 provides the estimates of unreliability of the HPCI system; provides results of trend analyses of HPCI system unreliability by calendar year and low-power license date (i.e., newer plants versus older plants); and compares PRA/IPE data and assumptions with those from the 1987–1998 operating experience.

- Section 4 provides results on the trends of failures and unplanned demands by calendar year and low-power license date. Also included in Section 4 are engineering insights into the factors affecting the system reliability.

- Section 5 contains the references.

- Appendix A provides summary lists of failures and unplanned demands from the LER data. The failure data used in the unreliability estimations are also provided in Appendix A.

- Appendix B provides a detailed explanation of the methods used for data collection, characterization, and analysis.

- Appendix C provides the fault tree model, data, and failure mode probabilities used in the comparison to PRA/IPEs.

2. DATA COLLECTION AND CLASSIFICATION

2.1 Scope of Study

This study updates HPCI system reliability analysis for the U.S. commercial BWRs with a dedicated HPCI system. The 24 BWRs are listed in Table 1. The original HPCI system reliability report (Ref. 1) was based on 1987–1993 operating experience in U.S. commercial BWRs. This report documents the results of risk-based and engineering analyses based on 1987–1998 operating experience. The reliability analysis focuses on the ability of the HPCI system to start and provide its emergency core cooling function for the required mission.

System boundaries. A simplified schematic of the HPCI system boundaries as assumed in this analysis is provided in Figure 1. No change was made to the boundary definition as compared to the original report.

Detailed discussion of the system description, operations and boundary is provided in the original report (Ref. 1, Section 2.1).

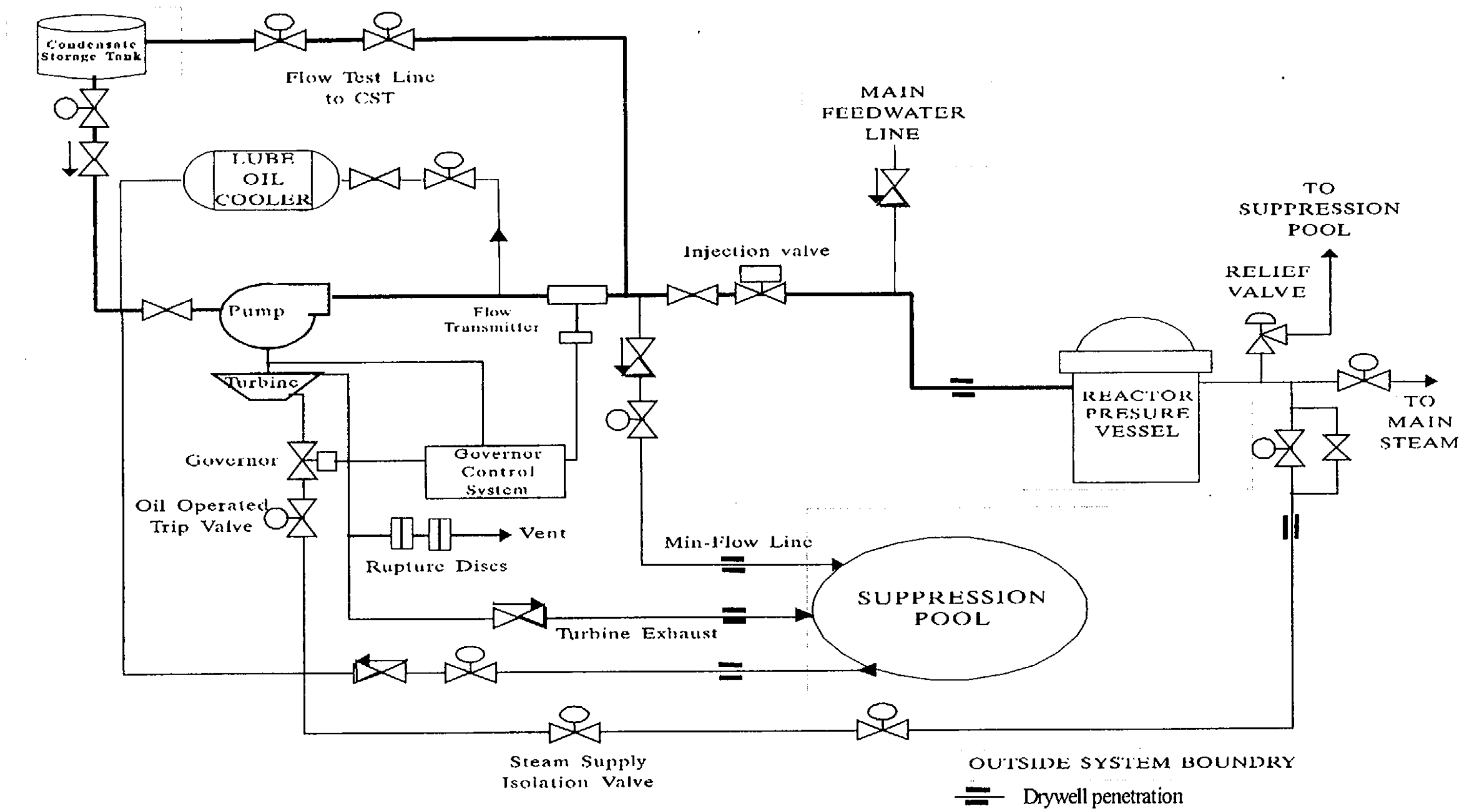
2.2 Data Source

The source of HPCI system operational data used in this report is Licensee Event Reports (LERs) identified by the Sequence Coding and Search System (SCSS) database. The SCSS database was searched for all HPCI records for the years 1994 through 1998. The full text version of each LER was reviewed for events involving unplanned system demands and inoperabilities. The data from the 1994–1998 experience were combined with the data set from the original HPCI system reliability study (based on 1987–1993 experience). This combined data was used in the risk-based and engineering analyses presented in this report.

Table 1. BWR plants with a dedicated HPCI system.

Plant	Docket	Operating Years[a]	Plant	Docket	Operating Years[a]
Browns Ferry 2	260	7.0	Hope Creek	354	10.4
Browns Ferry 3	296	3.0	Limerick 1	352	10.3
Brunswick 1	325	8.4	Limerick 2	353	8.7
Brunswick 2	324	9.1	Monticello	263	10.7
Cooper	298	9.3	Peach Bottom 2	277	8.7
Dresden 2	237	8.4	Peach Bottom 3	278	8.3
Dresden 3	249	8.6	Pilgrim	293	8.2
Duane Arnold	331	10.2	Quad Cities 1	254	8.7
Fermi 2	341	8.6	Quad Cities 2	265	8.5
FitzPatrick	333	8.7	Susquehanna 1	387	10.1
Hatch 1	321	10.6	Susquehanna 2	388	10.5
Hatch 2	366	10.4	Vermont Yankee	271	10.7

a. Operating years is the time the plant was operating. Plant shutdowns exceeding twenty-four hours are excluded.



BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

Figure 1. Simplified HPCI system diagram. (Elements enclosed in dashed lines are considered outside the system boundaries.)

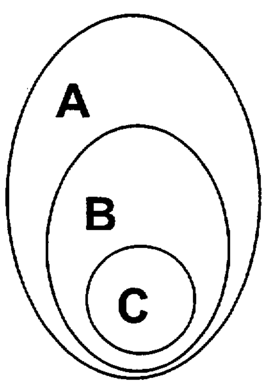
2.3 Data Characterization

The risk-based and engineering analyses of operational data are based on two different data sets. The Venn diagram in Figure 2 illustrates the relationship between these data sets. Data set A includes all LERs that identified a HPCI system inoperability from the SCSS database search. Data set B represents the inoperabilities that were classified as failures of the HPCI system. (A failure is defined as an event that prevents the HPCI system from performing its emergency core cooling safety function.) Data set C represents those actual failures identified from LERs for which the corresponding demands (both failures and successes) could be counted. Data set C is used for estimating the unreliability of the HPCI system.

The data in data set C are not simply all demand and failure on demand events that were found in the SCSS search. Certain criteria must be met to ensure that demand and failure data used in the risk-based analysis form a homogeneous population. These criteria are: (1) the data from the plants must be reported in accordance with the same reporting requirements; (2) the data from each plant must be statistically from the same population; and (3) the data must be consistent (i.e., from the same population) from an engineering perspective. The data review and screening helped to assure that these criteria were met.

The engineering analysis of the factors affecting HPCI system reliability focused on data set B, which includes data set C.

The characterization of the two types of data (demands and failures) used in the risk-based and engineering analyses are summarized below. In addition, the inoperability data that was not included in analyses, called faults, are also defined. A detailed discussion of data collection and characterization can be found in the original report (Ref. 1, Appendix A).



A Represents all the inoperabilities identified from the SCSS database search.

B Represents the inoperabilities that are classified as failures.

C Represents the subset of failures for which the demand counts could be determined or estimated, countable failures.

Figure 2. A Venn diagram showing the relationship between the inoperability and failure data sets.

2.3.1 Demand Characterization

Demand events used in the risk-based (unreliability) analysis of the HPCI system include unplanned demands, and system demands during cyclic (i.e., 18-month fuel cycle) and quarterly surveillance tests. The original report (Ref. 1) did not use quarterly test results in the HPCI system analysis. However, for this update, the quarterly test data were included in the analysis. The quarterly test contained in the 1987–1993 operating experience was reviewed and categorized to the definitions used in this report.

The three types of demands are defined below. Details on the counting of unplanned demands and surveillance test demands, and estimating run times are provided in the original report (Ref. 1, Appendix A, Sections A-1.2 and A-1.3). The method used to estimate the number of cyclic and quarterly surveillance test demands is discussed in Section A-3 in Appendix A of this report.

Unplanned demands. An *unplanned demand* is defined as a manual or automatic initiation of the system or component that was not part of a pre-planned evolution, such as maintenance or testing. The automatic initiation of the system or component can be caused by either an actual valid or invalid (spurious) initiation signal. Unplanned demands typically are the result of an actual low reactor pressure vessel water level conditions (manual or automatic actuation signal) or a spurious low level indication from the reactor pressure vessel level instrumentation. An inadvertent opening of the suppression pool suction valve is considered an unplanned demand for that valve. Spurious signals or inadvertent initiation signals that occurred during the performance of a surveillance test, or generated during maintenance activities on the HPCI system were not classified as unplanned demands.

Each LER was reviewed to determine what portion(s) of the system was demanded. In addition, the length of time the system operated was also obtained from the LER, if the LER so indicated. Component actuations that were judged as not representative of the environment expected during an actual accident condition were excluded form the count of unplanned demands for the applicable failure mode. Examples include inadvertent actuation of certain components while the plant was shutdown; and an unplanned demand of the HPCI system that was terminated by the operator because other methods of injection were readily available and operating. Each unplanned demand was carefully examined to identify those system components and those failure modes that were truly tested.

The components in the HPCI system that change state for each engineering safety features actuation signal during an unplanned demand are provided in Table A-4 in Appendix A of this report.

Cyclic surveillance test demands. The plant technical specifications require a simulation of the automatic start of the HPCI system with a periodicity of once a fuel cycle, and at least once every 18 months (referred to as cyclic tests). This test typically simulates the automatic actuation of system components. However, the injection valve is not tested under the same conditions that the valve would experience during an unplanned demand (flow to the vessel). Specifically, the injection valve is isolated from the rest of the system; therefore, the injection valve operates with no differential pressure applied across the valve. For unplanned demands, the valve is subjected to a differential pressure. Therefore, data from cyclic tests were not used to estimate the failure probability for the injection valve.

Quarterly surveillance test demands. In addition to the cyclic surveillance tests, ASME standard Section XI requires a surveillance test of the injection pump every three months. These quarterly tests are used to estimate the failure mode probabilities that involve the components being tested. These components include the HPCI pump, turbine and associated turbine control, pump suction valves associated with the condensate storage tank and suppression pool, and the main steam isolation valve to the turbine. The quarterly testing of the injection valve is not included due to the same reasoning used above for the cyclic surveillance test demands.

2.3.2 Failure Characterization

Each failure event was reviewed in detail to identify the characteristics of an actual failure used in the risk-based analysis. These characteristics are:

- Type of demand (i.e., method of discovery), such as an unplanned demand, or cyclic or quarterly surveillance test demand;

- Type of recovery of a failure, such as an actual recovered failure or a recoverable failure; and
- Type of failure (i.e., failure mode), such as fail to start, fail to run, maintenance-out-of-service, and failure to recover from a failure.

These characteristics are discussed further below.

Definitions of failure and mission. A *failure* is defined as an inability of the HPCI system to perform its design function (inject coolant into the reactor pressure vessel) for the assumed mission.

Each LER was reviewed in detail to determine whether the system was able to perform its safety function for two missions. The missions considered in this study are: (1) a *short-term mission* that requires the system to operate as long as it is needed following a routine plant transient (e.g., a few minutes up to several hours); and (2) a *long-term mission* which assumes the system must operate successfully for a period typically postulated in PRA/IPEs (e.g., 24 hours).

A successful response of a subsystem or component to a demand in a short-term mission could be classified as a failure in the long-term mission. For example, an oil leak in a motor that would allow the motor to operate for a short-term injection requirement might be judged to fail the motor, and hence the pump, during a long-term mission (e.g., 24-hour).

Recoveries from failures (recovered vs. recoverable). Recovery from initial failures is also considered in the unreliability calculations. To *recover* from a system failure, the operators have to recognize that the system is in a failed state, and then restore the function of the system without actually repairing or replacing hardware. The time and resources available for recovery depends on the specifics of an accident scenario and can vary greatly. An example of such a recovery would be an operator (a) noticing that the pump failed to start and (b) manually starting the pump from the control room within a few minutes. Each failure during an unplanned demand was evaluated to determine whether recovery by the operator occurred.

There were also some failures from which operators elected not to recover because the system was judged not to be needed. For example, if the HPCI pump tripped during automatic start and water level was being restored and maintained by other injection systems (e.g., reactor coolant isolation cooling system, reactor feedwater system), the operators may not have elected to manually restart the HPCI pump. Failures that were not attempted to be recovered were further analyzed to determine if they could have been recovered. If the failure mechanism was such that recovery was possible, but the other injection systems were successful, the failure was judged to be *recoverable*.

New failure modes. The original report characterized several failure modes based on the events identified during the classification of LER events. Three additional failure modes were included in the updated unreliability analysis. These failure modes relate to the failure to recover the failure events found in the 1987–1998 operating experience. All failure events, including the 1987—1993 data, were reviewed to determine whether the failures were recovered or recoverable. These two new failure modes and the other failure modes that were considered in the unreliability analyses are summarized below.

HPCI failure modes. The HPCI events identified as failures represented actual malfunctions which prevented the successful system operation when it was demanded. For example, when the HPCI system receives an automatic start signal as a result of an actual low reactor pressure vessel water level, high-drywell pressure, or a manual start signal, the system operates successfully if the HPCI turbine-driven pumps starts and obtains rated operating pressure and flow, the injection valve opens, and coolant flow is delivered to the reactor pressure vessel until flow from the HPCI system is no longer needed. System failure may occur at any point in this process. For the purposes of this study, the following failure modes have been identified in the 1987—1998 operating experience:

- *MOOS - Maintenance-out-of-service* occurs if a maintenance activity on the HPCI system prevented the system from starting automatically during an unplanned demand. The MOOS failure events were also categorized as to whether the plant was operating or shut down at the time of the unplanned demand. However, only MOOS failures that occurred while the plant was operating were used to estimate HPCI system unreliability.

- *FTSI - Failure to start, other than the injection valve* occurs if the HPCI system was in nominally in-service but failed to automatically or manually start, or develop sufficient injection pressure and flow to the RPV.

- *FRFTSI - Failure to recover from FTSI* occurs if a FTSI failure was not recovered or judged not to be recoverable.

- *FTSV - Failure to start, injection valve* occurs if the HPCI system was in service and the system starts and develops sufficient injection pressure but the injection valves fails to open.

- *FTRI - Failure to run, other than suction transfer* occurs if, at any time after the HPCI system successfully started (i.e., delivering sufficient coolant flow and pressure), the HPCI system fails to maintain flow and pressure while it is needed.

- *FRFTRI - Failure to recover from FTRI* occurs if a FTRI failure was not recovered or judged not to be recoverable.

- *FTRT - Failure to run, suction transfer* occurs if, at any time after the HPCI system successfully started (i.e., delivering sufficient coolant flow and pressure), the HPCI system fails to successfully transfer suction from the condensate storage tank to the suppression pool.

- *FRFTRT - Failure to recover from FTRT* occurs if a FTRT failure was not recovered or judged not to be recoverable.

- *FRO - Failure of the injection valve to reopen* occurs if the HPCI system initially started and injected water to the RPV but on subsequent demands to inject water for maintaining RPV water level the injection valves fails to reopen.

- *FRFRO - Failure to recover from FRO* occurs if a FRO failure was not recovered or judged not to be recoverable.

- *PMI – Probability that the event will require multiple injections* is based on the number of HPCI system injection demands that resulted in closing and reopening of the injection valve to maintain reactor pressure vessel water inventory.

A detailed discussion of the characterization, collection, and classification of failures is provided in the original report (Ref. 1, Appendix A, Section A-1.1).

2.3.3 Fault Characterization

Many of the LERs identified from the SCSS database searches involved system inoperabilities that did not (or would not) prevent the system from performing its intended design function if the system was called upon to perform. This type of inoperability is called a fault.

A fault is defined as a condition where the system would have been able to perform sufficiently well even though the system was declared not operable as defined by plant technical specifications.

As an example, the late performance of a technical specification required surveillance test would be classified as a fault (rather than a failure). This classification is based on the judgment that if an emergency situation were to require it, the system would still be capable of adequate safety injection to the RPV. Moreover, the LER would typically state that the system was available to respond and that the subsequent surveillance test was performed satisfactorily. If the system could not function successfully during the subsequent surveillance test, the event would then be classified as a failure.

In addition, administrative problems associated with HPCI were also classified as a fault, given the system had successfully passed a recent surveillance test or remained capable of injecting water into the RPV. As an example, the discharge piping was found to not have the required number of seismic restraints. However, the results of an engineering analysis in the safety analysis section of the LER indicated that the existing system configuration would successfully complete the short- and long-term missions postulated in this report. As a result, the event was classified as a fault.

Events involving HPCI system faults were not included in the risk-based and engineering analyses since the system was able to or could have performed its design function, by definition, for the short- and long-term missions.

2.4 Data Results

For 1987–1998 operating experience, the types of data (i.e., unplanned demands, cyclic tests, and quarterly tests), failure counts, and demand counts used for estimating probabilities for the failure modes associated with the HPCI system are provided in Table 2. The demand counts identified in Table 2 represent opportunities for HPCI system success. The logic used to identify the demand and failure counts for each failure mode and type of data is described in Section A-5 of Appendix A. The demand, failure, and fault data for the 1987–1998 experience are also provided in Appendix A.

A review of the data presented in Table 2 and the tables in Appendix A reveal:

- A total of 1,157 HPCI system demands was estimated from the 1987–1998 operating experience. These demands included 94 unplanned demands, 217 cyclic surveillance tests, and 846 quarterly surveillance tests. These demands were used to estimate failure probabilities for the unreliability estimates.
- A total of 46 HPCI system failures (excluding recovery failures) were identified during the 1,157 demands. One of these failures was due to the HPCI system being out of service for maintenance. These failure events were used to estimate failure probabilities for the unreliability estimates.
- Six HPCI system failures occurred during 94 unplanned demands. One of these unplanned demand failures was due to the HPCI system being out of service for maintenance.
- An additional 116 HPCI system failures were identified from the LERs for which a demand could not be determined or estimated. These failure events and the 46 countable failures were used in the engineering analysis of the data in Section 4.

Table 2. A summary of the HPCI system demands and associated failures identified in the unplanned demands (1987–1998) and surveillance tests for estimating failure probabilities.

Failure Mode	Unplanned Demands		Cyclic Tests		Quarterly Tests	
	f [a]	*d* [a]	*f* [a]	*d* [a]	*f* [a]	*d* [a]
Maintenance-out-of-service while not shut down (MOOS)[b]	1	94	—	—	—	—
Failure to start, other than injection valve (FTSI)	1	94	5	217	22	846
Failure to recover from FTSI (FRFTSI)	0	1	3	5	17	22
Failure to start, injection valve (FTSV)	0	79	—	—	—	—
Failure to recover from FTSV (FRFTSV)	0	1	—	—	—	—
Failure to run, other than suction transfer (FTRI)	2	83	2	212	9	824
Failure to recover from FTRI (FRFTRI)	1	2	1	2	6	9
Failure to reopen, injection valve (FRO)	2	12	—	—	—	—
Failure to recover from FRO (FRFRO)	2	2	—	—	—	—
Probability of multiple injections (PMI)	12	79	—	—	—	—
Failure to run, suction transfer (FTRT)	0	6	0	210	2	816
Failure to recover from FTRT (FRFTRT)	—	—	—	—	2	2

a. *f* denotes failures; *d* denotes demands.

b. In this report, the MOOS contribution to HPCI system unreliability was determined using those unplanned demand failures that resulted from the HPCI system being unavailable for maintenance (test, preventive, or corrective) at the time of the demand.

3. RISK-BASED ANALYSIS OF THE 1987–1998 OPERATING EXPERIENCE

3.1 Introduction

This section documents the results of the risk-based analysis performed using the HPCI system 1987–1998 operating experience. The risk-based analysis includes the following:

- Industry-wide HPCI system unreliability for a short-term mission.[a]
- Investigation of plant-specific HPCI system unreliabilities for a short-term mission.
- Investigation of industry-wide HPCI system unreliability trends for a short-term mission.
- Comparisons between the HPCI unreliabilities for a long-term mission derived from the 1987–1998 operating experience data and those derived from the HPCI component failure probabilities found in PRA/IPEs.

Findings. The following is a summary of the major findings related to HPCI system unreliability based on the 1987–1998 operating experience:

- ***Unreliability estimates***. The industry-wide unreliability of the HPCI system with recovery actions calculated from the 1987–1998 experience is 6.6E-02 per demand. If recovery is ignored, the industry-wide mean is 8.1E-02.
- ***Leading contributors.*** Failure of the injection valve to reopen (cycling the injection valve for subsequent reactor pressure vessel water level control) and failure to start of the system other than the injection valve are the leading contributors to the unreliability, 31% and 29%, respectively. The leading contributors to HPCI system unreliability without recovery actions are almost identical.
- ***Unreliability trends.*** Trend analysis of the estimates of HPCI unreliability when modeled as a function of calendar year identified no statistically significant decreasing trend within the industry estimates. No statistically significant decreasing trend was identified in HPCI system unreliability when modeled as a function of low-power license date (i.e., plant age).
- ***Plant variation.*** Statistical analyses identified between-plant differences in the data. Plant-specific estimates of HPCI system unreliability vary from about 5.5E-02 to 9.1E-02, or less than a factor of two. The differences between plants were very small, meaning the differences are not risk significant.
- ***Comparison to PRA/IPEs.*** The industry-wide arithmetic average of HPCI system unreliability calculated using data (e.g., component failure probabilities, maintenance unavailability) extracted from PRA/IPEs is about a factor of four lower than the industry-wide estimate based on the 1987–1998 experience.

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a. A *short-term mission* is a routine transient condition that includes a reactor trip and a demand for coolant injection by high-pressure makeup systems (RCIC or HPCI).

3.2 Estimates of HPCI Unreliability, Insights and Trends

HPCI system unreliability was based in the failures and demands found in the 1987–1998 operating experience. Therefore, the results of unreliability estimates and trends, and system reliability insights are presented in this section for the *short-term* operating mission. This mission requires the system to operate as long as it is needed following a plant transient (e.g., a few minutes up to several hours). Demands reported in LERs are of this nature.

The *long-term* mission that are postulated in PRA/IPEs involves accident conditions (e.g., medium and large loss-of-coolant accidents, main steam line breaks inside containment) requiring system operation for a 24-hour period. Since these events (demands) are extremely rare in the operating experience and surveillance testing do not require long run times, the unreliability estimates based on limited data population will not accurately represent the true reliability of the system under long-term operating conditions.

The risk-based analysis of the 1987–1998 operating experience for a short-term mission consists of the following steps:

- Demand and failure data are defined, collected, and classified;
- A fault tree model is developed to associate failure events with the assumptions and broadly defined failure modes in the data;
- First, data sets are analyzed and tested statistically to determine if significant variability was present (e.g., by plant, by year, and by demand source), then data sets are pooled, separated, and/or eliminated based on the results of these tests;
- Mean failure mode probabilities and uncertainty intervals are calculated using the most appropriate statistical method (based on statistical tests for data variability);
- The fault tree is quantified to estimate the system unreliability and uncertainty interval;
- Plant-specific estimates of HPCI system unreliability are estimated, if between-plant variation is detected during statistical testing; and
- Finally, an investigation of HPCI system unreliability trends by calendar year and by plant low-power license date completes the risk-based analysis.

The assumptions used in the development of the fault tree model and the statistical methods used in the risk-based analysis are summarized in Section B-1 of Appendix B in this report. A detailed discussion of the analysis methods can be found in the Appendix A to the original report (Ref. 1).

3.2.1 Estimates of HPCI Unreliability and Insights

The fault tree used to quantify the HPCI system unreliability using the 1987–1998 operating experience is shown in Figure 3. Table 3 presents the probabilities and associated uncertainty intervals calculated from the 1987–1998 operating experience for each of the failure modes and the estimated HPCI unreliability and associated uncertainty intervals resulting from quantifying the HPCI fault tree using the failure mode estimates. Figure 4 presents the percent contribution of the failure mode probabilities to overall system unreliability with and without recovery.

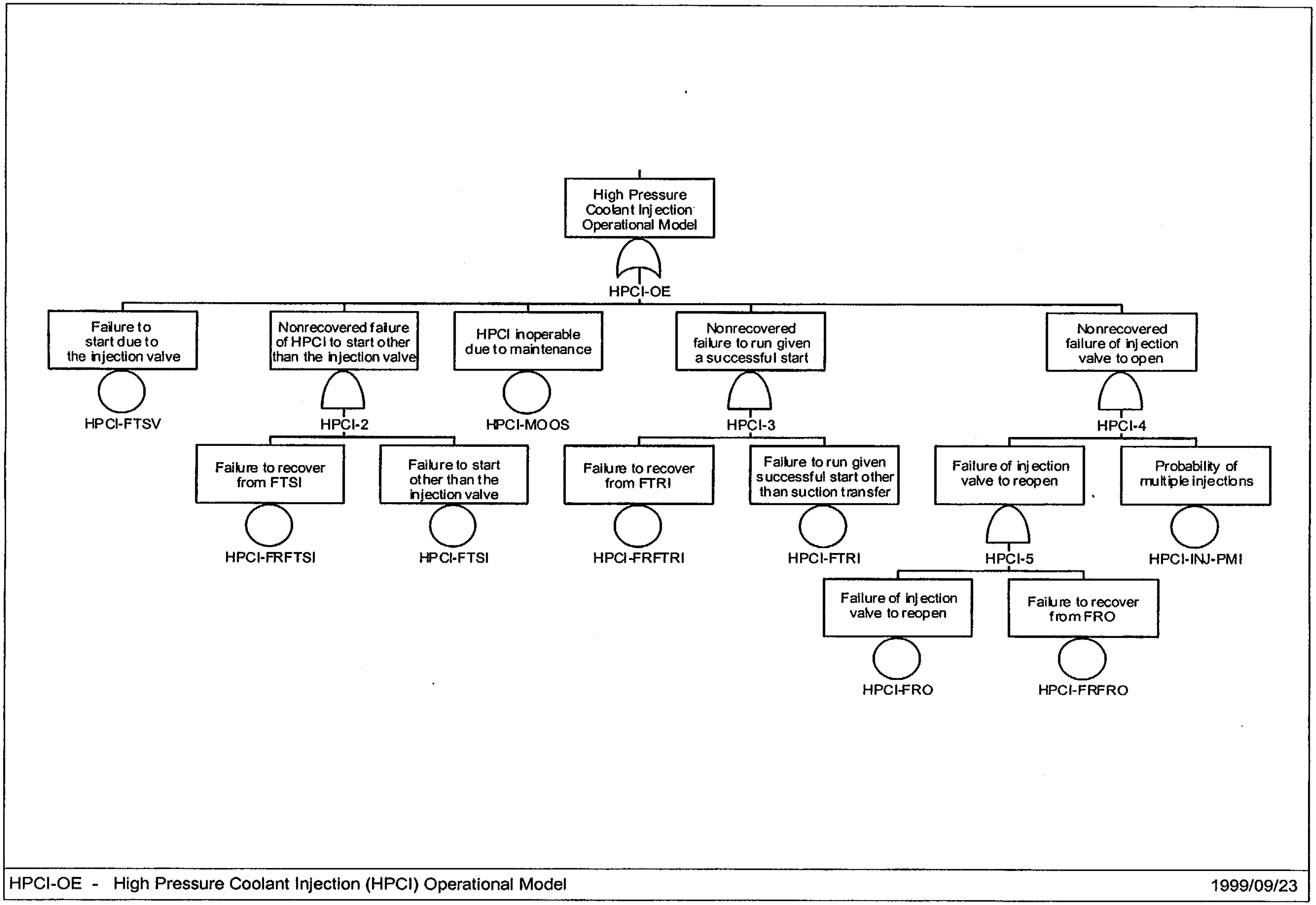


Figure 3. Fault tree for calculating HPCI system unreliability based on the 1987–1998 operating experience.

Table 3. HPCI system failure mode data (1987–1998), Bayesian probability estimates, and HPCI system unreliability estimates.

Failure Mode	Failure Mode Code	Failures	Demands	Bayesian Probability[a]			Model Used	
				5th %ile	Mean	95th%ile	Trend	Plant Differences
Maintenance-out-of-service while not shut down	MOOS	1	94	1.9E-03	1.6E-02	4.1E-02	Constant[d]	No
Failure to open, injection valve	FTSV	0	79	2.5E-03	6.3E-03	2.4E-02	Constant[d]	No
Failure to start, other than injection valve	FTSI	28	1157	6.2E-03	2.4E-02	5.1E-02	Constant[d]	Yes
Failure to recover from FTSI	FRFTSI	20	28	3.4E-01	7.2E-01	9.7E-01	Constant[d]	Yes
Failure to run, other than suction transfer	FTRI	13	1119	2.4E-04	1.1E-02	3.8E-02	Constant[d]	Yes
Failure to recover from FTRI	FRFTRI	8	13	4.6E-02	5.8E-01	9.9E-01	Constant[d]	Yes
Failure to reopen, injection valve	FRO	2	12	5.0E-02	1.9E-01	3.9E-01	Constant[d]	No
Failure to recover; injection valve reopening	FRFRO	2	2	4.3E-01	8.3E-01	1.0E+00	Constant[d]	No
Probability of multiple injections	PMI	12	79	1.9E-02	1.3E-01	3.2E-01	Constant[d]	Yes
HPCI system unreliability (with recovery)[b]				2.5E-02	6.6E-02[c]	1.2E-01	Constant[d]	Yes
HPCI system unreliability (without recovery)[b]				3.4E-02	8.1E-02[c]	1.4E-01	Constant[d]	Yes

a. For a failure mode with no trend or between-plant variation modeled, the estimate was calculated using a Jeffreys noninformative prior in a Bayes update distribution. The mean failure probability is calculated as: [(number of failures + 0.5) divided by (number of demands + 1). Examples: 1 failure in 94 demands is (1 + 0.5)/(94 + 1) = 1.6E-02.

b. Figure 3 presents the fault tree logic for calculating the unreliability. The basic algebraic equations for HPCI unreliability calculations are:

HPCI unreliability (with recovery) = MOOS + (FTSI * FRFTSI) + (FRTI * FRFRTI) + FTSV + (FRO * FRFRO * PMI).

HPCI unreliability (without recovery) = MOOS + FTSI + FRTI + FTSV + (FRO * PMI).

c. However, the final HPCI unreliability is not simply the sum of the individual failure mode probabilities.

d. Any evidence for a trend is weak, not statistically significant. The trend, if any, is too small to be seen in the data. Therefore, no trend is modeled.

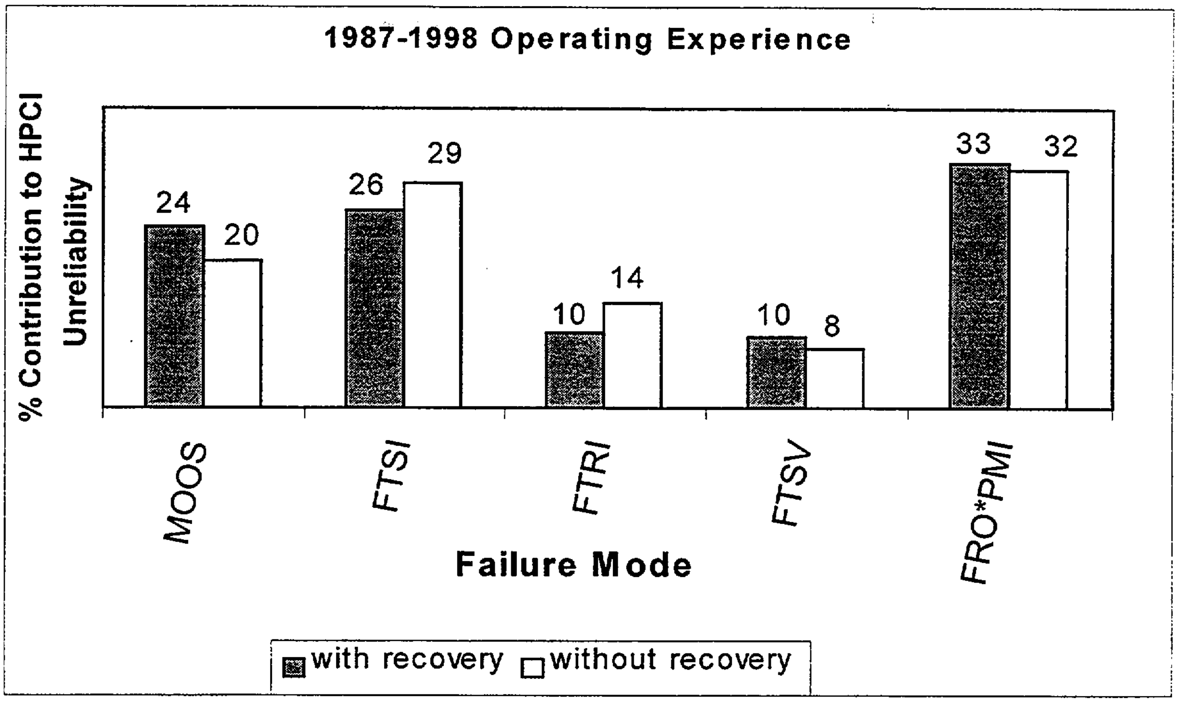


Figure 4. Bar chart of failure mode percentage contribution to HPCI system unreliability. (The percent contribution is the mean failure mode probability divided by the mean HPCI system unreliability.)

Unreliability estimates. The industry-wide unreliability of the HPCI system with recovery actions based on the 1987–1998 experience is 6.6E-02 per demand. If recovery is ignored, the industry-wide mean is 8.1E-02.

Leading Contributors. The leading contributors to HPCI system unreliability (with recover actions) based on the the1987–1998 operating experience are failure of the injection valve to reopen for subsequent reactor pressure vessel water level control (FRO*FRFRO*PMI—33%) and failure to start of the system other than injection valve (FTSI*FRFTSI—26%). Maintenance-out-of-service is the third leading contributor (MOOS—24%) to HPCI operational unreliability.

If recovery is ignored, failure of the injection valve to reopen (FRO*PMI—32%) is the leading contributor to HPCI operational unreliability. The remaining contributors are failure to start of the system other than injection valve (FTSI—30%), failure to start of the system due to the injection valve (FTSV—18%), maintenance-out-of-service (MOOS—16%), and failure to run (FTRI—14%).

Comparison to original report. HPCI unreliability based on the 1987–1998 operating experience has increased slightly compared to the earlier estimate presented in the original report. The unreliability estimated based on original 1987–1993 operating experience and the1987–1998 operating experience are 5.6E-2 and 6.6E-2, respectively. The small increase in the HPCI system reliability estimate based on the 1987–1998 operating experience is primarily due to differences in the fault tree models. The fault tree model used in the update (shown in Figure 3 of this report) includes failure of the injection valve to reopen (FRO*FRFRO*PMI) in the unreliability calculation. This failure mode was not included in the system unreliability estimate calculated in the original report.

3.2.2 Plant-Specific Estimates of HPCI Unreliability

The results of the statistical analysis showed between-plant variation for the fail to start other than the injection valve (FTSI) and failure to run of the injection system (FTRI) failure modes. For all other HPCI failure modes, significant variation was not observed between plants. Plant-specific failure probabilities for these failure modes were included in the model to estimate plant-specific HPCI system unreliabilities shown in Figure 5. The industry-wide unreliability from Table 3 is also shown in Figure 5. Peach Bottom 3 was found to have the highest HPCI system unreliability, but the differences between the plants were very small (the estimates range from 5.5E-02 to 9.1E-02), meaning the differences are not risk-significant. A risk-significant difference is defined in this report when the uncertainty interval for a plant mean is entirely to the right (higher unreliability) of the industry-wide mean.

Plant-specific failure mode probabilities and HPCI system unreliability results are provided in Appendix B in sections B-1 and B-2, respectively.

3.2.3 Investigation of Possible Unreliability Trends

Unreliability trend by calendar year. Estimates of HPCI unreliability when modeled as a function of calendar year were calculated to identify any overall trends within the industry estimates. Figure 6 displays the unreliability trend of the HPCI system by calendar year. The unreliability for each calendar year was obtained using the *constrained noninformative prior* for each failure mode pooled across plants for each

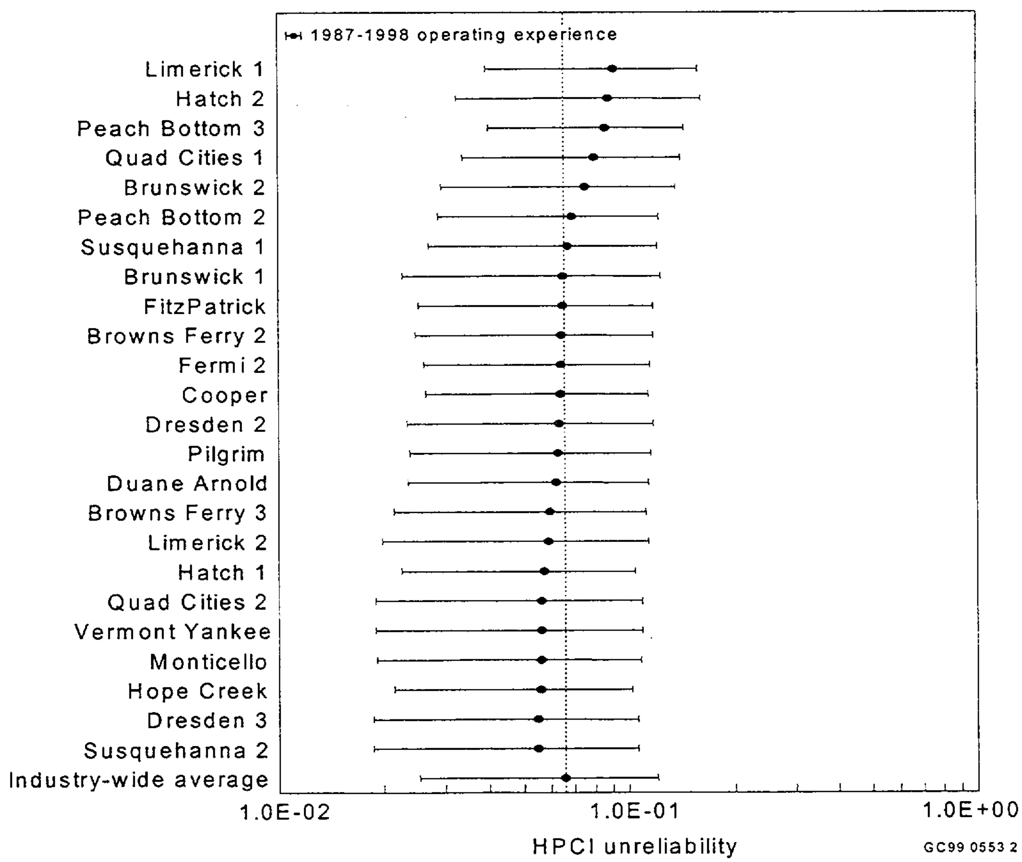


Figure 5. Plant-specific estimates of HPCI system unreliability. Differences between plants are small and not risk significant. The mean and uncertainty values associated with this plot are listed in Table B-10 in Appendix B.

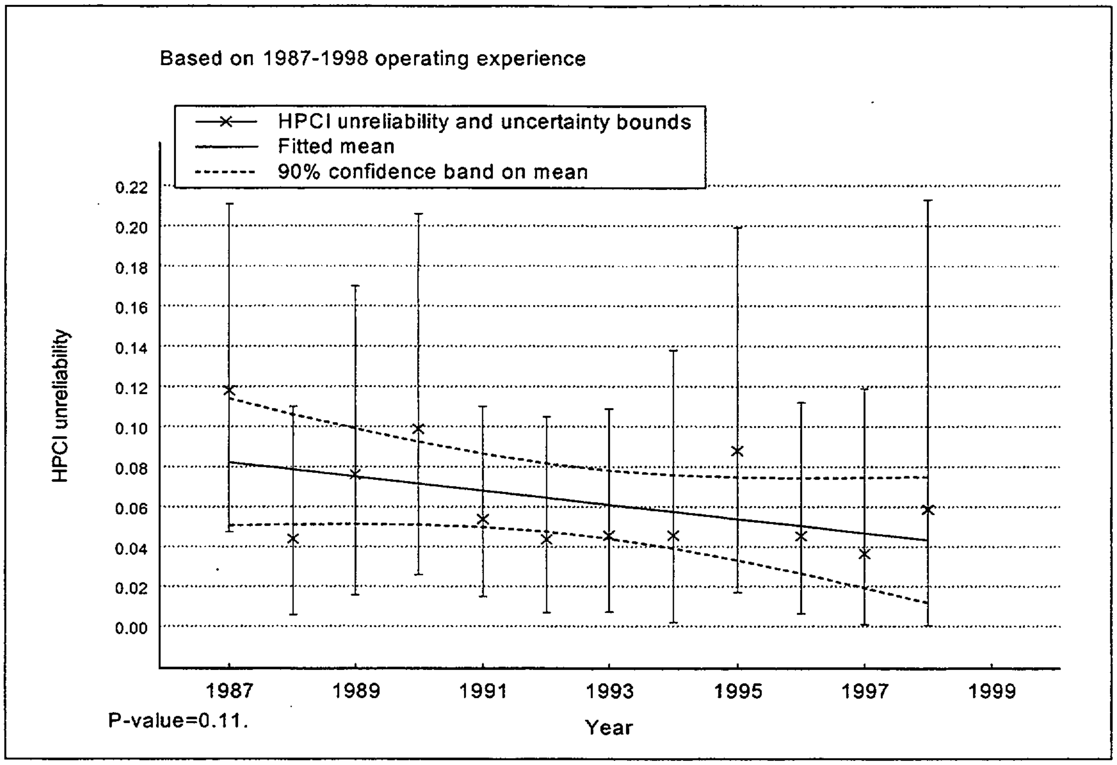


Figure 6. HPCI system unreliability (1987–1998) as a function of calendar year. The trend is not statistically significant.

calendar year. The calculated unreliabilities are based on the fault tree model depicted in Figure 3. The slope of the trend line is not statistically significant (p-value = 0.11).

HPCI system unreliability results for an operational mission, by year, are provided in Section B-4 in Appendix B.

Unreliability trend by low-power license date. To give some indication of the effect of plant aging (i.e., older plants versus newer plants) on HPCI system unreliability, plant-specific estimates of HPCI system unreliability were plotted against the plant low-power license date. The plot is shown in Figure 7. The slope of the trend line is not statistically significant (p-value = 0.90).

HPCI system unreliability results, by plant, are provided in Section B-3 in Appendix B. The technical details of the analysis method are given in the original report (Ref. 1, Appendix C, Section C-2).

3.3 Comparison with PRA/IPEs

Comparisons were made between the HPCI system unreliabilities based on 1987–1998 operating experience for a long-term operating mission and those reported in the PRA/IPEs. The conditions typically postulated in the PRA/IPEs were used in the comparison. The comparisons provide a *general* indication of the extent that unreliabilities based on 1987–1998 experience are consistent with those reported in the PRA/IPEs.

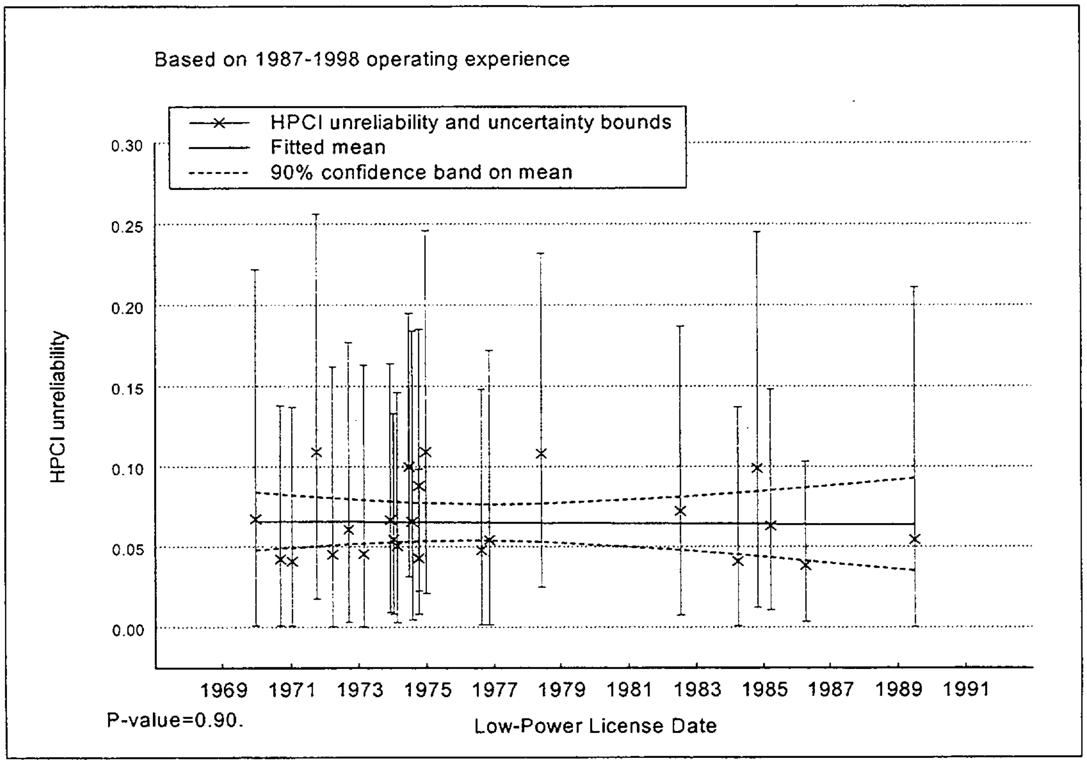


Figure 7. HPCI system unreliability (1987–1998) plotted as a function of plant low-power license date. The trend is not statistically significant.

Generally, the HPCI fault tree logic models were not available in the PRA/IPEs. Therefore, a direct comparison of the operating experience based estimate with the PRA/IPE values is not possible. However, the component failure probabilities used in calculating HPCI unavailability were available. In order to compare the PRA/IPE data and results to those calculated from the operational data, unreliabilities were approximated from the relevant information contained in the PRA/IPEs. The data and model used to estimate system unreliability for a short-term operating mission, and data from the PRA/IPEs were modified to produce a consistent comparison such that detected differences between the two could be expected to be real. The common fault tree developed for these comparisons is neither a complete model based on the 1987–1998 operating experience or a complete model from the PRA/IPEs perspective. However, the model used in the comparison analysis is sufficient to understand any differences in HPCI system unreliabilities and failure mode probabilities between estimates based on the 1987–1998 experience and values extracted from the PRA/IPEs.

The comparison of PRA/IPE results and results from the 1987–1998 operating experience for a long-term mission consists of the following steps:

- Additional demand and failure data from the 1987–1998 operating experience are defined, collected, and classified. This data involves demands and failures on portions of the system that are not demanded during the more routine short-term mission (e.g., suction transfer, long-term operating times for the HPCI pump).

- Component failure probabilities and operating assumptions from PRA/IPEs are collected. These failure probabilities were generally those identified as the major contributor to HPCI system unreliability.

- A fault tree model is developed to associate failure modes from the operating experience (for a long-term mission) with the assumptions and component failure probabilities from the PRA/IPEs.

- Plant-specific probabilities for the fault tree failure modes are estimated with data from each PRA/IPE. In addition, failure probabilities from the operating experience are calculated using the most appropriate data set and statistical method (based on statistical tests for data variability).

- The fault tree is quantified to estimate plant-specific HPCI system unreliability and uncertainty interval for each plant based on the PRA/IPE and operating experience data.

- Failure mode probabilities and system unreliability estimates based on PRA/IPE data and results based on the 1987–1998 experience are evaluated for differences.

Results. Figure 8 provides a comparison of plant-specific estimates of HPCI system unreliability calculated from the 1987–1998 operating experience and the PRA/IPE information. The dashed lines represent the corresponding industry-wide averages. These estimates were calculated from the PRA comparison fault tree model shown in Figure C-1 in Appendix C.

When making inferences about the results of this report to those contained in the PRA/IPEs, the reader needs to understand that the PRA/IPE results are based on reports that were submitted in the 1980 and early 1990 time frame. The data used in the earlier PRA/IPEs may not reflect the current performance of the HPCI system. Caution is advised when making absolute comparisons of the 1987–1998 operating experience findings to the PRA/IPEs. Whenever revised IPE data becomes readily available to the NRC, comparisons to the revised IPE information will be reflected in future updates to this study.

The industry-wide arithmetic average of HPCI system unreliability (with recovery actions) calculated using data (e.g., component failure probabilities, maintenance unavailability) extracted from PRA/IPEs is about a factor of three lower than the industry-wide estimate based on the 1987–1998 operating experience. Failure of the injection valve to reopen for subsequent reactor pressure vessel water level control is the leading contributor (FRO*FRFRO*PMI – 55%) to HPCI system unreliability based on the 1987–1998 experience and a long-term mission postulated in the PRA/IPEs. Failure to run is the second leading contributor (FTRI*FRFTRI – 42%). The contribution of the failure modes at a system cut set level to overall system unreliability based on the 1987–1998 experience is presented in Figure 9.

Comparison to original report. The current HPCI system unreliability estimate based on the 1987–1998 operating experience and the PRA comparison model is slightly larger as compared to the results in the original report (Ref. 1, Section 3.2). This is primarily due to including the failure of the injection valve to reopen (FRO*FRFRO*PMI) and failure of the suction transfer (FTRT*FRFTRT) into the unreliability model. Excluding these two failure modes from the current estimate will make the unreliability estimate compare well to the original report.

A detailed discussion of differences between PRA/IPE results and estimates based on the 1987–1993 operating experience can be found in Section 3.2 in the original report (Ref. 1). The original report provides a detailed comparison of differences in failure mode probabilities used in the unreliability comparisons and discusses plant-specific differences. Since the five addition years of operating experience only slightly improved failure mode probabilities and the information derived from the PRA/IPEs remains unchanged, the overall results presented in the original report still applies.

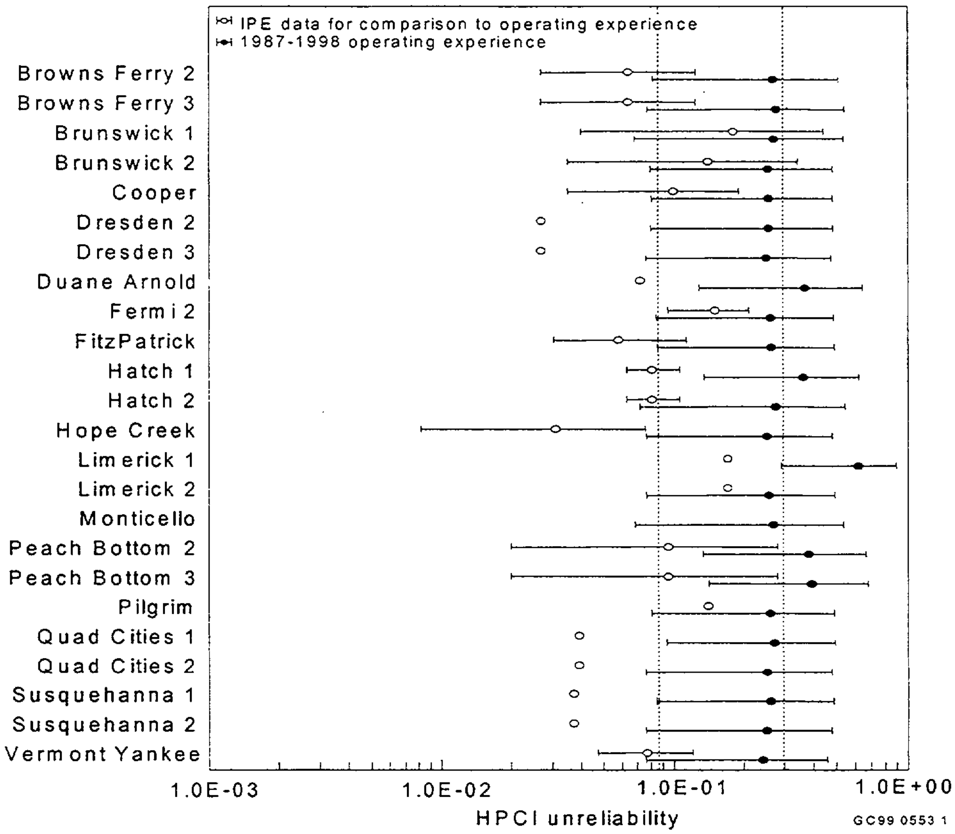


Figure 8. Plant-specific estimates of HPCI system unreliability calculated using the 1987–1998 operating experience compared to the unreliability estimates calculated using the PRA/IPE data. The estimates were calculated using the PRA comparison fault tree model shown in Figure C-1 of Appendix C.

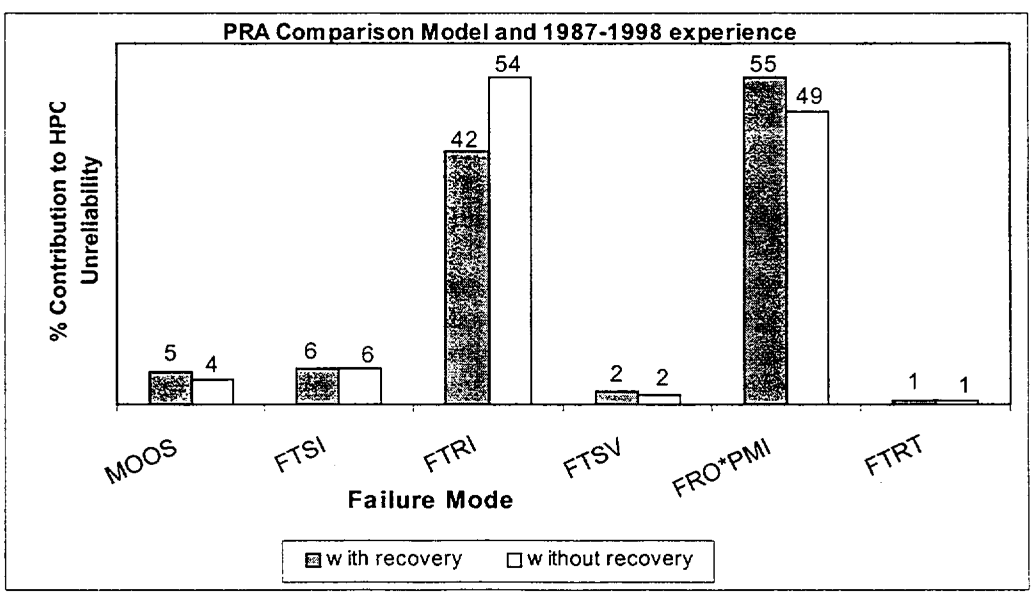


Figure 9. Bar chart of failure mode percentage contribution to HPCI system unreliability based on 1987—1998 and the PRA comparison fault tree model. (The percent contribution is the mean failure mode probability divided by the mean HPCI system unreliability.)

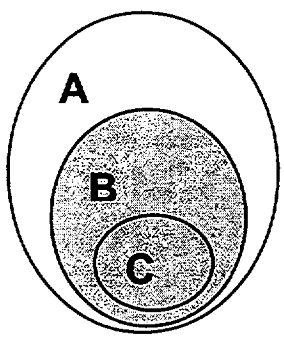
Table C-1 in Appendix C presents the data and statistical results of the HPCI unreliability analysis based on the 1987–1998 operating experience and the fault tree model used in the PRA/IPE comparisons. Figure C-1 in Appendix C is the fault tree model of the HPCI system used for quantifying the 1987–1998 experience for comparison to PRA/IP results. Comparison plots of plant-specific estimates of failure mode probabilities and system unreliability are presented in the original report (Ref. 1, Section 3.2).

4. ENGINEERING ANALYSIS OF THE 1987–1998 OPERATING EXPERIENCE

4.1 Introduction

This section documents the results of an engineering evaluation of the HPCI operational data derived from LERs. The objective of this analysis was to analyze the data and obtain insights into the performance of the HPCI system throughout the industry and at a plant-specific level. Failures were analyzed for industry-wide trends by calendar year and by low-power license date. In addition, failures were evaluated for factors affecting reliability, such as subsystem/component contribution to system failures by method of discovery, failure mode, and causal factors.

Data used in the engineering analysis. Unlike the risk-based analysis presented in Section 3, which used only failures for which corresponding demands (both failure and successes) could be determined or estimated, all LERs submitted during the evaluation period that identified a total system failure were considered in this analysis. As depicted in the Venn diagram in Figure 10, this includes the failure data in data set B, which includes data set C. Data set B includes all system failures (i.e., failure of the system to perform its design function) discovered during unplanned demands, surveillance tests (all types and frequencies), and other methods, such as preventive maintenance activities, design reviews, walkdowns, control room annunciators and indications, and plant tours.



A Represents all the inoperabilities identified from the SCSS database search.

B Represents the inoperabilities that are classified as failures.

C Represents the subset of failures for which the demand counts could be determined or estimated, countable failures.

Figure 10. Illustration of the failures used in the engineering analysis (shown in shaded regions).

The faults (as defined in Section 2.3.3) that were observed in the HPCI system generally are not risk-significant; therefore, the engineering analysis focuses only on the failures. The analysis identified 177 failures, of which one was for the HPCI system being out of service for maintenance. The analyses in this section focus on the remaining 176 failures.

Differences between reports. The scope of the engineering analysis and evaluation performed in this section correlates with the scope in the original report (Ref. 1). An evaluation of causal factors affecting reliability of the HPCI system and components that were detected during quarterly surveillance tests was added to this update.

Insights. The results of the data review reveal the following insights:

- *Unplanned demand frequency trends.* A statistically significant decreasing trend was identified in the frequency of the HPCI unplanned demands when modeled as a function of calendar year. When modeled as a function of low-power license dates (i.e., plant age), no statistically significant trend was identified in the unplanned demand frequency.

  - The unplanned demand frequency decreased by about a factor of nine over the 12-year period. This is consistent with the findings presented in Reference 3, *Rates of Initiating Events at U.S. Nuclear Power Plants 1987–1995*. In addition, the frequency of risk-significant transient initiators has declined and since the HPCI system unreliability has remained constant over time, the overall plant risk (for example, core damage frequency) has improved, given all other risk factors remain constant.

- ***Failure frequency trends***. Although no decreasing trend was statistically identified in the *measured or estimated* unreliability of the HPCI system, a highly statistically significant decreasing trend was identified in the frequency of HPCI system failures observed by all detection methods when modeled as a function of calendar year.

  - The frequency of all HPCI system failures decreased by about a factor of four during the 1987–1998 period. Based on the end point of the trend line (calendar year 1998), this frequency is equivalent to an expectation across the industry of about nine HPCI system failures per year.

  - No statistically significant trend was identified in the frequency of failures when modeled as a function of low-power license date indicating that the effects of HPCI system aging is not a significant factor in overall reliability. The effects of corrective maintenance and component replacement strategies and more experienced personnel may have reduced the number of age-related failures.

- ***Failure recovery.*** Generally, the failure mechanisms affecting HPCI system unreliability were of a nature that the HPCI system could not easily be recovered from the control room since the effect of recovery on the unreliability estimate is small. Actual repair of the failed component is required to return the HPCI system to an operable condition.

- ***Major contributor to system unreliability***. As presented earlier, the leading contributor to HPCI system unreliability is the failure of the injection valve to reopen for subsequent reactor pressure vessel water level control. Based on the limited unplanned demand data (79 demands), there is a 0.6% probability of the injection valve failing to initially open compared to 20% probability that the injection valve will fail to reopen if needed later during plant recovery. The failure probability of the injection valve to reopen is based on only two failure events from the 1987-1998 operating experience.

- ***Effectiveness of various detection methods***. Overall, testing of various types and frequencies was the most effective method in detecting failures. Testing identified about half of the HPCI system failures. Although quarterly and cycling surveillance testing as required by plant technical specifications resulted in 28% of the HPCI system failures, approximately 24% of the HPCI system failures were discovered by other routine tests and checks (e.g., weekly and monthly tests, post maintenance tests, etc.).

  The HPCI system injection valve is tested quarterly; however, the quarterly testing of this valve is done in an environment that does not produce the same stresses on the valve that the valve would encounter in an accident environment. In addition, the injection valve is not cycled repeatedly during the quarterly test.

- ***Leading component failures***. Two component groups contributed about 62% of all HPCI system failures: instrumentation and control (electronic) components and valves, 35% and 27%, respectively.

- ***Leading causes of failure.*** Seven out of ten failures of the HPCI system observed in the 1987–1998 experience were attributed to hardware-related problems. Personnel errors caused 17% of all HPCI system failures. However, 70% of these failures were immediately identified, meaning that the failures were of the nature where plant personnel were able to respond to the failures immediately after they occur.

Sections 4.1 through 4.4 provide a detailed summary of the industry data supporting the above results. Additional insights were derived from (1) an assessment of the operational data for trends and patterns in system performance across the industry and an evaluation of the relationship with low-power license date, (2) identification of the factors affecting HPCI system unreliability in the industry, and (3) a review of NRC regulatory initiatives related to HPCI system operations.

4.2 Industry-Wide Trends

Trends of unplanned demand frequency by year, failure frequency by year, and failure frequency by low-power license date are provided below. The frequency estimates are based on all failure data (i.e., from data set B in Figure 10, except for maintenance-out-of-service events). Trends of HPCI unreliability by year and low-power license date based on failures with associated demands (i.e., from data set C in Figure 2) are provided in Section 3.2.3.

4.2.1 Trends by Calendar Year—Unplanned Demand and Failure Frequencies

Figures 11 and 12 are illustrations of unplanned demand and failure frequencies, respectively, for each year of the study. The frequency is the number of events (unplanned demands or failures) that occurred in the specific year divided by the total number of plant operating years for the specific year.

The HPCI unplanned demand frequency that invoked the injection valve exhibited a highly statistically significant decreasing trend by calendar year over the 1987–1998 period, with a p-value[b] of 0.0003. Fewer demands per year have occurred in more recent years than the start of the study.

Analysis of the HPCI system failure frequency also identified a highly statistically significant decreasing trend (p-value is 0.0004) over the 1987–1998 period. The frequency of all HPCI system failures decreased by about a factor of four during the 1987–1998 period. Based on the end point of the trend line (calendar year 1998), this frequency is equivalent to an expectation across the industry of about nine HPCI system failures per year.

HPCI unplanned demand and failure frequency results by calendar year and by plant, are provided in Section B-4 in Appendix B.

b. The *p-value* used here is the probability of observing a trend as a result of chance alone. A *p-value* is considered statistically significant in this report if the *p-value* is smaller than 0.05. The discussion on interpreting time trends is provided in Reference 3 (Appendix E. page E-7).

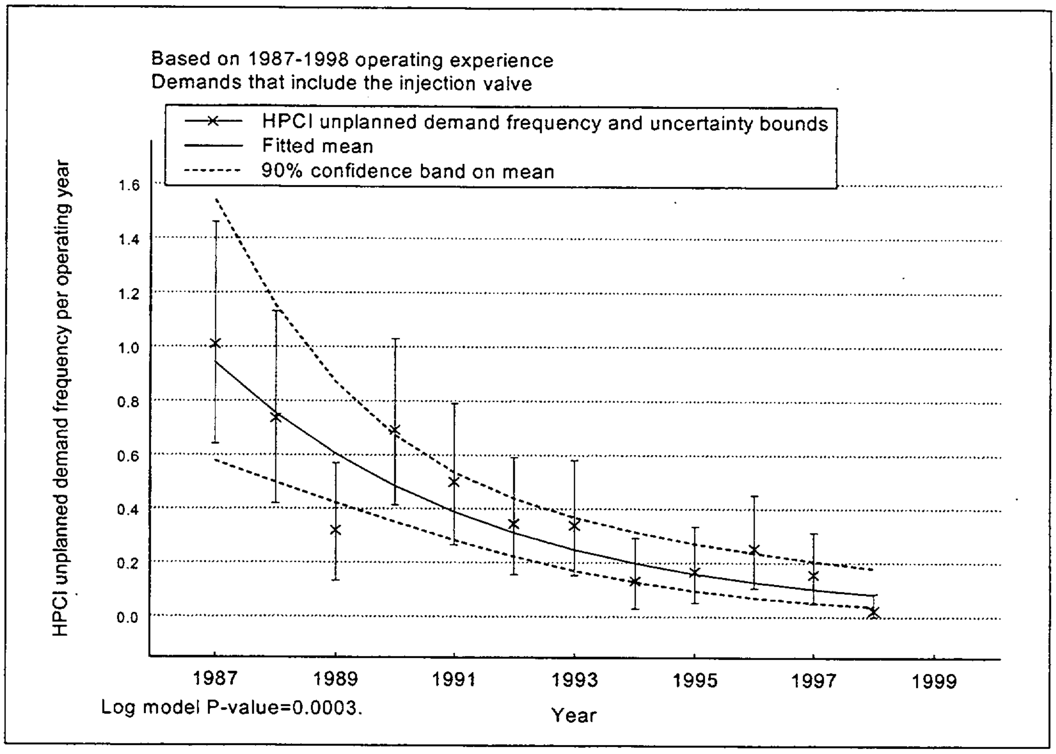


Figure 11. Frequency of HPCI system unplanned demands (1987–1998) as a function of calendar year. The decreasing trend is highly statistically significant.

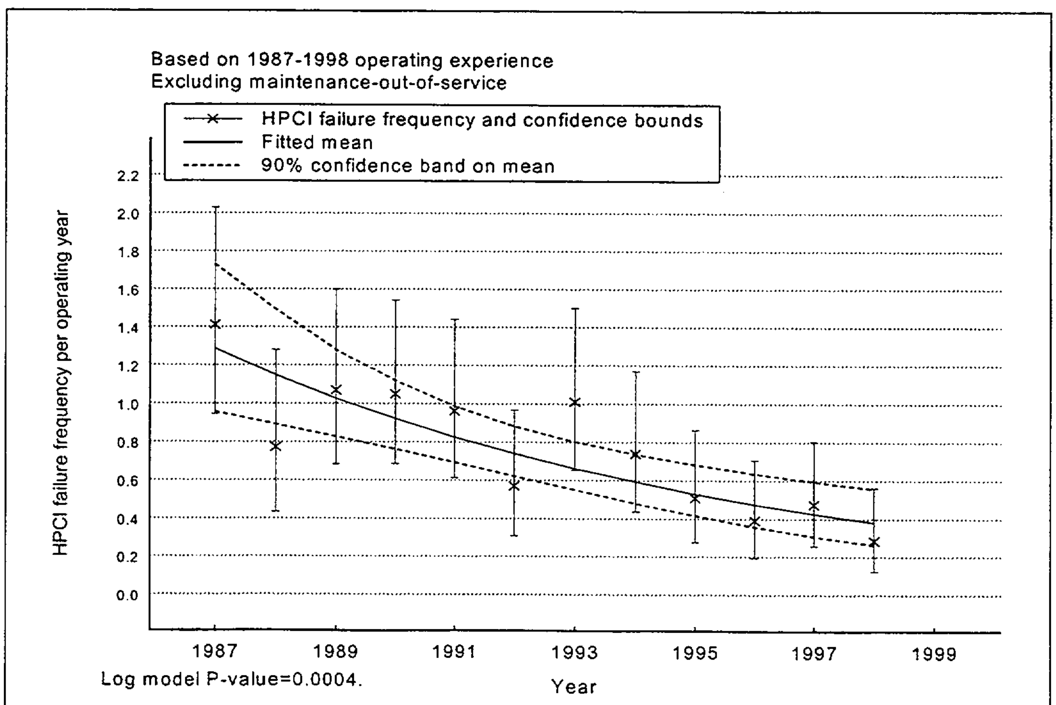


Figure 12. Frequency of HPCI system failures (1987–1998) observed by all detection methods when modeled as a function of calendar year. The decreasing trend is highly statistically significant.

4.2.2 Trends by Low-Power License Date–Unplanned Demand and Failure Frequencies

To determine if the age of the plant affects HPCI system performance, the plant-specific frequencies of unplanned demands and failures were plotted against the plant low-power license dates. Unplanned demands that invoked the injection valve were used in the analysis. The frequency for a plant is the total number of events (unplanned demands or failures) that occurred during the 1987–1998 period divided by the plant operating years. (See Table 1 for the operating years for each plant.) The trend plot of HPCI system unplanned demands by plant low-power license date is shown in Figure 13. The trend is not statistically significant (p-value = 0.87). The trend of HPCI system failures by low-power license date is shown in Figure 14. This trend is not statistically significant (p-value = 0.55).

A similar plot of failure frequencies was made previously using unreliability (Figure 7) with a limited set of failure data (i.e., failures with associated demand counts). The conclusion is the same for both plots. The trends are not statistically significant.

HPCI unplanned demand and failure frequency results, by plant low-power license date, are provided in Section B-3 in Appendix B.

4.2.3 Trends in Calendar Year and Age, Considered Together

The possibility of a trend with regard to both the age of a plant at the start of the study, and the calendar year, was considered for unplanned demand and failure frequencies. Trends in unplanned demands or failures when considering both the plant age and the calendar year are plausible: the calendar year reflects industry-wide culture and regulations, which have resulted in a decreasing rates of reactor

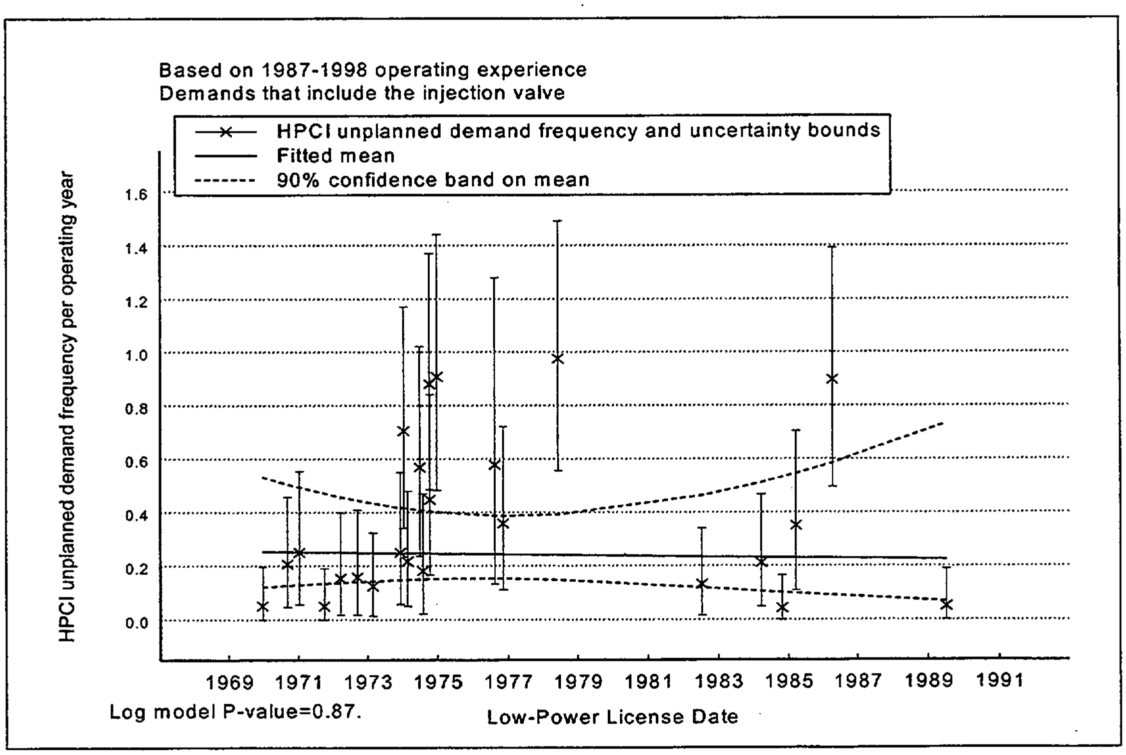


Figure 13. Frequency of unplanned demand of the HPCI system (1987–1998) as a function of low-power license date. The trend is not significant. Each point corresponds to a single plant and ignores the effect of calendar year for the plant.

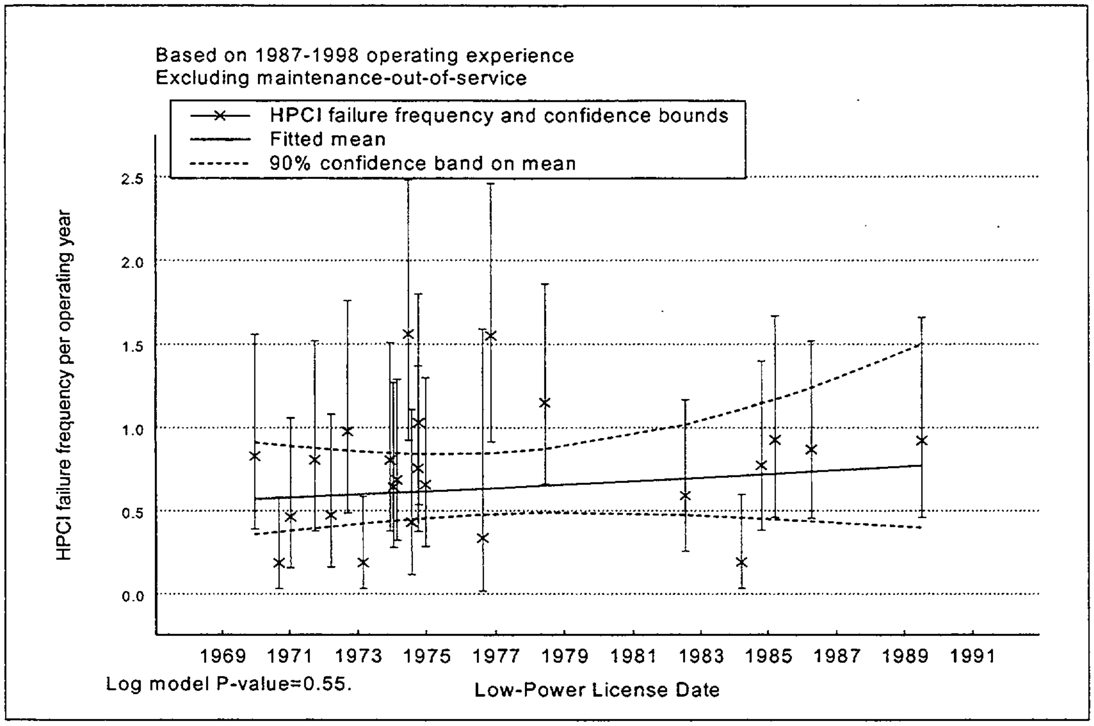


Figure 14. Frequency of HPCI system failure (1987–1998) as a function of low-power license date. The trend is not significant. Each point corresponds to a single plant and ignores the effect of calendar year for the plant.

trips; and plant age reflects the experience and learning at the particular plant. Because calendar year and plant age are closely related–a plant experiences increasing calendar year and increasing age together–the effects of the two variables were analyzed in a single model. The data were arranged in plant/year blocks, with a frequency for each (calendar year, low-power license date) combination for unplanned demands and failures. The data were evaluated using a log-linear model that seeks a trend in both calendar year and low-power license date.

Technical details of the analysis method are given in Reference 3 (Appendix A, Section A-4).

When the failure frequency was modeled as a function of both calendar year and low-power license year, the calendar year factor was statistically significant while the age factor was not significant (p-values of 0.0002 and 0.40, respectively). Similarly, when the unplanned demand frequency was modeled as a function of both calendar year and low-power license date, the calendar year factor was statistically significant while the age factor was not significant (p-values of 0.0001 and 0.85, respectively).

4.3 Factors Affecting HPCI Reliability

The HPCI system failures were reviewed several ways to identify the factors affecting overall system unreliability and the effectiveness of surveillance tests to detect these failures. The objectives of these reviews, to the extent that the failure data population will allow, are to:

- Identify the types of component failures (if any) that were major contributors to HPCI system unreliability;

- Identify insights from failures detected by other methods that were different from the failures found during unplanned demands and cyclic and quarterly surveillance tests required by the plant technical specifications;

- Identify the types of component failures that can not be detected by technical specification surveillance tests; and

- Identify common casual factors that contribute the most to HPCI system unreliability and HPCI system failure frequency.

The results of this analysis should identify the types of component failures that have the largest impact on the reliability of the HPCI system, which may suggest a focus where follow-up investigation is warranted.

Data used in this analysis. The forty-six system failures (data set C of the Venn diagram shown in Figure 10) used in the unreliability were reviewed for insights into the cause of failure, component failed, and the mode of failure on the HPCI system. In addition, the remaining 116 failures (identified as data set B, exclusive of data set C, shown in Figure 10) were used to assist in developing insights into the reliability performance of the HPCI system.

The reader is cautioned from making comparisons of the numbers provided in following tables with the number of failures used in the reliability analysis provided in Section 3. The tables include the contribution of support system failures (which were not used in the unreliability analysis) and exclude the contribution of maintenance-out-of-service (which was used in the unreliability analysis). In addition, failures in which an associated demand could not be determined or estimated were included in this engineering analysis.

4.3.1 Major Contributors to HPCI System Unreliability

Failure Recovery. Generally, the failure mechanisms affecting HPCI system unreliability were of a nature that the HPCI system could not easily be recovered from the control room since the effect of recovery on the unreliability estimate is small. Actual repair of the failed component is required to return the HPCI system to an operable condition.

The component failures that contribute the most to HPCI system unreliability are those associated with the dominant failure modes. Based on HPCI system unreliability for a short-term mission, failure of the injection valve to reopen for water level control and failure to start of the system other than the injection valve are the major failure modes of the HPCI system (see Figure 4 of Section 3.2.1), 33% and 26%, respectively. For mission times typically postulated in PRAs, failure to run of the system other than suction transfer and failure of the injection valve to reopen are the important contributors to HPCI system unreliability, 42% and 55%, respectively.

Failure of the injection valve. The ability of the injection valve to operate is important to HPCI system reliability regardless of whether the mission is short or long. Based on the information found in the LERs, the HPCI system is generally used for water level control during the onset of a transient requiring high-pressure injection. Once reactor-pressure-vessel water level is recovered, the HPCI system is generally returned to standby status as long as other means are available to maintain reactor-pressure-vessel water level. (Typically these systems are either reactor core isolation cooling system, reactor feed pumps, and control rod drive pumps.) If these systems are not available or unable to maintain water level in the reactor pressure vessel, the HPCI is maintained operational during the transient. During this situation, the injection valve is cycled for water level control. The failure of the injection valve to operate during the course of plant recovery is important if other high-pressure systems are unavailable to provide makeup water to the vessel.

Although this valve is tested quarterly, the injection valves failures that occurred during the unplanned demands are important since the quarterly testing of this valve is done in an environment that does not produce the same stresses on the valve that the valve would encounter in an accident environment. In addition, the injection valve is not cycled repeatedly during the quarterly test. The quarterly test of the injection valve is a stroke-test of the valve under a no-load condition on the motor operator. But under actual operating environment and during the initial stages of a transient, the HPCI pump delivers 5000gpm at 1100 psig in response to a demand for high-pressure injection. The injection valve is required to operate against a significantly higher differential pressure across the valve than during quarterly testing. The injection valve failures identified in the unplanned data were the result of thermal overload of the motor operator resulting from repeated use of the injection valve. The two injection valve failures to reopen that occurred during an unplanned demand are:

- During a reactor trip with MSIV isolation, the HPCI system responded successfully. However, on a subsequent start of the HPCI system for water level control, the injection isolation valve, 2-E41-F006 was closed and the system left running in the full-flow test (pressure control mode of operation). When the HPCI system was used later for water level control (approximately a half-hour of pressure control), the injection valve would not open. The cause of the valve failure was attributed to possible heat-related breakdown of the motor-operator internals. (LER 324/89-001)

- During a reactor trip with MSIV isolation, the HPCI system automatically initiated and injected on low reactor water level as required. Following water level recovery, HPCI injection valve 2E41-F006 closed automatically on high water level; however, it could not be re-opened when personnel subsequently attempted to start HPCI manually. The cause of the valve failure was due to the failure of the heater strip of the thermal overload relay in the valve motor's local starter causing an open circuit to the motor operator. (LER 366/90-001)

From a risk-based perspective, this failure mode is less important for a medium-break LOCA as compared to the small LOCA. For a medium LOCA, the HPCI system would be injecting water continuously into the reactor pressure vessel until low-pressure injection systems responded. However, for the smaller LOCA, HPCI will be required to maintain and control water level for a much longer period of time. Generally, when shutdown cooling can be initiated. During the time frame from the onset of the small LOCA until shutdown cooling can begin, the importance of the failure mode is much higher.

Based on the limited unplanned demand (79 demands), there is a 0.6% probability of the injection valve failing to initially open compared to 20 % probability that the injection valve will fail to reopen if needed later during plant recovery. Although there were no failures of the injection valve to initially open observed in the relatively small unplanned demand dataset, the importance of the injection valve to open initially may change as additional data is gathered. This is supported by the three injection valve failures observed during periodic surveillance testing of the injection valve. Two of these failures occurred during quarterly testing while the other was observed during a monthly test. Thermal overloading of the injection valve motor operator was the characteristic of one of these failures found during surveillance; similar to those found during the unplanned demands. The three failures are summarized below.

- Operations discovered the problem during the performance of a monthly surveillance procedure. The operators closed the valve remotely from the main control room and received a valve operator motor electrical overload alarm. Upon investigation the valve operator motor was found hot to the touch, the valve's breaker was found tripped open, and there was a burnt smell in the vicinity. The motor operator torque switch drive pinion gear roll pin had failed due to the pin design. Suspected causes contributing to the roll pin failure include hardened grease in the motor operator spring pack and the magnitude of the forces on the valve starting and stopping transients. Either cause could result in higher force on the roll pin. The valve is currently maintained open with a temporary modification to allow the HPCI System to be made operable. Corrective action planned includes installation of a torque switch with an improved design and a new spring pack resistant to grease buildup into the valve. (LER 293/94-002)

- The HPCI pump discharge inboard isolation valve (E4150-F006) failed to open. A dc ground existed in the valve limit switch compartment. A limit switch compartment spare space heater assembly was in contact with the opening contact of the valve torque switch. The ground was cleared by the removal of the space heater assembly. An investigation determined that the valve limit switch compartment spare space heater assembly bracket was grounding out the positive dc control voltage at the valve torque switch. This ground plus a pre-existing neutral ground on the Division II battery system provided a resistive short around the opening contactor coil of the motor operated valve. The space heater assemblies are only required for moisture protection when the valve operators are being stored or the valve is located outdoors. Heaters are non-functional and not required for valves located within the plant. As corrective action, a design change was issued to remove the spare heater assemblies from the affected valve and nine other valves. (LER 341/88-028)

- The HPCI system pump discharge valve (E4150-F006) failed to open when the open push-button was depressed as part of a routine surveillance test. The plant was shutdown at the time and HPCI was not required to be operable. The Limitorque valve motor was inspected. The pinion gear on the motor shaft was found to be loose. It had slipped axially along the shaft causing it to disengage from the drive gear. The set-screw was not holding the pinion gear to the shaft although the set-screw was properly secured with lock-wire. The cause of the event was determined to be a failure of the pinion gear set-screw. The vendor, Limitorque, was aware of similar failures and in 1989 issued a Maintenance Letter addressing the motor pinion gear installation. This letter includes a recommendation that the motor shaft be spot drilled to ensure an adequate set of the set-screw. (LER 341/97-002)

Failure to start, other than injection valve. For failure of the system to start other than the injection valve (failure mode FTSI), although there was only one FTSI failure observed during an unplanned demand, twenty-seven failures detected during either cyclic or quarterly testing were used for estimating HPCI system unreliability. The single failure that occurred during the unplanned demand resulted from a failed HPCI speed controller (I&C related) that caused erratic behavior in the automatic mode. This failure was recovered by manually controlling the HPCI system operation. I&C-related failures were the dominant component group observed in the cyclic and quarterly surveillance tests. This group of failures accounted for about 40% of the FTSI failure probability used in calculating the unreliability of the HPCI system. Failures associated either steam supply MOVs and the hydraulic turbine stop valve attributed 29% of the FTSI failure probability. Failures associated with either the turbine lube oil or hydraulic oil accounted for 18% of the FTSI failure probability.

Failure to run, other than suction transfer. Failure to run of the injection system (FTRI) represented about 10% of the HPCI system unreliability. Two of the thirteen failures used in FTRI failure probability occurred during an unplanned demand. One of the unplanned demand failures resulted from a low-pressure suction trip due to air trapped in the instrument line. The second failure to run was due to an oil leak associated with the turbine oil filter. For the remaining failures that occurred during cyclic or quarterly testing, I&C-related failures contributed to 54% of the FTRI failure probability. Various types of mechanical problems associated with the turbine or turbine control resulted in 23% of the FTRI failure probability.

Failure to run, suction transfer. Generally, suction transfer from the condensate storage tank to the suppression pool (FTRT) is not an issue for general transients where plant recovery is relatively short. However, for the more risk-significant transients that require the plant to be shutdown and cooled-down, the reliability of the suction transfer of HPCI system is an important factor. No failures of the suction transfer were seen in the unplanned demand data associated with suction transfer. Only six demands were identified in the unplanned demands where suction transfer occurred. These demands were the result of spurious opening of the suppression pool suction valve. The data is too sparse to make any conclusions about this failure mode during actual demands. There were two failures identified in the cyclic and quarterly test data. These failures were identified in 1988 and at the same plant. No other failures have been identified since that time. Since very few failures have been identified in the data, the effect of suction transfer on the ability of the HPCI system to operate for a long-term mission is negligible. There is about a 0.25 % probability of the suction transfer failure.

4.3.2 Contribution of Failures Detected by Other Methods (other than unplanned demands and cyclic/quarterly tests)

Failures that occurred during an unplanned demand or detected by cyclic/quarterly testing accounted for approximately 31% of the total number of failures identified during the LER review. These failures were used in the unreliability estimate since the number of HPCI system demands associated with these failures could be either counted directly or estimated from the surveillance frequencies. However, the remaining 116 failures could not be not used in the unreliability estimates since there either was no way to estimate a demand (success) count for these failures. These failures provide an additional source of failure information and were reviewed for additional insights and to assess their effect on HPCI system unreliability. An engineering review was performed of information relating to the detection method of the failures identified in the 1987–1998 operating experience. The detection method is the activity that was ongoing at the time of the failure. The detection method categories include:

- Unplanned demands—actual and inadvertent;
- Technical specification surveillance tests—cyclic and quarterly;
- Other system and component tests—weekly, monthly, post-maintenance tests, I&C functional checks, etc.;
- Inspections—walkdowns, casual observations, reviews, NRC inspections, maintenance inspections, etc.; and
- Immediate indication—local and control room annunciators/alarms/indications, component leaks, spurious containment isolations, personnel errors that were recognized during damage.

Table 4 provides a summary classification of all 161 failures (excludes maintenance-out-of-service) by detection method, HPCI subsystem, and component. Details of the events summarized in Table 4 are provided in Table A-2 of Appendix A. The engineering analysis presented below is based on the information presented in Table 4.

Table 4. HPCI system failures (1987–1998) partitioned by detection method and by subsystem and component category.[a]

Subsystem/Component	Unplanned Demand	TS Tests-Cyclic and Quarterly	Other Tests	Immediate Indications	Inspections	Total
Electrical ac & dc distribution						
Battery Charger				2		2
Inverter				9	3	12
Misc, Elect - wires, connections, terminal blocks, fuses				1		1
Motor Control Center			2	1		3
Relay, Other				1		1
Subtotal			2	14	3	19
HVAC						
Air Handling Unit (Room Cooler)					1	1
Injection (Discharge segments)						
Transmitter (includes sensors & switches)					1	1
Valve, Motor Operated	2	2	2		1	7
Subtotal	2	2	2		3	9
Injection (Suction segments)						
Transmitter (includes sensors & switches)	1		1			2
Pipe, gaskets, fittings, flanges		1				1
Valve, Motor Operated		2				2
Subtotal	1	3	1			5
Instrumentation & Control						
Controller, I&C		6	1	2	2	11
Misc, Elect - wires, connections, terminal blocks, fuses				3		3
Misc, I&C		1	3	13		17
Relay, Other				3		3
Transmitter (includes sensors & switches)				2	1	3
Unknown		1		1		2
Subtotal		8	4	24	3	39
Lube/Hydraulic Oil						
Misc, Mechanical	1		2			3
Motor			2			2
Motor Control Center				3		3
Pipe, gaskets, fittings, flanges				1		1
Pump		1				1
Process filter (mechanical)			1			1
Transmitter (inc. sensors & switches)		1	1			2

Table 4. (continued).

Subsystem/Component	Unplanned Demand	TS Tests-Cyclic and Quarterly	Other Tests	Immediate Indications	Inspections	Total
Valve, Air Operated					1	1
Valve, Relief		1				1
Subtotal	1	3	6	4	1	15
Pump w/o driver, includes booster						
Misc, Mechanical		1				1
Pump					2	2
Subtotal		1			2	3
Steam supply to turbine						
Misc, I&C		2				2
Pipe, gaskets, fittings, flanges		1		1		2
Transmitter (inc. sensors & switches)		2	3	3		8
Valve, Motor Operated		5	8	4	1	18
Subtotal		10	11	8	1	30
Turbine and turbine control						
Controller, I&C	1		1			2
Governor		4	3		1	8
Misc, Elect - wires, connections, terminal blocks, fuses		1				1
Misc, I&C		2				2
Misc, Mechanical		5		1		6
Pipe, gaskets, fittings, flanges			1			1
Turbine		1	1			2
Valve, Hydraulic Operated		5	3	1	2	11
Subtotal	1	18	9	2	3	33
Turbine Exhaust and Drains						
Misc, Mechanical			1			1
Pipe, gaskets, fittings, flanges				2	1	3
Vacuum Breaker			1			1
Valve, Air Operated				1	1	2
Valve, Check		1				1
Subtotal		1	2	3	2	8
Total	5	45	38	55	18	161

a. The reader is cautioned from making comparisons of the numbers provided in this table with the number of failures used in the unreliability analysis provided in Section 3. This table includes the contribution all failures resulting from unplanned demands, surveillance tests, and other means of detection. The failure data presented excludes maintenance-out-of-service.

Detection Method. Figure 15 is a bar chart comparison of the percent contribution of HPCI system failures by detection method. Overall, testing of various types and frequencies was the most effective method in detecting failures. Testing identified about half of the HPCI system failures. Although quarterly and cycling testing resulted in 28% of the HPCI system failures, approximately 24% of the HPCI system failures were discovered by other routine tests and checks (e.g., weekly and monthly tests, post maintenance tests, etc.).

Failures that are immediately indicated resulted in identifying about a third of all the HPCI system failures. Excluding the failures used in the unreliability estimates (unplanned demand failures, and quarterly and cyclic test failures), about 47% of the remaining 116 failures are immediately detected. That is, there are self-annunciated by alarms and visual indications where plant personnel can respond to the failure immediately. Since these failures are detected immediately, their affect on the plant risk is small since the failed system is declared inoperable and other safety systems are checked for operability. The failed system is then repaired and returned to operable status. A review of the information presented in Table 4 reveals that two major groups of components accounted for approximately 64% of the immediately detected failures. They are:

- Failures of instrument and control (I&C) components (e.g., transmitters, logic and control circuitry, turbine governor control) from all subsystems are immediately indicated; they account for about 49% of immediately-indicated failures and 42% of all I&C-related failures found by all detection methods.
- Failures associated with power supplies (e.g., inverters, motor control centers, battery chargers) from all subsystems account for about 31% of immediately-indicated failures and 77% of all power-supply related failures found by all detection methods.

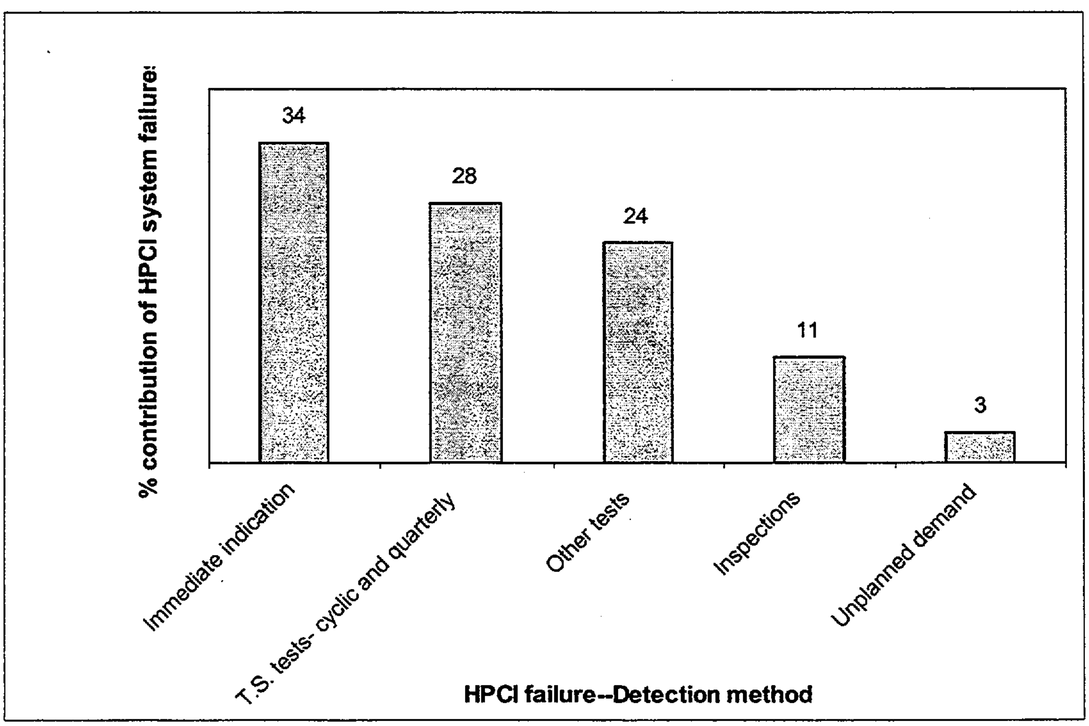


Figure 15. Bar chart comparison of the percentage contribution of HPCI system failures by detection method (1987–1998).

Inspections identified the least number of the HPCI system failures other than during an unplanned demand. Although this detection method may not be as effective in failure detection as testing, several of the failures found during inspections may not have been detected through surveillance testing. Since, testing generally only provides a short-term time interval to examine for failures, time-dependent failures may require a longer time to reveal themselves. Three of the inspection failures may not have been discovered during routine tests. These three failures would affect the long-term mission reliability of the HPCI system. The failures are briefly described below:

- The lube oil cooler pressure control valve failed to re-open after the HPCI turbine had been tripped following a routine surveillance test. Approximately three minutes after the turbine was tripped, the valve should have opened as the downstream cooling water pressure decreased. However, due to a controller malfunction, control air was still applied to the valve causing the valve to remain closed. An inspection of the valve air controller revealed a disconnected elastometric tube. (LER 298/94-007)

- A HPCI system room cooler was found not be operable due to broken drive belts. (LER 237/87-018)

- Maintenance personnel were performing a routine inspection when they discovered a damaged outboard mechanical seal of the HPCI system main pump. The spit ring retainer was displaced against the main pump journal bearing deflector, one of the two split rings had fallen into the pump drain casing, and the flange bushing was broken in several pieces. Some of these broken pieces also fell into the drain casing. Maintenance personnel observed no water leaking from the damaged mechanical seal. (LER 366/97-008)

4.3.3 Contribution of HPCI System Failures by Component and by Cause

- ***Component failures.*** In order to glean additional insights from the HPCI system failures, the components identified in Table 4 were classified into pedigree component groups. The groupings include specific HPCI motor- and hydraulic-operated valves as well as other valve failures (relief, air-operated, etc.); instrumentation and control circuitry (i.e., transmitters); all electrical and I&C failures related to the turbine governor and control; other instrumentation and control components/control circuitry (i.e., switches, electronic boards, etc.); power supplies (batteries, chargers, inverters, and motor control centers); HPCI pump exclusive of the driver; and HPCI turbine and control (mechanical). Table 5 provides the component grouping of the component failures that is provided in Table 4. A bar chart comparison of the percent contribution of failures in the major component groups and detection method is provided in Figure 16.

A review of the data presented in Table 5 and Figure 16 reveal:

- Two component groups contributed about 61% of the HPCI system failures: I&C-related components and valves, 35% and 26%, respectively.

The motor-operated valve failures contributed to 64% of all the valve failures identified in the HPCI system failures with two-thirds of the these failures involving the HPCI steam supply isolation. Approximately, twenty-five percent of these failures occurred in the 1994–1998 period suggesting an improvement in the failure frequency associated with these types of valves.

- About twenty percent of the I&C-related failures occurred in the 1994–1998 period suggesting an improvement in the failure frequency associated with this type of component.

Table 5. HPCI system failures (1987–1998) partitioned by detection method and by subsystem and component group.[a]

Component Group	Unplanned Demand	TS Tests-Cyclic and Quarterly	Other Tests	Immediate Indication	Inspections	Total
Valves						
Suppression pool suction		2				2
Turbine stop valve		5	3	1	2	11
Injection MOV	2	2	2		1	7
Steam supply MOV		5	8	4	1	18
Other valves		1	1	1	1	4
Subtotal	2	15	14	6	5	42
Electrical/I&C						
Transmitter	1	2	4	5	2	14
Turbine governor/control	1	7	4		1	13
Other logic/control circuits		9	4	15	2	30
Power supplies/MCC			2	15	3	20
Subtotals	2	18	14	35	8	77
Turbine/turbine control (mechanical)		6	2	1		9
HPCI pump					2	2
Lube/Hydraulic Oil	1	3	6	1	1	12
HVAC					1	1
Others		3	2	12	1	18
Total	5	45	38	55	18	161

a. The reader is cautioned from making comparisons of the numbers provided in this table with the number of failures used in the unreliability analysis provided in Section 3. This table includes the contribution all failures resulting from unplanned demands, surveillance tests, and other means of detection. The failure data presented excludes maintenance-out-of-service.

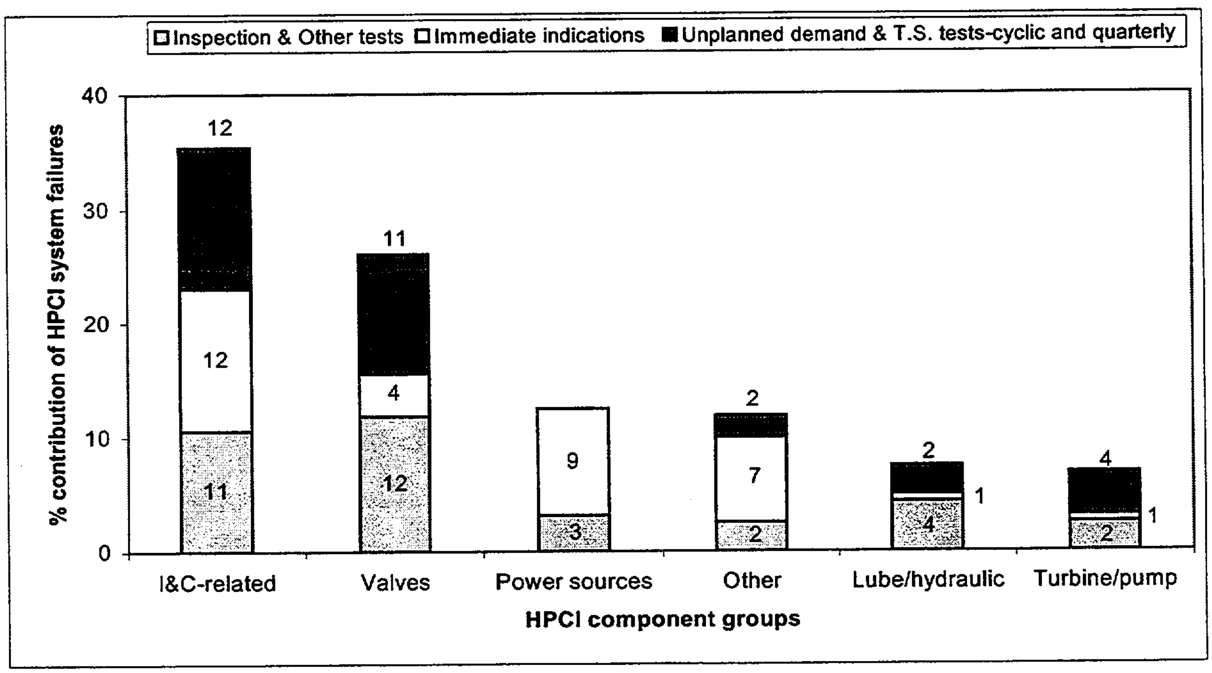


Figure 16. Bar chart comparison of the percentage contribution of HPCI system failures (1987–1998) by detection method and component groups. (*TS Tests*–cyclic and quarterly technical specification surveillance tests; *I&C-related*–all instrumentation and control components throughout the HPCI system; *power sources*–inverters, motor control center, battery chargers, etc.; *oil systems*–lubrication and hydraulic oil systems; *turbine/pump*–turbine, main and booster pumps mechanical components.)

Failure causes. Each failure event was reviewed in an engineering perspective to determine the cause of the HPCI system failure. The cause classification was based on the immediate cause of the failure and not a cause that may be determined through a root cause analysis of the failure that was provided in the LER. Specifically, the mechanism that actually resulted in the segment or component failing to function as designed was captured as the cause. This methodology precluded categorization of many of the failures as a "Management Deficiency" or simply a "Personnel Error," which many of the LERs identified as the cause. The cause codes includes design error, contamination, hardware failure (e.g., aging, wear, manufacturing defects), personnel error, and procedure error.

Table 6 provides a breakdown of HPCI system failures by detection method and failure cause category. Table A-2 of Appendix A provides the details that were used to develop Table 6. A review of the data in Tables 6 and A-2 reveal:

- Seven out of ten failures of the HPCI system observed in the 1987–1998 experience were attributed to hardware-related problems. The decrease in hardware-related failures with time is about in proportion to the decrease in the overall failure frequency.

- Personnel error caused 17% of the HPCI system failures. However, 70% of these failures were immediately identified, meaning that plant personnel were able to respond to the failure immediately. The personnel-related failures appear to be uniformly distributed over the 12-year period indicating that no trend of human performance can be discerned in these failures over time.

- The remaining failure causes (procedure, design, and contamination) identified in the 1987–1998 experience had too few failures to provide meaningful insights.

Failure mode. Table 7 provides a breakdown of the HPCI system failures by detection method and failure mode. Overall, failure to start is the leading mode of failure of the HPCI system. Approximately 80% of all HPCI system failures were attributed to the HPCI system failing to start. Actual testing of the HPCI system detected about half while the other half were identified by either inspections or immediate indications (e.g., alarms, etc.)

Table 6. HPCI system failures (1987–1998) partitioned by detection method and failure cause.[a]

	Failure Cause					
Detection Method	Design	Contamination	Hardware	Personnel	Procedure	Total
Unplanned Demand	—	—	5	—	—	5
T.S. tests- cyclic and quarterly	3	1	35	1	5	45
Other tests	3	1	28	3	3	38
Immediate indication	2	—	32	19	2	55
Inspections	—	1	13	4	—	18
Total	8	3	113	27	10	161

a. HPCI system failures identified from unplanned demands and cyclic and quarterly technical specification surveillance tests were used in the unreliability analysis (with the exception of FTSV) in Section 3. The counts do not include maintenance-out-of-service failures.

Twenty percent of the HPCI system failures resulted in the HPCI failing to run or affected its ability to run, if needed. Actual testing of the HPCI system detected 70% of the HPCI system ability to run once it has started. The remaining failures to run were observed by inspection or immediate indications.

Table 8 provides a comparison of the failures used in the unreliability calculation to the failures that were not used in the calculation. The components listed in Table 4 were classified into pedigree component groups that combine generic piece-parts listed in Table 4 into particular components and subsystems. The failure counts contained in Table 8 *exclude* failures that were classified as "immediate indication." The immediate-indicated failures were excluded since these failures are self-annunciated by alarms and visual indications where plant personnel can respond to the failure immediately. The failures presented in Table 8 either result in the reliability or availability of the HPCI system being lowered since the failures remain undetected for a longer period of time.

Further, when comparing the "Unreliability" column to the "Others" column provides a comparison of the types of component failures that are being detected during routine testing and inspections to the component failures detected during an unplanned demand or cyclic and quarterly testing. Figure 17 is a comparison of the failure to start and failure to run failures provided in Table 8. A review of the data in Table 8 and Figure 17 reveal:

- The percentage of I&C-related failures (e.g., transmitters, logic and control circuitry, turbine governor control) from all subsystems that occur during an unplanned demand, or quarterly and cyclic surveillance testing is approximately the same as those being discovered through inspection or other routine testing, about 30% to 40%. This generalization applies to both failure modes (failure to start and failure to run).

- The comparison of valve failures between the two detection method groups and failure modes yield:

Table 7. HPCI system failures (1987–1998) partitioned by detection method and failure mode.[a]

	Detection Method					
Failure mode	Unplanned Demand	T.S. tests- cyclic and quarterly	Other tests	Immediate indication	Inspections	Total
Failure to start, other than injection valve (FTSI)	1	30	29	49	14	123
Failure to start, injection valve (FTSV)	—	2	2	—	—	4
Failure to run, other than suction transfer (FTRI)	2	11	7	6	4	30
Failure to run, suction transfer (FTRT)	—	2	—	—	—	2
Failure to reopen, injection valve (FRO)	2	—	—	—	—	2
Total	5	45	38	55	18	161

a. HPCI system failures identified from unplanned demands and cyclic and quarterly technical specification surveillance tests were used in the unreliability analysis (with the exception of FTSV) in Section 3. The counts do not include maintenance-out-of-service failures.

Table 8. Component group comparison of the failures used in the unreliability estimate to failures that are not immediately detected.

COMPONENTS/GROUPS		All Failures				FTS				FTR			
		Unreliability[a,c]		Others[b,c]		Unreliability[a,c]		Others[b,c]		Unreliability[a,c]		Others[b,c]	
		#	% ↑	#	% ↑	#	% ↑	#	% ↑	#	% ↑	#	% ↑
VALVES													
Suppression Pool Suction MOV		2	4	–	–	–	–	–	–	2	13	–	–
Turbine Stop Valve		5	11	5	8	3	10	5	10	2	13	–	–
Injection MOV		2[d]	4	5	8	–	–	4	8	2	13	1	8
Steam supply MOV		5	11	9	15	5	17	9	19	–	–		–
Other valves		–	–	3	5	–	–	2	4	–	–	1	8
	Subtotal	14	31	22	36	8	27	20	42	6	40	2	15
ELECTRICAL/I&C													
Transmitters		3	7	6	10	2	7	5	10	1	7	1	8
Turbine governor/control		7	15	5	8	7	23	3	6	–	–	2	15
Other logic/control circuitry		8	18	9	15	3	10	8	17	5	33	1	8
Power supplies/MCC		–	–	5	8	–	–	5	10	–	–	–	–
	Subtotal	18	40	25	41	12	40	21	44	6	40	4	31
Turbine/Turbine Control (mechanical)		6	13	2	3	4	13	–	–	2	13	2	15
HPCI Pump		–	2	2	3	–	–	2	4	–	7	–	–
Lube/Hydraulic Oil Systems		4	9	7	11	4	13	5	10	–	–	2	15
HVAC		–	–	1	2	–	–	–	–	–	–	1	8
Others/Piping		3	7	2	3	2	7	–	–	1	7	2	15
	Totals	45		61		30		48		15		13	

a. Unreliability" columns include failures that were detected during unplanned demands, and cyclic and quarterly technical specifications surveillance tests.
b. ""Others" columns include failures that were detected by other tests and inspections, and *EXCLUDES* immediate indication failures.
c. "% ↑" represents the percent contribution of failure counts in that column.
d. Excludes the quarterly test from the injection valve counts.

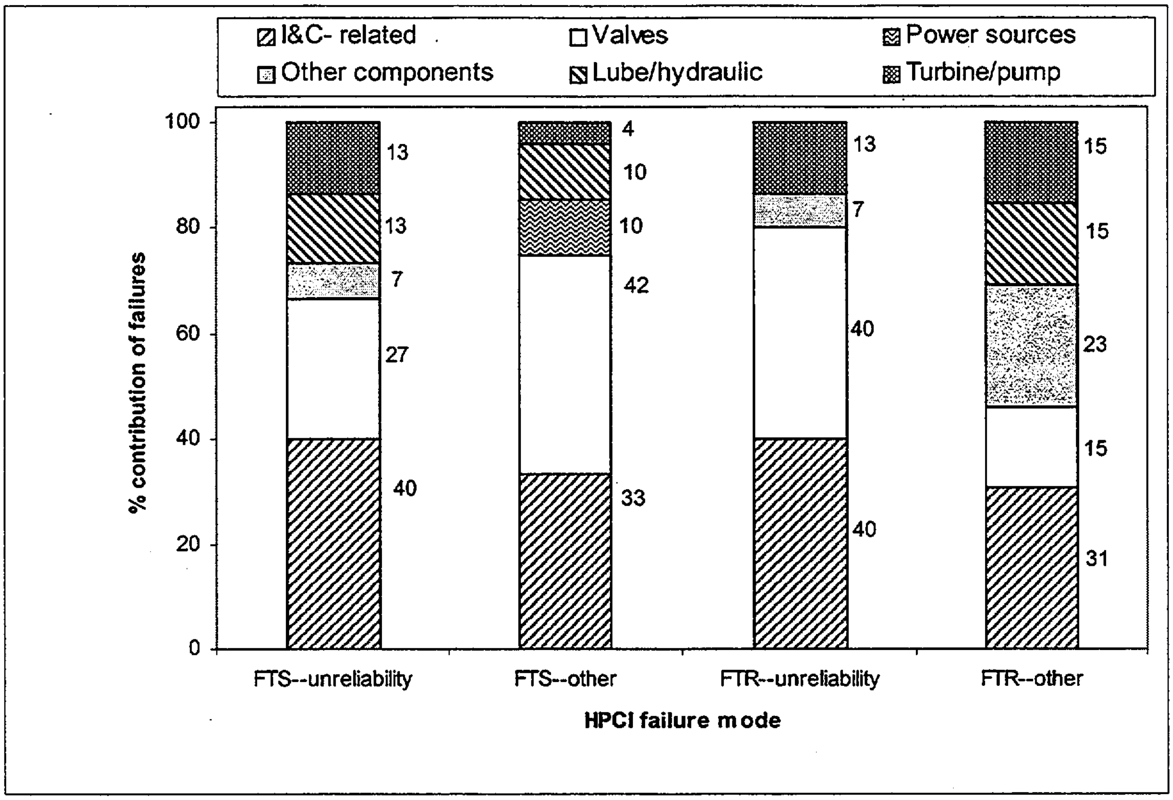


Figure 17. Bar chart comparison of the percentage contribution of HPCI system failures (1987-1998) in failure mode groups. Each bar represents the percent contribution of component group failures in the failure mode group (e.g., FTS-Unreliability). See Table 8 for failure counts. *(Unreliability* data includes failures detected during unplanned demands, and cyclic and quarterly technical specification surveillance tests. *Other* data includes failures detected during inspections and other tests, but excludes failures that were immediate indications.)

- For the failure to start, the percentage of valve-related failures that occur during an unplanned demand, or quarterly and cyclic surveillance testing is slightly lower that those being discovered through inspection or other routine testing; 27% and 42%, respectively.

- For failure to run, the valve failures are more likely to be detected during unplanned demand, or quarterly and cyclic surveillance testing than through routine testing or inspections; 40% and 15%, respectively.

- No lube/hydraulic related failures occurred during an unplanned demand or quarterly and cyclic surveillance testing. Lube/hydraulic oil related failures are being detected more through inspections and routine testing for the failure to run category than occur during an unplanned demand or quarterly and cyclic testing. A possible reason for this is that these types of failures are time dependent and do not appear during the short-term operation of the HPCI system during quarterly and cyclic testing. However, since these data are sparse, no defensible argument can be made.

- Failures associated with the turbine and turbine control/pump component group are not as likely to be detected during inspections and routine testing for the failure to start mode.

Most of these types of failures have been discovered during an unplanned demand or through quarterly and cyclic testing.

4.4 Comparisons to Regulatory Issues

The review of NRC regulatory initiatives related to the HPCI system operations included generic safety issues and generic communications, such as Generic Letters, Bulletins, and Information Notices. This review found no generic safety issues relating to the HPCI system performance; however, several generic communications were identified. Table 9 lists these generic communications.

The events from the operating experience that resulted in the issuance of these generic communications are summarized in the following sections. In addition, a companions of the generic issues with the 1987–1998 operating experience is also presented.

4.4.1 Generic Safety Issues

No generic safety issues that were currently open or previously closed were identified in NUREG-0933, *A Prioritization of Generic Safety Issues*, (Ref. 2) that involved the HPCI system.

Table 9. Generic communications issued by NRC pertaining to HPCI system.

Generic Communications	Title
NRC Bulletins (1971-1998)	
Bulletin 93-02	Debris Plugging of Emergency Core Cooling Suction Strainers
Bulletin 95-02	Unexpected Clogging of Residual Heat Removal Pump Strainer While Operating in Suppression Pool Cooling Mode
Bulletin 96-03	Potential Plugging of Emergency Core Cooling Suction Strainers By Debris in Boiling-Water Reactors
NRC Generic Letters (1986-1998)	
GL 95-07	Pressure Locking and Thermal Binding of Safety-Related Power-Operated Gate Valves
NRC Information Notices (1986-1998)	
IN 86-14 (Supp.1)	Overspeed Trips of AFW, HPCI, and RCIC Turbines (summarizes the results of an NRC case study "Operational Experience Involving Turbine Overspeed Trips," AEOD/C602)
IN 86-14 (Supp.2)	Overspeed Trips of AFW, HPCI, and RCIC Turbines
IN 88-67	PWR Auxiliary Feedwater Pump Turbine Overspeed Trip Failure
IN 90-76	Failure of Turbine Overspeed Trip Mechanism Because of Inadequate Spring Tension
IN 94-66	Overspeed of Turbine-Driven Pumps Caused by Governor Valve Stem Binding
IN 94-84	Air Entrainment in Terry Turbine Lubrication System
IN 96-08	Thermally Induced Pressure Locking of a High-Pressure Coolant Injection Gate Valves
IN 97-16	Preconditioning of plant Structures, Systems, and Components Before ASME Code Inservice Testing or technical Specification Surveillance Testing

4.4.2 Generic Communications

Generic communications issued by the NRC were reviewed for applicability to the HPCI system. These communications include bulletins, generic letters, and information notices. The review includes NRC bulletins issued since 1972 and information notices and generic letters issued since 1986.

The generic communications identified actual and potential failures involving the HPCI system. The information relating the to HPCI system were related to problems with the turbine overspeed trip mechanism, plugging of pump suction strainers due to debris in the suppression pool, and pressure locking and thermal binding of pump discharge gate valves.

Turbine overspeed trip failures. Several NRC information notices were issued during the first half of the 1987–1998 time period. The turbine overspeed trip failures discussed in these notices occurred in HPCI, reactor core isolation cooling, and auxiliary feedwater turbine in pressurized water reactors. Similar overspeed trip mechanisms are employed on the turbines to these three systems.

An NRC case study, AEOD/C602, *Operational Experience Involving Turbine Overspeed Trips*, (Ref. 4) identified 128 turbine overspeed trip events (20 involving the HPCI turbine) in the 14 year period from 1972 to 1985. A recent reliability study (in draft), NUREG-XXXX, Vol. 1, *Component Performance Study—Turbine-Driven Pumps, 1987–1998*, (Ref. 5), reports only one turbine overspeed trip to a safety-related injection system (HPCI, RCIC, AFW) in the 1987–1998 operating experience. The report indicated that the 1990 event (LER: 278/90-010) was related to the overspeed trip failure described in NRC Information Notice 88-67, *PWR Auxiliary Feedwater Pump Turbine Overspeed Trip Failure* (Ref. 6). This type of failure is no longer a contributor to HPCI system unreliability.

Debris Plugging of ECCS Suction Strainers. Three NRC bulletins were issued that involved the issue of debris plugging of emergency core cooling system (ECCS) suction strainers. NRC Bulletin 93-02, *Debris Plugging of Emergency Core Cooling Suction Strainers*, (Reference 7) was issued in 1993 to request plants to remove fibrous air filters and other temporary sources of fibrous material, not designed to withstand a loss-of-coolant accident (LOCA), from the containment.

In 1995, Limerick Unit 1 experienced a spurious open and stuck open safety relief valve during full power operations. Approximately 30 minutes after the initiation of suppression pool cooling, fluctuating motor current and flow were observed on the "A" loop believed to be caused by cavitation. This loop was secured. The "B" loop remained running. After the cooldown, both suction strainers in the "A" loop of were found to be almost entirely covered with a thin "mat" of material, consisting mostly of fibers and sludge. The "B" loop suction strainers had a similar covering, but less of it. In response to this event, NRC Bulletin 95-02, *Unexpected Clogging of Residual Heat Removal Pump Strainer While Operating in Suppression Pool Cooling Mode*, (Reference 8) was issued in 1995 to request plants, among other requirements, to establish a pool cleaning program and review their foreign material exclusion practices and correct any identified weaknesses.

The results of a NRC study, documented in NUREG/CR-6224 (Reference 9), demonstrate that for the study reference plant, there is a high probability that the available NPSH margin for the ECCS pumps will be inadequate following dislodging of insulation and other debris caused by a LOCA and transport of the debris to the suction strainers. In addition, the study calculated that the loss of NPSH could occur quickly (less than 10 minutes into the event). The study also demonstrated that determining the adequacy of NPSH margin for an ECCS system is highly plant-specific because of the large variations in such plant characteristics as containment type, ECCS flow rates, insulation types, plant layout, plant cleanliness, and available NPSH margin. As a result of this study, NRC Bulletin 96-03, *Potential Plugging of Emergency Core Cooling Suction Strainers By Debris in Boiling-Water Reactors*, (Reference 10) was issued in 1996 to request plants to implement appropriate procedural measures and plant modification to minimize the potential for clogging of ECCS suppression pool suction strainers by debris generated during a LOCA.

Pressure Locking and Thermal Binding of Valves. On August 17, 1995, the NRC issued Generic Letter (GL) 95-07, *Pressure Locking and Thermal Binding of Safety-Related Power-Operated Gate Valves* (Reference 11), to request that licensees take actions to ensure that safety-related power-operated gate valves that are susceptible to pressure locking or thermal binding are capable of performing their safety functions within the current licensing bases of the facility. GL 95-07 stated that pressure locking occurs in flexible-wedge and double-disk gate valves when fluid becomes pressurized within the valve bonnet and the actuator is not capable of overcoming the additional thrust required because of the differential pressure created across both valve disks.

NRC Information Notice 96-08, *Thermally Induced Pressure Locking of a High Pressure Coolant Injection Gate Valve* (Reference 12) was issued in 1996 to alert addressees to a loss of operational capability and the recently discovered damage to the internal components of a safety-related power-operated gate valve, both apparently caused by thermally induced pressure locking. On November 11, 1995, Susquehanna Steam Electric Station , Unit 1, was shut down to repair the main generator. During this forced outage, a bent retaining ring in the Unit 1 HPCI valve was discovered while performing a modification to eliminate susceptibility to pressure locking. This Anchor Darling 14-inch flexible-wedge motor-operated pressure seal gate valve is installed in the discharge line from the HPCI pump. The valve is located about three pipe diameters from the connection to the feedwater system piping, which the licensee believes is the source of heat that caused thermally induced pressure locking and the bent retaining ring.

No other generic communications related to the operability of the HPCI system was found.

5. REFERENCES

1. G.M. Grant, et al., *High-Pressure Coolant Injection (HPCI) System Performance, 1987—1993*, NUREG/CR-5500, Vol. 8 (INEL-94/0158), NUREG/CR in printing.

2. *A Prioritization of Generic Safety Issues*, NUREG-0933, U.S. Nuclear Regulatory Commission, December 1998.

3. J.P. Poloski, et al., *Rates of Initiating Events at U.S. Nuclear Power Plants: 1987–1995*, NUREG/CR-5750, February 1999.

4. *Case Study Report: Operational Experience Involving Turbine Overspeed Trips*, AEOD/C602, U. S. Nuclear Regulatory Commission, August 1986.

5. Houghton, J. R., H. G. Hamzehee, *Component Performance Study—Turbine-Driven Pumps, 1987–1998,* U.S. Nuclear Regulatory Commission, Draft under review, July 1999.

6. NRC Information Notice 88-67, *PWR Auxiliary Feedwater Pump Turbine Overspeed Trip Failure,* U.S. Nuclear Regulatory Commission, August 22, 1988.

7. NRC Bulletin 93-02 and Supplement 1, Debris Plugging of Emergency Core Cooling Suction Strainers, U.S. Nuclear Regulatory Commission, May 11, 1993, (supplement dated February 18, 1994).

8. NRC Bulletin 95-02, Unexpected Clogging of a Residual Heat Removal (RHR) Pump Strainer While Operating in Suppression Pool Cooling Mode, US. Nuclear Regulatory Commission, October 17, 1995.

9. *Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris*, NUREG/CR-6224, U.S. Nuclear Regulatory Commission, October 1995.

10. NRC Bulletin 96-03, Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors, U.S. Nuclear Regulatory Commission May 6, 1996.

11. NRC Generic Letter 95-07: Pressure Locking and Thermal Binding of Safety-Related Power-Operated Gate Valves, U.S. Nuclear Regulatory Commission, August 17, 1995.

12. NRC Information Notice 96-08: Thermally Induced Pressure Locking of a High Pressure Coolant Injection Gate Valve, U.S. Nuclear Regulatory Commission, February 5, 1996.

Appendix A

HPCI Operating Experience, 1987–1998

Appendix A

HPCI Operational Data, 1987–1998

A-1. HPCI INOPERABILITIES

Table A-1 provides a breakdown of the results of the screening and classification of the HPCI system inoperabilities (failures and faults). The breakdown also identifies the failure mode for the inoperabilities that were classified as failures, and the method of discovery. Details of the event classification methodology are provided in the original report (Reference 1, Appendix A).

Table A-2 is a listing of all the inoperability events that were classified for inclusion in the HPCI study. These events were used to provide the data summary listed in Table A-1. The events that were classified as failures include the applicable failure mode. For the unreliability estimation process, only the failures that occurred during an unplanned demand or that were found during the performance of cyclic and quarterly surveillance tests were used to estimate unreliability. Data used in the engineering analysis used all the failures.

A-2. HPCI UNPLANNED DEMANDS

Specific aspects of the LER review were included for the HPCI system: whether the HPCI system pump was demanded to start and run, and if the injection valve was demanded to open. The demands identified in Table A-3 may or may not have been in response to a reactor pressure vessel water level transient. The portion of the system demanded is identified in Table A-3 with a "Y" in the appropriate column. For the events that resulted in the running of the injection pump, the run time in hours is indicated if it was known or could be estimated.

Table A-4 describes the components in the HPCI system which respond to the various engineered safety actuation signals during an unplanned demand.

A-3. HPCI CYCLIC AND QUARTERLY SURVEILLANCE TESTING DEMANDS

The estimated number of HPCI cyclic surveillance testing demands is summarized by plant in Table A-5. The total number is 217 cyclic surveillance tests and 846 quarterly surveillance tests. Demand counts for cyclic surveillance tests were estimated as follows. The plants are required by plant technical specifications to perform the test at least every 18 months. The tests are typically scheduled to coincide with refueling outages. These refueling outage start dates were found in the monthly operating reports submitted by the licensees to the NRC. For this study, a plant was assumed to perform the cyclic surveillance test as part of starting up after each refueling outage. If the time period until the start of the next refueling outage was more than 550 days (18 months), the necessary number of intermediate tests was assumed. Quarterly test demands were estimated as four per year; however, a quarterly test was not counted during extended outages (lasting more than two calendar quarters). A cyclic test was counted in place of a quarterly test.

A-4. DATA USED FOR STATISTICAL ESTIMATION OF RELIABILITY

The 46 failures identified in Table A-2 for which a demand count could be determined or estimated were used to estimate unreliability. Table A-6 provides a summary description of these events used in estimating HPCI system unreliability.

The subsystems listed in Table A-2 are based on the following characterizations:

- ***Turbine and turbine control***– The turbine and turbine control includes the actual turbine, the turbine stop valve, governor valve, governor control systems (including both mechanical and electronic overspeed trips), turbine condenser functions and the gland seals.

- ***Turbine exhaust and drains*** –The exhaust and drains subsystem includes the turbine exhaust lines, associated valves and piping, steam drains, rupture discs and vent lines. Also included is the area between the turbine and the suppression pool (normal drain route).

- ***Steam supply*** –The steam supply subsystem includes the piping from the main steam line penetration to the turbine stop valve and it's associated valves, including MOVs and their associated circuit breakers.

- ***Electrical (ac & dc)*** – The electrical sub-system includes the circuit breakers, circuit breakers at the MCC, the MCC, the dc power systems (batteries not power cards), and the associated inverters. This also includes buses, and circuit breaker control circuits and related components (such as relays, switches, breakers and lights) that supply power to other subsystems such as the I&C subsystem. However, losses of control logic or control power will typically be included in the I&C subsystem depending on the location of the fault (if at the MCC then it is to be considered part of the electrical subsystem).

- ***HVAC***– The HVAC sub-system includes all the HVAC for the HPCI room coolers and associated piping (including the dedicated portions of the service water system). This includes dampers and damper controllers. However, this excludes room cooling for support system equipment (e.g. switchgear), which is coded as the relevant support system (e.g. electrical).

- ***Instrumentation & control***– The I&C subsystem includes all electronic flow and logic controls (including controllers) for the HPCI system, system EXCEPT those related to the turbine control, which will be coded under the turbine and turbine control subsystem. This also includes containment isolation logic (note that the containment/steam supply isolation box should be checked on the data input form). I&C also includes actuation, control and indication for the system (again except for those related to the turbine and turbine control). I&C subsystem includes logic and control power (e.g. power supply circuit boards). However, losses of electric power at the bus or MCC that supplies power to the I&C subsystem will typically be identified as the electrical subsystem.

- ***Injection (discharge)***– The injection (discharge) subsystem includes all piping and valves (including AOV's, MOV's) from the pump discharge outlet to the reactor pressure vessel injection point. This includes any flow, pressure, temperature and level transmitters directly connected to the discharge line that affect injection flow.

- *Injection (suction)*– The injection-suction subsystem includes all piping and valves (including AOVs, MOVs and their associated electronics and circuit breakers) from the condensate storage tank or Suppression Pool to the pump. This includes any flow, pressure, temperature and level transmitters directly connected to the suction line that affect injection flow.

- *Pump*– Includes pump (without turbine driver, which is listed separately) and booster pump (including driver and dedicated electrical or other support functions).

- *Lube Oil*– The lube oil subsystem includes the lube oil cooler and any lube oil to other parts of the system including the pump, turbine, etc. (Note that this subsystem also includes the control circuits, and equipment associated with the above mentioned equipment). Note that the HPCI lube oil coolers are cooled from HPCI pump discharge flow. There is no service water cooling of the HPCI lube oil cooler.

- *Hydraulic Oil*– Hydraulic oil sub-system includes lines up to the turbine stop valve, turbine control valve, and turbine governor.

- *Service Water*– The service water subsystem includes a loss of the shared portions of the service water. This subsystem should be used only when the support system box is checked on the data input form. Problems with the dedicated portions of the service water system to the HVAC will be coded as HVAC.

A-5. BASIS FOR COUNTING DEMAND AND FAILURE EVENTS USED FOR STATISTICAL ESTIMATION OF RELIABILITY

Table 2 in Section 2 in the main body of this report provides the types of data (i.e., cyclic and quarterly test and unplanned demands), failure counts, and demand counts used for estimating probabilities for the failure modes associated in the HPCI system. The logic used to identify the demand and failure counts for each failure mode and type of data is described below.

- For the HPCI system to have the opportunity to start, it could not be inoperable because of maintenance at the time of the demand. If so, there is no opportunity for HPCI to start. There were a total of 97 unplanned demands. Of the 97 events, 94 unplanned demands occurred while operating with one failure caused by the system being out for maintenance and 3 unplanned demands while shut down.

- The opportunities to start from the unplanned demands consist of the number of initial unplanned demands minus any MOOS failures observed, and minus any events that were cut short by the operator because the system was no longer needed. Each unplanned demand was coded to indicate whether it provided a test of whether the injection system could start (see the FTSI column in Table A-3).

- The failure to start of the HPCI system was partitioned into FTSI and FTSV to gain further insight into the reliability for this operational phase and to use as much of the cyclic and quarterly test data as possible. The cyclic and quarterly tests were used with the unplanned demands to estimate the probability of failure to start for the part of the system excluding the injection valve. 217 cyclic tests (see Table A-4) and 846 quarterly tests were estimated for the HPCI system for the 1987-1998 period. Five failures were observed in the cyclic tests while twenty-two failures were observed in the quarterly tests.

- The next operational event in an HPCI system response deals with FTSV. The injection valve opens when a permissive signal based on pump discharge pressure is activated. Therefore, the opportunities for FTSV consist of the FTSI unplanned demands minus any failures from FTSI, and minus any unplanned demands that did not challenge the injection valve. As with the FTSI unplanned demands, the demand counts were obtained directly from the FTSV column of Table A-3. The cyclic and quarterly tests of the HPCI system do not challenge the injection valve under the same stresses as those present in an unplanned demand. Therefore, these test opportunities of the injection valve are not included in the FTSV failure mode calculation.

- Although failures that occur on tests do not need to be immediately recovered, an assessment was made of whether the failure would have been recovered if it had occurred on an unplanned demand. Just two of the five FTSI failures on cyclic tests were judged to be recoverable while only five of the twenty-two quarterly test failures were judged to be recoverable.

- For the run phase of the HPCI system operation, the number of unplanned demands was obtained directly from the coded data (see the FTRI column of Table A-3). After a failure observed in testing, any subsequent failures occurring may be regarded as part of the corrective maintenance process, which are not required to be reported. Therefore, the cyclic and quarterly test FTRI demand count was reduced by their unrecovered FTSI failures.

- The failure to run of the HPCI system was partitioned into FTRI and FTRT to gain further insight into the reliability for this operational phase and to use as much of the data as possible. The FTRI counts are based on the unplanned demands and the cyclic and quarterly surveillance tests. The FTRT counts are based on the six unplanned demands judged to challenge this function, and on the 210 cyclic tests and 816 quarterly tests which also challenge the suction path transfer function of the injection system.

- The failures observed during the run phase were also evaluated to see if unplanned demands were recovered or could have been recovered, and if test failures could have been recovered easily if they had occurred on an unplanned demand. The FTRT failures were not judged to be easily recoverable.

- The failure of the HPCI system was also observed to result from the injection valve to reopen on subsequent injection demands. The failure of the injection valve to reopen (FRO) when needed for RPV water level control was not observed in all unplanned demands. The FRO counts are based on the twelve unplanned demands judged to challenge this operation of the HPCI system.

Table A-1. Summary of all HPCI system failures and faults listed in Table A-2 (1987–1998 experience).

Failure Mode	Method of Discovery: Unplanned Demands	Cyclic Tests	Quarterly Tests	Other Tests[a]	Other[b]	Overall Total
Failures						
Maintenance-out-of-service (MOOS)	1[c]	NA	NA	NA	NA	1
Failure to start (FTS)						
Failure to start, other than injection valve (FTSI)	1	5	22	34	63	125
Failure to start, injection valve (FTSV)	0	0	2	0	0	2
Total FTS	1	5	24	34	63	127
Failure to run (FTR)						
Failure to run, other than suction transfer (FTRI)	2	2	9	5	12	30
Failure to run, suction transfer (FTRT)	0	0	2	0	0	2
Total FTR	2	2	11	5	12	32
Failure of injection valve to reopen (FRO)	2	0	0	0	0	2
Total failures	6	7	35	39	75	162[d]
Equipment faults	6	17	50	41	62	176
Administrative faults	0	2	11	5	39	57
Grand Total	12	26	96	85	176	395

a. I&C functional tests and other scheduled surveillance with periodicity other than cyclic and quarterly.

b. Inspections, design reviews, post maintenance tests, control room indication and alarms, plant tours, etc. These failure events were not used to estimate unreliability, but were used in the engineering analysis.

c. The MOOS event occurred while the plant was not shutdown.

d. Includes the maintenance-out-of service event.

Table A-2. HPCI system inoperabilities that are classified as failures (1987–1998 experience).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Browns Ferry Unit 2	26094001	2/14/94	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Hardware
Browns Ferry Unit 2	26094004	4/15/94	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Hardware
Browns Ferry Unit 2	***26095005***	***6/7/95***	***FTSI***	***No***	***Surveillance Quarterly***	***Steam Supply to turbine***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Browns Ferry Unit 3	29697002	4/10/97	FTSI	Yes	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Brunswick Unit 1	32587001	1/26/87	FTSI	No	Inspection	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Brunswick Unit 1	32587023	12/31/87	FTSI	No	Surveillance Monthly	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Brunswick Unit 1	***32588011***	***4/20/88***	***FTRT***	***No***	***Surveillance Quarterly***	***Injection (Suction segments)***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Brunswick Unit 1	32588012	5/28/88	FTSI	No	Surveillance Monthly	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Brunswick Unit 1	32588017	7/1/88	FTSI	No	Surveillance Monthly	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Brunswick Unit 1	***32588018***	***7/13/88***	***FTRT***	***No***	***Surveillance Quarterly***	***Injection (Suction segments)***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Brunswick Unit 1	32589020	10/11/89	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Motor Control Center (includes - relays, switches, lights)	Hardware
Brunswick Unit 1	32590001	1/2/90	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Personnel

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Brunswick Unit 1	32590003	3/2/90	FTSI	No	Immediate indication	Turbine Exhaust and Drains	Pipe, gaskets, fittings, flanges	Hardware
Brunswick Unit 1	***32591018***	***7/18/91***	***FTRI***	***No***	***Unplanned demand***	***Lube Oil***	***Misc, Mechanical***	***Hardware***
Brunswick Unit 1	32594009	5/13/94	FTRI	No	Immediate indication	Lube Oil	Motor Control Center (includes - relays, switches, lights)	Hardware
Brunswick Unit 1	32594012	9/22/94	FTRI	No	Immediate indication	Lube Oil	Motor Control Center (includes - relays, switches, lights)	Personnel
Brunswick Unit 1	32596007	5/9/96	FTSI	No	Immediate indication	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Brunswick Unit 2	***32487001***	***1/5/87***	***FRO***	***No***	***Unplanned demand***	***Injection (Discharge segments)***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Brunswick Unit 2	32487004	3/11/87	FTRI	No	Inspection	Injection (Discharge segments)	Valve, Motor Operated (includes limit switches)	Hardware
Brunswick Unit 2	32489006	4/24/89	FTSI	No	Immediate indication	Steam Supply to turbine	Transmitter (inc. sensors & switches)	Hardware
Brunswick Unit 2	32490018	11/23/90	FTSI	No	Immediate indication	Instrumentation & Control	Relay, Other	Hardware
Brunswick Unit 2	32491020	12/14/91	FTSI	No	Post-maint. test Cyclic	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Personnel
Brunswick Unit 2	***32495002***	***5/10/95***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Misc, I&C***	***Hardware***
Cooper Station	29892014	7/31/92	FTSI	No	Immediate indication	Turbine and Turbine control	Misc, Mechanical	Hardware
Cooper Station	29893031	8/30/93	FTSI	No	Surveillance	Injection (Discharge	Valve, Motor Operated	Hardware

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
						segments)	(includes limit switches)	
Cooper Station	29894007	4/13/94	FTRI	No	Inspection	Lube Oil	Valve, Air Operated (includes limit switches & loss of air supply)	Hardware
Cooper Station	29897018	12/15/97	FTSI	Yes	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Cooper Station	***29898011***	***12/18/98***	***FTSI***	***No***	***Surveillance Quarterly***	***Steam Supply to turbine***	***Pipe, gaskets, fittings, flanges***	***Personnel***
Cooper Station	***29898012***	***12/17/98***	***FTSI***	***No***	***Surveillance Cyclic***	***Injection (Suction segments)***	***Pipe, gaskets, fittings, flanges***	***Procedure***
Dresden Unit 2	***23787012***	***4/22/87***	***FTSI***	***No***	***Surveillance Cyclic***	***Lube Oil***	***Transmitter (inc. sensors & switches)***	***Hardware***
Dresden Unit 2	23787018	6/6/87	FTRI	No	Inspection	HVAC	Air Handling Unit (Room Cooler)	Hardware
Dresden Unit 2	23788013	7/8/88	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Hardware
Dresden Unit 2	23794020	7/15/94	FTSI	No	Inspection	Pump w/o driver, includes booster	Pump	Personnel
Dresden Unit 2	23794021	8/4/94	FTRI	No	Surveillance Monthly	Turbine Exhaust and Drains	Valve, Check	Hardware
Dresden Unit 2	23797012	5/20/97	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Dresden Unit 2	23798003	1/28/98	FTSI	No	Immediate indication	Turbine Exhaust and Drains	Valve, Air Operated (includes limit switches & loss of air supply)	Hardware
Dresden Unit 3	24987002	2/25/87	FTSI	Yes	Surveillance Monthly	Lube Oil	Transmitter (inc. sensors & switches)	Hardware

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Dresden Unit 3	24993019	12/14/93	FTSI	Yes	Immediate indication	Instrumentation & Control	Relay, Other	Personnel
Dresden Unit 3	24993913	8/9/93	FTSI	No	Surveillance Monthly	Turbine and Turbine control	Valve, Hydraulic Operated (includes limit switches)	Hardware
Dresden Unit 3	24998003	4/9/98	FTSI	No	Immediate indication	Steam Supply to turbine	Pipe, gaskets, fittings, flanges	Procedure
Duane Arnold	33189002	1/26/89	FTRI	No	Surveillance Monthly	Turbine and Turbine control	Governor	Hardware
Duane Arnold	33189006	3/2/89	FTSI	No	Immediate indication	Instrumentation & Control	Transmitter (inc. sensors & switches)	Design
Duane Arnold	33189007	2/24/89	FTRI	No	Surveillance	Turbine and Turbine control	Governor	Hardware
Duane Arnold	33191007	8/6/91	FTSI	No	I&C test Monthly	Steam Supply to turbine	Transmitter (inc. sensors & switches)	Personnel
Duane Arnold	33193009	10/5/93	FTSI.	No	Immediate indication	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Duane Arnold	33193009	10/7/93	FTSI	No	Post-maint. test	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Duane Arnold	***33195012***	***12/12/95***	***FTRI***	***No***	***Surveillance Quarterly***	***Instrumentation & Control***	***Unknown***	***Hardware***
Fermi Unit 2	34188028	7/26/88	FTSV	No	Surveillance Quarterly	Injection (Discharge segments)	Valve, Motor Operated (includes limit switches)	Hardware
Fermi Unit 2	34190008	9/5/90	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Hardware
Fermi Unit 2	34190012	10/16/90	FTSI	No	I&C test Weekly	Steam Supply to turbine	Transmitter (inc. sensors & switches)	Hardware

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Fermi Unit 2	34191001	1/16/91	FTSI	No	I&C test Quarterly	Steam Supply to turbine	Misc, I&C	Hardware
Fermi Unit 2	***34191020***	***11/20/91***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Misc, Mechanical***	***Hardware***
Fermi Unit 2	34193001	1/4/93	FTSI	No	Immediate indication	Instrumentation & Control	Relay, Other	Hardware
Fermi Unit 2	***34193002***	***1/14/93***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Governor***	***Hardware***
Fermi Unit 2	34197002	2/16/97	FTSV	No	Surveillance Quarterly	Injection (Discharge segments)	Valve, Motor Operated (includes limit switches)	Hardware
FitzPatrick	***33387010***	***7/23/87***	***FTSI***	***No***	***Surveillance Quarterly***	***Lube Oil***	***Pump***	***Hardware***
FitzPatrick	***33388001***	***3/10/88***	***FTSI***	***No***	***Surveillance Quarterly***	***Steam Supply to turbine***	***Valve, Motor Operated (includes limit switches)***	***Procedure***
FitzPatrick	33389005	4/12/89	FTSI	No	Inspection	Turbine and Turbine control	Governor	Hardware
FitzPatrick	***33389018***	***10/8/89***	***FTSI***	***No***	***Surveillance Cyclic***	***Steam Supply to turbine***	***Transmitter (inc. sensors & switches)***	***Design***
FitzPatrick	***33389020***	***11/5/89***	***MOOS***	***No***	***Unplanned demand***	***Turbine and Turbine control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Hardware***
FitzPatrick	***33389025***	***11/30/89***	***FTSI***	***No***	***Surveillance Quarterly***	***Steam Supply to turbine***	***Transmitter (inc. sensors & switches)***	***Design***
FitzPatrick	***33395008***	***3/26/95***	***FTSI***	***No***	***Surveillance Cyclic***	***Instrumentation & Control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Procedure***
FitzPatrick	33396008	9/6/96	FTSI	No	Immediate indication	Electrical ac & dc	Inverter (includes all	Hardware

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
						Distribution	subcomponent failures)	
FitzPatrick	33397013	12/16/97	FTSI	No	I&C test Quarterly	Instrumentation & Control	Misc, I&C	Hardware
FitzPatrick	33398007	7/31/98	FTRI	No	Immediate indication	Lube Oil	Motor Control Center (includes - relays, switches, lights)	Personnel
Hatch Unit 1	32189006	3/29/89	FTSI	No	Inspection	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Hardware
Hatch Unit 1	***32190001***	***1/4/90***	***FTRI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Governor***	***Hardware***
Hatch Unit 1	32190015	7/30/90	FTSI	No	Inspection	Instrumentation & Control	Controller, I&C (includes entire instrument loop except for transmitters)	Hardware
Hatch Unit 1	***32191001***	***1/18/91***	***FTSI***	***Yes***	***Unplanned demand***	***Turbine and Turbine control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Hardware***
Hatch Unit 1	***32191033***	***12/30/91***	***FTRI***	***No***	***Surveillance Quarterly***	***Instrumentation & Control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Hardware***
Hatch Unit 1	***32192006***	***2/26/92***	***FTRI***	***Yes***	***Surveillance Quarterly***	***Instrumentation & Control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Hardware***
Hatch Unit 1	32195006	7/11/95	FTSI	No	Other surveillance Quarterly	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Hatch Unit 1	32196010	6/29/96	FTSI	No	Immediate indication	Turbine and Turbine control	Valve, Hydraulic Operated (includes limit switches)	Hardware
Hatch Unit 2	***36687004***	***6/16/87***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Governor***	***Hardware***
Hatch Unit 2	***36687009***	***8/3/87***	***FTRI***	***Yes***	***Unplanned demand***	***Injection (Suction segments)***	***Transmitter (inc. sensors & switches)***	***Hardware***
Hatch Unit 2	***36687017***	***11/19/87***	***FTSI***	***No***	***Surveillance Quarterly***	***Instrumentation & Control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Hardware***
Hatch Unit 2	36688001	1/6/88	FTSI	No	Post-maint. test	Turbine and Turbine control	Valve, Hydraulic Operated (includes limit switches)	Procedure
Hatch Unit 2	***36690001***	***1/12/90***	***FRO***	***No***	***Unplanned demand***	***Injection (Discharge segments)***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Hatch Unit 2	36690005	7/19/90	FTSI	No	Surveillance Weekly	Lube Oil	Motor	Hardware
Hatch Unit 2	36693007	8/25/93	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Hatch Unit 2	36693008	11/3/93	FTSI	No	Surveillance Weekly	Turbine and Turbine control	Valve, Hydraulic Operated (includes limit switches)	Hardware
Hatch Unit 2	36694002	3/1/94	FTRI	No	Surveillance Monthly	Turbine and Turbine control	Turbine	Design
Hatch Unit 2	36696002	6/26/96	FTSI	No	Surveillance	Lube Oil	Process filter (mechanical)	Contamination
Hatch Unit 2	36697001	1/25/97	FTSI	Yes	Immediate indication	Instrumentation & Control	Misc, I&C	Procedure

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Hatch Unit 2	36697008	8/18/97	FTSI	No	Inspection	Pump w/o driver, includes booster	Pump	Contamination
Hope Creek	35487027	6/26/87	FTSI	No	Immediate indication	Instrumentation & Control	Transmitter (inc. sensors & switches)	Hardware
Hope Creek	35488010	4/14/88	FTSI	No	Surveillance	Lube Oil	Misc, Mechanical	Personnel
Hope Creek	35489009	4/14/89	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Personnel
Hope Creek	35489012	6/7/89	FTSI	No	Immediate indication	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Hope Creek	35490009	6/7/90	FTRI	No	Post-maint. test	Lube Oil	Misc, Mechanical	Design
Hope Creek	35493008	11/1/93	FTSI	Yes	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Hope Creek	35495025	10/24/95	FTSI	No	Inspection	Turbine and Turbine control	Valve, Hydraulic Operated (includes limit switches)	Hardware
Hope Creek	35497006	3/22/97	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Hope Creek	***35497032***	***12/5/97***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Turbine***	***Hardware***
Limerick Unit 1	***35287015***	***5/14/87***	***FTRI***	***No***	***Surveillance Quarterly***	***Instrumentation & Control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Hardware***
Limerick Unit 1	***35287015***	***5/14/87***	***FTRI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Valve, Hydraulic Operated (includes limit switches)***	***Hardware***

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Limerick Unit 1	***35287066***	***12/8/87***	***FTRI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Misc, Mechanical***	***Hardware***
Limerick Unit 1	35291028	12/10/91	FTSI	No	Post-maint. test	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Limerick Unit 1	35292002	3/11/92	FTSI	No	Inspection	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Hardware
Limerick Unit 1	***35292015***	***7/7/92***	***FTRI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Misc, Mechanical***	***Contamination***
Limerick Unit 1	35296008	3/3/96	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Limerick Unit 1	***35296018***	***9/25/96***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Misc, Elect - wires, connections, TBs, fuses***	***Hardware***
Limerick Unit 2	35389010	10/13/89	FTSI	No	Inspection	Turbine Exhaust and Drains	Pipe, gaskets, fittings, flanges	Personnel
Limerick Unit 2	35390004	3/8/90	FTSI	No	Inspection	Turbine Exhaust and Drains	Valve, Air Operated (includes limit switches & loss of air supply)	Personnel
Limerick Unit 2	35390008	4/17/90	FTSI	No	Immediate indication	Steam Supply to turbine	Transmitter (inc. sensors & switches, code with subsystem not I&C)	Hardware
Limerick Unit 2	35391015	9/12/91	FTSI	No	Post-maint. test Quarterly	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Limerick Unit 2	35391017	11/15/91	FTSI	No	Immediate indication	Lube Oil	Pipe, gaskets, fittings, flanges	Hardware
Limerick Unit 2	35392001	1/4/92	FTSI	No	Inspection	Instrumentation & Control	Transmitter (inc. sensors & switches)	Hardware

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Limerick Unit 2	35392004	2/21/92	FTSI	No	Inspection	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Hardware
Limerick Unit 2	35393009	7/16/93	FTSI	No	Immediate indication	Steam Supply to turbine	Transmitter (inc. sensors & switches)	Hardware
Monticello	26389005	4/3/89	FTSI	No	Surveillance Monthly	Instrumentation & Control	Misc, I&C	Hardware
Monticello	***26394017***	***10/23/94***	***FTRI***	***No***	***Surveillance Cyclic***	***Steam Supply to turbine***	***Misc, I&C***	***Hardware***
Peach Bottom Unit 2	27787020	9/4/87	FTSI	No	I&C test Quarterly	Turbine and Turbine control	Governor	Hardware
Peach Bottom Unit 2	27790017	7/24/90	FTSI	Yes	Immediate indication	Electrical ac & dc Distribution	Battery Charger	Hardware
Peach Bottom Unit 2	27792004	3/16/92	FTSI	No	Surveillance	Turbine Exhaust and Drains	Misc, Mechanical	Hardware
Peach Bottom Unit 2	27793003	1/31/93	FTRI	No	Surveillance Monthly	Turbine and Turbine control	Pipe, gaskets, fittings, flanges	Hardware
Peach Bottom Unit 2	***27794004***	***7/18/94***	***FTSI***	***No***	***Surveillance Quarterly***	***Instrumentation & Control***	***Controller, I&C (includes entire instrument loop except for transmitters)***	***Hardware***
Peach Bottom Unit 2	***27796009***	***10/1/96***	***FTRI***	***No***	***Surveillance Cyclic***	***Pump w/o driver, includes booster***	***Misc, Mechanical***	***Procedure***
Peach Bottom Unit 2	27797003	6/1/97	FTSI	No	Immediate indication	Instrumentation & Control	Misc, Elect - wires, connections, TBs, fuses	Personnel
Peach Bottom Unit 3	27887007	8/29/87	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Relay, Other	Hardware
Peach Bottom Unit 3	***27889009***	***12/7/89***	***FTSI***	***No***	***Surveillance Quarterly***	***Lube Oil***	***Valve, Relief***	***Hardware***

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Peach Bottom Unit 3	***27890010***	***8/4/90***	***FTRI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Valve, Hydraulic Operated (includes limit switches)***	***Design***
Peach Bottom Unit 3	27890011	9/10/90	FTSI	No	Surveillance Monthly	Lube Oil	Motor	Hardware
Peach Bottom Unit 3	27891005	4/10/91	FTSI	No	Surveillance Monthly	Turbine Exhaust and Drains	Vacuum Breaker	Procedure
Peach Bottom Unit 3	27891014	9/5/91	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Personnel
Peach Bottom Unit 3	27892009	11/28/92	FTSI	No	Inspection	Instrumentation & Control	Controller, I&C (includes entire instrument loop except for transmitters)	Hardware
Peach Bottom Unit 3	27893001	1/25/93	FTSV	No	Surveillance Monthly	Electrical ac & dc Distribution	Motor Control Center (includes - relays, switches, lights)	Hardware
Peach Bottom Unit 3	27893005	8/9/93	FTSI	No	Surveillance Monthly	Instrumentation & Control	Controller, I&C (includes entire instrument loop except for transmitters)	Hardware
Peach Bottom Unit 3	27893009	11/13/93	FTSI	No	Surveillance Monthly	Electrical ac & dc Distribution	Motor Control Center (includes - relays, switches, lights)	Hardware
Peach Bottom Unit 3	27894004	9/24/94	FTSI	No	Immediate indication	Steam Supply to turbine	Valve, Motor Operated (includes limit switches)	Hardware
Peach Bottom Unit 3	***27895002***	***7/6/95***	***FTSI***	***No***	***Surveillance Quarterly***	***Steam Supply to turbine***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Peach Bottom Unit 3	***27896001***	***5/29/96***	***FTSI***	***No***	***Surveillance Cyclic***	***Turbine and Turbine control***	***Misc, I&C***	***Hardware***

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Pilgrim	***29389013***	***3/24/89***	***FTSI***	***No***	***Surveillance Quarterly***	***Steam Supply to turbine***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Pilgrim	29389028	9/7/89	FTSI	No	Surveillance Monthly	Turbine and Turbine control	Controller, I&C (includes entire instrument loop except for transmitters)	Hardware
Pilgrim	29390017	10/9/90	FTSI	No	Surveillance Monthly	Turbine and Turbine control	Governor	Hardware
Pilgrim	29393017	7/21/93	FTSI	No	I&C test	Instrumentation & Control	Misc, I&C	Procedure
Pilgrim	29394001	1/4/94	FTSI	Yes	Immediate indication	Instrumentation & Control	Unknown	Personnel
Pilgrim	29394002	3/9/94	FTSV	No	Surveillance Monthly	Injection (Discharge segments)	Valve, Motor Operated (includes limit switches)	Hardware
Pilgrim	29395002	2/2/95	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Design
Pilgrim	29398026	12/2/98	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Hardware
Quad Cities Unit 1	25487017	8/5/87	FTSI	No	Surveillance Monthly	Steam Supply to turbine	Transmitter (inc. sensors & switches)	Hardware
Quad Cities Unit 1	25489022	11/28/89	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Misc, Elect - wires, connections, TBs, fuses	Personnel
Quad Cities Unit 1	***25491012***	***5/7/91***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Valve, Hydraulic Operated (includes limit switches)***	***Hardware***
Quad Cities Unit 1	***25492002***	***2/6/92***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Valve, Hydraulic Operated (includes limit switches)***	***Procedure***

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Quad Cities Unit 1	***25493005***	***6/9/93***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Misc, Mechanical***	***Hardware***
Quad Cities Unit 1	25493012	7/26/93	FTRI	No	I&C test Monthly	Instrumentation & Control	Misc, I&C	Hardware
Quad Cities Unit 1	***25495004***	***3/29/95***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Misc, Mechanical***	***Hardware***
Quad Cities Unit 2	25491012	5/8/91	FTSI	No	Inspection	Turbine and Turbine control	Valve, Hydraulic Operated (includes limit switches)	Hardware
Quad Cities Unit 2	26590008	6/2/90	FTSI	No	Immediate indication	Instrumentation & Control	Controller, I&C (includes entire instrument loop except for transmitters (XMTR))	Hardware
Quad Cities Unit 2	26590012	11/24/90	FTRI	No	Immediate indication	Instrumentation & Control	Controller, I&C (includes entire instrument loop except for transmitters)	Hardware
Quad Cities Unit 2	26591003	1/22/91	FTSI	Yes	Post-maint. test Quarterly	Injection (Suction segments)	Transmitter (inc. sensors & switches)	Design
Susquehanna Unit 1	38787008	2/23/87	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Hardware
Susquehanna Unit 1	38788009	5/20/88	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Inverter (includes all subcomponent failures)	Hardware
Susquehanna Unit 1	38788022	11/4/88	FTSI	No	Immediate indication	Instrumentation & Control	Misc, Elect - wires, connections, TBs, fuses	Personnel
Susquehanna Unit 1	***38790007***	***2/15/90***	***FTSI***	***No***	***Surveillance Quarterly***	***Turbine and Turbine control***	***Valve, Hydraulic Operated (includes limit switches)***	***Hardware***

Table A-2. (continued).

Plant Name[a]	LER Number	Event date	Failure Mode	Recovered	Detection Method	Subsystem	Component	Cause
Susquehanna Unit 1	***38791002***	***2/7/91***	***FTSI***	***No***	***Surveillance Quarterly***	***Steam Supply to turbine***	***Valve, Motor Operated (includes limit switches)***	***Hardware***
Susquehanna Unit 1	38794013	8/25/94	FTSI	Yes	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Susquehanna Unit 1	38795016	12/31/95	FTRI	No	Immediate indication	Instrumentation & Control	Misc, Elect - wires, connections, TBs, fuses	Hardware
Susquehanna Unit 2	38887002	2/14/87	FTSI	No	Immediate indication	Instrumentation & Control	Misc, I&C	Personnel
Susquehanna Unit 2	38891015	12/16/91	FTRI	No	Immediate indication	Turbine Exhaust and Drains	Pipe, gaskets, fittings, flanges	Hardware
Vermont Yankee	27187016	11/5/87	FTRI	No	Inspection	Injection (Discharge segments)	Transmitter (inc. sensors & switches)	Personnel
Vermont Yankee	27192004	2/20/92	FTSI	No	Immediate indication	Electrical ac & dc Distribution	Battery Charger	Hardware

Table A-3. HPCI system unplanned demands (1987–1998 operating experience).

Plant Unit	LER	Event Date	Failure Mode Demands[a] MOOS	FTSI	FTSV	FTRI	FRO	FTRT	Pump Hours
Browns Ferry Unit 2	26097001	4/24/97	Y	Y	Y	Y	-	-	0.15
Browns Ferry Unit 3	29696002	4/21/96	Y	Y	Y	Y	-	-	0.02
Browns Ferry Unit 3	29696003	5/1/96	Y	Y	Y	Y	u	-	0.17
Brunswick Unit 1	32592003	1/17/92	Y	Y	Y	Y	-	-	0.02
Brunswick Unit 1	32594015	12/15/94	Y	Y	-	-	-	-	0
Brunswick Unit 1	32592005	2/29/92	Y	-	-	-	-	-	0
Brunswick Unit 1	32595015	7/13/95	Y	Y	Y	Y	Y	-	0.7
Brunswick Unit 1	32591018	7/18/91	Y	Y	Y	Y	-	-	0.08
Brunswick Unit 1	32595018	9/30/95	Y	Y	-	-	-	-	0
Brunswick Unit 2	32491001	1/25/91	Y	Y	Y	Y	-	-	0.03
Brunswick Unit 2	32487001	1/5/87	Y	Y	Y	Y	Y	-	0.03
Brunswick Unit 2	32490016	10/12/90	Y	Y	Y	Y	-	-	0.03
Brunswick Unit 2	32488018	11/16/88	Y	Y	Y	-	-	-	0.02
Brunswick Unit 2	32491021	12/17/91	Y	Y	Y	Y	-	-	0.08
Brunswick Unit 2	32492001	2/2/92	Y	Y	-	Y	-	-	0.08
Brunswick Unit 2	32487004	3/11/87	Y	Y	Y	Y	-	-	0.08
Brunswick Unit 2	32490008	8/16/90	Y	Y	Y	Y	-	-	0.05
Brunswick Unit 2	32490009	8/19/90	Y	Y	Y	Y	Y	-	0.75
Brunswick Unit 2	32490015	9/27/90	Y	Y	Y	Y	Y	-	0.52
Cooper Station	29887003	1/7/87	Y	Y	Y	Y	-	-	0.08
Cooper Station	29890011	10/17/90	Y	Y	Y	Y	-	-	0.08
Cooper Station	29889026	11/25/89	Y	Y	Y	Y	-	-	0.37
Cooper Station	29893038	12/14/93	Y	Y	Y	Y	-	-	0.05
Cooper Station	29887009	2/18/87	Y	Y	Y	Y	-	-	0.08
Cooper Station	29894004	3/2/94	Y	Y	Y	Y	-	-	0.02
Cooper Station	29888021	8/25/88	Y	Y	Y	Y	Y	-	1.5
Dresden Unit 2	23794017	7/4/94	-	-	-	-	-	Y	0
Dresden Unit 3	24989001	3/25/89	Y	Y	Y	Y	u	-	2.5
Dresden Unit 3	24996004	5/15/96	Y	Y	Y	Y	-	-	0.23
Duane Arnold	33189008	3/5/89	Y	Y	Y	Y	-	-	0.08
Duane Arnold	33189011	8/26/89	Y	Y	Y	Y	-	-	0.45
Fermi Unit 2	34188004	1/10/88	Y	Y	Y	Y	-	-	0.23
Fermi Unit 2	34192012	11/18/92	Y	Y	Y	Y	-	-	0.08
Fermi Unit 2	34195004	4/9/95	Y	Y	-	-	-	-	0
Fermi Unit 2	34196010	7/19/96	-	-	-	-	-	Y	0

Table A-3. (continued).

Plant Unit	LER	Event Date	MOOS	FTSI	FTSV	FTRI	FRO	FTRT	Pump Hours
			Failure Mode Demands[a]						
Fermi Unit 2	34193010	8/13/93	Y	Y	Y	Y	-	-	0.02
FitzPatrick	33397011	10/24/97	-	-	-	-	-	Y	0
FitzPatrick	33389020	11/5/89	Y	-	-	-	-	-	0
FitzPatrick	33396003	2/22/96	Y	Y	-	Y	-	-	0.35
FitzPatrick	33390009	3/19/90	Y	Y	Y	Y	-	-	0.08
FitzPatrick	33393009	4/20/93	Y	Y	Y	Y	-	-	0.03
FitzPatrick	33398004	5/1/98	Y	Y	-	-	-	-	0
FitzPatrick	33398008	8/3/98	Y	Y	-	-	-	-	0
FitzPatrick	33396010	9/16/96	Y	Y	Y	Y	-	-	0.02
FitzPatrick	33395013	9/5/95	Y	Y	Y	Y	-	-	0.02
Hatch Unit 1	32191001	1/18/91	Y	Y	Y	Y	-	-	0.08
Hatch Unit 1	32193013	10/22/93	Y	Y	Y	Y	-	-	0.07
Hatch Unit 1	32188018	12/17/88	Y	Y	Y	Y	-	-	0.23
Hatch Unit 1	32191007	2/27/91	Y	Y	Y	Y	-	-	0.07
Hatch Unit 1	32190013	6/20/90	Y	Y	Y	Y	-	-	0.08
Hatch Unit 1	32187011	7/23/87	Y	Y	Y	Y	-	-	0.1
Hatch Unit 1	32192021	8/27/92	Y	Y	Y	Y	-	-	0.23
Hatch Unit 1	32187013	8/3/87	Y	Y	Y	Y	-	-	0.52
Hatch Unit 1	32191017	9/11/91	Y	Y	Y	Y	-	-	0.08
Hatch Unit 1	32192024	9/30/92	Y	Y	-	Y	-	-	0.08
Hatch Unit 1	32188013	9/4/88	Y	Y	Y	Y	-	-	0.07
Hatch Unit 2	36690001	1/12/90	Y	Y	Y	Y	Y	-	0.03
Hatch Unit 2	36687003	1/26/87	Y	Y	Y	Y	Y	-	0.25
Hatch Unit 2	36697010	11/20/97	Y	Y	-	-	-	-	0
Hatch Unit 2	36695001	4/11/95	Y	Y	Y	Y	-	-	0.02
Hatch Unit 2	36687008	4/22/87	Y	Y	Y	Y	Y	-	0.25
Hatch Unit 2	36697007	4/22/97	Y	Y	Y	Y	-	-	0.02
Hatch Unit 2	36688017	5/27/88	Y	Y	Y	Y	-	-	0.08
Hatch Unit 2	36692009	6/25/92	Y	Y	Y	Y	-	-	0.08
Hatch Unit 2	36687006	7/26/87	Y	Y	Y	Y	Y	-	0.03
Hatch Unit 2	36687009	8/3/87	Y	Y	Y	Y	Y	-	0.07
Hatch Unit 2	36694007	8/30/94	Y	Y	Y	Y	-	-	0.33
Hatch Unit 2	36688020	8/5/88	Y	Y	Y	Y	-	-	0.05
Hatch Unit 2	36689005	9/3/89	Y	Y	-	-	-	-	0.02
Hope Creek	35488027	10/15/88	Y	Y	Y	Y	-	-	0.05

Table A-3. (continued).

Plant Unit	LER	Event Date	Failure Mode Demands[a] MOOS	FTSI	FTSV	FTRI	FRO	FTRT	Pump Hours
Hope Creek	35488029	11/1/88	Y	Y	Y	Y	-	-	0.17
Hope Creek	35490029	11/26/90	Y	Y	Y	Y	-	-	0.02
Hope Creek	35487017	2/24/87	Y	Y	Y	Y	-	-	0.08
Hope Creek	35490003	3/19/90	Y	Y	Y	Y	-	-	0.03
Hope Creek	35488012	4/30/88	Y	Y	Y	Y	Y	-	0.08
Hope Creek	35495014	7/3/95	-	-	-	-	-	Y	0
Hope Creek	35487034	7/30/87	Y	Y	Y	Y	U	-	0.08
Hope Creek	35487037	8/16/87	Y	Y	Y	Y	U	-	0.08
Hope Creek	35488022	8/26/88	Y	Y	Y	Y	-	-	0.03
Hope Creek	35487039	8/29/87	Y	Y	Y	Y	U	-	0.08
Hope Creek	35495020	9/8/95	-	-	-	-	-	Y	0
Limerick Unit 1	35298001	1/24/98	Y	Y	-	-	-	-	0
Limerick Unit 2	35394010	10/19/94	Y	Y	-	-	-	-	0
Limerick Unit 2	35395006	3/22/95	Y	Y	-	-	-	-	0
Monticello	26394018	10/26/94	Y	Y	-	Y	-	Y	0.5
Monticello	26387009	4/3/87	Y	Y	Y	Y	-	-	
Monticello	26391019	8/25/91	Y	Y	Y	Y	-	-	0.75
Peach Bottom Unit 2	27789033	12/20/89	Y	Y	Y	Y	-	-	0.38
Peach Bottom Unit 2	27793004	3/2/93	Y	Y	Y	Y	-	-	0.47
Peach Bottom Unit 3	27890002	1/28/90	Y	Y	Y	Y	Y	-	0.7
Peach Bottom Unit 3	27892008	10/15/92	Y	Y	Y	Y	-	-	0.17
Peach Bottom Unit 3	27890008	7/27/90	Y	Y	Y	Y	-	-	0.08
Peach Bottom Unit 3	27893004	7/30/93	Y	Y	Y	Y	-	-	0.08
Pilgrim	29396005	4/19/96	Y	Y	-	Y	-	-	0.85
Pilgrim	29390013	9/2/90	Y	Y	Y	Y	-	-	3.05
Quad Cities Unit 2	26587013	10/19/87	Y	-	-	-	-	-	0
Quad Cities Unit 2	26597001	2/27/97	Y	Y	Y	Y	-	-	0.02
Susquehanna Unit 1	38791008	7/31/91	Y	Y	Y	Y	-	-	0.02
Susquehanna Unit 2	38887006	4/16/87	Y	Y	Y	Y	-	-	0.02
Susquehanna Unit 2	38896004	7/14/96	Y	Y	Y	Y	-	-	0.02
Vermont Yankee	27191009	4/23/91	Y	Y	Y	Y	-	-	23

a. In each column, a "Y" flags the LERs counted as unplanned demands for the corresponding failure mode. With regard to a particular failure mode, each event flagged as "Y" is either a success or a failure. "-" identifies an event that did not allow an assessment of the associated failure mode (either there was no demand, or the demand was aborted by the operator and was too short to count).

Table A-4. Components in the HPCI system that change state for the various engineered safety features actuation signals during an unplanned demand.

Component	Engineered Safety Features Actuation Signals: Manual, or Low Vessel Level, or High Drywell Press.	High Vessel Level	Low CST Level, or High Suppression Pool Level
A. HPCI pump turbine	Start		
B. Service water pump	Start		
C. CST suction motor-operated valve	Open		
D. Min. flow line motor-operated valve	Throttle[a]	Throttle[a]	
E. Test flow line motor-operated valve	Close		
F. Injection discharge motor-operated valve	Open	Close	
G. Condensate storage tank test line motor-operated valve	Close		Close
H. Suppression pool suction motor-operated			Open

a. The valve throttles with pump discharge flow rate and not from an engineered safety features actuation signal.

Table A-5. BWR plants with a dedicated HPCI system and estimated number of quarterly and cyclic surveillance tests.

Plant	Cyclic Tests	Quarterly Tests	Plant	Cyclic Tests	Quarterly Tests
Browns Ferry 2	6	24	Hope Creek	10	38
Browns Ferry 3	4	9	Limerick 1	10	38
Brunswick 1	8	40	Limerick 2	9	29
Brunswick 2	10	38	Monticello	10	38
Cooper	10	38	Peach Bottom 2	11	29
Dresden 2	11	37	Peach Bottom 3	9	30
Dresden 3	10	38	Pilgrim	10	29
Duane Arnold	8	40	Quad Cities 1	9	39
Fermi 2	9	39	Quad Cities 2	12	36
FitzPatrick	11	37	Susquehanna 1	8	40
Hatch 1	8	40	Susquehanna 2	8	40
Hatch 2	8	40	Vermont Yankee	8	40

a. A cyclic test was assumed to take place of a quarterly test. In addition, a quarterly test was not counted during an extended plant outage. See section A-3 for details of surveillance test estimation.

Table A-6. Summary of the fort-six events used to estimate HPCI system unreliability.

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Browns Ferry Unit 2	26095005	6/7/95	FTSI	The unit 2 reactor was operating at 100% power. Operators were performing a surveillance to verify the operability of the HPCI system. The steam supply valve did not open on the first demand. Upon the second demand the valve did open and supplied enough steam (due to other valve line ups) that resulted in an overspeed trip of the HPCI turbine. HPCI was declared inoperable. Investigation revealed the open and close contacts of the operator were pitted and showed signs of arc deposits. The contacts were cleaned, the valve successfully stroked and the HPCI system returned to operable status.	No	No
Brunswick Unit 1	32588011	4/20/88	FTRT	POWER LEVEL - 100%. Performance of the instrument channel calibration and functional test of the unit 1 condensate storage tank low level interlock function of the HPCI system and the RCIC system revealed the HPCI pump suction from the suppression pool, e41-f041, would not open. Unit 1 was at 100%. E41-f041 would not open due to failure of the valve direct current (dc) powered motor, Limitorque corp. part no. 150-b56-189. The valve motor was replaced and the valve was returned to service. Test facility analysis of the failed motor concluded the most probable cause of the failure was breakdown of the motor winding insulation due to high inductive voltage surges across the motor shunt coil when the motor power supply circuit breaker is opened. Other failures of dc-powered motors were reported in lers 1-87-023 and 2-87-001. Modifications will be implemented to install surge protection within the shunt coil circuitry of dc motor control circuitry on units 1 and 2.	No	No
Brunswick Unit 1	32588018	7/13/88	FTRT	POWER LEVEL - 095%. Testing revealed the HPCI pump suction primary containment inboard isolation valve, 1-E41-f042, would not open. This test was the instrument channel calibration and functional test of the unit 1 condensate storage tank water level interlock functions of the high pressure coolant injection (HPCI) system and the reactor core isolation cooling (RCIC) system. The valve would not open due to a lack of electrical continuity in the opening logic resulting from a bent finger assembly of limit switch no. 4 of the logic. The bent finger is attributed to personnel error during an inspection on 7/8/88 of the valve operator torque switch and limit switch contacts as per maintenance instruction. The valve geared limit panel subassembly was replaced, the limit switch contacts were found operating properly.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Brunswick Unit 1	32591018	7/18/91	FTRI	An oil leak of approximately 0.435 gpm on the HPCI Turbine Oil Filter Inlet Pressure Gauge E41-PI-5549, drained about 10 of the approximately 88 gallons available during the 23 minutes prior to the leaks isolation. The leakage rate would have allowed another 45 minutes prior to the low level alarm and 60 minutes prior to a loss of oil pressure. If the oil leak had not been isolated eventually the oil operated HPCI trip valve would have closed due to low oil pressure, and the HPCI turbine would have stopped prior to bearing damage. This failure is actually less significant than most HPCI failure modes in that, if HPCI had been needed, it would have allowed significant HPCI operation prior to the actual system loss.	No	Yes
Brunswick Unit 2	32487001	1/5/87	FRO	POWER LEVEL - 100%. while increasing unit 2 main generator output voltage, an automatic reactor scram from 100% power occurred at 1612 hours on 1/5/87. primary containment isolation system groups 1, 2, 3, 6, and 8 isolations occurred in addition to autostarting of the high pressure coolant injection system, reactor core isolation system, and the units 1 and 2 common emergency diesel generators. During the scram recovery, the HPCI injection isolation valve, E41-f006, failed in the closed position. While controlling reactor level with the RCIC system, a reactor low level occurred at 2026 hours causing a reactor scram signal and PCIS groups 2, 6, and 8 isolations. The HPCI F006 failure is attributed to possible heat-related breakdown of the valve motor internals. The event at 2026 hours resulted from inability of the RCIC system to provide sufficient inventory makeup due to failure of the RCIC full flow test isolation valve E51-f022 to close. The F006 valve motor was replaced.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Brunswick Unit 2	32495002	5/10/95	FTSI	Unit 2 was in Operational Mode 1 at 100% power. The High Pressure Cooling Injection System was operable. During the performance of PT 9.2, HPCI System Operability Test, the HPCI turbine did not respond as expected. The Reactor Operator (RO) started the Auxiliary Oil Pump per procedure and the oil operated steam supply valves, E41-V8 and V9 stroked open. The V9 then unexpectedly went closed. The PT was secured and investigations were initiated to determine the cause of the V9 malfunction. The power supply to the governor speed control circuit was tested. Voltage readings across the wiring points of the resistor were obtained. The normal 125 VDC was available into the board but no voltage was measured on the output terminals. A failed resistor was replaced. PT 9.2 was resumed and was completed satisfactorily and HPCI was declared operable. The cause of the event was the failed resistor in the power supply circuit supplying the governor speed control circuit. The failure was caused by end of life burnout.	No	No
Cooper Station	29898011	12/18/98	FTSI	With the reactor at 10% power and 1000 psig, a steam leak occurred at the outlet flange of the turbine steam supply inlet valve. The steam leak occurred immediately upon starting the HPCI turbine for surveillance testing. The cause of the steam leak was determined to be due to misalignment of the flanges due to maintenance personnel error following replacement of the turbine steam supply valve.	No	Yes
Cooper Station	29898012	12/17/98	FTSI	The HPCI and RCIC turbines both tripped on overpseed during surveillance testing performed during plant startup from an outage. Reactor Pressure was approximately 160 psig. Technical Specifications require that HPCI be operable when reactor pressure exceeds 150 psig. Therefore, during evaluation of cause of the turbine overspeed trips, the reactor pressure was reduced below 150 psig. The cause of the overspeed trips was determined to be due to air binding in the common HPCI and RCIC pump suction piping from the CST. The cause of the air binding was determined to be that procedures did not provide adequate guidance for filling and venting the system after draining.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Dresden Unit 2	23787012	4/22/87	FTSI	While conducting startup operations at 1% rated thermal power, the reactor operator observed that the high pressure coolant injection (HPCI) turbine reset light was not lit. A unit shutdown to hot standby has been initiated due to a problem with the main turbine seal steam system. Investigation found the root cause of the turbine trip reset indication to be a loose hydraulic control system pressure switch contactor arm. Subsequently, while performing HPCI testing following repairs, the HPCI turbine was observed to trip while being brought up to speed. The turbine trip, which occurred while the HPCI emergency oil pump was on to support turning gear operation, was found to be caused by premature tripping of the HPCI auxiliary oil pump. Corrective actions included inspection, testing, and adjustment of the HPCI turbine hydraulic control system components.	No	No
Duane Arnold	33195012	12/12/95	FTRI	During quarterly HPCI system surveillance testing with the reactor at 100% power, a HPCI low flow alarm was received (<300 gpm). HPCI was manually tripped and declared inoperable. A review of transient strip charts showed that approximately 15 minutes into the run, HPCI inadvertently shutdown due to a turbine control systems signal. Less than a second later, the ramp generator reinitiated and the turbine returned to its previous operating conditions. No alarms were received for this in the control room since flow did not drop below the setpoint. Approximately 6 minutes later, the turbine again shutdown and did not restart. The low flow alarm was received this time, which alerted the operator who manually tripped the turbine. Extensive troubleshooting failed to determine the exact cause of this event. After troubleshooting and testing without note of additional problems, the HPCI system was declared operable. HPCI was inoperable approximately three days.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Fermi Unit 2	34191020	11/20/91	FTSI	POWER LEVEL - 100%. The High Pressure Coolant Injection System (HPCI) failed to start during performance of surveillance, 'HPCI Pump Time Response and Operability Test at 1000 PSI'. In compliance with the appropriate Limiting Condition for Operation, the HPCI system was declared inoperable and the Technical Specification Action Statement was entered. The system failed to start when the governor control valve (E4100F068) failed to open and admit steam to the HPCI turbine. The initial investigation showed that the Hydraulic Actuator (EGR), E41-K203, was not functioning, thus keeping the governor valve closed. The EGR was replaced. Post maintenance surveillance testing demonstrated that the HPCI system operated properly. Detroit Edison believes the cause of the EGR failure to be corrosion from water intrusion into the HPCI oil system. Investigation following the initial failure, subsequent surveillance testing, and a scheduled system outage determined the cause of the water intrusion to be a degraded barometric condenser vacuum pump (which was replaced following the subject EGR failure), and degraded turbine gland seals and turbine lube oil system sealing mechanisms (which were replaced in May of 1992). Procedure changes have been made to enhance monitoring of HPCI turbine vacuum during surveillance testing which should provide early warning of degrading barometric condenser vacuum pump and/or turbine sealing mechanism (carbon rings and dust collar) performance.	No	No
Fermi Unit 2	34193002	1/14/93	FTSI	POWER LEVEL - 098%. The High Pressure Coolant Injection System (HPCI) failed to start on a simulated auto injection signal during the performance of surveillance, 'HPCI Pump Time Response and Operability Test at 1025 psi'. The surveillance was suspended. Because surveillance 24.202.01 requires HPCI injection valve E41F006 to be deenergized in the closed position the Technical Specification Limiting Condition for Operation (LCO) had already been entered at 1313 hours with the HPCI system declared inoperable. HPCI failed to start due to a loss of supply voltage to the governor control system. This was caused by a failed voltage dropping resistor (E41K204). The resistor drops voltage from the 130 VDC bus to 48 VDC. The failed resistor was replaced with an identical resistor.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
FitzPatrick	33387010	7/23/87	FTSI	POWER LEVEL - 097%. Performing high pressure coolant injection system flow rate/pump operability/ valve operability test, the HPCI turbine stop valve (HOV-1) would not open when steam pressure was applied. Once steam pressure was removed the valve stroked open slower than normal. The cause of the slow opening was attributed to low auxiliary oil pump discharge pressure. replacement of the auxiliary oil pump and repair of HOV-1 hydraulic relay valve. The root cause was the failure of the inboard bearing in the auxiliary oil pump. The failed bearing caused reduced-pump performance resulting in lower discharge pressure. This bearing had been recently replaced but it could not be determined whether the failure was due to improper maintenance, a material problem or some other factor. The pump replacement also required readjustment of the hydraulic controls.	No	No
FitzPatrick	33388001	3/10/88	FTSI	During normal operation at 100% rated power when required to be operable by technical specification 3.5.c, HPCI was made inoperable when steam supply valve 23-MOV-14 failed to open during surveillance testing. The motor on 23-MOV-14 was destroyed by excessive current as a result of a procedure deficiency which did not require inspection and lubrication of the threads of the valve stem and stem nut when valves are repacked. Immediate corrective action was to replace the failed motor. Long-term corrective action is to revise the valve repacking procedure to require inspection, cleaning, and lubrication of the threads of the valve stem and stem nut. LERs 85-025, 86-014, 86-011, and 86-003 are related events in which safety-relate valve motors failed due to procedure deficiencies.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
FitzPatrick	33389018	10/8/89	FTSI	POWER LEVEL - 014%. A routine surveillance test of the high pressure coolant injection system was in progress during start-up after a planned three-week maintenance outage. A HPCI high steam flow signal closed the HPCI outboard steam supply isolation valves. Operators verified the absence of steam leakage. Inspection of the differential pressure transmitter, which provides the high steam flow signal, found the calibration was accurate. During recalibration a small quantity of air was observed to vent from the pressure instrument sensing lines. Initially, it was incorrectly believed that presence of non-condensible, but compressible air in the sensing lines, combined with the fast start transient, resulted in oscillations and a false high steam flow signal. Subsequently (LER-89-025), it was discovered that the high steam flow signal was valid and caused by use of a more conservative test procedure and overly conservative technical specification high steam flow and FSAR activation time limits. LERs-89-025 and ler-89-002 are related.	No	Yes
FitzPatrick	33389020	11/5/89	MOOS	POWER LEVEL - 100%. A reactor scram occurred from full power. An unidentified failure in an electronic control card of the electro-hydraulic control system for the main turbine is believed to have opened the bypass valves and closed the intercept and control valves. This reduction in steam flow caused a pressure transient resulting in a reactor high flux scram signal from the average power range monitor The high pressure coolant injection system was inoperable prior to the scram. The reactor core isolation cooling system was used to restore reactor water level.	No	No
FitzPatrick	33389025	11/30/89	FTSI	POWER LEVEL - 100%. The HPCI system isolated on a high steam flow signal during a surveillance test initiating a 7-day lco It failed to meet operability testing criteria during surveillance testing by requiring more than 25 secs to achieve full flow. Additional recording instruments were connected, vendor field engineers were obtained and extensive testing was performed. The NRC granted a temporary waiver of the setpoint requirements for the high steam flow isolation prior to expiration of the 7-day lco and approved a tech spec amendment increasing the high steam flow differential pressure setpoint. PORC approved increasing the fsar design basis required actuation time for HPCI from 25 to 30 secs. A 1981 vendor recommendation was implemented increasing the turbine start-up ramp time from 9 to 15 secs. Causes included an overly conservative tech spec limit and fsar basis for maximum actuation time and implementation of a more conservative procedure.	No	Yes

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
FitzPatrick	33395008	3/26/95	FTSI	During post-refueling outage surveillance testing of the HPCI system with the reactor at 20% power, the HPCI turbine tripped on overspeed when the cold quick start test was attempted. Investigation revealed that the HPCI flow controller output current limit circuit adjustment was not included in the flow controller calibration procedure. Actual controller output current was high enough to increase the time period of controller current saturation thus allowing turbine speed to overshoot and cause an overspeed trip. Corrective action included proper calibration of the controller and changes to the calibration procedure.	No	Yes
Hatch Unit 1	32190001	1/4/90	FTRI	POWER LEVEL - 100%. The high pressure coolant injection system was declared inoperable because rated flow was not maintained during the performance of normal surveillance testing. An investigation later discovered that a failed resistor resulted in a loss of the power supply to the electronic governor controlling the hpci turbine speed. The defective resistor was replaced, procedure 34sv-e41-002-1s, 'hpci pump operability', was performed successfully, and hpci was declared operable. The cause of this event is component failure. A failed resistor de-energized the electronic governor power supply. This component failure appears to be an isolated event.	No	No
Hatch Unit 1	32191001	1/18/91	FTSI	POWER LEVEL - 100%. A remote power transmission line failed at its attachment point to the supporting electrical tower. in addition, a breaker in the plant hatch 230 kv switchyard failed to fully open in response to the sensed electrical fault conditions resulting in the trip of the unit 1 main transformer aux. lockout relay. Trips, which, in turn, resulted in a reactor scram. This also resulted in a loss of power to the unit 1 nonessential electrical busses and the prevention of the normal automatic transfer to the alternate supply due to the transfer logic. Power was manually restored to nonessential loads within approx. 2 to 3 minutes allowing for the initiation of operator actions to restore feedwater flow. In the interim, to recover reactor water level, the high pressure coolant injection system automatically initiated. Although it exhibited erratic behavior in the automatic mode, it was successfully controlled manually and water level was restored and maintained with HPCI until feedwater flow was restored. Reactor pressure was controlled by the turbine bypass valves.	Yes	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Hatch Unit 1	32191033	12/30/91	FTRI	POWER LEVEL - 100%. The high pressure coolant injection system experienced flow oscillations of approximately 2000 gallons per minute while being tested in accordance with procedure 'hpci pump operability'. The procedure was being performed in order to meet the surveillance requirement of unit 1 technical specifications. In each case, the system was secured and declared inoperable. The cause of each event was intermittent failure of a transfer relay(s) internal to the HPCI system flow control unit, 1E41-K615. The relays function to transfer flow control between the manual and automatic modes. failure of the relay(s) caused HPCI system flow to oscillate excessively in each of the events.	No	Yes
Hatch Unit 1	32192006	2/26/92	FTRI	POWER LEVEL - 100%. The high pressure coolant injection system was declared inoperable due to it failing to achieve stable flow and pressure at rated conditions (greater than or equal to 4250 gpm at a pump discharge pressure of greater than or equal to 1080 psig) during testing. Specifically, upon manual initiation of the system, it achieved rated conditions and then became unstable with flow oscillating from 3000 to 5000 gpm. The flow controller was then transferred from the automatic mode to the manual mode; at that time, system flow stabilized at rated conditions. The system was secured and declared inoperable. The appropriate technical specifications limiting condition for operation was implemented. The HPCI flow control system control settings were adjusted to increase the stability of the system. The HPCI system was subsequently satisfactorily tested, experiencing no unusual flow oscillations in the automatic mode. The cause of the event was less than adequate maintenance procedures. Specifically, procedures did not address tuning the flow control system following maintenance on the system. Consequently, the tuning of the system was not adequate, resulting in instability in the flow control system.	Yes	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Hatch Unit 2	36687004	6/16/87	FTSI	POWER LEVEL - 090%. A surveillance on the high pressure coolant injection, the system was behaving erratically and HPCI was determined to be incapable of performing its intended safety function. Corrective maintenance was initiated on the HPCI system and on 6/18/87, two primary containment isolation system HPCI steam supply valve isolations occurred. These isolations were unplanned actuations of an engineered safety feature. The root causes for the events were: 1) a defective procedure, and 2) personnel errors. Specifically, a calibration procedure did not contain sufficient directions (or allow the use of reverse or direct acting governors, and on site and vendor personnel did not verify that correct parts were issued. corrective actions for these events included: 1) replacing equipment, 2) checking or calibrating equipment, 3) demonstrating HPCI operability, 4) issuing an as built notice, 5) placing spare parts on hold, 6) reviewing plant document, 7) revising or scheduling revisions to procedures, 8) initiating vendor feedback and audit reviews, 9) performing a 10 cfr part 21 evaluation, and 10) counseling personnel.	No	No
Hatch Unit 2	36687009	8/3/87	FTRI	POWER LEVEL - 090%. The HPCI system received a valid auto-initiation signal, injected, and a normal pump turbine startup occurred. As HPCI approached rated flow conditions, the turbine tripped on a low pump suction pressure signal. The trip signal cleared and the turbine trip reset automatically, per design. Since the initiation signal was still present, the HPCI turbine began, again, to ramp up to rated speed. However, the pump discharge gate valve, 2E41-F006, had received an auto-close signal from the first turbine trip and was continuing to close when the turbine reset itself. The discharge valve logic is such that once the valve has begun to stroke closed, it can not be stopped in mid-position and re-opened. The valve must continue to travel until the close stroke is completed. The valve then closed completely, momentarily stopping flow to the reactor vessel. The valve immediately reopened (since the initiating signal was still present), and HPCI delivered rated flow to the reactor vessel (second injection, for this event). Plant personnel concluded that the anomalous HPCI operation was the result of an air pocket in the HPCI pump suction instrument line. When maintenance personnel vented the instrument line, significant amounts of air were found. Several possibilities exist which could have caused the air to become entrapped, such as valve maintenance or the introduction of air during instrument calibration.	Yes	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Hatch Unit 2	36687017	11/19/87	FTSI	POWER LEVEL – 085% Plant operations personnel were performing a surveillance procedure and determined that the high pressure coolant injection system would not function correctly in the automatic mode of operation. This was a condition that could have prevented the automatic fulfillment of the safety function of HPCI to mitigate the consequences of an accident. The HPCI system would function correctly in the manual mode of operation. The root cause of this event is attributed to normal equipment aging. Specifically, a defective amplifier card and a defective solder joint were found in sub-modules of the controller amplifier. The corrective actions for this event included: 1) replacing the defective amplifier card, 2) repairing the solder joint, 3) calibrating the controller amplifier, and 4) demonstrating that the HPCIsystem was operable in the automatic mode of operation.	No	Yes
Hatch Unit 2	36690001	1/12/90	FRO	POWER LEVEL - 100%. The reactor scrammed because the main steamline isolation valves were less than 90% open. HPCI automatically initiated and injected on low reactor water level as required. Following water level recovery, HPCI injection valve 2E41-F006 closed automatically on high water level; however, it could not be re-opened when operations personnel subsequently attempted to start HPCI manually. The reactor core isolation cooling system and two control rod drive system pumps were used to control water level following the failure of valve 2E41-F006 to open. The cause of valve 2E41-F006 failing to open is component failure.	No	No
Hope Creek	35497032	12/5/97	FTSI	During HPCI system testing upon plant restart from an outage, the HPCI turbine tripped after starting, the trip then reset and the turbine restarted. Approximately 14 minutes into the run, increasing noise and vibration was detected coming from the turbine. The turbine was manually tripped and HPCI was declared inoperable. The cause of the HPCI trip was a tappet spring that had lost its force due to vibration affecting the spring adjusting sleeve. The cause of the HPCI noise and vibration was rubbing between the shaft and the carbon gland steam seal rings due to corrosion. The rubbing caused a hot spot that cause shaft bowing. The bowing further aggravated the rubbing and vibration. It is doubtful that the turbine could have run sufficiently long to perform its safety mission. Therefore, this event would be classified as a recovered fail to start followed by a fail to run.	No	Yes

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Limerick Unit 1	35287015	5/14/87	FTRI	POWER LEVEL - 076%. The high pressure coolant injection turbine shutdown after running for 25 minutes during the performance of an hpci system surveillance test. The unplanned HPCI turbine shutdown is believed to have resulted from a loose lead on the output of the flow controller. Also the valve stem of HPCI turbine stop valve FV-56-112 was discovered separated from the split coupling which connects the valve stem to the actuator stem. The threads inside the split coupling had been stripped. The separation of the valve stem from the split coupling is believed to have occurred when the valve opened and the disc overtravelled due to increased momentum created by a drift in the balance chamber adjustment. The balance chamber had been adjusted in accordance with general electric service information letter #352. The loose lead on the flow controller was tightened and the tightness of the other wire connections were checked and verified. The turbine stop valve has been repaired. The balance chamber adjustment will be checked quarterly for at least three quarters to prevent recurrence of the valve failure.	No	No
Limerick Unit 1	35287015c	5/14/87	FTRI	POWER LEVEL - 076%. The high pressure coolant injection turbine shutdown after running for 25 minutes during the performance of an HPCI system surveillance test. The unplanned HPCI turbine shutdown is believed to have resulted from a loose lead on the output of the flow controller. Also the valve stem of HCPI turbine stop valve FV-56-112 was discovered separated from the split coupling which connects the valve stem to the actuator stem. The threads inside the split coupling had been stripped. The separation of the valve stem from the split coupling is believed to have occurred when the valve opened and the disc overtravelled due to increased momentum created by a drift in the balance chamber adjustment. The balance chamber had been adjusted in accordance with general electric service information letter #352. The loose lead on the flow controller was tightened and the tightness of the other wire connections were checked and verified. The turbine stop valve has been repaired. the balance chamber adjustment will be checked quarterly for at least three quarters to prevent recurrence of the valve failure.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Limerick Unit 1	35287066	12/8/87	FTRI	POWER LEVEL - 099%. 'HPCI pump, valve and flow test', the high pressure coolant injection system was declared inoperable due to the erratic operation of the HPCI turbine stop valve. Approximately 20 minutes into the test, while in its full flow test configuration, the HPCI stop valve unexpectedly fully closed and reopened. The stop valve continued to close and reopen several times. An immediate investigation into the cause of the problem revealed that although a HPCI turbine overspeed condition was not present, the hydraulic-mechanical overspeed trip mechanism was cycling between the tripped and normal positions. The cause of the malfunction is believed to have been a blockage of a small internal drain port in the overspeed trip and automatic reset piston assembly.	No	No
Limerick Unit 1	35292015	7/7/92	FTRI	POWER LEVEL - 006%. While performing the High Pressure Coolant Injection (HPCI) system pump, valve, and flow surveillance test (ST), the HPCI system turbine stop valve unexpectedly fully closed and reopened. The turbine stop valve continued to close and reopen several times. An investigation revealed that particles had clogged equipment associated with the hydraulic-mechanical turbine overspeed trip mechanism, causing the stop valve movement. Cleaning and flushing of the hydraulic-mechanical overspeed trip mechanism internals was completed, the HPCI ST procedure was successfully performed. The source of the particles that had entered the HPCI hydraulic system could not be positively determined. To prevent the recurrence of a similar event, appropriate HPCI system maintenance procedures will be revised to ensure that flushing of the hydraulic system is performed during each refueling outage.	No	No
Limerick Unit 1	35296018	9/25/96	FTSI	During performance of HPCI pump and valve surveillance testing with the reactor operating at 100% power, the HPCI system failed to start. During system startup, the HPCI repeatedly tripped on overspeed and then restarted until operators manually secured the turbine. HPCI was declared inoperable. The cause was determined to be a loose speed sensor connection. HPCI was declared operable approximately 10 hours later after successful completion of the system surveillance test.	No	Yes

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Monticello	26394017	10/23/94	FTRI	While performing a surveillance test of the steam turbine driven High Pressure Coolant Pump (HPCI) at a reactor power of 12% and a reactor pressure of 910 psig, the steam supply valves closed due to an automatic high steam flow isolation signal. The test was being performed at a lower than normal steam pressure. The combination of reduced steam supply pressure and indicated turbine speed error cause the steam flow to produce a differential pressure across the venturi that was greater than the isolation setpoint (150,000 lbm/hr for 45 sec.). The HPCI system was declared inoperable and remained inoperable for approximately 24 hours while this event was being investigated. It should be noted that HPCI was available but not operable.	No	Yes
Peach Bottom Unit 2	27794004	7/18/94	FTSI	During performance of the normally scheduled HPCI system surveillance test at 88% reactor power, HPCI was declared inoperable because the turbine could not be raised to rated speed. Troubleshooting revealed that speed could not be increased to greater than 1000 rpm because the voltage regulator in the flow controller signal isolating device had failed. Following repairs, HPCI was tested. Test results were satisfactory.	No	No
Peach Bottom Unit 2	27796009	10/1/96	FTRI	HPCI was declared inoperable during system testing that was performed during power accension from a Unit 2 outage. The system was declared inoperable due to excessive heat on the booster pump outboard seal. The cause of the bad seal was determined to be due to misalignment of the outboard bearing housing. The misalignment occurred during corrective maintenance on the outboard bearing housing gaskets. The root cause was determined to be inadequate maintenance procedure guidance on alignment of the bearing housing following reassembly. Note that systems and components are normally tested to determine operability prior to placing them in service and prior to startup. HPCI testing is performed after startup to determine operability and HPCI cannot be tested during outages (no steam). Run time was estimated.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Peach Bottom Unit 3	27889009	12/7/89	FTSI	POWER LEVEL - 003%. high pressure coolant injection system was declared inoperable when it failed to start during a pump, valve and flow surveillance test. The HPCI turbine steam supply hydraulic stop valve had failed to open during the manual start attempt. The cause of this event was a loose lock nut open on the HPCI oil system relief valve RV-9214 which allowed the oil pressure setpoint to drift low. Therefore, the hydraulic stop valve was not supplied with sufficient pressure to allow it to lift open to admit steam to the HPCIi turbine. The cause of the RV-9214 lock nut being loose is unknown. Surveillance test ST 21.3 has been revised to verify proper HPCI auxiliary oil pump discharge pressure prior to plant startup. A lead seal wire will be placed on the HPCIi oil system relief valve caps to prevent any maintenance activities from inadvertently dislodging the lock nut.	No	No
Peach Bottom Unit 3	27890010	8/4/90	FTRI	POWER LEVEL - 085%. The high pressure coolant injection system was declared inoperable since the turbine stop valve would not stay in the opened position during system operation. Further investigation revealed that the manual and overspeed trip tappet assembly spring did not have adequate spring tension to maintain the tappet in the reset position. The spring tension was adjusted and HPCI was returned to an operable status. The cause of the spring tension force not being enough to reset the tappet is believed to be a design problem involving tappet swelling, which changes its clearances as described in general electric company rapid information communication service information letter (ricsil) 04, ricsil 37, sil 392, and nrc information notice 88-067. A new design, which is being provided by GE, will replace the existing tappet assembly.	No	No
Peach Bottom Unit 3	27895002	7/6/95	FTSI	HPCI was declared inoperable when the steam supply valve failed to open fully during quarterly surveillance testing. The cause was determined to be failed stator windings in the motor operator. Following repairs and post-maintenance testing, the HPCI system was returned to service the following day.	No	No
Peach Bottom Unit 3	27896001	5/29/96	FTSI	While operating at 100% power, HPCI was declared inoperable when the HPCI turbine control valve failed to open during performance of periodic surveillance testing. The cause was determined to be a failed solder connection in the speed and flow control circuit that prevented the control valve from opening. HPCI was returned to service the following day after repairs and testing.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Pilgrim	29389013	3/24/89	FTSI	POWER LEVEL - 025%. The high pressure system became inoperable during an operability surveillance test. The system became inoperable because a HPCI system turbine steam supply motor operated valve, normally in the closed position, would not open. The cause for the failure of the valve to open was two loose screws used to adjust the valve's torque switch setting. The loose screws affected the torque setting and consequently caused damage to some of the valve operator internals and the failure of the valve operator motor windings. The valve operator Limitorque size smb-1 was repaired and the motor was replaced. The torque switch was set and the screws were torqued to 18 inch-pounds. movats valve testing was performed with acceptable results. Additional corrective actions taken or planned include inspection of other safety-related motor operated valves, installing torque switch limiter plates and revision of applicable valve maintenance procedures. The motor (250 vdc, serial number m70557) was manufactured by Peerless Electric/h.k. Porter Company Inc.	No	No
Quad Cities Unit 1	25491012	5/7/91	FTSI	POWER LEVEL - 093%. High pressure coolant injection system was declared inoperable to perform HPCI system manual initiation test. During this test the HPCI turbine stop valve failed to stroke fully open. Upon investigating the problem, it was identified that the long bushing in the stuffing box of the stop valve had slid down the valve stem and the bushing pin had sheared. Unit two HPCI stop valve was checked to verify that the same problem did not exist. It was discovered that the long bushing was also partially out of the stuffing box with no bushing pin in the bushing. Unit two HPCI was declared inoperable. Inadequate vendor instructions which resulted in the stuffing boxes not being opened.	No	No
Quad Cities Unit 1	25492002	2/6/92	FTSI	POWER LEVEL - 099%. Unit one high pressure coolant injection system was declared inoperable after the stop valve was verified stuck in the open position. The HPCI stop valve failed while an operator was testing the pushbutton latch on the HPCI remote trip pushbutton. Upon investigating the problem, it was identified that weld at the base of the poppet guide of the stop valve had drawn the guide over enough to bind up the main poppet disk during operation. The failure of HPCI was due to inadequate work instructions for the overhaul of the valve. The stop valve was successfully repaired, tested, and declared operable.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Quad Cities Unit 1	25493005	6/9/93	FTSI	POWER LEVEL - 072%. Unit One was in the run mode at 72 percent rated core thermal power. At this time, the Nuclear Station Operator (NSO) was performing QCOS 23005, quarterly HPCI pump operability test, when numerous alarms were received in the control room including the HPCI turbine rupture disc high pressure alarm. The NSO then tripped the HPCI turbine. Subsequent investigation determined that the HPCI rupture disk had ruptured, releasing a steam/water mixture into the room. As a result of this, the secondary containment interlock doors and fire doors were damaged, and five people in attendance were injured (first and second degree burns). The cause of the rupture disk failure was due to a water slug that was present in the turbine casing. A contributing factor to this event was due to procedural inadequacies and interpretation problems during QCOS 2300-5 procedure. Short term corrective actions included repairing the damaged doors and a walkdown of the rooms to look for any significant operability concerns. Long term corrective actions include testing the HPCI and RCIC steam supply level switches on a periodic basis, changing the procedure to provide better guidance and interpretation, establishing inspection program for the HPCI and RCIC rupture disks, and providing training on the procedure and this event.	No	No
Quad Cities Unit 1	25495004	3/29/95	FTSI	The unit 1 reactor was operating at 100% power. Operators were performing the quarterly surveillance, " HPCI Pump Operability Test" when the Motor Speed Changer (MSC) failed to move off the Low Speed Stop (LSS). The surveillance was terminated and the HPCI system declared inoperable. Investigation revealed a failed LSS limit switch. The switch was replaced, tested and the HPCI was restored to operable status.	No	No
Susquehanna Unit 1	38790007	2/15/90	FTSI	POWER LEVEL - 097%. During performance of a quarterly high pressure coolant injection flow surveillance test, the HPCI stop valve did not open. Technical staff recommended that HPCI should not be restored to operable status without first correcting the HPCI stop valve response. The cause of this event is believed to be high balance chamber pressure seen in the HPCI stop valve in conjunction with the magnitude of the hydraulic and steam forces that existed when the HPCI flow surveillance test was run. Maintenance personnel reset the adjustment screws for the hpci stop valve balance chamber.	No	No

Table A-6. (continued).

Plant Name	LER Number	Event Date	Failure Mode	Event Description	Recovery	Recoverable
Susquehanna Unit 1	38791002	2/7/91	FTSI	POWER LEVEL - 100%. The HPCI outboard steam supply line isolation valve failed to open during a routine valve exercising surveillance test. After further attempts to open the valve were unsuccessful, HPCI was declared inoperable The cause of this event was unable to be determined although there was an apparent intermittent malfunction in the valve open control circuit which has not repeated. Wiring, relays, and terminations were completed and no discrepancies were found that could explain the event. The valve has been stroked successfully a number of times since the event. However, the frequency for the valve exercising surveillance test for this valve will be increased to monthly for the next quarter to ensure proper operation.	No	No

Appendix B

Basic Event Failure Probabilities and Unreliability Trends

Appendix B

Basic Event Failure Probabilities and Unreliability Trends

This appendix displays relevant HPCI system counts and the estimated probability of each failure mode, including distributions that characterize any variation observed between portions of the data. It lists the plant-specific unreliability estimates, and evaluates whether trends exist in the HPCI system data. Three types of detailed analyses are given:

- A plant-specific analysis for probability of individual failure modes;
- An investigation of the possible relation between plant low-power license date and HPCI performance as measured by unreliability, by the frequency of unplanned demands, and by the frequency of failures; and
- An investigation of whether overall performance as measured by these attributes changed during the twelve years of the study.

In addition to a presentation of the basic results, differences between this study (including 1994-1998 data) and the original HPCI reliability study (Reference B-1) are highlighted.

B-1. FAILURE MODE UNCERTAINTY DISTRIBUTIONS

In the first subsection below, statistical analysis of each HPCI failure mode is discussed. The resulting best estimates for each failure mode are summarized. In a second subsection, plant-specific estimates are listed for each applicable failure mode.

B-1.1 Analysis of Individual Failure Modes

Table B-1 contains results from the initial assessment of data for the twelve HPCI system failure modes including point estimates and confidence bounds for each probability of failure. Unlike the original HPCI report, the table contains two approaches for failure to run for injection: a demand-based approach for the short-term mission and a rate-based approach for the long-term mission typically postulated in PRA/IPEs. The twelve modes also include failure to recover probabilities for the modes for which potentially recoverable failures occurred. Each group of entries in the table corresponds to a failure mode in one of the two HPCI fault trees, Figures 3 and C-1. Note that the point estimate and bounds do not consider any special sources of variation (e.g., year or plant). The purpose of Table B-1 is to assist the analyst in understanding the relationships between the different data groupings. The data are listed by type of demand (unplanned demands and quarterly and cyclic testing, as applicable). Maintenance out of service data are listed by plant mode. The breakdowns allow patterns such as trends or outliers to become more apparent, if they exist. For example, comparison of confidence intervals provides an indication of the whether the data sets can be pooled.

Table B-2 summarizes the results from testing the hypothesis of constant probabilities or rates across groupings for each failure mode based on data source, on plant mode for MOOS, on time periods (the original study time period, 1987-1993, versus the added 1994-1998 time period), on plants, and on the twelve calendar years spanned by the study. Statistical evidence of differences across these groupings was found in a few cases, as indicated by small probability values in the table.

Table B-1. Point estimates and confidence bounds for HPCI failure modes (1987–1998 operating experience).

Failure mode	Data set	Failures f	Demands d [a]	Probability [b]
Maintenance out-of-service (MOOS)	**Unpl. demands (op.)** [c]	**1**	**94**	**(5.5E-04, 1.1E-02, 4.9E-02)**
	Unpl. demands (s/d.)	0	3	(0.0E+00, 0.0E+00, 6.3E-01)
	Unplanned demands	1	97	(5.3E-04, 1.0E-02, 4.8E-02)
Failure to start, injection valve (FTSV)	**Unplanned demands**	**0**	**79**	**(6.5E-04, 1.3E-02, 5.9E-02)**
Failure to start, other than injection valve (FTSI)	Unplanned demands	1	94	(5.5E-04, 1.1E-02, 4.9E-02)
	Cyclic tests	5	217	(9.1E-03, 2.3E-02, 4.8E-02)
	Quarterly tests	22	846	(1.8E-02, 2.6E-02, 3.7E-02)
	Pooled unpl. dem. & tests	**28**	**1157**	**(1.7E-02, 2.4E-02, 3.3E-02)**
Failure to recover FTSI (FRFTSI)	Unplanned demands	0	1	(0.0E+00, 0.0E+00, 9.5E-01)
	Cyclic tests	3	5	(1.9E-01, 6.0E-01, 9.2E-01)
	Quarterly tests	17	22	(5.8E-01, 7.7E-01, 9.1E-01)
	Pooled unpl. dem. & tests	**20**	**28**	**(5.4E-01, 7.1E-01, 8.5E-01)**
Failure to run, other than suction transfer (FTRI; short-term)	Unplanned demands	2	83	(4.3E-03, 2.4E-02, 7.4E-02)
	Cyclic tests	2	212	(1.7E-03, 9.4E-03, 2.9E-02)
	Quarterly tests	9	824	(5.7E-03, 1.1E-02, 1.9E-02)
	Pooled unpl. dem. & tests	**13**	**1119**	**(6.9E-03, 1.2E-02, 1.8E-02)**
Failure to run, other than suction transfer (FTRI) (rate for PRA comparison—see note d)	Unplanned demands	2	43.2 h	(8.2E-03, 4.6E-02, 1.5E-01)
	Cyclic tests	2	213.0 h	(1.7E-03, 9.4E-03, 3.0E-02)
	Quarterly tests	9	824.0 h	(5.7E-03, 1.1E-02, 1.9E-02)
	Pooled unpl. dem. & tests	**13**	**1080.2 h**	**(7.1E-03, 1.2E-02, 1.9E-02)**
Failure to recover FTRI (FRFTRI)	Unplanned demands	0	2	(0.0E+00, 0.0E+00, 7.8E-01)
	Cyclic tests	1	2	(2.5E-02, 5.0E-01, 9.7E-01)
	Quarterly tests	7	9	(4.5E-01, 7.8E-01, 9.6E-01)
	Pooled unpl. dem. & tests	**8**	**13**	**(3.5E-01, 6.2E-01, 8.3E-01)**
Probability of multiple injections (PMI)	**Unplanned demands**	**12**	**79**	**(9.0E-02, 1.5E-01, 2.3E-01)**
Failure to reopen, injection valve (FRO)	**Unplanned demands**	**2**	**12**	**(3.0E-02, 1.7E-01, 4.4E-01)**
Failure to recover FRO (FRFRO)	**Unplanned demands**	**2**	**2**	**(2.2E-01, 1.0E+00, 1.0E+00)**
Failure to run, suction transfer (FTRT)	Unplanned demands	0	6	(0.0E+00, 0.0E+00, 3.9E-01)
	Cyclic tests	0	210	(0.0E+00, 0.0E+00, 1.4E-02)
	Quarterly tests	2	815	(4.4E-04, 2.5E-03, 7.7E-03)
	Pooled unpl. dem. & tests	**2**	**1031**	**(3.4E-04, 1.9E-03, 6.1E-03)**
Failure to recover FTRT (FRFTRT)	Quarterly tests	2	2	(2.2E-01, 1.0E+00, 1.0E+00)
	Pooled unpl. dem. & tests	**2**	**2**	**(2.2E-01, 1.0E+00, 1.0E+00)**

a. Except for FTRI, for which running time (hours) is given.

b. The middle number is the point estimate, *f/d*, and the two end numbers form a 90% confidence interval.

c. Rows in bold refer to the data sets used in the unreliability analysis.

d. A 90% confidence interval for the failure rate was derived based on a Poisson distribution for the occurrence of failures. This rate was used with a total system mission time of 24 hours to derive the upper confidence limits for the probability of FTRI [probability=1-exp(rate*mission time)].

Table B-2. Evaluation of differences between groups for HPCI failure modes.

Failure mode	Data set	P-values for Test of Variation[a]				
		In Data Sources	In Plant Modes	In Time[b]	In Plant Units	In Years
Maintenance out-of-service (MOOS)	Unplanned demands (op.)	—	—	1.000	0.965	0.323
	Unplanned demands (s/d.)	—	—	0 f.	0 f.	0 f.
	Unplanned demands	—	1.000	1.000	0.958	0.294
Failure to start, injection valve (FTSV)	Unplanned demands	—	—	0 f.	0 f.	0 f.
Failure to start, other than injection valve (FTSI)	Unplanned demands	—	—	1.000	0.997	0.572
	Cyclic tests	—	—	0.664	0.379 (E)	0.825
	Quarterly tests	—	—	0.520	0.182 (E)	0.654
	Pooled unpl. dem. & tests	0.849	—	0.847	0.077 (E)	0.420
Failure to recover FTSI (FRFTSI)	Unplanned demands	—	—	0 f.	0 f.	0 f.
	Cyclic tests	—	—	1.000	0.172	0.287
	Quarterly tests	—	—	0.309	0.222	0.211
	Pooled unpl. dem. & tests	0.263	—	0.671	0.245 (E)	0.805
Failure to run, other than suction transfer (FTRI; short-term)	Unplanned demands	—	—	1.000	0.658	0.868
	Cyclic tests	—	—	0.208	0.735	0.625
	Quarterly tests	—	—	**0.049 (E)**	**0.001 (E)**	0.060 (E)
	Pooled unpl. dem. & tests	0.415	—	0.171	**0.013 (E)**	0.125 (E)
Failure to run, other than suction transfer (FTRI) (rate for PRA comparison)	Unplanned demands	—	—	0.678	**0.001 (E)**	0.621
	Cyclic tests	—	—	0.122	0.739	0.628
	Quarterly tests	—	—	**0.045 (E)**	**0.000 (E)**	0.063 (E)
	Pooled unpl. dem. & tests	0.120 [c]	—	0.145	**0.010 (E)**	0.068 [c] (E)
Failure to recover FTRI (FRFTRI)	Unplanned demands	—	—	0 f.	0 f.	0 f.
	Cyclic tests	—	—	—	0.157	0.157
	Quarterly tests	—	—	1.000	0.162	0.191
	Pooled unpl. dem. & tests	0.119	—	1.000	0.178 (E)	0.259
Probability of multiple injections (PMI)	Unplanned demands	—	—	0.679	0.571 (E)	0.227 (E)
Failure to reopen, injection valve (FRO)	Unplanned demands	—	—	1.000	0.920	0.840
Failure to recover FRO (FRFRO)	Unplanned demands	—	—	All f	All f	All f
Failure to run, suction transfer (FTRT)	Unplanned demands	—	—	0 f.	0 f.	0 f.
	Cyclic tests	—	—	0 f.	0 f.	0 f.
	Quarterly tests	—	—	0.505	**0.021**	**0.006**
	Pooled unpl. dem. & tests	1.000	—	0.504	**0.012**	**0.004**

Table B-2. (continued).

Failure mode	Data set	P-values for Test of Variation[a] In Data Sources	In Plant Modes	In Time[b]	In Plant Units	In Years
Failure to recover FTRT (FRFTRT)	Quarterly tests	—	—	All f	All f	All f
	Pooled unpl. dem. & tests	All f	—	All f	All f	All f

a. —, not applicable; 0 f., no failures (thus, no test); all f, no successes (thus, no test). In each case the failures and the demands or run times were grouped according to values of the variable in the column heading, and pooled over the other variables. P-values are based on chi-square tests in most cases. When probabilities for exactly two groups or three are being compared, as with differences in time (older vs. newer) or differences between demand types, Fisher's exact test is used. P-values less than 0.05 are in bold, flagging situations where possibly statistically significant differences exist. The statistics may not indicate true statistical significance because such tests are not always valid when the data are sparse, and because multiple testing is being performed which increases the opportunity to observe differences even in random data from constant failure rates. An **(E)** is shown if and only if an empirical Bayes distribution was found that accounts for any variation within the data set.

b. A comparison of the 1987-1993 time period of the original study (7 years) and the newly-added five years (1994-1998).

c. P-value computed using the HOMOG computer program [Reference B-2].

When failures occur according to a binomial distribution with the probability of failure varying from plant to plant or from year to year according to some beta distribution, empirical Bayes methods apply. In this case, the between-plant or between-year variation is modeled in the underlying beta distribution. The particular beta distribution is selected by finding the distribution that maximizes the likelihood of the observed data. For rates, a similar approach for analysis exists with Poisson-distributed event occurrences and an underlying gamma distribution for the failure rate. Further details on these methods are in Appendix A of Reference B-1 and in References B-3 through B-6.

B-1.1.1 HPCI System Failure Modes

Paragraphs below describe the particular data that were used to estimate the failure probability for each failure mode and the rationale for choosing particular models. When the data are sparse, or between-group variation is minimal, the likelihood function is flat or slopes down from the extremes of the possible range of parameters, so no unique set of parameters maximizing the likelihood can be found. Unless otherwise stated, this situation prevailed for the HPCI data. In this case, simple Bayes distributions were used in the unreliability analysis. As explained further in the references, these distributions update the Jeffreys noninformative prior (which imitates the effect of sampling variation with 0.5 failures in one demand) using the pooled industry total number of failures and total number of demands. The data sets selected for the reliability modeling are shown in bold in Table B-1.

With twelve instead of seven years of data, the data for each failure mode were also examined for time trends and trends with plant low-power license date. This subject is also addressed in the paragraphs below as applicable.

Maintenance-out-of-Service (MOOS). A single MOOS event occurred among the 94 unplanned HPCI demands during plant operation during the study period. Although the data show no significant differences between the two plant modes, the MOOS probability estimate obtained from the operating plant data, excluding the shutdown plant data, was used in this study. The data were not pooled across modes since an engineering/plant-operations perspective indicates that maintenance generally occurs at a higher rate during shutdown periods. Operating periods are more applicable for the estimates considered in this study, and are used to estimate the maintenance contribution to HPCI unreliability.

Failure to Start, Injection Valve (FTSV). The new data review resulted in 20 additional unplanned demands from the previous 59, and no failures.

Failure to Start, Other Than Injection Valve (FTSI). For the new data assessment, quarterly surveillance test data were judged to be rigorous enough to approximate the demand that an unplanned safety injection places on the HPCI system other than the injection valve. The quarterly test demands were estimated based on four tests per year, except that the cyclic tests were assumed to replace a quarterly surveillance whenever they occur. That is, the quarterly test demands in each year were reduced by the number (0 or 1) of cyclic tests in that year. Statistical tests did not reveal significant differences in the unplanned demand, quarterly and cyclic surveillance data, so they were pooled. The pooling minimizes the need to distinguish between quarterly and cyclic tests, which was an issue in the use of quarterly data in the original study.

The FTSI probability was somewhat less in the new data than the original study, but the probability difference between the two time periods was not statistically significant (p-value 0.85). The test for a trend using a log linear model for the data had similar results: the p-value was 0.46, which is not significant.

Significant plant-specific differences were found, so an empirical Bayes distribution reflecting plant differences was used in the unreliability analysis. The results from this distribution are listed in Section B-1.2, Table B-4.

Failure to recover FTSI. In the data from both quarterly and cyclic testing, most of the FTSI failures were judged to be recoverable. Just one failure occurred on an unplanned demand, and it was not judged to be recoverable. Since the unplanned demand data were sparse, the statistical test for differences between the unplanned demand and test data did not find significant differences. The unplanned demand and test data were pooled, and the empirical Bayes distribution found for the data grouped by plant was used in the analysis. (See Table B-5 in Section B-1.2).

Failure to run, other than suction transfer (short-term mission) (FTRI). Each demand for which the injection pump started is potentially an opportunity to assess the success or failure of the system in running for the short-term mission model. Those events in which HPCI was terminated immediately after the pump started were excluded. Long run times are not required for the short-term mission model, nor is the performance of the automatic transfer function for the suction source required. The quarterly and cyclic test data were applicable, since the test run times are estimated at an hour which is longer than all but four of the demands.

No statistically significant differences were found in the FTRI probability between the unplanned demands and two types of tests. Trends were not seen with regard to low-power license date. Since four of the thirteen failures occurred in 1987, the first year of the study period, a slightly significant decreasing trend was found in the failure probability with regard to calendar year. The p-value was 0.045 using a logit model, with log[p/(1-p)] decreasing as year increases; and the p-value was 0.107 using a simple log p model with a Bayesian update to the inputs (adding 0.48 to the failures and 39.48 to the demands) to make all the counts greater than zero. The test of differences between the 1987-1993 and added 1994-1998 period was not significant (p-value 0.171), and the test of overall differences in the twelve years of the study was not significant (p-value 0.125). Since just one of these four statistical evaluations had statistical significance, and it was not highly significant (e.g., with p-value less than 0.01), the FTRI probability data were not differentiated by plant year in the analysis other than in the yearly unreliability trend evaluation discussed in Section B-4.

For the primary unreliability analysis, the empirical Bayes distribution found for differences in plant shown in Table B-6 in the next section was used. The industry mean for the short-term mission failure to run was approximately a factor of four less than the corresponding estimate in the previous HPCI report.

Failure to run, other than suction transfer (hourly rate for comparison to PRA) (FTRI). Since short run times precluded the application of the operating experience directly to unreliability for the length of mission (24 hours) typically assumed in a risk assessment, an analysis based on failure rates was performed. Run times were either stated or estimated by the data reviewers for 82 of the unplanned demands. Most were fairly short, but one was 23 hours. The average unplanned demand run time of 0.52 hours was applied for the single demand for which the HPCI pump ran for an unknown length of time. One hour was used for each test run time.

As with the FTR probability, no statistically significant differences were found in the FTRI rate between the unplanned demands and two types of tests, and trends were not seen with regard to low-power license date. However, consideration of differences with regard to calendar year was more intriguing with the rate analysis than the probability analysis. Although the log model regression using least squares did not show a trend (p-value 0.21), a log model regression based on the failure data having a Poisson distribution did (p-value 0.037) (see Figure B-1). The latter model, which estimated the regression parameters using maximum likelihood rather than least squares, does not require strictly positive data, so no Bayesian adjustment of the data away from zero was needed.

When the decreasing trend is considered, the estimated 1998 FTRI rate is 0.0036/h, considerably less than the estimate (0.012/h) that considers all the data without this trend. Since the FTRI failure mode estimated at 0.012/h contributes over 40% to the HPCI unreliability, a reduction in this estimate would affect the results of this study.

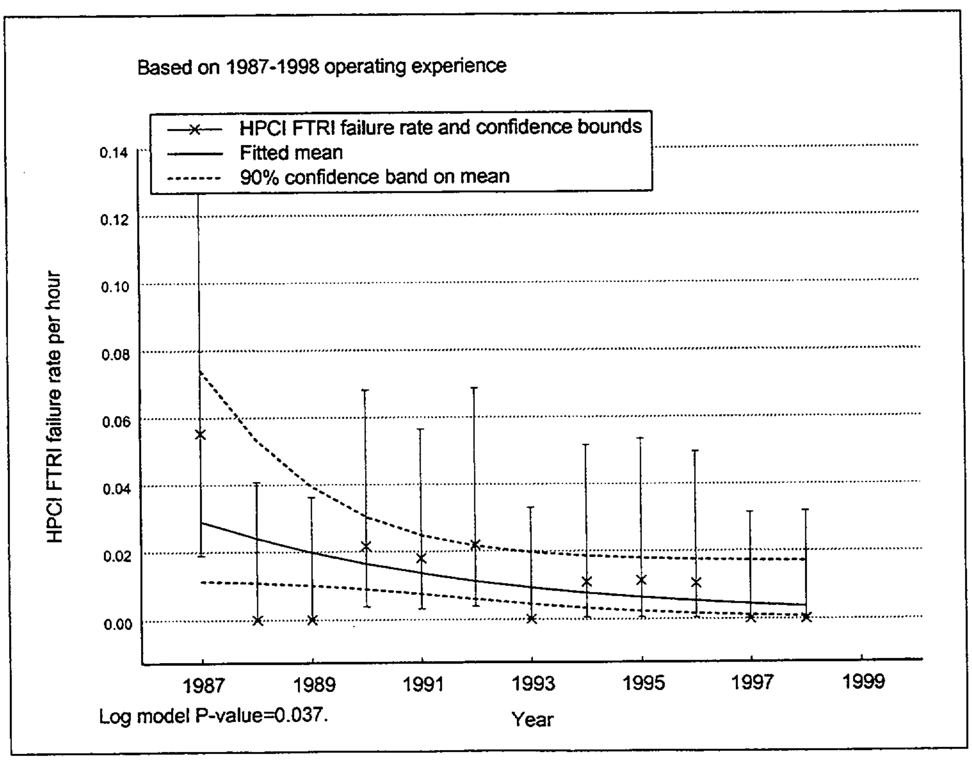


Figure B-1. Rate of HPCI failure to run (FTRI) as a function of calendar year.

To further investigate the significance of the trend in Figure B-1, the following points were considered:

- The test of differences between the 1987-1993 period and the added 1994-1998 period was not significant (p-value 0.145).
- The test of overall differences in the twelve years of the study also was not quite significant (p-value 0.068).
- The year with the four failures (1987) also had the least run time (72.4 h), whereas the other years with failures each had over 90 h. When this year is excluded from the evaluation, the trend of Figure B-1 disappears (the p-value drops to 0.45). (Omitting the 1987 data results in a drop in the pooled FTRI rate from 0.012/h to 0.0089/h.)
- In a regression analysis, the slope is most influenced by the points furthest from the middle. The fact that the slope is lost when 1987 data are omitted lessens the meaningfulness of the apparent trend.
- The 1987 data are the oldest data in the study, and thus may be the least relevant in assessing current performance.
- Statistical tests were performed to investigate the possibility of excluding the 1987 data. An exact test of the significance of a difference in 1987 compared with the other years gives a significant p-value of 0.009. However, after considering multiple testing and the fact that *some* year will be different among 12 years, the significance drops to 0.106. Thus, the statistical tests do not identify 1987 as an outlier or in themselves justify exclusion of 1987 data.
- The Figure B-1 trend was not *highly* significant (the p-value was not less than 0.01).
- Using all the data, a difference in plants was observed in the data with a highly significant p-value of 0.010.

Because 1987 data are judged to be relevant, but the effect of these data on the Figure B-1 trend tends to discredit the trend, the trend was not used in the analysis. Instead, the empirical Bayes distribution for differences between plants, listed in the next section (Table B-7), was used. The FTRI probability data were not differentiated by plant year in the analysis other than in the yearly unreliability trend evaluation discussed in Section B-4.

The rate evaluation leads to a gamma distribution. The gamma distribution on the rate, λ, was then converted to a beta distribution for the probability of failure in a 24-hour mission by matching the mean and variance of $[1\text{-}\exp(-24\lambda)]$, as described in the references. The resulting probability had a mean of 0.21, much higher than the estimate for the short-term mission failure to run.

Failure to Recover FTRI. Eight of the thirteen failures to run were not judged to be recoverable. There were no significant trends. The empirical Bayes distribution found for differences between plants (Table B-8) was used for the analysis.

Probability of Multiple Injections (PMI). The HPCI unplanned demands for the entire study period were reviewed in more detail than in the original HPCI study in order to distinguish whether injection was a part of the demand, rather than HPCI being used in a recirculation mode for pressure control. Furthermore, the demands were reviewed to identify the subset with multiple injections. The

HPCI failure mode caused by failure of the injection valve to reopen (FRO) was a possibility for these demands. For the short-term mission model, the probability of this failure was combined with the probability (PMI) of needing multiple injections to quantify this special source of unreliability (in the PRA comparison model, every demand was assumed to require multiple injection to sustain the reactor vessel level over a 24-hour period). Among 79 operational missions with HPCI system injection, 12 were judged to involve multiple injections, 62 had only single injections, and five were uncertain. The uncertain demands were not counted as demands in estimating the probability of multiple injections, and were not counted in estimating the probability of failure for the injection valve reopening. Thus, the uncertain demands had no direct impact on the overall quantification of the FRO failure mode in the short-term mission model where these two conditions were combined in an "and" gate.

Most of the demands with injection, and most of the multiple injections, occurred early in the study (60 of the 79 injections and 11 of the twelve known multiple injections were prior to 1993). Although the log linear modeling of the multiple injection probability showed no trends with respect to time or plant low-power license date, the logit model for a trend with calendar year did fit the data (the p-value was 0.048). This model specifies a linear relation in time for the logarithm of the ratio, $p/(1-p)$, and results in a steeply decreasing function for the PMI probability (from 0.28 for 1987 to 0.02 for 1997), with wide bounds (from 0.50 for the 1987 upper bound to 0.22 for 1997). This study used the between-plant empirical Bayes distribution found for the probability of multiple injection, with a mean of 0.13 and an upper bound of 0.32 (see Table B-9).

Failure to reopen, injection valve (FRO). In the twelve unplanned demands judged applicable for a possible failure of the injection valve to reopen, two failures were observed. Failures were also observed in some of the test demands, but these were not used in the study because no reporting method exists for determining the number of tests exercising multiple cycling of the injection valve. The two unplanned demand failures occurred in 1987 and 1990, the two years with the highest number of demands. With the sparse data, no trends or plant-specific differences were found. A simple Bayes distribution based on two failures in twelve demands was used to quantify the data.

As mentioned above in the PMI discussion, there was the possibility of having five additional demands. A simulation was performed to evaluate the significance of this uncertainty. In each pass of the simulation, the additional demands were counted, or not counted, by sampling from a binomial distribution with the ratio of known multiple injections to injections with the status known [12/(62+12)] as the probability of multiple injection. The simulation resulted in an average of 12.8 demands instead of 12 demands, and a FRO failure probability estimate of 0.18 with an upper bound of 0.37. This reduction of approximately 5% in the estimated FRO probability was not judged to have a significant impact on the HPCI unreliability results for the PRA comparison model. It does not apply for the results of the short-term model, since the probability of multiple injection would correspondingly increase by 5%.

Failure to run, suction transfer (FTRT). With just two failures of the automatic transfer function, the data were sparse. However, both failures occurred in 1988, the second year of the study period, and they were at the same plant (Brunswick 1). With twelve years and 24 plants, having the second failure in the same year and plant as the first, with random occurrences, has a probability of 1/12 for the year factor and 1/24 for the plant factor. The exact p-values are thus 0.088 for year differences and 0.044 for plant differences. In future updates of this analysis, the automatic transfer function failure mode might be evaluated further to ensure that these two failures are relevant. For the current study, the failures were retained and a simple Bayes distribution was used for the PRA comparison model unreliability analysis. This failure mode contributed less than 1% to the overall long-term mission HPCI unreliability.

Other Failure to Recover Failure Modes. Recovery was also modeled for the FRO and FTRT modes since failures were observed and recovery may be possible (recovery is not modeled for maintenance-out-of-service). The two FRO and two FTRT failures were judged not to be recoverable. Simple Bayes distributions were used to model the probabilities of failure to recover. The probability estimates were quite high (0.83 for both FRO and FRFTRT), with large uncertainty bounds.

B-1.1.2 Summary of Beta Distributions for Individual Failure Modes

Table B-3 and Tables 2 and 3 in the body of the report describe the Bayes distributions selected to describe the statistical variability in the data used to model HPCI injection and emergency power subsystem unreliabilities. The FTRI beta distribution was computed from a gamma distribution on the rate using the methods of Section A-2.1.5 of the original report.

Table B-3. Summary of data used for the HPCI unreliability analysis using the1987–1998 operating experience.

Failure Mode	Data Source [a]	f [a]	d [a] or Run Hours	Modeled Variation	Distribution[b] a	Distribution[b] b	Bayesian Probability 5th perc.	Bayesian Probability Mean	Bayesian Probability 95th perc.
Maintenance out-of-service (MOOS)—Up	A	1	94	Sampling	1.5	93.5	1.87E-03	1.58E-02	4.08E-02
Failure to start , injection valve (FTSV)	A	0	79	Sampling	0.5	79.5	2.48E-05	6.25E-03	2.39E-02
Failure to start, other than injection valve (FTSI)	A+C+Q	28	1157	Plant diff.	2.8	112.8	6.23E-03	2.41E-02	5.12E-02
Failure to recover FTSI (FRFTSI)	A+C+Q	20	28	Plant diff.	3.1	1.2	3.41E-01	7.16E-01	9.70E-01
Failure to run, other than suction transfer (FTRI; short-term)	A+C+Q	13	1119	Plant diff.	0.7	63.7	2.37E-04	1.14E-02	3.79E-02
Failure to run, other than suction transfer (FTRI) (rate for PRA comparison)[b]	A+C+Q	13	1080.2 h	Plant diff.	0.7	58.3 h	2.08E-04	1.20E-02	4.09E-02
Failure to run, other than suction transfer (FTRI) (24 hour probability for PRA comparison)	—	—	—	—	0.7	2.6	4.94E-03	2.14E-01	6.25E-01
Failure to recover FTRI (FRFTRI)	A+C+Q	8	13	Plant diff.	0.8	0.6	4.60E-02	5.77E-01	9.91E-01
Proability of multiple injections (PMI)	A	12	79	Plant diff.	1.6	10.2	1.88E-02	1.33E-01	3.19E-01
Failure to reopen, injection valve (FRO)	A	2	12	Sampling	2.5	10.5	4.97E-02	1.92E-01	3.90E-01
Failure to recover FRO (FRFRO)	A	2	2	Sampling	2.5	0.5	4.31E-01	8.33E-01	9.99E-01
Failure to run, suction transfer (FTRT)	A+C+Q	2	1031	Sampling	2.5	1029.5	5.56E-04	2.42E-03	5.36E-03
Failure to recover FTRT (FRFTRT)	A+C+Q	2	2	Sampling	2.5	0.5	4.31E-01	8.33E-01	9.99E-01

a. A: unplanned demands. C: cyclic tests. Q: quarterly tests. f: failures. d: demands.

b. Gamma distribution for rates. Beta distribution for probabilities.

B-1.2 Plant-Specific Failure Probabilities and Rates

This section provides plant-specific basic event failure probabilities for the failure modes that were modeled in the HPCI unreliability assessment. The data are in Tables B-4 through B-9.

Table B-4. Probability of HPCI system failure to start (other than injection valve) (FTSI), by plant (1987–1998 operating experience).

			Beta Distribution		
Plant	f[a]	d[a]	a	b	Empirical Bayes 90% Interval
Brunswick 1	0	53	2.00	118.98	(3.0E-03, 1.7E-02, 3.9E-02)
Brunswick 2	1	58	3.41	153.08	(6.7E-03, 2.2E-02, 4.4E-02)
Browns Ferry 2	1	31	3.35	126.19	(7.8E-03, 2.6E-02, 5.2E-02)
Browns Ferry 3	0	15	2.41	110.37	(4.8E-03, 2.1E-02, 4.7E-02)
Cooper	2	55	4.12	142.81	(9.9E-03, 2.8E-02, 5.3E-02)
Duane Arnold	0	50	2.03	118.74	(3.1E-03, 1.7E-02, 3.9E-02)
Dresden 2	1	48	3.44	145.10	(7.1E-03, 2.3E-02, 4.6E-02)
Dresden 3	0	50	2.03	118.74	(3.1E-03, 1.7E-02, 3.9E-02)
Fermi 2	2	52	4.06	138.13	(1.0E-02, 2.9E-02, 5.5E-02)
Hatch 1	1	59	3.41	153.77	(6.6E-03, 2.2E-02, 4.4E-02)
Hatch 2	2	61	4.23	151.72	(9.7E-03, 2.7E-02, 5.1E-02)
Hope Creek	1	58	3.41	153.08	(6.7E-03, 2.2E-02, 4.4E-02)
FitzPatrick	5	55	3.66	76.46	(1.5E-02, 4.6E-02, 8.9E-02)
Limerick 1	1	49	3.44	145.99	(7.1E-03, 2.3E-02, 4.6E-02)
Limerick 2	0	40	2.15	117.65	(3.5E-03, 1.8E-02, 4.1E-02)
Monticello	0	51	2.02	118.82	(3.0E-03, 1.7E-02, 3.9E-02)
Peach Bottom 2	1	42	3.43	139.26	(7.4E-03, 2.4E-02, 4.8E-02)
Peach Bottom 3	3	44	3.73	99.04	(1.2E-02, 3.6E-02, 7.1E-02)
Pilgrim	1	41	3.42	138.20	(7.4E-03, 2.4E-02, 4.8E-02)
Quad Cities 1	4	48	3.62	83.63	(1.3E-02, 4.1E-02, 8.1E-02)
Quad Cities 2	0	49	2.04	118.65	(3.1E-03, 1.7E-02, 4.0E-02)
Susquehanna 1	2	49	3.99	133.31	(1.0E-02, 2.9E-02, 5.6E-02)
Susquehanna 2	0	50	2.03	118.74	(3.1E-03, 1.7E-02, 3.9E-02)
Vermont Yankee	0	49	2.04	118.65	(3.1E-03, 1.7E-02, 4.0E-02)
Industry	28	1157	2.79	112.85	(6.2E-03, 2.4E-02, 5.1E-02)

a. f, failures; d, demands.

Table B-5. Probability of failure to recover from HPCI system failure to start (other than injection valve), by plant (1987–1998 operating experience).

Plant	f[a]	d[a]	Beta Distribution a	b	Empirical Bayes 90% Interval
Brunswick 1	0	0	2.35	0.93	—
Brunswick 2	1	1	2.74	0.82	(3.7E-01, 7.7E-01, 9.9E-01)
Browns Ferry 2	1	1	2.74	0.82	(3.7E-01, 7.7E-01, 9.9E-01)
Browns Ferry 3	0	0	2.35	0.93	—
Cooper	1	2	2.74	1.49	(2.7E-01, 6.5E-01, 9.4E-01)
Duane Arnold	0	0	2.35	0.93	—
Dresden 2	1	1	2.74	0.82	(3.7E-01, 7.7E-01, 9.9E-01)
Dresden 3	0	0	2.35	0.93	—
Fermi 2	2	2	2.68	0.64	(4.1E-01, 8.1E-01, 1.0E+00)
Hatch 1	0	1	1.07	0.77	(7.7E-02, 5.8E-01, 9.8E-01)
Hatch 2	1	2	2.74	1.49	(2.7E-01, 6.5E-01, 9.4E-01)
Hope Creek	0	1	1.07	0.77	(7.7E-02, 5.8E-01, 9.8E-01)
FitzPatrick	2	5	2.35	1.95	(1.8E-01, 5.5E-01, 8.9E-01)
Limerick 1	0	1	1.07	0.77	(7.7E-02, 5.8E-01, 9.8E-01)
Limerick 2	0	0	2.35	0.93	—
Monticello	0	0	2.35	0.93	—
Peach Bottom 2	1	1	2.74	0.82	(3.7E-01, 7.7E-01, 9.9E-01)
Peach Bottom 3	3	3	2.64	0.53	(4.4E-01, 8.3E-01, 1.0E+00)
Pilgrim	1	1	2.74	0.82	(3.7E-01, 7.7E-01, 9.9E-01)
Quad Cities 1	4	4	2.66	0.46	(4.7E-01, 8.5E-01, 1.0E+00)
Quad Cities 2	0	0	2.35	0.93	—
Susquehanna 1	2	2	2.68	0.64	(4.1E-01, 8.1E-01, 1.0E+00)
Susquehanna 2	0	0	2.35	0.93	—
Vermont Yankee	0	0	2.35	0.93	—
Industry	20	28	3.07	1.22	(3.4E-01, 7.2E-01, 9.7E-01)

a. f, failures; d, demands.

Table B-6. Probability of HPCI failure to run, other than suction transfer (short-term mission), by plant (1987–1998 operating experience).

Plant	f [a]	d [a]	Beta Distribution a	b	Empirical Bayes 90% Interval
Brunswick 1	1	51	1.58	103.70	(1.9E-03, 1.5E-02, 3.8E-02)
Brunswick 2	0	56	0.63	102.94	(7.2E-05, 6.1E-03, 2.1E-02)
Browns Ferry 2	0	30	0.66	84.28	(1.1E-04, 7.8E-03, 2.7E-02)
Browns Ferry 3	0	15	0.67	72.14	(1.4E-04, 9.2E-03, 3.2E-02)
Cooper	0	53	0.63	100.88	(7.5E-05, 6.2E-03, 2.2E-02)
Duane Arnold	1	50	1.58	102.50	(1.9E-03, 1.5E-02, 3.9E-02)
Dresden 2	0	47	0.64	96.70	(8.2E-05, 6.6E-03, 2.3E-02)
Dresden 3	0	50	0.64	98.80	(7.9E-05, 6.4E-03, 2.3E-02)
Fermi 2	0	49	0.64	98.10	(8.0E-05, 6.5E-03, 2.3E-02)
Hatch 1	3	59	2.57	82.25	(7.2E-03, 3.0E-02, 6.6E-02)
Hatch 2	1	57	1.61	110.78	(1.9E-03, 1.4E-02, 3.6E-02)
Hope Creek	0	57	0.63	103.63	(7.0E-05, 6.0E-03, 2.1E-02)
FitzPatrick	0	48	0.64	97.40	(8.1E-05, 6.5E-03, 2.3E-02)
Limerick 1	4	47	2.47	55.70	(9.9E-03, 4.2E-02, 9.3E-02)
Limerick 2	0	38	0.65	90.25	(9.6E-05, 7.2E-03, 2.5E-02)
Monticello	1	51	1.58	103.70	(1.9E-03, 1.5E-02, 3.8E-02)
Peach Bottom 2	1	41	1.53	91.43	(2.0E-03, 1.6E-02, 4.2E-02)
Peach Bottom 3	1	41	1.53	91.43	(2.0E-03, 1.6E-02, 4.2E-02)
Pilgrim	0	40	0.65	91.71	(9.2E-05, 7.0E-03, 2.4E-02)
Quad Cities 1	0	44	0.64	94.58	(8.7E-05, 6.8E-03, 2.4E-02)
Quad Cities 2	0	49	0.64	98.10	(8.0E-05, 6.5E-03, 2.3E-02)
Susquehanna 1	0	47	0.64	96.70	(8.2E-05, 6.6E-03, 2.3E-02)
Susquehanna 2	0	50	0.64	98.80	(7.9E-05, 6.4E-03, 2.3E-02)
Vermont Yankee	0	49	0.64	98.10	(8.0E-05, 6.5E-03, 2.3E-02)
Industry	13	1119	0.73	63.65	(2.4E-04, 1.1E-02, 3.8E-02)

a. *f*, failures; *d*, demands.

Table B-7. Rate of HPCI failure to run, other than suction transfer (FTRI), per hour (gamma distributions), by plant (1987–1998 operating experience) used for PRA/IPE comparison.

Plant	f[a]	Run Time, h	Gamma Distribution a	Gamma Distribution b	Empirical Bayes 90% Interval
Brunswick 1	1	48.80	1.56	97.97	(2.0E-03, 1.6E-02, 4.1E-02)
Brunswick 2	0	48.65	0.61	93.69	(6.8E-05, 6.5E-03, 2.3E-02)
Browns Ferry 2	0	29.15	0.63	79.23	(9.5E-05, 8.0E-03, 2.8E-02)
Browns Ferry 3	0	13.19	0.65	65.99	(1.3E-04, 9.8E-03, 3.4E-02)
Cooper	0	48.18	0.61	93.35	(6.8E-05, 6.6E-03, 2.3E-02)
Duane Arnold	1	48.53	1.55	97.65	(2.0E-03, 1.6E-02, 4.1E-02)
Dresden 2	0	47.00	0.61	92.51	(6.9E-05, 6.6E-03, 2.4E-02)
Dresden 3	0	50.73	0.61	95.17	(6.5E-05, 6.4E-03, 2.3E-02)
Fermi 2	0	46.33	0.62	92.03	(7.0E-05, 6.7E-03, 2.4E-02)
Hatch 1	3	49.61	2.46	71.75	(7.7E-03, 3.4E-02, 7.6E-02)
Hatch 2	1	47.21	1.55	96.07	(2.0E-03, 1.6E-02, 4.2E-02)
Hope Creek	0	47.70	0.61	93.01	(6.9E-05, 6.6E-03, 2.4E-02)
FitzPatrick	0	44.50	0.62	90.71	(7.2E-05, 6.8E-03, 2.4E-02)
Limerick 1	4	47.00	2.61	58.58	(1.1E-02, 4.5E-02, 9.8E-02)
Limerick 2	0	38.00	0.62	85.95	(8.1E-05, 7.3E-03, 2.6E-02)
Monticello	1	49.77	1.56	99.13	(2.0E-03, 1.6E-02, 4.0E-02)
Peach Bottom 2	1	39.85	1.51	87.08	(2.1E-03, 1.7E-02, 4.5E-02)
Peach Bottom 3	1	37.03	1.49	83.55	(2.1E-03, 1.8E-02, 4.7E-02)
Pilgrim	0	41.90	0.62	88.82	(7.6E-05, 7.0E-03, 2.5E-02)
Quad Cities 1	0	44.00	0.62	90.35	(7.3E-05, 6.8E-03, 2.4E-02)
Quad Cities 2	0	48.02	0.61	93.24	(6.8E-05, 6.6E-03, 2.3E-02)
Susquehanna 1	0	46.02	0.62	91.80	(7.1E-05, 6.7E-03, 2.4E-02)
Susquehanna 2	0	48.04	0.61	93.25	(6.8E-05, 6.6E-03, 2.3E-02)
Vermont Yankee	0	71.00	0.59	109.22	(4.8E-05, 5.4E-03, 2.0E-02)
Industry	13	1080.21	0.70	58.28	(2.1E-04, 1.2E-02, 4.1E-02)

a. f, failures.

Table B-8. Probability of failure to recover from HPCI system failure to run (FRFTRI), by plant.

Plant	f[a]	d[a]	Beta Distribution a	b	Empirical Bayes 90% Interval
Brunswick 1	0	1	0.20	0.39	(1.6E-06, 3.4E-01, 9.9E-01)
Brunswick 2	0	0	0.54	0.40	—
Browns Ferry 2	0	0	0.54	0.40	—
Browns Ferry 3	0	0	0.54	0.40	—
Cooper	0	0	0.54	0.40	—
Duane Arnold	1	1	0.79	0.26	(9.8E-02, 7.5E-01, 1.0E+00)
Dresden 2	0	0	0.54	0.40	—
Dresden 3	0	0	0.54	0.40	—
Fermi 2	0	0	0.54	0.40	—
Hatch 1	1	3	1.32	1.89	(5.9E-02, 4.1E-01, 8.3E-01)
Hatch 2	0	1	0.20	0.39	(1.6E-06, 3.4E-01, 9.9E-01)
Hope Creek	0	0	0.54	0.40	—
FitzPatrick	0	0	0.54	0.40	—
Limerick 1	4	4	1.53	0.19	(4.3E-01, 8.9E-01, 1.0E+00)
Limerick 2	0	0	0.54	0.40	—
Monticello	0	1	0.20	0.39	(1.6E-06, 3.4E-01, 9.9E-01)
Peach Bottom 2	1	1	0.79	0.26	(9.8E-02, 7.5E-01, 1.0E+00)
Peach Bottom 3	1	1	0.79	0.26	(9.8E-02, 7.5E-01, 1.0E+00)
Pilgrim	0	0	0.54	0.40	—
Quad Cities 1	0	0	0.54	0.40	—
Quad Cities 2	0	0	0.54	0.40	—
Susquehanna 1	0	0	0.54	0.40	—
Susquehanna 2	0	0	0.54	0.40	—
Vermont Yankee	0	0	0.54	0.40	—
Industry	8	13	0.83	0.61	(4.6E-02, 5.8E-01, 9.9E-01)

a. f, failures; d, demands.

Table B-9. Probability of multiple HPCI system injections (PMI), by plant (1987–1998 operating experience).

Plant	m [a]	i [a]	Beta Distribution a	b	Empirical Bayes 90% Interval
Brunswick 1	1	3	1.99	9.48	(3.5E-02, 1.7E-01, 3.8E-01)
Brunswick 2	3	9	3.08	10.95	(6.9E-02, 2.2E-01, 4.2E-01)
Browns Ferry 2	0	1	1.23	8.76	(1.1E-02, 1.2E-01, 3.2E-01)
Browns Ferry 3	0	2	1.18	9.20	(9.5E-03, 1.1E-01, 3.0E-01)
Cooper	1	7	2.24	14.17	(3.1E-02, 1.4E-01, 2.9E-01)
Duane Arnold	0	2	1.18	9.20	(9.5E-03, 1.1E-01, 3.0E-01)
Dresden 2	0	0	1.25	8.14	—
Dresden 3	0	2	1.18	9.20	(9.5E-03, 1.1E-01, 3.0E-01)
Fermi 2	0	3	1.13	9.53	(8.1E-03, 1.1E-01, 2.9E-01)
Hatch 1	0	10	0.86	11.03	(2.6E-03, 7.2E-02, 2.2E-01)
Hatch 2	5	11	3.15	7.78	(9.7E-02, 2.9E-01, 5.3E-01)
Hope Creek	1	10	2.19	16.38	(2.5E-02, 1.2E-01, 2.6E-01)
FitzPatrick	0	4	1.08	9.79	(6.8E-03, 9.9E-02, 2.7E-01)
Limerick 1	0	0	1.25	8.14	—
Limerick 2	0	0	1.25	8.14	—
Monticello	0	2	1.18	9.20	(9.5E-03, 1.1E-01, 3.0E-01)
Peach Bottom 2	0	2	1.18	9.20	(9.5E-03, 1.1E-01, 3.0E-01)
Peach Bottom 3	1	5	2.19	12.12	(3.4E-02, 1.5E-01, 3.3E-01)
Pilgrim	0	1	1.23	8.76	(1.1E-02, 1.2E-01, 3.2E-01)
Quad Cities 1	0	0	1.25	8.14	—
Quad Cities 2	0	1	1.23	8.76	(1.1E-02, 1.2E-01, 3.2E-01)
Susquehanna 1	0	1	1.23	8.76	(1.1E-02, 1.2E-01, 3.2E-01)
Susquehanna 2	0	2	1.18	9.20	(9.5E-03, 1.1E-01, 3.0E-01)
Vermont Yankee	0	1	1.23	8.76	(1.1E-02, 1.2E-01, 3.2E-01)
Industry	12	79	1.57	10.24	(1.9E-02, 1.3E-01, 3.2E-01)

a. m, number of multiple injection events; i, number of injection events.

B-2. PLANT-SPECIFIC RESULTS FOR HPCI SYSTEM RELIABILITY

The estimates in Tables B-4 through B-9 were applied in each of the HPCI fault trees. BWR HPCI data from Table B-3 were used for the modes having only sampling variation modeled. The means and variances of the failure modes were propagated through the fault tree logic for each plant to obtain a mean and variance for the short-term mission unreliability and the long-term mission unreliability. The resulting estimates were fitted to beta distributions, and the 5 and 95 percentiles were computed. The results are listed in Tables B-10 and C-2. Table B-10 applies to the short-term mission, while Table C-2 contains estimates for the postulated 24-hour long-term mission.

Fault Tree Model. The short-term unreliability of the HPCI system was calculated using the simple fault tree model shown in Figure 3 of the main report. Figure C-1 of Appendix C provides the fault tree model used for PRA comparison. Table C-1 of Appendix C provides a summary of the failure probability estimates (1987–1998 operating experience) used for the PRA comparison. The model was constructed to reflect the failure modes identified in the unplanned demands, cyclic tests, and quarterly test data from the 1987–1998 operating experience. No new failure modes where found in the more recent 1994–1998 experience.

Modeling Assumptions. The following conditions were assumed for the purposes of quantifying the short-term mission fault tree:

- A demand to provide high-pressure coolant injection to the RPV is received by the HPCI system
- The FTR contribution to the unreliability is estimated on a per mission demand basis
- The cycling of the injection valve to maintain RPV water inventory is modeled as the failure of the HPCI injection valve to reopen
- No suction transfer to the suppression pool is required.

Table B-10. HPCI unreliability estimates for the short-term mission, based on empirical Bayes distributions for each failure mode with plant variation, and simple Bayes distributions for the rest (1987–1998 operating experience).

	Beta Distribution		Emperical Bayes Probability[a]		
Plant	*a*	*b*	5th Percentile	Mean	95th Percentile
Browns Ferry 2	4.6	66.7	2.5E-02	6.4E-02	1.2E-01
Browns Ferry 3	4.2	65.9	2.1E-02	6.0E-02	1.1E-01
Brunswick 1	4.0	56.8	2.3E-02	6.5E-02	1.2E-01
Brunswick 2	4.7	57.1	2.9E-02	7.5E-02	1.4E-01
Cooper	5.2	76.0	2.7E-02	6.4E-02	1.1E-01
Dresden 2	4.3	63.7	2.3E-02	6.3E-02	1.2E-01
Dresden 3	3.8	66.0	1.9E-02	5.5E-02	1.1E-01
Duane Arnold	4.5	68.0	2.4E-02	6.2E-02	1.1E-01
Fermi 2	5.1	74.2	2.6E-02	6.4E-02	1.1E-01

Table B-10. (continued).

Plant	Beta Distribution		Emperical Bayes Probability[a]		
	a	*b*	5th Percentile	Mean	95th Percentile
FitzPatrick	4.7	67.8	2.5E-02	6.5E-02	1.2E-01
Hatch 1	4.8	79.3	2.3E-02	5.7E-02	1.0E-01
Hatch 2	4.3	44.4	3.3E-02	8.8E-02	1.6E-01
Hope Creek	4.6	78.3	2.2E-02	5.6E-02	1.0E-01
Limerick 1	5.6	55.4	4.0E-02	9.1E-02	1.6E-01
Limerick 2	3.8	60.1	2.0E-02	5.9E-02	1.1E-01
Monticello	3.9	64.9	1.9E-02	5.6E-02	1.1E-01
Peach Bottom 2	5.3	70.8	2.9E-02	6.9E-02	1.2E-01
Peach Bottom 3	6.5	68.8	4.0E-02	8.6E-02	1.4E-01
Pilgrim	4.5	67.2	2.4E-02	6.3E-02	1.2E-01
Quad Cities 1	5.4	61.5	3.4E-02	8.0E-02	1.4E-01
Quad Cities 2	3.8	63.3	1.9E-02	5.6E-02	1.1E-01
Susquehanna 1	5.0	68.7	2.7E-02	6.7E-02	1.2E-01
Susquehanna 2	3.8	66.0	1.9E-02	5.5E-02	1.1E-01
Vermont Yankee	3.8	63.3	1.9E-02	5.6E-02	1.1E-01

a. HPCI system unreliability was calculated from the fault tree model for a short-term mission (see Figure 3 of the main report).

B-3. INVESTIGATION OF RELATION TO PLANT LOW-POWER LICENSE DATE

The possibility of a trend in HPCI system performance with plant age as measured by a plant's low-power license date was investigated. The trend evaluation was performed for a plant-specific estimate of the unreliability, for the annual frequency of unplanned demands, and for the annual frequency of failures.

Unreliability trend. Table B-11 shows HPCI system unreliabilities by plant, along with the plant low-power license dates. The unreliabilities apply to the short-term mission, with just injection, relatively short run times, and no need for automatic transfer to draw from the suppression pool. These unreliabilities differ from Table B-10 because broad, constrained noninformative prior distributions were updated with plant-specific data for each failure mode. This approach yields unreliabilities that are very sensitive to the plant data. The analysis methods were described further the original analysis [Reference B-1]. The resulting updated distributions were combined for each plant according to the logic of the fault tree, and a beta distribution for the unreliability was obtained by matching the mean and variance as described in Section A-2.2 of the original report.

Table B-11. HPCI unreliability for the short-term mission, by plant, based on diffuse prior distributions and plant-specific data (1987–1998 operating experience).

Plant	Low-Power License Date	5th Percentile	Mean	95th Percentile
Dresden 2	12/22/69	1.14E-03	6.71E-02	2.22E-01
Monticello	09/08/70	9.32E-04	4.22E-02	1.38E-01
Dresden 3	01/12/71	6.94E-04	4.09E-02	1.37E-01
Quad Cities 1	10/01/71	1.75E-02	1.09E-01	2.56E-01
Quad Cities 2	03/21/72	3.62E-04	4.52E-02	1.62E-01
Pilgrim	09/15/72	3.15E-03	6.06E-02	1.77E-01
Vermont Yankee	02/28/73	3.78E-04	4.56E-02	1.63E-01
Peach Bottom 2	12/14/73	9.30E-03	6.66E-02	1.64E-01
Cooper	01/18/74	7.98E-03	5.45E-02	1.33E-01
Duane Arnold	02/22/74	2.83E-03	5.05E-02	1.46E-01
Peach Bottom 3	07/02/74	3.13E-02	9.97E-02	1.95E-01
Browns Ferry 2	08/02/74	4.42E-03	6.55E-02	1.84E-01
Hatch 1	10/13/74	8.19E-03	4.28E-02	9.84E-02
FitzPatrick	10/17/74	2.23E-02	8.78E-02	1.85E-01
Brunswick 2	12/27/74	2.10E-02	1.09E-01	2.46E-01
Browns Ferry 3	08/18/76	1.65E-03	4.77E-02	1.48E-01
Brunswick 1	11/12/76	1.47E-03	5.40E-02	1.72E-01
Hatch 2	06/13/78	2.47E-02	1.08E-01	2.32E-01
Susquehanna 1	07/17/82	7.48E-03	7.21E-02	1.87E-01
Susquehanna 2	03/23/84	6.94E-04	4.09E-02	1.37E-01
Limerick 1	10/26/84	1.24E-02	9.87E-02	2.45E-01
Fermi 2	03/20/85	1.08E-02	6.29E-02	1.48E-01
Hope Creek	04/11/86	3.56E-03	3.82E-02	1.03E-01
Limerick 2	07/10/89	1.32E-04	5.43E-02	2.11E-01

The data in Table B-11 are plotted in the main report, along with the fitted regression line. A straight line was fitted to the unreliability, and a straight line was also fitted to log(unreliability). The fit selected was the one that accounted for more of the variation, as measured by R^2, provided that it also produced a plot with regression confidence limits greater than zero. The regression-based confidence band shown as dashed lines on the plots applies to every point of the fitted line simultaneously; it is the Working, Hotelling, and Scheffé band, described in statistics books that treat linear regression.

No significant trends in the HPCI unreliability by low-power license dates were observed in the 1987–1998 operating experience.

Trends in frequencies of unplanned demands and failures. For the unplanned demand and failure frequency analyses, plant-specific event counts for the study period were normalized by the number of operating years during the study period for each plant. The operating years were estimated from a profile of plant operations based on the monthly reports submitted by the licensees. Table B-12 contains the raw data. The resulting frequencies were trended against plant low-power license date using basically the same linear regression method as for the unreliabilities. The unplanned demands that were trended were the 79 actual injection events. The maintenance events were excluded from the failures. The method of discovery was not considered in tabulating the failures.

A detail of the methodology for trending frequencies deserves mention. The log model cannot be used directly when a frequency is zero. Rather than simply use an (arbitrary) fraction of a failure or demand divided by exposure time to estimate a non-zero frequency for these cases, all the data for a particular frequency were adjusted uniformly. The constrained non-informative prior distribution was updated with plant-specific data, and the resulting plant-specific mean was used for the frequency. It was strictly positive, and therefore its logarithm was defined. For the HPCI system frequencies, this adjustment effectively added approximately 0.5 to each failure count and, depending on the frequency under consideration, from 0.7 to 1.4 years [t/(2N+1), where t is the total time and N is the total number of events] to each exposure time. This process results also in the calculation of 90% Bayesian uncertainty bounds for each frequency. Section A-3 of the original report provides more details about this method.

The results of the demand and failure frequency analyses are plotted in Section 4 in the body of the report. No trends with plant age (low-power license date) were found. There were significant differences in both demand and failure frequencies between plants, but these differences did not form a trend.

Table B-12. HPCI system demand, failure, and inoperability counts by plant (1987–1998 operating experience).

Plant Name	Study Years[a]	Demand Count[b]	Demand Frequency	Failure Count[c]	Failure Frequency	Inoperability Count	Inoperability Frequency
Brunswick 1	8.41	3	3.6E-01	13	1.5E+00	20	2.4E+00
Brunswick 2	9.12	9	9.9E-01	6	6.6E-01	20	2.2E+00
Browns Ferry 2	6.96	1	1.4E-01	3	4.3E-01	9	1.3E+00
Browns Ferry 3	2.98	2	6.7E-01	1	3.4E-01	3	1.0E+00
Cooper	9.30	7	7.5E-01	6	6.5E-01	12	1.3E+00
Duane Arnold	10.19	2	2.0E-01	7	6.9E-01	13	1.3E+00
Dresden 2	8.44	0	0.0E+00	7	8.3E-01	33	3.9E+00
Dresden 3	8.63	2	2.3E-01	4	4.6E-01	32	3.7E+00
Fermi 2	8.63	3	3.5E-01	8	9.3E-01	16	1.9E+00
Hatch 1	10.57	10	9.5E-01	8	7.6E-01	15	1.4E+00
Hatch 2	10.43	11	1.1E+00	12	1.2E+00	15	1.4E+00
Hope Creek	10.36	10	9.7E-01	9	8.7E-01	23	2.2E+00
FitzPatrick	8.71	4	4.6E-01	9	1.0E+00	22	2.5E+00
Limerick 1	10.33	0	0.0E+00	8	7.7E-01	13	1.3E+00
Limerick 2	8.67	0	0.0E+00	8	9.2E-01	10	1.2E+00
Monticello	10.73	2	1.9E-01	2	1.9E-01	7	6.5E-01
Peach Bottom 2	8.70	2	2.3E-01	7	8.0E-01	15	1.7E+00
Peach Bottom 3	8.33	5	6.0E-01	13	1.6E+00	19	2.3E+00
Pilgrim	8.19	1	1.2E-01	8	9.8E-01	15	1.8E+00
Quad Cities 1	8.68	0	0.0E+00	7	8.1E-01	26	3.0E+00
Quad Cities 2	8.46	1	1.2E-01	4	4.7E-01	22	2.6E+00
Susquehanna 1	10.13	1	9.9E-02	6	5.9E-01	11	1.1E+00
Susquehanna 2	10.49	2	1.9E-01	2	1.9E-01	7	6.7E-01
Vermont Yankee	10.72	1	9.3E-02	2	1.9E-01	11	1.0E+00
Industry	216.15	79	3.7E-01	160	7.4E-01	389	1.8E+00

a. Plant operating time during the study period.

b. Demands of the injection valve.

c. Excluding maintenance out of service events.

B-4. ANALYSIS BY YEAR, 1987–1998

The analyses of Section B-3 were modified to see if there was a time trend during the period of the study. As in Section B-3, the analyses apply to unreliability and to two frequencies (unplanned demand events per plant year and failures per year).

Unreliability trends. Table B-13 shows the unreliability by year for the short-term model. The estimates are obtained in the same manner as in Section B-3, except that the data used to update the constrained non-informative prior for each failure mode are pooled across plants for each calendar year instead of across calendar years for each plant. The linear model method to test for a trend was the same as described in Section B-3, except that the time variable was calendar year instead of low-power license date. The slope of the trend was not statistically significant for the HPCI short-term mission model. It was also not significant for the PRA comparison model unreliability estimates.

Trends in frequencies of unplanned demands and failures. Event frequencies by calendar year were also analyzed by pooling the data from all the plants during each calendar year. Table B-14 shows the raw data. For the unplanned demands, the adjustment described in the previous section was used to account for zero frequencies, and logarithmic models were selected in most cases to ensure positive trend lines.

A significant decreasing trend was seen in both the unplanned demands and the failures. Fewer demands per year and fewer failures per year have occurred in more recent years than at the start of the study. These findings are highly statistically significant (p-value=0.0003 for the demands and 0.0004 for the failures). Plots showing these trends are in Section 4 of the body of the report.

For frequencies, the possibility of a trend with regard to both the age of a plant at the start of the study, and the calendar year, was considered. The data were arranged in plant/year blocks, with a frequency for each (calendar year, low-power license date) combination. For both demands and failures, the data were evaluated using a log-linear model that seeks a trend in both calendar year and low-power license date. The result of the analysis was the same as for the separate analyses: the low-power license date was not significant but a calendar year decreasing trend was observed for both frequencies.

Table B-13. HPCI system unreliability for the short-term mission, by year, based on diffuse prior distributions and annual data (1987–1998 operating experience).

Year	5th Percentile	Mean	95th Percentile
1987	4.74E-02	1.18E-01	2.11E-01
1988	5.74E-03	4.38E-02	1.10E-01
1989	1.57E-02	7.60E-02	1.70E-01
1990	2.57E-02	9.88E-02	2.06E-01
1991	1.49E-02	5.36E-02	1.10E-01
1992	6.86E-03	4.35E-02	1.05E-01
1993	7.22E-03	4.55E-02	1.09E-01
1994	1.83E-03	4.55E-02	1.38E-01
1995	1.70E-02	8.78E-02	1.99E-01
1996	6.44E-03	4.52E-02	1.12E-01
1997	8.64E-04	3.65E-02	1.19E-01
1998	3.67E-04	5.86E-02	2.13E-01

Table B-14. HPCI system demand, failure, and inoperability counts by year.

Year	No. of Plant Operating Years in Study During Year	Demand Count [a]	Demand Frequency	Failure Count [b]	Failure Frequency	Inoperability Count	Inoperability Frequency
87	14.91	16	1.1E+00	21	1.4E+00	38	2.5E+00
88	14.26	11	7.7E-01	11	7.7E-01	31	2.2E+00
89	15.89	5	3.1E-01	17	1.1E+00	37	2.3E+00
90	18.16	13	7.2E-01	19	1.0E+00	34	1.9E+00
91	17.70	9	5.1E-01	17	9.6E-01	33	1.9E+00
92	17.55	6	3.4E-01	10	5.7E-01	22	1.3E+00
93	17.85	6	3.4E-01	18	1.0E+00	43	2.4E+00
94	17.61	2	1.1E-01	13	7.4E-01	31	1.8E+00
95	19.63	3	1.5E-01	10	5.1E-01	31	1.6E+00
96	20.44	5	2.4E-01	8	3.9E-01	32	1.6E+00
97	21.09	3	1.4E-01	10	4.7E-01	32	1.5E+00
98	21.07	0	0.0E+00	6	2.8E-01	25	1.2E+00
Total	216.15	79	3.7E-01	160	7.4E-01	389	1.8E+00

a. Demands of the injection valve.

b. Excludes maintenance out of service events.

B-5. REFERENCES

B-1. G. M. Grant, W. S. Roesener, D. G. Hall, C. L. Atwood, C. D. Gentillon, and T. R. Wolf, *High-Pressure Coolant Injection (HPCI) System Performance, 1987—1993*, INEL-94/0158, February, 1995.

B-2. C. L Atwood, *User's Guide to HOMOG: A Computer Program for Investigating Homogeneity of Poisson Data Sources*, EGG-EA-5726, 1982.

B-3. G. E. P. Box and G. C. Tiao, *Bayesian Inference in Statistical Analysis*, Reading, MA: Addison Wesley, 1973, Sections 1.3.4–1.3.5.

B-4. C. L. Atwood, *Hits per Trial: Basic Analysis of Binomial Data*, EGG-RAAM-11041, September 1994.

B-5. H. F. Martz and R. A. Waller, *Bayesian Reliability Analysis*, Malabar, FL: Krieger, 1991, Section 7.6.

B-6. M. E. Engelhardt, *Events in Time: Basic Analysis of Poisson Data*, EGG-RAAM-11088, September 1994.

Appendix C

Unreliability Model and Failure Probabilities used for Comparison to PRA/IPEs

Appendix C

Unreliability Model and Failure Probabilities used for Comparison to PRA/IPEs

The fault tree for estimating HPCI unreliability for comparisons to PRA/IPEs is shown in Figure C-1. The failure mode probabilities used to quantify the fault tree model are provided in Table C-1. In addition, the table presents the estimated HPCI unreliability and associated uncertainty intervals for the total HPCI system.

Plots of the PRA/IPE and 1987–1998 operating experience estimates of HPCI unreliability for PRA/IPE comparison are shown in Figure C-2 for the HPCI system. The estimates were calculated from the PRA/IPE comparison fault tree model depicted in Figure C-1. Table C-2 lists the plant-specific unreliabilities and uncertainties calculated from the 1987–1998 operating experience used in Figure C-2.

A bar chart of the percent contribution of failure modes to the mean HPCI system unreliability used in the PRA/IPE comparison for the HPCI system is shown in Figure C-3. The percent contribution is simply the mean failure mode probability divided by the mean system unreliability.

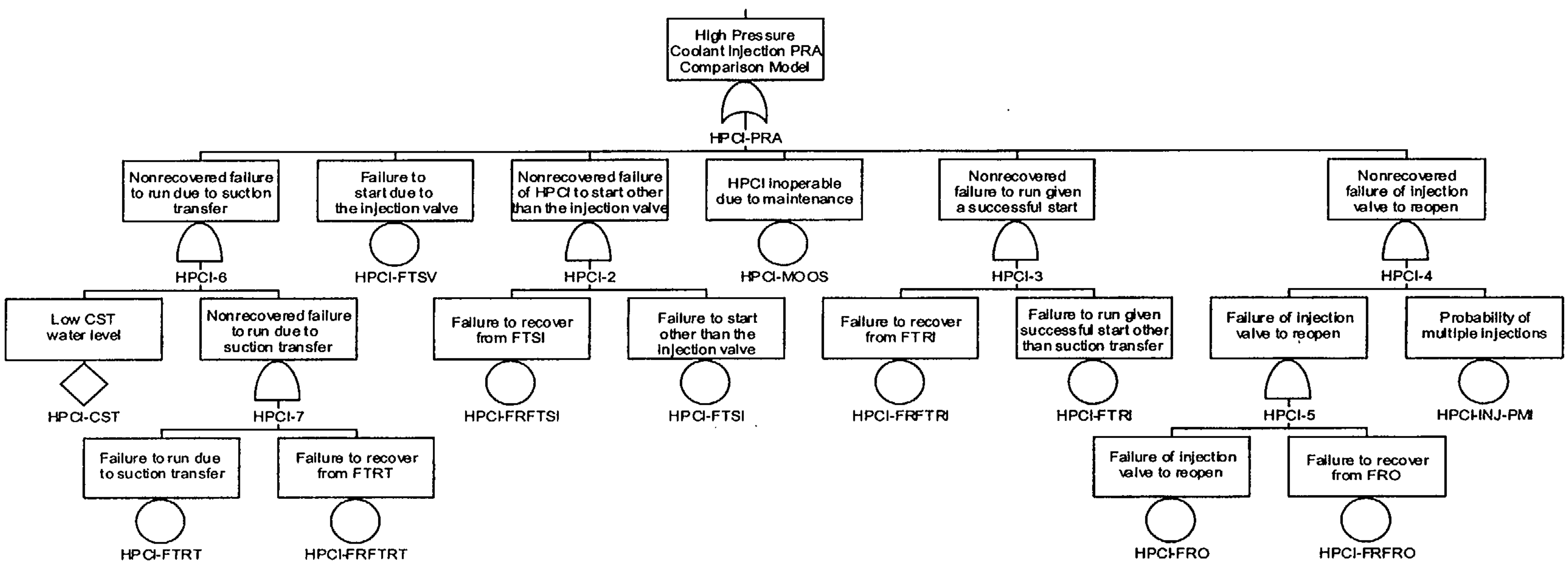


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Figure C-1. Fault tree for calculating HPCI system unreliability for comparison with PRA/IPE results.

Table C-1. HPCI system failure mode data (1987–1998) and Bayesian probability information for estimating unreliability.

Failure Mode	Failure Mode Code	Failures	Demands	Bayesian Probability[a]			Model Used	
				5th percentile	Mean	95th percentile	Trend	Plant Differences
Maintenance-out-of-service while not shut down	MOOS	1	94	1.9E-03	1.6E-02	4.1E-02	Constant[d]	No
Failure to open, injection valve	FTSV	0	79	2.5E-05	6.3E-03	2.4E-02	Constant[d]	No
Failure to start, other than injection valve	FTSI	28	1157	6.2E-03	2.4E-02	5.1E-02	Constant[d]	Yes
Failure to recover from FTSI	FRFTSI	20	28	3.4E-01	7.2E-01	9.7E-01	Constant[d]	Yes
Failure to run, other than suction transfer (rate)	FTRI	13	1080.2[b]	2.1E-04[c]	1.2E-02[c]	4.1E-02[c]	Constant[d]	Yes
Failure to recover from FTRI	FRFTRI	8	13	4.6E-02	5.8E-01	9.9E-01	Constant[d]	Yes
Failure to run, suction transfer	FTRT	2	1031	5.6E-04	2.4E-03	5.4E-03	Constant[d]	No
Failure to recover; suction transfer	FRFTRT	2	2	4.3E-01	8.3E-01	1.0E+00	Constant[d]	No
Failure to reopen, injection valve	FRO	2	12	5.0E-02	1.9E-01	3.9E-01	Constant[d]	No
Failure to recover; injection valve reopening	FRFRO	2	2	4.3E-01	8.3E-01	1.0E+00	Constant[d]	No
Probability of multiple injections	PMI	–[e]	–[e]	–[e]	–[e]	–[e]	–[e]	–[e]
HPCI system unreliability (with recovery)[f]				8.5E-02	2.9E-01[f]	5.6E-01	Constant[d]	Yes
HPCI system unreliability (without recovery)[f]				1.3E-01	4.0E-01[f]	7.0E-01	Constant[d]	Yes

a. The values in parentheses are the 5% uncertainty limit, the Bayes mean, and the 95% uncertainty limit.

b. The values presented are based on the estimated run hours of pump operation.

c. The failure to run estimates presented are hourly failure rates.

d. Any evidence for a trend is weak, not statistically significant. The trend, if any, is too small to be seen in the data. Therefore, no trend is modeled.

e. The long-term mission assumes the need for multiple injections to maintain water level. The probability value assigned for this event is 1.

f. Figure 3 presents the fault tree logic for calculating the unreliability. The basic algebraic equations for HPCI unreliability calculations are:

HPCI unreliability (with recovery) = MOOS + (FTSI * FRFTSI) + (FRTI * FRFRTI) + FTSV + (FRO * FRFRO * PMI).

HPCI unreliability (without recovery) = MOOS + FTSI + FRTI + FTSV + (FRO * PMI).

However, the final HPCI unreliability is not simply the sum of the individual failure mode probabilities.

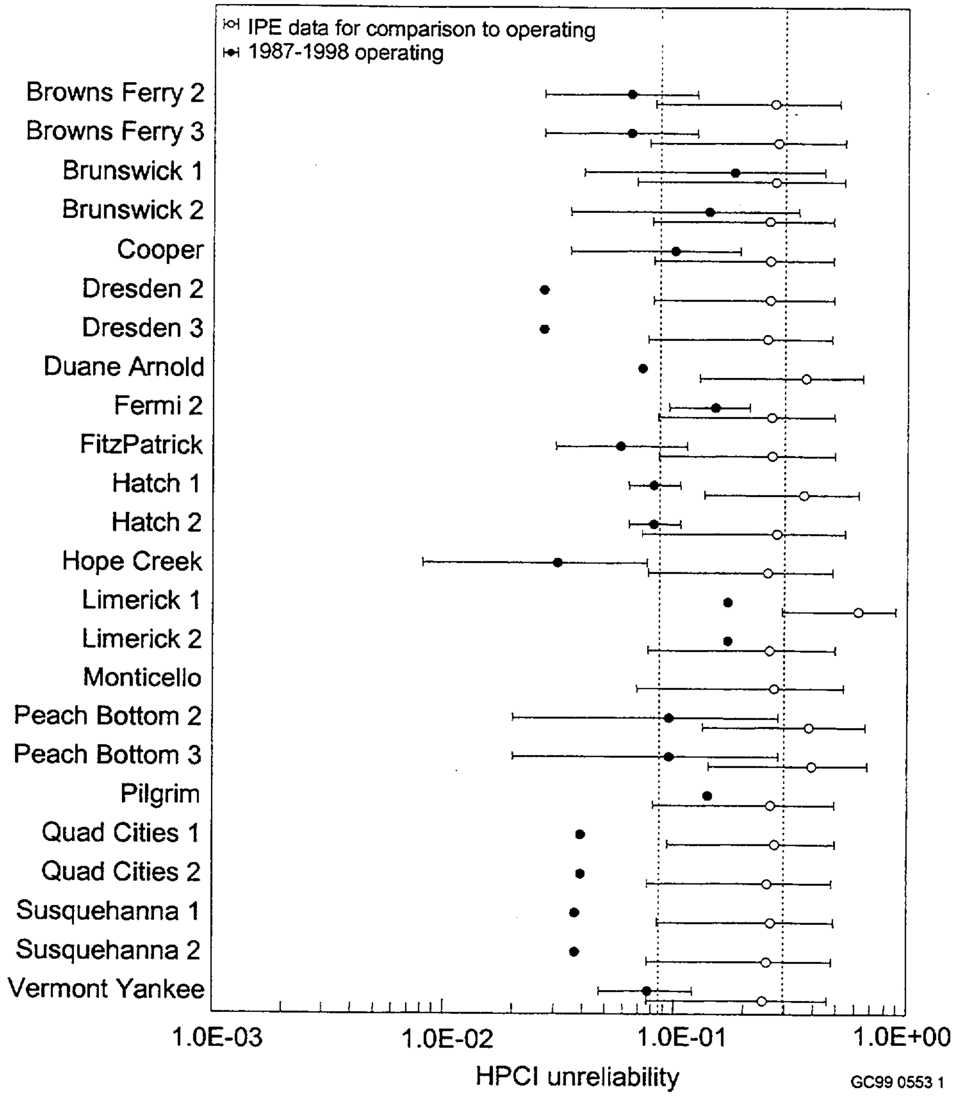

Figure C-2. Plots of the PRA/IPE and 1987-1998 operating experience estimates of HPCS unreliability for PRA/IPE comparison. The estimates were calculated from the comparison fault tree model depicted in Figure C-1.

Table C-2. HPCI system unreliability for the long-term mission for comparison to PRA/IPEs, based on empirical Bayes distributions for each failure mode with plant variation, and simple Bayes distributions for the rest (1987–1998 operating experience).

	Beta Distribution		Emperical Bayes Probability[a]		
Plant	*a*	*b*	5th Percentile	Mean	95th Percentile
Browns Ferry 2	2.83	7.72	8.16E-02	2.68E-01	5.07E-01
Browns Ferry 3	2.53	6.6	7.71E-02	2.77E-01	5.36E-01
Brunswick 1	2.31	6.25	6.82E-02	2.70E-01	5.35E-01
Brunswick 2	2.97	8.68	7.98E-02	2.55E-01	4.79E-01
Cooper	2.99	8.69	8.08E-02	2.56E-01	4.80E-01
Dresden 2	2.97	8.62	8.05E-02	2.56E-01	4.82E-01
Dresden 3	2.88	8.64	7.64E-02	2.50E-01	4.75E-01
Duane Arnold	3.1	5.37	1.28E-01	3.66E-01	6.42E-01
Fermi 2	3.07	8.72	8.43E-02	2.61E-01	4.85E-01
FitzPatrick	3.08	8.64	8.54E-02	2.63E-01	4.88E-01
Hatch 1	3.45	6.13	1.35E-01	3.60E-01	6.20E-01
Hatch 2	2.38	6.27	7.18E-02	2.75E-01	5.40E-01
Hope Creek	2.87	8.52	7.68E-02	2.52E-01	4.79E-01
Limerick 1	3.66	2.27	2.91E-01	6.17E-01	8.95E-01
Limerick 2	2.79	8.04	7.68E-02	2.57E-01	4.91E-01
Monticello	2.32	6.3	6.85E-02	2.69E-01	5.34E-01
Peach Bottom 2	3.04	4.94	1.33E-01	3.81E-01	6.65E-01
Peach Bottom 3	3.14	4.87	1.41E-01	3.92E-01	6.76E-01
Pilgrim	2.94	8.39	8.10E-02	2.60E-01	4.88E-01
Quad Cities 1	3.3	8.86	9.31E-02	2.71E-01	4.93E-01
Quad Cities 2	2.86	8.52	7.64E-02	2.52E-01	4.78E-01
Susquehanna 1	3.08	8.71	8.46E-02	2.61E-01	4.85E-01
Susquehanna 2	2.86	8.52	7.63E-02	2.51E-01	4.78E-01
Vermont Yankee	3.02	9.46	7.63E-02	2.42E-01	4.56E-01

a. HPCI system unreliability was estimated from the fault tree model used for PRA/IPE comparison (Figure C-1).

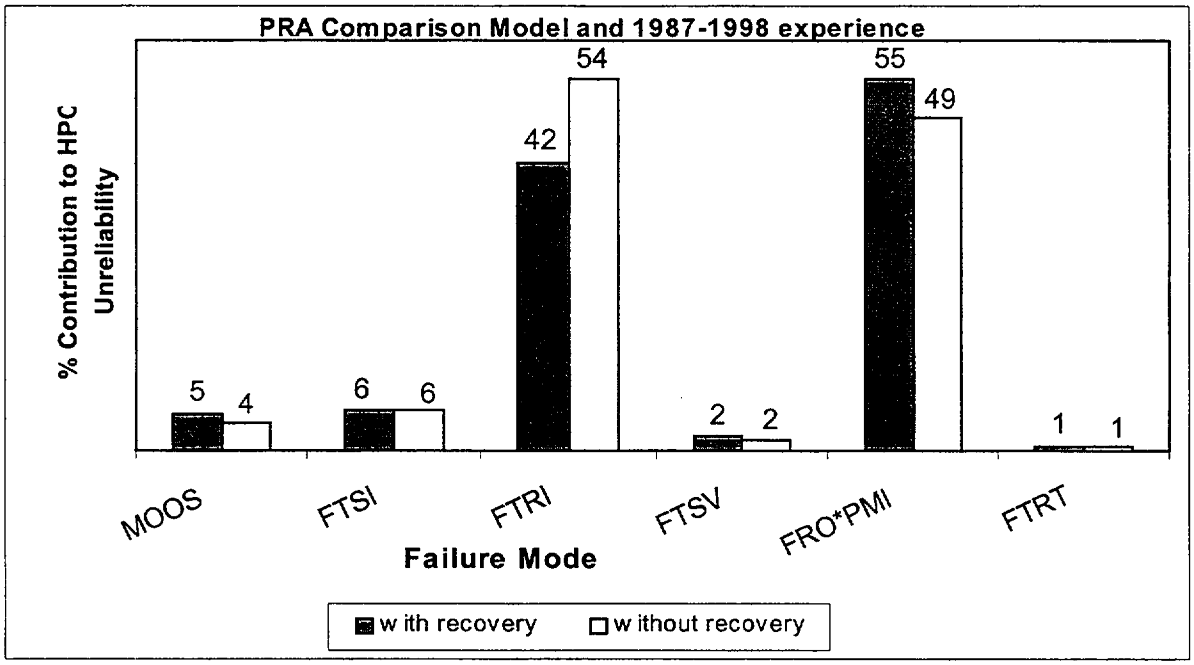

Figure C-3. Bar chart of failure mode percentage contribution to HPCI system unreliability calculated for comparison to PRA/IPE results. (The percent contribution is the mean failure mode probability divided by the mean HPCI system unreliability.)