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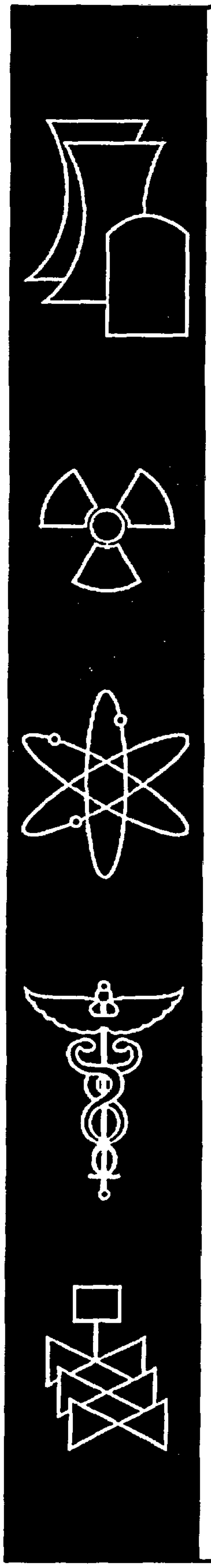

# Reliability Study: High-Pressure Coolant Injection (HPCI) System, 1987-1993

**Idaho National Engineering and Environmental Laboratory**

**U.S. Nuclear Regulatory Commission**
**Office of Nuclear Regulatory Research**
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# Reliability Study: High-Pressure Coolant Injection (HPCI) System, 1987-1993

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# ABSTRACT

This report documents an analysis of the safety-related performance of the high-pressure coolant injection (HPCI) system at U.S. commercial boiling water reactor plants during the period 1987–1993. Both a risk-based analysis and an engineering analysis of trends and patterns were performed on data from HPCI system operational events to provide insights into the performance of the HPCI system throughout the industry and at a plant-specific level. Comparison was made to Probabilistic Risk Assessment/Individual Plant Evaluations for 23 plants to indicate where operational data either support or fail to support the assumptions, models, and data used to develop HPCI system unreliability.

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# EXECUTIVE SUMMARY

This report presents a performance evaluation of the high-pressure coolant injection (HPCI) system at 23 U.S. commercial boiling water reactors (BWRs). The study was based on the operating experience from 1987 through 1993, as reported in Licensee Event Reports (LERs) and monthly nuclear power plant operating reports. The objectives of the study were:

1. To estimate HPCI system unreliability based on operational data, and to compare the results with the assumptions, models, and data used in Probabilistic Risk Assessments/Individual Plant Evaluations (PRA/IPEs).

2. To provide an engineering analysis of the trends and patterns seen in the HPCI system operational data.

The HPCI system was modeled using standard PRA techniques, and the operational data were used to develop the basic event failure probabilities to allow quantification of the models. Between-plant comparisons were made on the basis of these models. The results, using the actual plant operational data, were then compared to the results from current PRA/IPEs. The engineering analysis included both an industry-wide and a plant-specific examination. Investigation of trends and patterns in system failures and demands were based on operational time, low-power license date, subsystem, cause, and method of discovery.

Of the 303 events reported which involved the HPCI system during the evaluation period, 145 were classified as HPCI failures and 63 as HPCI actual unplanned demands occurring from a reactor pressure vessel (RPV) low-water level condition. In addition, a review of the Accident Sequence Precursor events for the same time period identified 19 events related to a demand of the HPCI system; 7 identified a system malfunction during an unplanned demand, 8 were unplanned demands with no system malfunction, and 4 were potential demands of the system when it was out-of-service for maintenance/testing.

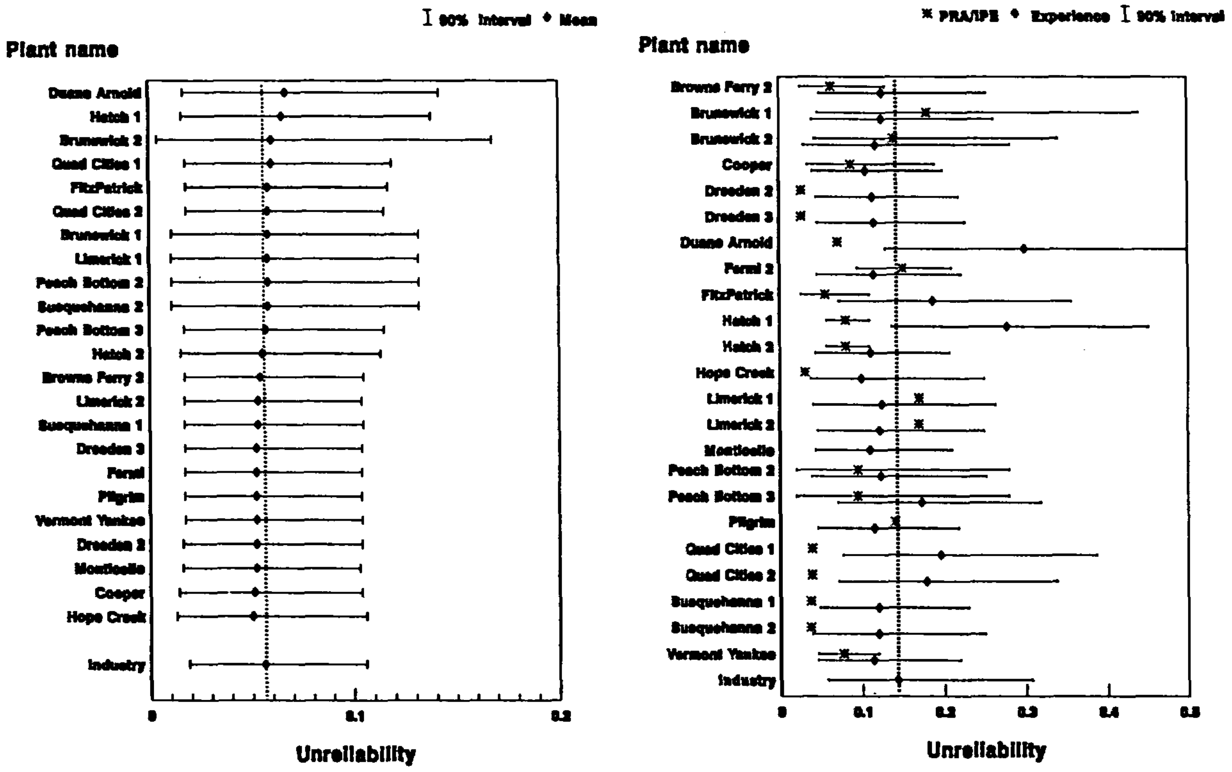
The results of the unreliability estimates computed from the operational data and the comparison with the PRA/IPEs are as follows:

- The observed industry-average unreliability of the HPCI system, taking credit for recovery actions, is 0.056. If recovery is excluded from the calculation, as is appropriate for comparisons with PRA/IPEs, the unreliability is 0.14. These numbers assume that the system is demanded to inject only once during a mission. If, instead, the normally closed injection motor-operated valve (MOV) between the HPCI pump discharge and the RPV is required to open more than once, the unreliability including recovery increases to 0.24. Although observed in the operational data, most PRA/IPEs do not model injection valve cycling.

- The observed plant-specific unreliability on a single injection, taking credit for recovery, ranged from 0.050 to 0.067. This variation was within the uncertainty range for each plant, as shown in the left side plot of Figure ES-1.

- The observed plant-specific unreliabilities for a single injection without taking credit for recovery actions is consistent with the values used in 12 of 23 PRA/IPEs, as shown in the right-side of Figure ES-1. Ten of the other 11 plants had observed unreliabilities greater than a factor of 3 higher than, and outside the uncertainty bounds of, the plant-specific PRA/IPE unreliabilities. The one remaining plant had insufficient information in the PRA/IPE to allow for a comparison.

- Comparison between the observed plant-specific basic event probabilities and the plant-specific PRA/IPE basic events probabilities yields the following:
  - The observed failure-to-run probability is greater than 10 times higher than that used in 13 of the PRA/IPEs, with 9 of the 13 PRA/IPE estimates exceeded by greater than 30 times.
  - The observed failure-to-start probability was in general agreement with the PRA/IPEs. However, two plants had probabilities greater than 6 times higher than those used in the PRA/IPEs, and the mean value used in those PRA/IPEs fell outside the uncertainty intervals-based on operational data.
  - The observed failure probability of the injection valve to open on the initial system demand to restore RPV level is greater than 10 times higher than that used in 10 of the PRA/IPEs.
  - The probability of being out of service for observed maintenance and testing for all plants is in agreement with the PRA/IPEs.



Unreliability with recovery actions included.

Unreliability comparisons without recovery.

**Figure ES-1.** HPCI system plant-specific unreliabilities compared to the plant-specific PRA/IPEs.

The principal results of the engineering review of the operational data are as follows:

- As shown in Figure ES-2, no correlation was seen between the plant's low-power license date and either the unreliability per operational year, or the rate of failures per operational year.

- While the rate of HPCI system unplanned demands and failures per plant operational year decreased during the 7-year period, the associated unreliability showed no significant trend. These trends are shown in Figure ES-3.

- Unplanned demand failures dominated the contribution to HPCI system unreliability prior to 1991, and cyclic test failures dominated HPCI system unreliability from 1991 on. There were no observed unplanned demand failures after 1991.

- The component failures and their failure mechanisms observed during unplanned demands were different than those found during the performance of surveillance tests.

- Failures associated with instrumentation and control circuits occurred twice as often when the HPCI system was in standby than during surveillance tests, with no failures observed during unplanned demands.

- Surveillance test failures were dominated by failures to start (74%), and unplanned demands were dominated by failures to run (55%).

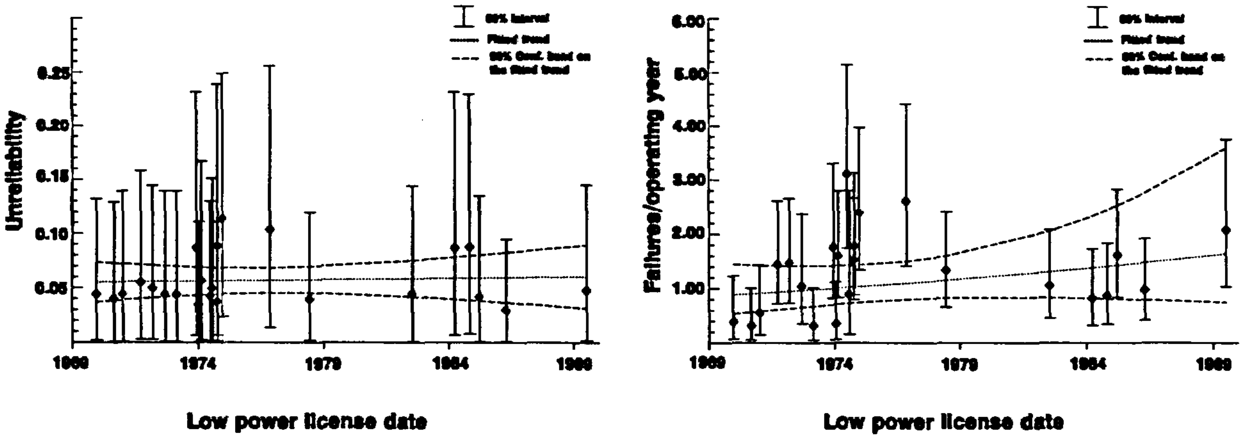
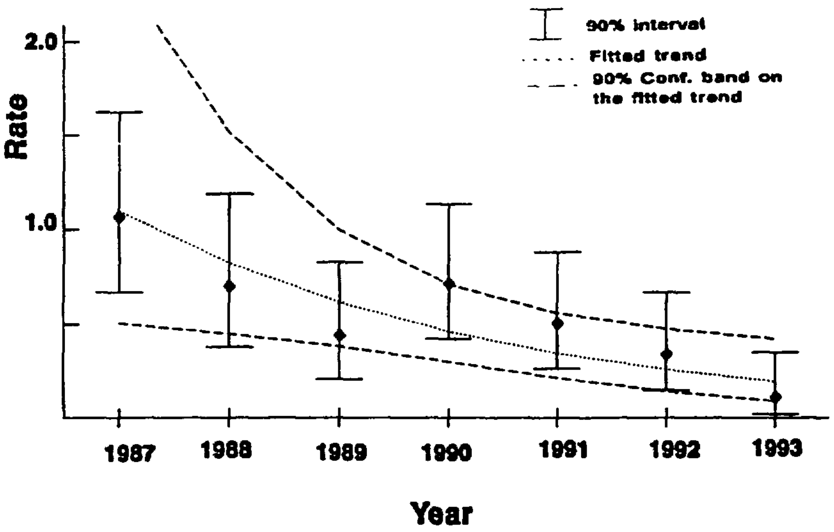
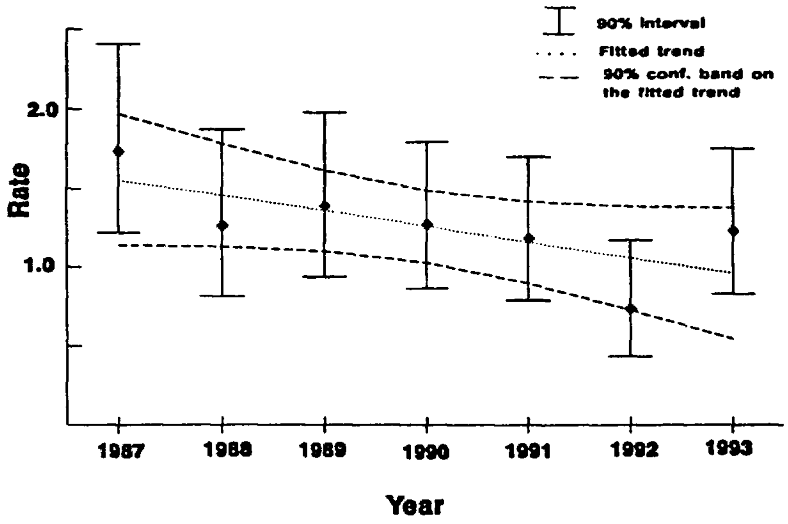


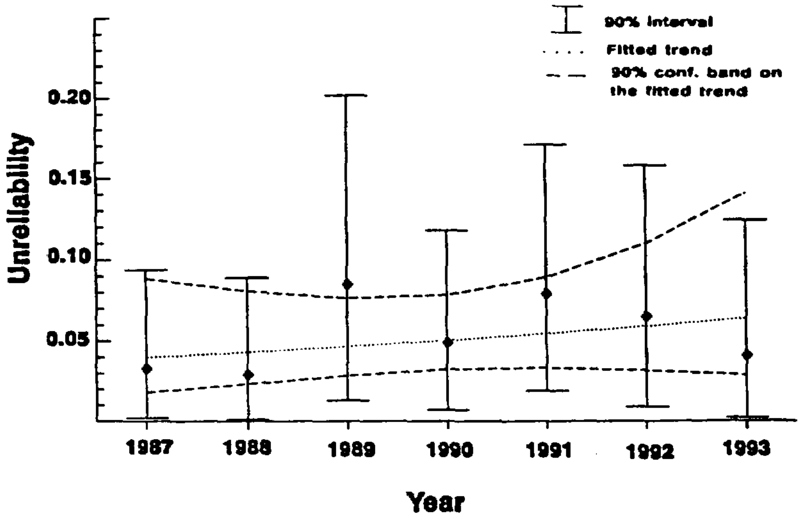
**Figure ES-2.** Plots of plant-specific HPCI system unreliabilities and failure rates per operational year plotted against plant-specific low power license date.



System unplanned demand rate



System failure rate



System unreliability

**Figure ES-3.** HPCI system unplanned demand rate, failure rate, and unreliability, per calendar year.

# ACKNOWLEDGMENTS

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Development of the content and objectives of the study benefitted from the invaluable contributions of J. R. Fragola and E. Lofgren of SAIC Corp.

# ACRONYMS

| | |
|---|---|
| AEOD | Analysis and Evaluation of Operational Data (NRC Office) |
| ASEP | Accident Sequence Evaluation Program |
| ASP | Accident Sequence Precursor |
| BWR | boiling water reactor |
| CCDP | conditional core damage probability |
| CRD | control rod drive |
| CST | condensate storage tank |
| ECCS | emergency core cooling systems |
| FRFTR | failure to recover from failure to run |
| FRFTS | failure to recover from failure to start |
| FRO | failure (of the injection valve) to reopen |
| FTR | failure to run |
| FTS | failure to start |
| FTSO | failure to start other than injection valve |
| FTSV | failure to start because of injection valve |
| HPCI | high-pressure coolant injection |
| HVAC | heating, ventilating, and air conditioning |
| INEL | Idaho National Engineering Laboratory |
| IPE | individual plant examination |
| LER | Licensee Event Report |
| MCC | motor control center |
| MOOS | maintenance and testing out of service |

|  |  |
|---|---|
| MOV | motor-operated valve |
| NRC | Nuclear Regulatory Commission |
| PRA | probabilistic risk assessment |
| RCIC | reactor core isolation cooling |
| RPV | reactor pressure vessel |
| SCSS | Sequence Coding and Search System |
| SRV | safety relief valve |
| TDP | turbine-driven pump |

# TERMINOLOGY

*Cyclic surveillance test*—The test of the system typically performed once per operating cycle, and required to be performed at least every 18 months.

*Demand rate*—The number of unplanned demands divided by the operating time, in years.

*Failure*—An inoperability in which the safety injection function is lost.

*Failure rate*—The number of failures divided by the operating time, in years.

*Failure of injection valve to reopen (FRO)*—A failure of the injection valve to open the second and subsequent times during a single HPCI mission.

*Failure to run (FTR)*—A failure of the HPCI system after the system reaches 90% of rated coolant flow. May or may not include FRO depending on context.

*Failure to start (FTS)*—A failure of the HPCI system prior to the system reaching 90% of rated coolant flow. This was sometimes divided into failure to start because of injection valve problems (FTSV), and failure to start for other reasons (FTSO).

*Inoperability*—An event in which the HPCI system is not fully operable as defined by applicable plant technical specifications or Safety Analysis Reports.

*Maintenance out of service (MOOS)*—A failure of the HPCI system due to the HPCI system being out of service for testing or maintenance.

*P-value*—The probability that the data set would be as extreme as it is, if the assumed model is correct. It is the significance level at which the assumed model would barely be rejected by a statistical test. A small P-value indicates strong evidence against the assumed model.

*Recovery*—The overcoming of a prior failure solely by operator actions without the need for any maintenance action or repair.

*Safety function available (SFA)*—An inoperability of the HPCI system in which the safety injection function is not lost.

*Safety function lost (SFL)*—Loss of the ability of the HPCI system to provide its safety injection function; same as failure.

*Safety injection function*—To start and to inject coolant to the RPV with at least 90% of the flow rate required by the plant technical specifications for the entire required mission time, automatically and without any operator action.

*Statistically significant*—Having a P-value of 0.05 or smaller when compared to the assumed model.

*Unplanned demand*—An automatic or manual signal for the HPCI system to start, as a result of actual need for RPV inventory restoration. (Unplanned demands as a result of a high drywell pressure condition were not observed in the operational data)

*Unreliability*—Probability that the system will fail to complete its required mission when demanded. This includes the contributions of MOOS, FTS, FTR and all other failure modes identified in the operational data. Recovery may or may not be included, depending on the context. The mission may or may not require repeated cycling of the injection valve, depending on the context.

# High-Pressure Coolant Injection (HPCI) System Performance, 1987–1993

## 1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC), Office for Analysis and Evaluation of Operational Data (AEOD) has, in cooperation with other NRC Offices, undertaken an effort to ensure that the stated NRC policy to expand the use of probabilistic risk assessment (PRA) within the agency is implemented in a consistent and predictable manner. As part of this effort, the AEOD Safety Programs Division has undertaken a review of nuclear power plant operating experience data. The approach is to compare the results as estimated in PRAs to actual operating experience. The first phase of the review involves the identification of risk-important systems from a PRA perspective and the performance of reliability and trending analysis on these identified systems. As part of this review, a risk-related performance evaluation of the HPCI system in U.S. commercial boiling water reactors (BWRs) was undertaken. The evaluation was directed at estimating HPCI system performance using actual operating experience.

The HPCI system performance study was based upon the operating experience during the period from 1987 through 1993, as reported in Licensee Event Reports (LERs) and monthly nuclear power plant operating reports. The objectives of the study were:

- To estimate HPCI system reliability based on operational data, and compare the results with the assumptions, models, and data used in Probabilistic Risk Assessment/Individual Plant Evaluations (PRA/IPEs).
- To provide an engineering analysis of the trends and patterns seen in the HPCI system operational data.

The report is arranged as follows. Section 1 provides the introduction. Section 2 describes the scope of the study, describes the HPCI system, and briefly describes the data collection and analysis methods. Section 3 presents the results of the risk-based analysis of the operational data. Section 4 provides the results of the engineering analysis of the operational data. Section 5 contains the references. Appendix A provides a detailed explanation of the methods used for data collection, characterization, and analysis. Appendix B gives summary lists of the data. Appendix C summarizes the detailed statistical analyses used to determine the results presented in Sections 3 and 4.

# 2. SCOPE OF STUDY

This study documents an analysis of the operational experience from 1987-1993 of the 23 U.S. commercial BWRs that have a dedicated HPCI system. Table 1 lists these plants along with their associated number of operating years. Operating years for each plant were estimated by calendar time minus all periods when the main generator was off-line for more than two calendar days. LER data were not collected for a given calendar year if there was no operating time in that year. Plants with no operational time during the study period were excluded from the study. Details of the calculation of operating time are provided in Appendix A, and plant exclusions are provided in Appendix B.

This analysis focused only on the emergency core cooling system (ECCS) coolant injection function. The principal elements of the study process are briefly described in Section 2.1 to provide an orientation to the detailed discussions that follow.

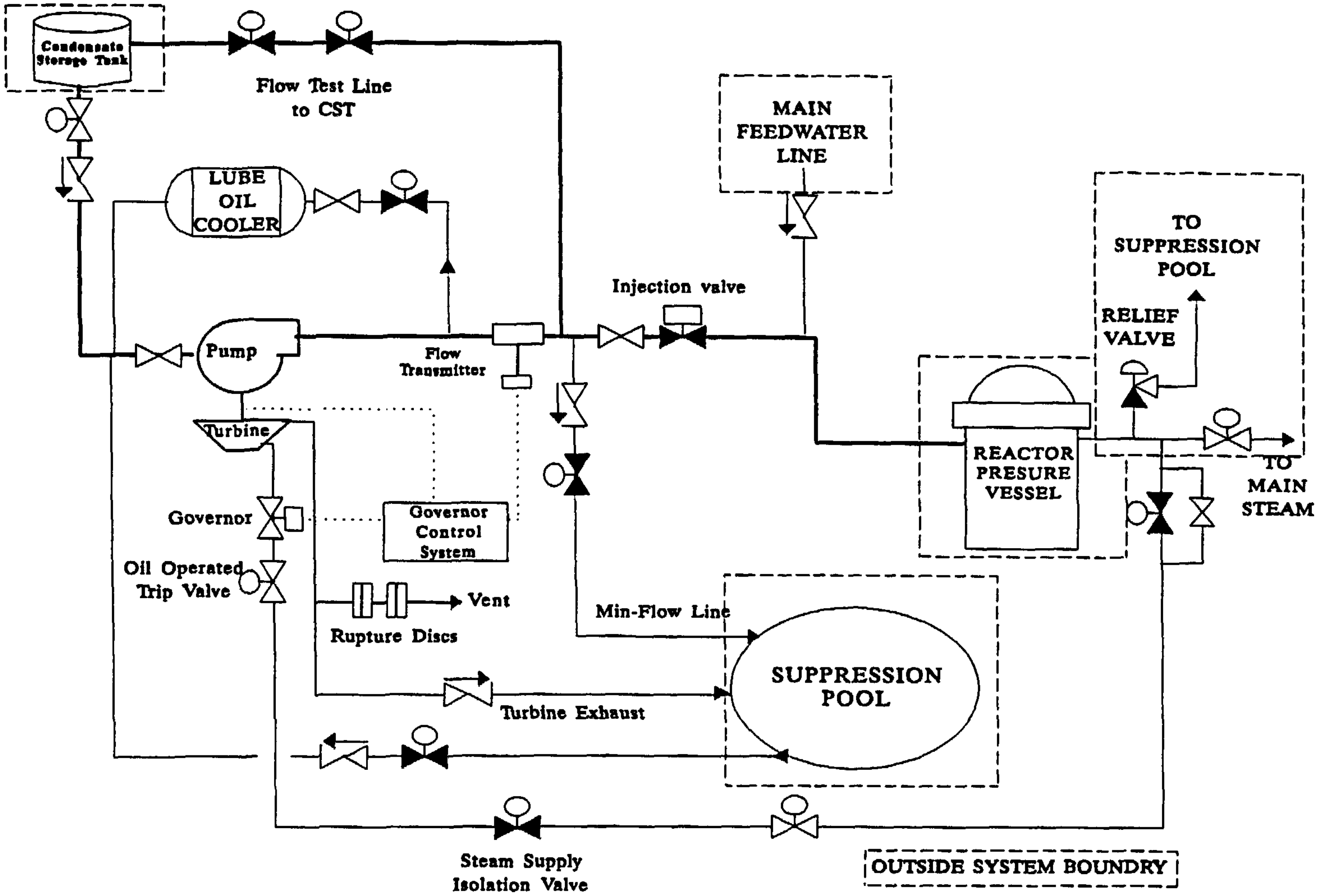
## 2.1 Description of System

The HPCI system is a single-train system that provides a reliable source of high-pressure coolant for cases where there is a loss of normal core coolant inventory. Figure 1 provides a simplified schematic diagram of the system.

The HPCI system consists of a steam turbine-driven pump, valves and valve operators, and associated piping, including that from the normal and alternate pump suction sources and the pump discharge up to the penetration of the main feedwater line. For this study, the part of the main feedwater line from the check valve upstream of the HPCI connection to the reactor vessel, including the check

**Table 1.** BWR plants with a dedicated HPCI system.

| Plant | Docket | Operating years | Plant | Docket | Operating years |
|---|---|---|---|---|---|
| Browns Ferry 2 | 260 | 2.2 | Limerick 1 | 352 | 5.7 |
| Brunswick 1 | 325 | 3.8 | Limerick 2 | 353 | 3.8 |
| Brunswick 2 | 324 | 4.6 | Monticello | 263 | 6.3 |
| Cooper | 298 | 5.6 | Peach Bottom 2 | 277 | 4.0 |
| Dresden 2 | 237 | 5.1 | Peach Bottom 3 | 278 | 3.5 |
| Dresden 3 | 249 | 5.4 | Pilgrim | 293 | 3.9 |
| Duane Arnold | 331 | 5.6 | Quad Cities 1 | 254 | 5.5 |
| Fermi 2 | 341 | 5.6 | Quad Cities 2 | 265 | 5.4 |
| FitzPatrick | 333 | 4.5 | Susquehanna 1 | 387 | 5.7 |
| Hatch 1 | 321 | 5.9 | Susquehanna 2 | 388 | 6.1 |
| Hatch 2 | 366 | 6.0 | Vermont Yankee | 271 | 6.2 |
| Hope Creek | 354 | 6.2 | | | |



BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

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

valve, was considered part of the HPCI system. The steam turbine-driven pump includes all steam piping from the main steam line penetration to the turbine, and turbine exhaust piping to the suppression pool, valves and valve operators, gland sealing steam, and the turbine auxiliary oil system.

Additional components that were considered to be part of the HPCI system were the circuit breakers at the motor control centers (MCCs) (but not the MCCs themselves), the dedicated DC power system that supplies HPCI system power and the associated inverters, and the initiation and isolation logic circuits with their associated detectors. Heating, ventilating, and air conditioning (HVAC) systems and room cooling associated with the HPCI system were included. However, only a specific loss of service water to individual HPCI room coolers was included, and not the loss of the entire service water system.

Support system failures were considered for possible inclusion in this HPCI study. However, examination of the operational data found no cases when support system failures clearly caused HPCI failure. In addition, the support system failure contribution to the overall HPCI system failure probabilities in the PRAs was found to be small. Therefore, support systems were treated as outside the scope of this study.

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

The HPCI system is also manually used to help control RPV pressure following a transient. Although this is not part of the ECCS design function it is depended on, in approximately 90% of the PRA/IPEs. However, only approximately 10% of the PRA/IPEs that depend on this function model the pressure control operation. In this mode, the turbine-driven pump is operated manually with the injection valve closed and the full-flow test-line MOV open. Turbine operation with the injection line isolated and the test line open allows the turbine to draw steam from the RPV, thereby reducing RPV pressure. Operation of the system in the pressure control mode may also occur with intermittent injection of coolant to the RPV. As steam is being drawn off the RPV, the RPV water inventory is reduced, resulting in the need for level restoration. When level restoration is required, the injection valve is opened and the test-line MOV is closed. Upon restoration of RPV water inventory, the system is returned to the pressure control line-up. This cycling between injection and pressure control can be repeated as necessary.

## 2.2 Operational Data Collection

HPCI system operational data as reported in LERs from 1987-1993 were reviewed. Because HPCI is a safety system, any malfunctions that result in the system not being operable as defined by the respective plant technical specifications or the Safety Analysis Report are required by 10 CFR 50.73 to be reported in LERs.

In this report, the term *inoperability* is used to describe any LER-reported HPCI event in which the HPCI system did not meet the operability requirements identified in applicable plant technical specifications or the Safety Analysis Report. It is distinguished from the term *failure*, which is an inoperability for which the ECCS function of the system (the ability to inject coolant on demand) is lost. Failures include such problems as failures to start and failures to run. Inoperabilities include these, and also problems such as events related to seismic design, and administrative events such as late performance of a test. Because analysis of the containment isolation safety function of HPCI is not included in this study, events such as failures to isolate the turbine steam supply were regarded as inoperabilities, not failures.

### 2.2.1 Data Collection and Characterization

To identify HPCI inoperabilities reported in the LERs, the Sequence Coding and Search System (SCSS) LER database was searched for all records for the years 1987–1993 that refer to an actual or potential HPCI system inoperability. Each identified LER was read completely with care taken to properly classify each event and to ensure consistency of the classification for each event. The LERs were reviewed to determine the types of failures, the causes of the event, the method of discovery, and the component that contributed to the failure. The data were then entered into a database.

For failures, an additional event attribute was captured, the system failure mode. When the HPCI system receives an automatic start signal as a result of an actual low RPV water level condition, the system functions successfully if the turbine starts and obtains rated speed and coolant pressure, the injection valve opens, and coolant flow is delivered to the RPV until the flow is no longer needed. Failure may occur at any point in this process. For the purposes of this study, failure modes that can occur in response to an actual low RPV water level are defined below:

- Maintenance and testing out of service (MOOS) occurs if, due to testing or maintenance, the HPCI system is prevented from starting automatically

- Failure to start (FTS) occurs if the system is in service but fails to automatically start and achieve at least 90% of the rated coolant flow

- Failure to run (FTR) occurs if, at any time after the system is delivering at least 90% of the rated coolant flow, the HPCI system fails to maintain this flow while it is needed.

Recovery from initial failures is also important in estimating system reliability. To recover from failure to start, operators have to recognize that the system was in a failed state, restart it without performing maintenance (for example, without replacing components), and restore coolant flow to the RPV. An example of such a recovery would be an operator (a) noticing that the injection valve had not opened during an automatic start of the system, and (b) manually operating the control switch for this valve, thereby causing the MOV to open fully and allow rated coolant flow to the RPV. Recovery from failure to run is defined in a similar manner. Each failure was evaluated to determine whether recovery by the operator occurred.

To estimate unreliability, information on the frequency and nature of HPCI demands was needed. The LERs provided information on unplanned demands following plant transients that resulted in an actual low RPV water level condition, that is, an actual need for the HPCI system. Unplanned demands as a result of a high drywell pressure condition were not observed in the operational data. These demands were identified by searching the SCSS database for all LERS containing HPCI actuations. The identified LERS were screened to determine the nature of the HPCI demand. Many of the unplanned demands were actuations of only a part of the system. The partial actuations included suction path shifts and relay actuations related to plant maintenance actions, such as removal of a fuse or shorting of test leads. These partial actuations did not exercise the HPCI system in response to an actual need for injection. Therefore, these records were excluded from the count of HPCI unplanned demands.

Data from the surveillance tests that are performed approximately every operating cycle were also used to help estimate the system unreliability. Plant technical specifications require that the cyclic (18-month) surveillance tests simulate automatic actuation of the system throughout its emergency operating sequence and that each automatic valve actuate to the correct position. Because of the completeness of the cyclic surveillance test as compared to other surveillance tests (monthly, quarterly, etc.), cyclic surveillance tests were also used to estimate unreliability. For more details on the counting of unplanned demands and surveillance test demands, see Section A-1.2 in Appendix A.

## 2.3 Operational Data Analysis

The scope of the risk-based and engineering analysis of the operational data are based on two different data sets. Figure 2 illustrates the relationship between these data sets. Data set A represents all the LERs that identified a HPCI system inoperability from the above-mentioned SCSS database searches. Data set B represents the inoperabilities that resulted in a loss of the safety injection function (failure) of the HPCI system. Data set C represents the LERs that identified a HPCI system failure for which a demand frequency could be determined or estimated.

The risk-based analysis of the operational data was based on the determination of unreliability which considers only the failures of the HPCI system, and only those for which a demand frequency could be estimated or determined—the failures that occurred during an unplanned demand or a cyclic surveillance test (data set C). The engineering analysis of the operational data examined all the system inoperabilities (data set A). In a few of these analyzes they focused only on the failures of the HPCI system (data set B) to highlight the events that were risk-significant.

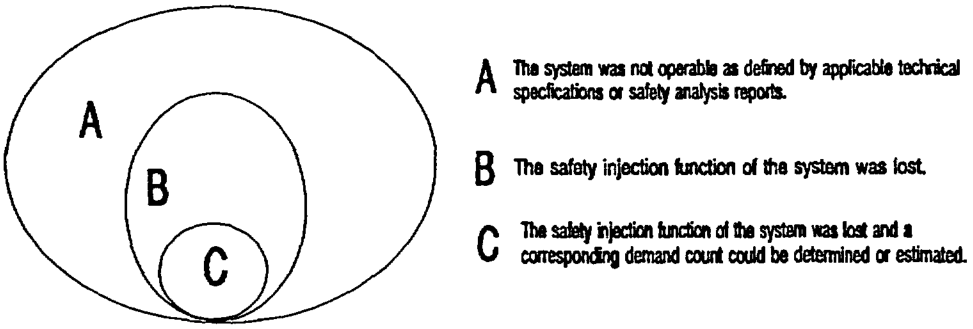


**Figure 2.** Illustration of the inoperability and failure data sets.

# 3. RISK-BASED ANALYSIS OF THE OPERATIONAL DATA

In this section, the operational data is analyzed in two ways. First, an evaluation of the HPCI system unreliability based on the operational data is performed to uncover trends and patterns within the data. Second, comparisons are made between HPCI system unreliabilities based on operational data and HPCI system unreliabilities reported in corresponding Probabilistic Risk Assessments/Individual Plant Examinations (PRA/IPEs). The objective of the trends and patterns analysis is to provide insights into the performance of the HPCI system on both an industry-wide and a plant-specific level. The objective of the comparisons are to indicate where operational data support or fail to support the assumptions, models, and data used in the PRA/IPEs.

HPCI system unreliability was calculated using a simple PRA model (fault tree). Basic event failure probabilities based on operational data (as developed in Appendix C) were used to quantify the model. HPCI system unreliability and basic event failure probabilities drawn from PRA/IPEs are included for comparison. A summary of the major findings is presented here.

- The observed industry-average unreliability of the HPCI system, taking credit for recovery actions, is 0.056. If recovery is excluded from the calculation, as is appropriate for comparisons with PRA/IPEs, the unreliability is 0.14. These numbers assume that the system is demanded to inject only once during a mission. If, instead, the normally closed injection motor-operated valve (MOV) between the HPCI pump discharge and the RPV is required to open more than once, the unreliability including recovery increases to 0.24. Although observed in the operational data, most PRA/IPEs do not model injection valve cycling.

- The observed plant-specific unreliability on a single injection, taking credit for recovery, ranged from 0.050 to 0.067. This variation was within the uncertainty range for each plant.

- The observed plant-specific unreliabilities for a single injection without taking credit for recovery actions is consistent with the values used in 12 of 23 PRA/IPEs. Ten of the other 11 plants had observed unreliabilities greater than a factor of 3 higher than, and outside the uncertainty bounds of, the plant-specific PRA/IPE unreliabilities. The one remaining plant had insufficient information in the PRA/IPE to allow for a comparison.

- Comparison between the observed plant-specific basic event probabilities and the plant-specific PRA/IPE basic events probabilities yields the following:

    - The observed failure-to-run probability is greater than 10 times higher than that used in 13 of the PRA/IPEs, with 9 of the 13 PRA/IPE estimates exceeded by greater than 30 times.

    - The observed failure-to-start probability was in general agreement with the PRA/IPEs. However, two plants had probabilities greater than 6 times higher than those used in the PRA/IPEs, and the mean value used in those PRA/IPEs fell outside the uncertainty intervals-based on operational data.

- The observed failure probability of the injection valve to open on the initial system demand to restore RPV level is greater than 10 times higher than that used in 10 of the PRA/IPEs.

- The probability of being out of service for observed maintenance and testing for all plants is in agreement with the PRA/IPEs.

## 3.1 Unreliability Based on Operational Data

### 3.1.1 Plant-specific Unreliability

The operational data for the HPCI system, from unplanned demands and cyclic surveillance tests, were statistically analyzed to develop basic event failure probabilities (see Appendices A and C). The following seven event categories were used:

Maintenance and testing Out Of Service (MOOS)
Failure To Start due to failures of hardware Other than the injection valve (FTSO)
Failure To Start due to injection Valve failure (FTSV)
Failure to Recover from FTS (FRFTS)
Failure To Run (FTR)
Failure to Recover from FTR (FRFTR)
Failure of injection valve to ReOpen (FRO)

Table 2 contains the failure probabilities and associated uncertainty intervals that were determined for each of the event categories (basic events) using the operational data. Where no significant differences were found between plants, the data were pooled and modeled as arising from a binomial distribution using the simple Bayes method. When between-plant variability could be estimated, the empirical Bayes method was employed. These methods are described in more detail in Appendix A, Section A-2.1.4.

Splitting the failure to start into two categories allowed use of the results of cyclic surveillance tests in the evaluation of FTSO. The cyclic surveillance tests were not usable in the evaluation of FTSV because the injection valve is not tested under the same conditions seen during unplanned demands (see Section A-1.2.2 of Appendix A and Section 4). FRO could have been included in the FTR basic event; however, because the failure is not modeled in most PRA/IPEs, and because the demands to reopen required special analysis, FRO was treated separately.

The unreliability of the HPCI system was calculated using the simple fault tree model shown in Figure 3. The model was constructed to reflect the logical combination of six of the seven failure modes developed using the operational data. FRO was excluded because it represents a failure mode not accounted for in most PRAs. FRO is addressed in Section 3.3. Table 3 contains the system unreliability and associated uncertainty intervals resulting from quantifying the fault tree using the data in Table 2. Also included in Table 3 are the probabilities for the four cut sets that make up the unreliability along with their percentage contribution.

**Table 2.** Basic event failure data and Bayesian probability information.

| Basic event | Failures[a] (f) | Demands[a] (d) | Modeled variation | Distribution | Bayes Mean and 90% interval[b] |
|---|---|---|---|---|---|
| Maintenance and testing out of service (MOOS) | 1 | 63 | Sampling | Beta(1.5, 62.5) | (0.0028, 0.023, 0.060) |
| Failure to start, other than injection valve (FTSO) | 11[c] | 170[c] | Between plant | Beta(0.41, 6.4) | (0.0001, 0.060, 0.24) |
| Failure to start, injection valve (FTSV) | 1 | 59[d] | Sampling | Beta(1.5, 58.5) | (0.0030, 0.025, 0.064) |
| Failure to recover from FTS (FRFTS) | 0 | 5 | Sampling | Beta(0.5, 5.5) | (0.0004, 0.0833, 0.31) |
| Failure to run (FTR) | 7[e] | 167[e] | Between plant | Beta(5.2, 117.4) | (0.017, 0.042, 0.076) |
| Failure to recover from FTR (FRFTR) | 2 | 3 | Sampling | Beta(2.5, 1.5) | (0.24, 0.63, 0.94) |
| Failure of injection valve to reopen (FRO) | 3 | 19.2[f] | Sampling and uncertain demand count | Beta( 2.3, 9.4) | (0.046, 0.20, 0.41) |

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a. Unplanned demands unless otherwise noted.

b. The middle number is the Bayes mean, and the end numbers form a 90% interval.

c. Composed of 4 failures during 59 unplanned demands (excludes 4 partial demands) and 7 failures during 111 cyclic surveillance tests.

d. Excludes 4 partial demands.

e. Composed of 3 failures during 56 unplanned demands (excludes 3 demands with FRO failures) and 4 failures during 111 cyclic surveillance tests.

f. This is a best estimate for a very uncertain number. The number of demands for multiple injections could be as small as 11 or as large as 46.

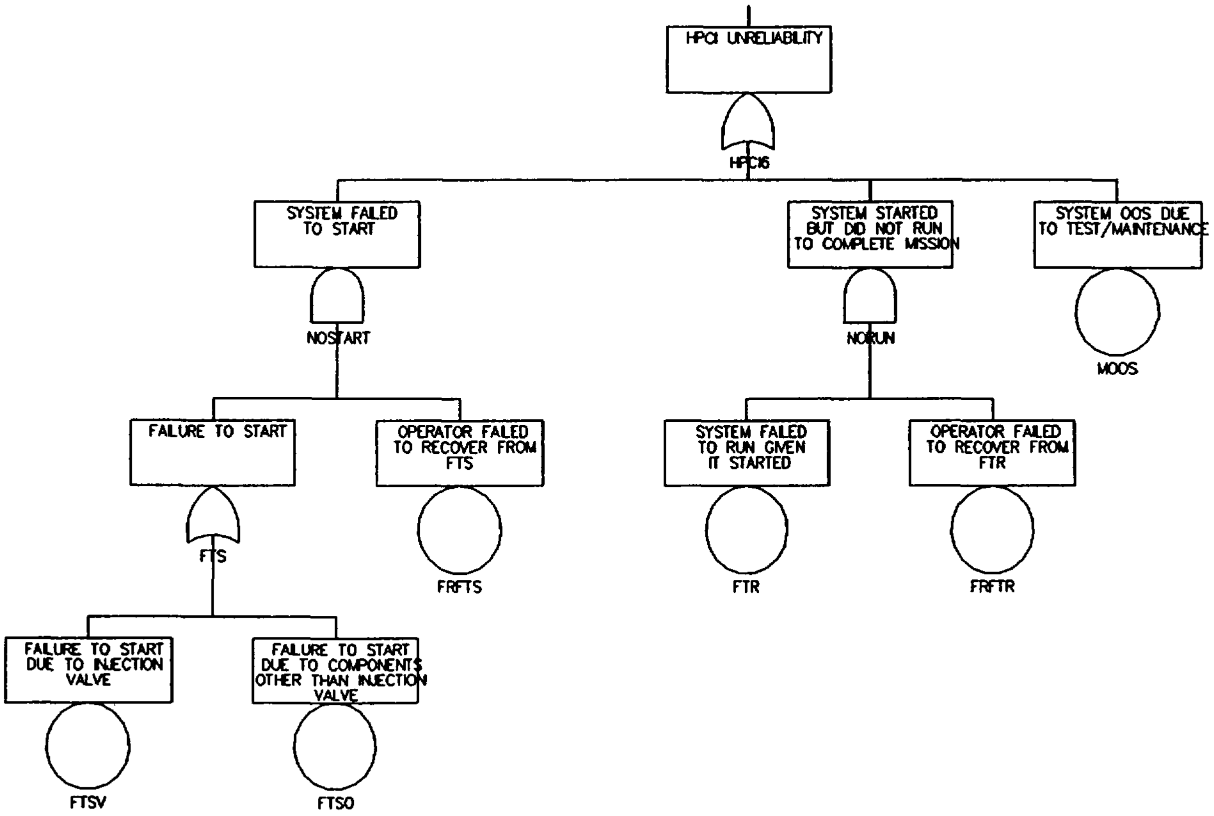

**Figure 3.** HPCI unreliability evaluation model (includes recovery actions, excludes failure of injection the valve to reopen.

**Table 3.** HPCI system unreliability, with recovery actions, based on industry-wide experience. Failure of the injection valve to reopen is excluded.

| Contributor | Contributor probability | Percentage contribution[a] |
|---|---|---|
| FTR*FRFTR | 0.026 | 47 |
| MOOS | 0.023 | 42 |
| FTSO*FRFTS | 0.0050 | 9 |
| FTSV*FRFTS | 0.0021 | 4 |
| **Unreliability** | **0.056[b]** | **100** |

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a. Percentages sum to slightly more than 100% because the unreliability is the union of the four contributors, and the probability of this union is less than the sum of the individual probabilities.

b. The 90% uncertainty interval bounds are: 0.021, 0.11. This uncertainty corresponds to the randomness of the data and to between-plant variation. Other sources of uncertainty are discussed in Section C-4 of Appendix C.

The mission times of the observed demands were significantly shorter (less than 1 hour and typically just a few minutes) than the mission times of 5 to 24 hours that are typically used in modeling the HPCI system in plant PRA/IPEs. For this reason, the FTR probability and the overall unreliability value may be nonconservative relative to the performance that can be expected under reactor transient or accident conditions that require mission times greater than 1 hour.

Plant-specific unreliabilities were calculated to investigate differences between plants. Statistical analysis (details are provided in Appendix C) determined that MOOS, FTSV, FRFTS and FRFTR show no significant plant-to-plant variation while the failure probabilities for the FTSO and FTR events do show a plant-to-plant variation. As a result, plant-specific values for FTSO and FTR were determined. The plant-specific values are recorded in Appendix C (Tables C-3 and C-4) and were used to calculate the plant-specific unreliabilities shown in Figure 4. The industry-wide unreliability from Table 2 is also shown in Figure 4. Duane Arnold and Hatch 1 were found to have the highest HPCI system unreliability, but the differences between plants were very small. The unreliability estimates ranged from 0.050 to 0.067.

### 3.1.2 Investigation of Possible Trends

Unreliability was also calculated to reveal any overall trend that may be present. The method used here for calendar years and for plants differs from the method used to produce Figure 4; the statistical methods used for trend analysis of a sparse data set differs from the method used to determine plant-to-

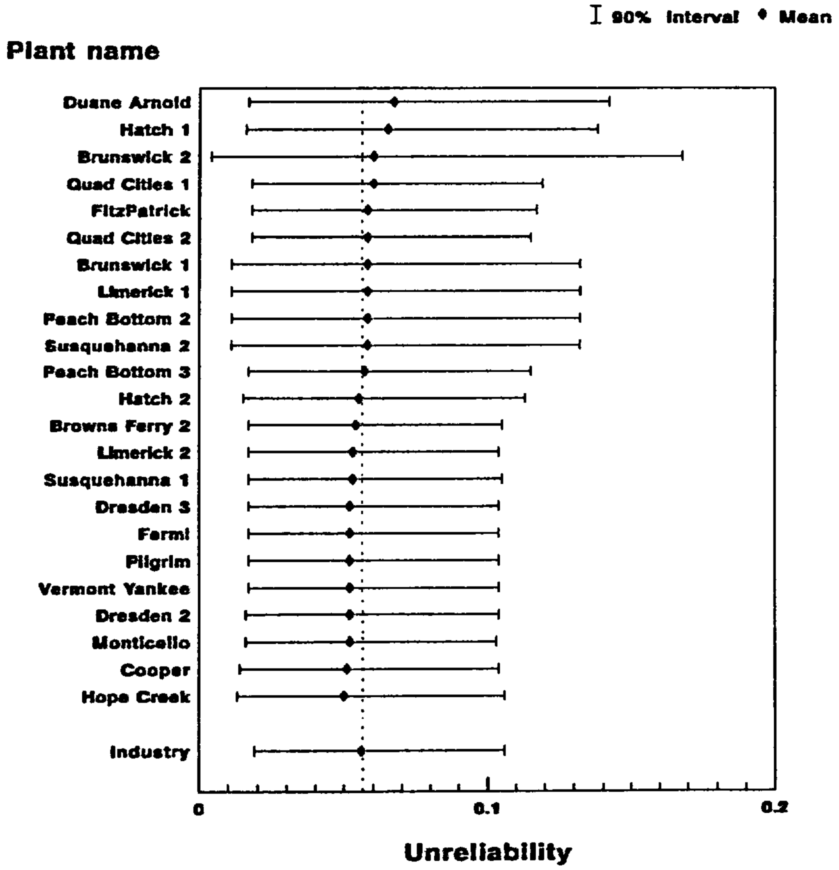

Figure 4. Plant-specific HPCI system unreliabilities, including recovery actions and excluding failure of the injection valve to reopen.

plant differences using a larger data set. The details are presented in Section A-2.1.4 of Appendix A and in Sections C-2 and C-3 of Appendix C. The calculated unreliabilities include operator action to recover from failures to start or run, and exclude the failure of the injection valve to reopen. Figure 5 shows the unreliability by year. The slope of the trend line is not statistically significant (P-value = 0.29).

To give some indication of the effect of the passage of time on HPCI performance, plant-specific unreliability was plotted against the plant low-power license date. The plot is shown in Figure 6 with 90% uncertainty bars plotted vertically. A trend line and a 90% confidence band for the fitted trend line are also shown in the figure. The slope of the trend line is not statistically significant (P-value = 0.77).

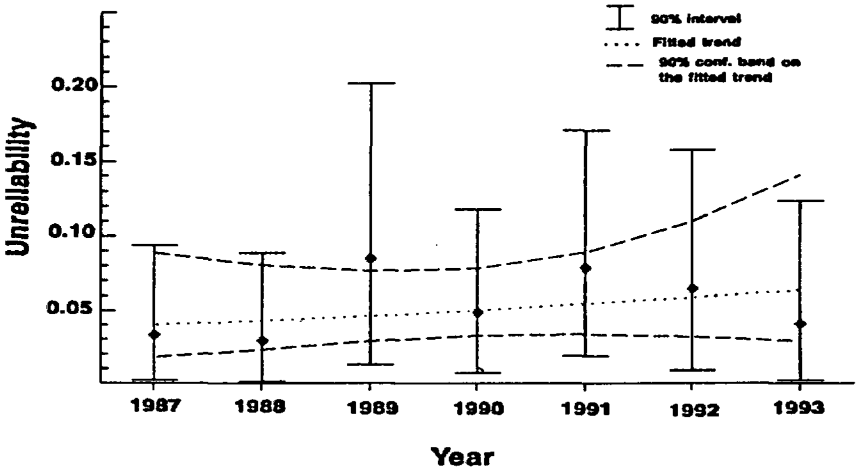

**Figure 5.** HPCI system unreliability by year, including recovery and excluding failure of the injection valve to reopen. The plotted trend is not statistically significant (P-value = 0.29).

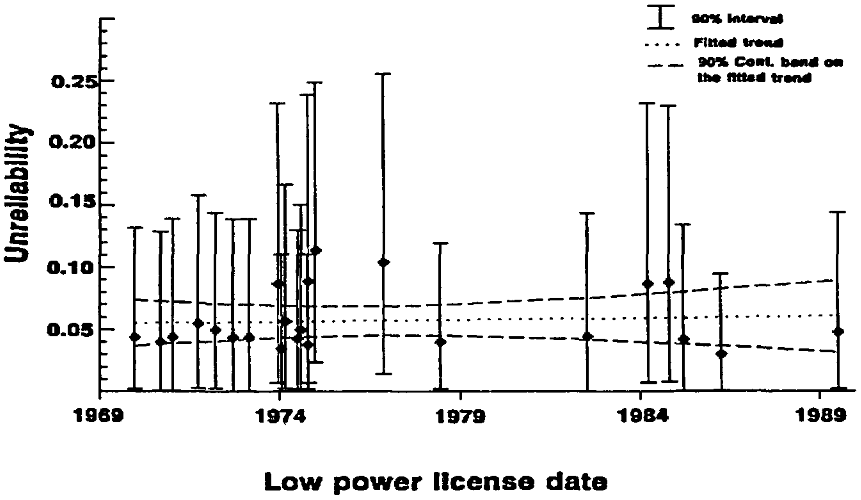

**Figure 6.** Plant-specific HPCI system unreliabilities plotted against low-power license dates. The unreliability includes recovery and excludes failure of the injection valve to reopen. The plotted trend is not statistically significant (P-value = 0.77).

## 3.2 PRA Comparison

The simple fault tree model shown in Figure 3 provided the logic for combining plant-specific event failure probabilities to calculate unreliabilities for comparison with the PRA/IPE values for the HPCI system. However, since most PRA/IPEs model recovery at the event tree level and not at the fault tree level, the recovery events FRFTS and FRFTR were not included. The plant-specific values used are listed in Appendix C, Tables C-3 and C-4. The values used for comparison were taken from 16 PRA/IPEs (References 1 through 16). Seven of the 16 PRA/IPEs reflect data from two plants each, thus every plant listed in Table 1 is represented.

The models in the PRA/IPEs include hardware failures, human errors, support system failures, and unavailabilities caused by tests or maintenance. Occasionally, operator actions and hardware failures associated with level- or pressure-control operations were also modeled at the fault tree level. To allow comparison of PRA/IPE results to unreliabilities based on operational data, contributions to the system unreliability from support systems and from manual level- or pressure-control operations were removed and the PRA/IPEs were requantified. This modification resulted in a change in reliability of less than 10% in all but two plants. The requantified PRA/IPE values, along with the plant-specific estimates of unreliability, are shown in Table 4 and graphically in Figure 7.

The PRA/IPE mean values of unreliability range from 0.027 to 0.18. The mean values of unreliability based on plant-specific experience range from 0.11 to 0.28, with all but two less than or equal to 0.20. The means differ by less than a factor of 2 in 12 of the plants and greater than 3 in 10 of the plants, as indicated by the "Comparison Ratio" column in Table 4.[a] In all 10 cases with differences greater than a factor of 3, the plant-specific experience is higher than the PRA/IPE value. In addition, in all 10 cases, the mean value from the PRA/IPE fell below the uncertainty intervals based on plant-specific experience. The primary cause of the difference in unreliability in 2 of the 10 cases was a difference in the FTSO failure probability. The difference in the other eight cases were caused primarily by differences in the FTR failure probability. The differences in failure probabilities are discussed in the following paragraphs.

In addition to the plant-specific unreliability comparisons, the PRA/IPE modeling of the HPCI system was analyzed by comparing the probabilities used for the basic events that contributed to the HPCI system unreliability. Figure 8 is a plot of plant-specific event failure probabilities from the PRA/IPE with the values determined using industry experience for each of the four basic failure modes.

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[a] The HPCI system unreliability for Monticello was not reported in the PRA/IPE.

**Table 4.** Comparison of HPCI system unreliabilities from PRA/IPEs with corresponding plant-specific and industry-wide unreliabilities based on operational data.

| PRA/IPE | PRA/IPE (Without support system failures and manual operation) | Plant-specific experience | Comparison ratio[a] |
|---|---|---|---|
| | B | C | C/B |
| Browns Ferry 2 | 0.064[b] | 0.13 | 2.0 |
| Brunswick 1 | 0.18 | 0.13 | 0.7 |
| Brunswick 2 | 0.14 | 0.13 | 0.9 |
| Cooper | 0.088[b] | 0.11 | 1.3 |
| Dresden 2 | 0.027 | 0.11 | 4.1* |
| Dresden 3 | 0.027 | 0.12 | 4.4* |
| Duane Arnold | 0.072[b] | 0.30 | 4.2* |
| Fermi 2 | 0.15[b] | 0.12 | 0.8 |
| FitzPatrick | 0.056 | 0.19 | 3.4* |
| Hatch 1 | 0.081[b] | 0.28 | 3.5* |
| Hatch 2 | 0.081[b] | 0.11 | 1.4 |
| Hope Creek | 0.031[b] | 0.10 | 3.2* |
| Limerick 1 | 0.17[b] | 0.13 | 0.8 |
| Limerick 2 | 0.17[b] | 0.12 | 0.7 |
| Monticello | -[c] | 0.11 | -[c] |
| Peach Bottom 2 | 0.095 | 0.17 | 1.8 |
| Peach Bottom 3 | 0.095 | 0.12 | 1.3 |
| Pilgrim | 0.14[b] | 0.12 | 0.9 |
| Quad Cities 1 | 0.039 | 0.20 | 5.1* |
| Quad Cities 2 | 0.039 | 0.18 | 4.6* |
| Susquehanna 1 | 0.037[b] | 0.12 | 3.2* |
| Susquehanna 2 | 0.037[b] | 0.12 | 3.2* |
| Vermont Yankee | 0.054[b] | 0.11 | 2.0 |
| Industry | — | 0.14 | — |

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a. Comparison ratios greater than 3 are noted with an asterisk.

b. Estimated value based on major basic events reported in PRA/IPE, fault tree not available.

c. Value not available.

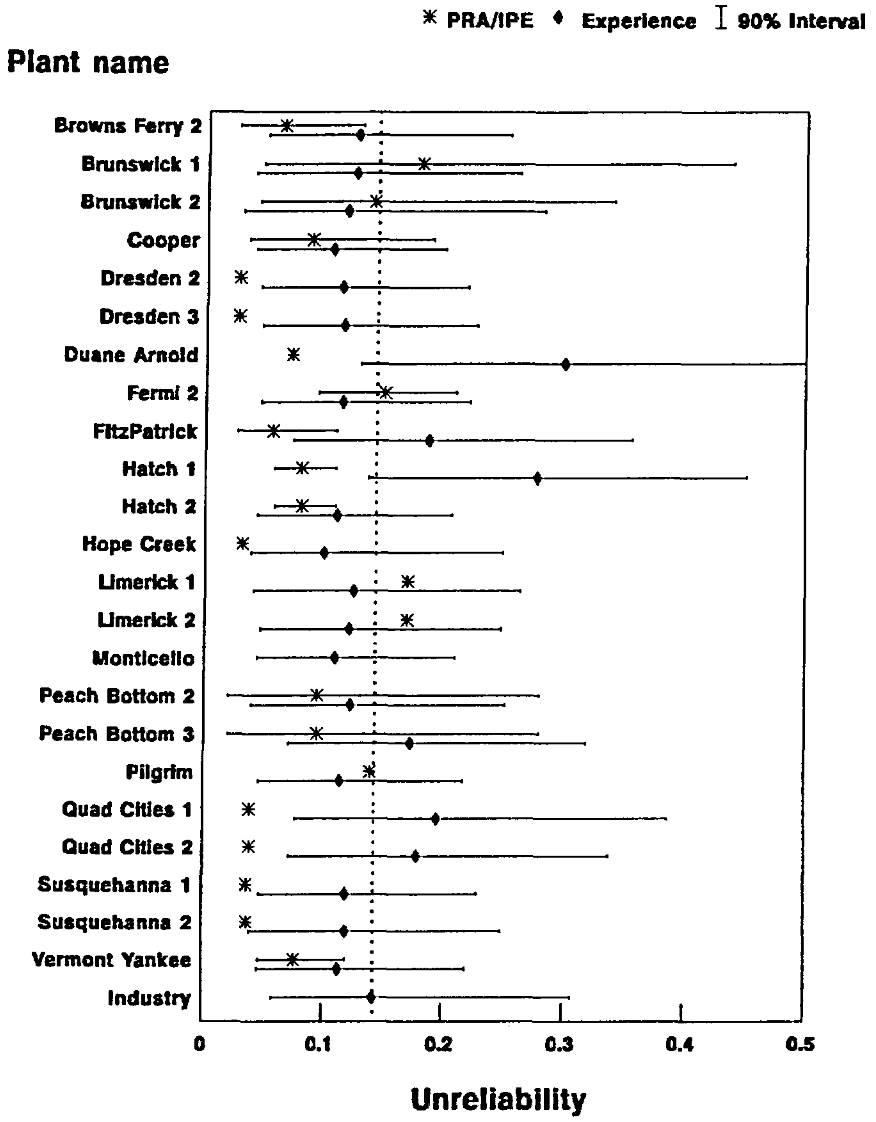


**Figure 7.** Comparison of HPCI unreliabilities from PRA/IPEs and industry experience. Recovery actions and failure of the injection valve to reopen are excluded.

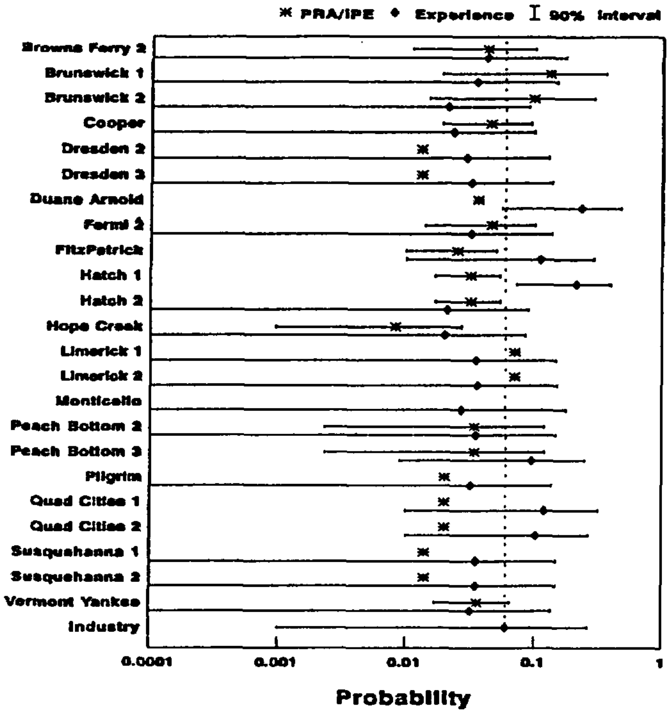
To make the comparisons, the basic events from the PRA/IPEs had to be grouped into the same four event categories as were used for the operational data. With only a few exceptions, the event categories include the following events from the PRA/IPEs:

FTSO: Turbine-driven pump (TDP) failure to start, failure of steam supply valves to open including isolation MOV(s), trip and throttle valve and governor valve failures, failure of motor-driven auxiliary lube oil pump to start.

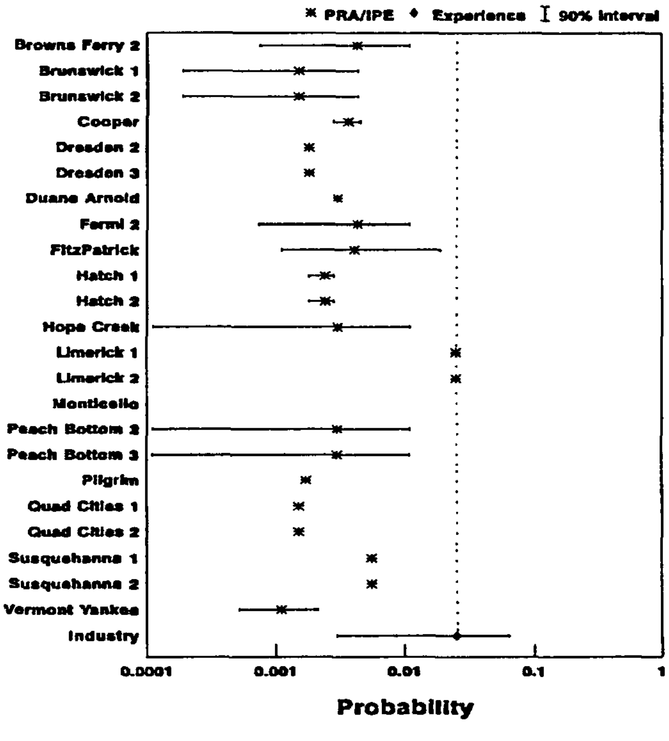
FTSV: Failure of injection valve to open.

FTR: TDP failure to run.

MOOS: TDP and major MOV testing and maintenance.

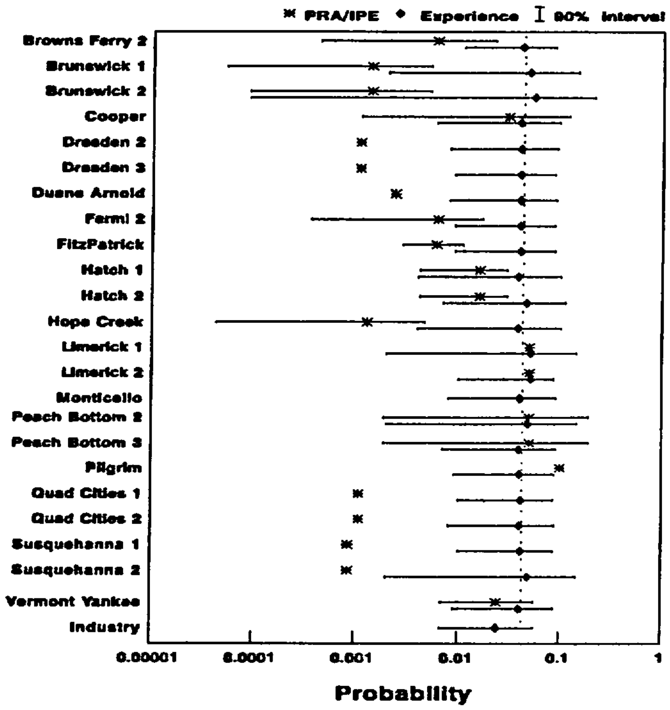


Failure to start due to failures of hardware other than the injection valve

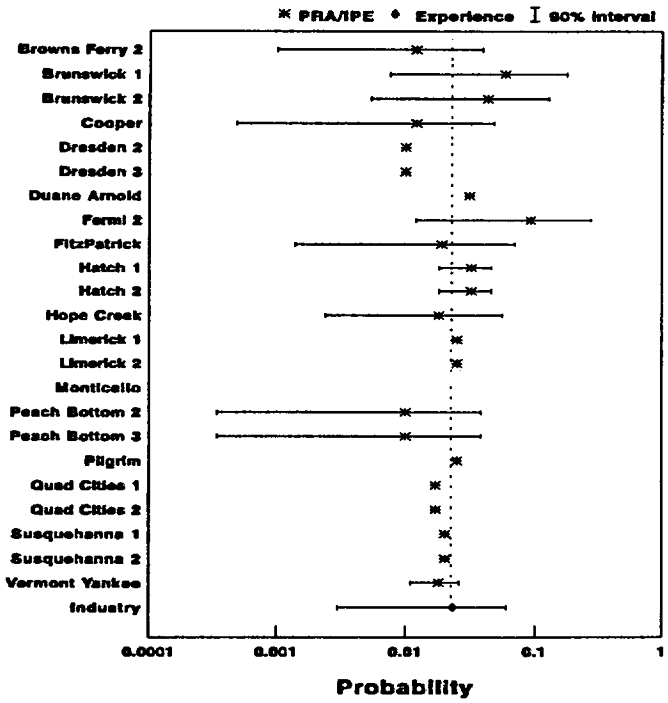


Failure to start due to failure of the injection valve

**Figure 8.** Comparisons of probabilities of plant-specific HPCI system failure mode from PRA/IPEs and industry experience.



Failure to run



Maintenance and testing out of service

**Figure 8.** (continued).

There were three exceptions to the events included in these categories: (a) the failure to start for Brunswick 1 and 2 included a steam drain failure (3% of the total unreliability); (b) instrumentation and control errors were rigorously modeled for FitzPatrick and were included as start failures (14% of the total unreliability); (c) the basic events for Limerick were atypical. In the case of Limerick, events defined as TDP-FTS or TDP-FTR were not specifically noted. As a result, the categorization of Limerick events is estimated based on the short description of the various basic events provided in the PRA/IPE. The events included in the four categories account for 99–100% of each PRA/IPE HPCI system unreliability, without support systems and without manual pressure- or level-control operation. While there may be numerous additional basic events in a given PRA/IPE, their effect on the system unreliability is quite small.

In reviewing the basic event failure probability comparisons in Figure 8, the criteria for identifying notable differences was that either the PRA/IPE mean value falls outside the uncertainty interval from industry experience or the mean values differed by more than a factor of 10. Table 5 lists those plants for which notable differences were identified.

The Duane Arnold and Hatch 1 failure-to-start from failures of equipment other than the injection valve (FTSO) probabilities were found to be significantly higher than the values used in the PRA/IPEs, and are the highest failure probabilities of all plants considered. The plant-specific FTSO probabilities for the remainder of the industry were in general agreement with the probabilities used in their respective PRA/IPE.

The mean failure-to-start due to the injection valve (FTSV) probability based on industry experience was a factor of 10 or more higher than the values from 10 plant PRA/IPEs. This may be due to using MOV failure rates based on failures of MOVs in a wide range of applications rather than for the specific application in which the MOV is used in the HPCI system. For example, the Quad Cities plant-specific value used in the PRA/IPE was calculated based on MOV data from several systems, of which 46 MOV failures were observed out of 31,652 demands. It is unlikely that there were 31,652 demands of MOVs to operate under conditions similar to those present during an unplanned demand of the HPCI system.

Thirteen plants were found to have mean failure-to-run (FTR) probabilities that were higher than the PRA/IPE value by a factor of 10 or more. The Peach Bottom PRA/IPE (Peach Bottom is not one of the thirteen) suggests a likely cause of this problem. Specifically, it is noted that generic pump failure-to-run numbers in the Accident Sequence Evaluation Program (ASEP) database (a commonly used generic database) were based on plant operational hours, not pump operational hours. If the generic ASEP FTR is recalculated (as in the Peach Bottom PRA/IPE) based on actual pump run time, the resulting generic value is similar to the Peach Bottom plant-specific value of 0.0053 per hour, yielding 0.026 to 0.13 for a typical 5–24 hour mission. These values bracket the FTR based on plant-wide experience and are large compared to the full mission FTR values of 0.001 to 0.0062 used by the 13 plants showing notable differences.

**Table 5.** PRA/IPEs having basic events probabilities that differ from industry experience.

| Plant | FTSO | FTSV | FTR | MOOS |
|---|---|---|---|---|
| Browns Ferry 2 | | | X | |
| Brunswick 1 & 2 | | X | X | |
| Dresden 2 & 3 | | X | X | |
| Duane Arnold | X | | X | |
| Fermi 2 | | | X | |
| FitzPatrick | | | X | |
| Hatch 1 | X | X | | |
| Hatch 2 | | X | | |
| Hope Creek | | | X | |
| Pilgrim | | X | | |
| Quad Cities 1 & 2 | | X | X | |
| Susquehanna 1 & 2 | | | X | |
| Vermont Yankee | | X | | |

## 3.3 Additional PRA Insights

Two insights were gained as a result of reviewing the PRA/IPEs to develop plant-specific values of HPCI system unreliability and to extract the basic events failure probabilities. First, it was found that most of the PRA/IPEs do not model the HPCI system in the way it is commonly operated. Specifically, the maintenance of level following initial injection, which places extra demands on the hardware and operators, is either not modeled or, if modeled, does not include the risk-important basic events. Second, even those PRA/IPEs that do model the system more rigorously do not reflect the impact of such operation on the hardware; i.e., the failure probabilities associated with injection valve operation do not correspond with operational experience.

The major responses upon initial demand for the HPCI system include: opening of the steam isolation valve to the HPCI turbine; starting of the lubrication/hydraulic oil system pump; opening of the turbine stop and governor valves, which brings the turbine up to speed; and the opening of the injection valve. At this point, the HPCI system is injecting water into the RPV in a continuous fashion. The HPCI design flow, which is based on conservative licensing assumptions, exceeds the flow requirements for the majority of actual HPCI demands based on operating experience. As a result, in order to control level shortly after the beginning of most events, the HPCI system must be placed in manual control and the flow diverted to either the torus or back to the suction source (likely the condensate storage tank). If such action is not taken quickly, the system will automatically trip on high level. If the automatic trip fails and the operator does not take manual control, then the reactor system will overfill, water will enter the main steam line and subsequently the HPCI turbine. When this happens, the turbine is assumed to be lost for the remainder of the event.

Placing of the HPCI system in manual control requires various operator actions and numerous hardware responses. From a hardware perspective, cycling of the injection valve and test line MOV and manual speed control of the turbine is required. If manual control of the turbine is not used or is not available, the turbine must be secured (tripped) and/or the injection valve must be completely shut. As the RPV level falls, the HPCI system must be realigned or restarted.

Eleven PRA/IPEs model operator actions to control RPV level. Restart of tripped or secured turbine-driven pumps is also considered by eight PRA/IPEs. However, only two model the hardware associated with the turbine speed controller or the injection valve; thus, the first insight is that most PRA/IPEs do not model the HPCI system in the way it is commonly operated during an event. A summary of the modeling approach for 20 PRA/IPEs is shown in Table 6. (The modeling for the other three PRA/IPEs considered in this report did not contain the necessary information to be included in the summary).

For the two PRA/IPEs that do model the hardware associated with manual control of the HPCI system, the failure probabilities used for cycling of the injection valve are on the order of 0.001. Plant experience indicates that three failures of the injection valve occurred out of approximately 19 mission demands to reopen, resulting in a failure probability of 0.20 (see FRO in Table 2). The difference in failure rate is a factor of 200; thus, the second insight is that even those PRA/IPEs that do model the system more rigorously do not reflect the impact of such operation on the hardware. The effect is quite large. The system unreliability assuming a single injection, based on industry experience and including operator recovery actions, is 0.056 (Table 2). The addition of the FRO mode in the fault tree model results in a system unreliability of 0.24, an increase of greater than a factor of 4. The 90% interval on this unreliability is (0.094, 0.44).

**Table 6.** Summary of PRA/IPE modeling of operator actions and hardware associated with manual control of HPCI.

| Plant | Operator actions for manual control included in model? | Hardware modeled other than restart of pump |
|---|---|---|
| Browns Ferry 2 | Yes | Models turbine flow controller |
| Brunswick 1 & 2 | No | None |
| Cooper | Yes | None |
| Dresden 2 & 3 | Yes | None |
| Duane Arnold | No | None |
| Fermi 2 | Yes | None |
| FitzPatrick | No | Models restart of lube oil pump and reopening of steam and injection valves |
| Hatch 1 & 2 | Yes | None |
| Hope Creek | Yes | None |
| Peach Bottom 1 & 2 | No | None |
| Pilgrim | No | None |
| Quad Cities 1 & 2 | Yes | None |
| Susquehanna 1 & 2 | No | None |
| Vermont Yankee | Yes | None |

# 4. ENGINEERING ANALYSIS OF THE OPERATIONAL DATA

This section documents the results of an engineering evaluation of the HPCI operational data derived from LERs and the Accident Sequence Precursor (ASP) database. The objective of this analysis was to analyze the data and provide insights into the performance of the HPCI system throughout the industry and at a plant-specific level. Unlike the PRA assessment provided in Section 3, all LERs submitted during the evaluation period and the ASP events that mentioned the HPCI system were considered as part of this analysis; no data were excluded. The LER data used in this evaluation include the 240 HPCI system inoperabilities, of which 145 were classified as failures, and the 63 HPCI unplanned system demands. The ASP database contained 19 events related to a demand of the HPCI system; 7 identified a system malfunction during an unplanned demand, 8 were unplanned demands with no system malfunction, and 4 were potential demands of the system when it was out-of-service for maintenance/testing.

The results of the operational data review were:

- While the rate of HPCI system unplanned demands and failures per plant operational year decreased during the 7-year period, unreliability showed no significant trend.

- Unplanned demand failures dominated the contribution to HPCI system unreliability prior to 1991, and cyclic test failures dominated HPCI system unreliability from 1991 on. There were no observed unplanned demand failures after 1991.

- The component failures and their failure mechanisms observed during unplanned demands were different than those found during the performance of surveillance tests.

    - Component failures observed during unplanned demands were dominated by injection valve and turbine governor malfunctions. Malfunctions of the injection valve due to pressure locking were recovered in 1 out of 4 instances, while governor malfunctions that were a result of water in the steam lines and erratic operation under varying flow conditions were always recovered.

    - Component failures observed during the performance of surveillance tests were dominated by steam line MOV and turbine governor malfunctions. Malfunctions of the steam line MOV were the result of improper maintenance and thermal binding, and governor malfunctions were the result of contaminated oil, calibration anomalies, and hardware failures.

- Failures associated with instrumentation and control circuits occurred twice as often when the HPCI system was in standby than during surveillance tests, with no failures observed during unplanned demands.

    - The demand-related failures that were observed in these circuits only occurred during the performance of a surveillance test and not during an unplanned demand. These demand-related failures were predominantly the result of personnel error and procedural problems. Examples of these failures included; miscalibration of detectors and sensors which would have prevented or degraded system response during an unplanned demand.

  - and inadvertent shorting of relays and blown fuses that resulted in spurious trips of the containment isolation function of the system.

  - The failures discovered when the system was in standby were primarily time-related failures. The types of time-related failures observed were; invertor failures, resistor and relay failures, and detector shorts from moisture intrusion. These time-related failures were identified by control room annunciators and other system indication available to control room operators.

- There was no correlation observed between the plant's low-power license date and the rate of failures per operational year.

The following subsections provide a comprehensive summary of the industry data supporting the above results as well as additional insights derived from: (a) an assessment of the operational data for trends and patterns in system performance across the industry and at specific plants, (b) identification of the subsystems and causes that contribute to the system failures, (c) a comparison of the failure mechanisms found during surveillance tests and unplanned demands, (d) evaluation of the relationship between system failures and low-power license date, and (e) Accident Sequence Precursor events involving the HPCI system.

## 4.1 Industry-wide Evaluation

### 4.1.1 Trends by Year

Table 7 provides the HPCI system inoperabilities, failures, and unplanned demands that occurred in the industry for each year of the study period. Figures 9, 10 and 11 are illustrations of inoperability, failure, and unplanned demand rates for each year of the study with 90% uncertainty intervals. Figures 10 and 11 include a fitted trend line and a 90% confidence band for the fitted trend. The rate is the number of events that occurred in the specific year divided by the total number of plant operational years for the specific year.

**Table 7.** Number of HPCI system inoperabilities, failures, and unplanned demands by year.[a]

| Classification | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | Total |
|---|---|---|---|---|---|---|---|---|
| Inoperabilities | 38 | 31 | 39 | 35 | 31 | 22 | 44 | 240 |
| Failures | 26 | 18 | 22 | 23 | 21 | 13 | 22 | 145 |
| Unplanned Demands | 16 | 10 | 7 | 13 | 9 | 6 | 2 | 63 |
| Cyclic Surveillance Test Demands | 12 | 13 | 18 | 16 | 17 | 20 | 15 | 111 |
| Plant Operational Years | 15.0 | 14.3 | 15.9 | 18.29 | 17.8 | 17.6 | 17.9 | 116.6 |

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[a] Each entry consists of events that occurred that year. Shutdowns longer than two calendar days are excluded from the operating year.

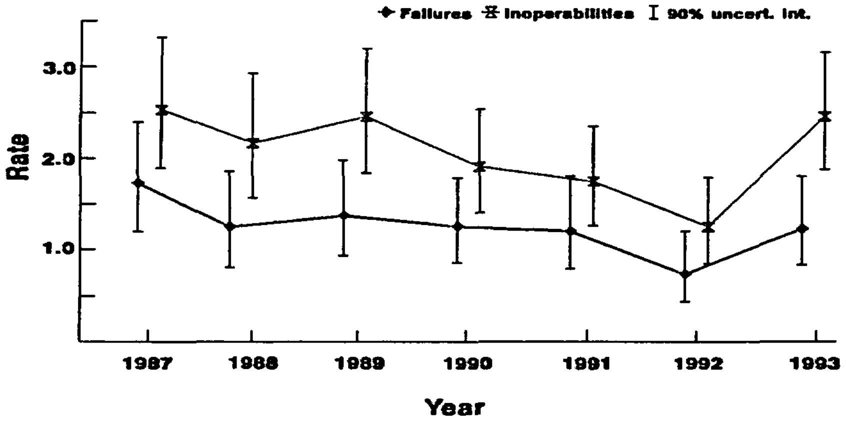

Figure 9. HPCI inoperabilities and failures per plant operational year, with 90% uncertainty intervals.

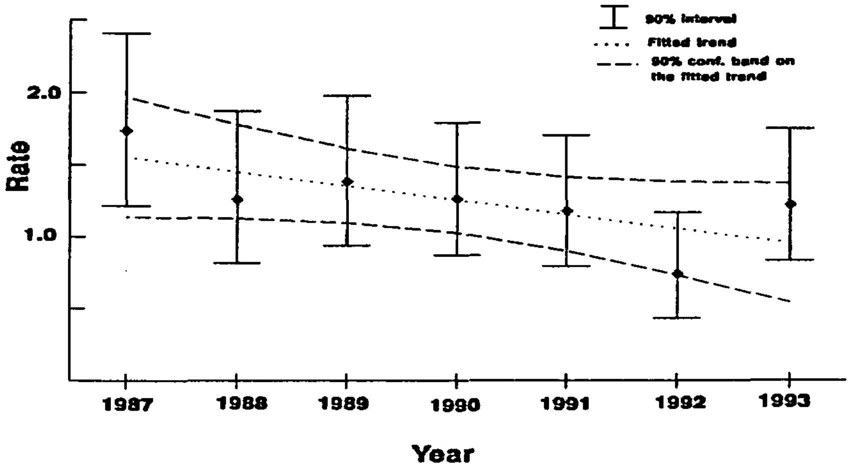

Figure 10. HPCI failures per plant operational year, with 90% uncertainty intervals and confidence band on the fitted trend. The trend is almost significant (P-value = 0.07).

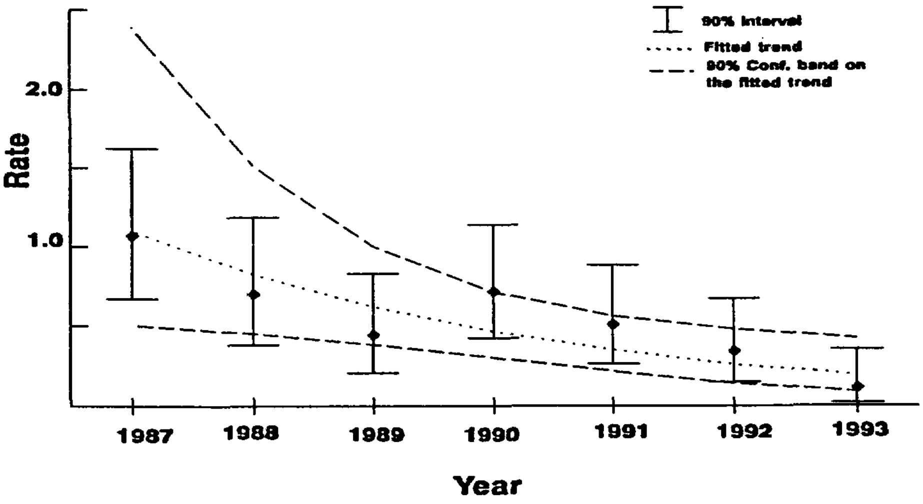

Figure 11. HPCI unplanned demands per plant operational year, with 90% uncertainty intervals and confidence band on the fitted trend. The trend is statistically significant (P-value=0.01).

Analysis of the inoperabilities and failure trends showed, in general, a decrease over the past 7 years. Analysis of the unplanned demands trend showed, a statistically significant, decrease over the past 7 years.

While the failure rate illustrated in Figure 10 shows a nearly significant decreasing trend (P-value = 0.07) and the unplanned demand rate illustrated in Figure 11 shows a significant decreasing trend (P-value = 0.01), the unreliability, presented previously in Figure 5, shows no significant trend (P-value = 0.29). To determine the mechanism that contributed to the relatively constant unreliability, an analysis of the HPCI demand and failure data was performed. The results of the demand and failure data analysis indicated the following:

- The demands prior to 1991 were approximately evenly distributed between cyclic surveillance tests (59) and unplanned demands (46). From 1991 on, there were three times the number of cyclic surveillance test demands (52) than unplanned demands (17).
- The failures prior to 1991 were experienced approximately 3 times as often on unplanned demands (13) as cyclic surveillance tests failures (4). From 1991 on, there were significantly more cyclic test failures (8) than unplanned demand failures (1).

Thus, the unplanned demand failures dominated the contribution to HPCI system unreliability prior to 1991, and cyclic test failures dominated HPCI system unreliability from 1991 on, with a net result of a constant HPCI system unreliability. A review of the subsystems and components contributing to system unreliability is discussed in the following subsection.

### 4.1.2 HPCI Subsystem Failures

The HPCI subsystems that failed or contributed to the HPCI system failures and inoperabilities were reviewed. The percentages of failures and inoperabilities caused by each subsystem were approximately the same; therefore further analysis only focused on the failures. Table 8 summarizes the percentage of the total number of HPCI system failures for each subsystem, for each method of discovery.

As indicated in Table 8, failures that occurred during unplanned demands were split between the turbine and turbine control valves subsystem and the coolant piping and valves subsystem, with no failures attributed to the instrumentation and control subsystem. During surveillance tests, the turbine and turbine control valves accounted for about the same percentage as during unplanned demands,

**Table 8.** Subsystem contribution to HPCI system failures, by method of discovery.

| Subsystem | Method of discovery | | |
|---|---|---|---|
| | Unplanned demand | Surveillance test | Other |
| Turbine and Turbine Control Valves | 58% | 61% | 32% |
| Instrumentation and Control | 0% | 28% | 60% |
| Coolant Piping and Valves | 42% | 11% | 8% |

however, instrumentation and control subsystem failures were observed, and they were more dominant than the failures observed in the coolant piping and valves subsystem. Failures that were found other than during the performance of a surveillance test or unplanned demand were dominated by the instrumentation and control subsystem.

The unplanned demand failures associated with the turbine and turbine control valves subsystem primarily occurred prior to 1991 (only one failure occurred from 1991 on), while surveillance test failures were approximately evenly distributed throughout the study period. Failures associated with the coolant piping and valves subsystem found during the performance of surveillance tests were approximately evenly distributed throughout the study period, however, all unplanned demand failures occurred prior to 1991.

Failures associated with the instrumentation and control subsystem varied from year-to-year, with no specific trend in the number of failures that occurred in any one year or over the study period. The failures associated with this subsystem occurred twice as often when the HPCI system was in standby than during a demand (surveillance test or unplanned). The demand-related failures that were observed in this subsystem only occurred during the performance of a surveillance test and not during an unplanned demand. These demand-related failures were predominantly the result of personnel error and procedural problems. Examples of these failures included; miscalibration of detectors and sensors which would have prevented or degraded system response during an unplanned demand, and inadvertent shorting of relays and blown fuses that resulted in spurious trips of the containment isolation function of the system.

Analysis of the failures discovered by other means in the instrumentation and control subsystem indicated that the observed failures were primarily time-related failures when the system was in standby and not demand-related failures. This observation is the result of the subsystem being normally in continuous operation (energized). The types of time-related failures observed in this subsystem were component malfunctions that included; invertor failures, resistor and relay failures, and detector shorts from moisture intrusion. These time-related failures were identified by control room annunciators and other system indication available to control room operators.

To further analyze the subsystem failures, the components that caused the subsystem to fail were reviewed. The failures were characterized by over forty specific HPCI component failures. Although these component failures were diverse, seven components accounted for over half of the inoperabilities and failures. These seven components were the auxiliary oil pump, injection valve, flow controller, turbine governor, isolation logic, inverter, and steam-line motor operated valve. The percentage of components causing both the inoperabilities and failures were about the same; therefore further analysis only focused on the failures. Table 9 summarizes the percentage of the total number of HPCI system failures for each method of discovery, partitioned by the seven components.

Three components, the auxiliary oil pump, governor, and injection valve, caused over 80% of the unplanned demand failures. The surveillance test failures were more diverse with three components, the auxiliary oil pump, governor, and steam line MOV, causing about 50% of the failures. The failures found other than during a demand (surveillance test or unplanned) were even more diverse with inverter failures being higher than the other components.

As shown in Table 9, failures experienced during unplanned demands were more likely to be failures of the injection valve and turbine governor than any other component. These two components comprised 66% of the unplanned demand failures, however, they were a significantly smaller contribution to surveillance test failures (21%). This appears to be a result of a difference in the way the HPCI system is called upon to operate during unplanned demands and how surveillance tests are performed. In surveillance tests, the HPCI turbine is not run for an extended period of time with varying flowrates, nor is the injection valve tested at rated pressures and flow rates. The technical specification requirements for the surveillance tests do not require flow to the vessel or the governor to function for an extended period of time with varying flowrates. During unplanned demands, the HPCI system generally responds to the initial event and is placed in a full-flow test mode for reactor vessel pressure control or for future injection needs. However, the injection valve was observed to fail in 20% of the subsequent injection attempts. This indicates that surveillance tests are finding problems associated with the system, however, there are a limited number of components (governor and injection valve) that are not fully tested in the manner in which they are operated during an unplanned demand. The data also show that the largest contributor to surveillance test failures is the steam line MOV and turbine governor, but there have been no steam line MOV failures during unplanned demands. In addition, during conditions other than unplanned demands and surveillance tests, inverter failures were the largest contributor to that discovery method, but they have not caused any failures during surveillance tests or unplanned demands.

**Table 9.** Component contribution to HPCI system failures, by method of discovery.

| | | Method of Discovery | | |
|---|---|---|---|---|
| Component | Subsystem | Unplanned demand | Surveillance test | Other |
| Auxiliary oil pump | Turbine & Turbine Control Valves | 17% | 12% | 4% |
| Turbine governor | Turbine & Turbine Control Valves | 33% | 17% | 6% |
| Steam line MOV | Turbine & Turbine Control Valves | 0% | 20% | 10% |
| Flow controller | Instrumentation & Control | 0% | 7% | 10% |
| Isolation logic | Instrumentation & Control | 0% | 7% | 6% |
| Inverter | Instrumentation & Control | 0% | 0% | 18% |
| Injection valve | Coolant Piping & Valves | 33% | 4% | 6% |
| Other | — | 17% | 33% | 40% |

Thus, the component failures observed during an unplanned demand were dominated by injection valve and turbine governor malfunctions, and the failures observed during the performance of surveillance tests were dominated by turbine governor and steam line MOVs malfunctions. Analysis of the mechanisms that contributed to the differences in component failures observed during and unplanned demand and surveillance tests indicated the following.

Governor problems experienced during an unplanned demand were caused by two mechanisms; (1) water in the steam lines, and (2) inappropriate needle valve adjustments. Water in the steam lines caused the turbine to overspeed and trip. Even though the governor reset automatically as designed during the unplanned demands, water in the steam lines was observed during the performance of a surveillance test to cause the turbine rupture discs to fail and discharge steam directly into the HPCI room. The steam discharge into the HPCI room resulted in a turbine isolation and a loss of the HPCI system. This type of loss of the HPCI system was only modeled or assumed to occur in a few of the PRA/IPEs reviewed for this study.

The inappropriate needle valve adjustment resulted in erratic operation of the governor which, in turn caused flow oscillations. These flow oscillations were readily identified and recovered by plant operators by taking manual control of the system. The needle valve was adjusted properly for the steady-state surveillance test flow requirements; however, this adjustment was not adequate to prevent the erratic operation governor response under the varying flow rates experienced during an unplanned demand. A review of several emergency operating procedures indicated that taking manual control of the governor during the execution of an emergency operating procedure was not typically considered.

Injection valve failures during an unplanned demand were observed to have occurred during subsequent injection attempts in 3 out of 4 injection valve failures. The failures of the injection valves were associated with the motor operators. Specifically, it appears that pressure locking of the valve occurred after the first injection attempt, and were not recovered. The other injection valve failure that occurred was the result of operator error and was quickly recovered.

The governor failures observed during the performance of a surveillance tests were varied and causes included calibration anomalies, malfunctions of the ramp-generator electronic modules that resulted in speed oscillations, contamination of the governor oil with water which resulted from steam leakage through the steam supply isolation valves, and electrical grounds and failures of the governor power supply drooping resistor. These were the same type of malfunctions identified in the AEOD Special Study (AEOD/S93-02), *Operating Experience Feedback Reliability of Safety Related Steam Turbine-driven Pumps.*[17] The dominant contributors to the governor failures during initial system start were water and foreign material in the oil that causes a turbine overspeed trip, and water in the steam lines overspeeding the turbine. As shown later in Table 10, FTS of the system was a dominant failure mode of the system during surveillance testing. Other turbine and turbine control subsystem malfunctions included failures of the steam inlet valve limit switches, dirty governor linkages, malfunction of the flow control units, and failures of the auxiliary oil pump.

The steam line MOV failures observed during the performance of surveillance tests were primarily the result of either improper maintenance or thermal binding of the valve internals. Examples of the improper maintenance include (1) improperly adjusted torque switches, (2) insufficient or improper lubricant, or (3) improper assembly of the valve internals. As a result of each of these failure mechanisms the steam line MOV failed to open, and in some cases the motor-operators were destroyed in attempts to open the valve. These steam line MOV failures were a significant contributor to the high percentage of FTS events observed during surveillance testing, and were modeled in the PRA/IPEs reviewed for this study as a significant contributor to the FTS basic event. Based on the failure mechanism and number of failures of this component found during the performance of surveillance testing tends to indicate that surveillance tests are detecting these failures prior to the failure affecting system response during an unplanned demand.

### 4.1.3 Operational Failures

The failure modes FTS and FTR (including FRO—the cyclic operations of the injection valve) were partitioned by method of discovery to determine if a difference exists and to evaluate the differences. Table 10 provides the results of the data partition.

The review of these two failure modes, FTR and FTS, indicated that these failure modes contribute differently between the surveillance test failures and the unplanned demand failures. The FTS failure mode was dominant during surveillance testing. This failure mode was observed in 74% of the surveillance test failures. However, the dominant failure mode during an unplanned demand was FTR, which was observed in 55% of the unplanned demand failures. Moreover, on unplanned demands, all of the FTS events were recovered but only one FTR event was recovered.

Among the FTS surveillance test failures, equipment problems associated with the turbine and turbine control subsystem were the most significant contributor. These failures were the same type of failures observed during the unplanned demands, and of the type that is expected during a cold quick start of the system. This would indicate that surveillance testing of the HPCI turbine closely mimics the stresses that the turbine would observe during an unplanned demand.

Among the FTR unplanned demand failures, equipment problems associated with the system MOVs (primarily injection valve) were the most significant contributor. However, MOV failures did not account for a significant number of the surveillance test failures. The MOV failures occurred during subsequent injection, as discussed in Section 3.3., and reflect HPCI system failure in a mode of operation that differs considerably from the manner in which surveillance tests are conducted. Surveillance tests require the MOVs to be opened, but do not require repeated cycling.

**Table 10.** Failure modes partitioned by method of discovery.

| | Method of Discovery | | |
|---|---|---|---|
| Failure mode (exclude MOOS) | Unplanned demand | Surveillance test | Other |
| Fail-to-start | 45% | 74% | 87% |
| Fail-to-run | 55% | 26% | 13% |

## 4.2 Plant-specific Evaluation

Table 11 shows the following information for each plant: operating years, number of inoperabilities, the number of failures, the number of unplanned demands, and the rate of failures and of unplanned demands. As used here, a *rate* is simply an event count divided by the number of operating years.

The failure rates and unplanned demand rates are plotted in Figure 12. In each plot, the plants are listed from the highest to lowest rate. For each plant, the point estimate is shown with the 90% confidence interval. For any plant whose confidence interval lies entirely to the right of the industry average, shown by the vertical dashed line, the corresponding entries in Table 10 are shown by an asterisk. Note that 60% (38 of 63) of the unplanned demands for HPCI occurred among 4 of the 23 units (Brunswick 2, Hatch 1 and 2, and Hope Creek).

Because the plants with high failure rates do not necessarily have high demand rates, Figure 13 shows the two rates plotted on the two axes of one graph. The points that are far from (0, 0) in this graph are labeled with the plant name. Points in the lower left are not labeled, to prevent clutter. Any point in the upper right of the graph corresponds to a plant with both a high failure rate and a high rate of unplanned demands.

Table 12 provides the number of inoperabilities, failures, and demands for each plant per year over the evaluation period. Fourteen of the twenty-three plants had at least one year with high numbers of inoperabilities, failures, or unplanned demands including: Brunswick 1 and 2, Dresden 2 and 3, Duane Arnold, Hatch 1 and 2, Peach Bottom 3, Pilgrim, and Quad Cites 1 and 2. Each of these plants are discussed below.

Brunswick 1 and 2 have had a relatively high and consistent number of the inoperabilities and failures, between 1987-1991, as compared to the industry. Since then both units were shutdown most of the period and have reported no HPCI events. At both units reoccurring MOV problems dominated the system failures. At Brunswick 1 the MOV failures were experienced primarily in the steam supply lines to the turbine, and at Brunswick 2 the MOV failures were experienced with the injection valve. Many of the MOV failures were a result of thermal binding problems or motor insulation breakdown. Unit 1 has had only one unplanned demand, while Unit 2 has had a high number of unplanned demands (10) and four failures occurred during unplanned demands.

Dresden 2 has had several years (1987, 1988, 1989 and 1993) with a high number of inoperabilities; however, only a few of these inoperabilities were considered to be failures. Dresden 2 had no unplanned demands. Dresden 3 had performance similar to Unit 2. The HPCI system inoperabilities reported at both units throughout the study period were diverse and caused by unrelated problems. Examples of the

**Table 11.** HPCI inoperabilities, failures, and demands differentiated by plant.

| Plant name | Operating years | Inoperabilities | Failures | Failure rate | Demands | Demand rate |
|---|---|---|---|---|---|---|
| Browns Ferry 2 | 2.25 | 2 | 2 | 0.89 | 0 | 0.00 |
| Brunswick 1 | 3.83 | 15 | 10* | 2.61* | 1 | 0.26 |
| Brunswick 2 | 4.59 | 17 | 11* | 2.40* | 10* | 2.18* |
| Cooper | 5.64 | 5 | 2 | 0.35 | 5 | 0.89 |
| Dresden 2 | 5.09 | 18 | 2 | 0.39 | 0 | 0.00 |
| Dresden 3 | 5.42 | 15 | 3 | 0.55 | 1 | 0.18 |
| Duane Arnold | 5.63 | 11 | 9 | 1.60 | 2 | 0.36 |
| Fermi 2 | 5.55 | 11 | 9 | 1.62 | 2 | 0.36 |
| FitzPatrick | 4.49 | 15 | 8 | 1.78 | 3 | 0.67 |
| Hatch 1 | 5.89 | 10 | 9 | 1.53 | 10* | 1.70* |
| Hatch 2 | 5.97 | 9 | 8 | 1.34 | 9* | 1.51* |
| Hope Creek | 6.15 | 9 | 6 | 0.98 | 9* | 1.46* |
| Limerick 1 | 5.70 | 7 | 5 | 0.88 | 0 | 0.00 |
| Limerick 2 | 3.85 | 9 | 8 | 2.08 | 0 | 0.00 |
| Monticello | 6.28 | 4 | 2 | 0.32 | 2 | 0.32 |
| Peach Bottom 2 | 3.97 | 13 | 7 | 1.76 | 1 | 0.25 |
| Peach Bottom 3 | 3.54 | 14 | 11* | 3.11* | 4 | 1.13 |
| Pilgrim | 3.85 | 11 | 4 | 1.04 | 1 | 0.26 |
| Quad Cities 1 | 5.53 | 15 | 8 | 1.45 | 0 | 0.00 |
| Quad Cities 2 | 5.44 | 14 | 8 | 1.47 | 0 | 0.00 |
| Susquehanna 1 | 5.67 | 7 | 6 | 1.06 | 1 | 0.18 |
| Susquehanna 2 | 6.05 | 6 | 5 | 0.83 | 1 | 0.17 |
| Vermont Yankee | 6.22 | 3 | 2 | 0.32 | 1 | 0.16 |
| Industry | 116.61 | 240 | 145 | 1.24 | 63 | 0.54 |

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a. Asterisk values correspond to rates that are approximately ≥2 times industry average.

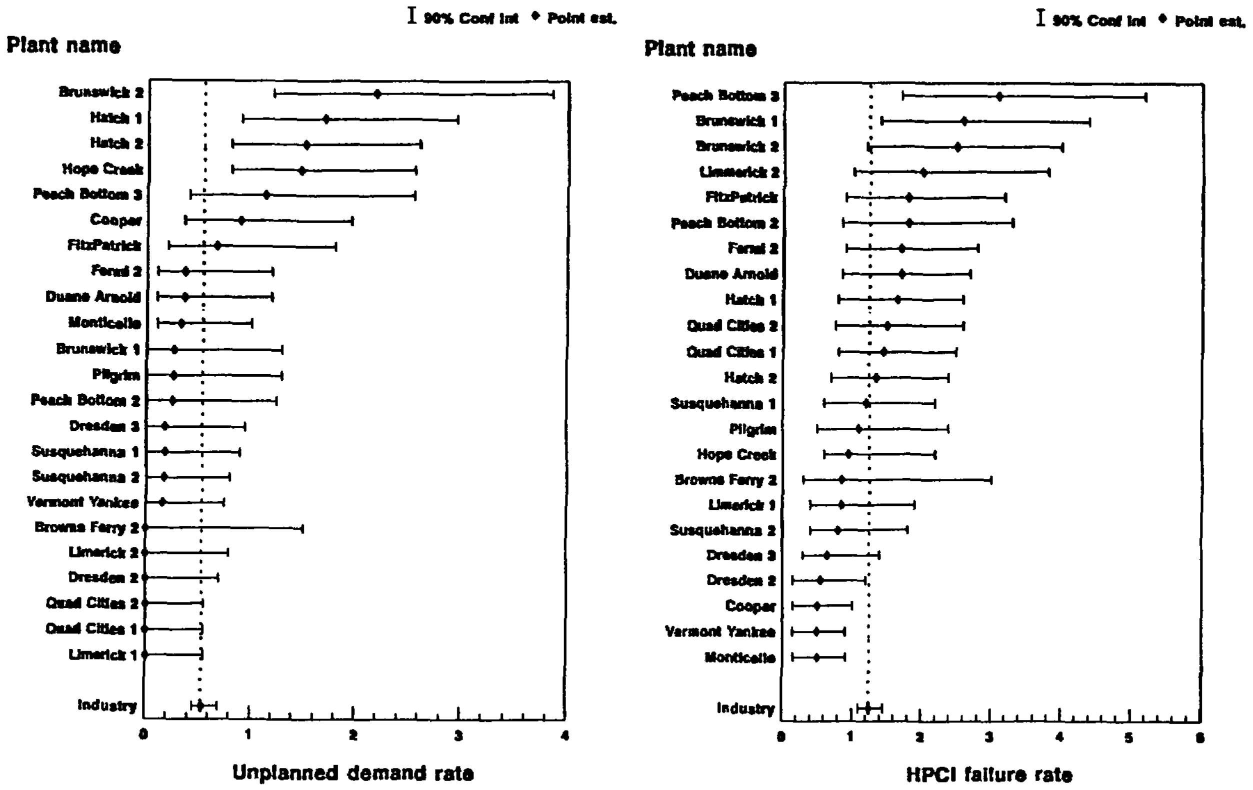

**Figure 12.** Plant-specific HPCI system unplanned demand and failure rates.

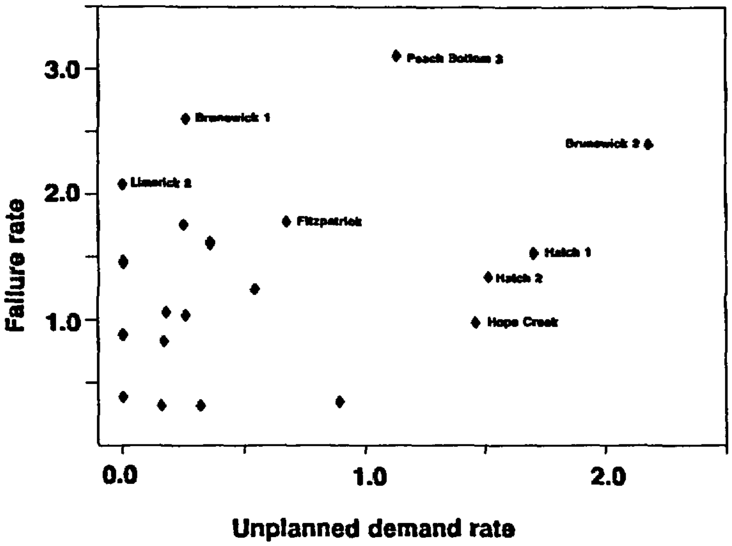

**Figure 13.** HPCI system plant-specific failure rates versus unplanned demand rate.

**Table 12.** Plant-specific HPCI events by year.

| | 1987 | | | 1988 | | | 1989 | | | 1990 | | | 1991 | | | 1992 | | | 1993 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plant name(docket) | I | F | D | I | F | D | I | F | D | I | F | D | I | F | D | I | F | D | I | F | D |
| Browns Ferry 2 (260) | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| Brunswick 1 (325) | 2 | 2 | 0 | 6 | 4 | 0 | 2 | 1 | 0 | 3 | 2 | 0 | 2 | 1 | 1 | 0* | 0* | 0* | 0* | 0* | 0* |
| Brunswick 2 (324) | 4 | 2 | 2 | 4 | 2 | 1 | 4 | 3 | 0 | 4 | 3 | 4 | 1 | 1 | 2 | 0* | 0* | 1* | 0 | 0 | 0 |
| Cooper (298) | 0 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 1 | 0 | 2 | 1 | 0 |
| Dresden 2 (237) | 3 | 1 | 0 | 3 | 1 | 0 | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 5 | 0 | 0 |
| Dresden 3 (249) | 4 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 5 | 2 | 0 |
| Duane Arnold (331) | 1 | 1 | 0 | 3 | 2 | 0 | 4 | 3 | 2 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 2 | 0 |
| Fermi 2 (341) | 0 | 0 | 0 | 2 | 2 | 1 | 1 | 0 | 0 | 2 | 2 | 0 | 3 | 2 | 0 | 1 | 1 | 1 | 2 | 2 | 0 |
| FitzPatrick (333) | 2 | 1 | 0 | 1 | 1 | 0 | 6 | 4 | 1 | 2 | 1 | 1 | 2 | 1 | 0 | 0* | 0* | 0* | 2 | 0 | 1 |
| Hatch 1 (321) | 1 | 1 | 2 | 3 | 2 | 1 | 1 | 1 | 0 | 2 | 2 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 2 | 0 | 0 |
| Hatch 2 (366) | 3 | 3 | 4 | 1 | 1 | 2 | 0 | 0 | 1 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 0 |
| Hope Creek (354) | 1 | 1 | 4 | 1 | 1 | 3 | 2 | 2 | 0 | 3 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 |
| Limerick 1 (352) | 2 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 0 |
| Limerick 2 (353) | 0* | 0* | 0* | 0* | 0* | 0* | 2 | 1 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 1 | 1 | 0 |
| Monticello (263) | 2 | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Peach Bottom 2 (277) | 2* | 2* | 0* | 0* | 0* | 0* | 3 | 2 | 1 | 2 | 1 | 0 | 2 | 0 | 0 | 1 | 1 | 0 | 3 | 1 | 0 |
| Peach Bottom 3 (278) | 1 | 1 | 0 | 0* | 0* | 0* | 1 | 1 | 0 | 3 | 2 | 2 | 4 | 3 | 0 | 2 | 1 | 1 | 3 | 3 | 1 |
| Pilgrim (293) | 0* | 0* | 0* | 0* | 0* | 0* | 4 | 2 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 5 | 1 | 0 |
| Quad Cities 1 (254) | 4 | 2 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 2 | 1 | 0 | 5 | 3 | 0 |
| Quad Cities 2 (265) | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 4 | 2 | 0 | 0 | 0 | 0 | 5 | 3 | 0 |
| Susquehanna 1 (387) | 2 | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 2 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Susquehanna 2 (388) | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| Vermont Yankee (271) | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Total | 38 | 26 | 16 | 31 | 18 | 10 | 39 | 22 | 7 | 35 | 23 | 13 | 31 | 21 | 9 | 22 | 13 | 6 | 44 | 22 | 2 |

* Plant shutdown > 70% of the year. I = Inoperabilities F = Failures D = Unplanned demands

HPCI related problems are: personnel error for incorrect installation of RPV level indicating switches, broken room cooler drive belts, inadvertent actuation of relays during testing, and loose trip reset switches.

Duane Arnold has had nine failures, primarily in 1988, 1989 and 1993, that were associated with turbine and turbine control valve subsystem, specifically the governor and steam line MOVs. The governor failures were malfunctions while starting the system (FTS), and were reoccurring problems in 1988 and 1989. These failures were also identified in Section 3.2 as resulting in a high unreliability estimate for the system.

Hatch 1 has had a consistent history over the entire evaluation period of having a few (1 to 3) inoperabilities, failures, and demands each year. The exception to this is 1993, when no events were reported. In addition, Hatch 1 was identified in Section 3.2 as having had a high FTS probability as compared to the plant-specific PRA/IPE probability for FTS. A review of the operational data indicated that governor problems that were recovered were the significant contributor to the high FTS probability. Hatch 2's HPCI performance has been more erratic than Hatch 1. Hatch 2 has had 2 to 3 inoperabilities and failures in 1987, 1990 and 1993, and nine unplanned demands have occurred over the evaluation period, with four of them occurring in 1987. The failures at Hatch 2 involved several different components, however, for both units failures associated with the MOVs throughout the system and the turbine governor are the most significant contributors to system failures. The causes of the component failures include, administrative problems with procedures and preventative maintenance, and personnel errors during performance of maintenance.

Peach Bottom 3 has had a consistently high number of inoperabilities, failures and demands since 1990. A review of the operational data since 1990 indicated that maintenance practices caused most of the inoperabilities and failures. These include administrative problems with procedures and preventative maintenance, and personnel errors during the performance of maintenance. Examples of the failures include two failures caused by insufficient spring force to reset the turbine governor due to administrative problems with procedures, two failures caused by a misaligned relay on the injection valve, and the failure to tighten the locking nuts resulting in low oil pressure and water in the exhaust line.

Pilgrim has had just two years with a high number of inoperabilities (1989 and 1993); however, only a few of these inoperabilities were considered to be failures. A review of the operational data for these years indicated several diverse and unrelated problems, such as an NRC Generic Letter 89-10 issue with the steam line outboard isolation valve, outdated and not revised wiring drawings, procedural problems, blown fuses in the flow controller, and a partially plugged HPCI flow orifice.

Quad Cities 1 has had only two years with high numbers of inoperabilities and failures (1987 and 1993). Quad Cities 2 has had three years of high numbers of inoperabilities and failures (1990, 1991, and 1993). No unplanned demands were reported in the operational data for either unit. A review of the operational data for these years indicated diverse and unrelated problems associated with the system at both units. Examples include excessive condensation in the turbine casing, late performance of check valve surveillance test requirements, trapped air in an instrument line, and a blown fuse in a logic circuit.

## 4.3 An Evaluation of HPCI Failures Based on Low-power License Date

To indicate how the passage of time affects HPCI performance, plant-specific total failures per operational year were plotted against the plant low-power license date. The failure rate for a plant was estimated as the (number of failures)/(number of plant operational years), with plant operational years estimated as described in Section A-1.3 of Appendix A. The rates and 90% uncertainty intervals are plotted in Figure 14. A fitted trend line, and 90% confidence band on the fitted line, is also shown in the figure. The trend is not statistically significant (P-value = 0.21).

A similar plot was made previously using unreliability (Figure 6). The conclusion is the same for both plots. The trend is not statistically significant.

## 4.4 Accident Sequence Precursor Review

The events identified by the ASP Program (NUREG/CR-4674) were reviewed. The purpose of this review was to relate the operational data to the types of events that resulted in a conditional core damage probability (CCDP) of greater than 1.0E-6. The search for ASP events was limited to the 1987-1993 study period, and included all ASP events in which the HPCI system was identified in the ASP database.

The search resulted in the identification of 19 events in which the HPCI system was mentioned. The number of events ranged from two events in 1987 to seven events in 1989, with no observed trend over the study period. These events occurred at 12 different plants. FitzPatrick and Brunswick Unit 2 each accounted for three events (15% each), Hatch Units 1 and 2 and Pilgrim each accounted for two events (10% each). The remaining seven events occurred at seven different plants.

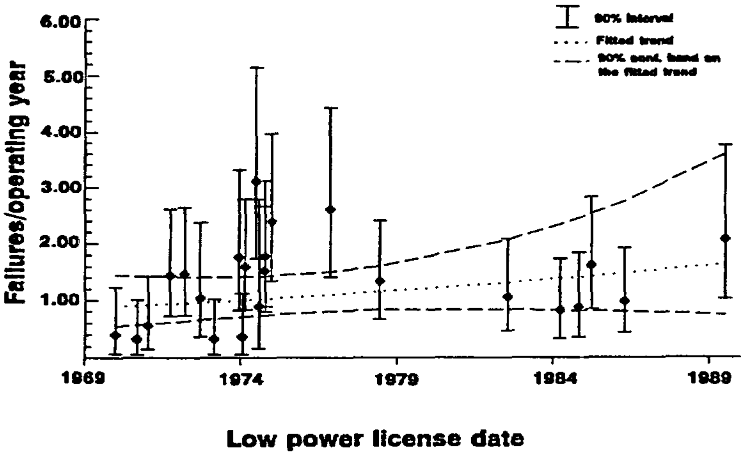

**Figure 14.** Failures per operating year, by plant, plotted against low-power license date. The trend is not statistically significant (P-value=0.21).

The 19 ASP events were each related to a demand of the HPCI system; 7 identified a system malfunction during an unplanned demand, 8 were unplanned demands with no system malfunction, and 4 were potential demands of the system when it was out-of-service for maintenance/testing. A brief description of the ASP events that identified a system malfunction during an unplanned demand are provided in Table 13. The ASP events that identified a HPCI unplanned demand without a system malfunction or a potential need of the HPCI system when it was out-of-service for maintenance or testing are listed in Table 14.

The ASP events that identified a demand and subsequent HPCI system malfunction had a CCDP that ranged from 1.0E-5 to 2.4E-4. The common element found in the ASP events for which the HPCI system malfunctioned was that the reactor core isolation cooling system (RCIC) system was unable to maintain RPV level, and a second control rod drive (CRD) pump had to be started to augment RCIC injection flow until restoration of normal feedwater occurred. These events are highlighted by three events in which failure of the injection valve occurred when the system was restarted or realigned for subsequent RPV injection.

The ASP events that identified a HPCI demand with no system malfunction had a CCDP that ranged from 3.1E-6 to 2.9E-4. Three of the ASP events indicated that the HPCI system was demanded to restore RPV level as a result of a loss of normal feedwater flow. Three of the ASP events involved use of the HPCI system only in the pressure control mode, and the remaining two of events were only partial actuations of the HPCI system, with no injection into the reactor vessel.

The four ASP events in which the system was unavailable because of maintenance were directly associated with a safety relief valve (SRV) actuation. The SRV actuations occurred during performance of a surveillance test that fulfilled the requirements of the limiting condition for operation (LCO) action statement for the HPCI system unavailability; because the HPCI system was unavailable, the SRVs were tested, which created a potential need for HPCI. In two of the three events involving SRV actuations, the SRV either failed open (short duration 5 seconds) or was inadvertently opened. The other SRV actuation event resulted in a high flux reactor scram when a SRV was cycled open. Even though during the SRV actuation events the HPCI system was not available, the RCIC system was available and was used for RPV water level control. However, the potential did exist that if an SRV failed open (unrecovered), the RCIC system would not have been able to maintain RPV water inventory.

**Table 13.** Summary of the ASP events in which a HPCI malfunction was identified during an unplanned demand.

| Plant name | LER number | Event date | CCDP | Description |
|---|---|---|---|---|
| Brunswick 1 | 32591018 | 07/18/91 | 6.0E-5 | A loss of feedwater resulted in a reactor scram. HPCI was used to restore RPV level. An oil leak was subsequently found that would only allow for the system to operate for 45 minutes. |
| Brunswick 2 | 32487001 | 01/05/87 | 2.4E-4 | A turbine trip resulted in a reactor scram and SRV actuations to limit RPV pressure. HPCI was started to control RPV level. When level was restored, HPCI was aligned for RPV pressure control. During a subsequent need for RPV level restoration the HPCI injection valve failed to open. Both CRD pumps and RCIC were used to restore RPV levels. |
| Brunswick 2 | 32487004 | 03/11/87 | 1.0E-5 | A loss of feedwater resulted in a reactor scram. HPCI auto-started to restore RPV level. When level was restored, HPCI was aligned for RPV pressure control. During a subsequent need for RPV level restoration the HPCI injection valve would not reopen as a result of thermal binding. The valve motor operator was damaged in attempts to open the valve. |
| Dresden 3 | 24989001 | 03/25/89 | 1.3E-5 | A loss of offsite power caused a turbine trip and reactor scram. HPCI was manually started for RPV level control. An operator did not complete the procedure for manually starting HPCI, resulting in no lube oil cooling. While investigating and resolving the high bearing oil temperature, HPCI tripped on high RPV level. |
| Hatch 1 | 32191001 | 01/08/91 | 1.1E-5 | A loss of offsite power resulted in a reactor scram. HPCI was actuated to restore RPV level, but operated erratically due to a failed speed controller. Turbine bypass valves were used to control RPV pressure. |
| Hatch 2 | 36690001 | 01/12/90 | 6.0E-5 | A false low condenser vacuum signal resulted in a reactor scram. SRVs automatically opened to limit RPV pressure and HPCI auto-started to restore RPV level. Subsequently, HPCI tripped on high RPV level. With continued cycling of the SRVs to limit RPV pressure, the level was reduced to the HPCI auto-start setpoint. However, the injection valve would not reopen due to a failed overload relay for the motor operator. Both CRD pumps and RCIC were used to maintain RPV level. |
| Pilgrim | 29390013 | 09/02/90 | 8.4E-5 | A failure in the feedwater control system caused the operators to manually scram the reactor. HPCI was manually started for level control. The HPCI turbine tripped during the start; however, it automatically reset and HPCI was started successfully. Flow oscillations were noted during the 2 minutes of operation. HPCI was later started for pressure control. Again, the turbine tripped during the start, but automatically reset and started. Flow oscillations were again noted and the system operated in manual control for the 3 hours it was required. |

**Table 14.** Listing of the ASP events that identified a HPCI unplanned demand without a system malfunction or a potential need of the HPCI system when it was out-of-service for maintenance or testing.

| Plant name | LER number | Event date | CCDP |
|---|---|---|---|
| Brunswick 2 | 32489009 | 06/17/89 | 3.6E-5 |
| Dresden 2 | 23790002 | 01/16/90 | 3.1E-6 |
| Dresden 3[a] | 24989001 | 03/25/89 | 1.3E-5 |
| Duane Arnold | 33189003 | 04/04/89 | 6.5E-6 |
| FitzPatrick[a] | 33389003 | 03/06/89 | 6.5E-6 |
| FitzPatrick[a] | 33389020 | 11/05/89 | 1.3E-5 |
| FitzPatrick[a] | 33389023 | 11/12/89 | 1.3E-5 |
| Hatch 1 | 32188018 | 12/17/88 | 1.5E-5 |
| Hatch 2 | 36688017 | 05/27/88 | 2.0E-5 |
| Limerick 2 | 35389013 | 12/11/89 | 1.5E-5 |
| Pilgrim | 29391024 | 10/30/91 | 1.2E-4 |
| Vermont Yankee | 27191009 | 04/23/91 | 2.9E-4 |

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a. This ASP event was a potential demand of the system when it was out-of-service for maintenance/testing

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# Appendix A
# HPCI Data Collection and Analysis Methods

# Appendix A
# HPCI Data Collection and Analysis Methods

To characterize high pressure coolant injection (HPCI) system performance, operational data pertaining to the HPCI system from U. S. commercial nuclear power plants from 1987 through 1993 were collected and reviewed. For new plants, data started at the low power license date. First, all reported system inoperabilities and unplanned demands were characterized and studied from the perspective of overall trends and the existence of patterns in the performance of particular plant. The inoperabilities included such problems as spurious actuations or failures affecting containment isolation, as well as failures of HPCI's designed safety function of injecting coolant into the reactor pressure vessel (RPV). Second, the failures (losses of safety function) were analyzed from an engineering perspective to identify the major system performance issues. A quantitative analysis then focused on the failures for which system demands could also be estimated. From a knowledge of these failures and the associated demands, occurrence probabilities for each failure mode and the system unreliability were estimated. Finally, HPCI failure probabilities from probabilistic risk assessments (PRAs) were evaluated by comparing them to the estimated unreliability.

Descriptions of the methods for the basic data characterization and the estimation of unreliability are provided below. The descriptions give details of the methods, summaries of the quality assurance measures used, and discussion of some of the reasoning behind the choice of methods.

## A-1. DATA COLLECTION AND CHARACTERIZATION

### A-1.1 Inoperabilities and Failures

Because HPCI is a single-train safety system, train-level inoperabilities, including those occurring during testing, are also system-level inoperabilities. Therefore, they are required to be reported in Licensee Event Reports (LERs). 10 CFR 50.73 also requires the LER reporting of any operation or condition prohibited by a plant's technical specifications.

The Sequence Coding and Search System (SCSS) LER database was searched for any HPCI system inoperabilities reported in LERs for the period 1987 through 1993. The SCSS data search included all timing codes: actual immediate inoperabilities; actual preexisting inoperabilities, both previously detected and not previously detected; and potential inoperabilities. Preexisting detected inoperabilities in SCSS include cases with the HPCI system out of service for maintenance when demanded. Two engineers with plant experience independently read each identified LER completely. The entire study team discussed those LERs that were especially difficult to interpret or classify. In addition, information obtained from the plants by the NRC staff helped guide the data classification for certain failures.

To characterize HPCI system performance, each inoperability was screened for the following:

- Whether the HPCI system's safety function, as described in Section 2.1, was lost. In this study, the term *inoperability* is used to describe any LER-reported HPCI problem. It is distinguished from the term *failure*, which is used for the subset of inoperabilities for which the safety function of the system was lost.

- For failures, the system failure mode [failure to start (FTS), failure to run (FTR), both, or out of service for maintenance (MOOS)] and whether recovery from the failure was successful, as defined in Section 2.2.1.

- For FTR, the run time prior to failure, although this information was not given in enough LERs to be usable.

- The immediate cause of the event (e.g., equipment, personnel, or procedures), and the subsystem and component involved in the inoperability.

- The method of discovery of the event (unplanned actuation, surveillance test, normal plant operations, design review), and, for surveillance tests, the test frequency.

Further details of the inoperability characterization and database structure are included in Appendix B.

Identification of the test frequency was important, because failures must be matched with associated demands for the estimation of unreliability. Failures that occurred during unplanned demands were fairly easy to identify from the LER narratives. Distinguishing cyclic surveillance test failures from failures on other types of tests, however, was not always clear because the same or similar procedures are often used. The LER narratives were used for an initial classification. Then, for each failure that had been initially classified as occurring either on a cyclic surveillance test or a quarterly test, INELs OUTINFO database was examined to determine the status of the plant on the date of the failure. (The OUTINFO database is compiled from the monthly operating reports submitted by the licensees, and shows each plant's outage periods.) If the failure occurred while the plant was starting up after a refueling outage, or within a month after the refueling, the test was classified as a cyclic test. Otherwise, it was not. Although this process may result in the exclusion of cyclic surveillance test failures performed on mid-cycle outages (one possible occurrence in the HPCI data) and the inclusion of failures during other tests that happened to occur soon after a refueling outage, the uncertainty in classification is not expected to have a major impact on the results of this study.

Finally, software was applied to the inoperability database to search for illegal values in critical fields, and study team members scrutinized printouts of the database records, especially those describing failures.

## A-1.2 Demands

For the reliability estimation process, demand counts must be associated with failure counts. The first demand issue is the determination of what types of demands, and associated failures, to consider in this process. Two criteria were important. First, each demand must reasonably approximate conditions for required accident/transient response. The tests used to estimate unreliability need to be at least as stressful on the tested portion of the system as an unplanned actuation. For this study, this requirement meant that the whole system must be exercised in the test (with one exception relating to the reactor injection valve, which was modeled separately). Second, counts or estimates of the number of demands and associated failures must be available.

### A-1.2.1 Unplanned Demands

Unplanned demands for RPV injection clearly meet these conditions. As with the inoperabilities, the SCSS database was used to count HPCI unplanned demands. All LERs that involved the HPCI system in any way were identified. Since HPCI is a safety system, unplanned actuations are a 10 CFR 50.73 reportability requirement, and therefore all the unplanned HPCI actuations should be included in the identified LERs. The LERs that involved HPCI were scanned for unplanned actuations of the HPCI system. Unplanned demands were only counted if they were in response to an actual need for high pressure coolant injection.

Actuations in the data were excluded if they occurred at a plant without a HPCI system of the design considered in this study. Also, those involving erroneous, or spurious, actuations were not used for the unreliability calculations, because they often exercised only a small portion of the HPCI system, and often occurred in connection with maintenance work (e.g., suction path shifts, removing fuses, and shorting test leads).

In a few unplanned demands in response to plant transients, the HPCI system did not inject coolant to the RPV because RPV level was restored by other systems (e.g., feedwater or RCIC). In these partial actuations, the system was known not to be off-line; i.e., the system was shown not to be in a maintenance or testing outage. Whether the system would fully function, however, was not demonstrated in these demands. These unplanned demands were used only in the assessment of maintenance and testing unavailability. Depending on the nature of the demand, they may also indicate success for the system starting, except for the injection valve. However, they were not used in this way in this study because the LER narratives did not clarify whether rated pressure was achieved.

Database records were created only for *initial* system demands. If the LER reported several attempts immediately following each other, only one demand was counted for this report; this is true even if the LER specified the number of attempts. For example, if HPCI was started, shut down, and restarted during a single plant event, a failure after the initial start was classified as a failure to run. The unplanned demands identified in this review are listed in Appendix B.

### A-1.2.2 Surveillance Tests

Routine surveillance tests of the HPCI system are performed every operating cycle, quarter, and month; these tests may provide more data for estimating HPCI system reliability. HPCI failures during these tests are a 10 CFR 50.73 reportability requirement since HPCI is a safety system. Therefore, the failure count from routine surveillance tests is believed to be as complete as possible. To ensure accuracy in comparing the surveillance test demands and associated failures with the type of demand modeled in the PRAs, the completeness of each of these tests was evaluated based on a detailed review of several available technical specifications for Design Class 3 and 4 BWRs. The conclusions of the technical specifications review were as follows:

- The cyclic surveillance tests require the system to be functionally tested. This testing includes simulated automatic actuation of the system throughout its emergency operating sequence and verification that each automatic valve in the flow path actuates to its correct position. The ability of the HPCI turbine to sustain coolant flow (in a recirculation mode) over a period of time is also verified. However, these cyclic surveillance tests do not in all cases challenge the injection valve at the pressures, flow rates and temperatures that the system would experience during a demand for emergency operation. Some plant technical specifications actually state that injection of coolant into the reactor vessel may be excluded from the test. Therefore, the cyclic surveillance tests were regarded as demands on the system except for the injection valve. Test failures reported in LERs can be identified as occurring on cyclic tests by supplementing the LER narrative with the event date and the dates of the plant's refueling outages, because cyclic tests are typically performed just after a refueling outage.

- The quarterly tests also test the entire system except for the injection valve. However, the LERs do not always specify what type of surveillance test was being performed when a failure occurred. For some plants, failures from quarterly tests and post-maintenance tests are indistinguishable in the LERs. The date of the event does not help distinguish the two. Since post-maintenance surveillance tests are not periodic, realistic demand counts for these tests cannot be estimated. Therefore, both quarterly and post-maintenance test results were not used for estimating unreliability.

- Monthly tests exercise even less of the system, and therefore were not used.

Demand counts for cyclic surveillance tests were estimated as follows. The plants are required to perform the test at least every 18 months. The tests are typically scheduled to coincide with starting up from refueling outages. These startup dates are found in the OUTINFO database. For this study, a plant was assumed to perform the cyclic surveillance test 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.

### A-1.3 Operational Time

The reported system inoperabilities, failures, and unplanned demands were studied from the perspective of overall trends and the existence of patterns in the performance of particular plant units. These assessments were based on rates of occurrence per operational year. Thus, estimation of the operational time for each plant and year was also part of the data collection.

Operational time, ideally, is the time when the reactor pressure was greater than 150 psig. This time was not known exactly. The INEL database OUTINFO lists the starting and ending dates of all periods when the main generator is off-line, for each plant. During short generator off-line periods, the reactor may remain critical and pressurized; therefore, the starting and ending days of such outages were treated as operational periods. The outages likewise were treated as operational if they spanned two calendar days or less. The operational time for a plant was estimated by calendar time minus all periods when the main generator was off-line for more than two calendar days.

## A-2. ESTIMATION OF UNRELIABILITY

As discussed in Section 3.1, seven failure modes were identified for the estimation of unreliability: out of service for testing or maintenance at the time of a demand (MOOS), failure to start because of failure of the injection valve (FTSV), failure to start for some other reason (FTSO), failure to recover from failure to start (FRFTS), failure of the injection valve to reopen during an attempt to inject after the initial injection (FRO), failure to run (other than by FRO) for the required duration of HPCI performance given a successful start (FTR), failure to recover from failure to run (FRFTR).

Failures to start were divided into two modes, FTSV and FTSO, because the cyclic surveillance tests do not fully exercise the injection valve at all plants, but they test the balance of the system. Failures to run were divided into two modes, the generic FTR, and failure of the injection valve to reopen (FRO), because FRO represents a special mechanism, which cannot occur unless the mission requires more than one injection, and which is not always modeled in the PRA/IPEs.

PRA/IPEs typically model recovery as a single act. Instead, two recovery modes were defined above, because this division matches the data naturally. In an additional investigation performed in an early phase of this study, the two recovery modes were combined, and the total probability of failure to recover was estimated. This modeling difference was found to have a minimal effect on the final answers, and therefore is not repeated in this final report.

In this statistical analysis process, the FTR probabilities were modeled simply as successes or failures to meet performance demands. The mission durations varied from one demand to another. The conventional approach, not followed here, estimates a failure rate and specifically accounts for the fact that unreliability tends to increase as the mission time gets longer. Time-based estimates were not generated in this unreliability study because of the difficulty of quantifying mission times and operational times. In each PRA, a mission time is assumed, (e.g., 5 to 24 hours). However, in the operational events, the mission times are generally much shorter, and often are not reported.

The individual probabilities were combined to estimate the total unreliability, or probability of failure to start and run for the required mission time given a demand. Estimating the unreliability and the associated uncertainty involves two major steps: (a) estimating probabilities and uncertainties for the different failure modes, and (b) combining these estimates. These two steps are described below.

## A-2.1 Estimates for Each Failure Mode

Estimating the probability for a failure mode requires a decision about which data sets (unplanned demands, cyclic surveillance tests, or both) to use, a determination of the failure and demand counts in each data set, and a method for estimating the failure probability and assessing the uncertainty of the estimate.

### A-2.1.1 A Priori Choice of Data Sets

Maintenance unavailability does not occur on planned actuations (i.e., tests). Recoveries are typically not attempted after a failure on a test. And, at some plants, the injection valve is not tested on the cyclic surveillance test, and surveillance tests do not involve subsequent attempts to reinject. Therefore, useful data for the failure modes MOOS, FRFTS, FRFTR, FTSV, and FRO were found only in the unplanned demands, not in the cyclic surveillance tests. For the modes FTSO and FTR, both the unplanned demands and the cyclic surveillance tests were relevant, and the data were examined as described below, to show which sets to use.

### A-2.1.2 Demand and Failure Counts

In three unplanned demands, the HPCI system was deliberately shut down, manually or automatically, before the injection valve opened. Such an actuation demanded that the HPCI system be in service (a MOOS event would have been a reported failure). In addition, some of these cases *may* have been demands for the system, other than the injection valve, to start, but the LER narratives did not give enough information to discern whether that part of the system successfully started or was shut down before it had the opportunity. Therefore those three events were counted as demands for MOOS, but not for any other failure mode.

The unplanned demands were counted by failure mode as follows. The total number of demands was obtained as described in Section A-1.2. This number was divided into demands for the full system ($D_{\text{full}}$) and demands in which the system was shut down before the injection valve could open ($D_{\text{partial}}$). (Note, any MOOS event was counted as a demand on the full system; with the assumption that the system would have been called on to inject if possible.) The total $D_{\text{full}} + D_{\text{partial}}$ was the number of demands for HPCI availability, and applies to the MOOS failure mode.

The number of demands for FTSO was taken to be $D_{\text{full}}$ minus the number of MOOS events. Since injection valve operation is the last step in the start-up sequence, the number of demands for FTSV was taken to be the number of demands for FTSO minus the number of unrecovered FTSO events. The number of demands for recovery from fail to start, FRFTS, was the total number of failures to start, both FTSO and FTSV.

The number of demands for FTR was the number of demands for FTSV minus the number of unrecovered FTSV events minus the number of FRO events. Note that the FRO events were not considered as full demands for FTR, that is, as full opportunities for the system to fail while running. The number of demands for recovery from FTR was the number of FTR events.

For FRO, failure of the injection valve to reopen, the number of demands was very uncertain. They were estimated, and the uncertainty was quantified, as described in Section C-1.1.7 of Appendix C.

The above discussion has considered only unplanned demands. The demands for FTSO and FTR during the cyclic surveillance tests were estimated as follows. The number of demands to start (failure mode FTSO) were taken to be the estimated number of cyclic surveillance tests. After a failure to start on a test, the plant personnel normally terminate the test, fix the problem, and again attempt to start and run the system. The first attempt, resulting in a failure, was counted in this study as a test demand to start, but the later post-maintenance attempt(s) were not. If the intervening repairs did not change the ability of the system to run, a demand to run was then counted. This was the case if the failure to start resulted from, for example, procedural errors, instrumentation problems, problems with the auxiliary oil pump, or problems with the injection valve. Failures to start because of governor problems were considered to affect the ability of the pump to run, and the event was not counted as a demand to run. In other cases, an engineer read the LER narrative to decide if the event should be considered a demand to run.

### A-2.1.3 Data-Based Choice of Data Sets

At this point, failures and demands had been counted or estimated for two sets of data, unplanned demands and cyclic surveillance tests. To determine which data to use for FTSO and FTR, failure probabilities and their associated 90% confidence intervals were computed separately for unplanned demands and cyclic surveillance tests. The confidence intervals assume binomial distributions for the number of failures observed in a fixed number of demands, with independent trials and a constant probability of failure in each data set. A comparison of the plotted confidence intervals gave a visual indication of whether the data sets could be pooled.

The hypothesis that the underlying probability for unplanned demands and for cyclic surveillance tests is the same was tested for each failure mode. Fisher's exact test (described in many statistics books) was used, based on a contingency table with two rows corresponding to failures and successes and two columns corresponding to unplanned demands and cyclic surveillance tests. For the failure modes in which this hypothesis could not be rejected, the two sources of data were pooled; otherwise, the unplanned demands data set was selected as most closely reflecting true operating conditions.

To further characterize the individual probability estimates and their uncertainties, probabilities and confidence bounds were computed in each data set and in the selected pooled data sets for each year and plant unit. The hypothesis of no differences across each of these groupings was tested in each data set, using the Pearson chi-square test. Often, the expected cell counts were small enough that the asymptotic chi-square distribution was not a good approximation for the distribution of the test statistic; therefore, the computed p-values were only rough approximations. They are adequate for screening, however.

As with Fisher's exact test, a premise for these tests is that variation between subgroups in the data be less than the sampling variation, so that the data can be treated as having constant probabilities of failure across the subgroups. When statistical evidence of differences across a grouping is identified, this hypothesis is not satisfied. For such data sets, confidence intervals based on overall pooled data are too short, not reflecting all the variability in the data. However, the additional between-subgroup variation is likely to inflate the likelihood of rejecting the hypothesis of no significant systematic variation between years, plant units, or data sources, rather than to mask existing differences in these attributes.

### A-2.1.4 Estimation of Failure Probability Distributions

Three methods of modeling the data for the unreliability calculations were employed. They all use Bayesian tools, with the unknown probability of failure for each failure mode represented by a probability distribution. An updated probability distribution, or *posterior* distribution, is formed by using the observed data to update an assumed *prior* distribution. One important reason for using Bayesian tools is that the resulting distributions for individual failure modes can be propagated easily, yielding an uncertainty distribution for the overall unreliability.

In all three methods, Bayes' Theorem provides the mechanics for this process. The prior distribution describing failure probabilities is taken to be a *beta* distribution. The beta family of distributions provides a variety of distributions for quantities lying between 0 and 1, ranging from bell-shaped distributions to J- and U-shaped distributions. Given a probability ($p$) sampled from this distribution, the number of failures in a fixed number of demands, $n$, is taken to be binomial($n$,$p$). Use of the beta family of distributions for the prior on $p$ is convenient because, with binomial data, the resulting output distribution is also beta. More specifically, if $a$ and $b$ are the parameters of a prior beta distribution, $a$ plus the number of failures and $b$ plus the number of successes are the parameters of the resulting posterior beta distribution. The posterior distribution thus combines the prior distribution and the observed data, both of which are viewed as relevant for the observed performance.

The three methods differ primarily in the selection of a prior distribution, as described below. After describing the basic methods, a summary section describes additional refinements that are applied in conjunction with these methods.

***Simple Bayes Method.*** Where no significant differences were found between groups (such as plants), the data were pooled, and modeled as arising from a binomial distribution with a failure probability $p$. The assumed prior distribution was taken to be the Jeffreys noninformative prior distribution.[A-1] More specifically, in accordance with the processing of binomially distributed data, the prior distribution was a beta distribution with parameters, $a=0.5$ and $b=0.5$. This distribution is diffuse, and has a mean of 0.5. Results from the use of noninformative priors are very similar to traditional confidence bounds. See Atwood[A-2] for further discussion.

In the simple Bayes method, the data were pooled, not because there were no differences between groups (such as plants), but because the sampling variability within each group was so much larger than the variability between groups that the between-group variability could not be estimated. The dominant variability was the sampling variability, and this was quantified by the posterior distribution from the pooled data. Therefore, the simple Bayes method used a single posterior distribution for the failure probability. It was used both for any single group and as a generic distribution for industry results.

***Empirical Bayes Method.*** When between-group variability could be estimated, the *empirical Bayes* method was employed.[A-3] Here, the prior beta($a$, $b$) distribution is estimated directly from the data for a failure mode, and it models between-group variation. The model assumes that each group has its own probability of failure, $p$, drawn from this distribution, and that the number of failures from that group has a binomial distribution governed by the group's $p$. The likelihood function for the data is based on the observed number of failures and successes in each group and the assumed beta-binomial model. This function of $a$ and $b$ was maximized through an iterative search of the parameter space, using a SAS routine.[A-2] In order to avoid fitting a degenerate, spike-like distribution whose variance is less than the variance of the observed failure counts, the parameter space in this search was restricted to cases where the sum, $a$ plus $b$, was less than the total number of observed demands. The $a$ and $b$ corresponding to the maximum likelihood were taken as estimates of the generic beta distribution parameters representing the observed data for the failure mode.

The empirical Bayes method uses the empirically estimated distribution for generic results, but it also can yield group-specific results. For this, the generic empirical distribution is used as a prior, which is updated by group-specific data to produce a group-specific posterior distribution. In this process, the generic distribution itself applies for modes and groups, if any, for which no demands occurred (such as plants with no unplanned demands).

The empirical Bayes method was always used in preference to the simple Bayes method when a chi-square test found a statistically significant difference between groups. Because of concerns about the power of the chi-square test, discomfort at drawing a fixed line between significant and nonsignificant, and an engineering belief that there were real differences between the groups, an attempt was made for each failure mode to estimate an empirical Bayes prior distribution over years and over plants. The fitting of a nondegenerate empirical Bayes distribution was used as the index of whether between-group variability could be estimated. The simple Bayes method was used only if no empirical Bayes distribution could be fitted, or if the empirical Bayes distribution was nearly degenerate, with smaller dispersion than the simple Bayes posterior distribution. Sometimes, an empirical Bayes distribution could be fitted even though the chi-square test did not find a between-group variation that was even close to statistically significant. In such a case, the empirical Bayes method was used, but the numerical results were almost the same as from the simple Bayes method.

When more than one empirical Bayes prior distribution was fitted for a failure mode, such as a distribution describing variation across plants and one describing variation across years, the general principle was to select the distribution with the largest variability (highest 95th percentile). Exceptions to this rule were only based on engineering judgement regarding the most important sources of variation, or the needs of the application.

***Alternate Method for Some Group-Specific Investigations.*** Occasionally, the unreliability was modeled by group (such as by plant or by year) to see if trends existed, such as trends due to time or age. The above methods tend to mask any such trend. The simple Bayes method pools all the data, and thus yields a single generic posterior distribution. The empirical Bayes method typically does not apply to all of the failure modes, and so masks part of the variation. Even when no differences can be seen between groups for any one failure mode, so that the above methods would pool the data for each failure mode, the failures of various modes could all be occurring in a few years or at a few plants. They could thus have a cumulative effect and show a clearly larger unreliability for those few years or plants. Therefore, it is useful to calculate the unreliability for each group (each year or plant) in a way that is very sensitive to the data from that one group.

It is natural, therefore, to update a prior distribution using only the data from the one group. The Jeffreys noninformative prior is suitably diffuse to allow the data to drive the posterior distribution toward any probability range between 0 and 1, if sufficient data exist. However, when the full data set is split into many groups, the groups often have sparse data and few demands. Any Bayesian update method pulls the posterior distribution toward the mean of the prior distribution. More specifically, with beta distributions and binomial data, $f$ failures and $d$ demands, the estimated posterior mean is $(a+f)/(a+b+d)$. The Jeffreys prior, with $a = b = 0.5$, thus pulls every failure probability toward 0.5. When the data are sparse, the pull toward 0.5 can be quite strong, and can result in every group having a larger estimated unreliability than the population as a whole. In the worst case of a group and failure mode having no demands, the posterior distribution mean is the same as that of the prior, 0.5, even though the overall industry experience may show that the probability for the particular failure mode is, for example, less than 0.1. Since industry experience is relevant for the performance of a particular group, a more practical prior distribution choice is a diffuse prior whose mean equals the estimated industry mean. Keeping the prior diffuse, and therefore somewhat noninformative, allows the data to strongly affect the posterior distribution; and using the industry mean avoids the bias introduced by the Jefferys prior distribution when the data are sparse.

To do this, the "constrained noninformative prior" was used, a generalization of the Jeffreys prior defined in Reference A-4 and summarized here. The Jeffreys prior is defined by transforming the binomial data model so that the parameter $p$ is transformed, approximately, to a location parameter $\phi$. The uniform distribution for $\phi$ is noninformative. The corresponding distribution for $p$ is the Jeffreys noninformative prior. This is generalized using the maximum entropy distribution[A-5] for $\phi$, constrained so that the corresponding mean of $p$ is the industry mean from the pooled data, $(f+0.5)/(d+1)$. The maximum entropy distribution for $\phi$ is, in a precise sense, as flat as possible subject to the constraint. Therefore, it is quite diffuse. The corresponding distribution for $p$ is found. It does not have a convenient form, so the beta distribution for $p$ having the same mean and variance is found. This beta distribution is referred to here as the constrained noninformative prior. It corresponds to an assumed mean for $p$ but to no other prior information. For various assumed means of $p$, the noninformative prior beta distributions are tabulated in Reference A-4.

For each failure mode of interest, every group-specific failure probability was found by a Bayesian update of the constrained noninformative prior with the group-specific data. The resulting posterior distributions were pulled toward the industry mean instead of toward 0.5, but they were sensitive to the group-specific data because the prior distribution was so diffuse.

***Additional Refinements in the Application of Group-Specific Bayesian Methods.*** For both the empirical Bayes distribution and the constrained noninformative prior distribution, beta distribution parameters are estimated from the data. A minor adjustment[A-6] was made in the posterior beta distribution parameters for particular plants and years to account for the fact that the prior parameters $a$ and $b$ are only estimated, not known. This adjustment increases the group-specific posterior variances somewhat.

Both group-specific failure probability distribution methods use a model, namely, that the failure probability $p$ varies between groups according to a beta distribution. In a second refinement, lack of fit to this model was investigated. Data from the most extreme groups (plants, stations, or years) were examined to see if the observed failure counts were consistent with the assumed model, or if they were so far in the tail of the beta-binomial distribution that the assumed model was hard to believe. Two probabilities were computed, the probability that, given the resulting beta posterior distribution and binomial sampling, as many or more than the observed number of failures for the group would be observed, and the probability that as many or fewer failures would be observed. If either of these probabilities was low, the results were flagged for further evaluation of whether the model adequately fitted the data. This test was most important with the empirical Bayes method, since the empirical Bayes prior distribution might not be diffuse. No strong evidence against the model was seen in this study. See Atwood[A-2] for more details about this test.

Group-specific updates were not used with the simple Bayes approach because this method is based on the hypothesis that significant differences in the groups do not exist.

## A-2.2 The Combination of Failure Modes

The results for each failure mode must be combined to obtain the unreliability. For the primary results, stated in the body of this report, a simple fault tree was used to quantify the failure probability in a simple fault tree. A Monte Carlo analysis was performed in each case, using a sample of size 5,000, to quantify the uncertainty in the estimated unreliability.

For the group-specific investigations reported in Appendix C, performing a Monte Carlo simulation for each group was too tedious. Therefore, the following algebraic approximation was used. The method is presented in more generality by Martz and Waller[A-7], but is summarized for the present application here. According to the logic model, the unreliability is given by

$$\text{Unreliability} = \text{Prob[MOOS or ((FTSV or FTSO) and FRFTS) or (FTR and FRFTR)]}.$$

This can be rewritten by repeatedly using the facts that

$$\text{Prob}(A \text{ and } B) = \text{Prob}(A)^*\text{Prob}(B)$$
$$\text{Prob}(A \text{ or } B) = 1 - \text{Prob}(\text{not } A)^*\text{Prob}(\text{not} B) = 1 - [1 - \text{Prob}( A)]^*[1 - \text{Prob}(B)]$$

where $A$ and $B$ are any independent events. The resulting algebraic expression is linear in each of the six failure probabilities.

The estimated mean and variance of the unreliability can therefore be obtained by propagating the means and variances of the six failure probabilities. These means and variances are readily available from the beta distributions. Propagation of the means uses the fact that the mean of a product is the product of the means, for independent random variables. Propagation of variances of independent factors is also readily accomplished, based on the fact that the variance of a random variable is the expected value of its square minus the square of its mean. In practice, estimates are obtained by the following process:

- Compute the mean and variance of each beta distribution.
- Compute the mean and variance of the unreliability for each case using simple equations for expected values of sums for "or" operations and of products for "and" operations.
- Compute parameters for the beta distribution with the same mean and variance.
- Report the mean of the unreliability and the 5th and 95th percentiles of the fitted beta distribution.

The calculated means and variances are exact. The 5th and 95th percentiles are only approximate, however, because they assume that the final distribution is a beta distribution. Monte Carlo simulation for the percentiles is more accurate than this method if enough Monte Carlo runs are performed, because the output uncertainty distribution is empirical and not required to be a beta distribution. Nevertheless, the approximation seems to be close in cases where comparisons were made, and therefore the beta approximation was used when many unreliabilities needed to be found and compared. In particular, the method was used for the unreliabilities by plant and by year in Appendix C.

# A-3. REFERENCES

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A-4. Corwin L. Atwood, *Constrained Noninformative Priors*, INEL-94/0074, October 1994.

A-5. B. Harris, "Entropy," *Encyclopedia of Statistical Sciences, Vol. 5*, S. Kotz and N. L Johnson, editors, 1982, pp. 512-516.

A-6. Robert E. Kass and Duane Steffey, "Approximate Bayesian Inference in Conditionally Independent Hierarchical Models (Parametric Empirical Bayes Models)," *Journal of the American Statistical Association*, *84*, 1989, pp. 717-726, Equation (3.8).

A-7. H. F. Martz and R. A. Waller, "Bayesian Reliability Analysis of Complex Series/Parallel Systems of Binomial Subsystems and Components," *Technometrics*, *32*, 1990, pp. 407-416.

# Appendix B

# HPCI Operational Data, 1987–1993

# Appendix B

# HPCI Operational Data, 1987–1993

In subsections below, listings of the data used for the high-pressure coolant injection (HPCI) performance study are provided. First, the plants used are listed. Then their inoperabilities are described and listed. Unplanned demands are then described, followed by cyclic surveillance testing actuations. Finally, a tabular summary is given for the data used to estimate unreliability.

## B-1. PLANTS USED

Each of the data listings is restricted to the period from 1987 to 1993, and to the set of plants listed in Table B-1 below. Among plants, additional exclusions occurred, as follows. There was no operational time for Browns Ferry 2 in 1987, 1988, 1989, or 1990; for FitzPatrick in 1992; for Peach Bottom 2 in 1988; for Peach Bottom 3 in 1988; and for Pilgrim in 1987 and 1988. The data for these plants were not used for the years they were not operational. Some plants were excluded altogether: Browns Ferry 1 and 3, although they are boiling water reactors (BWRs) with HPCI systems, were not included in the study because they were in an extended shutdown throughout the entire study period. Nine Mile Point 1 was not included, although its Licensee Event Reports (LERs) refer to an "HPCI" system, because this system is similar to the feedwater coolant injection system. Finally, Millstone 1 was not included in the study even though it is a BWR because it uses a feedwater coolant injection system instead of an HPCI system.

**Table B-1.** BWR plants with dedicated HPCI system.

| Plant | Docket | Operating years | Plant | Docket | Operating years |
|---|---|---|---|---|---|
| Browns Ferry 2 | 260 | 2.2 | Limerick 1 | 352 | 5.7 |
| Brunswick 1 | 325 | 3.8 | Limerick 2 | 353 | 3.8 |
| Brunswick 2 | 324 | 4.6 | Monticello | 263 | 6.3 |
| Cooper | 298 | 5.6 | Peach Bottom 2 | 277 | 4.0 |
| Dresden 2 | 237 | 5.1 | Peach Bottom 3 | 278 | 3.5 |
| Dresden 3 | 249 | 5.4 | Pilgrim | 293 | 3.9 |
| Duane Arnold | 331 | 5.6 | Quad Cities 1 | 254 | 5.5 |
| Fermi 2 | 341 | 5.6 | Quad Cities 2 | 265 | 5.4 |
| FitzPatrick | 333 | 4.5 | Susquehanna 1 | 387 | 5.7 |
| Hatch 1 | 321 | 5.9 | Susquehanna 2 | 388 | 6.1 |
| Hatch 2 | 366 | 6.0 | Vermont Yankee | 271 | 6.2 |
| Hope Creek | 354 | 6.2 | | | |

The last column of Table B-1 shows the operating years for each plant during the study. These are estimated from information in OUTINFO.DBF, a database maintained by the INEL for NRC/AEOD. Based primarily on monthly operating reports submitted to the NRC by the licensees, the database provides starting and ending dates for generator off-line periods. To estimate operating time for this study, the starting and ending days themselves are treated as operational days. Periods between these dates that are at least two calendar days long are treated as outage periods and subtracted from the total number of operational days in year for a plant.

## B-2. HPCI INOPERABILITIES

The search of the SCSS database for HPCI inoperabilities resulted in the identification of 240 events during the 1987 through 1993 time period. In 145 of these, the inoperability was severe enough for the system to have lost its safety injection function (failure). Since HPCI is a safety system, and LER reportability requirements require the reporting of losses of system-level safety functions, all losses of HPCI safety function are believed to be included in this set of events. Table B-2 provides a breakdown of the failure modes for inoperabilities in which the safety function of HPCI was lost. The breakdown also gives counts according to the method of discovery for inoperabilities that occurred during unplanned demands and cyclic surveillance tests; 23 of the 24 failures in these categories were used to estimate operational unreliability (see footnote d of the Table B-2).

**Table B-2.** HPCI inoperability counts.

| | Method of discovery | | | | |
|---|---|---|---|---|---|
| | Unplanned demands | Cyclic surveillance tests | Other surveillance tests | Other[a] | Total |
| Safety function lost[b] (SFL) | | | | | |
| Maintenance out of service (MOOS) | 1 | NA | NA | NA | 1 |
| Failure to start | | | | | |
| Other than injection valve (FTSO) | 4 | 7[c] | 50 | 42 | 103 |
| Injection valve (FTSV) | 1 | 1[d] | 2 | 3 | 7 |
| Failure of injection valve to reopen (FRO) | 3 | NA | NA | NA | 3 |
| Failure to run (FTR) | 3 | 4 | 17 | 7 | 31 |
| Subtotal, SFL | 12 | 12 | 69 | 52 | 145 |
| Safety function not lost (SFA) | 0 | 7 | 49 | 39 | 95 |
| Grand Total | 12 | 19 | 118 | 91 | 240 |

[a] Observation, design review etc.

[b] No events occurred for which the system failed to start, was recovered from failure to start, then failed to run.

[c] One of the cyclic surveillance test FTS events was judged to affect the ability of the system to run, and was thus not included as a demand to run.

[d] Excluded from analysis of unreliability due to cyclic surveillance testing requirements. Since such failures are not consistently identified in these tests, observation of this failure was incidental, as with failures from other discovery methods. The test was counted as a demand to run.

Table B-3 defines the column headings listed in Table B-4. In particular, the column headings reflect the database fields that were used in this study. Table B-4 is a listing of the 240 HPCI system inoperabilities found in the SCSS database.

**Table B-3.** Column heading abbreviations used in Table B-4.

| Column Heading | Definition |
|---|---|
| SFL | Safety function lost: T, true—the problem was significant enough to prevent the system from injecting fluid to the RPV with at least 90% of the rated flow, for the length of time needed; F, false—no loss of the safety function as defined here.[a] The footnote c marks those inoperabilities for which both the safety function was lost and the number of demands could be counted (i.e., the discovery methods was either A, for unplanned demands, or S, for surveillance tests). In the latter case, the surveillance test had to be a cyclic surveillance test. Cyclic surveillance tests are marked in Table B-4 in the discovery method column with 'S(C).' |
| Fail mode | Failure mode (PRA-related information): FTR, failure to run (including case in which RPV the injection valve fails to reopen); FTS, failure to start; MOOS, maintenance and testing out-of-service; N/A, no specific category applies. |
| Recv./run dem | Recovery/run demand:<br>Recovery, T, true, if the failure was recovered; F, false, otherwise.<br>Run demand, applicable for failures to start during surveillance testing. T, true, if an eventual demand to run following a failure to start and associated repair was not affected by the failure to start; F, false, if the failure in starting affected the ability of the system to run and, therefore, the event should not be counted in the analysis of the probability of failure to run. |
| Disc Meth. | Discovery method: O, operational occurrence, in which an inoperability was discovered through the normal course of routine plant operations; S, surveillance test; D, design review; A, unplanned demand as a result of an actual plant transient. |
| Subsys. | Subsystem: T, turbine and turbine control valves; I, instrumentation and control; F, coolant piping and valves; and H, HVAC. |

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a. An example of the safety function being lost is the injection valve failing to open on an initiation signal, resulting in no coolant flow to the reactor pressure vessel. Inoperabilities for which the safety function is not lost include; single failure design faults, problems with high energy line break barriers, problems with seismic restraints, and cable separation problems.

**Table B-4.** HPCI inoperabilities.

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Browns Ferry 2 | 26091015 | 07/31/91 | T | FTR | T/F | S | F |
| Browns Ferry 2 | 26092003 | 04/23/92 | T | FTS | F/T | S | I |
| | | | | | | | |
| Brunswick 1 | 32587001 | 01/26/87 | T | FTS | F/F | O | T |
| Brunswick 1 | 32587023 | 12/31/87 | T | FTS | F/T | S | T |
| Brunswick 1 | 32588011 | 04/20/88 | T | FTR | F/F | S | F |
| Brunswick 1 | 32588012 | 05/28/88 | T | FTS | F/T | S | T |
| Brunswick 1 | 32588014 | 06/06/88 | F | N/A | F/F | S | I |
| Brunswick 1 | 32588017 | 07/01/88 | T | FTS | F/T | S | T |
| Brunswick 1 | 32588019 | 07/05/88 | F | FTS | F/F | D | F |
| Brunswick 1 | 32588018 | 07/13/88 | T | FTR | F/F | S | F |
| Brunswick 1 | 32589005 | 07/23/89 | F | FTS | F/F | O | I |
| Brunswick 1 | 32589020 | 10/11/89 | T | FTS | F/F | O | F |
| Brunswick 1 | 32590001 | 01/02/90 | T | FTS | F/F | O | I |
| Brunswick 1 | 32590003 | 03/02/90 | T | FTS | F/F | O | T |
| Brunswick 1 | 32590008 | 05/14/90 | F | FTR | F/F | O | F |
| Brunswick 1 | 32591018 | 07/18/91 | T[b] | FTR | F/F | A | T |
| Brunswick 1 | 32591025 | 08/23/91 | F | FTS | F/F | S | T |
| | | | | | | | |
| Brunswick 2 | 32487001 | 01/05/87 | T[b] | FTR[c] | F/F | A | F |
| Brunswick 2 | 32487004 | 03/11/87 | T[b] | FTR[c] | F/F | A | F |
| Brunswick 2 | 32487005 | 03/30/87 | F | N/A | F/F | O | I |
| Brunswick 2 | 32487006 | 04/24/87 | F | FTS | F/F | S | I |
| Brunswick 2 | 32588014 | 06/06/88 | F | N/A | F/F | S | I |
| Brunswick 2 | 32588019 | 07/05/88 | F | FTS | F/F | D | F |
| Brunswick 2 | 32488012 | 07/25/88 | T | FTS | F/F | O | T |
| Brunswick 2 | 32488018 | 11/16/88 | T[b] | FTS[d] | T/F | A | F |
| Brunswick 2 | 32489002 | 02/21/89 | F | FTR | F/F | O | T |
| Brunswick 2 | 32489005 | 03/13/89 | T | FTS | F/F | D | F |
| Brunswick 2 | 32489006 | 04/24/89 | T | FTS | F/F | O | I |
| Brunswick 2 | 32489013 | 09/09/89 | T | FTS | F/T | S | T |
| Brunswick 2 | 32490008 | 08/16/90 | T[b] | FTR | F/F | A | T |

Table B-4. (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Brunswick 2 | 32490013 | 09/06/90 | T | FTS | F/F | S | T |
| Brunswick 2 | 32490018 | 11/23/90 | T | FTS | F/F | O | I |
| Brunswick 2 | 32490020 | 12/26/90 | F | FTR | F/F | O | F |
| Brunswick 2 | 32491020 | 12/14/91 | T[b] | FTR | F/F | S(C) | T |
| Cooper | 29888022 | 08/27/88 | F | FTS | F/F | S(C) | T |
| Cooper | 29892008 | 06/11/92 | F | FTR | F/F | S | F |
| Cooper | 29892014 | 07/31/92 | T | FTS | F/F | O | T |
| Cooper | 29893015 | 04/20/93 | F | FTS | F/F | D | F |
| Cooper | 29893031 | 08/30/93 | T | FTS | F/F | O | F |
| Dresden 2 | 23787012 | 04/22/87 | T | FTS | T/F | S | T |
| Dresden 2 | 23787018 | 06/06/87 | F | FTR | F/F | O | H |
| Dresden 2 | 23787029 | 10/01/87 | F | FTR | F/F | S | T |
| Dresden 2 | 23788009 | 05/09/88 | F | FTR | F/F | S | T |
| Dresden 2 | 23788013 | 07/08/88 | T | FTS | F/F | O | I |
| Dresden 2 | 23788015 | 08/25/88 | F | FTS | F/F | S | I |
| Dresden 2 | 23789011 | 03/14/89 | F | FTR | F/F | O | T |
| Dresden 2 | 23789014 | 04/07/89 | F | FTR | F/F | S | F |
| Dresden 2 | 23789022 | 08/27/89 | F | FTR | F/F | O | H |
| Dresden 2 | 23789029 | 10/23/89 | F | N/A | F/F | O | F |
| Dresden 2 | 23790008 | 08/20/90 | F | FTR | F/F | O | T |
| Dresden 2 | 23792007 | 02/18/92 | F | N/A | F/F | S | T |
| Dresden 2 | 23792024 | 07/11/92 | F | N/A | F/F | S | T |
| Dresden 2 | 23793009 | 03/02/93 | F | FTR | F/F | D | T |
| Dresden 2 | 23793016 | 08/05/93 | F | FTS | F/F | S | T |
| Dresden 2 | 23793019 | 10/01/93 | F | FTR | F/F | S | I |
| Dresden 2 | 23793021 | 10/01/93 | F | FTR | F/F | D | F |
| Dresden 2 | 23793023 | 10/12/93 | F | FTS | F/F | O | T |

Table B-4. (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Dresden 3 | 24987002 | 02/25/87 | T | FTS | T/T | S | T |
| Dresden 3 | 24987014 | 09/06/87 | F | N/A | F/F | S | F |
| Dresden 3 | 24987017 | 09/12/87 | F | FTR | F/F | S | T |
| Dresden 3 | 24987015 | 09/15/87 | F | FTR | F/F | S | F |
| Dresden 3 | 24989005 | 04/12/89 | F | FTS | F/F | O | T |
| Dresden 3 | 24989004 | 10/22/89 | F | FTR | F/F | O | H |
| Dresden 3 | 24992011 | 04/08/92 | F | FTR | F/F | S | T |
| Dresden 3 | 24992017 | 07/17/92 | F | N/A | F/F | S | T |
| Dresden 3 | 24992019 | 10/15/92 | F | FTR | F/F | S | I |
| Dresden 3 | 24992024 | 12/30/92 | F | N/A | F/F | S | T |
| Dresden 3 | 24993013 | 08/09/93 | T | FTS | F/F | S | T |
| Dresden 3 | 24993018 | 08/16/93 | F | FTR | F/F | S | T |
| Dresden 3 | 23793021 | 10/01/93 | F | FTR | F/F | D | F |
| Dresden 3 | 24993017 | 11/01/93 | F | FTR | F/F | S | H |
| Dresden 3 | 24993019 | 12/14/93 | T | FTS | T/F | O | T |
| Duane Arnold | 33187023 | 07/14/87 | T[b] | FTS | F/T | S(C) | T |
| Duane Arnold | 33188001 | 01/11/88 | T | FTR | F/F | S | I |
| Duane Arnold | 33188002 | 04/11/88 | T | FTS | F/T | S | T |
| Duane Arnold | 33188004 | 06/09/88 | F | FTS | T/F | S(C) | T |
| Duane Arnold | 33189002 | 01/26/89 | T | FTR | F/F | S | T |
| Duane Arnold | 33189007 | 02/24/89 | T | FTR | F/F | O | T |
| Duane Arnold | 33189006 | 03/02/89 | T | FTS | F/F | O | I |
| Duane Arnold | 33189016 | 12/12/89 | F | FTS | F/F | S | T |
| Duane Arnold | 33191007 | 08/06/91 | T | FTS | F/F | S | I |
| Duane Arnold | 33193009 | 10/05/93 | T[b] | FTS | F/T | S(C) | T |
| Duane Arnold | 33193009 | 10/07/93 | T[b] | FTS | F/T | S(C) | T |
| Fermi 2 | 34188005 | 01/11/88 | T | FTS | F/F | O | T |
| Fermi 2 | 34188028 | 07/26/88 | T | FTS | F/F | S | F |
| Fermi 2 | 34189004 | 01/18/89 | F | N/A | F/F | S | I |

**Table B-4.** (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Fermi 2 | 34190008 | 09/05/90 | T | FTS | F/F | O | I |
| Fermi 2 | 34190012 | 10/16/90 | T | FTS | F/T | S | I |
| Fermi 2 | 34191001 | 01/16/91 | T | FTR | F/F | S | I |
| Fermi 2 | 34191016 | 07/02/91 | F | FTS | F/F | S | T |
| Fermi 2 | 34191020 | 11/20/91 | T | FTS | F/F | S | T |
| Fermi 2 | 34192001 | 02/05/92 | T | FTS | F/F | S | T |
| Fermi 2 | 34193001 | 01/04/93 | T | FTS | F/F | O | I |
| Fermi 2 | 34193002 | 01/14/93 | T | FTS | F/T | S | I |
| | | | | | | | |
| FitzPatrick | 33389002 | 03/02/89 | F | FTS | F/F | S | T |
| FitzPatrick | 33387010 | 07/23/87 | T | FTS | F/T | S | T |
| FitzPatrick | 33387015 | 09/16/87 | F | FTR | F/F | S | I |
| FitzPatrick | 33388001 | 03/10/88 | T | FTS | F/T | S | T |
| FitzPatrick | 33389005 | 04/12/89 | T | FTS | F/F | O | T |
| FitzPatrick | 33389014 | 08/17/89 | F | FTR | F/F | O | T |
| FitzPatrick | 33389018 | 10/08/89 | T | FTS | F/T | S | I |
| FitzPatrick | 33389020 | 11/05/89 | T[b] | MOOS | F/F | A | T |
| FitzPatrick | 33389025 | 11/30/89 | T | FTR | F/F | S | I |
| FitzPatrick | 33390005 | 02/20/90 | F | FTS | F/F | S | F |
| FitzPatrick | 33390009 | 03/19/90 | T[b] | FTS | T/F | A | T |
| FitzPatrick | 33391015 | 08/19/91 | F | FTS | F/F | S(C) | T |
| FitzPatrick | 33391019 | 09/17/91 | T | FTR | F/F | S | T |
| FitzPatrick | 33393010 | 04/20/93 | F | FTS | F/F | O | T |
| FitzPatrick | 33393026 | 12/02/93 | F | FTS | F/F | O | I |
| | | | | | | | |
| Hatch 1 | 32187013 | 08/03/87 | T[b] | FTS | T/F | A | T |
| Hatch 1 | 32188012 | 08/26/88 | T | FTS | F/F | S | T |
| Hatch 1 | 32188013 | 09/04/88 | T[b] | FTS | T/F | A | T |
| Hatch 1 | 32188017 | 12/09/88 | F | FTS | F/F | S(C) | T |
| Hatch 1 | 32189006 | 03/29/89 | T | FTS | F/F | O | I |
| Hatch 1 | 32190001 | 01/04/90 | T | FTS | F/F | S | T |

**Table B-4.** (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Hatch 1 | 32190015 | 07/30/90 | T | FTS | F/F | O | T |
| Hatch 1 | 32191001 | 01/18/91 | T[b] | FTS | T/F | A | T |
| Hatch 1 | 32191033 | 12/30/91 | T[b] | FTS | F/T | S(C) | I |
| Hatch 1 | 32192006 | 02/26/92 | T | FTS | F/T | S | I |
| Hatch 2 | 36687004 | 06/16/87 | T | FTS | F/T | S | I |
| Hatch 2 | 36687009 | 08/03/87 | T[b] | FTR | T/F | A | F |
| Hatch 2 | 36687017 | 11/19/87 | T | FTS | F/T | S | I |
| Hatch 2 | 36688001 | 01/06/88 | T | FTS | F/T | S | T |
| Hatch 2 | 36690001 | 01/12/90 | T[b] | FTR[c] | F/F | A | F |
| Hatch 2 | 36690005 | 07/19/90 | T | FTS | F/F | S | T |
| Hatch 2 | 36691001 | 12/19/90 | F | FTR | F/F | S | F |
| Hatch 2 | 36693007 | 08/25/93 | T | FTS | F/T | S | I |
| Hatch 2 | 36693008 | 11/03/93 | T | FTS | F/F | S | T |
| Hope Creek | 35487027 | 06/26/87 | T | FTS | F/F | O | I |
| Hope Creek | 35488010 | 04/14/88 | T | FTS | F/F | O | T |
| Hope Creek | 35489009 | 04/14/89 | T | FTS | F/F | O | I |
| Hope Creek | 35489012 | 06/07/89 | T | FTS | F/F | O | T |
| Hope Creek | 35490009 | 06/07/90 | T | FTR | F/F | O | T |
| Hope Creek | 35490026 | 11/14/90 | F | FTR | F/F | O | T |
| Hope Creek | 35490031 | 11/29/90 | F | FTR | F/F | S | F |
| Hope Creek | 35493005 | 08/14/93 | F | FTR | F/F | S | F |
| Hope Creek | 35493008 | 11/01/93 | T | FTS | F/T | S | I |
| Limerick 1 | 35287015 | 05/14/87 | T | FTR | F/F | S | I |
| Limerick 1 | 35287066 | 12/08/87 | T | FTR | F/F | S | T |
| Limerick 1 | 35288007 | 03/09/88 | F | FTR | F/F | S(C) | I |
| Limerick 1 | 35290011 | 04/20/90 | F | FTR | F/F | S | H |
| Limerick 1 | 35291028 | 12/10/91 | T | FTS | F/F | O | T |
| Limerick 1 | 35292002 | 03/11/92 | T | FTS | F/F | O | I |

**Table B-4.** (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Limerick 1 | 35292015 | 07/07/92 | T[b] | FTR | F/F | S(C) | T |
| | | | | | | | |
| Limerick 2 | 35389008 | 09/22/89 | F | FTR | F/F | O | H |
| Limerick 2 | 35389010 | 10/13/89 | T | FTS | F/F | O | T |
| Limerick 2 | 35390004 | 03/08/90 | T | FTS | F/F | O | T |
| Limerick 2 | 35390008 | 04/17/90 | T | FTS | F/F | O | I |
| Limerick 2 | 35391015 | 09/12/91 | T | FTS | F/T | S | T |
| Limerick 2 | 35391017 | 11/15/91 | T | FTS | F/T | S | T |
| Limerick 2 | 35392001 | 01/04/92 | T | FTS | F/F | O | I |
| Limerick 2 | 35392004 | 02/21/92 | T | FTS | F/F | O | I |
| Limerick 2 | 35393009 | 07/16/93 | T | FTS | F/F | O | I |
| | | | | | | | |
| Monticello | 26387007 | 03/27/87 | T | FTS | F/T | S | T |
| Monticello | 26387020 | 11/20/87 | F | FTR | F/F | D | F |
| Monticello | 26389005 | 04/03/89 | T | FTS | F/F | S | I |
| Monticello | 26389011 | 06/22/89 | F | N/A | F/F | O | F |
| | | | | | | | |
| Peach Bottom 2 | 27787020 | 09/04/87 | T | FTS | F/F | S | T |
| Peach Bottom 2 | 27787023 | 10/14/87 | T | FTS | F/F | O | I |
| Peach Bottom 2 | 27789004 | 03/20/89 | T | FTS | F/F | D | T |
| Peach Bottom 2 | 27789009 | 05/05/89 | T[b] | FTR | F/F | S(C) | T |
| Peach Bottom 2 | 27789022 | 10/03/89 | F | N/A | F/F | O | I |
| Peach Bottom 2 | 27790017 | 07/24/90 | T | FTS | F/F | O | I |
| Peach Bottom 2 | 27790026 | 09/13/90 | F | FTR | F/F | S | H |
| Peach Bottom 2 | 27791017 | 05/18/91 | F | FTR | F/F | S | H |
| Peach Bottom 2 | 27791033 | 10/15/91 | F | FTS | F/F | S | T |
| Peach Bottom 2 | 27792004 | 03/16/92 | T | FTS | F/F | O | T |
| Peach Bottom 2 | 27793001 | 01/01/93 | F | FTS | F/F | S | T |
| Peach Bottom 2 | 27793003 | 01/31/93 | T | FTR | F/F | S | T |
| Peach Bottom 2 | 27793016 | 12/21/93 | F | FTS | F/F | S | I |

**Table B-4.** (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Peach Bottom 3 | 27887007 | 08/29/87 | T | FTS | F/F | O | I |
| Peach Bottom 3 | 27889009 | 12/07/89 | T[b] | FTS | F/T | S(C) | T |
| Peach Bottom 3 | 27890001 | 01/08/90 | F | FTS | T/F | S(C) | T |
| Peach Bottom 3 | 27890010 | 08/04/90 | T | FTR | F/F | S | T |
| Peach Bottom 3 | 27890011 | 09/10/90 | T | FTS | F/F | S | T |
| Peach Bottom 3 | 27891003 | 02/25/91 | T | FTS | F/F | S | T |
| Peach Bottom 3 | 27891005 | 04/10/91 | T | FTR | F/F | S | T |
| Peach Bottom 3 | 27891013 | 08/25/91 | F | FTS | F/F | S(C) | H |
| Peach Bottom 3 | 27891014 | 09/05/91 | T | FTS | F/F | O | I |
| Peach Bottom 3 | 27892004 | 06/25/92 | F | FTR | F/F | S | T |
| Peach Bottom 3 | 27892009 | 11/28/92 | T | FTS | F/F | O | I |
| Peach Bottom 3 | 27893001 | 01/25/93 | T | FTS | F/F | S | F |
| Peach Bottom 3 | 27893005 | 08/09/93 | T | FTS | F/F | S | F |
| Peach Bottom 3 | 27893009 | 11/13/93 | T[b] | FTS | F/T | S(C) | F |
| Pilgrim | 29389013 | 03/24/89 | T | FTS | F/T | S | T |
| Pilgrim | 29389025 | 08/05/89 | F | FTR | F/F | O | T |
| Pilgrim | 29389028 | 09/07/89 | T | FTS | F/F | S | T |
| Pilgrim | 29389036 | 11/22/89 | F | FTR | F/F | O | T |
| Pilgrim | 29390017 | 10/09/90 | T | FTS | F/F | S | T |
| Pilgrim | 29391005 | 03/25/91 | F | FTR | F/F | O | H |
| Pilgrim | 29393001 | 01/26/93 | F | FTR | F/F | S | I |
| Pilgrim | 29393015 | 06/30/93 | F | FTS | F/F | S | F |
| Pilgrim | 29393016 | 07/19/93 | F | FTR | F/F | S | I |
| Pilgrim | 29393017 | 07/21/93 | T | FTS | F/F | S | I |
| Pilgrim | 29393024 | 09/30/93 | F | FTS | F/F | D | T |
| Quad Cities 1 | 25487004 | 03/02/87 | T | FTR | F/F | S | F |
| Quad Cities 1 | 25487006 | 04/03/87 | F | FTR | F/F | S | T |
| Quad Cities 1 | 25487017 | 08/05/87 | T | FTS | F/F | S | I |
| Quad Cities 1 | 25487031 | 12/23/87 | F | FTR | F/F | S | F |

**Table B-4.** (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./ run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Quad Cities 1 | 25488009 | 06/08/88 | F | FTS | F/F | O | T |
| Quad Cities 1 | 25489022 | 11/28/89 | T | FTS | F/F | O | I |
| Quad Cities 1 | 25490017 | 08/11/90 | F | N/A | F/F | S | T |
| Quad Cities 1 | 25491012 | 05/07/91 | T[b] | FTS | F/F | S(C) | T |
| Quad Cities 1 | 25492002 | 02/06/92 | T | FTS | F/T | S | T |
| Quad Cities 1 | 25492027 | 10/09/92 | F | FTR | F/F | S | H |
| Quad Cities 1 | 25493001 | 02/04/93 | T | FTR | F/F | O | F |
| Quad Cities 1 | 25493005 | 06/09/93 | T | FTS | F/F | S | T |
| Quad Cities 1 | 25493010 | 07/20/93 | F | FTS | F/F | S | I |
| Quad Cities 1 | 25493012 | 07/26/93 | T | FTR | F/F | S | I |
| Quad Cities 1 | 26593014 | 08/02/93 | F | FTR | F/F | D | F |
| Quad Cities 2 | 26587003 | 01/27/87 | T[b] | FTS | F/T | S(C) | T |
| Quad Cities 2 | 26588002 | 02/23/88 | F | FTR | F/F | O | H |
| Quad Cities 2 | 26590008 | 06/02/90 | T | FTS | F/F | O | T |
| Quad Cities 2 | 26590009 | 09/15/90 | F | FTR | F/F | O | T |
| Quad Cities 2 | 26590012 | 11/24/90 | T | FTR | F/F | O | T |
| Quad Cities 2 | 26591001 | 01/02/91 | F | N/A | F/F | O | T |
| Quad Cities 2 | 26591003 | 01/22/91 | T | FTS | F/F | S | F |
| Quad Cities 2 | 25491012 | 05/08/91 | T | FTS | F/F | S | T |
| Quad Cities 2 | 26591011 | 10/15/91 | F | FTR | F/F | O | T |
| Quad Cities 2 | 26593003 | 01/11/93 | T | FTS | F/F | O | I |
| Quad Cities 2 | 25493001 | 02/04/93 | T | FTR | F/F | O | F |
| Quad Cities 2 | 26593011 | 06/02/93 | F | FTS | F/F | S | T |
| Quad Cities 2 | 26593014 | 08/02/93 | F | FTR | F/F | D | F |
| Quad Cities 2 | 26593015 | 08/15/93 | T | FTS | F/F | S | T |
| Susquehanna 1 | 38787008 | 02/23/87 | T | FTS | F/F | O | I |
| Susquehanna 1 | 38787019 | 05/07/87 | F | N/A | F/F | O | I |
| Susquehanna 1 | 38788009 | 05/20/88 | T | FTS | F/F | O | I |
| Susquehanna 1 | 38788022 | 11/04/88 | T | FTS | F/F | O | I |

**Table B-4.** (continued).

| Plant name | LER number | Event date | SFL | Fail. mode[a] | Recv./run dem. | Disc. Meth. | Sub-Sys. |
|---|---|---|---|---|---|---|---|
| Susquehanna 1 | 38790007 | 02/15/90 | T | FTS | F/T | S | T |
| Susquehanna 1 | 38791002 | 02/07/91 | T | FTS | F/T | S | T |
| Susquehanna 1 | 38791015 | 11/07/91 | T | FTR | F/F | S | T |
| | | | | | | | |
| Susquehanna 2 | 38887002 | 02/14/87 | T | FTS | F/F | S | I |
| Susquehanna 2 | 38887007 | 04/13/87 | T | FTS | F/F | S | T |
| Susquehanna 2 | 38888001 | 01/27/88 | F | FTR | F/F | S | T |
| Susquehanna 2 | 38890001 | 02/16/90 | T | FTR | F/F | S | I |
| Susquehanna 2 | 38891015 | 12/16/91 | T | FTR | F/F | O | T |
| Susquehanna 2 | 38892002 | 04/22/92 | T[b] | FTR | F/F | S(C) | T |
| | | | | | | | |
| Vermont Yankee | 27187016 | 11/05/87 | T | FTR | F/F | O | I |
| Vermont Yankee | 27191007 | 03/13/91 | F | FTS | F/F | S | T |
| Vermont Yankee | 27192004 | 02/20/92 | T | FTS | F/F | O | I |

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a. The database does not distinguish between FTSO and FTSV (both coded as FTS) or between FTR and FRO (both coded as FTR). Unless otherwise indicated by a footnote, the failure modes in this column were analyzed as FTSO and FTR. Footnotes identify failure modes analyzed as FTSV or FRO.

b. This event was used in the estimation of unreliability.

c. Analyzed as FRO.

d. Analyzed as FTSV.

## B-3. HPCI UNPLANNED DEMANDS

The search for unplanned demands initially identified 122 events in the SCSS data. Detailed review of each LER showed that 60 of these were full demands that would result in injection of coolant to the RPV if the HPCI system performed correctly. Three additional demands were identified, corresponding only to the possibility of a MOOS failure. These three events were events in which the HPCI turbine received a start signal from an actual low RPV water level condition, but main feedwater and RCIC recovered the low level condition before the HPCI injection valve received an open signal. They are indicated by (P), for *partial*, in Table B-5. All 63 demands are listed in Table B-5.

## B-4. HPCI CYCLIC SURVEILLANCE TESTING DEMANDS

The estimated number of HPCI cyclic surveillance testing demands is summarized by plant in Table B-6. The yearly counts also appear in Table B-7. The total is 111 tests.

## B-5. DATA USED FOR STATISTICAL ESTIMATION OF UNRELIABILITY

The data used for estimating the unreliability are summarized in Table B-7. In the FTSO and FTR cells, the count is given as the sum of two numbers, the count for unplanned demands and the count for cyclic surveillance tests. The other columns show counts for unplanned demands only. For the failure (SFL) counts listed in Table B-7 the data from Table B-2 during unplanned demands and cyclic surveillance tests were used. For the unplanned demand counts the data in Table B-7 was determined as follows.

- MOOS, the total number of demands used was the 63 unplanned demands listed in Table B-5.
- FTSO and FTSV, the total number of demands used was the 63 unplanned demands listed in Table B-5, minus the 4 partial demands, plus the 111 test demands listed in Table B-6
- FRFTS, the total number of demands was the number of FTS (FTSO, FTSV) events that occurred during unplanned demands
- FTR, the total number of demands used was the 63 unplanned demands used in Table B-5, minus the 4 partial demands, minus the FRFTS events, minus the 3 demands that an FRO event occurred, plus the 111 test demands listed in Table B-6
- FRFTR, the total number of demands was the number of FTR events that occurred during unplanned demands.

Other details of the data are provided in the footnotes of Table B-7.

**Table B-5.** HPCI unplanned demands.

| Plant | LER number | Event date | Plant | LER number | Event date |
|---|---|---|---|---|---|
| Brunswick 1 | 32591018 | 07/18/91 | Hatch 1 | 32192021 | 08/27/92 |
| Brunswick 2 | 32487001 | 01/05/87 | Hatch 1 | 32192024(P) | 09/30/92 |
| Brunswick 2 | 32487004 | 03/11/87 | Hatch 2 | 36687003 | 01/26/87 |
| Brunswick 2 | 32488018 | 11/16/88 | Hatch 2 | 36687008 | 04/22/87 |
| Brunswick 2 | 32490008 | 08/16/90 | Hatch 2 | 36687006 | 07/26/87 |
| Brunswick 2 | 32490009(P) | 08/19/90 | Hatch 2 | 36687009 | 08/03/87 |
| Brunswick 2 | 32490015 | 09/27/90 | Hatch 2 | 36688017 | 05/27/88 |
| Brunswick 2 | 32490016 | 10/12/90 | Hatch 2 | 36688020 | 08/05/88 |
| Brunswick 2 | 32491001 | 01/25/91 | Hatch 2 | 36689005 | 09/03/89 |
| Brunswick 2 | 32491021 | 12/17/91 | Hatch 2 | 36690001 | 01/12/90 |
| Brunswick 2 | 32492001(P) | 02/02/92 | Hatch 2 | 36692009 | 06/25/92 |
| Cooper | 29887003 | 01/07/87 | Hope Creek | 35487017 | 02/24/87 |
| Cooper | 29887009 | 02/18/87 | Hope Creek | 35487034 | 07/30/87 |
| Cooper | 29888021 | 08/25/88 | Hope Creek | 35487037 | 08/16/87 |
| Cooper | 29889026 | 11/25/89 | Hope Creek | 35487039 | 08/29/87 |
| Cooper | 29890011 | 10/17/90 | Hope Creek | 35488012 | 04/30/88 |
| Duane Arnold | 33189008 | 03/05/89 | Hope Creek | 35488022 | 08/26/88 |
| Duane Arnold | 33189011 | 08/26/89 | Hope Creek | 35488029 | 11/01/88 |
| Dresden 3 | 24989001 | 03/25/89 | Hope Creek | 35490003 | 03/19/90 |
| Fermi 2 | 34188004 | 01/10/88 | Hope Creek | 35490029 | 11/26/90 |
| Fermi 2 | 34192012 | 11/18/92 | Monticello | 26387009 | 04/03/87 |
| FitzPatrick | 33389020 | 11/05/89 | Monticello | 26391019 | 08/25/91 |
| FitzPatrick | 33390009 | 03/19/90 | Peach Bottom 2 | 27789033 | 12/20/89 |
| FitzPatrick | 33393009 | 04/20/93 | Peach Bottom 3 | 27890002 | 01/28/90 |
| Hatch 1 | 32187011 | 07/23/87 | Peach Bottom 3 | 27890008 | 07/27/90 |
| Hatch 1 | 32187013 | 08/03/87 | Peach Bottom 3 | 27892008 | 10/15/92 |
| Hatch 1 | 32188013 | 09/04/88 | Peach Bottom 3 | 27893004 | 07/30/93 |
| Hatch 1 | 32188018 | 12/17/88 | Pilgrim | 29390013 | 09/02/90 |
| Hatch 1 | 32190013 | 06/20/90 | Susquehanna 1 | 38791008 | 07/31/91 |
| Hatch 1 | 32191001 | 01/18/91 | Susquehanna 2 | 38887006 | 04/16/87 |
| Hatch 1 | 32191007 | 02/27/91 | Vermont Yankee | 27191009 | 04/23/91 |
| Hatch 1 | 32191017 | 09/11/91 | | | |

**Table B-6** . Estimated number of cyclic surveillance tests.

| Plant name | Total | Plant name | Total |
|---|---|---|---|
| Browns Ferry 2 | 3 | Limerick 1 | 5 |
| Brunswick 1 | 4 | Limerick 2 | 4 |
| Brunswick 2 | 5 | Monticello | 6 |
| Cooper | 6 | Peach Bottom 2 | 4 |
| Dresden 2 | 7 | Peach Bottom 3 | 4 |
| Dresden 3 | 5 | Pilgrim | 5 |
| Duane Arnold | 6 | Quad Cities 1 | 5 |
| Fermi | 4 | Quad Cities 2 | 7 |
| FitzPatrick | 4 | Susquehanna 1 | 4 |
| Hatch 1 | 5 | Susquehanna 2 | 4 |
| Hatch 2 | 4 | Vermont Yankee | 5 |
| Hope Creek | 5 | Total | 111 |

**Table B-7.** HPCI system failure and demand data per year.

| Year | Fails/ dems. | Maint. out of service (MOOS) | Fail to start, other than injection valve (FTSO)[a] | Fail to start, injection valve (FTSV) | Fail to recover from FTS (FRFTS) | Fail to run (FTR)[a] | Fail to recover from FTR (FRFTR) | Inject. valve fail to reopen (FRO) |
|---|---|---|---|---|---|---|---|---|
| 1987 | SFL | 0 | 1 + 2 = 3 | 0 | 0 | 1 + 0 = 1 | 0 | 2 |
| | Dems. | 16 | 16 + 12 = 28 | 16 | 1 | 14[b] + 12 = 26 | 1 | —[e] |
| 1988 | SFL | 0 | 1 + 0 = 1 | 1 | 0 | 0 + 0 = 0 | 0 | 0 |
| | Dems. | 10 | 10 + 13 = 23 | 10 | 2 | 10 + 13 = 23 | 0 | — |
| 1989 | SFL | 1 | 0 + 1 = 1 | 0 | 0 | 0 + 1 = 1 | 0 | 0 |
| | Dems. | 7 | 6 + 18 = 24 | 6 | 0 | 6 + 18 = 24 | 0 | |
| 1990 | SFL | 0 | 1 + 0 = 1 | 0 | 0 | 1 + 0 = 1 | 1 | 1 |
| | Dems. | 13 | 12[c] + 16 = 28 | 12 | 1 | 11[b] + 16 = 27 | 1 | — |
| 1991 | SFL | 0 | 1 + 2 = 3 | 0 | 0 | 1 + 1 = 2 | 1 | 0 |
| | Dems. | 9 | 9 + 17 = 26 | 9 | 1 | 9 + 16 = 25 | 1 | — |
| 1992 | SFL | 0 | 0 + 0 = 0 | 0 | 0 | 0 + 2 = 2 | 0 | 0 |
| | Dems. | 6 | 4[c] + 20 = 24 | 4 | 0 | 4 + 20 = 24 | 0 | |
| 1993 | SFL | 0 | 0 + 2 = 2 | 0 | 0 | 0 + 0 = 0 | 0 | 0 |
| | Dems. | 2 | 2 + 15[d] = 17 | 2 | 0 | 2 + 16 = 18 | 0 | — |
| Total | SFL | 1 | 4 + 7 = 11 | 1 | 0 | 3 + 4 = 7 | 2 | 3 |
| | Dems. | 63 | 59 + 111 = 170 | 59 | 5 | 56 + 111 = 167 | 3 | —[e] |

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a. In each column, the first number in the sum corresponds to unplanned demands, while the second, if any, corresponds to cyclic tests.

b. Unplanned demands for which the injection valve failed to reopen on a subsequent injection are excluded (counted neither as successes nor as failures for FTR).

c. This excludes unplanned demands for which the system was intentionally (manually or automatically) shut down before it had the opportunity to develop rated pressure and inject coolant into the RPV.

d. This excludes one cyclic test failure caused by injection valve problems (and excludes the corresponding demand). A demand to run after the repair is included in the FTR data.

e. The total number of demands for multiple injections can only be approximated, with large uncertainty. See Section C-1.1.7 for the method. No attempt is made to estimate the demands for multiple injections in individual years.

# Appendix C

# Basic Event Failure Probabilities and Unreliability Trends

# Appendix C

# Basic Event Failure Probabilities and Unreliability Trends

This appendix analyzes the relevant HPCI data and obtains the probability of each failure mode (basic event), including distributions that characterize any variation observed between portions of the data. It then evaluates the time-based unreliability trends of the HPCI system. 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 data and HPCI performance, as measured by unreliability and by failures per year; and an investigation of whether overall performance changed during the seven years of the study.

## C-1. BASIC EVENT FAILURE PROBABILITIES

### C-1.1 Analysis of Individual Failure Modes

Table C-1 contains results from the initial assessment of data for six of the seven failure modes, including point estimates and confidence bounds for the probability of failure for each mode. These results are plotted in Figure C-1.

Table C-2 summarizes the results from testing the hypothesis of constant probabilities across groupings for each failure mode based on data source (if applicable), calendar years, and plant units. Statistical evidence of differences across these groupings was found only for the FTSO mode. For the FTSO combined unplanned demand and cyclic surveillance test data, noticeable variation between plant units was seen. No significant differences between data sources were seen for the two relevant failure modes (FTSO and FTR), and no differences between calendar year were seen for any of the failure modes. FRO is not considered in Table C-2 because of the difficulty in estimating the number of demands for multiple injection.

Mode-specific results are discussed in subsections below. The plant units that account for much of the variation in the data for each failure mode are highlighted, and the implications of the Table C-2 tests for the analysis of unreliability are described. The latter include the data sets used and the type of modeling selected to calculate the distributions that characterize sampling and/or between-group variation. The resulting distributions, summarized in Table C-3 and Figure C-2 at the end of this section, are used to compute uncertainty bounds for the overall unreliability estimate.

**Table C-1.** Point estimates and confidence bounds for HPCI failure modes.

| Failure mode | Data source | Failures *f* | Demands *d* | Probability[a] |
|---|---|---|---|---|
| Maintenance out of service (MOOS) | Unplanned demands | 1 | 63 | (0.001, 0.016, 0.073) |
| Failure to start, other than injection valve (FTSO) | Unplanned demands | 4 | 59 | (0.023, 0.068, 0.148) |
| | Cyclic surveillance tests | 7 | 111 | (0.030, 0.063, 0.115) |
| | Pooled | 11 | 170 | (0.037, 0.065, 0.105) |
| Failure to start, injection valve (FTSV) | Unplanned demands | 1 | 59 | (0.001, 0.017, 0.078) |
| Failure to recover from FTS (FRFTS) | Unplanned demands | 0 | 5 | (0.000, 0.000, 0.451) |
| Failure to run (FTR) | Unplanned demands | 3 | 56 | (0.015, 0.054, 0.133) |
| | Cyclic surveillance tests | 4 | 111 | (0.012, 0.036, 0.081) |
| | Pooled | 7 | 167 | (0.020, 0.042, 0.077) |
| Failure to recover from FTR (FRFTR) | Unplanned demands | 2 | 3 | (0.135, 0.667, 0.983) |
| Failure of injection valve to reopen (FRO) | Unplanned demands | 3 | 11-46 | -[b] |

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

b. Because the number of demands for subsequent injection is so uncertain, no confidence interval is found. A Bayesian estimate is given in Table C-3.

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

| | | P-values for test of variation[a] | | | |
|---|---|---|---|---|---|
| Failure mode | Data source | Between data sources | Between years | Between plant units | Entities with relatively high failure counts[b] |
| Maintenance out of service (MOOS) | Unplanned demands | — | NS | NS | FitzPatrick |
| Failure to start, other than injection valve (FTSO) | Unplanned demands | — | NS | NS | Hatch 1 |
| | Cyclic surveillance tests | — | NS | NS | Duane Arnold |
| | Pooled | NS | NS | 0.029 | Duane Arnold and Hatch 1 |
| Failure to start, injection valve (FTSV) | Unplanned demands | — | NS | NS | — |
| Failure to recover from FTS (FRFTS) | Unplanned demands | — | NF | NF | — |
| Failure to run (FTR) | Unplanned demands | — | NS | NS | Brunswick 1 unit;<br>Brunswick station |
| | Cyclic surveillance tests | — | NS | NS | — |
| | Pooled | NS | NS | NS | Brunswick station |
| Failure to recovery from FTR (FRFTR) | Unplanned demands | — | NS | NS | — |

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a. —, not applicable; NS, not significant (p-value >0.05); NF, no failures (thus, no test).

b. Years and plant units whose contribution to the chi-square statistic is in the upper 1% of a chi-square distribution with one degree of freedom are flagged.

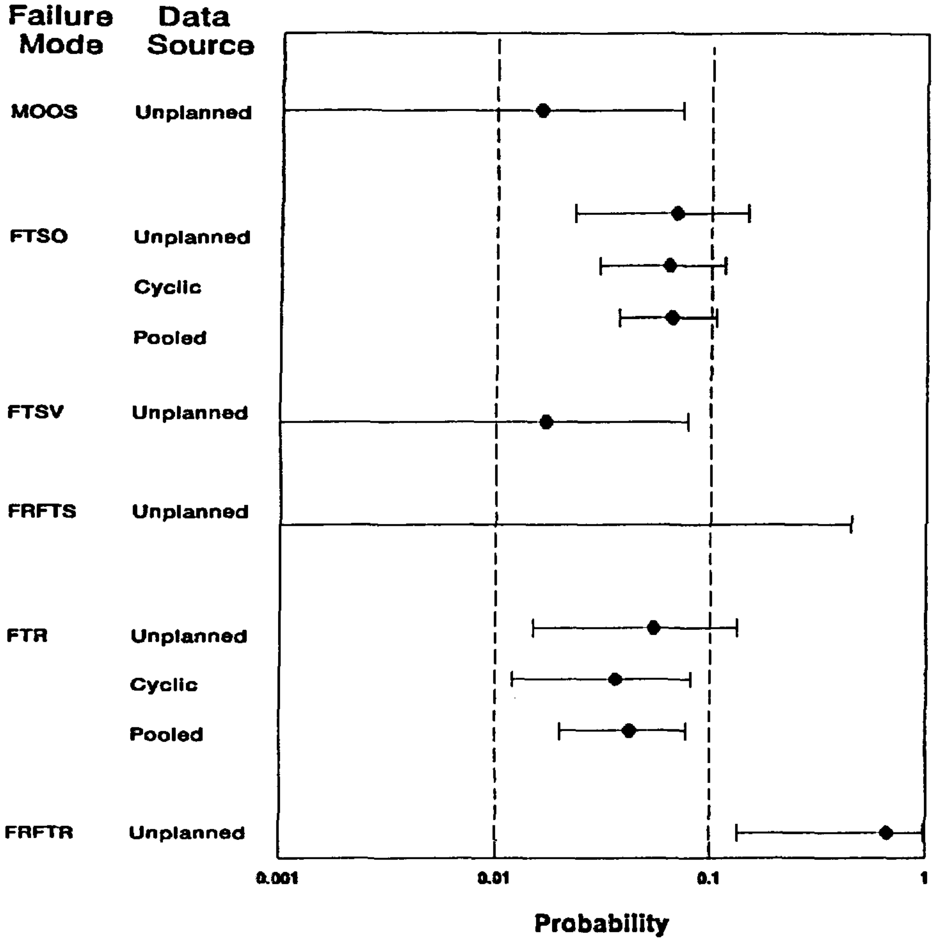

**Figure C-1.** Point estimates and confidence bounds for HPCI failure modes.

### C-1.1.1 Maintenance Out of Service

The single maintenance out of service event occurred among the three (relatively few) unplanned HPCI demands at FitzPatrick. Based on demand counts, the probability of an event occurring at FitzPatrick instead of some other unit if the occurrence probability per demand is the same across units is 3/63, or 0.048. Since such a test is being performed for more than 20 plants, FitzPatrick being the plant that experienced the MOOS event is not statistically significant. In accordance with the methods described in Section A-2.1.4 of Appendix A, a simple Bayes beta distribution describing approximately the same variation as the confidence interval was derived. This distribution was used in the variance propagation to quantify the statistical variation in the HPCI unreliability estimate.

### C-1.1.2 Failure to Start, Other than Injection Valve

As shown in Table C-2 and in the overlapping confidence intervals of Figure C-1, no statistically significant difference was noted between the unplanned demand and cyclic surveillance test data for the FTSO failure mode. For the unreliability evaluation, an empirical Bayes distribution was successfully fitted for each of the data sets for variation in plant unit. These distributions likewise overlapped, showing the statistical validity of combining the two data sets.

Hatch 1 and Duane Arnold were the plant units accounting for much of the variation observed in the FTSO data. Four of eleven failures occurred at Hatch 1, while three occurred at Duane Arnold. Discussion of the reason these plants have high FTSO valves are provided in Section 4.2

A beta distribution was fitted for the combined data for variations in plant unit. This distribution showed much greater variability than the confidence interval, and was used to evaluate plant-specific probabilities.

### C-1.1.3 Failure to Start, Injection Valve

As with the MOOS failure mode, just one failure was identified. No significant between-group statistical variation was found among the 59 unplanned demands for which RPV injection was attempted. A simple Bayes beta distribution describing approximately the same variation as the confidence interval was calculated.

### C-1.1.4 Failure to Recover from FTS

The injection valve problem and the four other HPCI system failures to start were all recovered by operator actions in the control room, or an automatic reset of the governor. Thus, there were no failures to recover, and no between-group differences in the data. For unreliability evaluations, the simple Bayes beta distribution was used.

### C-1.1.5 Failure to Run

Since no significant differences were seen between the unplanned demand data and the cyclic surveillance test data, these data sets were pooled.[a] No overall statistically significant differences were observed between years or plant units. Of the 7 failures, one occurred at Brunswick 1 and two occurred at Brunswick 2; thus, the Brunswick station stood out, although not to a statistically significant degree.

With seven failures in 167 demands, an empirical Bayes distribution was successfully fitted for differences between plant units. This beta distribution was just slightly wider than the distribution obtained from the simple Bayes method, as would be expected since the differences across plant units are not statistically significant (Table C-2). The upper 95th percentile of the beta distribution for the probability of failure to run based on treating the data as homogeneous is 0.0735, and is 0.0756 when treated as varying among plants. The beta distribution based on variation among plants was selected for evaluating plant-specific failure to run probabilities, although little difference was seen.

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[a] Observing no significant differences for data from unplanned demands and cyclic surveillance tests appears to differ from the overall surveillance test conclusions discussed in Section 4. However, that discussion considers both FTR and FRO as failures to run. Also, the cyclic tests considered here are only a subset of the surveillance tests discussed in Section 4.

### C-1.1.6 Failure to Recover from FTR

Among the three failures to run on unplanned demands, the failure at Hatch 2 was recovered while those at Brunswick 1 and Brunswick 2 were not recovered. These data are not sufficient to draw conclusions about differences in years or plant units. The simple Bayes beta distribution was used for unreliability evaluations.

### C-1.1.7 Failure of Injection Valve to Reopen on Subsequent Injections

Three issues were unique to this failure mode: estimating the number of demands for multiple injections, quantifying the uncertainty in this estimate, and propagating that uncertainty into the distribution for the probability of failure on demand.

The number of demands for multiple injections was very uncertain, and was estimated as follows. The LER narratives corresponding to demands to run were read. Of these 59 narratives, 12 specifically mentioned restarts, and 47 did not. Every LER was classified as describing multiple injections, or describing a single injection, or being unclear. If the narrative was brief, it was classified as unclear. The counts are tabulated here.

| | Multiple injections | Single injection | Unclear | Total |
|---|---|---|---|---|
| Restart mentioned | 8 | 2 | 2 | 12 |
| Restart not mentioned | 3 | 11 | 33 | 47 |
| Total | 11 | 13 | 35 | 59 |

Observe that the LERs that mentioned restarts were relatively easy to classify; typically they involved multiple injections, although in two cases only one of the starts opened the injection valve and two cases were unclear. Hardly any of the unclear narratives mentioned restarts. Therefore, the 14 classified cases when restart was not mentioned were extrapolated to all the unclear cases. Because, among the cases with no restart mentioned, there were 3 multiple injections out of 14 events, the best estimate of the number of multiple injections, out of the 35 unclear events, was

$$35 \times (3 + 1/2)/(14 + 1) \doteq 8.167.$$

This number, plus the 11 clear cases of multiple injection, gave 19.167 as the best estimate of the number of demands for multiple injection.

To reflect uncertainty in the true number of demands for multiple injections, a probability distribution on the number of such demands was defined. There are many grounds for uncertainty in the number of demands for multiple injections, including (a) the small size, 14, of the sample usable for estimating the fraction of events that demand multiple injections, and (b) the question of whether the 14 events used to estimate the fraction are fully representative of the 35 unclear events. Because the uncertainty is very large, the distribution among the unclear cases was chosen to be as nearly uniform as possible, subject to the constraint that the mean be 8.167. More precisely, the discrete maximum entropy distribution was used. (See Reference C-1.) In the present case, this distribution has the form

$$P(j \text{ demands for multiple injections}) = c\, r^j, \text{ for } 0 \le j \le 35.$$

The numbers $c$ and $r$ are those that make the probabilities sum to 1.0 and make the mean equal the specified value, 8.167. They were found by numerical iteration.

The uncertainty in the number of demands was quantified in the above way. This uncertainty was then applied to the Bayes distribution for the failure probability, as follows.

Let $p$ denote the probability of failure of the injection valve during a demand for multiple injections. The posterior distribution of $p$, based on $f$ failures and a *known* number of demands, $d$, would be

$$\text{beta}(f + 0.5,\ d - f + 0.5\ ),$$

based on the simple Bayes method explained earlier. Because the number of demands is unknown, with an uncertainty quantified by a probability distribution, the posterior distribution was taken to be a mixture,

$$\Sigma_j\, c\, r^j\, \text{beta}(f + 0.5,\ 11 + j - f + 0.5\ )$$

with $j$ ranging from 0 to 35. For any term in the sum, the total number of demands is the 11 events known to use multiple injections plus $j$ of the 35 unclear cases.

The moments $E(p)$ and $E(p^2)$ were then found by evaluating

$$\Sigma\, c\, r^j\, E(\,p \mid j\,) \text{ and}$$

$$\Sigma\, c\, r^j\, E(\,p^2 \mid j\,).$$

The beta distribution having those moments was found, and taken as the posterior distribution of $p$. The spread of this distribution reflects both the random observed number of failures and the uncertain number of demands.

### C-1.1.8 Summary of Beta Distributions for Individual Failure Modes

Table 2 in the body of this report describes the beta distributions selected to model the statistical variability observed in the data for estimating the probabilities used to model HPCI unreliability. The data are graphed in Figure C-2. This table and figure differ from Table C-1 and Figure C-1 because they give Bayes distributions and intervals, not confidence intervals. This allows the results for the failure modes to be combined to give an uncertainty distribution on the unreliability, as described in Section 3.1.1 of this report.

## C-1.2 Plant-Specific Basic Event Failure Probabilities

This section provides plant-specific basic event failure probabilities for the two failure modes where between-plant variation could be modeled, namely, failure to start other than from injection valve problems (FTSO) and failure to run (FTR). These are used to find the plant-specific unreliabilities shown in Figure 4.

As described in Section A-2.1.4 of Appendix A, for each failure mode an attempt was made to model between-plant variation by fitting an empirical Bayes beta distribution. For the HPCI data, only FTSO and FTR allowed the fitting of a nondegenerate distribution. These were the two modes corresponding to the largest data sets, using both unplanned demands and cyclic surveillance tests. The failure mode FTSO also showed a statistically significant difference between the plants (P-value = 0.029), as measured by the Pearson chi-squared test, while the failure mode FTR did not show such a difference (P-value = 0.36). These findings are mirrored by the fitted distributions, a relatively broad one for FTSO and a relatively concentrated one (giving intervals numerically close to confidence intervals) for FTR. Plant-specific failure probabilities were found for each of the two failure modes, using the empirical Bayes method described in Appendix A. For the other failure modes, neither the chi-square test nor the attempt to fit an empirical Bayes distribution gave any indication of a difference between plants. Therefore, for each of these modes the generic distribution was used, based on pooling the data from all the plants.

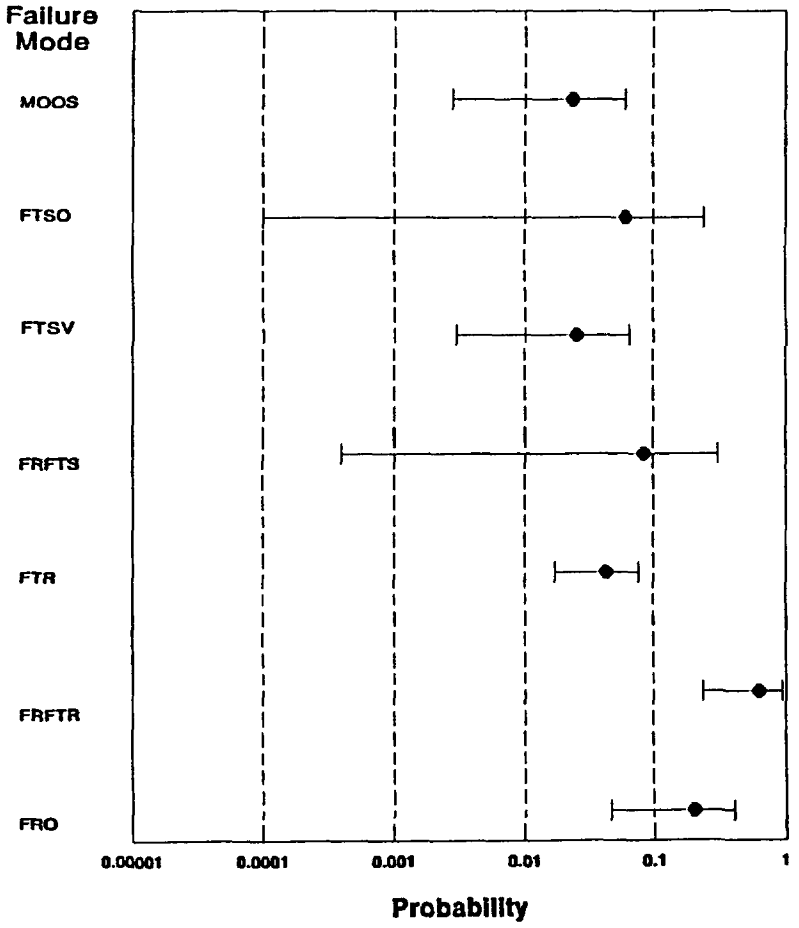

**Figure C-2.** HPCI Bayes means and 90% intervals for each failure mode.

Plant-specific basic event failure probabilities for FTSO are shown in Table C-3 and Figure C-3. For the column labeled "Empir. Bayes 90% interval" in the table, the middle number is the mean of the empirical Bayes distribution and the end points include 90% of the Bayes probability, leaving 5% in each tail. Table C-3 also shows the raw counts, and 90% confidence intervals. For the column labeled "90% conf. interval," the middle number is the point estimate, the fraction of demands that resulted in failure, and the end points form the confidence interval. Note that the empirical Bayes intervals are more consistent with each other than the confidence intervals are, because the empirical Bayes method pulls the extreme plants toward the general population. Table C-4 and Figure C-4 show the same kind of information as Table C-3 and Figure C-3, but for the failure mode FTR.

## C-2. INVESTIGATION OF RELATION TO PLANT LOW POWER LICENSE DATE

This section investigates whether the age of the plant, as reflected in the low-power license date, is related to the unreliability of the HPCI system. A simple approach is to plot the plant-specific unreliability against the plant low-power license date. The unreliabilities from Table C-3 were not used because (a) the failure probabilities for most of the failure modes in the calculation of Table C-3 were generic, not plant specific, and (b) the two plant-specific failure probabilities were constructed via a model that does not allow dependence on time or age. Instead, for each failure mode the constrained noninformative prior was used (i.e., a diffuse prior with the industry mean, as described in Section A-2.1.4 of Appendix A). For each plant this prior was updated with the plant-specific data to obtain a plant-specific failure probability that was highly sensitive to the data from the plant. These distributions for the six failure modes were combined as explained in Section A-2.2, to yield plant-specific unreliabilities that were very sensitive to the plant-specific data. The resulting unreliabilities, with 90% intervals, are shown in Table C-5.

The plot of plant-specific unreliability against low-power license date is shown in Figure 6 of the body of this report, with 90% uncertainty bars plotted vertically. The 90% intervals were not used in the trend calculations, but are shown as a matter of interest. Linear regression (least squares fitting) was used to see if there was a trend, here and in the work described later in this appendix. A straight line was fitted to the unreliabilities (shown as dots in the plot), 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 all confidence limits greater than zero. For the data set in Table C-5, the straight line fit to unreliability was selected. The trend line and a 90% confidence band for the fitted line are also shown in the figure. The confidence band applies to every point of the fitted line simultaneously; it is the band due to Working, Hotelling, and Scheffé, described in statistics books that treat linear regression.

The slope of the trend line in Figure 6 is not statistically significant. The plants that are rather old but not the oldest seem to have the worst unreliabilities, but this apparent pattern may be only a result of randomness—note the wide uncertainty intervals for all the plants.

**Table C-3.** Probability of FTSO, by plant.

| Plant | $f$ | $d$ | 90% conf. interval[a] | $a$ | $b$ | Empir. Bayes 90% interval[b] |
|---|---|---|---|---|---|---|
| Browns Ferry 2 | 0 | 3 | (0.000, 0.000, 0.632) | 0.37 | 8.59 | (0.000, 0.042, 0.174) |
| Brunswick 1 | 0 | 5 | (0.000, 0.000, 0.451) | 0.37 | 10.28 | (0.000, 0.035, 0.146) |
| Brunswick 2 | 0 | 13 | (0.000, 0.000, 0.206) | 0.35 | 16.67 | (0.000, 0.021, 0.089) |
| Cooper | 0 | 11 | (0.000, 0.000, 0.238) | 0.35 | 15.09 | (0.000, 0.023, 0.098) |
| Duane Arnold | 3 | 8 | (0.111, 0.375, 0.711) | 2.24 | 7.46 | (0.055, 0.231, 0.472) |
| Dresden 2 | 0 | 7 | (0.000, 0.000, 0.348) | 0.36 | 11.91 | (0.000, 0.029, 0.126) |
| Dresden 3 | 0 | 6 | (0.000, 0.000, 0.393) | 0.36 | 11.10 | (0.000, 0.032, 0.135) |
| Fermi 2 | 0 | 6 | (0.000, 0.000, 0.393) | 0.36 | 11.10 | (0.000, 0.032, 0.135) |
| FitzPatrick | 1 | 6 | (0.009, 0.167, 0.582) | 1.23 | 9.96 | (0.010, 0.110, 0.289) |
| Hatch 1 | 4 | 14 | (0.104, 0.286, 0.540) | 3.38 | 12.56 | (0.072, 0.212, 0.395) |
| Hatch 2 | 0 | 13 | (0.000, 0.000, 0.206) | 0.35 | 16.67 | (0.000, 0.021, 0.089) |
| Hope Creek | 0 | 14 | (0.000, 0.000, 0.193) | 0.35 | 17.46 | (0.000, 0.020, 0.085) |
| Limerick 1 | 0 | 5 | (0.000, 0.000, 0.527) | 0.37 | 10.28 | (0.000, 0.035, 0.146) |
| Limerick 2 | 0 | 13 | (0.000, 0.000,0 .527) | 0.37 | 9.44 | (0.000, 0.038, 0.159) |
| Monticello | 0 | 8 | (0.000, 0.000, 0.312) | 0.36 | 12.71 | (0.000, 0.027, 0.117) |
| Peach Bottom 2 | 0 | 5 | (0.000, 0.000, 0.451) | 0.37 | 10.28 | (0.000, 0.035, 0.146) |
| Peach Bottom 3 | 1 | 8 | (0.006, 0.125, 0.471) | 1.30 | 12.31 | (0.009, 0.095, 0.248) |
| Pilgrim | 0 | 6 | (0.000, 0.000, 0.393) | 0.36 | 11.10 | (0.000, 0.032, 0.135) |
| Quad Cities 1 | 1 | 5 | (0.010, 0.200, 0.657) | 1.19 | 8.74 | (0.010, 0.120, 0.316) |
| Quad Cities 2 | 1 | 7 | (0.007, 0.143, 0.521) | 1.27 | 11.15 | (0.010, 0.102, 0.267) |
| Susquehanna 1 | 0 | 5 | (0.000, 0.000, 0.451) | 0.37 | 10.28 | (0.000, 0.035, 0.146) |
| Susquehanna 2 | 0 | 5 | (0.000, 0.000, 0.451) | 0.37 | 10.28 | (0.000, 0.035, 0.146) |
| Vermont Yankee | 0 | 6 | (0.000, 0.000, 0.393) | 0.36 | 11.10 | (0.000, 0.032, 0.135) |
| Industry | 11 | 170 | (0.037, 0.065, 0.105)[c] | 0.4 | 6.3 | (0.000, 0.060, 0.242)[d] |

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a. The middle number is the maximum likelihood estimate, $f/d$, and the end numbers form a 90% confidence interval.

b. The middle number is the Bayes mean, $a/(a+b)$, and the end numbers form a 90% interval.

c. This confidence interval is too short, because it assumes no variation between plants.

d. This empirical Bayes interval models the substantial variation between plant, but not the randomness of events within a plant.

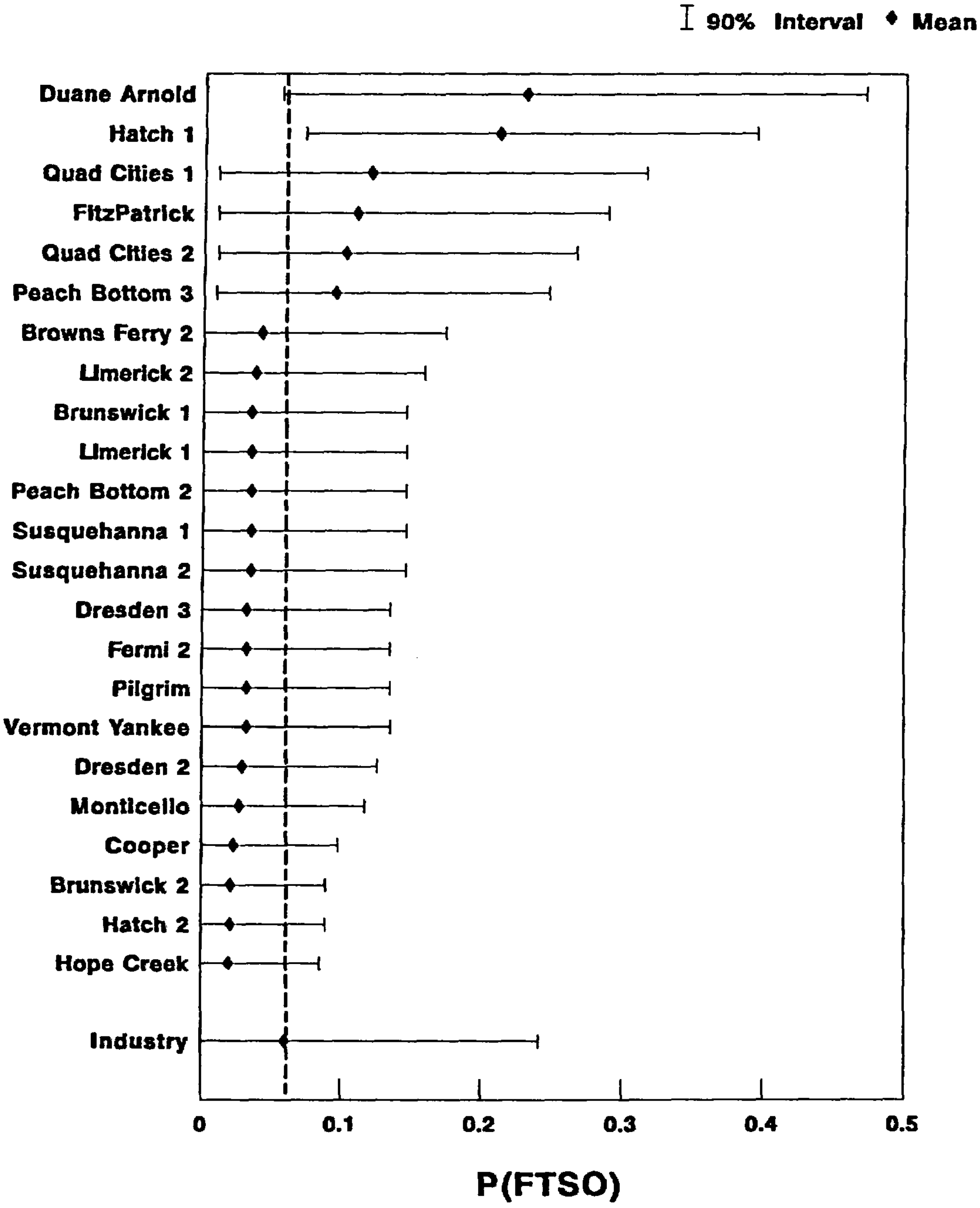

**Figure C-3.** HPCI Empirical Bayes probability of FTSO, by plant.

**Table C-4.** Probability of FTR, by plant.

| Plant | $f$ | $d$ | 90% conf. interval[a] | $a$ | $b$ | Empir. Bayes 90% interval[b] |
|---|---|---|---|---|---|---|
| Browns Ferry 2 | 0 | 3 | (0.000, 0.000, 0.632) | 2.81 | 65.36 | (0.011, 0.041, 0.087) |
| Brunswick 1 | 1 | 5 | (0.010, 0.200, 0.657) | 0.90 | 17.77 | (0.002, 0.048, 0.146) |
| Brunswick 2 | 2 | 11 | (0.033, 0.182, 0.470) | 0.42 | 7.33 | (0.000, 0.054, 0.215) |
| Cooper | 0 | 11 | (0.000, 0.000, 0.238) | 1.67 | 41.37 | (0.006, 0.039, 0.096) |
| Dresden 2 | 0 | 7 | (0.000, 0.000, 0.348) | 2.27 | 54.52 | (0.008, 0.040, 0.089) |
| Dresden 3 | 0 | 6 | (0.000, 0.000, 0.393) | 2.42 | 57.84 | (0.009, 0.040, 0.088) |
| Duane Arnold | 0 | 8 | (0.000, 0.000, 0.312) | 2.11 | 51.50 | (0.008, 0.040, 0.091) |
| Fermi 2 | 0 | 6 | (0.000, 0.000, 0.393) | 2.42 | 57.84 | (0.009, 0.040, 0.088) |
| FitzPatrick | 0 | 6 | (0.000, 0.000, 0.393) | 2.42 | 57.84 | (0.009, 0.040, 0.088) |
| Hatch 1 | 0 | 14 | (0.000, 0.000, 0.193) | 1.31 | 33.38 | (0.004, 0.038, 0.101) |
| Hatch 2 | 1 | 12 | (0.004, 0.083, 0.339) | 1.73 | 35.97 | (0.007, 0.046, 0.112) |
| Hope Creek | 0 | 14 | (0.000, 0.000, 0.193) | 1.31 | 33.38 | (0.004, 0.038, 0.101) |
| Limerick 1 | 1 | 5 | (0.010, 0.200, 0.657) | 0.90 | 17.77 | (0.002, 0.048, 0.146) |
| Limerick 2 | 0 | 4 | (0.000, 0.000, 0.527) | 2.70 | 63.48 | (0.010, 0.041, 0.087) |
| Monticello | 0 | 8 | (0.000, 0.000, 0.312) | 2.11 | 51.10 | (0.008, 0.040, 0.091) |
| Peach Bottom 2 | 1 | 5 | (0.010, 0.200, 0.657) | 0.90 | 17.77 | (0.002, 0.048, 0.146) |
| Peach Bottom 3 | 0 | 9 | (0.000, 0.000, 0.283) | 1.95 | 47.72 | (0.007, 0.039, 0.092) |
| Pilgrim | 0 | 6 | (0.000, 0.000, 0.393) | 2.42 | 57.84 | (0.009, 0.040, 0.088) |
| Quad Cities 2 | 0 | 7 | (0.000, 0.000, 0.348) | 2.27 | 54.52 | (0.008, 0.040, 0.089) |
| Quad Cities 1 | 0 | 4 | (0.000, 0.000, 0.527) | 2.70 | 63.48 | (0.010, 0.041, 0.087) |
| Susquehanna 1 | 0 | 5 | (0.000, 0.000, 0.451) | 2.57 | 60.90 | (0.010, 0.041, 0.087) |
| Susquehanna 2 | 1 | 5 | (0.010, 0.200, 0.657) | 0.90 | 17.77 | (0.002, 0.048, 0.146) |
| Vermont Yankee | 0 | 6 | (0.000, 0.000, 0.393) | 2.42 | 57.84 | (0.009, 0.040, 0.088) |
| Industry | 7 | 167 | (0.020, 0.042, 0.077)[c] | 5.17 | 117.43 | (0.017, 0.042, 0.076)[d] |

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a. The middle number is the maximum likelihood estimate, $f/d$, and the end numbers form a 90% confidence interval.

b. The middle number is the Bayes mean, $a/(a+b)$, and the end numbers form a 90% interval.

c. This confidence interval assumes no variation between plants. It is nearly the same as the empirical Bayes interval, because the variation between plants is so small.

d. This empirical Bayes interval models the variation between plants, but not the randomness of events within a plant.

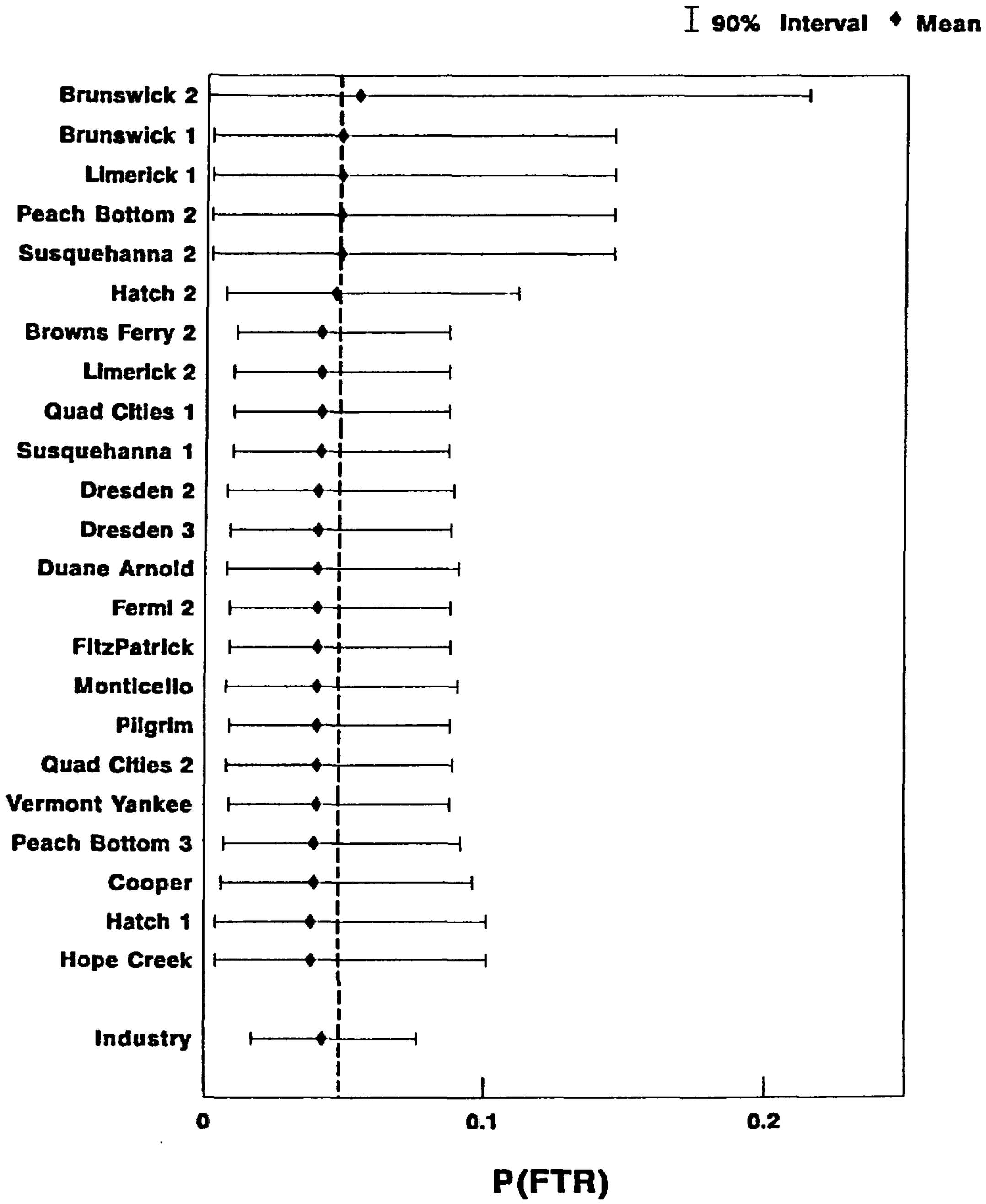

Figure C-4. HPCI Empirical Bayes probability of FTR, by plant.

**Table C-5.** Plant-specific unreliabilities, based on constrained noninformative prior distributions, ordered by low power license date.

| Plant | Low power date | 90% interval[a] |
|---|---|---|
| Dresden 2 | 12/22/69 | (0.008, 0.048, 0.115) |
| Monticello | 09/08/70 | (0.005, 0.046, 0.119) |
| Dresden 3 | 01/12/71 | (0.005, 0.048, 0.125) |
| Quad Cities 1 | 10/01/71 | (0.011, 0.057, 0.133) |
| Quad Cities 2 | 03/21/72 | (0.010, 0.054, 0.124) |
| Pilgrim | 09/15/72 | (0.005, 0.048, 0.125) |
| Vermont Yankee | 02/28/73 | (0.005, 0.048, 0.125) |
| Peach Bottom 2 | 12/14/73 | (0.012, 0.073, 0.172) |
| Cooper | 01/18/74 | (0.005, 0.042, 0.108) |
| Duane Arnold | 02/22/74 | (0.010, 0.062, 0.146) |
| Peach Bottom 3 | 07/02/74 | (0.007, 0.050, 0.121) |
| Browns Ferry 2 | 08/02/74 | (0.008, 0.052, 0.126) |
| Hatch 1 | 10/13/74 | (0.007, 0.049, 0.120) |
| FitzPatrick | 10/17/74 | (0.011, 0.075, 0.181) |
| Brunswick 2 | 12/27/74 | (0.022, 0.091, 0.192) |
| Brunswick 1 | 11/12/76 | (0.016, 0.082, 0.187) |
| Hatch 2 | 06/13/78 | (0.006, 0.047, 0.118) |
| Susquehanna 1 | 07/17/82 | (0.006, 0.049, 0.128) |
| Susquehanna 2 | 03/23/84 | (0.012, 0.073, 0.172) |
| Limerick 1 | 10/26/84 | (0.015, 0.074, 0.167) |
| Fermi 2 | 03/20/85 | (0.005, 0.048, 0.123) |
| Hope Creek | 04/11/86 | (0.005, 0.039, 0.098) |
| Limerick 2 | 07/10/89 | (0.008, 0.051, 0.123) |

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a. The middle number is the Bayes mean, and the end numbers form a 90% interval. The calculations use a diffuse prior, updated by plant-specific data, for each failure mode. Therefore, the intervals are wide, and the means vary greatly between plants.

The above result used only those failures that occurred during unplanned demands and cyclic surveillance tests, for which demand counts are available. To make use of all the data, the plant-specific rate of failures per operating year was also estimated. The simplest technique was used: the rate for a plant was estimated as the quotient (number of failures)/(number of operating years), with operating time estimated as described in Section A-1.3 of Appendix A. The rates, and 90% confidence intervals assuming Poisson counts, are plotted in Figure 14 of the body of this report. As was done for Figure 6, a trend line was fitted to rate and to log(rate). The second fit accounted for more of the variability and was therefore selected. That gave the trend line a small curvature when translated back to the original units. This trend line, with a 90% confidence band, is shown in the figure.

The conclusions are the same as from Figure 6. The trend is not statistically significant; if there is no difference in the plants, there is a 21% chance of seeing as much trend as shown, just from randomness alone. The worst three plants are Peach Bottom 3, Brunswick 1, and Brunswick 2. Their lower confidence limits lie above the fitted line.

## C-3 ANALYSIS BY YEAR, 1987–1993

The analyses of Section C-2 were modified to see if there was a time trend during the period of the study. Table C-6 and Figure 5 show the unreliability by year, pooling the data from all the plants during any one calendar year, and using a diffuse (constrained noninformative) prior with the industry-based mean for each failure mode and each year. The linear model method to test for a trend was the same as in Section C-2, except that the time variable was calendar year instead of low power license date, and the logarithmic fit was selected. The slope of the trend is not statistically significant.

Figure 10 shows the rate of failures per plant-operating year, plotted against calendar year. The calculation method was the same as above, except the logarithmic transformation was not necessary. The slope is almost statistically significant (P-value = 0.07). The difference in data between Figures 5 and 10 is that 5 is based only on failures that could be used to estimate the unreliability, while C-10 is based on all failures, however they occurred or were discovered.

The rate of unplanned demands per year was analyzed in the same way as failures per year. The better fit to the data was obtained by not using the logarithmic transformation, but the resulting confidence band for the fitted line was negative at one end. Therefore, the trend based on the logarithmic transformation is shown as Figure 11 in the body of this report. The slope is statistically significant (P-value = 0.01).

**Table C-6.** Unreliability by year, based on constrained noninformative prior distributions and annual data. The unreliability includes recovery and excludes the FRO failure mode.

| Year | 90% interval[a] |
|---|---|
| 1987 | (0.007, 0.042, 0.101) |
| 1988 | (0.005, 0.038, 0.094) |
| 1989 | (0.015, 0.072, 0.160) |
| 1990 | (0.011, 0.052, 0.114) |
| 1991 | (0.020, 0.074, 0.153) |
| 1992 | (0.015, 0.064, 0.140) |
| 1993 | (0.007, 0.046, 0.114) |

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a. The middle number is the Bayes mean, and the end numbers form a 90% interval.

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11. ABSTRACT *(200 words or less)*

This report documents an analysis of the safety-related performance of the high-pressure coolant injection (HPCI) system at U.S. commercial boiling water reactor plants during the period 1987-1993. Both a risk-based analysis and an engineering analysis of trends and patterns were performed on data from HPCI system operational events to provide insights into the performance of the HPCI system throughout the industry and at a plant-specific level. Comparison was made to Probabilistic Risk Assessment/Individual Plant Evaluations for 23 plants to indicate where operational data either support or fail to support the assumptions, models, and data used to develop HPCI system unreliability.

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