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FROM: Charles E. Rossi, Director *Charles E. Rossi*
Safety Programs Division
Office for Analysis and Evaluation
of Operational Data

SUBJECT: SPECIAL REPORT - REACTOR CORE ISOLATION COOLING SYSTEM RELIABILITY 1987-1993, AEOD/S97-02 (INEL-95-0196)

Attached for your use and information is the final report on the reactor core isolation cooling (RCIC) system reliability. This is the fourth in a series of system reliability study reports which focus on using operational data to determine the reliability of the risk significant systems in U.S. commercial reactors. The results are compared with Probabilistic Risk Assessments (PRAs) and Individual Plant Examinations (IPEs). Insights from an engineering analysis of the data are also included. Earlier drafts of this report were provided to NRR, RES and the Regions for review and comment. These comments were resolved in meetings with the commentors, and the results incorporated into this final report.

The operating experience covers the period from 1987 through 1993 and was obtained primarily from Licensee Event Reports. Notable findings and observations include:

- The RCIC system unreliability (including recovery) was 0.04 for short-term missions of less than 15 minutes and 0.08 for missions of 15 minutes or longer. The short-term unreliability improved over the seven-year study period, but the long-term unreliability remained fairly constant. The annual failure rate remained fairly steady, while the annual unplanned demand rate exhibited a significant decrease. No significant trends were identified in the RCIC system unreliability relating to plant age.

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- Failures to start not associated with the injection valve were the leading contributors to the short-term unreliability. These failures were primarily caused by mechanical problems with the turbine speed control that were not easily recovered by simple operator actions. For long-term unreliability, failures to restart were the prime contributors. Three of the four failures observed during the long missions were hardware problems associated with valve cycling that were not easily recovered.

- Generally, the RCIC system unreliability estimates approximated from the PRA/IPEs were slightly lower but within the uncertainty intervals of the observed operational demand-based unreliability. The plants for which the IPE values were completely outside the uncertainty bounds of the operating data used turbine-driven pump failure rates that were at least an order of magnitude different than the average hourly rate calculated from the operating experience.

- The modeling of RCIC operation in PRA/IPEs does not appear to be consistent with the operational experience. Restarts and/or recirculation are generally either not modeled or are modeled using nominal failure probabilities associated with initial operation. Thus, care should be exercised when relying on PRA/IPE results that are significantly influenced by RCIC modeling or failure probabilities.

- The operational data contained five instances where multiple systems either failed or had the potential to fail concurrently with an RCIC failure indicating potential common cause failure mechanisms. In two of the five instances, the RCIC and high pressure coolant injection systems were affected during an unplanned demand.

- Although the components involved varied, the nature of the failures experienced during actual demands was generally similar to those experienced during surveillance tests. This is unlike the operational reliability experience found during studies of the high pressure coolant injection and emergency diesel generator systems.

These findings are discussed in more detail in the report. Graphical and tabular displays, along with specific discussions, are included so that individual plant strengths and weaknesses can be seen. Specific failures and failure mechanisms are identified and characterized.

Upcoming reports in this series include the high pressure core spray (HPCS) systems at boiling water reactors (BWRs), and the auxiliary/emergency feedwater (AFW/EFW) systems at pressurized water reactors (PWRs). We are also developing simplified models of the reactor protection systems (RPS) for both PWRs and BWRs to estimate their reliability based on actual operating experience.

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Reactor Core Isolation Cooling System Reliability, 1987–1993

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ABSTRACT

This report documents an analysis of the safety-related performance of the reactor core isolation cooling (RCIC) system at U.S. commercial boiling water reactor plants from 1987 to 1993. Both a risk-based analysis and an engineering analysis of trends and patterns were performed on RCIC operating data to provide insights into the performance of the RCIC system throughout the industry and at a plant-specific level. Comparisons were made to Probabilistic Risk Assessments and Individual Plant Evaluations (PRA/IPEs) for the 29 plants having a RCIC system to indicate where operating data either support or fail to support the assumptions, models, and data used to develop the RCIC system unreliability estimates provided by the PRA/IPEs.

Job Code Number E8246—Technical Assistance in Reliability and Risk Analysis

EXECUTIVE SUMMARY

This report presents a performance evaluation of the reactor core isolation cooling (RCIC) system at 29 U.S. commercial boiling water reactors (BWRs). The evaluation was based on the operating experience from 1987 through 1993, as reported in Licensee Event Reports (LERs). The objectives of the study were: (1) to estimate the system unreliability based on operating experience and to compare these estimates with the assumptions, models, and data used in Probabilistic Risk Assessments and Individual Plant Evaluations (PRA/IPEs), and (2) to review the operating data from an engineering perspective to determine trends and patterns seen in the data and provide insights into the failures and failure mechanisms associated with the operation of the RCIC system.

The RCIC system unreliabilities were estimated using a fault tree model to associate event occurrences with broadly defined failure modes such as failure to start or failure to run. The probabilities for the individual failure modes were calculated by reviewing the failure information, categorizing each event by failure mode and then estimating the corresponding number of demands (both successes and failures). Twenty-one plant risk source reports (i.e., PRAs, IPEs and NUREGs) were used for comparison with the RCIC reliability results obtained in this study. The information extracted from the source documents contain RCIC statistics for all but one of the 29 plants. The major findings are:

- The RCIC system unreliability (including recovery) calculated based on the operating experience data in which RCIC is required to inject to the reactor vessel for short term missions (less than 15 minutes) is 0.04. The short term missions typically follow a reactor scram where feedwater is available and the main steam isolation valves are open. If recovery is excluded, the short term mission unreliability is 0.06. This unreliability is primarily attributed to failures to start, typically as a result of problems in controlling turbine speed where the problem is caused by either personnel error or hardware problems that result in turbine overspeed trips.

- The estimate of RCIC system unreliability calculated based on the operating experience data in which RCIC is required to inject to the reactor vessel for missions that are longer than 15 minutes and up to several hours is 0.08. The long term missions typically follow a reactor scram where feedwater is not available and/or the reactor vessel is isolated. If recovery is excluded, the long term mission unreliability is 0.16. The difference in the unreliability estimate calculated for the long term missions as compared to the short term missions is attributed mainly to restarting the turbine and maintaining reactor vessel water level. This unreliability is primarily due to hardware failures associated with restarting the turbine or the cycling of motor-operated valves.

- The estimate of RCIC system unreliability for the 24-hour missions typically modeled in PRAs is 0.18. If recovery is excluded, the mission unreliability is 0.43. The unreliability is dominated by failure to run (24-hour mission time), failure to restart, and failure during the recirculation mode of operation.

- Figures ES-1 and ES-2 display plant-specific estimates of RCIC system unreliability for three specific sets of mission requirements. Figure ES-1 estimates are based on the operating experience data extrapolated to the 24-hour mission typically modeled in PRA/IPEs. Figure ES-2 displays plant-specific estimates with separate estimates for short term (shorter than 15 minutes in duration) and long term (longer than 15 minutes) missions.

- For the short term mission unreliability, failures attributed to the start sequence (other than injection valve) are the leading contributor (48%). The leading contributor to the long term mission unreliability is the failure to restart the RCIC system for subsequent injection of coolant (41%). Failure to run (FTR) is the largest contributor (36%), based on a 24-hour mission time, for the RCIC system PRA-based unreliability. For the failure to run failure mode, the failures found during unplanned demands were the result of personnel errors in operation of the flow controller and a spurious isolation of the turbine steam supply. The spurious isolation of the turbine steam supply was a failure mechanism not identified as a major contributor to the system failure probability in the PRA/IPEs.

- Comparing the estimates of RCIC system unreliability calculated from the information contained in PRA/IPEs to the estimates (with recovery) calculated from the operating experience data revealed that most (approximately 75%) of the PRA/IPE point estimates lie within the uncertainty interval associated with the operating experience estimate. However, about 21% of the PRA/IPE estimates predict better performance than identified by the estimates calculated from the operating experience data. These plants fall below the 5th percentile of the distribution computed from the operating experience data.

- It was found that most of the PRA/IPEs do not model the RCIC system in the way it is observed to be operated in the operating experience data. Specifically, the maintenance of reactor vessel water level by either restart and/or recirculation following initial injection is generally not modeled. For the PRA/IPEs that model the system with the restart and/or recirculation modes of RCIC, the failure probabilities assigned to these modes of operation appear to be too optimistic. For example, the initial failure to start (other than the injection valve) probabilities and the restart failure probabilities differ by about a factor of 2.6 according to the operating experience data. However, the PRA/IPEs use the same probabilities for restart as for initial start. According to the operating experience data, the failure to restart contribution to overall unreliability is about a factor of two greater than the failure to start (other than the injection valve) contribution (27% versus 12%, respectively).

- The operating data contained five instances where multiple systems (RCIC, high pressure coolant injection, and sometimes reactor water cleanup) either had failed or had the potential to fail concurrently; these instances may be common cause failures. The events involved motor-operated valves, the steam leak detection circuitry, and the turbine governors. In two of the five instances the RCIC and high pressure coolant injection systems were affected during an unplanned demand. The other events were discovered during surveillance testing (2) and other routine plant operations (1).

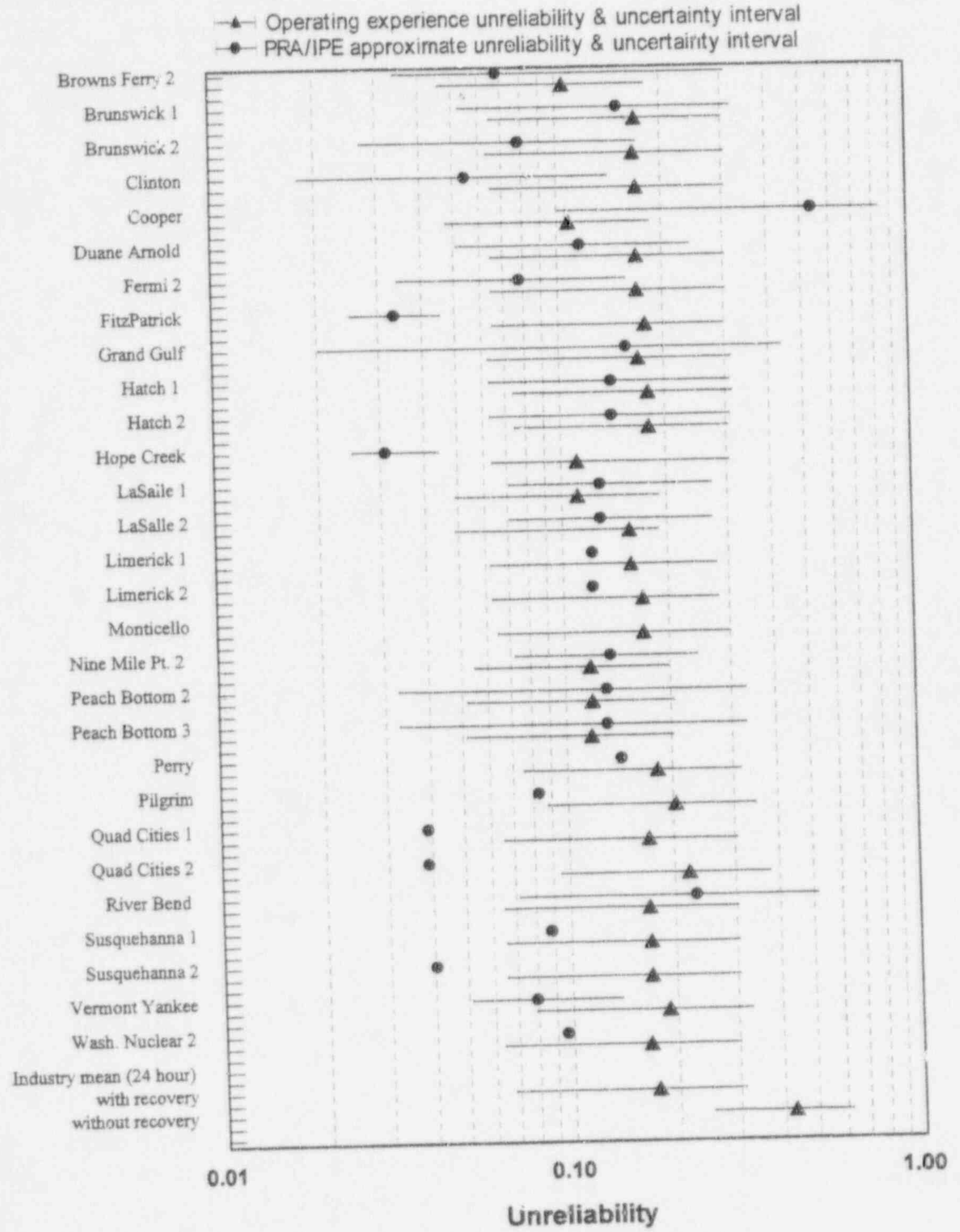

Figure ES-1. Plant-specific estimates of RCIC system unreliability for 24-hour missions derived from PRA/IPE assumptions and information and from operating experience data.

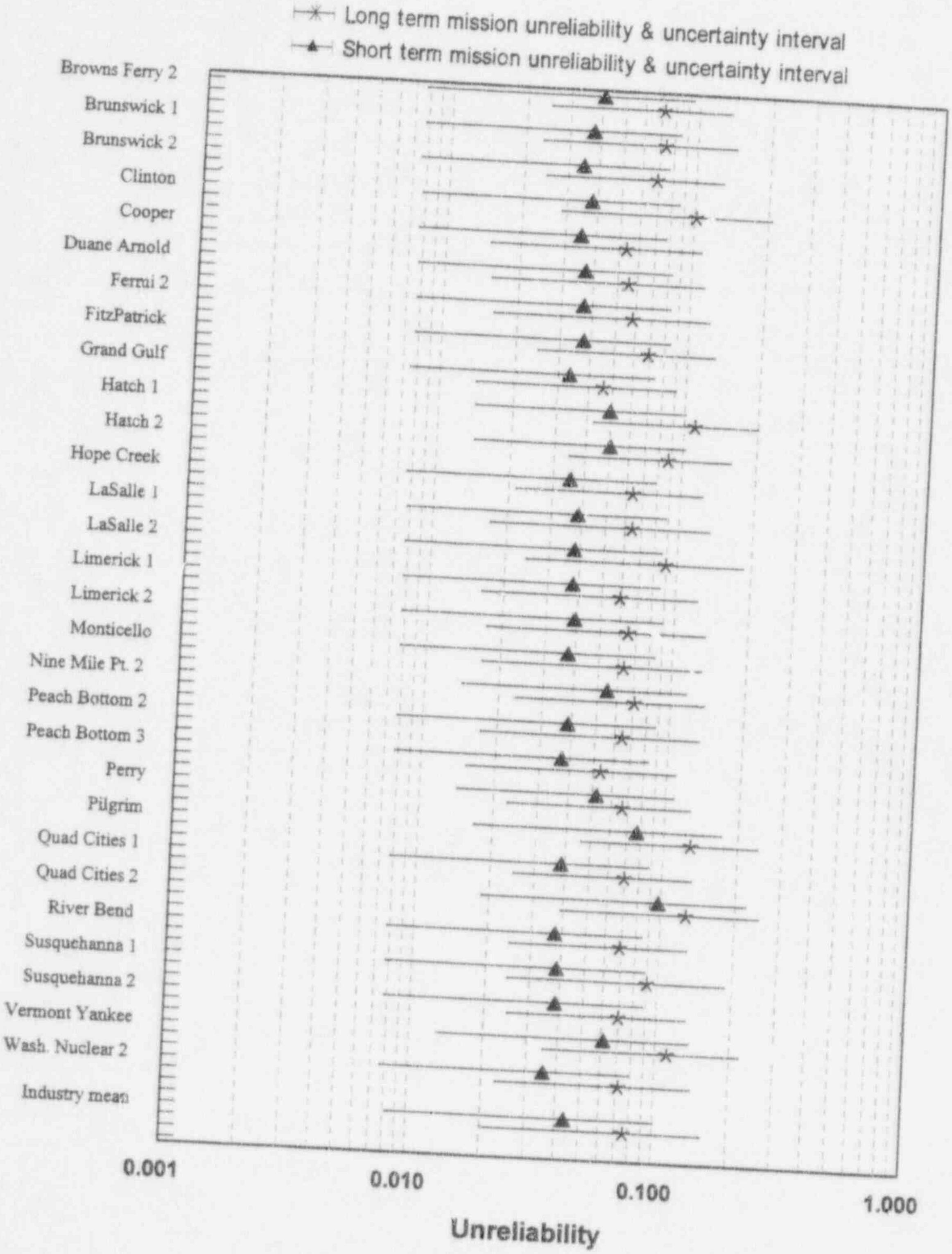

Figure ES-2. Plant-specific estimates of RCIC system unreliability for the short term and long term missions observed in the operating experience.

- For the short term missions, a decreasing trend in RCIC system unreliability with respect to calendar year was identified by statistical analysis of the operating data. In addition, some indication of a trend was identified in the short term unreliability with regard to low-power license date, but it is not a strong indication. More data (i.e., more operating experience) are needed before this trend can be statistically verified or disproved. No statistical trends were identified with regard to long term RCIC unreliability. Figures ES-3 and ES-4 provide plots of the short term RCIC unreliability.

- When plotted against plant operating year (see Figure ES-5), the unplanned demand frequency exhibits a statistically significant decreasing trend. This is likely a result of a corresponding decrease in unplanned plant trips, which typically include a RCIC system actuation. Failure frequency exhibits no trend when plotted against plant operating year (Figure ES-6). There was no correlation observed between the plant's low-power license date and the frequency of failures per operating year (Figure ES-7). The average number of failures per operating year was 0.62. This average frequency was observed for plants licensed from 1970 through 1990. Two plants licensed in the 1970s and two plants licensed in the 1980s had relatively high failure frequencies.

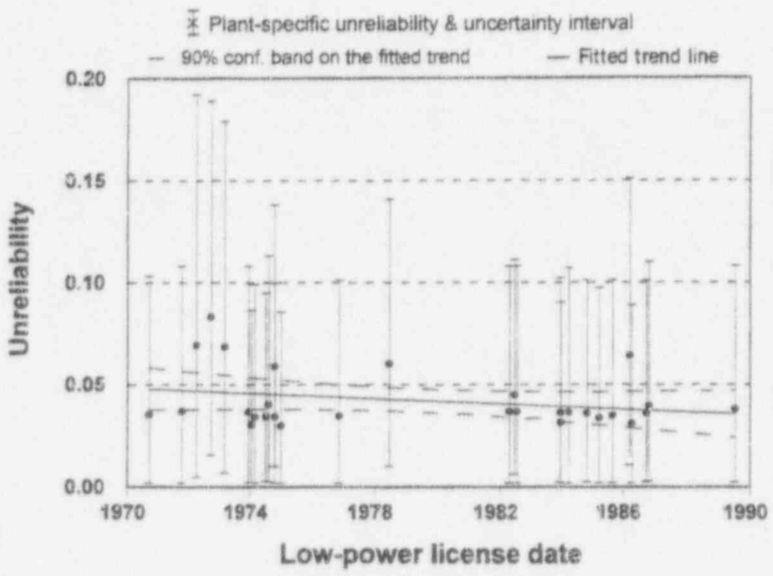

Figure ES-3. Plant-specific RCIC system unreliabilities (including recovery) for short term missions plotted against low-power license dates. The plotted trend indicates some increase in reliability (i.e., reduced unreliability), but the trend is not statistically significant (P-value = 0.15).

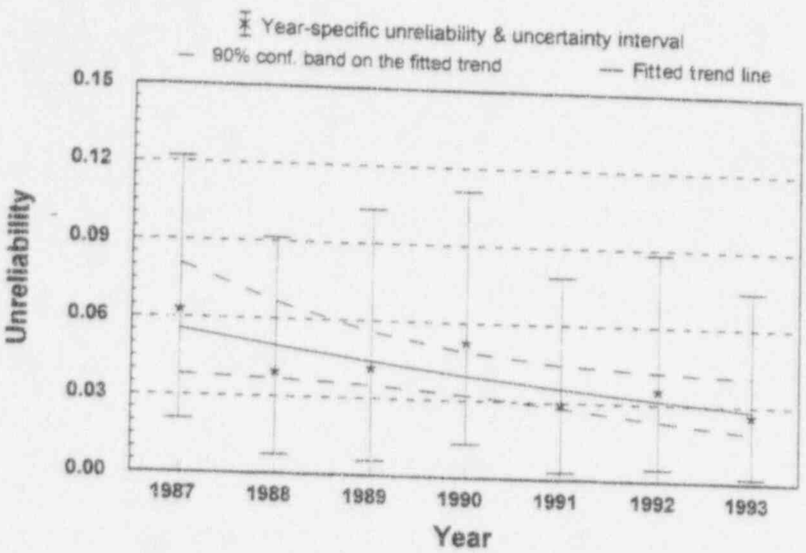

Figure ES-4. RCIC system unreliabilities (including recovery) for short term missions by calendar year. The plotted trend is statistically significant (P-value = 0.03).

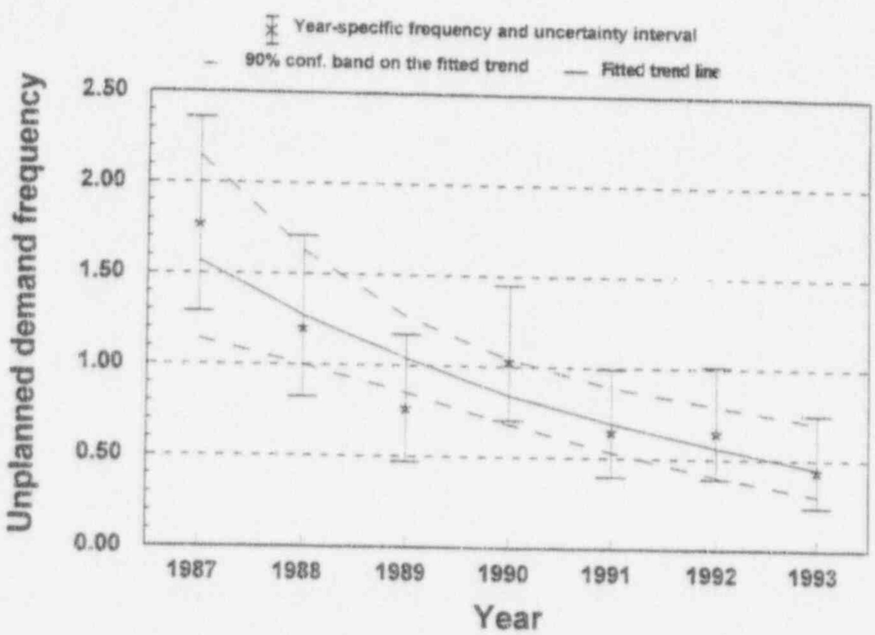

Figure ES-5. RCIC unplanned demands per plant operating year, with 90% uncertainty intervals and confidence band on the fitted trend. The trend is statistically significant (P-value = 0.003).

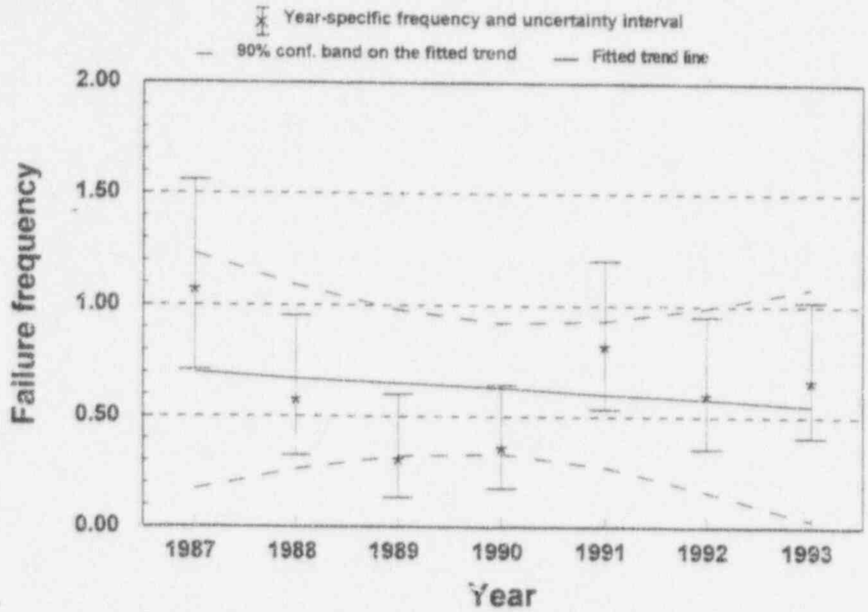

Figure ES-6. RCIC failures per plant operating year, with 90% uncertainty intervals and confidence band on the fitted trend. The trend is not statistically significant (P-value = 0.67)

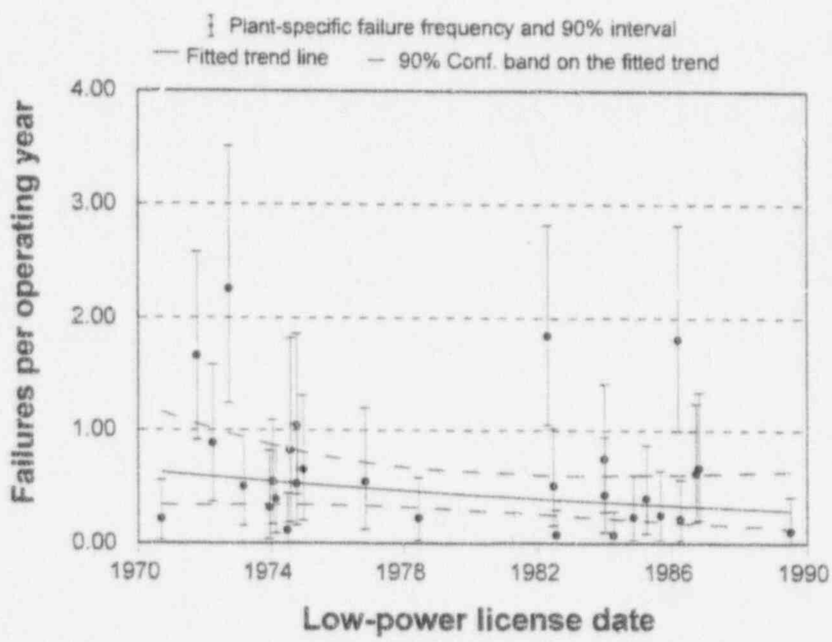

Figure ES-7. Plant-specific RCIC system failures per operating year, plotted against low-power license date. The trend is not statistically significant (P-value = 0.17).

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Technical contributions by A. J. Luptak and D. A. Prawdzik of the INEL are also included.

CONTENTS

FIGURES

TABLES

ACRONYMS

ADS	automatic depressurization system
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
CFR	Code of Federal Regulations
CRD	control rod drive
CST	condensate storage tank
ECCS	emergency core cooling system
ESF	engineered safety feature
FR	failure to recover
FRC	failure to transfer during recirculation
FRS	failure to restart
FTR	failure to run
FTS	failure to start
FTSO	failure to start other
FTSV	failure to start injection valve
HELB	high-energy line break
HPCI	high-pressure coolant injection
HPCS	high-pressure core spray
HVAC	heating, ventilating, and air conditioning

IFRS	if restart (probability that a RCIC mission requires a restart)
INEL	Idaho National Engineering Laboratory
LER	Licensee Event Report
LPCI	low-pressure coolant injection
LPCS	low-pressure core spray
LOCA	loss-of-coolant accident
MCC	motor control center
MOOS	maintenance-out-of-service
MOV	motor-operated valve
MSIV	main steam isolation valve
NPRDS	Nuclear Plant Reliability Data System
NRC	Nuclear Regulatory Commission
NSSS	nuclear steam supply system
ORNL	Oak Ridge National Laboratory
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RCIC	reactor core isolation cooling
RHR	residual heat removal
RPV	reactor pressure vessel
SAS	SAS Institute, Inc.'s commercial software package
SCSS	Sequence Coding and Search System (database maintained at ORNL)
SRV	safety relief valve
TDP	turbine-driven pump

TERMINOLOGY

Demand—An event requiring the RCIC system to inject coolant to the reactor pressure vessel (RPV). This event may be the result of a scheduled (i.e., surveillance test) or an unscheduled (i.e., unplanned) demand. An unplanned demand is either a manual or automatic start as a result of an actual low RPV water level condition. Engineered safety feature (ESF) actuations of portions of the system (e.g., steam supply isolation valve closures for containment isolation) were not considered as demands.

Failure—An inoperability in which the injection function was lost. For estimating the operational unreliability, a subset of the failures was used. (That is, only those that occurred on unplanned actuations or cyclic surveillance tests were used.)

Failure to run-short term (FTR-ST)—A FTR with a mission time of less than 15 minutes for RCIC.

Failure to run-long term (FTR-LT)—A FTR with a mission time of at least 15 minutes for RCIC.

Failure to run (FTR)—Any failure to complete the mission after a successful start. This includes obvious cases of failure to continue running, and also cases when the system started and injected, tripped off for a valid reason, and then could not be restarted. Excluded from the failure to run events were failures to restart and failures to transfer during recirculation to injection.

Failure to restart (FRS)—Failure to restart occurs if, during an unplanned demand, after a successful start and run to restore RPV level, the RCIC system is shut down (manually or as a result of a high level trip), and subsequently the system is demanded to restart (automatically on low vessel level or manually) and fails to restart. The failure to restart can occur on any restart attempt

Failure to transfer during recirculation (FRC)—Failure to transfer during recirculation occurs if, during an unplanned demand of the system, the test return-line MOV is opened to divert flow from the RPV to the CST and subsequently fails to close, or the injection valve fails to re-open, resulting in no flow to the vessel for level restoration.

Failure to start—Failure of the system to start and inject coolant into the RPV on a valid demand signal.

Fault—An inoperability in which the injection function of the system was *not* lost. This includes administrative technical specifications violations such as late performance of a surveillance test.

If restart (IFRS) - Probability that a RCIC mission requires the RCIC system to restart (see Failure to restart).

Inoperability—An event affecting the RCIC system such that it did not meet the operability requirements of plant technical specifications and therefore was required to be reported in a LER.

Maintenance-out-of-service (MOOS)—RCIC system failure attributed to the system being out of service for either preventive or corrective maintenance at the time of the unplanned demand.

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

Mission time—The elapsed clock time from the first demand for the system until plant conditions are such that the system is no longer required. PRAs typically assume that RCIC is needed for injection throughout the entire mission time. In the plant operating experience, this period includes not only injection but recirculation through the test return line or system shut down and restart.

Operating conditions—Conditions in which technical specifications require RCIC operability, typically with the reactor vessel pressurized.

Operating data—A term used to represent the industry operating experience as reported in LERs. It is also referred to as operating experience or industry experience.

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

P-value—The probability that the data would be as extreme as it is, assuming the model or hypothesis is correct. It is the significance level (0.05 for this study) at which the assumed model or hypothesis is statistically rejected.

Recovery—An act that enables the RCIC system to be recovered from a failure without maintenance intervention. Generally, recovery of the RCIC system was only considered in the unplanned demand events. Each failure reported during an unplanned demand was evaluated to determine whether recovery of the system by operator actions had occurred. Typically a failure was recovered if the operator was able to reposition a switch, open a valve or reset the governor to restore injection to the RPV. Events that required replacing components were not considered as recoveries. In addition, recovery was not considered during the performance of a surveillance test.

Unreliability—Probability that the RCIC system will not perform its required mission. This happens if the system is out of service for maintenance, or if the RCIC system fails to start, run, restart or transfer during recirculation modes of operation.

Reactor Core Isolation Cooling System Reliability, 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 to monitor and report upon the functional reliability of risk-important systems in commercial nuclear power plants. The approach is to compare the estimates and associated assumptions as found 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, AEOD sponsored the Idaho National Engineering Laboratory (INEL) in conducting a risk-related performance evaluation of the reactor core isolation cooling (RCIC) system in the U.S. commercial boiling water reactors (BWRs) that have a RCIC system. This report documents the results of that evaluation.

The evaluation measures RCIC system unreliability using actual operating experience under conditions most representative of circumstances that would be found in response to a postulated vessel isolation event. To perform this evaluation and make risk-based comparisons to the relevant information provided in the PRAs, the unreliability estimates provided in this study are based on the RCIC system performing its risk-significant function. The estimates of RCIC system unreliability were based on data from unplanned demands, as a result of transient response, and from full system functional tests that best simulate system response in a vessel isolation event. The data from these sources are considered to best represent the plant conditions found during accident conditions. Data from component failures that did not result in a loss of injection function of the system were not included.

Failures and associated demands that occurred during tests that are intended only to demonstrate operability of portions of the system were also excluded. These types of partial system tests do not challenge the system as a whole. A complete system response is required for accident mitigation. Therefore, only tests that challenge the entire system are included.

This study was based upon the operating experience during the period from 1987 through 1993, as reported in Licensee Event Reports (LERs) found in the Sequence Coding and Search System (SCSS). The objectives of the study were to:

- Estimate unreliability based on operational data, and compare the results with the assumptions, models, and data used in PRAs and Individual Plant Examinations (IPEs).
- Provide an engineering analysis of the factors affecting system unreliability and determine if trends and patterns are present in the RCIC system operational data.

The report is arranged as follows. Section 2 describes the scope of the study and includes brief descriptions of the RCIC system, the data collection, and analysis methods. Section 3 presents the results of the reliability analysis of the operating data and the comparisons to the PRA/IPE information. Section 4 provides the results of the engineering analysis of the operating data. Section 5 lists 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 of the body of the report.

2. SCOPE OF STUDY

This study documents an analysis of the operating experience of the 29 BWRs listed in Table 1, all of which have a RCIC system. The analysis focused on the ability of the RCIC system to start and provide adequate core cooling flow for its required mission time. The containment isolation function associated with the RCIC system is not within the scope of this study. The system description and boundaries, data collection, failure categorization, and limitations of the study are briefly described in this section.

The data used in this report were limited to the set of plants listed in Table 1. For the newer plants, data started from the low-power license date. Browns Ferry 1, Browns Ferry 3, and Shoreham were excluded even though they are BWRs with RCIC systems, because these plants did not operate during the study period.

Table 1 also provides the docket number for each plant and the number of operating years during the study period. The number of operating years for a plant was 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. Details of the calculation of operating time are provided in Appendix A, and plant data results are provided in Appendix B.

Table 1. BWR plants with a RCIC system selected for the study and the operating years during the 1987 through 1993 timeframe.

Plant Name	Docket	Operating years	Plant Name	Docket	Operating years
Browns Ferry 2	260	2.3	Limerick 2	353	3.8
Brunswick 1	325	3.8	Monticello	263	6.3
Brunswick 2	324	4.6	Nine Mile Pt. 2	410	4.5
Clinton	461	4.9	Peach Bottom 2	277	4.0
Cooper	298	5.6	Peach Bottom 3	278	3.5
Duane Arnold	331	5.6	Perry	440	5.0
Fermi 2	341	5.6	Pilgrim	293	3.9
FitzPatrick	333	4.5	Quad Cities 1	254	5.5
Grand Gulf	416	6.1	Quad Cities 2	265	5.4
Hatch 1	321	5.9	River Bend	458	5.3
Hatch 2	366	6.0	Susquehanna 1	387	5.7
Hope Creek	354	6.2	Susquehanna 2	388	6.1
LaSalle 1	373	5.4	Vermont Yankee	271	6.2
LaSalle 2	374	5.2	Wash. Nuclear 2	397	5.1
Limerick 1	352	5.7			

2.1 System Operation and Description

The RCIC system is a single train standby system required by plant technical specifications (see References 1 through 6) for safe shut down of the plant. The system is not considered to be part of the emergency core cooling system (ECCS), and does not have a loss of coolant accident (LOCA) function. The RCIC system is designed to ensure that sufficient reactor water inventory is maintained in the vessel to permit adequate core cooling.[7] This prevents the reactor fuel from overheating in the event that:

1. A complete plant shut down occurs under conditions of a loss of the feedwater system before the reactor is depressurized to a point where the shut down cooling system can be placed into operation.
2. The reactor pressure vessel (RPV) is isolated in conjunction with a loss of coolant flow from the feedwater system.

Following a normal reactor shut down, core fission product decay heat causes steam generation to continue, albeit at a reduced rate. During this time, the turbine bypass system diverts the steam to the main condenser, and the RCIC system supplies the makeup water required to maintain reactor vessel inventory. (Note that the RCIC system is just one of a number of systems capable of performing this function.) The turbine-driven pump supplies makeup water from the condensate storage tank (CST) to the reactor vessel. An alternate source of water is available from the suppression pool. The turbine is driven by a portion of the steam generated by the decay heat and exhausts to the suppression pool. This operation continues until the vessel pressure and temperature are reduced to the point that the residual heat removal (RHR) system can be placed into operation.

2.1.1 System Operation

Based on the operating data reviewed for this study, the RCIC system was found to have two operational missions. We categorized these two missions as either short term or long term, depending on the plant conditions associated with the need for RCIC to provide coolant flow to the RPV. The distinction between the two operational missions is based on the time the system was operated for the particular event. The short term missions were defined as those missions where the use of RCIC for coolant injection was required for less than 15 minutes. These short term missions were typically only a few minutes in duration. The long term missions were defined as those missions where the need for RCIC operation was required beyond 15 minutes. Long term missions may have required RCIC operation for several hours.

The short term missions observed in the operating data were of two types: either they required the RCIC system to start automatically on a low RPV water level signal, or they required operators to manually start the system to mitigate a RPV water level transient. For both of these cases, the need for RCIC was observed following a reactor scram from high power operations and may have involved either a RPV level control problem or a closure of the turbine stop valves. In these events the RCIC system quickly restored the RPV water level. In a few cases the system was restarted a second time to restore RPV water level. Overall, the use of the system was required for only a few minutes. In these short term missions, feedwater was available or was restored within a few minutes to provide normal RPV water level control.

In some of the short term missions the plant experienced a reactor scram during power operations without a loss of normal feedwater or a closure of the turbine stop valves. In these cases the void collapse associated with the scram caused a demand for RCIC injection; the high-pressure core spray (HPCS) or high-pressure coolant injection (HPCI) systems (depending on plant design) also automatically initiated to supply makeup water to the reactor vessel. In these cases the systems were shut down after RPV water level was restored to the normal operating band.

The long term missions observed in the operating data were events where the plant would experience a reactor scram during power operations either as a result of a loss of normal feedwater or an isolation of the reactor vessel. In either case, RCIC would operate to provide adequate RPV water level for periods of time up to several hours. For these long term missions, either the control room operator would manually initiate the RCIC system, or the system would automatically start at the predetermined low reactor water level setpoint. At this point the system would inject until the system was shut down by the operator or the high level trip setpoint was reached, at which time the RCIC turbine steam supply and coolant injection valves were closed. With the continued steam generated by decay heat and corresponding lowering of vessel level (as a result of safety relief valve or turbine bypass valve operation), the system would be re-started during the event and the cycle repeated one or more times.

As an alternative to having the system either manually or automatically cycled on and off between high and low vessel level setpoints, the system can be used to raise level to the normal operating level band, and then the control room operator can open the test-return-line motor-operated valve (MOV) and divert RCIC flow back to the CST. This practice, similar to the pressure control mode of operation of the HPCI system, would minimize repeated restarts of the system. The RCIC system would operate continuously throughout the event by providing flow to the vessel when needed and by recirculating flow back to the CST through the test-return-line when not needed. In these events the injection and test-return-line MOVs are cycled for the duration of the event, which could last several hours. If the RCIC system were to fail during the event, the HPCS/HPCI system could provide adequate vessel coolant inventory.

For some BWR designs there is another option available for removing decay heat during a planned isolation event when the main condenser is not available. With this option, the RCIC system would operate in conjunction with the RHR system in the steam condensing mode. In this mode, condensed steam is delivered from the RHR heat exchangers through an interconnection to the RCIC pump suction for return to the RPV. Thus, closed loop cooling is provided by this mode. This mode of operation was not observed in the operating data reviewed in this study.

2.1.2 System Description

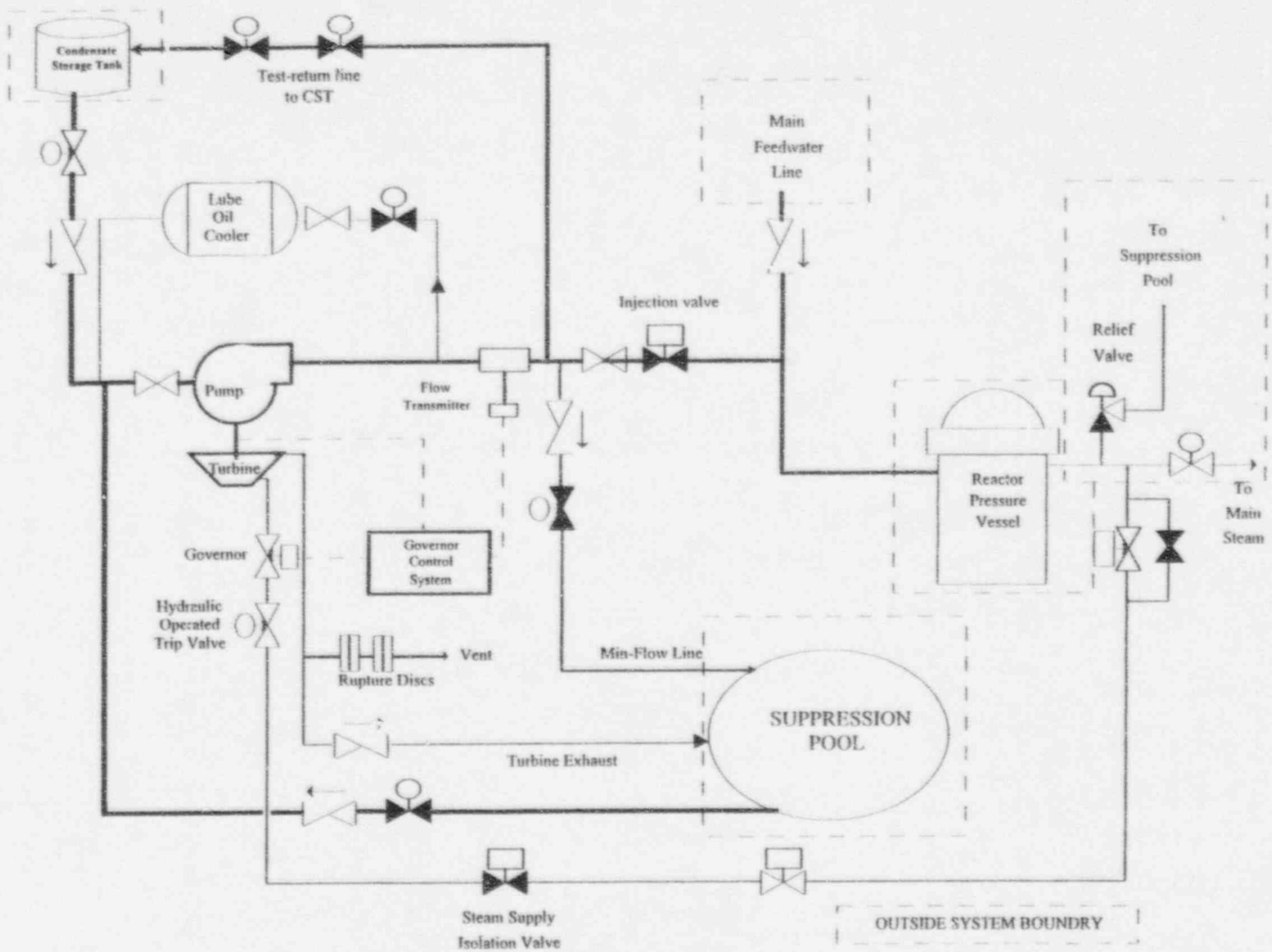
The RCIC system is a single train standby system that contains a single 100% capacity steam turbine-driven pump. The RCIC system is capable of delivering reactor grade water from the CST to the RPV using reactor-decay-heat-generated steam as a source of energy to drive the turbine-driven pump. In the event that CST water is not available, an alternate source of water is available from the suppression pool. Figure 1 provides a simplified diagram of a typical RCIC system.

The RCIC system steam turbines (at all plants) are Dresser-Rand Terry-Turbodyne (Terry) turbines designed for constant capacity over varying ranges of inlet steam pressure, typically 1040 psig to 50 psig. These turbines have horsepower ratings that vary from 460 to 875 with associated pump flow rates from

400 to 800 gpm, depending on plant design. All Terry turbines that drive RCIC pumps use Woodward governors (type EG-M with EGR actuators) for speed control, including prevention of overspeed during "cold quick-starts." The ratings for the RCIC system varies by plant design class, with the older Design Class II plants having the smaller capacity systems and the newer Design Class VI plants having the higher capacity systems. However, because of the overall similarities of the system in the various design classes (same equipment manufacturer), no distinction was made in this report between the different design classes.

Turbine "cold quick-starts" are required to meet pump starting time limits in Safety Analysis Reports, and other requirements specified to meet the reactor safety analyses of the nuclear steam supply system vendor. A cold start is considered to be a start that occurs when a turbine has not been operated for at least 72 hours. Turbine "quick-starts" occur when the turbine is required to reach rated speed and pump flow in 30 to 120 seconds. Since standby turbines are idle for extended periods of time, lubricating oil drains from the turbine bearings, leaving the bearings vulnerable to excessive wear. Standby turbines supplied by Terry typically also use turbine lubricating oil as the hydraulic operating fluid for the governors and actuators. To provide bearing lubrication and governor oil on quick starts, a pressurized lubrication oil system is provided that uses a shaft-driven lubrication oil pump. The shaft-driven pump provides lubrication oil to the turbine bearings and governor assembly as soon as the turbine begins to roll, enhancing both turbine lubrication and governor response.

To control turbine speed, a governor valve is provided for the turbine; the valve is typically supplied by Terry. The governor valve is fully open at the beginning of a quick-start and is designed to assume speed control during the startup when the turbine speed reaches the governor's minimum speed setting (approximately 2000 rpm). During a quick start the turbine steam admission valve opens fully and the turbine accelerates rapidly to the governor's minimum speed setting. At the minimum speed setting the governor starts to control turbine speed by throttling closed the governor valve. This limits the acceleration of the turbine to prevent an overspeed trip of the turbine. The closing of the governor valve slows the turbine to a speed less than the minimum speed. At this point the governor in conjunction with the ramp-generator increases turbine speed in a controlled manner to rated speed by slowly opening the governor valve. The ramp-generator controls and limits the time for the turbine to reach rated speed to approximately 30 seconds after the governor gains control. If inlet steam flow is excessive during a quick start, the governor valve cannot close sufficiently to limit speed before the turbine overspeeds.



BWR Reactor Core Isolation Cooling

Figure 1. Simplified RCIC system schematic.

The RCIC system instrumentation and control consists of system initiation and containment isolation circuitry. These two circuits provide different functions, both of which can contribute to system unreliability. The purpose of the initiation circuitry is to initiate actions (that is, start up the RCIC system) to ensure adequate core cooling when the reactor vessel is isolate . from its prin..ry heat sink and normal coolant makeup flow from the feedwater system is insufficient or unavailable. The purpose of the containment isolation circuitry is to initiate closure of appropriate containment isolation valves to limit fission product release should a RCIC steam line rupture occur.

The RCIC system initiation circuit allows for manual and automatic initiation of the system. Automatic initiation occurs for conditions of low reactor water level. The low reactor water level parameter is monitored by four transmitters that are connected to relays whose contacts are arranged in a one-out-of-two taken twice logic arrangement. Once initiated, the RCIC logic seals in and can be reset by the operator only when the reactor vessel level signals have cleared. Upon system initiation, the turbine steam supply valve opens to supply steam to the turbine, and the injection valve and the suction valve from the CST open to supply coolant flow to the RPV. In addition, the test-return line isolation valve is closed to allow full system flow and maintain primary containment isolation. Failure of any one of these valves to function during an initiation results in a failure of the system.

The RCIC system containment isolation circuitry typically provides automatic closure of the RCIC turbine steam supply isolation valves and turbine exhaust valve in the event of a steam line failure (high energy line break). The parameters monitored typically include high steam flow, low steam line pressure, high room delta-temperature, and high area temperature. Isolation of these valves disables the RCIC injection function: however, failure of this circuit to close these valves would not preclude operation of the system. During system standby a spurious isolation of the steam supply line caused by this circuit contributes to system unavailability, and during system operation the spurious isolation can contribute to system unreliability.

2.1.3 System Boundaries

The RCIC system for this study was partitioned into three subsystems for analysis purposes. These subsystems are; (1) the Turbine and Turbine Control Valves, (2) Coolant Piping and Valves, and (3) Instrumentation and Control. These three subsystems are composed of the following:

- The Turbine and Control Valves subsystem includes the turbine and governor assembly and associated controls. Also included with this subsystem are all steam piping from the main steam line penetration to the turbine, the turbine exhaust piping to the suppression pool with associated valves, and the turbine control and steam line isolation valves and valve operators.

- The Coolant Piping and Valves subsystem includes the turbine-driven pump assembly and associated fluid piping, including the normal (from the CST) and alternate (from the suppression pool) pump suction sources and the pump discharge to the reactor pressure vessel penetration or main feedwater line, depending on plant design. Included with this subsystem are the associated valves and valve operators. The suppression pool and the CST are not included in the system boundaries.

- The Instrumentation and Control subsystem includes the circuits for system initiation, operation, and containment isolation of the RCIC steam lines. However, each failure of these circuits was

screened to ensure that the component identified in the circuit was dedicated to the RCIC system before it was included in this report.

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

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

2.2 Collection of Plant Operating Data

The source of RCIC system operational data used in this report was LERs found using the Sequence Coding and Search System (SCSS) database. The SCSS database was searched for all RCIC records for the years 1987 through 1993. In addition, to ensure as complete a data set as possible, a search was conducted of all the immediate notification reports (required by 10 CFR 50.72) that identified the RCIC system. The immediate notification report search results identified fewer events than the SCSS LER search results, and the events identified in the immediate notification reports were captured in the LERs. Also, the immediate notification reports did not contain the necessary detail about the RCIC event to conduct a reliability analysis. Thus, only the LER data were used in this report.

2.2.1 Inoperability Data Collection and Characterization

The LER rule (10 CFR 50.73) specifies when events are to be reported to the NRC. The section most relevant to the reporting of RCIC system inoperabilities is 10 CFR 50.73(a)(2)(v): *Any event or condition that alone could have prevented the fulfillment of the safety function of structures or systems that are needed to: (A) Shut down the reactor and maintain it in a safe shutdown condition; (B) Remove residual heat; (C) Control the release of radioactive material; or (D) Mitigate the consequences of an accident.* However, RCIC is not part of the emergency core cooling system (ECCS) nor is it normally classified as an engineered safety feature (ESF). Therefore, it is not clear that RCIC is relied upon to perform a safety that would be directly reportable. Nevertheless, all plants with RCIC systems have submitted LERs documenting RCIC inoperabilities, with the majority being reported under section (a)(2)(v).

Since it is not normally classified as an ESF, RCIC system actuations are not specifically covered by the event reporting rules [i.e., section (a)(2)(iv)]. However, the RCIC shares low-low reactor water level actuation setpoints with the ESF high pressure coolant injection or high pressure core spray systems (HPCI/HPCS). Event reporting requirements, state that each LER (i.e., HPCI/HPCS actuation report) shall contain a clear, specific, narrative description of what occurred so that knowledgeable readers not familiar with the details of a particular plant can understand the complete event. Thus, any unplanned actuation of RCIC from low-low reactor water level will also result in a reportable actuation of HPCI/HPCS and the

report on the HPCI/HPCS should also describe the RCIC system actuation. All HPCI/HPCS actuations were reviewed in order to verify and count the number of RCIC unplanned demands.

RCIC is commonly included in plant technical specifications (TS) because of its similar function to the ECCS. Therefore, RCIC system failures are directly reportable if the system function is lost for a period that exceeds the TS Limiting Condition for Operation (LCO) or if the reactor completes a shutdown in order to correct a RCIC malfunction [i.e., section (a)(2)(i)].

A full function test of the entire RCIC system is nominally to be conducted every 18 months (typically required by TS). This is the basis for estimating RCIC test demands. Corrections to this 18 month cycle are based on information provided in monthly operating reports, and are included to account for shorter of longer operating periods. As mentioned above, RCIC failures in general, might not necessarily be required to be reported under section (a)(2)(v). However, the LERs reviewed for this study (i.e., 1987-1995) identified three instances where failures of RCIC were reported during the cyclic tests. An engineering and statistical comparison of these failure data (failures and demands) with those identified during unplanned demands indicated that the two data sets were similar and because of this, the cyclic test data were used and pooled with the demand data in the analysis of RCIC reliability. The net effect of not including the cyclic test data due to concerns relating to reportability of failures increases the uncertainty of the failure probability estimates without changing the mean value for the system appreciably. These reporting requirement, in combination with the other reporting criteria and the knowledge of RCIC actuations concurrent with reportable HPCI/HPCS actuations, provides a sufficiently accurate sample of RCIC demands and associated failures to make meaningful RCIC demand reliability estimates.

In this report, the term *inoperability* is used to describe any reported RCIC malfunction. The inoperabilities were subsequently classified as *faults* and *failures* for purposes of computing reliability estimates. The fault and failure classifications were based on an independent review of the events. The term *failure* is used to identify the subset of the inoperabilities for which the coolant injection function of the RCIC system is lost. The term *fault* is used to describe the subset of inoperabilities that are not classified as failures.

Failure Classification—All of the LERs identified in the SCSS database search were independently reviewed by a team of U.S. commercial nuclear power plant experienced personnel, with care taken to properly classify each event and to ensure consistency of the classification for each event. Because the focus of this report is on risk and reliability, it was necessary to review the full text of each LER and classify or exclude events based on the available information reported in the LER. Specifically, the information necessary for determination of reliability, such as, classification of RCIC failures and faults, failure modes, failure mechanisms, causes, etc. in this report, were based on the independent review of the LERs. The SCSS data search was used only to identify LERs for screening for this study; no data characterization, evaluation, or reliability analysis was performed on the information encoded in the SCSS database

Two engineers independently evaluated the full text of each LER from a risk and reliability perspective. At the conclusion of the independent review, the data from each LER review were combined, and classification of each event was agreed upon by the engineers. The events that were identified as failures that could contribute to system unreliability were peer reviewed by the NRC technical monitor and technical consultants that have extensive experience in reliability and risk analysis. The peer review was

conducted to ensure consistent and correct classification of the failure event for the reliability estimation process.

Failure classification of the inoperability events was based on the ability of the RCIC system to function as designed for at least a 24 hour mission or until the system was no longer needed (for actual missions longer than 24 hours). Each LER was reviewed to determine if the system would have been reasonably capable of performing its design function. Examples of the types of inoperabilities that are classified as failures include: (1) malfunctions of the initiation circuit that prevent the system from starting in automatic; (2) malfunction of the injection MOV to open with the turbine operating properly and RPV water level at or below the initiation setpoint; (3) RPV water level at or below the initiation setpoint and the system out of service for pre-planned maintenance; and (4) malfunction of the flow controller that either prevents the system from providing flow to the RPV, or requires the operator to place the controller in manual because of erratic operation.

The RCIC events identified in this study as failures represent actual malfunctions that prevented the successful operation of the system. When the RCIC system receives an automatic start signal as a result of an actual low RPV water level condition or a manual start, the system functions successfully if the turbine starts and obtains rated speed and 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, the following failure modes were observed in the operating data:

- Maintenance-out-of-service (MOOS) occurs if, because of maintenance activities the RCIC system is prevented from starting during an unplanned demand.

- Failure to start (FTS) occurs if the system is in service but fails to automatically or manually start, obtain rated speed in the turbine, or develop sufficient injection pressure and flow to the reactor pressure vessel.

- Failure to run (FTR) occurs if, at any time after the system is delivering sufficient coolant flow, the RCIC system fails to maintain this flow to the RPV while it is needed.

- Failure to restart (FRS) occurs if, during an unplanned demand and after a successful start and run to restore RPV level, the RCIC system is shut down (manually or as a result of a high level trip), and subsequently is demanded to restart (automatically on low vessel level or manually) and fails to restart. The failure to restart can occur on any restart attempt.

- Failure to transfer during recirculation (FRC) occurs if, during an unplanned demand of the system, the test return-line MOV is opened to divert flow from the RPV to the CST and subsequently fails to close, or the injection valve fails to re-open, resulting in no flow to the vessel for level restoration.

Recovery of failures is important and was considered when estimating system unreliability. To recover from a failure, operators have to recognize that the system is 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 MOV 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 coolant flow to the RPV. Recovery for the other failure modes is

defined in a similar manner. Each failure was evaluated to determine whether recovery by an operator occurred.

The analysis section of each LER was used to determine if the system would have been able to perform as required even though the system was declared not operable as defined by plant technical specifications. As an example, the LER may have been submitted for the late performance of a technical-specification-required surveillance test. This event would be classified as a fault and not a failure in this study. This classification is based on the judgment that given a demand, the system would still be capable of functioning as designed. Moreover, plant personnel typically would state in the LER that the system was available to respond and that the subsequent surveillance test was performed satisfactorily. If the system failed the subsequent surveillance test, the event would have been classified as a failure. In addition, administrative problems associated with RCIC were also classified as faults, given that the system had successfully passed a recent surveillance test or remained capable of injecting water into the RPV. As an example, the discharge piping was found not to have the required number of seismic restraints. However, the results of an engineering analysis for the missing restraint provided by the plant in the safety analysis section of the LER indicated that the existing system configuration would successfully complete the missions postulated in this report. As a result, the event would be classified as a fault.

2.2.2 Collection and Characterization of Demand Data

For the reliability estimation process, the total number of demands associated with a specific set of failures must be known. Two criteria are important in selecting data sets for reliability analysis. First, useful data must, of course, be *countable*. Reasonable assurance must exist that both the number of failures and demands can be consistently estimated, and that sufficient detail will be present in the failure reports to match the failures to the applicable demand estimates.

The second criterion is that the demands must reasonably approximate the conditions being considered in the unreliability analysis. The unplanned demands or tests must be rigorous enough that successes as well as failures provide meaningful system performance information. The determination of whether each demand reasonably approximates conditions for required accident/transient response depends in turn on the missions being modeled by each failure probability estimate.

Unplanned demands—LERs can be used to provide information on unplanned demands following plant transients that resulted in an actual low RPV water level condition, that is, an actual need for the RCIC system. These unplanned demands were identified by searching the SCSS database for all LERs containing scrams while the reactor was critical for plants having a RCIC system during the 1987-1993 study period. These critical reactor scram events are reportable under 10 CFR 50.73(a)(2)(iv). The textual description in the LER provided the basis for determining if the RCIC system was used to mitigate the consequences of a RPV water level control transient during the scram. In addition, unplanned HPCI and HPCS engineered safety feature (ESF) actuations are reportable under the same reporting requirements as reactor scrams. The HPCI and HPCS ESF actuations on low RPV water level are typically at the same setpoint as for the RCIC system. In almost every case that there was a HPCI or HPCS actuation, a RCIC actuation was also identified by the plant. Also, for the critical reactor scram events that identified either a feedwater problem, a main steam line isolation valve closure, or a turbine supply valve closure, the use of the RCIC system was also identified in the LER. Therefore, identification of RCIC demands is possible, even if the system is not normally a 10 CFR 50.73 reportable system, by a search for critical reactor scrams, and HPCI and HPCS ESF actuations, which are reportable.

The LERs that described RCIC actuations were screened to determine the nature of the actuation. The RCIC actuations identified in the LERs that were classified in this study as RCIC unplanned demands were events that resulted in the RCIC system actually providing coolant flow to the RPV. Some of the actuations were demands of only a part of the system. The partial demands did not exercise the RCIC system in response to an actual need for injection, because RPV water level was restored using another source (typically feedwater) before the injection valve opened. Therefore, these records were excluded from the count of RCIC unplanned demands.

Surveillance Test Demands—A review of several plant technical specifications indicated that plants are required to simulate an actuation of the automatic start of the RCIC system once a fuel cycle, or once every 18 months (referred to as cyclic tests). These tests typically start the system by a cold quick-start of the turbine-driven pump; however, flow to the vessel is not required to be demonstrated. Because of the completeness of the cyclic surveillance test as compared to other tests, the cyclic surveillance test data were included in the system unreliability calculation. However, because the injection valve is not tested under the conditions the valve would experience during an unplanned demand (flow to the vessel), data from cyclic tests were not used to estimate the failure probability for this valve. For more details on the counting of unplanned demands and surveillance test demands, see Section A-1.2 in Appendix A.

Less complete demonstrations (e.g., quarterly or monthly surveillance testing) of the system's operability were not included in the analyses performed for this report. Data from testing that was judged as not demonstrating the injection function or did not result from a cold quick-start of the system were excluded. Some BWR plants initiate quarterly surveillance tests with a hot or cold turbine quick-start, while others may use a slow start with the turbine speed initially brought to the slow speed stop. The hot quick-starts and slow starts were judged not representative of the type of demand the system would experience during a low vessel level transient. Moreover, any condensate that may have collected in the steam line is drained during these tests, and the system is warmed up and possibly checked for factors that could cause a cold quick-start to fail. Therefore, the data from these tests were excluded from the system reliability analysis; however, information on the types and causes of failures observed during these tests were reviewed in the engineering analysis section of this report.

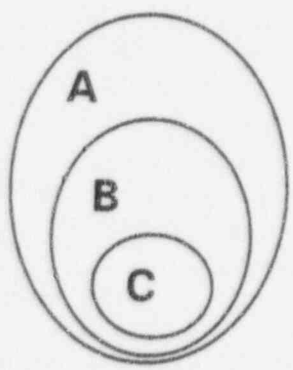
2.3 Data Analysis Methods

The risk-based and engineering analysis of the plant operating data are based on two different data sets. The Venn diagram in Figure 2 illustrates the relationship between these data sets. Data set A represents all the LERs that identified a RCIC system inoperability from the above-mentioned SCSS database search. Data set B represents the inoperabilities that were classified as failures of the RCIC system. Data set C represents those actual failures identified from LERs for which the corresponding demands (both failures and successes) could be counted. It is data set C that provides the basis for estimating the unreliability of the RCIC system. Data set C contains all relevant failures that occurred during either an unplanned full demand or a cyclic surveillance test (full demands). The only criteria are the occurrence of a *real* failure and the ability to count all corresponding full demands (i.e., both failures and successes). Data set C represents the minimum requirements for the data used in the risk-based analysis of the operating experience.

To eliminate any bias in the analysis of the failure and demand data in data set C and to ensure a homogeneous population of data, three additional selection criteria on the data were imposed. These criteria were: (1) the data from the plants must be reported in accordance with the same reporting

requirements, (2) the data must be statistically from the same population, and (3) the data must be consistent (i.e., from the same population) from an engineering perspective. Each of these three criteria must be met or the results of the analysis would be incorrectly influenced. As a result of these three criteria, the failure and demand data that comprise data set C were not analyzed strictly on the ability to count the number of failures and associated demands for a risk-based mission, but also to ensure that each of the above three criteria were met.

The purpose of the engineering analysis was to provide qualitative insights into RCIC system performance and not to calculate quantitative estimates of unreliability. Therefore, the engineering analysis used all of the RCIC inoperabilities appearing in the operational data. That is, the engineering analysis focused on data set A, which includes data set C, with an engineering analysis of the factors affecting RCIC system reliability. However, the maintenance-out-of-service (MOOS) events were excluded from the engineering analysis because although they result in the inability of the RCIC system to supply coolant to the vessel, they do not always involve an actual failure of the system. An unplanned full demand of the RCIC system while maintenance was being performed on that system during power operating conditions was considered in estimating unreliability, but was not part of the engineering analysis.



A The RCIC system was inoperable as defined by applicable technical specifications.

B The injection function of the RCIC system was lost (failure).

C The injection function of the RCIC system was lost (failure) and the demand count could be determined or estimated.

Figure 2. Illustration of the relationship between the data sets.

3. RISK-BASED ANALYSIS OF THE PLANT OPERATING DATA

In this section, the data pertaining to the capability of the RCIC system to inject water into the reactor pressure vessel [referred to as operating experience data for the purposes of this section of the report] were assembled from LERs and analyzed in two ways. *First, estimates of RCIC unreliability were calculated from the operating experience data.* These unreliability estimates are based on the operational missions that RCIC encounters during transients that include a reactor trip, reactor vessel isolation, and a demand for coolant injection by high pressure makeup systems (i.e., RCIC or HPCI/HPCS). Generally, these transients can be categorized as either a short or long term operation of RCIC. For example, a transient that results in reactor trip with a loss of feedwater, with no immediate recovery of feedwater, would demand (but not necessarily require, since HPCI/HPCS would normally be available) the operation of RCIC for high pressure makeup to restore and maintain RPV water level (i.e., long term operation of RCIC). A reactor trip with feedwater available, however, would not require long term RCIC operation (RCIC operates in the short term, restoring RPV water level). For the purposes of this study, estimates of RCIC unreliability were calculated for these two types of transient categories, resulting in two different operational missions for the RCIC system.

For the short term operation category (i.e., where feedwater is available), the need for long term RCIC is not necessary since feedwater (and additional makeup by HPCI/HPCS) can supply makeup water to the reactor vessel. For this case, RCIC initially receives an actuation signal in response to a low water level caused by shrink/void collapse. However, the low water level is restored immediately since feedwater is available and RCIC is operated only for a short period of time before it is secured.

For the long term operation category (i.e., where feedwater is not available), the need for RCIC is greater, since high pressure makeup to the reactor vessel is limited. In this case, RCIC (as well as HPCI/HPCS) initially receives an actuation signal in response to a low reactor water level. Since feedwater is not available, operation of RCIC is used to restore and maintain reactor water level. Generally, in this category of transients, following initial restoration of water level, RCIC is operated intermittently to inject water for maintaining reactor water level.

Additionally, the estimates of RCIC system unreliability are analyzed to uncover trends and patterns in RCIC system performance in U.S. commercial nuclear power plants. Plant-specific and industry-wide trend and pattern analyses provide insights into the reliability performance of the RCIC system.

Second, comparisons are made between the RCIC unreliabilities derived from operating experience data and those reported in selected Probabilistic Risk Assessments (PRAs), Individual Plant Examinations (IPEs), and NUREGs. To provide an appropriate comparison, the conditions typically postulated in the PRA/IPEs were also assumed for quantifying the RCIC unreliability model. The comparisons provide an indication of the extent to which unreliabilities based on operating experience data are consistent with those reported in the PRAs, IPEs, and NUREGs.

RCIC unreliability information was extracted from 21 plant risk information reports (PRAs, IPEs, and NUREGs) and used in the comparisons. These reports document risk information for 29 BWR plants. However, one report (the Monticello IPE) did not contain sufficient information to estimate RCIC unreliability. For the purposes of this study, the risk information reports will be referred to collectively as PRA/IPEs.

RCIC system unreliabilities derived from plant operating data were estimated using fault tree logic to associate fault event occurrences with broadly defined failure modes such as failure to start or failure to run. The probabilities for the individual failure modes were calculated by reviewing the failure information (see Appendix C), categorizing each failure event by failure mode, and then estimating the corresponding number of demands (both successes and failures). RCIC system unreliability was also estimated from PRA/IPE information. Generally, the system fault logic models were not available in the PRA/IPE submittals. However, the component failure probabilities used in calculating the unavailability of the RCIC system were available. In order to provide a comparison of PRA/IPE estimates of unreliability to those calculated from the operational data, estimates were made from the relevant information contained in the PRA/IPEs. The component failure probabilities were extracted and linked to the corresponding system failure modes identified in the fault tree developed for the analysis of the operating experience data. The component failure probabilities extracted from the PRA/IPEs are those identified as the major contributors to RCIC unavailability. Therefore, the PRA/IPE estimates approximated for this study should be different, but not significantly, from those used in PRA/IPE quantification.

A summary of the major findings in this section of the report are:

- The RCIC system unreliability (including recovery) for the short term, long term, and PRA-based (24-hour) missions calculated from the operating experience data are 0.04, 0.08, and 0.18, respectively. The difference in the unreliability estimates calculated for the short and long term operational missions versus the PRA-based missions is attributed mainly to the inclusion of additional modes of operation (subsequent restart of RCIC for maintaining RPV water level and/or recirculation of RCIC flow back to the CST) for long duration missions. If recovery is excluded, the short term, long term, and PRA-based estimates of RCIC system unreliability are 0.06, 0.16, and 0.43, respectively.

- For the short term operational unreliability, failures attributed to the start sequence (other than the injection valve) are the leading contributors (48%). The leading contributor to the long term operational unreliability is the ability to restart the RCIC system for subsequent injection of coolant (41%). Failure to run is the largest contributor (36%) for the PRA-based 24-hour mission time unreliability.

- A decreasing trend in short term mission unreliability when plotted against calendar year was identified by statistical analysis of the operating data. For the short term mission, no clear trend was identified in RCIC system unreliability when plotted against low-power license date. No statistical trends of RCIC unreliability were identified with regard to long term mission unreliability of RCIC.

- Comparing the estimates of RCIC system unreliability calculated from the information contained in PRA/IPEs to the estimates calculated from the operating experience data revealed that approximately 75% of the PRA/IPE point estimates lie within the 90% uncertainty interval calculated from the operating experience data. However, most of the PRA/IPE estimates that are outside the uncertainty band on the operating experience estimate fall below the 5th percentile (i.e., they predict better RCIC performance than indicated by the plant operating data).

- Most of the PRA/IPEs do not model the RCIC system in the way it is observed to be operated the operating experience data. Specifically, the maintenance of RPV water level by either restart and/or recirculation following initial injection is generally not modeled. For the PRA/IPEs that model the system with restart and/or recirculation mode of RCIC, the failure probabilities assigned

to these modes of operation appear to be too optimistic. For example, according to the operating experience data, the initial failure to start (other than the injection valve) probabilities and the restart failure probabilities differ by about a factor of 2.6. However, the PRA/IPEs use the same failure probabilities for restart as for initial start. The restart contribution to overall unreliability is a factor of 2 greater than the initial fail to start contribution, 27% versus 12%, respectively, according to the operating experience data.

3.1 Estimates of RCIC Unreliability

Estimates of RCIC train unreliability were calculated using the unplanned demands and cyclic tests reported in the LERs. The failure data were used to develop failure probabilities for the observed failure modes defined in Section 2. The types of data (i.e., cyclic test and unplanned demands), failure counts, and demand counts used for estimating probabilities for each of the RCIC system failure modes are identified in Table 2. The contributions to the unreliability of the RCIC system from support systems outside the RCIC boundary defined in Section 2.1.3 are excluded from the failure counts.

Table 2. Failure data sources and counts used for estimating RCIC failure probabilities by failure mode.

	Unplanned demands		Cyclic tests	
Failure mode	failures	demands	failures	demands
Maintenance-out-of-service (MOOS)[a]	1	133	—	—
Failure to start, other than injection valve (FTSO)	7	132	3	142
Failure to recover from FTSO (FRFTS)	4	7	—	—
Failure to start, injection valve (FTSV)	0	128	—	—
Failure to run (FTR)				
Short term operation (FTR-ST)	0	56	—	—
Long term operation (FTR-LT)	2	72	0	141
Failure to recover from FTR (FRFTR)	1	2	—	—
Failure to restart (FRS)	4	18[b]	—	—
Failure to recover from FRS (FRFRS)	2	4	—	—
Failure to transfer during recirculation (FRC)	2	72	—	—
Failure to recover from FRC (FRFRC)	0	2	—	—

a. In this report, the MOOS contribution to RCIC system unreliability was determined using the unplanned demand failures that resulted from the RCIC system being unavailable because preventive or corrective maintenance was being performed at the time of the demand and with the plant not shut down.

b. Number of long term operation missions requiring RCIC to restart. During these 18 missions there were approximately 46 restart demands.

The demand counts identified in Table 2 represent opportunities for RCIC system success. Each failure observed in a RCIC operational phase that was not recovered takes away an opportunity from a following phase. With this in mind, the counts in Table 2 are based on the following logic:

1. For the RCIC system to have the opportunity to start, the system could not be inoperable due to maintenance at the time of the demand. If so, then there is no opportunity for RCIC to start. The opportunities to start consist of the number of initial demands minus any MOOS failures observed. There were 132 unplanned demand opportunities (133 unplanned demands minus 1 MOOS failure) for the system to start. The cyclic tests accounted for an additional 142 demands. Three failures were identified for FTSO as the result of cyclic testing. The failure to start the RCIC system was partitioned into FTSO and FTSV to gain additional insights into the reliability for this operational phase and to use as much of the cyclic test data as possible.

2. The next operating event in a RCIC system response deals with FTSV. Therefore, any FTSO failure eliminates an opportunity for FTSV. The opportunities for FTSV consist of 132 demands minus any failures that were not recovered from FTSO. There were four non-recovered FTSOs, thereby reducing the FTSV demand count to 128. The FTSV unplanned demand counts differ from the FTSO demands, since the injection valve receives a permissive signal to open only if adequate pump discharge pressure is present and the low RPV water level signal is locked in. Since the injection valve is not tested under the conditions experienced during an unplanned demand, cyclic test data were not used for FTSV.

3. For the unplanned demands there were 7 FTSO events, three of which were recovered. The three failures observed during testing are not included in the estimation of recovery (neither as demands nor as failures) since if any failures occur, the test is terminated and no immediate effort is made to recover from the failure.

4. For the run phase of the unplanned demands, there were a total of 128 successful starts (125 plus 3 recovered FTSO events). These FTR counts were classified as either short term or long term missions. A short term mission is defined as a mission where RCIC operated for less than 15 minutes. There were 56 short term missions with no corresponding failures. A long term mission is defined as a mission where RCIC operated for 15 minutes or more. There were 72 long term missions with 2 failures identified. The cyclic tests accounted for an additional 141 opportunities for RCIC to run. As stated earlier, tests are generally terminated at the time of failure, and then the failure is repaired and the test is rescheduled. To capture as much of the test performance data as possible, if the LER indicated that the failure mechanism (in this case for FTSO) would not have affected the "run" phase of the RCIC system, and the run segment was performed at the conclusion of the repair (FTSO), then the test demands were included in the FTR counts as opportunities for success. Two of the three FTSO failures fall into this category. Therefore, two additional test demands are included in the FTR category (142-3+2=141). The cyclic tests are classified as long term mission since the duration of the run segment of the test is typically greater than 15 minutes.

5. For the unplanned demands, the failures observed during the run phase have the opportunity to be recovered. Of the two failures to run that occurred among the long term missions, one was recovered. Failures observed during the run phase of a cyclic test generally result in the test being terminated, and no effort to recover the failure is attempted. Therefore, no fail to recover entries for the test-related events would be tabulated even if failures had occurred.

6. The FRS data consists of the number of events that identified restarts of the RCIC system for subsequent coolant injection to the RPV (i.e., long term events) and any failures observed during this operational phase. Of the long term missions, 25% required the RCIC system to restart an average of 2.5 times per mission.

7. Two of the four FRS failures were recovered.

8. The remaining operational phase of the RCIC involves the recirculation mode. The number of cycles (i.e., transfer during recirculation to injection and back to recirculation) was not provided in the LERs. Additionally, no method to estimate the number of valve cycles was identified that would be defensible. Therefore, the demand count corresponds to the number of missions in which RCIC operated in the recirculation mode.

9. All of the FRC failures were recovered.

In calculating the failure probabilities for the individual failure modes, the operating experience data were analyzed and tested (statistically) to determine if significant variability was present in the data. All data were initially analyzed by plant, by year, and by source (i.e., unplanned and cyclic test demands). Each data set was modeled as a binomial distribution with confidence intervals based on sampling uncertainty. Various statistical tests (Fisher's exact test, Pearson chi-squared test, etc.) were then used to test the hypothesis that there is no difference between the types and sources of data.

Because of concerns about the appropriateness and power of the various statistical tests and an engineering belief that there are real differences between groups, an empirical Bayes method to model variation was attempted regardless of the results of the statistical tests for differences. The simple Bayes method was used if no empirical Bayes could be fitted. [For more information on this aspect of the data analysis, see Appendixes A and C (Sections A-2.1 and C-1.1)]. In the simple Bayes case, the uncertainty in the calculated failure rate is dominated by random or statistical uncertainty (also referred to as sampling uncertainty). The simple Bayes method essentially pools the data and treats this as a homogeneous population. If, on the other hand, an empirical Bayes distribution was fitted, then the uncertainty is dominated by the plant-to-plant (or year-to-year) variability. That is, the data were not pooled, and individual plant (or year)-specific failure probabilities were calculated based on the factor that produced the variability.

The failure to start mode was partitioned into two categories to allow the use of the cyclic test data along with the unplanned demand data in the evaluation of FTSO. The cyclic test data were not used to estimate the FTSV probability, because the injection valve is not tested under the same conditions seen during unplanned demands. Section 4 of this report contains the engineering insights into this aspect of the data. Data from both cyclic tests and unplanned demands were used in estimating the FTR probability.

There is no estimate for the probability of not recovering FTSV failures. This event was left as an undeveloped event since no failures and hence no demands for recovery were observed. Since FTSO and FTSV involve different components of the system, it was deemed inappropriate to consider FTSV recovery the same as FTSO and apply the recovery probability for FTSO at a higher level (i.e., FTS) in the fault tree.

For the MOOS failure mode, pooling of the unplanned demand data with cyclic test data was not done, since plant personnel are unlikely to initiate an RCIC system test if the RCIC system is out of service for maintenance. Only MOOS events that resulted from an unplanned demand while the plant was not shut down are included in the unreliability estimates. No statistical plant-to-plant variability exists for the MOOS failure mode.

3.1.1 RCIC Unreliability For a Short Term Mission

The unreliability of the RCIC system for conditions requiring short term operation of RCIC was calculated using the system fault tree model shown in Figure 3. This particular mission is for conditions that do not rely solely on RCIC for maintenance of RPV water level. Typically, these events are associated with conditions that result in a reactor trip with feedwater being available as the primary source of water for RPV. Therefore, RCIC is not needed for RPV water level maintenance. Transients of this nature where RCIC is initially demanded, with feedwater available to restore RPV water level, generally are of very short duration. For these transients, RCIC is started and runs for a short period of time before it is either automatically or manually stopped. Based on the operating data, the time of RCIC operation for these types

of missions is generally in the 5 to 10 minute range and is less than 15 minutes. These types of demands are referred to as *short term*.

Estimates of RCIC unreliability for short term operation were calculated from the operating experience data. The following failure modes were used in estimating RCIC system unreliability for the short term mission:

- Maintenance-out-of-service (MOOS)
- Failure To Start—Other than the Injection Valve (FTSO)
- Failure To Start—Injection Valve (FTSV)
- Failure to Recover from FTSO (FRFTS)
- Failure To Run—short term (FTR-ST)

Table 3 contains the failure probabilities and associated uncertainty intervals calculated from the operating experience data for each of the failure modes for the short term mission of the RCIC system. The cyclic test data are not included for estimating the FTR-ST probability, since the run times associated with the cyclic tests are greater than the typical run time for the short term mission. Table 4 contains the estimated RCIC unreliability and associated uncertainty intervals resulting from quantifying the fault tree depicted in Figure 3 and using the operating experience estimates in Table 3. For the purposes of quantifying the fault tree, the following conditions were assumed:

- A demand to inject coolant to the RPV is received by the RCIC system.
- RCIC is required to restore RPV water level.
- Feedwater and/or other high pressure makeup systems are also available to restore and maintain RPV water level.
- RCIC operation is required only for the short term (i.e., less than 15 minutes).

The recovery probability for FTSO is included in the overall estimate of RCIC unreliability for the system short term mission, since the operating experience data show the RCIC system was recovered from certain failures. However, this estimate is calculated from sparse data. The non-recovery probabilities calculated tend to be relatively high compared to the recovery probabilities stated in the PRA/IPEs. With only one or two opportunities, the current operating data give little evidence to support a lower failure to recover probability. In addition, more opportunities are needed in the operating data to reduce the uncertainty associated with the failure to recover estimates. No recovery probability is calculated for a failure mode if no failures were observed for the particular failure mode.

Also included in Table 4 are the unreliabilities for each of the failure modes that contribute to the overall unreliability for short term operation, along with their percentage contribution. The unreliability estimates include the failure-to-recover probability. The mean estimate of RCIC unreliability without considering recovery is 0.06 for short term missions. The effect of recovery on the estimate of RCIC unreliability is about a factor of 1.5 improvement.

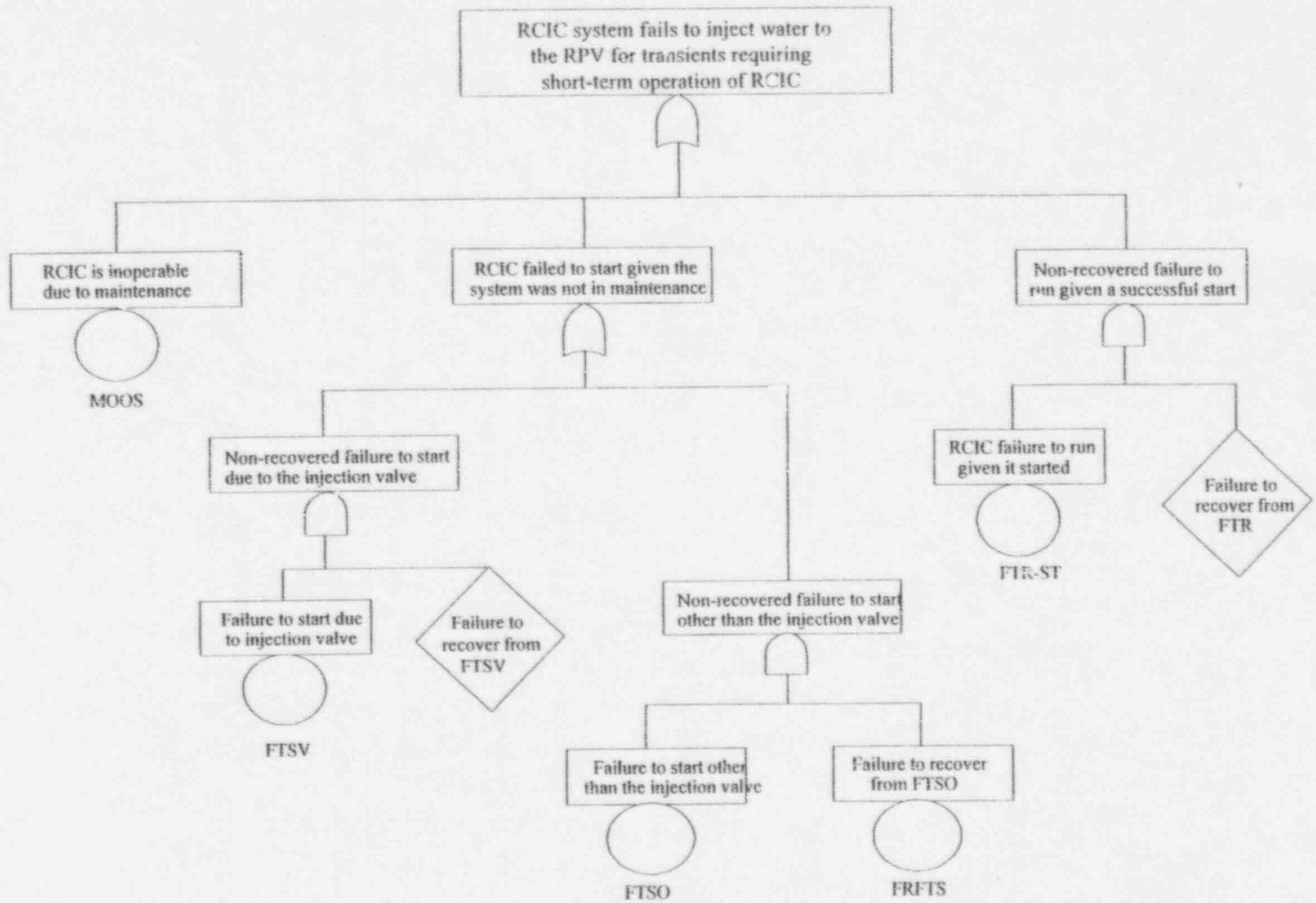


Figure 3. Unreliability model of RCIC system for a short term mission.

Table 3. RCIC failure probability data, by failure mode, for short term missions.

Failure mode	f[a]	d[a]	Modeled variation	Distribution	Bayes mean and 90% interval[b]
Maintenance-out-of-service (MOOS)	1	133	Sampling	Beta (1.5, 132.5)	(1.3F-3, 1.1E-2, 2.9E-2)
Failure to start, other than the injection valve (FTSO)	10	274	Plant-to-plant	Beta (0.7, 17.5)	(5.4E-4, 3.7E-2, 1.2E-1)
Failure to start, injection valve (FTSV)	0	128	Sampling	Beta (0.5, 128.5)	(1.5E-5, 3.9E-3, 1.5E-2)
Failure to recover from FTSO (FRFTS)	4	7	Sampling	Beta (4.5, 3.5)	(2.8E-1, 5.6E-1, 8.3E-1)
Failure to run-short term (FTR-ST)	0	56	Sampling	Beta (0.5, 56.5)	(3.5E-5, 8.8E-3, 3.4E-2)

a. f, failures; d, demands

b. The values in parenthesis are the 5% uncertainty limit, the Bayes mean, and the 95% uncertainty limit.

Table 4. Estimates of RCIC unreliability for short term operation.

Contributor	Unreliability due to contributor	Percentage contribution
MOOS	0.011	24
FTSV	0.004	9
FTSO*FRFTS	0.021	47
FTR-ST	0.009	20
RCIC Unreliability (mean)	0.044	
90% Uncertainty Interval	0.0082, 0.10	

3.1.2 RCIC Unreliability For a Long Term Mission

The unreliability of the RCIC system for conditions requiring long term operation of RCIC was calculated using the system fault tree model shown in Figure 4. The model reflects the operating mission of RCIC for conditions that rely on RCIC for maintenance of RPV water level. Typically, transients associated with these conditions result from a reactor trip and feedwater being unavailable as the primary source of water for the RPV. Therefore, RCIC is needed for RPV water level maintenance. Transients of this nature where RCIC is initially demanded, with feedwater unavailable to restore water RPV level, generally are of longer duration than the short term mission discussed in the previous section. For these transients, RCIC is started/restarted and runs for the duration of the event. Based on the operating data, the time of RCIC operation for transients of this nature exceeds 15 minutes. These types of demands are referred to as *long term* missions.

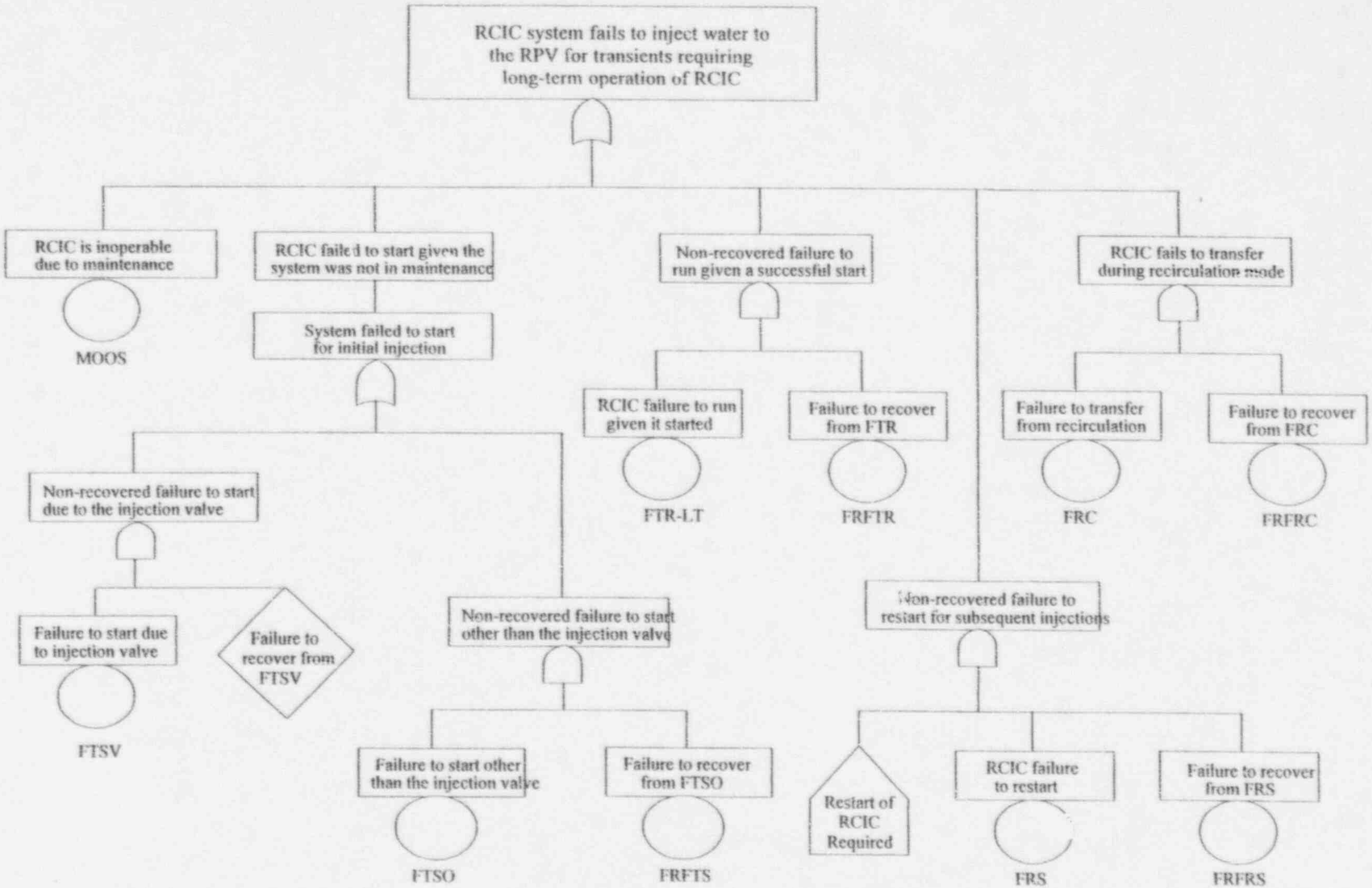


Figure 4. Unreliability model of RCIC system for a long term mission.

Estimates of RCIC unreliability for long term operation were calculated from the operating experience data. The following failure modes were used in estimating RCIC system unreliability for the long term mission:

- Maintenance-out-of-service (MOOS)
- Failure To Start—Other than the Injection Valve (FTSO)
- Failure To Start—Injection Valve (FTSV)
- Failure to Recover from FTSO (FRFTS)
- Failure To Run—long term (FTR-LT)
- Failure to Recover from FTR (FRFTR)
- Failure to Restart (FRS-LT)
- Failure to Recover from FRS (FRFRS)
- Failure to Transfer During Recirculation (FRC-LT)
- Failure to Recover from FRC (FRFRC)

Table 5 contains the failure probabilities and associated uncertainty intervals calculated from the operating experience data for the long term mission of the RCIC system. The FTR-LT probability in Table 5 reflects the failures that occurred for the long term missions, which includes the cyclic test data. In addition to the failure mode probabilities tabulated in Table 3, an additional probability was estimated to account for the restart contribution to the long term mission. This adjustment normalizes those events that entered into the restart mode to the number of long term events. This was done since only about 25% of the long term missions resulted in the restart mode. Table 6 contains the estimated RCIC unreliability and associated uncertainty intervals resulting from quantifying the fault tree depicted in Figure 4 and using the operating experience estimates in Table 5. For the purposes of quantifying the fault tree, the following conditions were assumed:

- A demand to inject coolant to the RPV is received by the RCIC system.
- RCIC is required to restore RPV water level.
- Feedwater and/or other high pressure makeup systems are not available to restore and maintain RPV water level.
- Restart of the RCIC system is required for subsequent level restoration.
- RCIC operation is required for long term maintenance of RPV water level.
- RCIC operates in the recirculation mode following restart.

Also included in Table 6 are the unreliabilities for each of the failure modes that contribute to the overall unreliability for the long term operation along with their percentage contribution. The estimates include recovery. The mean estimate of RCIC unreliability without considering recovery is 0.16 for the long term missions. The effect of recovery on the estimate of RCIC unreliability is about a factor of two improvement.

The plant-specific unreliability estimates for the short term and long term missions of RCIC are shown in Figure 5. The calculations for the results in Figure 5 are provided in Appendix C.

Table 5. RCIC failure probability data, by failure mode, for long term missions.

Failure mode	f[a]	d[a]	Modeled variation	Distribution	Bayes mean and 90% interval[b]
Maintenance-out-of-service (MOOS)[c]	1	133	Sampling	Beta (1.5, 132.5)	(1.3E-3, 1.1E-2, 2.9E-2)
Failure to start, other than the injection valve (FTSO)[c]	10	274	Plant-to-plant	Beta (0.7, 17.5)	(5.4E-4, 3.7E-2, 1.2E-1)
Failure to start, injection valve (FTSV)[c]	0	128	Sampling	Beta (0.5, 128.5)	(1.5E-5, 3.9E-3, 1.5E-2)
Failure to recover from FTSO (FRFTS)[c]	4	7	Sampling	Beta (4.5, 3.5)	(2.8E-1, 5.6E-1, 8.3E-1)
Failure to run—long term (FTR-LT)	2	213	Sampling	Beta (2.5, 211.5)	(2.7E-3, 1.2E-2, 2.6E-2)
Failure to recover from FTR (FRFTR)	1	2	Sampling	Beta (1.5, 1.5)	(9.7E-2, 5.0E-1, 9.0E-1)
Probability restart required (IFRS)	18[d]	72	Plant-to-plant	Beta (0.9, 2.5)	(1.7E-2, 2.6E-1, 6.8E-1)
Failure to restart(FRS-LT)	4	18	Sampling	Beta (4.5, 14.5)	(9.8E-2, 2.4E-1, 4.1E-1)
Failure to recover from FRS (FRFRS)	2	4	Sampling	Beta (2.5, 2.5)	(1.7E-1, 5.0E-1, 8.4E-1)
Failure to transfer during recirculation (FRC-LT)	2	72	Sampling	Beta (2.5, 70.5)	(8.0E-3, 3.4E-2, 7.5E-2)
Failure to recover from FRC (FRFRC)	0	2	Sampling	Beta (0.5, 2.5)	(8.7E-4, 1.7E-1, 5.7E-1)

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

b. The values in parenthesis are the 5% uncertainty limit, the Bayes mean, and the 95% uncertainty limit.

c. These failure modes are identical to those for the short term mission and are taken directly from Table 3.

d. This entry corresponds to the number of long term unplanned missions that identified at least one restart of RCIC.

Table 6. Estimates of RCIC unreliability for long term operation.

Contributor	Unreliability due to contributor	Percentage contribution
MOOS	0.011	14
FTSV	0.004	5
FTSO*FRFTS	0.021	27
FTR-LT*FRFTR	0.006	8
IFRS*FRS-LT*FRFRS	0.031	39
FRC-LT*FRFRC	0.006	8
RCIC Unreliability (mean)	0.076	
90% Uncertainty Interval	0.02, 0.16	

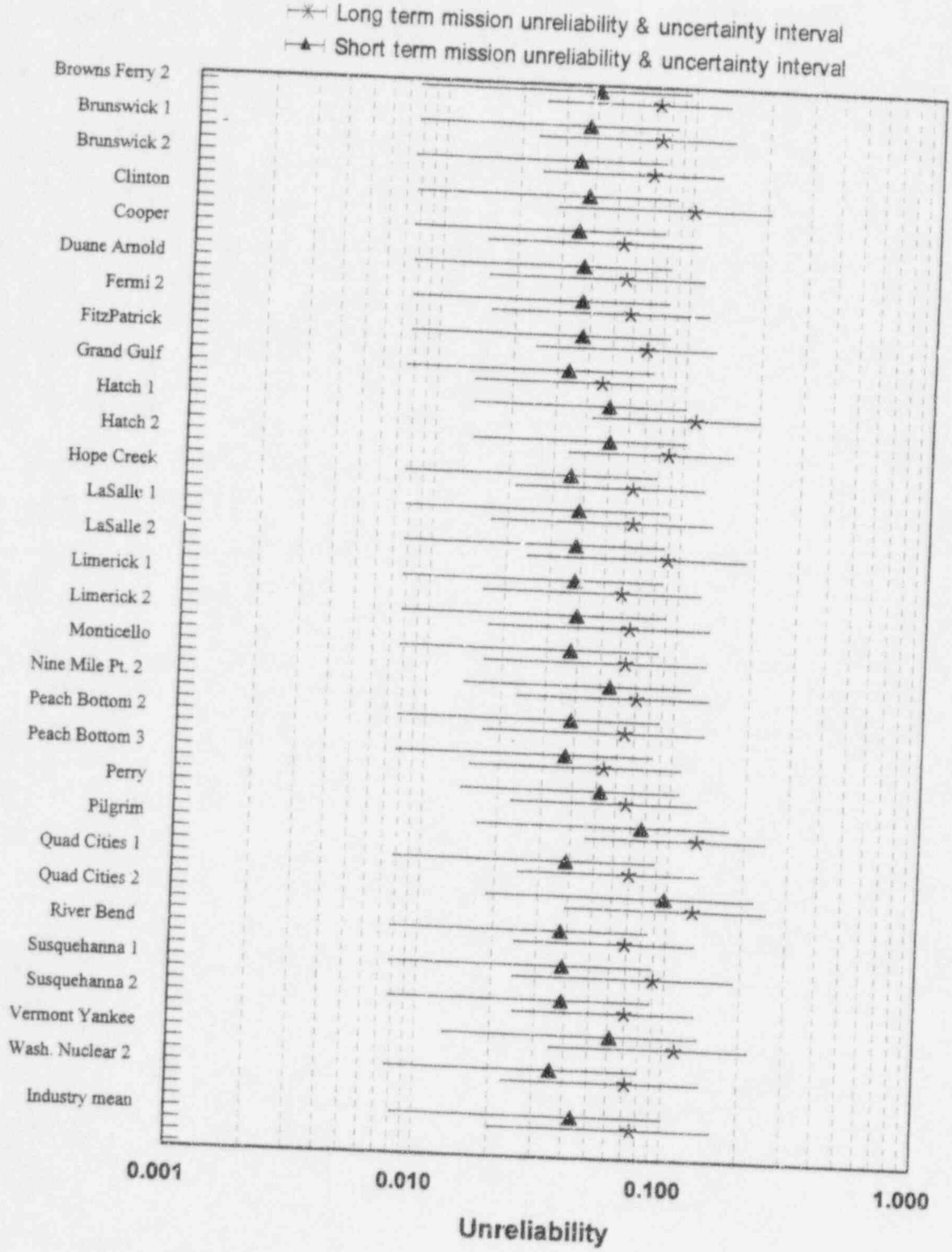


Figure 5. Plant-specific estimates of RCIC system unreliability for short and long term missions calculated from the operating experience data.

3.1.3 Investigation of Possible Trends

Unreliability for short term missions on a per year basis was calculated to reveal if any overall trend exists within the industry. Figure 6 displays the unreliability trend of the RCIC system for a short term mission by calendar year. The unreliability for each calendar year was obtained using the constrained noninformative prior for each failure mode pooled across plants for each calendar year as described in Appendix C. The calculated unreliabilities include operator action to recover from failures. The slope of the trend line is statistically significant (P-value = 0.03). A statistical analysis of the unreliability for long term missions per calendar year (not shown) revealed no trend (P-value = 0.86).

To determine if plant aging (i.e., older plants versus newer plants) has an effect on RCIC system performance, plant-specific unreliability calculated for a short term mission was plotted against the plant low-power license date. The plot is shown in Figure 7, with 90% uncertainty bars plotted vertically. As with the trend in year, constrained noninformative priors were used in processing the data. 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 = 0.15). The corresponding trend of long term unreliability (not shown) identified no trend (P-value = 0.23).

3.2 Comparison to PRA/IPEs

The fault tree model shown in Figure 4 provided the logic for calculating RCIC system unreliability based on the postulated conditions stated in the PRA/IPEs. The logic model also provided the template for mapping relevant PRA/IPE component failure probabilities into a RCIC system model. The mapping provides a relational structure for comparing PRA/IPE results to the various operating experience estimates. The component failure probabilities were taken from 21 PRA/IPEs (References 9 through 30) documenting 29 plants. Comparisons of estimates of RCIC system unreliability were made for all of the plants listed in Table 1, except Monticello (which did not report basic event data or system reliability data in their IPE).

To provide consistency in the comparisons of PRA/IPE results to the corresponding results of operating experience data, the contributions to the RCIC unreliability from support systems outside the RCIC boundary defined in Section 2.1.3 were also excluded from the PRA/IPE models. The recovery events FRFTS, FRFTR, FRFRS and FRFRC are included in the unreliability analysis of the operating experience data to provide a "best" estimate of unreliability. The recovery failure modes identified in the operating experience data are of such a nature that actual diagnosis and repair of the RCIC system is not required to make the system operational. Generally, the events listed in these categories require a restarting of the system if the automatic initiation circuitry did not start the system. Hence the term "best" is used to describe the estimates of RCIC unreliability with recovery included. PRA/IPEs may model this type of event at the system level. However, because of the summary nature of the information provided in many of the PRA/IPEs (e.g., the lack of information related to model/quantification assumptions) and the small contribution this type of recovery (i.e., recovery from an automatic initiation failure) has on the final estimate, these actions are not explicitly accounted for in the PRA/IPE results.

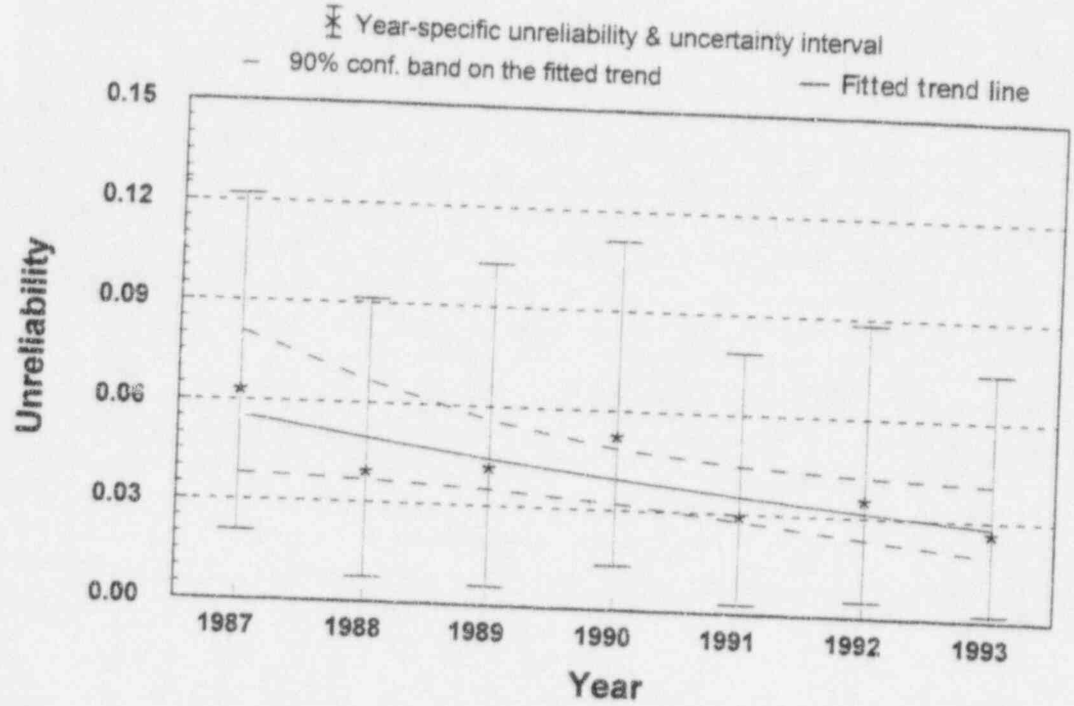


Figure 6. RCIC system unreliability (includes recovery) for a short term mission plotted against calendar year. The plotted trend is statistically significant (P-value = 0.03).

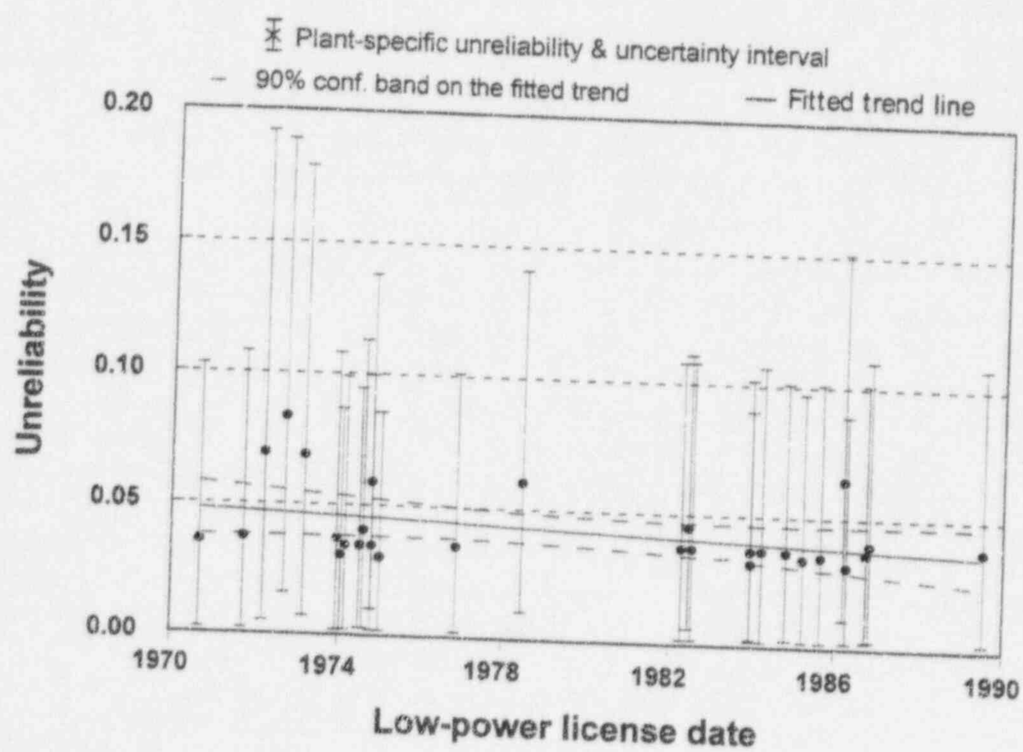


Figure 7. Plant-specific RCIC system unreliabilities (includes recovery) for a short term mission plotted against low-power license dates. The plotted trend indicates some increase in reliability (i.e., reduced unreliability) but it is not statistically significant (P-value = 0.15).

Other types of recovery modeled in PRA/IPEs involve actual diagnosis and repair or bypass of the components that experience a catastrophic failure. These types of recovery are generally modeled at the accident scenario level (i.e., accident sequence cut set), since diagnosis and repair of the failed equipment is required. Evaluating the potential for recovery of the various system failures identified in the accident sequence cut set provides for the optimum recovery strategy to be considered. This type of recovery is significantly different from the recovery (i.e., no repair required) failure modes identified in the operating experience data, where only the recovery requiring no repair is used.

In contrast to the short term and long term mission unreliability estimates calculated in Section 3.1, the failure probability estimates associated with the PRA mission for the FTR and FRC modes of RCIC operation were not calculated on a per demand basis. Hourly failure rates were used to quantify the probability of failure to run and the probability of failure to transfer in and out of the injection phase and recirculation mode. Hourly failure rates are typically used in PRA applications for the failure to run probability calculations. For the recirculation failure mode, it was not possible to estimate the number of demands (valve cycles). Therefore, the FRC calculation is based on hours of RCIC operation for the long term missions.

For the FTR and FRC calculations, the injection and recirculation run times stated in the LERs for the unplanned demands were used. Approximately half of the run times, however, were not specified in the LERs. The run times were separated into those known or believed to be greater than or equal to 15 minutes, called long, and those that were less than 15 minutes, called short. The 15 minute limit corresponds to the natural breakpoint identified in the data and also correlated to the short and long term operation regimes defined by the operating data. The short run times were applied just to the failure to run mode, and not to the recirculation failure mode, under the assumption that only the long term missions would use the RCIC recirculation mode. The long run times were applied to both the failure to run and failure to transfer during recirculation modes. For both sets of demands, an average run time was calculated based on the known run times. The duration of the unknown run times were approximated using these averages. This approach resulted in 0.06 hours per unspecified short run time and 2.5 hours per unspecified long run time.

A total of 179 unplanned demands (calculated from the 133 unplanned start demands and the 46 additional demands for restarts) were evaluated in the initial data set for the run time data. Of the total 179 demands, one was lost because of a MOOS and six were non-recovered failures to start or failures to restart. Table 7 provides a summary of all but one of the run times associated with the RCIC unplanned demands. The table accounts for 171 demands.

The single run time not included in Table 7 was an event with several restarts for which the total event time was known but some individual run times were not known. For this event, which included several short run times and one long run time, the single unknown long demand run time was estimated to be 3.6 hours (the difference between the total event time stated in the LER and the total of the estimated short run times). Including this event, the total long demand run time is estimated to be 208.3 hours.

Table 7. Run times (hours) estimated from the RCIC unplanned demands.

	Short run times (less than 15 minutes)			Long run times (at least 15 minutes)		
	Initial start	Restart	Total	Initial start	Restart	Total
Number known	38	4	42	35	10	45
Total known run time (hr)	2.2	0.4	2.6	68.1	45.6	113.7
Average known run time (hr)	0.06	0.09	0.06	1.9	4.6	2.5
Number unknown	28	20	48	27	9	36[a]
Projected total run time (hr)	3.9	2.1	5.5	120.6	86.7	204.7

a. Excluding a single long run time for which the total mission time was known.

One and one-half hours of running time were assumed for each cyclic test. The run time assumption is based on the information provided by a survey of INEL personnel (ex-plant operators, examiners, maintenance, etc.) who have plant experience or knowledge of the cyclic surveillance test for RCIC. This time was used only in estimating the failure rates for the failure to run mode. The 141 test demands resulted in 211.5 hours of run time. These test hours were not used for the failure during recirculation mode, since the cyclic tests do not exercise the injection valve under the stresses expected under transient/accident conditions.

Based on the above discussions, the run time used in calculating the FTR failure rate was estimated at 425.3 hours (i.e., short demands plus long demands plus test demands). The recirculation mode time was estimated at 208.3 hours.

The failure rate and probability estimates based on operating experience data that were used in the unreliability calculations are listed in Table 8. Plant-specific estimates were calculated using an empirical Bayes method for those failure modes identified with plant-to-plant variability. Appendix C contains the result of the plant-specific analysis. If no variability existed, the industry average probabilities (or rates where applicable) for the respective failure modes were applied to all plants.

3.2.1 Estimates of RCIC System Unreliability for PRA Comparisons

Table 9 contains the estimated RCIC unreliability and associated uncertainty intervals resulting from quantifying the fault tree using the operating experience estimates in Table 8. For the purposes of quantifying the fault tree, the following conditions were assumed:

- A demand to inject coolant to the RPV is received by the RCIC system.
- RCIC is required to restore RPV water level.
- The RCIC system is required to be operational for 24 hours.
- RCIC is secured at the predetermined high level trip.
- Feedwater and/or other high pressure makeup systems are not available to restore RPV water level.
- One restart of the RCIC system is required for subsequent level restoration.
- RCIC operates in the recirculation mode for the remainder of the mission following restart.
- The FTR and FRC are calculated using an hourly failure rate and assuming a mission time of 24 hours.

Also included in Table 9 are the unreliabilities for failure combinations that contribute to the system unreliability, along with their percentage contribution. The unreliability estimate includes the failure to recover probabilities. The corresponding mean estimate and associated 90% uncertainty interval of RCIC unreliability without considering recovery are 0.25, 0.43, 0.62. The effect of recovery on the estimate of RCIC unreliability is about a factor of 2.4 improvement.

Table 8. RCIC failure probability data, by failure mode, normalized for comparison to PRA/IPE information.

Failure mode	f[a]	d[a]	Modeled variation	Distribution	Bayes mean and 90% interval[b]
Maintenance-out-of-service (MOOS)	1	133	Sampling	Beta(1.5, 132.5)	(1.3E-3, 1.1E-2, 2.9E-2)
Failure to start, other than the injection valve (FTSO)	10	274	Plant-to-plant	Beta(0.7, 17.5)	(5.4E-4, 3.7E-2, 1.2E-1)
Failure to start, injection valve (FTSV)	0	128	Sampling	Beta(0.5, 128.5)	(1.5E-5, 3.9E-3, 1.5E-2)
Failure to recover from FTSO (FRFTS)	4	7	Sampling	Beta(4.5, 3.5)	(2.8E-1, 5.6E-1, 8.3E-1)
Failure to run (FTR)	2	425[c]	Sampling	Gamma(2.5, 25.3) Beta(2.5, 17.0)	(1.4E-3, 5.9E-3, 1.3E-2)[d] (3.2E-2, 1.3E-1, 2.7E-1)
Failure to recover from FTR (FRFTR)	1	2	Sampling	Beta(1.5, 1.5)	(9.7E-2, 5.0E-1, 9.0E-1)
Failure to restart (FRS)	4	46	Sampling	Beta(4.5, 42.5)	(3.7E-2, 9.6E-2, 1.7E-1)
Failure to recover from FRS (FRFRS)	2	4	Sampling	Beta(2.5, 2.5)	(1.7E-1, 5.0E-1, 8.4E-1)
Failure to transfer during recirculation (FRC)	2	208[c]	Sampling	Gamma(2.5, 208.3) Beta(2.5, 9.3)	(2.8E-3, 1.2E-2, 2.7E-2)[d] (6.4E-2, 2.4E-1, 4.7E-1)
Failure to recover from FRC (FRFRC)	0	2	Sampling	Beta(0.5, 2.5)	(8.7E-4, 1.7E-1, 5.7E-1)

a. f, failures; d, demands

b. The values in parenthesis are the 5% uncertainty limit, the Bayes mean, and the 95% uncertainty limit.

c. This entry is the estimated hours of operation while in this mode.

d. The values for the Gamma represent hourly failure rates, whereas the fitted Beta distribution is the failure probability based on a 24-hour mission time.

Table 9. Estimates of RCIC unreliability (with recovery and a 24-hour mission time) based on the operating experience data.

Contributor	Unreliability due to contributor	Percentage contribution
MOOS	0.011	6
FTSV	0.004	2
FTSO*FRFTS	0.021	11
FTR*FRFTR	0.064	34
FRS*FRFRS	0.048	26
FRC*FRFRC	0.04	21
RCIC Unreliability (mean)	0.18	
90% Uncertainty Interval	0.068, 0.31	

3.3 PRA Insights

In addition to the overall RCIC system unreliability comparisons, the component failure probabilities from the PRA/IPEs were grouped into the same system failure mode categories defined for the analysis of the operating experience data. The component failure modes identified in the PRA/IPEs were grouped according to the following breakdown:

- 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 lubrication oil pump to start.
- FTSV: Failure of the injection valve to open.
- FTR: TDP failure to run, lubrication oil cooling water supply valve fails to open, and the minimum flow valve fails to close.
- MOOS: RCIC system maintenance unavailability.

The majority of the PRA/IPEs stated that the failure of the minimum flow control valve to close would not affect rated flow to the reactor vessel either because of the small size of the line and/or because of installed flow limiting orifices. Therefore, for these plants, the minimum flow valve failing to close was not included in the PRA/IPE unreliability estimate.

While there might be additional component failure modes in a given PRA/IPE for the RCIC system, the effect of not including these in the system failure probability estimate is judged to be small. Additionally, about 30% of the PRA/IPEs mention that either restart or recirculation mode of the RCIC system was modeled. For these plants the system unreliability was estimated with the restart operation assumed. However, because of the summary nature of the IPE submittals, insufficient information was available to reproduce that portion of the RCIC system model dealing with the recirculation mode of operation. The failure modes FRS and FRC were not included for those plants not identifying these RCIC modes of operation in the PRA/IPE. The FRS and FRC failure modes, although not explicitly modeled in a majority of the PRA/IPEs, are discussed separately in section 3.3.4.

The plant-specific estimates of RCIC unreliability based on operating experience data and the approximate PRA/IPE estimates are plotted in Figure 8 for comparison. The PRA/IPE estimates of RCIC unreliability range from 0.03 to 0.54, with an average unreliability of 0.12. The unreliability estimates calculated from the operating experience data range from 0.17 to 0.22. The PRA/IPE estimates were calculated according to the mission times stated in the respective reports. These mission times range from 6 hours to 24 hours with the predominant run time being 24 hours. The plant-specific estimates of RCIC unreliability are calculated to the mission times stated in the PRA/IPEs. A mission time of 24 hours is used except for the following: 6 hours - Browns Ferry 2 and Nine Mile Pt. 2; 8 hours - Cooper and LaSalle 1 and 2; 10 hours - Peach Bottom 2 and 3; 20 hours - Limerick 1 and 2. Generally, the RCIC system unreliability estimates (i.e., means) approximated from the PRA/IPE are slightly lower than the estimates based on operating experience data but well within the uncertainty bounds. However, the PRA/IPE estimates for several plants fall outside the uncertainty interval.

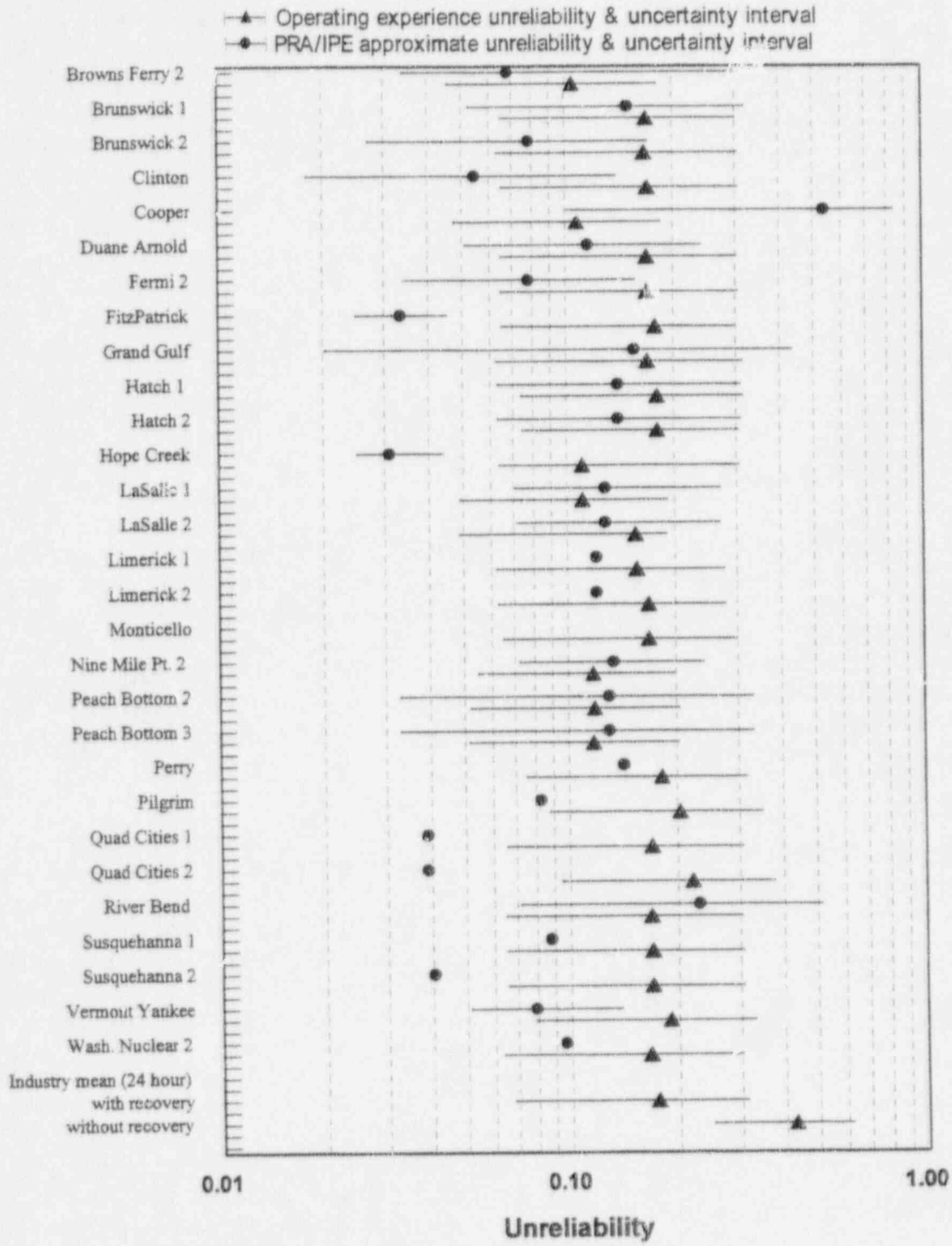


Figure 8. Plot of the PRA/IPE and operating experience estimates of RCIC system unreliability and uncertainties with recovery calculated for the missions postulated in the PRA/IPEs. (For some plants the information documented in the PRA/IPEs was insufficient for generating uncertainty intervals.)

The Cooper IPE reported a mission time of 8 hours with an unreliability estimate of 0.54. The operating experience estimate and associated uncertainty interval for Cooper based on an 8-hour mission time with recovery is 0.05, 0.11, 0.19. The Cooper IPE estimate is about a factor of 3 higher than the 8-hour upper 95% uncertainty bound (0.19). The main reason for the large Cooper estimate is the hourly failure rate (8.7E-2 per hour) for FTR used in the IPE. The Cooper IPE estimate of FTR is stated as being based on plant-specific information and not generic data. No additional information is provided in the Cooper IPE to explain the high failure rate for the RCIC pump

The plants identified with a PRA/IPE-based unreliability below the 5% uncertainty interval indicated by the plant operating data used hourly failure rates for the turbine-driven pump that were at least an order-of-magnitude lower than the average hourly rate calculated from the PRA/IPE population. The hourly rates for these plants ranged from about 2.2E-4 to 3.8E-5 per hour. The average hourly rate calculated from the PRA/IPE information is 5.1E-3 per hour. The mean hourly rate calculated from the operating experience data is 5.9E-3 per hour. Further insights on the failure to run mode are provided in Section 3.3.2.

3.3.1 Failure to Start

As stated earlier, failure to start was subdivided into two failure modes to use as much of the unplanned demand and cyclic test data as possible and to provide additional insights into the reliability of the RCIC system. Figure 9 is a plot of the probability of failure to start due to equipment other than the injection valve (FTSO) for both the operating experience and the PRA/IPEs data. The probability of FTSO for all of the PRA/IPEs lies within the uncertainty bounds generated from the operating experience data. The PRA/IPE estimates (based on averages) of FTSO have a tendency to be slightly higher than the mean probability based on the operating experience data. The average FTSO probability for the PRA/IPEs is 3.6E-2 per demand, whereas the operating experience mean is 3.3E-2 per demand.

The operating experience data used for estimating the FTSO probability includes a failure (see Appendix B, Table B-7, Perry LER number 44087012) that led to a design change, already in practice at many plants, that should prevent this particular mode of valve failure from recurring. There are merits for including as well as excluding this failure from the FTSO operating experience data. However, for the sake of completeness, the failure is included. The effect of this failure on the RCIC estimates is negligible. The FTSO probability without the failure included is 3.3E-2 per demand compared to 3.7E-2 with the failure included. The RCIC unreliability estimate of 1.8E-1 is not affected by including or excluding this failure. The effects of including this failure at the plant-specific level (i.e., Perry estimates) is similar to those mentioned above (i.e., negligible).

The Quad Cities 2 estimate for FTSO (0.14) calculated from the operating experience data falls outside the 95% uncertainty limit (0.12) for the overall population. Quad Cities 2 accounted for three of the ten failures for FTSO and nine of the 274 demands. Although the estimated mean for FTSO for Quad Cities 2 is greater than the 95th percentile of the generic distribution estimated for FTSO, the finding is not statistically significant (P-value = 0.40). Further insights into the statistical analysis of FTSO are provided in Appendix C (Section C-1.1.2).

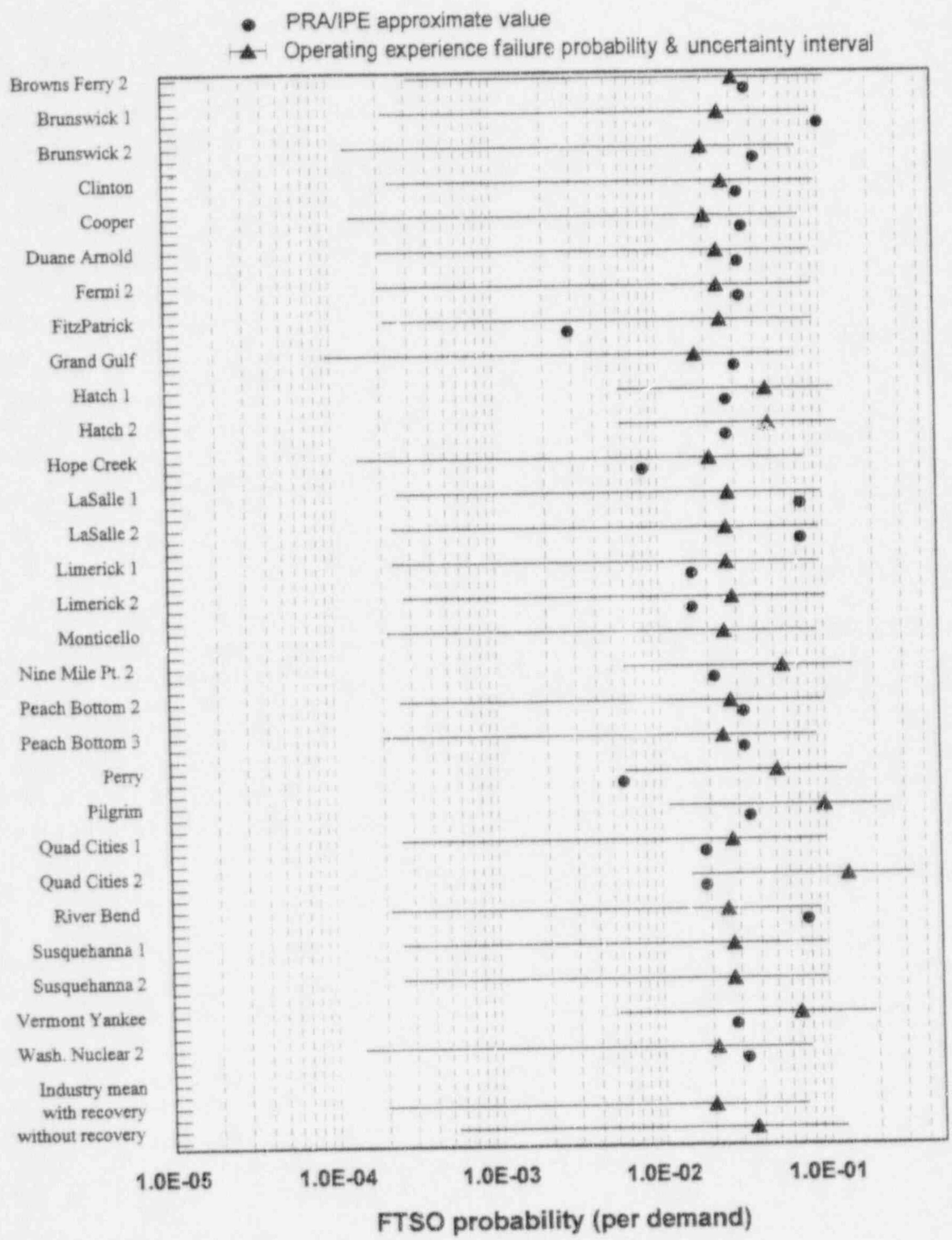


Figure 9. Plot of the PRA/IPE and operating experience estimates of the failure probability for failure to start (other than the injection valve).

For the FTSV failure mode, the average of the PRA/IPE values is 6.5E-3 per demand compared to the mean estimate of 3.9E-3 per demand calculated from the operating experience data The uncertainty in the operating experience data is dominated by sampling rather than plant-to-plant variability. Therefore, the industry average estimate is applicable to all plants. Generally, the failure to start due to the injection valve failing to open (FTSV) estimates for the PRA/IPEs fall within the 90% uncertainty interval of the operating experience estimate. Only the LaSalle PRA/IPE had an FTSV estimate (0.045) that fell outside the upper 95% uncertainty bound (0.015). The LaSalle estimate is reported as being calculated from generic data and not plant-specific information but uses a very detailed fault tree modeling individual relays. Figure 10 displays the PRA/IPE and the operating experience estimates for FTSV. The operating experience estimate with recovery for FTSV is not included, since there were no FTSV failures and therefore no opportunities for recovery.

For the Susquehanna plants, it was not possible to break down the failure to start into FTSO and FTSV, because there was not enough detail in the PRA/IPE. The failure to start probabilities reported for Susquehanna 1 and 2 are 6.3E-2 and 9.8E-3 per demand, respectively. No probabilities are entered for these two plants in the FTSO and FTSV plots.

3.3.2 Failure to Run

Failure to run is the largest contributor to RCIC unreliability according to the operating experience data. To allow comparisons to be made independent of the assumed mission times, estimates of hourly failure rates are provided in Figure 11. The hourly failure rates for the PRA/IPEs are those reported for the turbine-driven pump failure to run. Approximately 39% of the PRA/IPE estimates fall within the 90% uncertainty interval of the operating experience data (without recovery). The majority, approximately 57%, use estimates that fall outside the 5% lower bound. However, the average of the PRA/IPE values does not differ greatly from the mean estimate calculated from the operating experience data, 5.1E-3 versus 5.9E-3 per hour, respectively. Cooper was the only IPE that used an hourly failure rate estimate that was greater than the 95% uncertainty limit of the operating experience estimate.

A possible explanation for the low PRA/IPE hourly rates is the use of generic pump failure-to-run data contained in sources such as the Accident Sequence Evaluation Program (ASEP) database (a commonly used generic database). The ASEP estimates are based on plant operational hours, not pump operating hours. Hence, the ASEP estimates represent a standby hourly failure rate. For the purposes of estimating unreliability, the failure rate of interest is an operating failure rate. The Peach Bottom PRA recalculated the generic ASEP FTR based on actual pump run time. The resulting estimate, normalized to an operating hourly failure rate, is 5.3E-3 per hour. The Peach Bottom updated estimate is approximately the same as the mean estimate calculated from the operating experience data.

Another issue to note when comparing PRA/IPE FTR estimates with operating experience data is the influence of unknown run times identified in the operating experience data. To use the operating experience data completely, the average of the known run times was assumed for the unknown times. The effect of substituting the average of the known times for the unknown times on the hourly estimate has not been determined. The uncertainty associated with this is not accounted for in the estimation process but is not expected to significantly broaden the uncertainty intervals. Further information on the statistical treatment of the FTR data can be found in Appendix C.

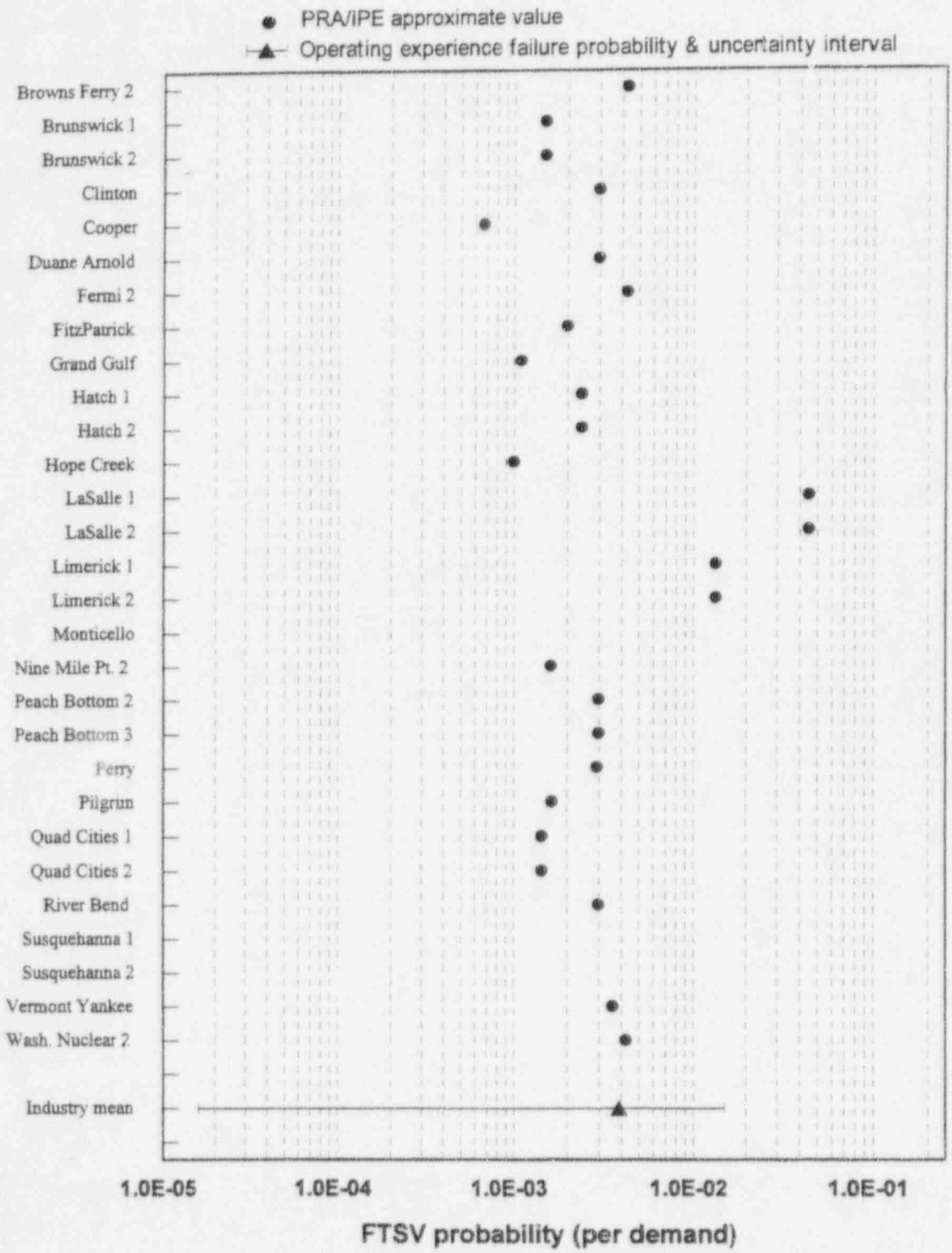


Figure 10. Plot of the PRA/IPE and operating experience estimates of the failure probability for failure to start due to injection valve. No plant-to-plant variation was observed in operating experience data, so the industry-wide mean applies to all plants.

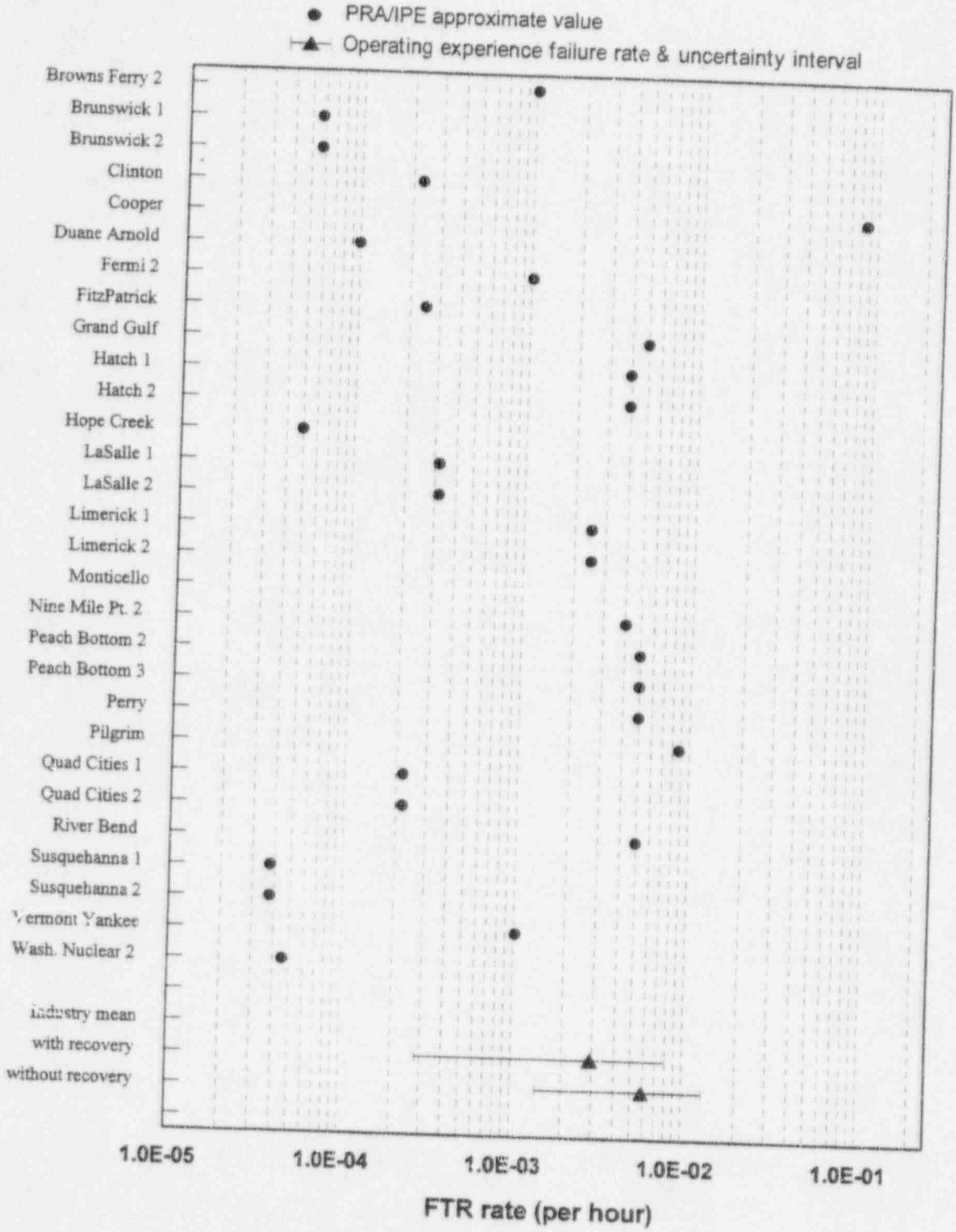


Figure 11. Plot of the PRA/IPE and operating experience estimates of the fail-to-run hourly failure rate. No plant-to-plant variation was observed in the operating experience data, so the industry-wide mean applies to all plants.

3.3.3 Maintenance-out-of-service

The MOOS contribution to the total RCIC unreliability is about 6% (calculated on a 24-hour mission time and based on operating experience data), compared to the 18% contribution estimated from the PRA/IPEs. The average MOOS probability for the PRA/IPEs is 2.1E-2 per demand, whereas the operating experience mean is 1.1E-2 per demand. Several of the PRA/IPEs have MOOS being a major contributor to RCIC system unreliability. However, the total reliability for the RCIC system at these plants is better than those at the other plants.

A possible explanation for the larger contribution, based on PRA/IPE estimates, may be the fact that RCIC is not a designated ECCS system. The technical specifications for RCIC are not as restrictive when considering the limiting condition of operation for the RCIC system as compared to an ECCS system, such as HPCI. Another reason may be due to the different methods used to calculate the PRA/IPE and operating experience estimates. In this study, maintenance failures and demands were based only on instances when the RCIC system was required to inject water into the reactor (i.e., a reliability parameter.) Risk analyses generally account for the MOOS probability as an unavailability estimate (i.e., fraction of RCIC down time compared to total plant operating time). In theory (i.e., infinitely large sample) these two estimates should be equivalent. For this reason, the reader is cautioned when making absolute comparisons of the PRA/IPE and operating experience MOOS estimates.

Figure 12 plots the PRA/IPE estimates and the mean estimate and associated uncertainty calculated from the operating experience data. The range of MOOS estimates found in the PRA/IPEs is approximately 4.2E-4 to 5.8E-2 per demand. Comparing this range of values to the uncertainty interval for the MOOS failure probability reveals one plant lying below the lower 5% uncertainty bound. The probability of MOOS for this plant is a factor of 50 lower than the PRA/IPE average for MOOS. Nine PRA/IPEs used a mean probability of MOOS that was greater than the upper 95% uncertainty bound estimated from the operating experience data. The River Bend IPE reported the largest MOOS failure probability. However, the River Bend MOOS contribution (25%) to the RCIC system failure probability compares favorably to the MOOS contribution (27%) based on operating experience data.

3.3.4 Restart Failure and Failure to Transfer During Recirculation

Extracting the corresponding data from the PRA/IPEs to make comparisons to the FRS and FRC failure modes was not possible for most plants, because of the summary nature (i.e., lack of details) of the PRA/IPEs. For these reasons, the focus of the RCIC restart/recirculation discussion is based primarily on the estimates for FRS and FRC derived from the operating experience data.

Not all plants entered into the restart mode during a long term operational mission of the RCIC system. Approximately 50% of the plants (11 of 23 plants) identified restarts of the RCIC in the LER text. Approximately 25% (18 of 72 long term missions) of the RCIC system initiations resulted in entering the restart mode of operation. Based on the restart information contained in the LERs, the RCIC system was restarted 46 times.

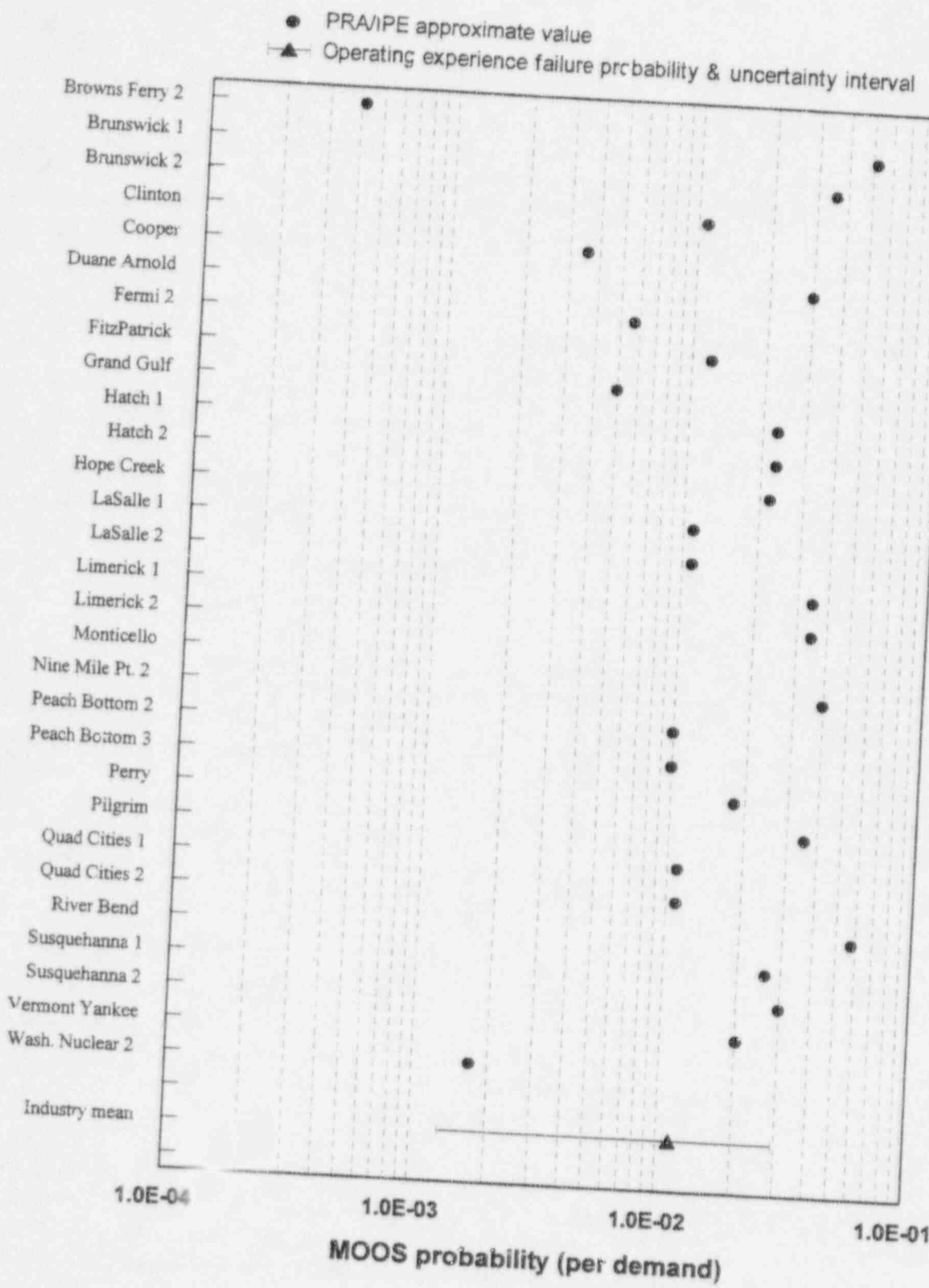


Figure 12. Plot of the PRA/IPE and operating experience estimates of the failure probability for maintenance-out-of-service failures. No plant-to-plant variation was observed in the operating experience data, so the industry-wide mean applies to all plants.

Estimates of the failure probability for FRC and associated 90% uncertainty bounds calculated from the operating experience data are 2.8E-3, 1.2E-2, and 2.7E-2 per hour. The estimates are expressed in hours because the number of cycles would be expected to increase as system operating time (i.e., recirculation phase) increases, and there was no way to count the number of valve cycles during this mode of operation.

However, two insights were gained as a result of reviewing the PRA/IPEs for the relevant information on RCIC system unreliability and associated failure data. First, it was found that most of the PRA/IPEs do not model the RCIC system in the way it is observed to be operated based on the operating experience data. Specifically, the maintenance of level following initial injection by either restart and/or recirculation, which places extra demands on the hardware and operators, is generally not modeled. Collectively, FRS and FRC modes (operating experience data with recovery) contribute approximately 50% to RCIC unreliability for a postulated PRA mission. Based on the limited PRA/IPE information, these two modes were either not modeled, or if modeled, were not identified as major failure modes of RCIC operation. Only 8 of the 29 PRA/IPEs mentioned restart and/or recirculation modes as phases of RCIC operation. Further, for the PRA/IPEs identifying these modes, no details on the quantification of the failures modes were provided. For the purposes of this study, the PRA/IPE results displayed are calculated assuming one restart and no recirculation. Second, for the PRA/IPEs that model the system with restart and/or recirculation mode of RCIC, the component failure probabilities assigned to these modes of operation appear to be optimistic compared to the estimates calculated from the operating experience data. For example, the initial failure to start (other than the injection valve) probabilities and the restart failure probabilities differ from each other by about a factor of 2.6, based on the operating experience data. However, the PRA/IPEs appear to use the same component failure probabilities for restart as for initial start. As shown in Table 9, the restart contribution to overall unreliability is a factor of 2 greater than the FTSO contribution, 26% versus 11%, respectively. Statistical analysis of the FTSO data (7 failures in 132 demands) and FRS data (4 failures in 46 demands) identified no statistical difference (P-value = 0.41) between the two failure modes; however, the FTSO and FRS data sets were not pooled, because from an engineering perspective, there is a difference between a cold start and a hot-quick start of the system.

4. ENGINEERING ANALYSIS OF THE PLANT OPERATING DATA

This section documents the results of an engineering evaluation of the RCIC system operational data derived from LERs. The objective of this evaluation was to analyze the data and provide insights into the performance of the RCIC system. Unlike the risk assessment provided in Section 3, for this evaluation all LERs submitted during the evaluation period and all the Accident Sequence Precursor (ASP) events that mentioned the RCIC system were considered; no data were excluded.

The engineering data analysis provides qualitative insights into the performance of the RCIC system throughout the industry and on a plant-specific basis. These qualitative insights characterize the factors contributing to the quantitative estimates of RCIC reliability presented previously in Section 3. The reader is cautioned when comparing the individual plant data to the unreliability estimates provided in Section 3. A plant-specific estimate derived solely from the failure data at a particular plant may result in a different estimate than one derived from the population as a whole, especially when the data are sparse. In addition, the effects of recovery will influence any comparisons to the results shown in Section 3. Appendix A provides additional information into the effects of performing plant or group-specific investigations.

The results of the operational data review were:

- The frequency of system failures per year showed no statistically significant trend. However, a decreasing trend in the frequency of system unplanned demands per year was statistically significant. The decrease in RCIC unplanned demands appears to be related to the decrease in the average number of critical reactor scrams that have occurred over the same time period, which typically include a demand for RCIC injection.

- There were eight failures observed during short term missions; these are failures that directly affect system unreliability. These failures included one maintenance-out-of-service event and seven failures to start. Three of the failures to start were recovered.

  The one maintenance-out-of-service event occurred when the system was demanded to restore reactor vessel level (following a full power reactor scram) at a time when the system was unavailable because of routine instrumentation surveillance testing.

  For the failures to start, five were associated with turbine speed control, one was associated with the operation of the automatic start circuit, and one was associated with the turbine steam supply valve. These failures were caused by personnel error (2) and hardware malfunctions (5). The two personnel-error-related failures and one hardware failure associated with the turbine speed control were recovered by operator actions.

- In addition to the eight short term mission failures, there were eight failures observed during long term missions. These failures included two failures to run, four failures to restart, and two failures during transfer from recirculation to reactor vessel injection. Five of these failures were recovered by operator actions.

For the two failures to run, one was caused by a personnel error in the operation of the flow controller, and the other by a spurious isolation of the turbine steam supply. Only the personnel error in operation of the flow controller was recovered by operator actions.

The four failures of the RCIC system to restart were the result of hardware problems. The failure to restart probability was twice the failure to start probability; the difference might be the result of the difference in failure mechanism. Specifically, the failures that contributed to failure to start were primarily turbine speed control problems, while the restart failures were primarily related to cycling valves. Two of the four restart failures were recovered by operator actions.

The two failures to transfer from recirculation to reactor vessel injection were the result of hardware-related problems causing the test-return line MOV not to fully close on demand. Both of these failures were recovered by operator actions (a second valve in the test return-line was closed).

- During the performance of cyclic surveillance tests, only three failures of the RCIC system were observed. These three failures were classified as failures to start and were the result of hardware (2) and procedural (1) problems. Two of these failures were associated with the flow controller, and the other failure was associated with the turbine exhaust check valve.

- Failures detected by methods other than during the performance of a test or unplanned demand were primarily (62%) associated with the instrument and controls subsystem, specifically the isolation logic circuit. While a few isolation logic malfunctions were caused by procedural problems or personnel error, the majority were the result of hardware failures (i.e., detectors, relays, transmitters, etc.)

- The operating data contained five instances where multiple systems either had failed or had the potential to fail at the same time, possibly as the result of a common cause mechanism. The events involved motor-operated valves, the steam leak detection circuitry, and the turbine governors. These events are important because common cause failures across systems are generally not modeled or considered in the PRA/IPEs. In two of the five instances, the RCIC and HPCI systems were affected during an unplanned demand. The other events were discovered during surveillance testing (2) and other routine plant operations (1).

- There was no correlation observed between the plant's low-power license date and the frequency of failures per operational year. The average number of failures per operating year was 0.62, and this average frequency was observed for plants licensed from 1970 through 1990. Two plants licensed in the 1970s and two plants licensed in the 1980s had relatively high failure frequencies.

The following subsections provide a comprehensive summary of the operating data supporting the above results, as well as additional insights derived from: (a) an assessment of the operating 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) an evaluation of the relationship between system failures and low-power license date, and (e) Accident Sequence Precursor (ASP) events involving the RCIC system.

4.1 Industry-wide Evaluation

4.1.1 Trends by Year

Table 10 tabulates the RCIC system faults, failures, and unplanned demand events that occurred in the industry for each year of the study period. Figures 13 and 14 are illustrations of the failure and unplanned demand frequencies for each year of the study with 90% uncertainty intervals. The figures include a fitted trend line and a 90% confidence band for the fitted trend. The frequency is the number of events that occurred in the specific year divided by the total number of plant operating years for the calendar year.

Table 10. Number of RCIC system faults, failures, and unplanned demands by year.[a]

Classification	1987	1988	1989	1990	1991	1992	1993	Total
Faults	7	5	10	4	4	7	12	49
Failures[b]	20	11	6	8	19	13	15	92
Unplanned demand events	33	23	15	23	15	14	10	133
Restarts during unplanned demand events	0	26	2	8	5	3	2	46
Plant operating years[c]	18.7	19.1	19.7	22.4	23.3	21.7	22.7	147.6

a. Each entry consists of the number of events or restarts that occurred that calendar year.
b. The one event where the system was out of service for pre-planned maintenance was excluded from the failure count.
c. Shut downs longer than two calendar days are excluded from the operational years calculation.

The results of the trend analysis of the RCIC failures per operating year show, in general, no trend over the past seven years. Analysis of the trend of RCIC system unplanned demand events per operating year shows a statistically significant decreasing trend over the past seven years. The data indicate a decrease in the frequency of RCIC unplanned demand events of approximately a factor of four from 1987 through 1993. A potential factor affecting the decrease in the frequency of RCIC unplanned demands is the corresponding decrease in the average number of critical reactor scrams occurring during the same period. Approximately a factor of three decrease, from 3.6 to 1.1, is observed in the frequency of reactor scrams. (See AEOD *Performance Indicators for Operating Commercial Nuclear Power Reactors Data through March 1995*). It appears that the decrease in RCIC unplanned demands is related to the decrease in the average number of critical reactors scrams.

4.1.2 Factors Affecting RCIC Reliability

The RCIC system failures were reviewed to determine the factors affecting overall system reliability. To direct the review, the system failures were partitioned by method of discovery for each subsystem and component within each subsystem. The methods of discovery are unplanned demands, surveillance tests (all types and frequencies), and other. The other category includes failures found from design reviews, walkdowns, control room annunciators and indications, plant tours, etc. The results of this data partition are provided in Tables 11 and 12 and illustrated in Figures 15 and 16. The data counts provided in the tables and figures exclude the one event where the system was out of service for pre-planned maintenance, because there were no failed components.

Table 11. Subsystem contribution to RCIC system failures by method of discovery.

Subsystem	Method of discovery		
	Unplanned demand[a]	Surveillance test	Other
Turbine and Turbine Control Valves	6	24	13
Instrumentation and Control (I&C)	6	11	23
Coolant Piping and Valves	3	5	1
Total	15	40	37

a. Excludes the one event where the system was out of service for pre-planned maintenance, because no component failed.

Table 12. Component co.tribution to RCIC system failures by method of discovery.

Component	Subsystem	Method of discovery		
		Unplanned demand	Surveillance test	Other
Turbine governor	Turbine & Turbine Control Valves	2	15	—
Steam line MOV	Turbine & Turbine Control Valves	3	9	8
Flow controller	Instrumentation & Control	5	6	2
Isolation logic	Instrumentation & Control	1	5	19
Injection valve	Coolant Piping & Valves	1	4	1
Other	—	3	1	7
Total		15	40	37

a. Excludes the one event where the system was out of service for pre-planned maintenance, because no component failed.

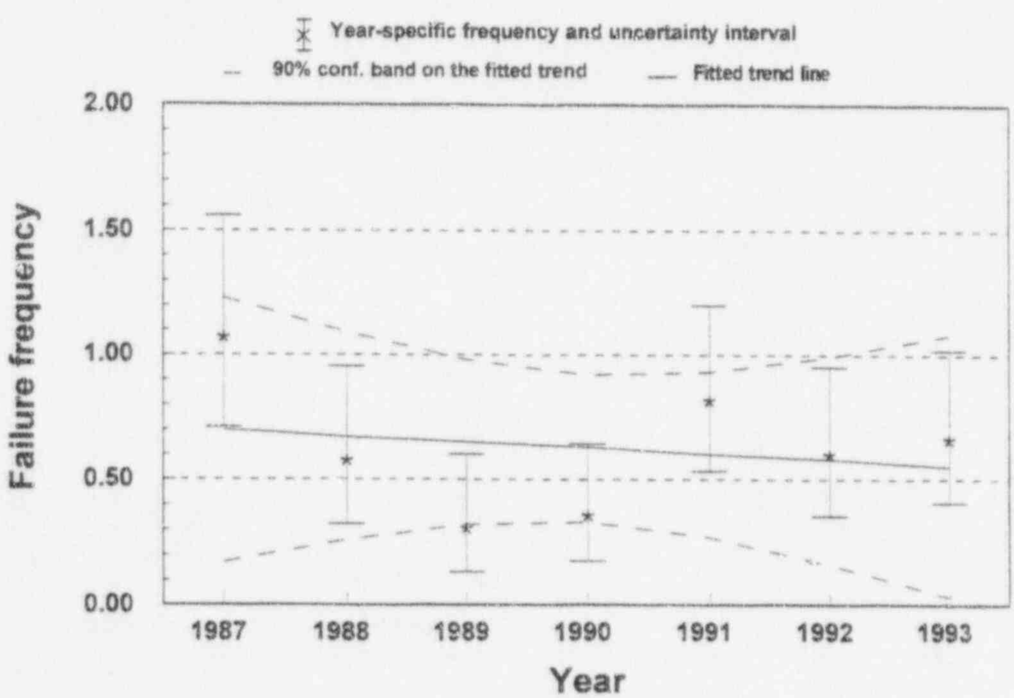


Figure 13. RCIC failures per plant operating year, with 90% uncertainty intervals and confidence band on the fitted trend. The trend is not statistically significant (P-value = 0.67).

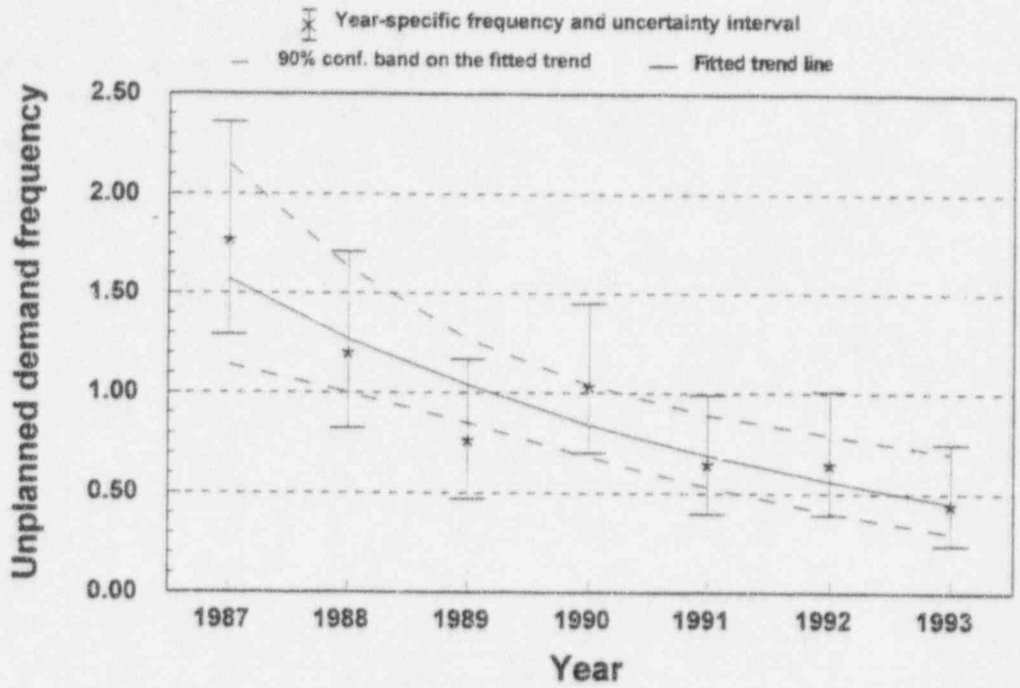


Figure 14. RCIC unplanned demand events per plant operating year, with 90% uncertainty intervals and confidence band on the fitted trend. The trend is statistically significant (P-value = 0.003).

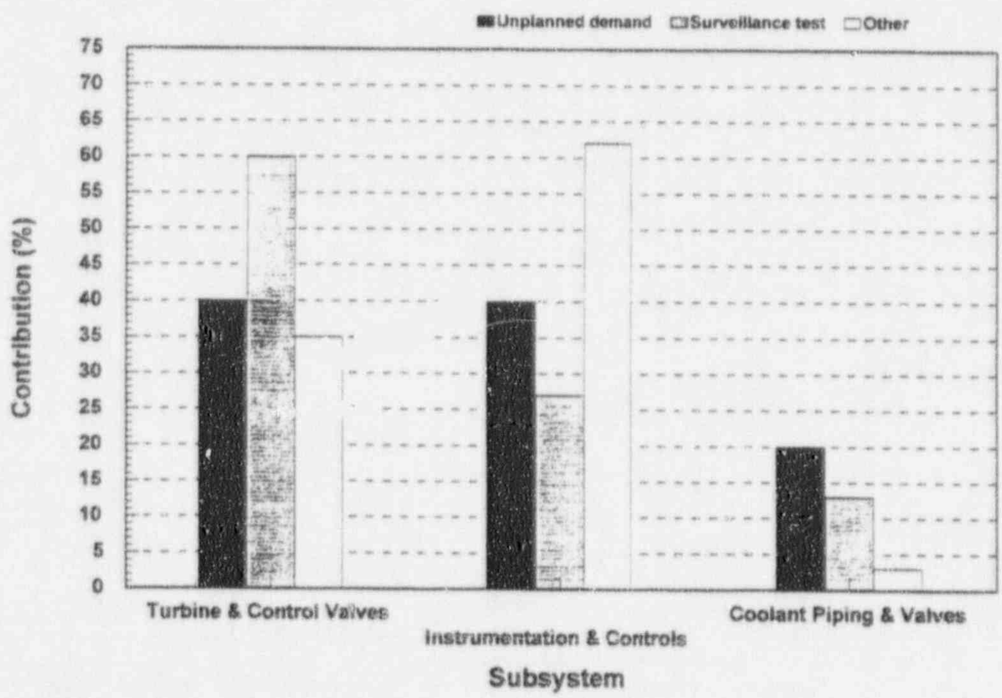


Figure 15. Histogram of the RCIC subsystem failures by method of discovery.

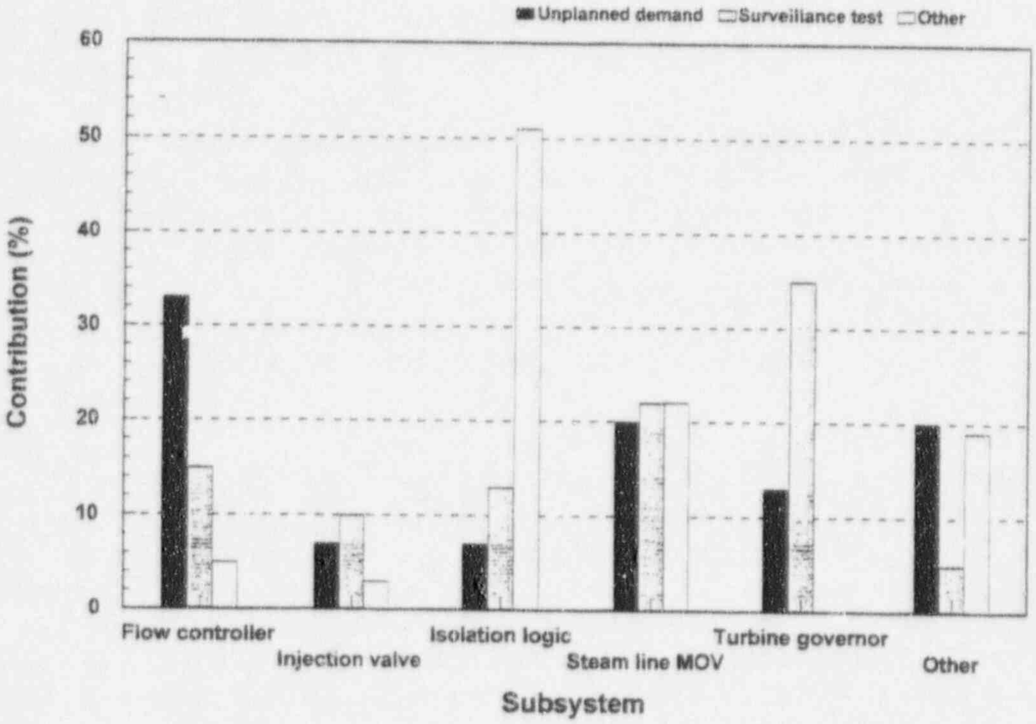


Figure 16. Histogram of the RCIC component failures by method of discovery.

As shown in Figure 15, no one subsystem clearly dominated the failures found during unplanned demands. Of the three subsystems, Turbine and Control Valves and Instrument and Controls subsystems collectively contribute 80%, while coolant piping and valves makes-up the remaining 20%. During surveillance tests, the turbine and turbine control valves subsystem was dominant and accounted for 60% of the failures (24 of 40). The smallest contribution to surveillance test failures were attributed to the coolant piping and valves subsystem, 13% (5 of 40). For failures that were found other than during the performance of a surveillance test or an unplanned demand, the I&C subsystem failures were dominant, 62% (23 of 37), and most of these failures resulted in a system isolation.

Factors Affecting Reliability during Short Term Missions—Failure to start was the primary contributor to system unreliability during short term missions. These short term missions typically occurred as a result of a reactor scram with normal feedwater available, and decay heat was able to be removed using the main condenser (MSIVs open). If a loss of main feedwater occurred, in these events, it was recovered quickly by plant operators. The missions were on the average about 5 minutes in duration. During these short duration unplanned demands, only two failure modes were observed in the operating data: maintenance-out-of-service (one event), and failure to start (seven events). Three of the failures to start were recovered by operators restarting the system manually or taking manual control of the flow controller.

The maintenance-out-of-service event was observed during an automatic reactor scram from 100% reactor power. The scram was a result of a lightning strike that caused a high flux signal in the power range instrumentation. The RCIC system received a start signal, but did not inject, because the trip throttle valve

was closed in preparation for an instrument surveillance test. Normal feedwater was used to restore and maintain reactor vessel level, and the HPCS system was operable in standby throughout the event. This maintenance-out-of-service event was selected for the ASP program for analysis, and was assigned a conditional core damage probability (CCDP) of 1.2E-6. The CCDP for this event was a result of both the lightning strike on offsite power and RCIC being out of service for testing.

For the FTSO failure mode, problems associated with turbine speed control contributed to most of the failures. These failures were caused by personnel error (2) and hardware malfunctions (5). The two personnel-error-related failures and one hardware-related failure were recovered by operator actions. Even though an unplanned demand of the system, which typically is a cold quick-start of the turbine, is the most stressful, no failures of the system can be attributed to a cold quick-start. The cold quick-start failures that would be expected include (a) failures due to low oil temperatures resulting in turbine overspeed trips, and (b) condensate in the steam supply lines causing either overspeed or high exhaust pressure trips.

The two personnel-error-related failures were the result of operators inadvertently not starting the system manually in accordance with established procedures. In the first instance a loss of offsite power event occurred, during which an operator did not open the injection valve in the manner specified by procedure; this operator error resulted in a turbine trip. At the plant where this failure occurred, the flow element is located in the main piping downstream of the minimum flow bypass line. The location of the flow element results in no flow being sensed by the flow transmitter on manual starts until the injection valve is opened. This arrangement causes the turbine governor valve to open fully in an attempt to achieve rated flow. If the operator does not open the injection valve quickly after starting the turbine, the turbine trips on overspeed in approximately four seconds. In the second instance, a reactor trip occurred during which plant recovery was hampered by a loss of two buses powered by the reserve auxiliary transformer (loss of normal feedwater). The control room operator depressed the automatic start push-button for RCIC and observed the injection valve opening; however, the operator believed the RCIC turbine had tripped on overspeed and released the push-button. The start sequence was not completed, resulting in no RCIC flow to the RPV. When reactor vessel level reached -12 inches and with feedwater still not available (17 minutes later), operators used the manual RCIC start procedure to restart RCIC and restore reactor vessel level.

The five hardware-related failures were primarily attributed to problems associated with turbine speed control, specifically, the flow controller (2) and turbine governor (2). The other failure was associated with the turbine steam supply valve. The flow controller failures were attributed to a limit switch failure and a problem with the automatic controller. The limit switch malfunction failed to pick-up the relay, which provides the ramp switch signal to the Woodward controller. This resulted in the controller not responding to speed demands. The automatic controller failure caused flow, speed, and pressure oscillations. The controller was shifted to manual, and turbine performance parameters stabilized. The LER did not state a cause or corrective action for the controller failure in automatic. However, based on other plants experiencing similar problems, the failure could have been the result of excessive feedback.

The turbine governor failures were the result of a failed diode in the magnetic pickup module and a loose mechanical trip linkage. The failed diode caused an overspeed trip of the turbine. The diode failed as a result of higher than normal amperage conditions over a period of years. The high amperage was caused by a bent internal pin connection inside the module, which prevented a good power supply connection. The loose mechanical trip linkage caused the RCIC turbine to trip on three start attempts. The loose trip linkage resulted from repeated closing of the trip and throttle valve, normal system vibration, and a slight rounding of the tappet nut latching surface. Additionally, a substance (possibly from a joint sealing compound) was

found in the tappet guide of the tappet and ball assembly. This caused a sluggish reset action, resulting in improper resetting of the trip and throttle valve. The substance may have contributed to the turbine tripping at 200 to 500 rpm below the trip setpoint.

The failure associated with the turbine steam supply was a result of the valve failure to open on the start sequence. The cause was an undersized motor-operator and the normally closed position of the valve. Plant design required the valve to be closed, which was unique to the plant. The plant design was changed to require the valve to be normally open to correct the cause of the failure.

Factors Affecting Reliability during Long Term Missions—In addition to the maintenance-out-of-service and failure to start events observed in the short term missions, three other failure modes were observed in the long term missions. These three failure modes are failure to run, failure to restart, and failure to transfer during recirculation. During short term system operation, typically with normal feedwater available, the RCIC system is not likely to experience these failure modes because, once RCIC restores normal vessel level, the feedwater system will maintain level and the RCIC system is shut down. However, when normal feedwater is not available or when the reactor vessel is isolated, safety relief valves are cycled or the HPCI system is operated in the pressure control mode to maintain vessel pressure within desirable limits. As a result, the water level in the reactor vessel lowers because of continued steam generation by decay heat. With the continued lowering of vessel level, the control room operator could manually initiate the RCIC system and restore reactor vessel level. Once level was restored, the operator can divert RCIC flow back to the CST through the test-return line MOV, or as an alternative, the operator can allow the system to automatically cycle on and off between the high and low reactor vessel water level setpoints. In either case, long term operation of the system can result in failures to run and either repeated starts and possible failures to restart, or flow diversion and possible failure of the test-return-line MOV in the open position.

There were two failures that contributed to the failure to run probability, and these were associated with the flow controller and an isolation of the turbine steam supply during turbine operation. The flow controller failure caused the turbine to trip, which was recovered by operator action. The trip was attributed to operator error in the adjustment of the RCIC flow controller before switching from manual to automatic mode. The isolation of the turbine steam supply was the result of the high room delta-T instrument indicating a steam line leak; however, no leak existed. The cause of the high room delta-T was excessive room cooling resulting from low service water temperatures. The isolation was not recovered by operator actions. The isolation of the turbine steam supply was not identified as a major contributor to system unreliability in the PRA/IPEs reviewed for this study

There were four failures that contributed to the failure to restart probability, and these failures were the result of hardware problems. As discussed previously in Section 3, the restart failure probability is twice that of the failure to start probability. The mechanism of the failures that contributed to the failure to restart probability is different than the mechanism of the failures that contributed to the failure to start probability. This difference in the mechanism of the failures may indicate a potential reason for the difference in failure probabilities. Specifically, speed control problems contributed to a majority of the failures to start, and valve-related problems contributed to a majority of the restart failures. The speed control problems caused the turbine to trip on initial start or caused flow and pressure oscillations that resulted in the need for operators to take manual control of the system. However in contrast to the failures to start, the restart failures were, in three out of the four cases, the result of valve failures resulting from cycling the valve.

One of t.. valve-related restart failures was a malfunction of the turbine steam supply valve. The valve failed to fully close on a high level trip, and as a result, the turbine tripped on overspeed during the restart. This overspeed trip occurred several times for the same reason during the event and was recovered by operator actions. (Since the number of restarts and subsequent failures was not provided in the LER, only one restart and failure were counted in the unreliability analysis.)

The second valve-related restart failure was caused by tripping of the thermal overload devices for the turbine, with the throttle valve being tripped on the fourth restart attempt (this failure was not recovered by operator actions). The thermal overload devices would not reset to allow subsequent system starts. No specific cause for the tripped thermal overload devices was identified in the LER.

The other valve-related restart failure was the result of a failure of the injection MOV to function properly. During the event the RCIC system tripped on high reactor vessel water level; however, the injection valve exhibited stem binding and overloaded the motor-operator, tripping the breaker with the valve partially open. With the valve partially open, the subsequent system restart resulted in only a small amount of flow to the reactor vessel. Operators did not recover the system for this event. In addition to this RCIC injection valve failure, the HPCI system did not function as designed and had to be controlled manually throughout the loss of feedwater event.

The fourth restart failure (not valve-related) was associated with the turbine and was the result of condensate in the steam lines that could not be drained fast enough through the drains lines. The condensate flashed to steam as the steam supply valve was opened and caused a high exhaust pressure trip of the turbine (this event was recovered by operator actions). This type of turbine trip would normally be expected during a cold quick-start, and not during a hot start. Even though the high exhaust pressure trip functioned properly, bursting of the turbine exhaust rupture discs from high pressure could have failed the system for the duration of the event. A review of the PRA/IPEs indicated that turbine exhaust failures due to this mechanism are not identified as contributing to the system failure probability.

The events that contributed to the failure to transfer during recirculation were the result of hardware-related problems associated with the test-return line MOV. In both of the observed failures, the test-return line MOV failed to fully close on demand, resulting in a significant reduction of flow to the vessel. In each case the failure of the system was recovered by dispatching an operator to locally close the MOV or close a second manual valve in the test-return line. In one of these events, the loss of RCIC flow was compounded by a concurrent loss of HPCI due to failure of the HPCI injection MOV to open on demand.

Factors Affecting Reliability During Surveillance Tests—During the performance of cyclic surveillance tests only three failures of the RCIC system were observed. These three failures contributed to the FTSO failure mode and were the result of hardware and procedural problems. Two of these failures were associated with the flow controller and the other failure was associated with the turbine exhaust check valve. One flow controller problem was caused by the proportional band being too narrow. A small change in the controller output caused large fluctuations in the process variable, which produced offscale flow oscillations. The other flow controller failure occurred at the same plant during the next cyclic test and was the result of the same proportional band adjustment problem. The failure of the exhaust check valve in the RCIC turbine exhaust line resulted in a turbine trip immediately after initiation, with the trip being due to high exhaust pressure. Several repeated start attempts also resulted in an immediate turbine trip on high exhaust pressure. Investigation revealed that the disk of the check valve had broken away from the disc arm

and lodged in the valve body, thus restricting turbine exhaust flow. In contrast to the above FTSO failures, there were no failures found during the performance of cyclic tests that contributed to the FTR failure mode or any other failure mode.

During the performance of other surveillance tests (quarterly, monthly, etc.), there were 37 failures of the system. Of these 37 failures, 34 were associated with either the FTSO or FTSV failure mode, and only three were associated with the FTR failure mode. Hardware-related problems associated with the turbine governor and steam line MOV contributed to most of these failures.

Analysis of the mechanisms that caused the governor failures indicated that governor problems were primarily caused by electrical-related malfunctions, with one exception. On three occasions, at the same plant, the governor valve experienced sticking between the valve stem and the carbon packing spacer rings. This failure has not recurred since 1992. Examples of the mechanisms that caused the electrical malfunctions of the governor are: a failed transistor in the control valve circuit, improper calibration of the governor controller, failure of the speed control actuator, and a broken speed sensor for the control logic.

Analysis of the mechanisms that caused the steam line MOV malfunctions indicated that these failures were caused by diverse and unrelated hardware problems; however, one plant did have five failures of this valve to open in one year, all of indeterminate cause. This plant's design has been changed such that a normally-open valve is used rather than a normally-closed valve. No additional failures have been reported at this plant. Other than some personnel errors, the causes of the steam line MOV malfunctions were split between electrical and mechanical hardware failures. The largest number of malfunctions were the result of limit switch or torque switch failures. Examples of other failures include: grounded circuits due to water intrusion, corrosion buildup between the stem and stem nut, a broken disk retainer pin, MOV breaker trip due to valve hydraulic lock, and a motor-operator detached from its yoke because of loose cap screws.

Overall Factors Affecting System Reliability—Overall, for the unplanned demand failures, malfunctions associated with controlling system flow under varying flow rates coupled with personnel errors in operation of the flow controller are the major contributors to system unreliability. System failures that occurred during long term operation of the system represent a significant contribution to system unreliability. These restart and recirculation failures are generally not modeled or are only vaguely mentioned in the PRA/IPEs; however, they collectively represent 43% of the system unreliability. In addition, the restart and recirculation failures are not observed during the performance of surveillance tests, indicating that long term operation, as assumed to occur during a loss of feedwater or vessel isolation, is not well mimicked during surveillance tests.

Comparison of the Operating Experience and Surveillance Test Failures—A comparison was made with the failures and failure mechanisms experienced during operating experiences (unplanned and cyclic test demands) versus surveillance tests (other than cyclic). The results of this comparison indicated that for the FTSO failure mode during operating experiences, problems associated with controlling system flow under varying flow conditions contributed to a majority of the failures, while during other surveillance tests, failures from other mechanisms (e.g., steam line MOV and governor problems) contributed to a majority of the failures. For the FTR failure mode, a meaningful comparison was not possible due to the sparse number of FTR events observed in the data.

Other Factors—Failures discovered by means other than during the performance of a test or unplanned demand were dominated by instrumentation and controls subsystem faults, specifically the isolation logic circuit. A review of these instrumentation and controls subsystem failures indicated that the failures primarily occurred as a result of failed process detectors. These failures were generally identified by control room annunciators and other system indications available to plant operators.

While a few isolation logic malfunctions were caused by procedural problems or personnel error, the overwhelming majority have been the result of electrical hardware failures. The largest number have occurred from temperature sensor/switch malfunctions. The others were a variety of circuit card, calibration unit, or trip unit malfunctions. The failure of one sensor or switch isolates the system and disables the system from initiating when given an automatic or manual start signal. Although significant in terms of numbers of events, because these spurious isolation events are self-annunciated and therefore quickly repaired, they do not contribute significantly to the system unreliability.

4.1.3 Potential Common Cause Failure Susceptibility Across Systems

During the review of the operational data selected for this study, several instances were observed where either a failure or a potential failure of more than one component or system occurred. These failures are of concern because they indicate a potential for defeating the diversity and redundancy of plant systems. In addition, some of these failures could have defeated the same system at multiple plant sites (e.g., both RCIC systems at Units 1 and 2). The events may not in all cases be common cause failures, however, they represent a susceptibility of multiple systems failing to operate when demanded. While in some cases only one component may have actually failed, the information provided in the LER indicated that other failures in the same system or across systems as a result of the same mechanism were possible. Specifically, the corrective actions taken by plant personnel were such that preventive measures were taken on several systems or components in an effort to lesson the chance of similar failures in the future.

No quantitative analysis of these events is provided in this section, because of the uncertainty in interpreting and classifying the failures, especially across systems and where multiple unit plant sites are involved. This section only provides an identification and qualitative review of the events, because these are generally not modeled or considered in the PRA/IPEs.

The operating experience data contained five instances where multiple systems had the potential to fail concurrently. Two of these events were observed during unplanned demands, and affected both the RCIC and HPCI systems. Two were observed during surveillance tests, and one during routine plant operations. Two of the events affected the RCIC and HPCI systems at both units of a two-unit site. Table 13 provides a listing of these five events, the plants and systems involved, and a brief description of each event.

A review of the events indicated that three of the five events involved motor-operated valves failing to operate, one event involved the steam leak detection circuitry, and one event the turbine governors. Three of the five events were caused by hardware-related problems, and the other two events can be attributed to maintenance practices.

Two of the motor-operated valve events occurred at the Brunswick site and were attributed to hardware-related failures. The cause of the failures was attributed to heat-related breakdown of the motor-operator windings as a result of high current flow. The high current flows were the result of either (a) attempting to operate the valve against high differential pressures or (b) voltage transients.

The first Brunswick event was found during surveillance testing that affected the RCIC and HPCI system suction valves from the suppression pool for both units. The suction valve failures affect the long term operation of the systems and would contribute to the failure to run probability. These failures have a greater influence on HPCI completing a long term risk-based mission than RCIC, because the long term mission requirements for RCIC do not in all cases require a suction source from the suppression pool. Specifically, during a vessel isolation event or loss of normal feedwater, the water source from the condensate storage tank (normal supply) would be sufficient to mitigate the consequences of the event.

The other Brunswick event occurred at Unit 2 during an unplanned demand of both the RCIC and HPCI systems. Both systems were needed to mitigate the consequences of a reactor vessel low-level condition following a reactor scram when feedwater was not available. In both cases the systems were being used to reduce reactor vessel pressure, and a motor-operated valve failed to reposition to allow subsequent injection of coolant to the reactor vessel. In this event the HPCI injection valve failed to open and was not recovered, and the RCIC test return-line valve failed to close, diverting flow from the vessel. The RCIC valve failure was recovered when operators shut another valve in the test return line, thereby re-establishing flow to the vessel. This event was selected for the ASP program for analysis and was assigned a CCDP of 2.4E-4.

The other motor-operated valve event occurred at the Quad Cities site during monthly surveillance testing and involved the RCIC and HPCI system for both units. The improper torque switch settings of 14 motor-operated valves in these systems were identified. The valves included the pump suctions (normal and alternate) and discharge, and test return-line isolations. The torque switch settings were such that the valves would not open under a differential pressure. The pump discharge and test return-line valves could be subjected to multiple cycling against a differential pressure during a vessel isolation or loss of normal feedwater event. These two events typically do not require continuous injection, and operators could be switching modes of system operation (i.e., recirculation/pressure control or injection) as necessary to control reactor vessel water level or pressure. Failure of these valves to operate would have resulted in a loss of injection by flow diversion through the test return line.

A steam leak detection system failure was caused by internal problems with test switches that resulted in the spurious isolation of the RCIC, HPCI, and RWCU systems during routine plant operations at Duane Arnold. Troubleshooting of the steam leak detection system switch panel revealed that a light tapping of the input and output leads for the test switches would result in switch actuation. Because the isolation signal logic is a one-out-of-one circuit, any one switch actuation would induce a short spurious actuation signal that would result in a system isolation. The switches were replaced and a modification was installed in the system to increase the time delay from one to three seconds to prevent the spurious short-duration signals from isolating these systems.

Table 13. Potential common cause failure susceptibility across systems.

Plant name	Event date	LER number	Systems involved	Description
Brunswick 1&2	12/31/87	32587023 32588011	RCIC, HPCI Units 1 & 2	The RCIC turbine steam supply and HPCI pump suction DC motor operators failed during a quarterly surveillance test due to voltage transients caused by opening the power supply breaker to the motor-operators. The shunt coils were damaged as a result of the high current, which necessitated the replacement of the motor-operators. To prevent additional failures, surge suppression devices were installed in the control circuitry for DC motor operators at both units.
Brunswick 2	01/05/87	32487001	RCIC, HPCI	An automatic reactor scram occurred as a result of a primary lockout trip of the main generator. During the scram recovery, the RCIC test return-line motor-operated valve failed in the open position and the HPCI injection motor-operated valve failed in the closed position. The failure of both these valves rendered both systems inoperable for reactor vessel injection. The motor operator was replaced on the HPCI injection valve, and the RCIC test return-line valve stem anti-rotation device was replaced.
Duane Arnold	02/24/89	33189006	RCIC, HPCI, Reactor water cleanup (RWCU)	An isolation of the RCIC system occurred due to a spurious signal from the steam leak detection system. Troubleshooting determined the cause to be a nearly broken thermocouple wire on a detection module. On 03/02/89, an isolation of the HPCI system occurred as a result of a spurious signal from the steam leak detection system. Troubleshooting revealed an internal problem within the test switches and the thermocouple wires on the detection modules. The test switches were replaced for the HPCI, RCIC, and RWCU system steam leak detection systems.
Pilgrim	09/02/90	29390013	RCIC, HPCI	An unplanned manual reactor scram was initiated at 60% reactor power in response to difficulties experienced in controlling reactor vessel water level. During the event, the RCIC system was declared inoperable as a result of the turbine tripping on three start attempts. The trips were caused by a loose mechanical overspeed trip linkage. The HPCI system also experienced two overspeed turbine trips on start attempts. The exact cause for the HPCI overspeed trips was not identified in the LER. In addition, the RCIC suction piping experienced a pressure transient as a result of the injection check valve not fully seating after the second start attempt.
Quad Cities 1&2	01/25/88	25488003	RCIC, HPCI Units 1 & 2	While performing the monthly motor-operated valve surveillance test for the RCIC system at Unit 1, the pump discharge valve would not open on the first two attempts. The valve did open on the third attempt. Investigation revealed that the torque switch bypass limit was set too close to the full closed position. The setpoint of the torque switch prevented the valve from opening under a differential pressure. The torque switch bypass limit setpoints were adjusted for 13 additional motor-operated valves for the Unit 1 HPCI and Unit 2 HPCI and RCIC systems.

The turbine governor problems were maintenance related, and affected the HPCI and RCIC systems during startup attempts from an unplanned demand at Pilgrim. The systems were needed to maintain reactor vessel level following a manual reactor scram initiated as a result of difficulties in controlling water level. The RCIC governor problem that resulted in three overspeed trips during start attempts was discussed earlier in Section 4.1.2. The HPCI turbine experienced two overspeed trips on start attempts. Flow oscillations were also observed with the flow controller in automatic while in the pressure control mode of operation. The cause of the turbine trips was attributed to the oil relay pilot supply valve being open to a position different than that specified by the vendor. Additionally, there were organic impurities and a significant amount of water in the turbine oil. Each of these factors may have contributed to the turbine trips. The cause of the flow oscillations was attributed to two factors: the design of the flow control system and the position of the EG-R hydraulic-actuator-needle valve. The LER specified that the flow controller was not designed for low flow conditions, only full injection flow. Also, the needle valve was found one complete turn open, instead of one-quarter turn open as specified by the vendor. The improper needle valve position caused the turbine to respond too quickly to flow changes (excess feedback). This event was selected for the ASP program for analysis and was assigned a CCDP of 8.4E-5.

4.2 Plant-Specific Evaluation

Table 14 shows the following information for each plant: operating years during the study period, number of faults, number of failures, number of unplanned demand events and restarts, and the frequency of failures, unplanned demand events, and restarts per unplanned demand event. As used here, a *frequency* is simply an event count divided by the number of operating years. The number of failures listed in Table 14 does not include the one event where the system was out of service for pre-planned maintenance when a demand occurred.

The reader is cautioned when comparing the individual plant data to the reliability estimates provided in Section 3. Plant-specific estimates derived solely from the failure and demand data at a particular plant may produce results that differ from those presented in Section 3. There are several reasons for this, two of which are the sparse data associated with RCIC system performance at individual plants and the ability to recover from RCIC system failures. Although, sparse data alone do not create differences between the best estimates of unreliability presented in Section 3 (which are calculated using Bayesian statistics) and what can be calculated if only the individual plant data were used (that is, using classical statistics). Sparse data provide the opportunity for rare or atypical performance to overly influence any unreliability estimate that is based solely on the plant-specific data. (Note that in the long run the atypical high reliability performance will be balanced out by atypical low reliability. "Sparse data" is defined here such that the RCIC system experience is not sufficient to allow the data to converge on the true unreliability.) This atypical data can result in the unreliability estimate either overpredicting or underpredicting the true unreliability of the RCIC system. Of course it is impossible to determine absolutely whether or not the sparse data are atypical of the true system performance; maybe the system really is as reliable as the data suggest. Nevertheless, to minimize the chance of producing non-representative estimates based on sparse data, the best estimates presented in Section 3 are calculated using Bayesian statistics that use all knowledge of RCIC performance across the industry.

Table 14. RCIC faults, failures, and unplanned demands differentiated by plant.

Plant name	Operating years	Faults	Failures	Failure frequency	Unplanned demands[a]	Unplanned demand frequency[b]
Browns Ferry 2	2.25	0	2	0.89	0/0	0.00/0.00
Brunswick 1	3.83	1	2	0.52	4/1	1.04/0.25
Brunswick 2	4.59	3	3	0.65	10/6	2.18/0.60
Clinton	4.87	0	3	0.62	2/14	0.41/7.00
Cooper	5.64	0	3	0.53	8/0	1.42/0.00
Duane Arnold	5.63	1	2	0.36	4/0	0.71/0.00
Fermi 2	5.55	1	2	0.36	5/0	0.90/0.00
FitzPatrick	4.49	0	5	1.11	4/0	0.89/0.00
Grand Gulf	6.10	2	3[c]	0.49	14/1	2.29/0.07
Hatch 1	5.89	0	3	0.51	12/12	2.04/1.00
Hatch 2	5.97	0	1	0.17	12/2	2.01/0.17
Hope Creek	6.15	0	1	0.16	8/1	1.30/0.13
LaSalle 1	5.44	7	11	2.02	2/0	0.37/0.00
LaSalle 2	5.21	7	4	0.77	1/1	0.19/1.00
Limerick 1	5.70	4	1	0.18	2/0	0.35/0.00
Limerick 2	3.85	1	0	0.00	1/0	0.26/0.00
Monticello	6.28	0	1	0.16	2/0	0.32/0.00
Nine Mile Pt. 2	4.47	0	3	0.67	6/0	1.34/0.00
Peach Bottom 2	3.97	0	1	0.25	2/0	0.50/0.00
Peach Bottom 3	3.54	0	0	0.00	4/0	1.13/0.00
Perry	5.00	1	10	2.00	9/0	1.80/0.00
Pilgrim	3.85	6	10	2.59	4/3	1.04/0.75
Quad Cities 1	5.53	7	10	1.81	1/0	0.18/0.00
Quad Cities 2	5.44	4	5	0.92	2/0	0.37/0.00
River Bend	5.29	1	1	0.19	3/0	0.57/0.00
Susquehanna 1	5.67	0	0	0.00	2/1	0.35/0.50
Susquehanna 2	6.05	0	0	0.00	2/0	0.33/0.00
Vermont Yankee	6.22	1	3	0.48	1/1	0.16/1.00
Wash. Nuclear 2	5.07	2	2	0.39	6/3	1.18/0.50
Industry	147.56	49	92	0.62	133/46	0.91/0.35

a. The first value corresponds to the number of events, and the second value corresponds to the number of restarts that were identified in those events.

b. The first value is the frequency of unplanned demand events per operating year, and the second value is the frequency of restarts per event.

c. The number of events listed excludes the one MOOS event that occurred at this plant.

The second issue to consider when reviewing the individual plant experience is the possibility of recovering from a RCIC system failure. Industry-wide, there were several opportunities in which plant personnel, due to circumstances of the particular events, attempted to recover the RCIC system from a failure event. In about half of these instances, the recovery was successful. Consequently, the unreliability

estimates presented in Section 3 include the likelihood that the failure events will be successfully recovered, whereas the results of individual plant-specific comparisons presented in Section 4 do not necessarily include consideration of recovery.

The unplanned demand and failure frequencies are plotted in Figures 17 and 18, respectively. The data plotted in Figure 17 for unplanned demands are for events only and do not include restart demands. To account for plants with no failures or unplanned demands, Bayes statistical techniques were used to estimate the failure and unplanned demand frequencies shown in the figures. In each plot, the plant-specific point estimate is shown with the 90% uncertainty interval. As the data in Table 14 indicate, a small percentage of plants account for many of the failures and unplanned demands. Specifically, 47% of the failures occurred at 14% of the plants (LaSalle 1, Perry, Pilgrim, and Quad Cities 1). Furthermore, 53% of the unplanned demands for RCIC occurred at 24% of the plants (Brunswick 2, Grand Gulf, Hatch 1 and 2, and Perry).

Because the plants with high failure frequencies do not necessarily have high demand frequencies, Figure 19 shows the two frequencies from Figures 17 and 18 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. To avoid clutter, points in the lower left are not labeled. Any point in the upper right of the graph corresponds to a plant with both a high failure frequency and a high frequency of unplanned demands. Based on the data displayed in Figure 19, eight plants were selected for detailed review of their failure and unplanned demand data: Brunswick 2, Grand Gulf, Hatch 1 and 2, LaSalle 1, Perry, Pilgrim, and Quad Cities 1.

Brunswick 2—Brunswick 2 has a relatively high frequency associated with unplanned demands as compared to the industry average. The demands were primarily associated with reactor scrams. The plant had a low frequency of failures. Brunswick 2 reported only three failures. However, two were observed during unplanned demands. One of the unplanned demand failures had a concurrent HPCI failure and was selected for ASP analysis; the resulting CCDP was 2.4E-4. One of the two unplanned demand failures contributed to the failure to transfer from recirculation (this failure was recovered by plant operators), and the other was a failure to restart. The failure to transfer from recirculation was the result of a hardware failure of the test-return-line MOV. The failure to restart was the result of the thermal overload devices for the trip and throttle valve being tripped on the fourth restart attempt. The other failure was the result of a malfunction in the steam leak detection circuit, which caused a steam supply isolation when the system was in standby. Brunswick 1 reported only two failures, none of which were observed during an unplanned demand or cyclic surveillance test. Both failures were unrelated hardware problems associated with the steam leak detection system and the turbine governor.

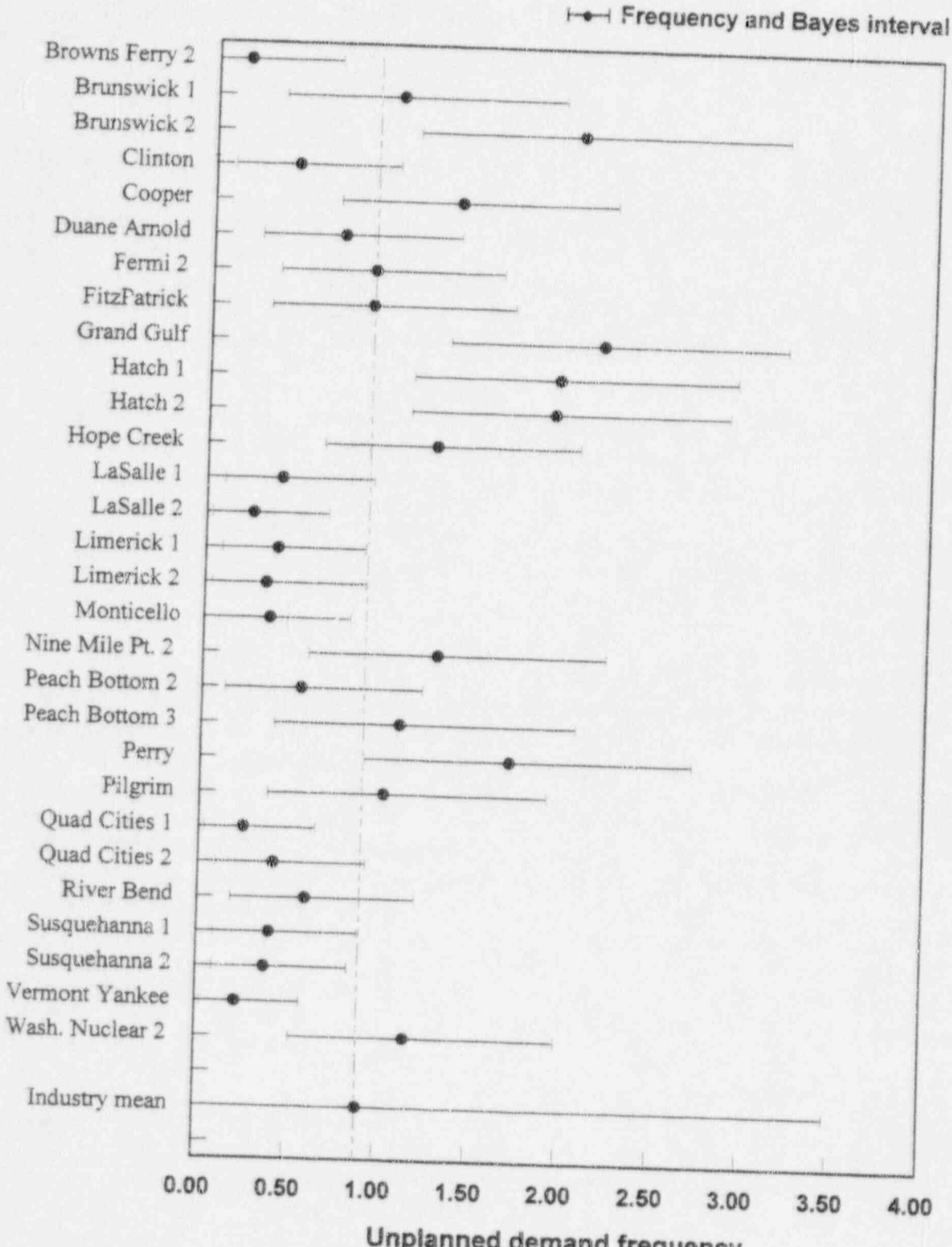


Figure 17. Plant-specific unplanned demand events per operating year with 90% Bayesian intervals.

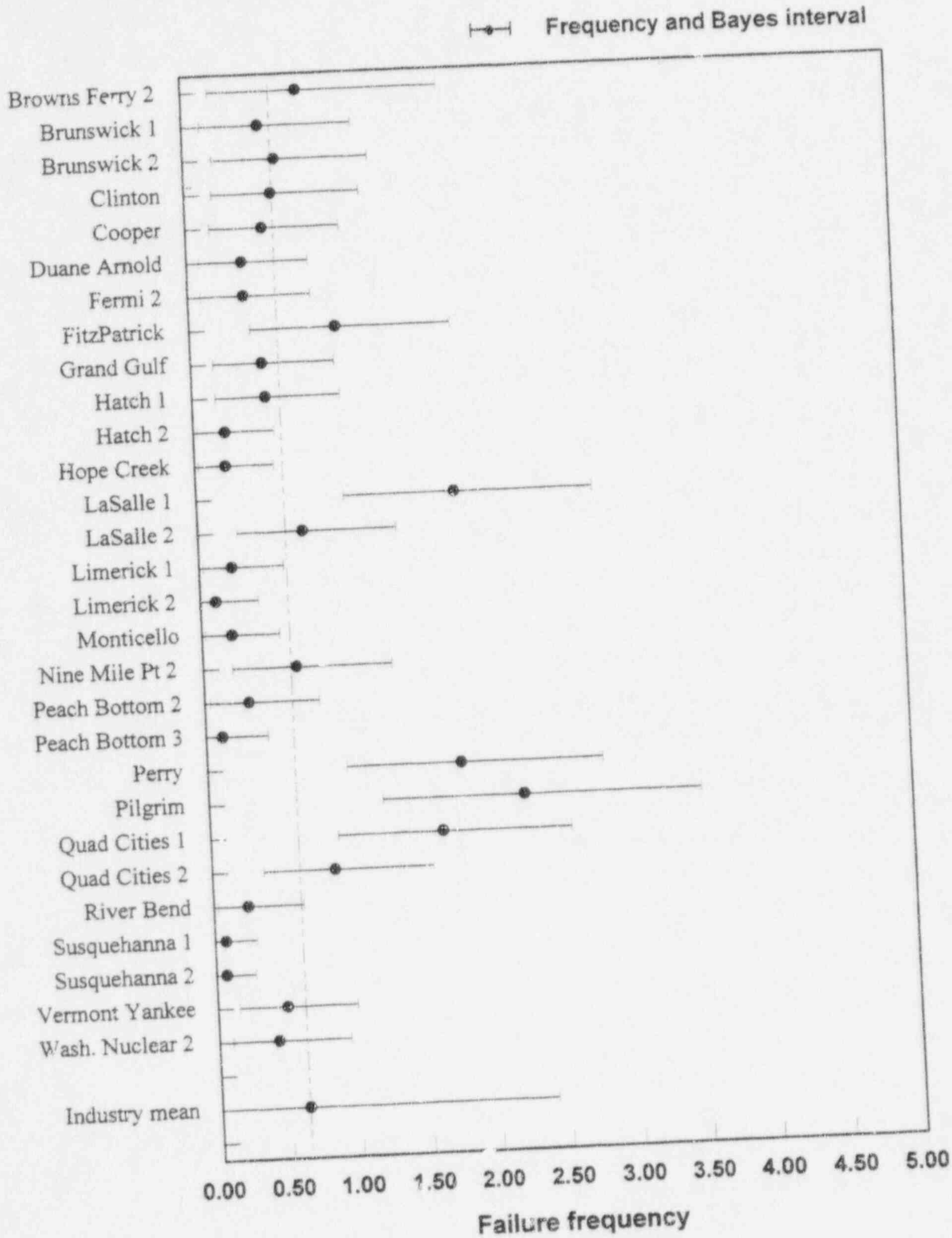


Figure 18. Plant-specific RCIC system failures per operating year with 90% Bayesian intervals.

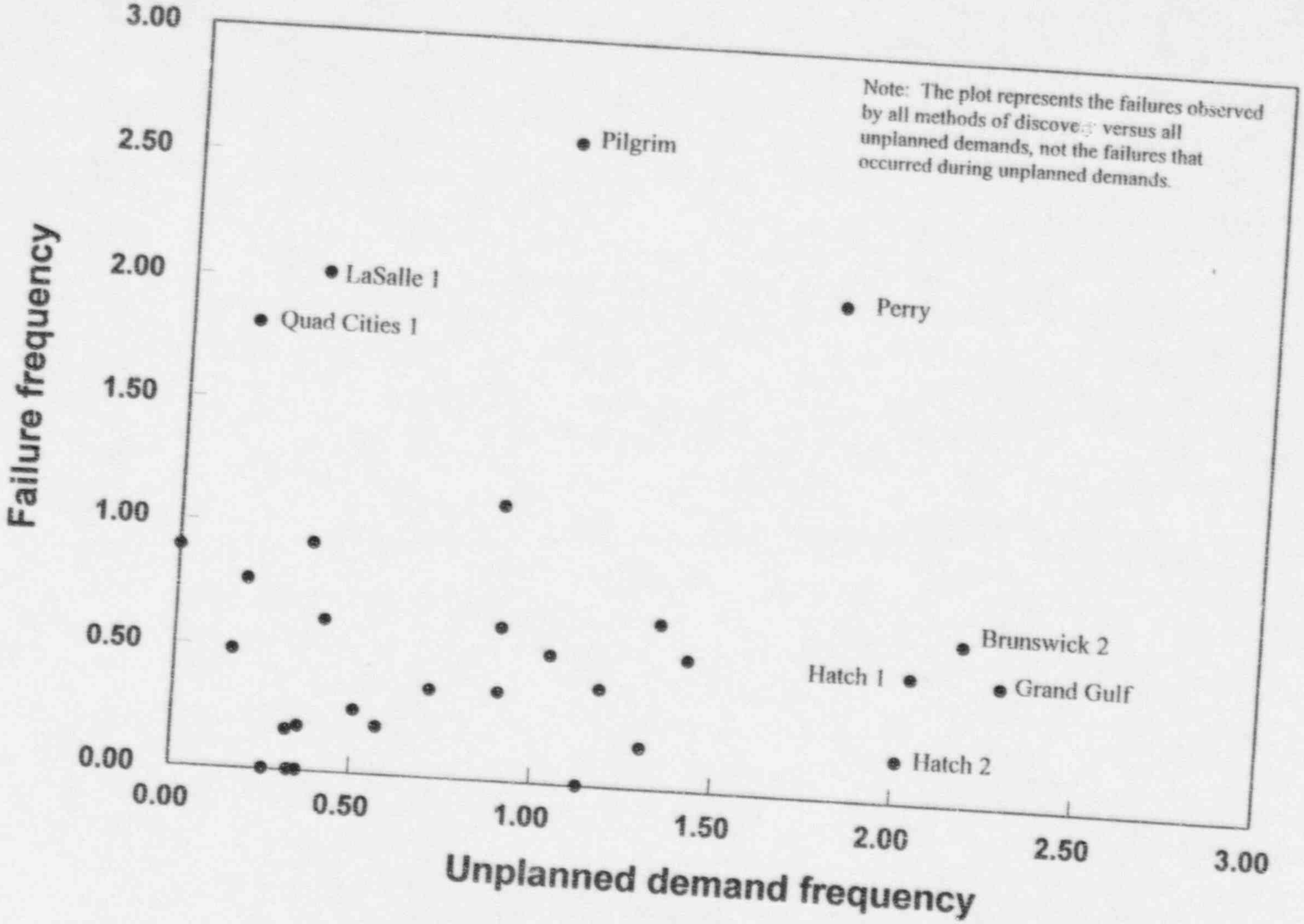


Figure 19. Plant-specific unplanned demand event frequency versus plant-specific failure frequency.

Grand Gulf—Grand Gulf has a relatively high frequency associated with unplanned demands as compared to the industry average. The demands were primarily associated with reactor scrams. The plant reported four failures, of which one was a MOOS event in 1989. The system was out of service for an instrumentation surveillance test when a lightning strike on an offsite power line resulted in a reactor scram and low RPV water level condition. This event was selected by the ASP program for analysis, the resulting CCDP was 1.2E-6. The other three failures at Grand Gulf were associated with the instrumentation for the steam leak detection circuit. These failures resulted in system isolations while in a standby status. These three failures were observed in 1992 (1) and 1993 (2).

Hatch Units 1 and 2—Hatch Units 1 and 2 have relatively high demand frequencies as compared to the industry average. While the site only reported four failures during the study period, all four failures occurred during unplanned demands (three at Unit 1 and one at Unit 2). Two of the events were classified as failures to start and the other two as failures to restart. The failures were observed from 1987 through 1991. A review of the individual failure events indicated that all four failures were hardware-related failures. The two restart failures occurred at Hatch Unit 1 and both involved malfunctions of MOVs, specifically the turbine steam supply and coolant injection valves. The turbine steam supply valve failure was the result of set screws backing out of the stem for the torque switch, which caused the valve to partially close (this was the only event at Hatch that was recovered). The injection MOV failure was the result of a blown fuse in the valve actuator control power circuit. This interrupted power to the valve, thus preventing valve operation. When the injection valve failed, the HPCI system malfunctioned in the automatic mode and had to be controlled manually. The third failure at Hatch Unit 1 was attributed to an electrical malfunction of the turbine governor; specifically, a failed EG-M pickup module caused an overspeed trip of the turbine. The RCIC failure observed at Hatch Unit 2 was a flow control malfunction. This failure prevented RCIC injection to the RPV. The failure was due to a failed switch on the flow control valve that provides the ramp switch signal to the Woodward controller. This resulted in the controller not responding to speed demands. All four of the RCIC failures were events selected for ASP analysis. These events had CCDPs that ranged from 7.7E-6 to 2.0E-5. Each of the events included a loss of feedwater or offsite power that contributed to the CCDP value.

LaSalle Unit 1—LaSalle Unit 1 had a relatively low unplanned demand frequency, and a failure frequency that is relatively high as compared to the industry average. There were no failures reported during unplanned demands or cyclic surveillance tests. However, there were eight reported failures during the performance of quarterly surveillance tests. Seven of these eight failures were attributed to failures in the turbine and turbine control subsystem. Seven of the eight were classified as failures to start. The one failure to run was caused by a failure of the governor. Most of the failures were caused by hardware-related problems that occurred at a frequency of one or two per year throughout the study period (with the exception of 1993, where five failures were observed). While LaSalle 1 experienced a relatively high failure frequency, LaSalle Unit 2 reported only four failures. One failure occurred during an unplanned demand and was classified as a failure to restart. This event at LaSalle Unit 2 was selected by the ASP program for analysis and was estimated to have a CCDP of 6.1E-6. The three other failures were found during quarterly surveillance tests. The failures were observed in 1992 and 1993. The failures at LaSalle Unit 2 were all hardware-related problems different from those observed at LaSalle Unit 1. The failures at LaSalle Unit 2 were associated with the flow controller and steam line MOV.

Perry—Perry has plant-specific failure and unplanned demand frequencies that are relatively high as compared to the industry averages. Of the ten failures reported at Perry, two contributed to system unreliability. Both failures occurred during an unplanned demand. One failure was the result of an

isolation of the turbine steam supply caused by a high room delta-T instrument indicating a steam line leak; however, no leak existed. The cause of the high room delta-T was excessive room cooling resulting from low service water temperatures. The isolation was classified as a failure to run and was not recovered by operator actions. The other failure was a failure to start event caused by a malfunction of the steam supply valve to open. This was a design problem that was corrected by changing the valve configuration from normally closed to normally open. Both of the unplanned demand failures at Perry were selected for ASP analysis, and the events were assigned CCDPs of 1.4E-6 and 6.6E-6, respectively.

The other eight failures all occurred in 1987. Five of the failures were reoccurring problems with the steam supply line MOV that were corrected. Three were recurring problems with the steam leak detection system that were corrected, and one was a result of a personnel error. The recurring failures of the steam supply line MOV and steam leak detection circuit were all problems occurring shortly after receiving the low-power license. The unplanned demands that occurred at Perry were distributed throughout the study period and were typically a result of feedwater problems resulting in reactor scrams.

Pilgrim—Pilgrim has a relatively high failure frequency as compared to the industry average. A review of the factors contributing to the system unreliability indicated that two failures were observed during unplanned demands (no cyclic surveillance test failures were observed). Both of the unplanned demand failures at Pilgrim were selected by the ASP program for analysis. In these events the RCIC failure occurred concurrent with a HPCI failure or a loss of offsite power. The resulting CCDP for these events was 8.4E-5 and 1.2E-4. The failures during unplanned demands at Pilgrim were classified as failures to start. One failure was attributed to an improper manual start sequence as specified in the operating procedure and/or a loose mechanical overspeed trip. This failure was not recovered by operator actions. The other was the result of the operator not opening the injection valve as specified in the procedure for a manual start (the location of the flow element contributed to the failure). This failure was subsequently recovered.

A review of the individual failure events (all 10 reported failures) for Pilgrim indicated approximately 60% of the failures can be attributed to personnel error or procedure problems. The other 40% were hardware-related malfunctions. These failures occurred on an average of about two per year from 1990 through the end of the study period, with four failures occurring in 1993. The failures at Pilgrim primarily contributed to the FTSO failure mode. The failures were found in all subsystems (except the coolant piping and valves subsystem) and included failures of the governor, the trip throttle valve, the steam supply MOVs, the flow controller, and the steam leak detection instrumentation.

Quad Cities 1—Quad Cities 1 has a failure frequency that is relatively high as compared to the industry average, and a relatively low unplanned demand frequency. All ten failures that were observed at Quad Cities 1 occurred from 1987 through 1991. Only one unplanned demand occurred during this review period. A review of the operating data for these years indicated that about half of the failures were caused by malfunctions of either the pump discharge or steam supply valves. Examples include torque switches set wrong, dirty limit switch contacts, binding of the torque switch cam, and contacts failing to close due to the roller binding.

Even though Quad Cities 2 had a relatively low failure frequency of 0.92 and a relatively low unplanned demand frequency (0.37), three of the five observed failures contributed to the unreliability estimate provided in Section 3. Of these three failures, one was observed during an unplanned demand, and two were observed during the performance of cyclic surveillance tests. These failures were all classified as

failures to start. The unplanned demand failure was the result of operator error in starting the system during a loss of feedwater event. The operator inadvertently tripped the turbine during the start sequence. The trip was reset and the system was manually restarted several minutes later. Both of the reported failures that occurred during cyclic surveillance tests were associated with the flow controller. One flow controller problem was caused by the proportional band being set too narrow. A small change in the controller output caused large fluctuations in the process variable, which produced offscale flow oscillations. The other flow controller failure occurred during the next cyclic test (two years later) and was the result of the same proportional band adjustment problem.

4.3 Evaluation of RCIC Failures Based on Low-power License Date

To determine if the age of the plant affects RCIC performance, a trend of plant-specific total failures per operational year was plotted against the plant low-power license date. The failure frequency for a plant was estimated as: (number of failures)/(number of plant operational years), with plant operational years estimated as described in Section A-1.3 of Appendix A. The frequencies and 90% Bayesian intervals are plotted in Figure 20. A fitted trend line and 90% confidence band on the fitted line are also shown in the figure. A similar plot based on unreliability for short term missions was presented earlier in this report (Figure 7). Shown in Figure 20 noticeably it is not statistically significant (P-value = 0.17). Specifically, there was no correlation observed between the plant's low-power license date and the frequency of failures per operational year. The average number of failures per operating year was 0.62, and this average frequency was observed for plants licensed from 1970 through 1990. Two plants licensed in the 1970s (Pilgrim and Quad Cities 1) and two plants licensed in the 1980s (LaSalle 1 and Perry) had relatively high failure frequencies. Considering that about half of the plants in the study were licensed in each time frame (i.e., 1970s and 1980s) having two plants in each time frame with high failure frequencies is consistent with the trend indicated in Figure 20.

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 operating 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 RCIC system was identified in the ASP database.

The search resulted in the identification of 31 events in which the RCIC system was mentioned. Of these 31 events, five simply stated that RCIC was available without mentioning any RCIC inoperability or actuation, therefore, only 26 events were analyzed further. The 26 ASP events were evenly distributed over the seven year review period ranging from two events in 1988 to five events in 1987, 1989, and 1991. These events occurred at 17 different plants. Pilgrim, Hatch 1, Perry, and Brunswick 2 each accounted for three events (12% each), Hatch 2 accounted for two events (8%). The other 12 events occurred at twelve different plants.

Twenty-five of the ASP events were related to a demand of the RCIC system; 13 identified a system malfunction during an unplanned demand, and 12 were unplanned demands with no system malfunction. A brief description of the ASP events that identified a system malfunction during an unplanned demand is provided in Table 15. The ASP events that identified a RCIC unplanned demand without a system malfunction or a potential need of the RCIC system when it was out of service for maintenance are listed in Table 16.

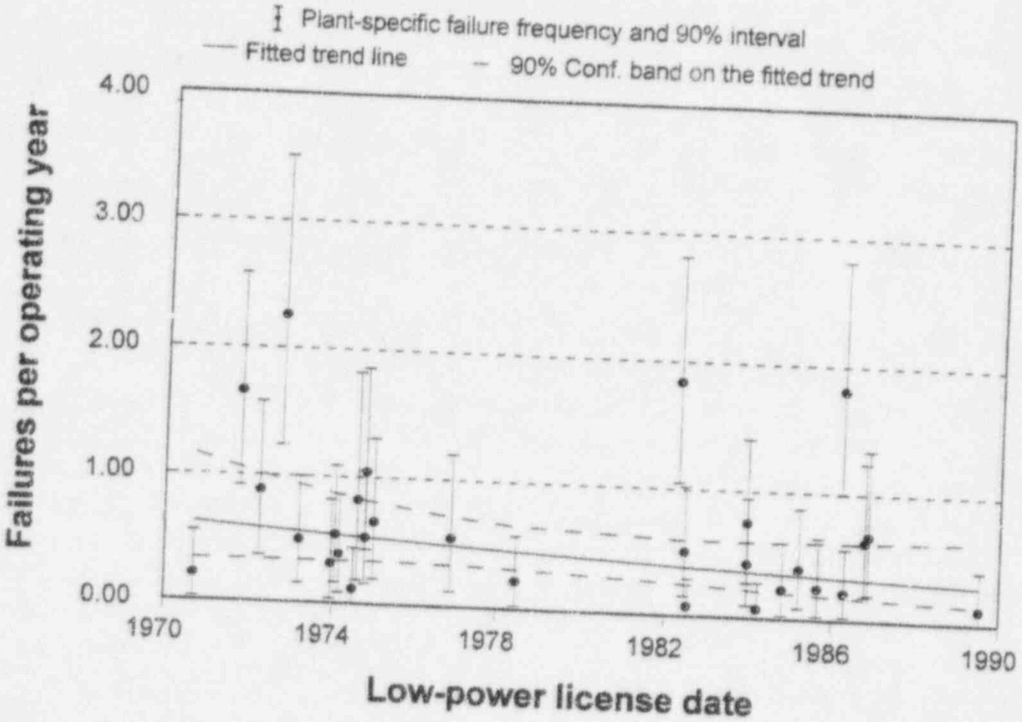


Figure 20. Plant-specific RCIC system failures per operating year, plotted against low-power license date. The decreasing trend is not statistically significant (P-value = 0.17).

The ASP events that identified a demand and subsequent RCIC system malfunction had a CCDP that ranged from 1.2E-6 to 2.9E-4. No common element was found in the ASP events for which the RCIC system malfunctioned. The ASP events that indicated that a demand of the RCIC system had occurred were primarily initiated or caused by turbine trip events, loss of feedwater events, or loss of offsite power events. The causes of the RCIC malfunctions were also diverse. Three of the malfunctions were RCIC turbine overspeed trips caused by inappropriate operator actions while manually starting the system or switching from manual to automatic control. Two of the malfunctions were failures of the steam supply valve to open. The remaining eight failures were all for different causes.

The ASP events that identified a RCIC demand with no system malfunction had a CCDP that ranged from 6.5E-6 to 3.8E-4. Three of the ASP events indicated that the RCIC system was demanded to restore RPV level as a result of vessel isolation. Three of the ASP events involved use of the RCIC system to restore level in response to a main turbine trip event; two events were initiated due to loss of feedwater; and two events were initiated by loss of offsite power. One ASP event was caused by a loss of service water, and one event was only a partial actuation of the RCIC system, with no injection into the reactor vessel.

Table 15. Summary of the ASP events in which a RCIC malfunction was identified during an unplanned demand.

Plant name	LER number	Event date	CCDP	Description
Brunswick 2	32487001	01/05/87	2.4E-4	A failure of the voltage regulator caused a turbine trip, which resulted in a reactor scram and SRV actuations to limit RPV pressure. RCIC was started to control RPV level; however it was ineffective because the full flow test line was partially open. During the time RCIC system was degraded, HPCI was inoperable due to the injection valve failing closed. After isolating the RCIC full flow test line, both CRD pumps and RCIC were used to restore RPV level.
Grand Gulf	41689016	11/07/89	1.2E-6	A reactor scram was caused by an electrical spike from a lightning strike. The RCIC system received an actuation signal but was out of service in preparation for surveillance testing. Vessel level was recovered by the feedwater system.
Hatch 1	32187011	07/23/87	7.7E-6	A loss of feedwater resulted in a reactor scram. RCIC automatically actuated but tripped on overspeed due to a failure of an electronic component in the electric governor magnetic pickup module.
Hatch 1	32188018	12/17/88	1.5E-5	A reactor scram occurred when the turbine tripped due to loss of electrohydraulic control system pressure. After use of the RCIC system, the RCIC turbine steam supply valve failed to close fully due to a loose yoke bushing. During subsequent restart of the RCIC system, the turbine tripped on overspeed due to the turbine supply valve previously not going completely closed. The turbine was reset and restarted. This scenario was repeated several times while safety relief valves were used for pressure control.
Hatch 1	32191001	01/18/91	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. During subsequent recovery actions, RCIC failed due to failure of the injection valve. Injection valve failed when being closed from initial actuation.
Hatch 2	36688017	05/27/88	2.0E-5	A loss of feedwater resulted in a reactor scram. RCIC automatically started but the pump failed to ramp up to full speed due to a failure of a limit switch on the injection valve.
LaSalle 2	37492012	08/27/92	6.1E-6	A reactor scram occurred when the turbine tripped due to a failed thrust bearing indication. RCIC automatically started but later tripped due to high reactor vessel level. Two subsequent attempts to restart RCIC resulted in trips due to high exhaust pressure caused by water in the steam lines downstream from the turbine. The third attempt to start RCIC was successful.
Perry	44087012	03/02/87	6.6E-6	A loss of feedwater resulted in a reactor scram. The RCIC received an automatic actuation signal but didn't initiate due to failure of the steam supply valve to open.
Perry	44090002	01/07/90	1.4E-6	A loss of feedwater resulted in a reactor scram. The RCIC automatically actuated but tripped after 37 minutes due to high room differential temperature. The high differential temperature trip was

Table 15. (continued)

Plant name	LER number	Event date	CCDP	Description
				caused by cooling water flow and the differential temperature trip set-point set improperly for winter time operations.
Pilgrim	29390013	09/02/90	8.4E-5	A failure in the feedwater control system caused the operators to manually scram the reactor. RCIC manually started but tripped on overspeed. Two more attempts were made, but both resulted in overspeed trips. HPCI was manually started for level control; however, turbine trips on startup and subsequent flow oscillations were noted until the system was taken to manual control. The RCIC trips were caused by an inadequate procedure and looseness in the mechanical overspeed linkage.
Pilgrim	29391025	10/30/91	1.2E-4	A loss of offsite power occurred shortly after the plant was shut down in response to a severe storm. RCIC was manually started but tripped on overspeed when the injection valve was not opened promptly after starting the turbine. RCIC was reset and started; however, starting an RHR pump caused a voltage transient that tripped the RCIC inverter and prevented RCIC from attaining rated flow. The RCIC system was shut down, the inverter reset, and RCIC started successfully.
Pilgrim	29393004	03/13/93	4.6E-6	A loss of offsite power and reactor scram were caused by a severe storm. RCIC was used several times during shut down for level and pressure control. An overload alarm was received on the RCIC turbine barometric condenser condensate pump, but it did not affect the operability of the RCIC system.
Vermont Yankee	27191009	04/23/91	2.9E-4	A switchyard breaker failure caused a turbine trip and reactor scram. RCIC tripped on overspeed due to operator error while switching from manual to automatic control.

Table 16. Listing of the ASP events that identified a RCIC unplanned demand without a system malfunction or a potential need of the RCIC system when it was out of service for maintenance.

Plant name	LER number	Event date	CCDP
Brunswick 1	32591018	07/18/91	6.0E-5
Brunswick 2	32487004	03/11/87	1.9E-5
Brunswick 2	32489009	06/17/89	3.6E-5
Duane Arnold[a]	33189003	02/02/89	6.5E-6
FitzPatrick	33389020	11/05/89	1.3E-5
Hatch 2	36690001	01/12/90	6.0E-5
LaSalle 1	37393015	09/14/93	1.3E-4
Limerick 2[b]	35389013	12/11/89	1.5E-5
Nine Mile Pt. 2	41091017	08/13/91	3.8E-4
Perry	44093010	03/26/93	1.2E-4
Quad Cities 1	25492004	02/06/92	6.9E-6
Wash. Nuclear 2	39787002	03/22/87	6.5E-6

a. This ASP event was a potential demand of the system when it was out of service for maintenance. However, the system did not receive a start signal, nor was it required to inject.

b. This ASP event identified a short duration demand of the RCIC system; however, the signal cleared before RCIC could start and inject to the RPV.

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Appendix A
RCIC Data Collection and Analysis Methods

Appendix A
RCIC Data Collection and Analysis Methods

To characterize reactor core isolation cooling (RCIC) system performance, operating data pertaining to the RCIC system from U.S. commercial nuclear boiling water reactor plants having RCIC systems were collected and reviewed. This appendix provides descriptions for the data collection and the subsequent data characterization for the estimation of RCIC system unreliability. The descriptions give details of the methodology, summaries of the quality assurance measures used, and discussions of the reasoning behind the choice of methods.

A-1. DATA COLLECTION AND CHARACTERIZATION

The source of RCIC system operating data used in this report was LERs found using the Sequence Coding and Search System (SCSS) database. The SCSS database was searched for all RCIC records for the years 1987 through 1993. To ensure the data set was as complete as possible given the LER reporting requirements, a search was conducted of all the immediate notification reports required by 10 CFR 50.72 for the same time period that mentioned the RCIC system. The immediate notification report search results identified fewer events than the SCSS LER search results. Moreover, the RCIC events identified in the immediate notification reports were also captured in the LERs. Also, the immediate notification reports did not contain the detail necessary to conduct a reliability analysis. This being the case, only the LER data were used in this report.

In the subsections below, methods for acquiring the data used in this study are described.

A-1.1 Inoperability Identification and Classification

The LER rule (10 CFR 50.73) specifies when events are to be reported to the NRC. The section most relevant to the reporting of RCIC system inoperabilities is 10 CFR 50.73(a)(2)(v): *Any event or condition that alone could have prevented the fulfillment of the safety function of structures or systems that are needed to: (A) Shut down the reactor and maintain it in a safe shutdown condition; (B) Remove residual heat; (C) Control the release of radioactive material; or (D) Mitigate the consequences of an accident.* However, RCIC is not part of the emergency core cooling system (ECCS) nor is it normally classified as an engineered safety feature (ESF). Therefore, it is not clear that RCIC is relied upon to perform a safety that would be directly reportable. Nevertheless, all plants with RCIC systems have submitted LERs documenting RCIC inoperabilities, with the majority being reported under section (a)(2)(v).

Since it is not normally classified as an ESF, RCIC system actuations are not specifically covered by the event reporting rules [i.e., section (a)(2)(iv)]. However, the RCIC shares low-low reactor water level actuation setpoints with the ESF high pressure coolant injection or high pressure core spray systems (HPCI/HPCS). Event reporting requirements, state that each LER (i.e., HPCI/HPCS actuation report) shall contain a clear, specific, narrative description of what occurred so that knowledgeable readers not familiar with the details of a particular plant can understand the complete event. Thus, any unplanned actuation of RCIC from low-low reactor water level will also result in a reportable actuation of HPCI/HPCS and the report on the HPCI/HPCS should also describe the RCIC system actuation. All

HPCI/HPCS actuations were reviewed in order to verify and count the number of RCIC unplanned demands.

RCIC is commonly included in plant technical specifications (TS) because of its similar function to the ECCS. Therefore, RCIC system failures are directly reportable if the system function is lost for a period that exceeds the TS Limiting Condition for Operation (LCO) or if the reactor completes a shutdown in order to correct a RCIC malfunction [i.e., section (a)(2)(i)].

A full function test of the entire RCIC system is nominally to be conducted every 18 months (typically required by TS). This is the basis for estimating RCIC test demands. Corrections to this 18 month cycle are based on information provided in monthly operating reports, and are included to account for shorter of longer operating periods. As mentioned above, RCIC failures in general, might not necessarily be required to be reported under section (a)(2)(v). However, the LERs reviewed for this study (i.e., 1987-1995) identified three instances where failures of RCIC were reported during the cyclic tests. An engineering and statistical comparison of these failure data (failures and demands) with those identified during unplanned demands indicated that the two data sets were similar and because of this, the cyclic test data were used and pooled with the demand data in the analysis of RCIC reliability. The net effect of not including the cyclic test data due to concerns relating to reportability of failures increases the uncertainty of the failure probability estimates without changing the mean value for the system appreciably. These reporting requirement, in combination with the other reporting criteria and the knowledge of RCIC actuations concurrent with reportable HPCI/HPCS actuations, provides a sufficiently accurate sample of RCIC demands and associated failures to make meaningful RCIC demand reliability estimates.

In this report, the term *inoperability* is used to describe any reported RCIC malfunction. The inoperabilities were subsequently classified as *faults* and *failures* for purposes of computing reliability estimates. The fault and failure classifications were based on an independent review of the events. The term *failure* is used to identify the subset of the inoperabilities for which the coolant injection function of the RCIC system is lost. The term *fault* is used to describe the subset of inoperabilities that are not classified as failures.

A-1.1.1 Failure Classification

Each of the LERs identified in the SCSS database search was reviewed by a team of U.S. commercial nuclear power plant experienced personnel, with care taken to properly classify each event and to ensure consistency of the classification for each event. Because the focus of this report is on risk and reliability, it was necessary to review the full text of each LER and classify or exclude events based on the available information reported in the LER. Specifically, the information necessary for determination of reliability, such as, classification of RCIC failures and faults, failure modes, failure mechanisms, causes, etc. in this report were based on the independent review of the information provided in the LERs.

Two engineers independently evaluated the full text of each LER from a risk and reliability perspective. At the conclusion of the independent review, the data from each independent LER review were combined, and classification of each event was agreed upon by the engineers.

Failure classification of the inoperability events was based on the ability of the RCIC system to function as designed. Each LER was reviewed to determine if the system reasonably performed its assigned function. Examples of the types of inoperabilities that are classified as failures include:

- Malfunction of the initiation circuit, preventing the system from starting automatically.
- Malfunction of the injection MOV to open with the turbine operating properly and RPV water level at or below the initiation setpoint.
- RPV water level at or below the initiation setpoint and the system out of service for pre-planned maintenance.
- Malfunction of the flow controller either preventing the system from providing flow to the RPV, or requiring the operator to place the controller in manual because of erratic operation.
- Failure of the test return-line MOV to close when demanded.
- Spurious closure of the containment isolation valves during system operation.
- Turbine overspeed trips on startup.
- Personnel error in operation of the flow controller, causing the turbine to trip.

The RCIC events identified in this study as failures represent actual malfunctions that prevented the successful operation of the system. When the RCIC system receives an automatic start signal as a result of an actual low RPV water level condition or a manual start, the system functions successfully if the turbine starts and obtains rated speed and pump 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, the following failure modes were observed in the operating data:

- Maintenance-out-of-service (MOOS) occurs if, due to maintenance, the RCIC system is prevented from starting during an unplanned demand.
- Failure to start (FTS) occurs if the system is in service but fails to automatically or manually start, obtain rated speed in the turbine, develop sufficient injection pressure, and provide flow to the reactor pressure vessel.
- Failure to run (FTR) occurs if, at any time after the system is delivering sufficient coolant flow, the RCIC system fails to maintain this flow to the RPV while it is needed.
- Failure to restart (FRS) occurs if, during an unplanned demand after a successful start and run to restore RPV level, the RCIC system is shutdown (manually or as a result of a high level trip), and subsequently the system is demanded to restart (automatically on low vessel level or manually) and fails to restart. The failure to restart can occur on any restart attempt.
- Failure to transfer during recirculation (FRC) occurs if, during an unplanned demand of the system, the test return-line MOV is opened to divert flow from the RPV to the CST and subsequently fails to close, or the injection valve fails to re-open, resulting in no flow to the vessel for level restoration.

Recovery of failures is important and was considered when estimating system unreliability. To recover from a failure, operators have to recognize that the system is 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 MOV 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 for the other failure modes is defined in a similar manner. Each failure during an unplanned demand was evaluated to determine whether recovery by an operator occurred.

In addition to the failure mode data, other information concerning the event was collected from the detailed review of the full text of the LER:

- The plant conditions at the time of the event (e.g., power operations, hot/cold shutdown, or refueling).
- For events classified as failures to run, the run time before the failure.
- The immediate cause of the event (e.g., hardware, personnel, or procedures)
- The subsystem and component involved.
- The method of discovery of the event (unplanned demand, surveillance test, other routine plant operations), and for surveillance tests, the test frequency.

For the events not classified as failures, the analysis section of each LER provided information to aid in determining if the system would have been able to perform as required even though the system was not operable as defined by plant technical specifications. As an example, the LER may have been submitted specifically for the late performance of a technical-specification-required surveillance test. This event would be classified as a fault and not a failure in this study. This classification is based on the judgment that given a demand for the system, the system would still be capable of functioning as designed. Moreover, plant personnel typically would state in the LER that the system was available to respond and that the subsequent surveillance test was performed satisfactorily. If the system failed the subsequent surveillance test the event would have been classified as a failure.

In addition, administrative problems associated with RCIC were also classified as faults, given the system had successfully passed a recent surveillance test or remained operable as defined by the requirements identified in safety analysis reports or a plant-performed engineering analysis. As an example, the discharge piping was found not to have the required number of seismic restraints. However, the results of an engineering analysis for the missing restraint provided by the plant in the safety analysis section of the LER indicated that the existing system configuration would adequately perform its assigned mission. From the information provided by plant personnel in the LER, the event would be classified as a fault.

As a result of the review and evaluation of the full text of the LER, the number of events classified as failures and used in this study to estimate RCIC unreliability will differ from the number of events and classification that would be identified in a simple SCSS database search. Differences between the data used in this study and a tally of events from a SCSS search would stem primarily from the reportability requirements identified for the LER and the exclusion of events for which the failure mechanism is outside the RCIC system boundary defined for this study.

Each LER usually has the reportability requirements identified in Block 11 of page 1. As an example, the event is reported based on the requirements identified in 10 CFR 50.73 (a)(2)(i), technical specification prohibited operation or condition. The LER may be submitted specifically for the late performance of a technical-specification-required surveillance test. This event would be classified as a failure in the SCSS coding methodology. However, for this study late performance of a surveillance test was classified as a fault.

Other differences would be observed because the definition of failure used in this study and that used in the SCSS database are not the same. Specifically, a system that is out of service for maintenance at the time of an unplanned demand would not be classified as a failure in the SCSS database, however, it would be classified as a failure for this study in an effort to estimate a maintenance-out-of-service

unavailability. Also, the SCSS database would identify a system as failed if the system is out of service for pre-planned maintenance and another system subsequently fails, for example, if the RCIC system is out of service for maintenance when the HCPI system fails a surveillance test. The SCSS database would identify both systems as failed; however, pre-planned maintenance of the RCIC system without a corresponding demand is not counted as a failure in this study.

Because of these differences, the reader is cautioned from making comparisons of the data used in this study with a simple tally of events from SCSS without first making a detailed evaluation of the data provided in the LERs from a reliability and risk perspective. The results of the LER review and classification are provided in Appendix B, Section B-2.

A-1.2 Demands

To estimate unreliability, demand counts must be associated with failure counts. The set of system demands must be complete and consistent with the set of failures in order to be used in the reliability calculations. Two criteria are important in selecting data sets for reliability analysis. First, the data must of course, be *countable*. Reasonable assurance must exist that the total number of events can be estimated, that all failures associated with these events will be reported, and that sufficient detail will be present in the failure reports to match the failures to a complete set of corresponding demands.

The second criterion is that the demands must reasonably approximate the conditions being considered in the unreliability analysis. The unplanned demands or tests must be rigorous enough that successes as well as failures provide meaningful system performance information. Since one of the purposes of the study is to compare unreliability estimates based on plant operating experience with the unreliabilities predicted by the PRAs, it is important that the unplanned demands included in the study be as challenging as the scenarios modeled in the PRAs.

A-1.2.1 Unplanned Demands

LERs can be used to provide information on unplanned demands following plant transients that resulted in an actual low RPV water level condition (that is, an actual need for the RCIC system). These unplanned demands were identified by searching the SCSS database for all LERs containing critical reactor scrams for plants having a RCIC system during the 1987-1993 study period. Critical reactor scram events are reportable under 10 CFR 50.73 (a)(2)(iv). In addition to critical reactor scram events, unplanned HPCI and HPCS engineered safety feature (ESF) actuations are reportable under the same reporting requirements as reactor scrams. The LERs reporting ESF actuations of these system were also searched for RCIC actuations.

LERs reporting critical reactor scram events were reviewed to determine if the RCIC system was used to control RPV water level during the scram. Also, for the critical reactor scram events that identified a feedwater problem, a main steam line isolation valve closure, or turbine supply valve closure, any use of the RCIC system would be identified in the LER. Unplanned HPCI and HPCS ESF actuations on low RPV water level are typically at the same setpoint as for the RCIC system. Therefore, RCIC actuations would be found in the LERs reporting HPCI and HPCS actuations. As a result, identification of all the RCIC demands associated with a RPV water level transient is possible, even if

the system is not a designated ESF system, by a search of the LERs for critical reactor scrams, and HPCI and HPCS ESF actuations, which are reportable.

The LERs that described RCIC actuations were screened to determine the nature of the RCIC actuation. The RCIC actuations identified in the LERs that were classified in this study as RCIC unplanned demands were events that resulted in actual coolant flow to the RPV. RCIC failures observed during a low vessel level condition, which normally would have resulted in flow to the vessel, were also included in the unplanned demand count. In addition, events where a low RPV water level condition existed (that normally would have required RCIC to start) and the RCIC system was identified as out of service for maintenance were also included in the unplanned demand count. For each of the unplanned demands, the associated running time and the number of restarts were obtained if it was stated or could be reasonably estimated from the sequence of events stated in the LER. This determination was particularly important for quantifying the failure modes associated with the long term and PRA missions, as explained in Section A-2.

Some of the RCIC actuations identified in the LERs were demands of only a part of the system. These partial demands did not exercise the RCIC system in response to an actual need for injection, because RPV water level was restored using another source (typically feedwater) before the injection MOV opened. These events were excluded from the count of RCIC unplanned demands because the demands did not meet the second criterion identified above. That is, the partial demands did not reasonably approximate the conditions being considered in the unreliability analysis. This conclusion is based on: (1) the injection MOV was not required to open, thereby completing the start sequence of the system, and (2) the flow controller was not required to operate in the same manner as would be observed during situations that result in flow to the vessel.

Other events excluded from the demand counts include ESF actuations associated with containment isolation. ESF actuations associated with RCIC's containment isolation function were excluded even though they are reportable in LERs [10 CFR 50.73(a)(2)(iv)], because the containment isolation function was outside the scope of this study. Specifically, demands for closure of the turbine steam supply and/or exhaust valves are not germane to estimating RCIC injection reliability.

Because of the above identified exclusions from the count of unplanned demands, the reader is cautioned from making comparisons of the data used in this study with a simple tally of events from SCSS without first making a detailed evaluation of the data provided in the LERs based on a full system response to a low RPV level transient. The results of the LER review and evaluation for unplanned demands are provided in Appendix B, Section B-3.

A-1.2.2 Surveillance Tests

Data from the surveillance tests that are performed on a periodic basis may be used to estimate selected aspects of RCIC system unreliability. For reasons described below, surveillance tests that are conducted on a cyclic interval (approximately 18 month) were included in the unreliability calculation for the RCIC system.

Routine surveillance tests of the RCIC system are performed every operating cycle, quarter, and month. As discussed in Section 2.2.1, the RCIC system 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 demands modeled in the PRAs, the completeness of each of these tests was evaluated based on a detailed review of several sets of technical specifications. 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 start 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 RCIC turbine to sustain coolant flow (through the test return line) over a period of time is also verified. Therefore, the cyclic surveillance tests were regarded as demands on the system that reasonably approximated the conditions being considered in the unreliability analysis. However, these cyclic surveillance tests do not in all cases challenge the injection MOV at the pressures, flow rates and temperatures that the system would experience during a demand for RPV level restoration. Some plant technical specifications actually state that injection of coolant into the reactor vessel may be excluded from the test. Therefore, the injection MOV was excluded from consideration in the analyses. 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 after a refueling outage.

- The quarterly tests also test the system except for the injection MOV. 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 could not be estimated. In addition, hot quick starts and slow starts of the turbine are generally performed during these tests. Because a hot quick start and a slow start are not the type of starts the system would experience during a demand for RPV level restoration following a transient, these demands were not considered as reasonably approximating the conditions being considered in the unreliability analysis. Therefore, both quarterly and post-maintenance test results were not used for estimating unreliability.

- Monthly tests typically exercise only part of the system (i.e., MOV cycling, instrument calibration checks, etc.), and therefore were not used in the unreliability estimates. These surveillance tests were not regarded as demands on the system that reasonably approximated the conditions being considered in the PRAs.

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 startup from refueling outages. These startup dates are found in the monthly operating reports submitted by the licensee and entered in the NRC's OUTINFO database. For this study, a plant was assumed to perform the cyclic surveillance test after each refueling outage. If the time to the start of the next refueling outage was more than 550 days (18 months), the necessary number of intermediate tests were assumed.

A-1.3 Times for Rates

The reported system failures and unplanned demands were characterized and 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 operating year. Thus, estimation of the operating time for each plant and year was also part of the data collection. Operating time, ideally, is the time when the reactor pressure is at or above the pressure requirement identified in plant technical specifications for RCIC operation. This time was not known exactly. The NRC's 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 operating 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.

Rates were also used to quantify the overall probability of failure to run and the probability of failure to switch to an injection mode of operation from the recirculation mode for the PRA mission. For these calculations, the injection and recirculation run times stated in the LERs were used for the unplanned demands. However, in about half the instances, the duration of the run time was not specified in the LERs. For the purpose of estimation, the run times were separated into those known or believed to be greater than 15 minutes, called long, and those that were less than 15 minutes, called short. The short run times were applied only to the failure to run mode, and not to the recirculation failure mode. The short demands for RCIC injection typically only result in RCIC starting and injecting long enough to restore RPV level. These short demands were with normal feedwater available, which was used to maintain RPV water level after the level was restored. The engineering and operational aspects of the RCIC function when normal feedwater is not available require the RCIC system to be used for longer periods of time until normal feedwater is restored. In these long demands RCIC would restore RPV level and then be placed in the recirculation mode until RPV level dropped sufficiently to require subsequent injection. For the long run time missions the exposure times were applied to both the failure to run and failure to transfer during recirculation modes. For both sets of demands, an average run time was calculated based on the known run times. The duration of the unknown run times was then approximated using these averages. In practice, this algorithm resulted in an estimate of 0.06 hours per unspecified short run time, and 2.53 hours per unspecified long run time.

As noted in the section on tests (above), based on the operating experience obtained from the LER narratives and discussions with plant-experienced operators, one and one-half hours of running time was estimated for each cyclic test. This time was applied in estimating overall failure to run probabilities. It was not used for the failure during recirculation mode because that failure mode is failure to transfer from recirculation to injection, and injecting into the RPV is not part of the test.

A-2. ESTIMATION OF UNRELIABILITY

RCIC unreliability estimates were generated for two operating missions and a PRA-based mission. In the operating missions, each LER was treated as a single mission, either short term or long term. Each mission was treated as a success or a failure. As discussed in Section 3.1.1, the following failure modes were considered for the short term operational missions: maintenance-out-of-service (MOOS), failure to start other than the injection valve (FTSO), failure to recover from FTSO (FRFTS), failure of the injection valve to open (FTSV), and failure to run in the short term mission (FTR-ST). Failures to start were divided into two modes, FTSV and FTSO, because the injection valve is isolated before the cyclic surveillance operability testing (the balance of the system is tested). Recovery from FTSV and from FTR-ST were not modeled because there were no data (no demands for either recovery).

The estimate for failure to run in the short term mission was based solely on the unplanned demands that were identified as short term missions.

RCIC system requirements are more rigorous for long term operating missions. In addition to the MOOS and failure to start components described above (FTSO, FRFTS, and FTSV), the long term mission requires a longer and more varied running period, recirculation, and possibly system restarts. Failure to run in the long term mission (FTR-LT) was estimated from the number of long term missions, including cyclic test missions, and the associated failures. Failure to recover (FRFTR) from these failures was also modeled, using the unplanned long-term mission events. Long term mission recirculation (FRC-LT) and failure to recover from these events (FRFRC) were modeled in the same way as the long term failures to run, except that testing data were not judged applicable. Three failure modes were associated with restart failures: the probability of restart being needed in an event (IFRS), the probability of a restart failure given an event needing one or more restarts (FRS-LT), and the probability of failure to recover from such events (FRFRS).

As discussed in Section 3.2, ten failure modes were identified for the estimation of unreliability for the PRA mission. They are similar to the long term mission, but with the following exceptions:

Failure to run (FTR): Since the PRA mission time postulated in the PRA/IPEs spans running times of at least 6 hours and as long as 24 hours, the actual running time associated with each event was used to develop a failure rate. The fact that short missions provide less information concerning long term running than long missions was thus considered; both sets of events were used.

Failure to recover from FTR (FRFTR): Failures from both short and long term missions were combined to estimate the FRFTR probability (numerically, the same results were obtained as for the long term mission, since no running failures were observed in the short term missions).

Failure during recirculation (FRC): As with failure to run, the actual running times were used to quantify a rate of failure. The rate was based on those running periods that were at least 15 minutes long.

Failure to restart (FRS): The PRA-based mission modeling differs in two ways from the long term operating mission. These differences are explained below.

In accordance with the treatment of restarts in the IPE models, which tends to be sketchy and not detailed, exactly one restart was assumed for the PRA-based mission. After the initial injection of coolant, a restart followed by continued operation in the recirculation mode is assumed. Of course, the frequency of events requiring restart is not applicable to the PRA mission, since the PRA mission assumes rare degraded conditions (such as a small break LOCA) that generally are not seen in the operating data.

Since a single restart is assumed, its failure probability estimate is based on the total number of restarts observed in the data, rather than the number of events having one or more restarts. Furthermore, all events rather than just long term mission events are considered (three restarts occurred among 56 short term missions, whereas 43 restarts occurred among 72 long term missions). For MOOS, FTSO, FTSV, FRFTS, FRFRC, and FRFRS, no differences from the modeling for the long term mission apply.

In the statistical analysis process for the PRA-based mission, a rate-based analysis was performed for two failure modes, FTR and FRC. For FTR, most of the demands were relatively short compared with the mission times typically assumed in PRAs. Rate-based models specifically account for the fact that unreliability tends to increase as the mission time gets longer. The data provided no evidence that the failure rates were increasing or decreasing.

Since actual running times were often unknown, these were estimated for much of the data. This introduces additional uncertainty into the estimates. For example, the estimated standard deviation of the average used for the unknown long run times is approximately 22% of the average. This uncertainty has not been accounted for in the overall estimates. However, the effect of this uncertainty parameter on the overall model uncertainty is negligible. For the current study, use of the rates to account for longer mission times was important in spite of the fact that the uncertainty in this process was not quantified, since a large range of running times was present in the operating events.

For failure to transfer during recirculation, a natural estimate of the probability of failure for the PRA mission would come from the ratio of the number of failures and number of times transfers were attempted. However, the LERs do not provide the transfer demand information. Assuming that the number of demands is proportional to the total time spent in the recirculation mode leads to the use of an occurrence rate for this failure mode for the PRA mission. For modeling purposes, recirculation was assumed to be the mode of RCIC operation during demands lasting at least one-quarter hour. As with the failure to run, the uncertainty associated with estimating the length of the unspecified recirculation running times using an average based on known running times was not quantified in the current study.

Recovery modes were modeled for applicable initial failure modes; i.e., each initial failure mode was considered except for MOOS. The two failure to start modes, FTSV and FTSO, were not combined in the modeling of recovery because no injection valve failures occurred. Thus, no information exists in the operating data to characterize recovery from FTSV separate from an overall failure to start recovery. The other three recovery modes correspond naturally to divisions in the data. Actions to recover from failures to start generally differ from the types of actions required to mitigate failures to run, failures to restart, and failures to transfer out of recirculation.

In the PRA/IPE comparisons, the recovery failure modes are included. Although PRAs typically model recovery separately, the recovery event defined for this study encompasses only those failures for which no actual diagnosis and physical repair of a failed component occurred. Examples of these events include the recovery of a failure related to automatic start that was recovered by the operator manually starting the system. This kind of recovery is different from PRA-defined recoveries that require diagnosis and actual repair of failed equipment that will restore the system to operating status. Generally, PRAs take credit for the recovery failure modes defined for this study if procedures/training direct the operator to perform these actions.

The individual failure mode probabilities identified for the short term mission and the probabilities identified for the long term mission were combined to estimate the total unreliability for each of these missions. Similarly, the individual failure probabilities, failure rates, and mission times were combined to estimate the total unreliability for the PRA mission. Estimating each unreliability and its 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

Out of service for maintenance is only associated with an unplanned demand of the RCIC system's injection function. Recovery is typically not attempted after a failure on a test. Surveillance tests do not involve attempts to inject or to transfer during recirculation to injection. The surveillance tests were judged similar to the long term rather than the short term operational mission. Therefore, useful data for the failure modes MOOS, FTSV, FRFTS, FTR (short term), FRC, FRFRC, IFRS, FRS, and FRFRS, were found only in the unplanned demands, not in the cyclic surveillance tests. For the start failure mode FTSO and the failure to run failure modes FTR (PRA-based and long term), both the unplanned demands and the cyclic surveillance tests were relevant. Statistical tests, described further below, were used to determine whether the data for the unplanned demands and tests could be combined for these modes.

A-2.1.2 Demand and Failure Counts

The unplanned demands were counted by failure mode as follows. The total number of demands, d_{full}, was obtained as described in Section A-1. This number of demands applies to the MOOS failure mode. The number of demands for FTSO was taken to be d_{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 initial demands to run was the number of demands for FTSV minus the number of unrecovered FTSV events. A run time was known or estimated for each of these events. Based on the run time, the events were divided into short and long term missions. The run times in all the events were considered for the PRA failure to run mission. The number of demands for restart was based on the number of events with restart for the long term mission and on the number of restarts indicated in the LERs for the PRA mission. In the long term mission case, the fraction of long term events that required restart was used to estimate the probability of needing one or more restarts. Additional run times accrued from each restart for which no unrecovered failures to restart occurred. The number of recirculation demands, for which run times for the transferring function were assessed, is the number of demands with total run times equaling or exceeding 15 minutes. Failures in running and failures in recirculation were modeled such that neither failure prevented observation of success for the other failure mode. For each recovery mode, the number of demands is the number of corresponding failures.

Cyclic surveillance tests also result in demands for the FTSO and FTR modes. The number of demands to start (failure mode FTSO) was 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 attempts 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 system to run; such events were not counted as demands to run. In other cases, an engineer read the LER narrative to decide if the event should be considered a demand to run. Based on discussions with plant-experienced operators, one and one-half hours of run time was estimated for each applicable test demand to run that was not cut short by failure.

A-2.1.3 Data-Based Choice of Data Sets

At this point, failures and demands or running times 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, FTSO failure probabilities and FTR rates and their associated 90% confidence intervals were computed separately for unplanned demands and cyclic surveillance tests. The confidence intervals for FTSO and FTR long term 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. Similarly, the confidence intervals for FTR (i.e., hourly failure rates) assume Poisson distributions for the number of failures observed in a fixed time period, with independent failures and a constant failure occurrence rate 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 failure probability for unplanned demands and for cyclic surveillance tests is the same was tested for the FTSO 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 for 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.

A similar procedure was used to compare the rates for failure to run in the unplanned and test demand data sets. A chi-square test was performed to assess whether the data provide evidence for separate rates in the two data sets. Further details on the assessment of failure rates are in Section A-2.1.6 below.

A-2.1.4 Additional Assessments of Data Groupings Using Demands

To further characterize individual probability estimates and their uncertainties, probabilities and confidence bounds were computed in each applicable data set and in the selected pooled data sets for each year and for each 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 between-subgroup variation is likely to result in the rejection of the hypothesis of no significant systematic variation between years, plant units, or data sources, rather than to mask existing differences in these attributes.

A-2.1.5 Estimation of Failure Probability Distributions using Demands

Three methods of modeling the failure/demand 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-shape 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 is taken to be binomial. 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. In the absence of fitted empirical Bayes distributions described in the next paragraph, 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 industry 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 would be assigned to any groups for which no demands occurred.)

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.

Alternate Method for Some Group-Specific Investigations. Occasionally, the unreliability was modeled by group (such as by plant, by year or by design class) 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, 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. Because 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 Jeffreys 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 ϕ. The uniform distribution for ϕ is noninformative. The corresponding distribution for p is the Jeffreys noninformative prior. The generalization replaces the uniform distribution for ϕ with the constrained maximum entropy distribution[A-5] for which the corresponding mean of p is the industry mean from the pooled data, $(f+0.5)/(d+1)$. The maximum entropy distribution for ϕ 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 distribution parameters 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 means instead of toward 0.5, but they were sensitive to the group-specific data because the prior distributions for each failure mode were 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, years, and classes 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 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-2.1.6 Assessments and Estimation of Failure Probability Distributions using Rates

As stated above, the FTR and FRC probabilities for the PRA model were derived from hourly rates of occurrence rather than from failures and demands. Chi-square test statistics were computed to identify significant differences, if any, among plant units and among calendar years for the two occurrence rates. Bayesian methods similar to those described above were also used. The analyses for rates are based on event counts from Poisson distributions, with gamma distributions that reflect the variation in the occurrence rate across subgroups of interest or across the industry. The *simple Bayes* procedure for rates results in a gamma distribution with shape parameter equal to $0.5+f$, where f is the number of failures, and scale parameter $1/T$, where T is the total pooled running time. An *empirical Bayes* method also exists, but the data were too sparse to find a non-degenerate distribution. Finally, the *constrained noninformative prior* method was applied in a manner similar to the other failure modes this resulted in gamma distributions for the rates. These methods are described further in References A-8 and A-4.

The resulting gamma distributions for uncertainty in FTR and FRC were converted to beta distributions describing the probability of failure during a specified mission time. Given an occurrence rate, say r, the probability of failure in mission time T (assuming a Poisson distribution for the occurrence of failures) is:

$$p(r) = 1-\exp(-rT).$$

If $E(r)$ is the mean of the rate and $V(r)$ is its variance, and r has a gamma distribution with parameters (a,b), then it can be shown that the mean of $p(r)$ is

$$1-(1 + T/b)^{-a}$$

and the variance of $p(r)$ is

$$(1 + 2T/b)^{-a} - (1 + T/b)^{-2a}.$$

These equations were applied using the gamma distribution means and variances for the rates for the two failure modes. Beta distributions having the resulting means and variances were computed by matching moments. This evaluation was performed for the mission times that span the range of mission times typically assumed for RCIC in PRAs, namely, 24 hours, 8 hours, and 6 hours.

A-2.2 The Combination of Failure Modes

The failure mode probabilities are combined to obtain the unreliability. An algebraic approximation was used to quantify the model. 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 models, the mission unreliabilities are given by the following expression:

Short term mission unreliability = Prob[MOOS or (FTSO and FRFTS) or FTSV or FTR-ST].

Long term mission unreliability = Prob[MOOS or (FTSO and FRFTS) or FTSV or (FTR-LT and FRFTR) or (IFRS and FRS-LT and FRFRS) or (FRC-LT and FRFRC)].

PRA mission unreliability = Prob[MOOS or (FTSO and FRFTS) or FTSV or (FTR and FRFTR) or (FRS and FRFRS) or (FRC and FRFRC)].

Each of these expressions 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 failure probabilities.

The estimated mean and variance of the unreliability can therefore be obtained by propagating the means and variances of the 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:

- Select appropriate beta distributions for each failure mode for the group.
- 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 first step in this process requires further discussion. When no empirical Bayes distribution can be fitted for variation between groups for a particular failure mode and grouping, such as plant, a single generic distribution describing industry performance for that failure mode is used for all the plants. However, there may be more than one choice for this distribution. Generic industry distributions may exist that reflect variation in some other variable, such as year. In that case, the distribution showing year-to-year variation is a more accurate model of the industry data for the failure mode than the noninformative distribution that reflects just sampling variation. The Jeffreys noninformative prior updated with industry data was selected only when no other empirical Bayes distributions were found for the data being analyzed. Of course, for the group-specific trend investigations for which a minimal amount of data filtering occurs, the beta distributions derived from updating the constrained noninformative priors were used.

The means and variances calculated from the above process 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 would be more accurate than this method if enough Monte Carlo runs were 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 for the overall unreliability and for unreliabilities by plant and by year in Appendix C.

A-3. ESTIMATION OF RATE DISTRIBUTIONS FOR TREND ANALYSIS

In addition to the analyses used to estimate system unreliability, the overall rates of failures, unplanned demands, and restarts per unplanned demand were analyzed by plant and by year to identify possible trends and patterns. Two specific analyses were performed for these three occurrence rates. First, the rates were compared to determine whether significant differences exist among the plants or among the calendar years. Rates and confidence bounds were computed for each type of rate for each year and plant unit. The hypotheses of simple Poisson distributions for the occurrences with no differences across the year and plant groupings were tested, using the Pearson chi-square test. The computed P-values are approximate since the expected cell counts were often small; however, they are useful for screening.

Regardless of whether particular years or plants were identified as having different occurrence frequencies, the occurrence frequencies were also modeled by plant and by year to see if trends exist. For plants, trends with regard to plant age were assessed, as measured from the plant low-power license date. For years, calendar trends were assessed. Least-squares regression analyses were used to assess the trends. The paragraphs below describe certain analysis details associated with the frequency trend analyses.

With sparse data, estimated event frequencies (event counts divided by time) are often zero, and regression trend lines through such data often produce negative frequency estimates for certain groups (years or ages). Since occurrence frequencies cannot be negative, log models are considered. Thus, the analysis determines whether log (frequency) is linear with regard to calendar time or age. An adjustment is needed in order to include frequencies that are zero in this model.

Using $0.5/t$ as a rate estimate in such cases is not ideal. Such a method penalizes groups that have no failures, increasing only their estimated frequency. Furthermore, industry performance may show that certain events are very rare, so that $0.5/t$ would be an unrealistically high estimate. A method that adjusts the frequencies uniformly for all the grouping levels (plants or years) and that uses the overall frequency information contained in the industry mean is needed for sparse data and rare events.

As stated in Section A-2.1.6, constrained noninformative priors can be formed for frequencies. This method meets the requirements identified above. Because it also produces occurrence frequencies for each group (each year or plant) in a way that is very sensitive to the data from that one group, it preserves trends that are present in the unadjusted frequency data. The method, described in Reference A-4, involves updating a prior distribution using only the data from a single group. For rates, such distributions are gamma distributions rather than beta distributions. Since industry experience is relevant for the performance of a particular group, a practical prior distribution choice is a diffuse prior whose mean equals the estimated industry mean, $(0.5+N)/T$, where N is the total number of events across the industry and T is the total exposure time. This specification for the prior distribution mean is the constraint. Keeping the prior diffuse, and therefore somewhat noninformative, allows the data to strongly affect the posterior distribution. This goal is achieved by basing the modeling on a maximum entropy distribution. The details are explained in Reference A-4; the resulting prior distribution is a gamma distribution with shape parameter 0.5 and scale parameter $T/(2N+1)$. The mean of the updated

posterior distribution is used in the regression trending. This process thus adds 0.5 uniformly to each event count and *T/(2N+1)* to each group exposure time.

In practice, an additional refinement in the application of the constrained noninformative prior method adjusts the posterior gamma distribution parameters for particular plants and years to account for the fact that the prior distribution gamma scale parameter is only estimated, not known. This adjustment[A-6] increases the group-specific posterior variances somewhat.

A-4. REFERENCES

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Appendix B

RCIC Operating Data, 1987–1993

Appendix B
RCIC Operating Data, 1987–1993

In subsections below, listings of the data used for the reactor core isolation cooling (RCIC) system 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 demands. 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. Table B-1 includes all the boiling water reactors (BWRs) with a RCIC system except for Browns Ferry 1 and 3 and Shoreham. These plants were excluded because they were in extended shutdown throughout the study period. Some of the plants listed had calendar-year-long or longer periods in which they did not operate. Specifically, 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 when they did not operate.

The operating years for each plant during the study period are shown in Table B-1. Operating years were estimated from information in the OUTINFO database. This database is developed from 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 operating periods. Periods between these dates that are at least two calendar days long are treated as outage periods and subtracted from the total number of operating days in that year for a plant.

B-2. RCIC INOPERABILITIES

The search for RCIC inoperabilities resulted in the identification of 142 inoperability events during the 1987 through 1993 time period. Some of the LERs found during the search identified multiple inoperabilities either at a dual unit site or inoperabilities on different dates at the same plant. As a result, the number of unique LERs will be different than the number of unique inoperabilities found for this study. Of the 142 inoperabilities, 93 were classified as failures based on a detailed review of the LER by a team of engineers with commercial nuclear power plant experience. The classification was based on a risk perspective. Therefore, the number of failures would be different than the number of failures based on a definition provided by plant technical specifications for the system. Table B-2 provides a breakdown of the inoperabilities by method of discovery and by failure mode for the inoperabilities classified as failures for this study.

Table B-3 defines the column headings used in Table B-4. Table B-4 is a listing of the RCIC inoperability events. In the injection function lost (IFL) column, *footnote a* marks the failures for which both the design function was lost and the number of demands could be counted (i.e., the method of discovery is either A, for unplanned demands, or S, for surveillance). In the latter case, the surveillance

had to be a cyclic surveillance test. Cyclic surveillance tests are marked in Table B-4 in the method of discovery column with "(C)."

Table B-1. BWR plants selected for this study with their associated operating years.

Plant Name	Docket	Operating years	Plant name	Docket	Operating years
Browns Ferry 2	260	2.3	Limerick 2	353	3.8
Brunswick 1	325	3.8	Monticello	263	6.3
Brunswick 2	324	4.6	Nine Mile Pt 2	410	4.5
Clinton	461	4.9	Peach Bottom 2	277	4.0
Cooper	298	5.6	Peach Bottom 3	278	3.5
Duane Arnold	331	5.6	Perry	440	5.0
Fermi 2	341	5.6	Pilgrim	293	3.9
FitzPatrick	333	4.5	Quad Cities 1	254	5.5
Grand Gulf	416	6.1	Quad Cities 2	265	5.4
Hatch 1	321	5.9	River Bend	458	5.3
Hatch 2	366	6.0	Susquehanna 1	387	5.7
Hope Creek	354	6.2	Susquehanna 2	388	6.1
LaSalle 1	373	5.4	Vermont Yankee	271	6.2
LaSalle 2	374	5.2	Wash. Nuclear 2	397	5.1
Limerick 1	352	5.7			

Table B-2. RCIC inoperability counts.

	Method of discovery				
Failures	Unplanned demands	Cyclic surveillance tests	Other surveillance tests	Other[a]	Total
Maintenance-out-of-service (MOOS)	1	NA	NA	NA	1
Failure to start					
Other than injection valve (FTSO)	7	3	29	35	74
Injection valve (FTSV)	0	0	4	1	5
Failure to restart (FRS)	4	NA	NA	NA	4
Failure to transfer (FRC)	2	NA	NA	NA	2
Failure to run (FTR)	2	0	4	1	7
Subtotal, Failures	16	3	37	37	93
Faults	2	0	22	25	49
Grand Total	18	3	59	62	142

a. Plant tours, control room annunciators/indication, design review etc.

Table B-3. Column heading definitions and abbreviations use in Table B-4.

Column Heading	Definition
Plant name	Self-explanatory
LER number	Self-explanatory. However, in some cases the LER number listed is for the unplanned demand in which a failure was observed. It is not unusual for a plant to report the unplanned demand in one LER and mention that the system did not respond as designed (i.e., LER number XXX89001) and a follow up LER (i.e., LER number XXX89003) provide the details of the failure and subsequent corrective actions. Also, the LER number may not match the docket number for a dual unit site. The LER may be under a Unit 1 number because the event affected both units, however, a failure may also be identified at Unit 2.
Event date	The event date is typically the date identified in Block 5 of the LER. In some cases the Block 5 date may be different than the failure date, because the system may have run for a period of time before the failure. In all cases the event date is the date of the actual failure.
IFL	Injection function lost (failure): T (true) indicates that the deficiency was such that the system would **not** have been able to respond as designed for a risk-based mission. F (false) indicates that the deficiency was such that the system would have been able to respond as designed for a risk-based mission. These events (IFL = F) are referred to as faults. The T/F determination is based on a review of the full text of the LER. These classifications are not based on the reportability requirements identified in Block 11 of the LER.
Failure mode	The failure mode is risk-related information provided only for the events that are classified as failures (i.e., IFL = T). FTS, failure to start; FTSV failure to start due to the injection valve; FTR, failure to run; FRS, failure to restart the system for subsequent injections; FRC, failure to transfer during recirculation to injection; MOOS, maintenance-out-of-service.
Method of discovery	The method of discovery identifies how the inoperability was found. O, operational occurrence, through the normal course of routine plant operations. This category includes operator walkdowns, control room annunicators or alarms, etc. S, periodic surveillance test, [S(C)] identifies a cyclic surveillance test; A, unplanned demand.
Subsystem	Subsystem: T, turbine and turbine control valves; I, instrumentation and controls; F, coolant piping and valves; H, dedicated heating, ventilation, or room cooling.

Table B-4. RCIC inoperabilities.

Plant Name	LER Number	Event Date	IFL	Failure Mode	Method of Discovery	Subsystem
Browns Ferry 2	26093001	01/24/93	T	FTSO	O	T
Browns Ferry 2	26093009	08/22/93	T	FTSO	S	I
Brunswick 1	32588014	06/06/88	F	N/A	S	I
Brunswick 1	32588020	09/15/88	T	FTSO	S	T
Brunswick 1	32591013	05/07/91	T	FTSO	O	I
Brunswick 2	32487001	01/05/87	T[a]	FRC	A	F
Brunswick 2	32487003	02/02/87	F	N/A	S	I
Brunswick 2	32487007	05/04/87	T	FTSO	O	I
Brunswick 2	32588014	06/06/88	F	N/A	S	I
Brunswick 2	32490008	08/16/90	F	N/A	A	H
Brunswick 2	32490009	08/19/90	T[a]	FRS	A	T
Clinton	46187052	09/02/87	T	FTSO	O	I
Clinton	46187067	11/24/87	T	FTSO	S	I
Clinton	46191004	08/19/91	T	FTSO	O	I
Cooper	29890009	08/08/90	T	FTSO	S	T
Cooper	29892005	03/25/92	T	FTSO	O	T
Cooper	29892012	07/15/92	T	FTSO	S	T
Duane Arnold	33188001	01/11/88	F	N/A	S	T
Duane Arnold	33189006	02/24/89	T	FTSO	O	I
Duane Arnold	33191007	08/06/91	T	FTSO	S	T
Fermi 2	34187012	05/05/87	F	N/A	O	I
Fermi 2	34187023	06/11/87	T	FTSO	S	I
Fermi 2	34188005	02/10/88	T	FTSO	O	T
FitzPatrick	33387013	09/05/87	T	FTSO	O	I
FitzPatrick	33388002	03/10/88	T	FTSO	O	T
FitzPatrick	33389021	10/31/89	T	FTSV	S	F
FitzPatrick	33389024	11/29/89	T	FTSO	S	I
FitzPatrick	33390004	02/07/90	T	FTSO	O	I
Grand Gulf	41689016	11/07/89	T[a]	MOOS	A	T
Grand Gulf	41692020	12/15/92	T	FTSO	O	I
Grand Gulf	41693004	05/17/93	T	FTSO	O	I
Grand Gulf	41693005	06/08/93	F	N/A	O	I
Grand Gulf	41693006	07/20/93	T	FTSO	O	I
Grand Gulf	41693017	11/26/93	F	N/A	S	T
Hatch 1	32187011	07/23/87	T[a]	FTSO	A	T
Hatch 1	32188018	12/17/88	T[a]	FRS	A	T
Hatch 1	32191001	01/18/91	T[a]	FRS	A	F
Hatch 2	36688017	05/27/88	T[a]	FTSO	A	I
Hope Creek	35491016	07/24/91	T	FTSO	O	I

Table B-4. (continued)

Plant Name	LER Number	Event Date	IFL	Failure Mode	Method of Discovery	Subsystem
LaSalle 1	37387015	03/28/87	F	N/A	S	F
LaSalle 1	37387039	12/16/87	F	N/A	O	F
LaSalle 1	37388015	07/12/88	T	FTSO	S	T
LaSalle 1	37389017	05/15/89	F	N/A	O	H
LaSalle 1	37389020	05/29/89	F	N/A	O	I
LaSalle 1	37389021	06/09/89	T	FTSO	S	T
LaSalle 1	37390007	06/18/90	T	FTSO	S	T
LaSalle 1	37390009	05/11/90	F	N/A	S	I
LaSalle 1	37390011	08/01/90	F	N/A	S	I
LaSalle 1	37391012	07/29/91	T	FTSO	S	T
LaSalle 1	37391017	10/23/91	T	FTSO	S	T
LaSalle 1	37392005	04/06/92	T	FTSO	S	T
LaSalle 1	37393003	01/29/93	F	N/A	S	H
LaSalle 1	37393003	01/30/93	T	FTR	S	T
LaSalle 1	37393004	02/10/93	T	FTSO	O	T
LaSalle 1	37393007	02/26/93	T	FTSO	S	T
LaSalle 1	37393008	03/07/93	T	FTSO	S	I
LaSalle 1	37393016	10/22/93	T	FTR	S	I
LaSalle 2	37487020	11/19/87	F	N/A	S	I
LaSalle 2	37489018	12/16/89	F	N/A	O	I
LaSalle 2	37491005	06/21/91	F	N/A	S	I
LaSalle 2	37492008	06/15/92	F	N/A	S	T
LaSalle 2	37492009	07/14/92	F	N/A	S	T
LaSalle 2	37492010	08/10/92	T	FTSO	S	T
LaSalle 2	37492012	08/27/92	T[a]	FRS	A	T
LaSalle 2	37493001	02/22/93	F	N/A	S	I
LaSalle 2	37493002	02/23/93	T	FTSO	S	I
LaSalle 2	37493006	08/19/93	F	N/A	O	H
LaSalle 2	37493010	12/25/93	T	FTSO	S	I
Limerick 1	35289002	01/04/89	F	N/A	O	I
Limerick 1	35289012	02/15/89	F	N/A	O	F
Limerick 1	35289039	06/01/89	F	N/A	O	I
Limerick 1	35289050	08/25/89	F	N/A	O	F
Limerick 1	35291016	06/10/91	T	FTSO	O	T
Limerick 2	35289050	08/25/89	F	N/A	O	F
Monticello	26389006	04/14/89	T	FTSO	O	T
Nine Mile Pt. 2	41088011	03/01/88	T	FTSO	O	I
Nine Mile Pt. 2	41091017	08/13/91	T[a]	FTSO	A	I
Nine Mile Pt. 2	41092024	12/04/92	T	FTSO	O	I
Peach Bottom 2	27791034	10/22/91	T	FTSO	O	I
Perry	44087003	01/10/87	T	FTSO	S	T
Perry	44087003	01/22/87	T	FTSO	S	T
Perry	44087003	02/17/87	T	FTSO	O	T
Perry	44087003	03/12/87	T	FTSO	O	T

Table B-4. (continued)

Plant Name	LER Number	Event Date	IFL	Failure Mode	Method of Discovery	Subsystem
Perry	44087006	02/08/87	T	FTSO	O	I
Perry	44087012	03/02/87	T[a]	FTSO	A	T
Perry	44087040	06/2487	F	N/A	O	I
Perry	44087044	06/24/87	T	FTSO	O	I
Perry	44087063	09/06/87	T	FTSO	O	I
Perry	44087075	11/14/87	T	FTSO	O	T
Perry	44090002	01/07/90	T[a]	FTR	A	I
Pilgrim	29390013	09/02/90	T[a]	FTSO	A	T
Pilgrim	29391001	01/25/91	T	FTSO	S	T
Pilgrim	29391004	03/19/91	F	N/A	S	I
Pilgrim	29391020	08/15/91	T	FTR	S	T
Pilgrim	29391021	10/09/91	F	N/A	D	I
Pilgrim	29391025	10/30/91	T[a, b]	FTSO	O	I
Pilgrim	29392003	03/25/92	T	FTSO	O	T
Pilgrim	29392007	06/18/92	F	N/A	S	I
Pilgrim	29392010	08/18/92	F	N/A	S	I
Pilgrim	29392015	11/25/92	T	FTSO	O	T
Pilgrim	29393002	02/25/93	T	FTSO	S	T
Pilgrim	29393004	03/13/93	F[b]	N/A	A	H
Pilgrim	29393007	03/17/93	T	FTSO	O	I
Pilgrim	29393013	05/30/93	T	FTR	S	T
Pilgrim	29393021	08/24/93	T	FTR	O	I
Pilgrim	29393025	10/24/93	F	N/A	S	F
Quad Cities 1	25487003	02/05/87	T	FTSO	S	I
Quad Cities 1	25487032	12/23/87	T	FTSO	S	F
Quad Cities 1	25488003	01/25/88	T	FTSV	S	F
Quad Cities 1	25488011	06/25/88	T	FTSO	O	I
Quad Cities 1	25488013	08/22/88	F	N/A	O	H
Quad Cities 1	25489001	01/06/89	T	FTSV	O	O
Quad Cities 1	25489005	05/22/89	F	N/A	S	I
Quad Cities 1	25490005	03/13/90	T	FTSO	S	T
Quad Cities 1	25490023	10/31/90	F	N/A	O	H
Quad Cities 1	25491009	04/26/91	T	FTSO	S	T
Quad Cities 1	25491018	09/13/91	T	FTSO	O	I
Quad Cities 1	25491021	10/25/91	F	N/A	S	I
Quad Cities 1	25491029	04/24/91	T	FTSV	S	F
Quad Cities 1	25492005	12/01/91	T	FTSV	S	F
Quad Cities 1	25492026	10/27/92	F	N/A	O	I
Quad Cities 1	25493001	02/04/93	F	N/A	O	F
Quad Cities 1	25493004	03/31/93	F	N/A	O	H
Quad Cities 2	26587009	08/01/87	T[a]	FTSO	A	I
Quad Cities 2	26587016	11/03/87	F	N/A	S	T
Quad Cities 2	26588003	03/01/88	T	FTSO	S	T
Quad Cities 2	26590006	05/08/90	T[a]	FTSO	S(C)	I
Quad Cities 2	26592015	05/12/92	T[a]	FTSO	S(C)	I
Quad Cities 2	26592017	05/24/92	F	FTR	O	H
Quad Cities 2	26592020	08/11/92	T	FTSO	S	T
Quad Cities 2	26593018	08/28/93	F	N/A	O	T
Quad Cities 2	26593022	10/07/93	F	N/A	O	H

Table B-4. (continued)

Plant Name	LER Number	Event Date	IFL	Failure Mode	Method of Discovery	Subsystem
River Bend	45888027	12/19/88	F	N/A	O	T
River Bend	45892027	11/25/92	T	FTSO	O	T
Vermont Yankee	27187018	11/14/87	T[a]	FTSO	S(C)	T
Vermont Yankee	27189014	07/18/89	F	N/A	S	F
Vermont Yankee	27191009	04/23/91	T[a]	FTR	A	I
Vermont Yankee	27192015	04/24/92	T	FTSO	O	I
Wash. Nuclear 2	39788003	02/04/88	T[a]	FRC	A	F
Wash. Nuclear 2	39791001	01/08/91	T	FTSO	O	I
Wash. Nuclear 2	39792016	04/22/92	F	N/A	O	I
Wash. Nuclear 2	39793013	03/18/93	F	N/A	O	F

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

b. This event indicated 2 inoperabilities for the same date.

B-3. RCIC UNPLANNED DEMANDS

The results of the data search and screening of the SCSS data file for unplanned demands of the RCIC system's injection function identified 133 LERs in which at least one demand for RCIC's injection function occurred. Detailed review of each of the LERs showed that there were 179 operating experiences of the RCIC system's injection function. These events are listed in Table B-5 with the plant name and event date. Included in the table are the number of demands associated with each event, the run times associated with each demand for the first three demands if given in the LER, and the total mission time. If no run times were given in the LER then a long or short classification was assigned to the event based on a review of the event. The times listed in the table are in a HHMM format (e.g., 0516 corresponds to 5 hours and 16 minutes).

B-4. RCIC CYCLIC SURVEILLANCE TESTING DEMANDS

The estimated number of RCIC cyclic surveillance testing demands is summarized by plant in Table B-6. The method used to estimate the number of cyclic surveillance tests is described in Appendix A, Section A-1.2.2. The total is 142 tests.

B-5. DATA USED FOR STATISTICAL ESTIMATION OF UNRELIABILITY

A subset of the inoperabilities was used for estimating unreliability. The first requirement for this subset was loss of the safety function. Table B-7 provides a summary description of the events used to determine system unreliability. The Table lists the events by those that occurred during unplanned demands and cyclic surveillance tests alphabetically by plant name.

Table B-5. RCIC unplanned demands.

Plant	LER Number	Event Date	Number of Pump Starts	Run Time Start(1)	Run Time Start(2)	Run Time Start(3)	Total Mission Time
Brunswick 1	32587019	07/01/87	1	Long	-	-	Long
Brunswick 1	32591018	07/18/91	1	Short	-	-	Short
Brunswick 1	32592003	01/17/92	2	0001	0017	-	0018
Brunswick 1	32592005	02/29/92	1	0516	-	-	0516
Brunswick 2	32487001	01/05/87	1	0429	-	-	0429
Brunswick 2	32487004	03/11/87	1	0146	-	-	0146
Brunswick 2	32488018	11/16/88	1	Long	-	-	Long
Brunswick 2	32489009	06/17/89	1	1206	-	-	1206
Brunswick 2	32490008	08/16/90	1	0007	-	-	0007
Brunswick 2	32490009	08/19/90	4	0001	0023	0009	Long
Brunswick 2	32490015	09/27/90	4	0004	0015	0017	Long
Brunswick 2	32490016	10/12/90	1	0020	-	-	0020
Brunswick 2	32491001	01/25/91	1	0009	-	-	0009
Brunswick 2	32492001	02/02/92	1	Short	-	-	Short
Clinton	46188019	07/12/88	13	0002	0005	Short	0421
Clinton	46189029	07/14/89	3	0009	0110	Long	Long
Cooper	29887003	01/07/87	1	Short	-	-	Short
Cooper	29887006	01/10/87	1	Long	-	-	Long
Cooper	29887009	02/18/87	1	Short	-	-	Short
Cooper	29887011	05/17/87	1	Short	-	-	Short
Cooper	29888021	08/25/88	1	Long	-	-	Long
Cooper	29889026	11/25/89	1	Long	-	-	Long
Cooper	29890011	10/17/90	1	Short	-	-	Short
Cooper	29893038	12/14/93	1	Short	-	-	Short
Duane Arnold	33189008	03/05/89	1	Long	-	-	Long
Duane Arnold	33189011	08/26/89	1	0026	-	-	0026
Duane Arnold	33190002	03/29/90	1	Long	-	-	Long
Duane Arnold	33190019	10/19/90	1	0006	-	-	0006
Fermi 2	34187017	05/13/87	1	Short	-	-	Short
Fermi 2	34187025	06/25/87	1	0016	-	-	0016
Fermi 2	34188004	01/10/88	1	Long	-	-	Long
Fermi 2	34192012	11/18/92	1	Short	-	-	Short
Fermi 2	34193010	08/13/93	1	Short	-	-	Short
FitzPatrick	33387008	06/10/87	1	Short	-	-	Short
FitzPatrick	33389020	11/05/89	1	Short	-	-	Short
FitzPatrick	33390009	03/19/90	1	Short	-	-	Short
FitzPatrick	33393009	04/20/93	1	0001	-	-	0001
Grand Gulf	41688006	01/20/88	1	0031	-	-	0031
Grand Gulf	41689006	05/05/89	1	Short	-	-	Short
Grand Gulf	41689010	07/22/89	1	0002	-	-	0002
Grand Gulf	41689012	08/14/89	1	Long	-	-	Long
Grand Gulf	41689016	11/07/89	1	N/A[a]	-	-	N/A

Table B-5. (continued)

Plant	LER Number	Event Date	Number of Pump Starts	Run Time Start(1)	Run Time Start(2)	Run Time Start(3)	Total Mission Time
Grand Gulf	41689019	12/30/89	1	Long	-	-	Long
Grand Gulf	41690011	07/24/90	1	0130	-	-	0130
Grand Gulf	41690017	09/16/90	2	Short	Short	-	Short
Grand Gulf	41690028	12/10/90	1	Long	-	-	Long
Grand Gulf	41690029	12/18/90	1	Long	-	-	Long
Grand Gulf	41691004	06/11/91	1	Short	-	-	Short
Grand Gulf	41691005	06/17/91	1	Long	-	-	Long
Grand Gulf	41691007	07/28/91	1	Short	-	-	Short
Grand Gulf	41692013	06/18/92	1	Short	-	-	Short
Hatch 1	32187011	07/23/87	1	N/A[a]	-	-	N/A
Hatch 1	32187013	08/03/87	1	0003	-	-	0003
Hatch 1	32188013	09/04/88	1	Short	-	-	Short
Hatch 1	32188018	12/17/88	10	0113	Long	Long	Long
Hatch 1	32190013	06/20/90	1	0005	-	-	0005
Hatch 1	32190021	10/15/90	1	Long	-	-	Long
Hatch 1	32191001	01/18/91	2	0020	N/A[a]	-	0020
Hatch 1	32191017	09/11/91	2	0009	Long	-	Long
Hatch 1	32192021	08/27/92	2	0002	Long	-	Long
Hatch 1	32192024	09/30/92	1	Short	-	-	Short
Hatch 1	32193013	10/22/93	1	Long	-	-	Long
Hatch 1	32193016	12/07/93	1	0005	-	-	0005
Hatch 2	36687003	01/26/87	1	0015	-	-	0015
Hatch 2	36687008	04/22/87	1	Long	-	-	Long
Hatch 2	36687006	07/26/87	1	0002	-	-	0002
Hatch 2	36687009	08/03/87	1	0004	-	-	0004
Hatch 2	36688008	03/21/88	1	0003	-	-	0003
Hatch 2	36688011	04/17/88	2	0018	Long	-	Long
Hatch 2	36688017	05/27/88	1	N/A[a]	-	-	N/A
Hatch 2	36688020	08/05/88	1	0004	-	-	0004
Hatch 2	36689005	09/03/89	1	Long	-	-	Long
Hatch 2	36690001	01/12/90	2	Long	Long	-	Long
Hatch 2	36691004	02/14/91	1	0015	-	-	0015
Hatch 2	36692009	06/25/92	1	0003	-	-	0003
Hope Creek	35487017	02/24/87	1	Long	-	-	Long
Hope Creek	35487034	07/30/87	1	Short	-	-	Short
Hope Creek	35487037	08/16/87	1	Long	-	-	Long
Hope Creek	35487039	08/29/87	1	Long	-	-	Long
Hope Creek	35488012	04/30/88	2	0026	Long	-	Long
Hope Creek	35488027	10/15/88	1	0018	-	-	0018
Hope Creek	35488029	11/01/88	1	0010	-	-	0010
Hope Creek	35490003	03/19/90	1	Short	-	-	Short
LaSalle 1	37392003	03/01/92	1	Short	-	-	Short
LaSalle 1	37393015	09/14/93	1	0755	-	-	0755
LaSalle 2	37492012	08/27/92	2	0001	Long	-	Long
Limerick 1	35287048	09/19/87	1	0152	-	-	0152
Limerick 1	35291009	04/12/91	1	0025	-	-	0025

Table B-5. (continued)

Plant	LER Number	Event Date	Number of Pump Starts	Run Time Start(1)	Run Time Start(2)	Run Time Start(3)	Total Mission Time
Limerick 2	35390015	09/10/90	1	0227	-	-	0227
Monticello	26387009	04/03/87	1	Short	-	-	Short
Monticello	26391019	08/25/91	1	Long	-	-	Long
Nine Mile Pt. 2	41088001	01/20/88	1	0002	-	-	0002
Nine Mile Pt. 2	41088012	03/05/88	1	0003	-	-	0003
Nine Mile Pt. 2	41088014	03/13/88	1	0102	-	-	0102
Nine Mile Pt. 2	41089014	04/13/89	1	Long	-	-	Long
Nine Mile Pt. 2	41091017	08/13/91	1	0145	-	-	0145
Nine Mile Pt. 2	41091023	12/12/91	1	0056	-	-	0056
Peach Bottom 2	27789033	12/20/89	1	0001	-	-	0001
Peach Bottom 2	27792012	07/17/92	1	0030	-	-	0030
Peach Bottom 3	27890002	01/28/90	1	0036	-	-	0036
Peach Bottom 3	27890008	07/27/90	1	Long	-	-	Long
Peach Bottom 3	27792010[b]	07/04/92	1	0335	-	-	0335
Peach Bottom 3	27892008	10/15/92	1	0200	-	-	0200
Perry	44087012	03/02/87	1	N/A[a]	-	-	N/A
Perry	44087042	06/17/87	1	Long	-	-	Long
Perry	44087064	09/09/87	1	0003	-	-	0003
Perry	44087072	10/27/87	1	0003	-	-	0003
Perry	44088012	04/27/88	1	0037	-	-	0037
Perry	44088023	06/08/88	1	0406	-	-	0406
Perry	44090002	01/07/90	1	0037	-	-	0037
Perry	44092017	09/10/92	1	0001	-	-	0001
Perry	44093010	03/26/93	1	Long	-	-	Long
Pilgrim	29390013	09/02/90	1	N/A[a]	-	-	N/A
Pilgrim	29391025	10/30/91	2	0043	0402	-	0445
Pilgrim	29393004	03/13/93	3	0516	0042	0006	0603
Pilgrim	29393022	09/10/93	1	0044	-	-	0044
Quad Cities 1	25490004	03/10/90	1	0001	-	-	0001
Quad Cities 2	26587009	08/01/87	1	0004	-	-	0004
Quad Cities 2	26587013	10/19/87	1	0002	-	-	0002
River Bend	45888018	08/25/88	1	0001	-	-	0001
River Bend	45888021	09/06/88	1	0001	-	-	0001
River Bend	45889008	02/25/89	1	Short	-	-	Short
Susquehanna 1	38787013	04/02/87	1	0004	-	-	0004
Susquehanna 1	38791008	07/31/91	2	0003	0739	-	0742
Susquehanna 2	38887006	04/16/87	1	Short	-	-	Short
Susquehanna 2	38890005	05/28/90	1	0009	-	-	0009
Vermont Yankee	27191009	04/23/91	2	0219	1841	-	2100
Wash. Nuclear 2	39787002	03/22/87	1	Short	-	-	Short

Table B-5. (continued)

Plant	LER Number	Event Date	Number of Pump Starts	Run Time Start(1)	Run Time Start(2)	Run Time Start(3)	Total Mission Time
Wash. Nuclear 2	39787020	07/02/87	1	0056	-	-	0056
Wash. Nuclear 2	39787022	07/06/87	1	Long	-	-	Long
Wash. Nuclear 2	39788003	02/04/88	2	0001	1213	-	1214
Wash. Nuclear 2	39788006	02/13/88	3	0001	0001	Short	Short
Wash. Nuclear 2	39793027	08/03/93	1	Short	-	-	Short

a. A non-recovered failure occurred during the demand, therefore there was no run time associated with the demand.

b. Although LER number is a Unit 2 number, the report describes an event that occurred at Unit 3.

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

Plant Name	Total	Plant Name	Total
Browns Ferry 2	3	Limerick 2	4
Brunswick 1	4	Monticello	6
Brunswick 2	5	Nine Mile Pt 2	5
Clinton	5	Peach Bottom 2	4
Cooper	6	Peach Bottom 3	5
Duane Arnold	5	Perry	5
Fermi 2	4	Pilgrim	5
FitzPatrick	4	Quad Cities 1	5
Grand Gulf	6	Quad Cities 2	7
Hatch 1	5	River Bend	5
Hatch 2	4	Susquehanna 1	4
Hope Creek	5	Susquehanna 2	4
LaSalle 1	4	Vermont Yankee	5
LaSalle 2	6	Wash. Nuclear 2	7
Limerick 1	5	Total	142

Table B-7. Summary of RCIC failure events used for unreliability.

Plant Name	Failure Mode	LER Number	Event Date	Description
Unplanned Demand Failures				
Brunswick 2	FRC (Recovered)	32487001	01/05/87	A failure of the voltage regulator caused a turbine trip, which resulted in a reactor scram and SRV actuations to limit RPV pressure. RCIC was started to control RPV level. Two hours after the initial injection and restoration of RPV level, RCIC was unable to maintain RPV level because the full flow test line would not fully close due to a failure of the valve stem antirotation device. During the time the RCIC system was degraded, HPCI was inoperable due to the injection valve failing closed. After isolating the RCIC full flow test line, both CRD pumps and RCIC were used to restore RPV level.
Brunswick 2	FRS (Not Recovered)	32490009	08/19/90	Following a reactor scram event caused by an inadvertent MSIV isolation of the RPV, the RCIC trip and throttle valve could not be reset for a fourth system restart. The cause of the failure to reset the trip and throttle valve was that the thermals for the motor operator had tripped.
Grand Gulf	MOOS (Not Recovered)	41689016	11/07/89	A reactor scram was caused by an electrical spike from a lighting strike. The RCIC system received an actuation signal but was out of service in preparation for surveillance testing. Vessel level was recovered by the feedwater system.
Hatch 1	FTSO (Not Recovered)	32187011	07/23/87	A loss of feedwater resulted in a reactor scram. RCIC automatically actuated but tripped on overspeed due to a failure of an electronic component in the electric governor magnetic pickup module.
Hatch 1	FRS (Recovered)	32188018	12/17/88	A reactor scram occurred when the turbine tripped due to loss of electrohydraulic control system pressure. After use of the RCIC system, the RCIC turbine steam supply valve failed to close fully due to loose yoke bushing. During subsequent restart of the RCIC system, the turbine tripped on overspeed due to the turbine supply valve previously not going completely closed. The turbine was reset and restarted. This scenario was repeated several times while safety relief valves were used for pressure control.
Hatch 1	FRS (Not Recovered)	32191001	01/18/91	A loss of offsite power resulted in a reactor scram. HPCI and RCIC were actuated to restore RPV level, but operated erratically due to a failed speed controller. Turbine bypass valves were used to control RPV pressure. During subsequent recovery actions, RCIC failed due to failure of the injection valve. The injection valve failure was caused by a blown fuse on the valve actuator control power circuit, which occurred when the valve was closed after the initial actuation.

Table B-7. (continued)

Plant Name	Failure Mode	LER Number	Event Date	Description
Hatch 2	FTSO (Not Recovered)	36688017	05/27/88	A loss of feedwater resulted in a reactor scram. RCIC automatically started, but the pump failed to ramp up to full speed due to a failure of a limit switch on the injection valve.
LaSalle 2	FRS (Recovered)	37492012	08/27/92	An automatic reactor scram occurred as a result of a main turbine stop valve closure trip. The RCIC system auto-started due to a low RPV water level signal within a few seconds of the scram. Water level was promptly restored by RCIC injection. During subsequent RCIC restart attempts, the turbine tripped twice as a result of high exhaust pressure. The high exhaust pressure trips were the result of water in the exhaust lines. In both cases the RCIC steam line drain valves operated properly, but there was insufficient time to drain all the water from the steam lines between start attempts.
Nine Mile Pt. 2	FTSO (Recovered)	41091017	08/13/91	An automatic reactor scram occurred as a result of a turbine trip caused by a "B" phase main transformer internal fault. The RCIC system was manually started when operators recognized that the two operating reactor feedwater pumps had tripped. The RCIC turbine experienced flow, speed, and pressure oscillations while in the automatic mode and was transferred to manual control. Subsequently turbine performance parameters stabilized.
Perry	FTSO (Not Recovered)	44087012	03/02/87	The RCIC system failed to auto-start following an automatic reactor scram that occurred as a result of a low reactor vessel water level. The cause of the RCIC failure was attributed to a normally closed steam supply isolation valve that failed to open. The plant design was changed to require the valve to be normally open in order to preclude a recurrence of this failure. This failure was identified in LER 44087012; however, the corrective action was reported in LER 44087003 as a revision.
Perry	FTR (Not Recovered)	44090002	01/07/90	A loss of feedwater resulted in a reactor scram. The RCIC system automatically actuated but tripped after 37 minutes due to high room differential temperature. The high differential temperature trip was caused by high cooling water flow and the differential temperature trip set point set improperly for winter time operations.
Pilgrim	FTSO (Not Recovered)	29390013	09/02/90	A failure in the feedwater control system caused the operators to manually scram the reactor. The RCIC system was manually started but tripped on overspeed. Two more start attempts were made, but both resulted in overspeed trips. The HPCI system was manually started for level control. The RCIC trips were caused by an inadequate procedure and a loose mechanical overspeed linkage.

Table B-7. (continued)

Plant Name	Failure Mode	LER Number	Event Date	Description
Pilgrim (2 failures)	FTSO (Recovered)	29391025	10/30/91	A loss of offsite power occurred shortly after the plant was shutdown in response to a severe storm. RCIC was manually started but tripped on overspeed when the injection valve was not opened promptly after starting the turbine. RCIC was reset and started; however, starting an RHR pump caused a voltage transient which tripped the RCIC inverter and prevented RCIC from attaining rated flow. The RCIC system was shutdown, the inverter reset, and RCIC started successfully. (Note: The second failure was caused by a problem in the 4160 vac power system, which is outside the RCIC system boundaries assumed for this study. Therefore, this second failure was not included in the unreliability calculations.)
Quad Cities 2	FTSO (Recovered)	26587009	08/01/87	A main transformer fault caused a generator trip and reactor scram. Power to both feedwater pumps was also lost due to a loose termination. An operator attempted to initiate RCIC by pushing the automatic initiation push-button but failed to maintain the button depressed long enough. Believing that RCIC had tripped, the operator then manually started RCIC and injected in the RPV to maintain level.
Vermont Yankee	FTR (Recovered)	27191009	04/23/91	A switchyard breaker failure caused a turbine trip and reactor scram. RCIC tripped on overspeed due to operator error while swiching from manual to automatic control.
Wash. Nuclear 2	FRC (Recovered)	39788003	02/04/88	A technician error caused the main steamline isolation valves to close while operating at full power. A reactor scram occurred and safety relief valves opened to maintain reactor pressure. The RCIC system was manually started to maintain vessel level. To maintain reduced feedwater flow to the reactor, part of the RCIC flow was being recirculated to the condensate storage tank. During this operation, the test return line valve failed to fully close, although the valve position indication indicated "closed". Operators were able to maintain the desired flow to the reactor vessel by closing a second valve in the test return line.
Cyclic Surveillance Test Failures				
Quad Cities 2	FTSO	26590006	05/08/90	During cyclic surveillance testing, the RCIC pump flow experienced large oscillations. The proportional band setting on a newly installed flow controller was set to respond too quickly to flow changes, causing the unstable flow.
Quad Cities 2	FTSO	26592015	05/12/92	During cyclic surveillance testing, the RCIC pump flow experienced large oscillations. The proportional band setting on the flow controller was set too narrow, causing the unstable flow.

Table B-7. (continued)

Plant Name	Failure Mode	LER Number	Event Date	Description
Vermont Yankee	FTSO	27187018	11/14/87	During an initiation of a full flow surveillance test, the RCIC turbine tripped due to high RCIC turbine exhaust pressure. The disk of a check valve in the turbine exhaust line had broken from the disk arm and lodged in the valve body, thus restricting the turbine exhaust flow.

Appendix C

Failure Probabilities and Unreliability Trends

Appendix C
Failure Probabilities and Unreliability Trends

This appendix displays relevant reactor core isolation cooling (RCIC) system event counts and the estimated probability of each failure mode, including distributions that characterize any variation observed between portions of the data. It then summarizes the investigation of whether trends exist in the RCIC data. Three types of detailed analyses are given: a plant-specific analysis for probability of individual failure modes; an investigation of the possible relation between plant low-power license date and RCIC performance, as measured by unreliability and by the frequency of failures; and an investigation of whether overall performance as measured by these attributes changed during the seven years of the study.

C-1. FAILURE MODE PROBABILITIES

C-1.1 Analysis of Individual Failure Modes

Table C-1 contains results from the initial assessment of data for the modeled failure modes, including point estimates and confidence bounds for the probability of 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 year, and plant unit. Statistical evidence of differences across these groupings, based on chi-square statistics, was found in only two cases: between plants for the FTSO mode and for the probability that a RCIC restart is required (IFRS) mode.

Specific descriptions of the particular data used to analyze each failure mode are contained in subsections below. The plant units that account for much of the variation in the data for each failure mode are identified, and the implications of the Table C-2 tests for the analysis of unreliability are described. The latter include the rationale for choosing particular data sets and types of modeling to calculate the distributions that characterize sampling and/or between-group variation.

C-1.1.1 Maintenance-out-of-service (MOOS)

The single maintenance-out-of-service event occurred during one of the 14 unplanned RCIC demands at Grand Gulf. Based on demand counts, the probability of a MOOS event occurring at Grand Gulf instead of some other plant if the occurrence probability per demand is the same across plants is 14/132, or 0.11. Since such a test is being performed for more than 20 plants, Grand Gulf 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 RCIC unreliability estimate.

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

Failure Mode	Data source	Failures f	Demands d	Probability[a]
Maintenance-out-of-service (MOOS)	Unplanned	1	133	(0.000, 0.008, 0.035)
Failure to start (other) (FTSO)	Unplanned	7	132	(0.025, 0.053, 0.097)
	Cyclic	3	142	(0.006, 0.021, 0.054)
	Pooled	10	274	(0.020, 0.036, 0.061)
FTSO recovery failure (FRFTS)	Unplanned	4	7	(0.225, 0.571, 0.871)
Failure to start (valve) (FTSV)	Unplanned	0	128	(0.000, 0.000, 0.023)
FTR-short mission (FTR-ST)	Unplanned	0	56	(0.000, 0.000, 0.052)
FTR-long mission (FTR-LT)	Unplanned	2	72	(0.005, 0.028, 0.085)
	Cyclic	0	141	(0.000, 0.000, 0.021)
	Pooled	2	213	(0.002, 0.009, 0.029)
Failure to run rate (FTR)	Pooled	2	—	—
	Unplanned	2	—	—
	Cyclic	0	—	—
FTR recovery failure (FRFTR)	Unplanned	1	2	(0.025, 0.500, 0.975)
Prob.(restart required) (IFRS)	Unplanned	18	72	(0.168, 0.250, 0.348)
FRS-long mission (FRS-LT)	Unplanned	4	18	(0.080, 0.222, 0.439)
FRS-PRA mission (FRS)	Unplanned	4	46	(0.030, 0.087, 0.188)
FRS recovery failure (FRFRS)	Unplanned	2	4	(0.098, 0.500, 0.902)
Recirculation failure rate (FRC)	Unplanned	2	—	—
FRC-long mission (FRC-LT)	Unplanned	2	72	(0.005, 0.028, 0.085)
FRC recovery failure (FRFRC)	Unplanned	0	2	(0.000, 0.000, 0.776)

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

C-1.1.2 Failure to Start, Other than Injection Valve (FTSO)

Table C-2 shows statistically significant differences in FTSO between Quad Cities 2 and the other BWR plants in the combined unplanned demand and cyclic surveillance test data. 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. Consequently, the data for unplanned demands and cyclic surveillance test were pooled for the subsequent analyses.

The empirical Bayes distribution was fitted to describe differences in FTSO probabilities among plants. This distribution showed much greater variability than the confidence interval. For example, in the homogeneous model used to develop the confidence interval, the P-value associated with Quad Cities 2's three failures in nine demands was 0.0026 (with a total of 10 failures in 274 demands). However, an assumption implicit in the use of any empirical Bayes distribution is that variation exists among members of the population for the variable being modeled. Plant-specific beta distributions for the FTSO probability obtained by updating the generic beta distribution were fairly wide, reflecting the sparseness of the plant-specific data. In the non-homogeneous model arising from the fitted empirical Bayes distribution, the P-value for Quad Cities 2 is just 0.017. However, there are nearly 30 plants involved in the evaluation that provide opportunities to see data in the tails of the distribution. Accounting for the many plants and multiple opportunities, the P-value for having 3 or more failures in nine demands for at least one plant with the beta-binomial model is approximately 0.40, which is not significant.

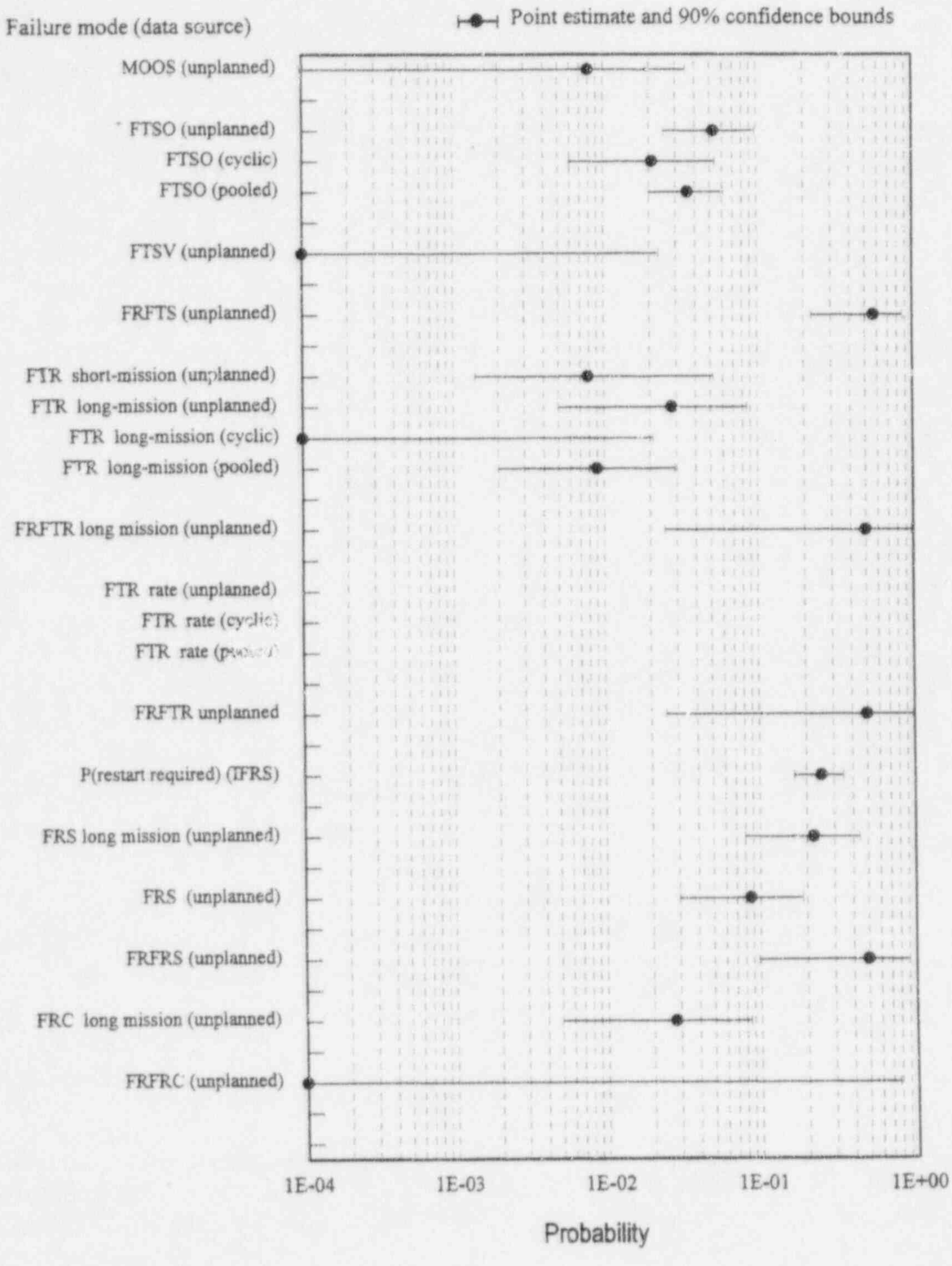

Figure C-1. Point estimates and confidence bounds for RCIC failure modes.

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

Failure Mode	Demand type	P-values for test of variation[a] In demand types	In years	In plants	Entities with relatively high chi-square statistics[b]
Maintenance-out-of-service (MOOS)	Unplanned	—	1F	1F	—
Failure to start, other than injection valve (FTSO)	Unplanned	—	NS	NS	None
	Cyclic test	—	NS	NS	—
	Pooled	NS	NS	0.031	Quad Cities 2
Failure to recover from FTSO (FRFTS)	Unplanned	—	NS	NS	—
Failure to start, injection valve (FTSV)	Unplanned	—	0F	0F	—
Failure to run–short term (FTR-ST)	Unplanned	—	0F	0F	—
Failure to run–long term (FTR-LT)	Unplanned	—	NS	0.006	None. However, 1 failure in 1 demand at Vermont Yankee
	Cyclic test	—	0F	0F	—
	Pooled	NS	NS	NS	None
Failure to run (rate) (FTR)	Unplanned	—	NS	NS	None
	Cyclic test	—	NS	NS	None
	Pooled	NS	NS	NS	None
Failure to recover from failure to run (FRFTR)	Unplanned	—	1F	1F	—
Prob(restart required) (IFRS)	Unplanned	—	NS	0.037	None
Failure to restart–long mission (FRS-LT)	Unplanned	—	NS	NS	None
Failure to restart (FRS)	Unplanned	—	NS	NS	None
Failure to recover from failure to restart (FRFRS)	Unplanned	—	NS	NS	None
Failure to transfer from recirc. (rate) (FRC)	Unplanned	—	NS	NS	None
Failure to transfer from recirc.–long term (FRC-LT)	Unplanned	—	NS	NS	None
Failure to recover from failure to transfer from recirc. (FRFRC)	Unplanned	—	0F	0F	—

a. –, not applicable; NS, not significant (P-value >0.05); 0F, no failures (thus, no test); 1F, only one failure (thus, no test).

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

C-1.1.3 Failure to Recover from FTSO (FRFTS)

Of the total of six RCIC system failures to start after unplanned demands, there were only three recoveries by operator actions. None of the chi-square tests showed significant differences between plants or years for the failure to recover from FTS data. A simple Bayes beta distribution was used for the unreliability analysis.

C-1.1.4 Failure to Start, Injection Valve (FTSV)

For the FTSV failure mode, no failures were identified. No significant differences were found between plants. Therefore, a simple Bayes beta distribution describing approximately the same variation as the confidence interval was calculated for the three unreliability analyses. No estimate was developed for failure to recover from FTSV since there were no failures.

C-1.1.5 Failure to Run, Short Term Mission (FTR-ST)

For the short term and long term missions, failure to run probabilities were calculated from the number of missions and the number of failures. Among the unplanned demands, 56 were assessed as short term missions (the longest of which lasted 10 minutes). No failures to run occurred among these events. Thus, a simple Bayes beta distribution describing approximately the same variation as the confidence interval for the FTR-ST probability was calculated for the short term mission unreliability analysis.

C-1.1.6 Failure to Run, Long Term Mission (FTR-LT)

As just stated above, failure to run probabilities were calculated from the number of missions and the number of failures. Two failures to run occurred, and both were among the 72 long term unplanned demands. No failures to run occurred among the cyclic surveillance tests. A chi-square test for differences between these two groups has a P-value of 0.11, which is not significant. The two data sets were pooled. No noticeable differences in the data subgroups were found, and no empirical Bayes distributions were found. Thus, a simple Bayes beta distribution describing approximately the same variation as the confidence interval for the FTR-LT probability was calculated for the long term mission unreliability analysis.

C-1.1.7 Failure to Run, PRA Mission (FTR)

As observed above, two failures to run occurred among the unplanned demands, and no failures occurred among the cyclic surveillance tests. A chi-square test for differences in these two groups has a P-value of 0.16, which is not significant. The two data sets were pooled. No noticeable differences in the data subgroups were found, and no empirical Bayes distributions were found. Thus, a simple Bayes gamma distribution describing approximately the same variation as the confidence interval for the FTR rate was calculated for the PRA mission unreliability analysis.

C-1.1.8 Failure to Recover from FTR (FRFTR)

Among the two failures to run on unplanned demands, only the one at Perry was not recovered. These data are not sufficient to draw conclusions about differences in years or plants. The simple Bayes beta distribution was used for unreliability for the long term model and for the PRA mission evaluation. Since neither of the failures occurred on the short term missions, failure to recover for the short term missions was not modeled.

C-1.1.9 Failure to Restart, Long Term Mission (FRS-LT and IFRS)

Among the 72 unplanned long term missions, eighteen had restarts. The eighteen missions involved a total 43 restarts at eleven different plants (for comparison, among 56 short term missions, three restarts occurred in two events, one of which was at a twelfth plant). For the long term missions, the need for restart was combined with the overall mission restart success or failure, without regard to the particular number of restarts involved in each restart event.

Empirical Bayes distributions were found both for between-plant variation and for between-year variation for the probability of needing restart demands (based on the 18 events among the 72). Thus, plant-specific estimates were available for the plants having restarts as part of the long term missions. The generic empirical Bayes distribution was used for the other plants in this model.

In the eighteen long term missions with restarts, one restart failure was observed in each of four missions. The failures occurred at three different plants, and the plant having two failures (Hatch 1) also had the most restart demands (four events with opportunities for restart failure). Thus, no evidence for differences among these plants in the mission restart failure probability was found. No empirical Bayes distributions were fitted to the data. The simple Bayes beta distribution was used for unreliability for the long term mission model.

C-1.1.10 Failure to Restart, PRA Mission (FRS)

In the total unplanned demands, 46 restarts occurred in 20 events involving a total of twelve plants. The estimate of a single failure to restart probability for the PRA missions was developed from the plant-specific data based on the fact that 4 failures to restart occurred among the 46 demands. Although, as stated above, two of the failures occurred at Hatch 1, Hatch also had among the highest number of restart demands (12) (six plants had one each). Therefore, the FRS probability for Hatch was not found to be significantly different the probability for the other plants. One of the failures occurred at LaSalle 2, a plant having just one demand. On the other hand, Clinton had no restart failures in 14 demands. With just four failures and many plants with few demands, the data were too sparse to estimate an empirical Bayes distribution for differences among plants or among years. The simple Bayes prior distribution was applied to characterize the FRS probability for PRA mission unreliability estimation.

C-1.1.11 Failure to Recover from FRS (FRFRS)

No failures occurred in the few restarts in the short unplanned missions. Therefore, a single estimate for recovery can be applied to both the long term mission model and the PRA model. Two of the four failures to restart were not recovered. These data are not sufficient to draw conclusions about differences in plant units. The simple Bayes beta distribution was used for both the long term mission model and the PRA model unreliability evaluations.

C-1.1.12 Failure to Transfer during Recirculation, Long Term Mission (FRC-LT)

For the long term missions, the simple approach of counting missions with recirculation and counting the number of failures in these missions was used. Based on plant operations, run times lasting at least 15 minutes were assumed to involve recirculation. Each of the long term mission events (whose total length was at least 15 minutes) had at least one such long operating period. Two failures to transfer during recirculation occurred in the 72 long term unplanned demands, one each at Brunswick 1 and Washington Nuclear 2. These data are not sufficient to draw conclusions about differences in plants. The simple Bayes beta distribution was used to characterize the long term operations probability for failure.

C-1.1.13 Failure to Transfer during Recirculation, PRA Mission (FRC)

For the PRA missions, the fact that some events had more time in recirculation than others was considered in the modeling. Some of the events involved two or three long periods. The number of switches from recirculation to injection during these periods was not known, but no evidence to discount the idea that the number of switches would be roughly proportional to the run time was found in the data. The lengths of the known long periods varied from the cutoff of 15 minutes to as long as 18.7 hours. To fully accommodate the recirculation performance information contained in these events, a rate-based analysis was performed for the PRA model. Rates were computed from the number of failures and the total time in recirculation estimated for each plant and year. For the rate-based PRA model as well as the probability-based long term model discussed in the previous section, the two failures to transfer during recirculation were not sufficient to draw conclusions about differences in plant units. The simple Bayes gamma distribution was used to characterize FRC rates for the PRA mission unreliability estimates.

C-1.1.14 Failure to Recover from FRC (FRFRC)

Both of the failures to transfer during recirculation were recovered. These data are not sufficient to draw conclusions about differences in plants. The simple Bayes beta distribution was used for both the long term model and the PRA model unreliability evaluations.

C-1.1.15 Summary of Beta Distributions for Individual Failure Modes

Tables 3, 5, and 8 in the main body of this report describe the beta and gamma distributions selected to model the statistical variability observed in the data for each RCIC unreliability model. These tables differ from Table C-1 and Figure C-1 because the Bayes distributions and intervals shown on Tables 3, 5, and 8 are not confidence intervals. The Bayes distributions allow the results for the failure modes to be combined to give an uncertainty distribution for each unreliability model.

C-1.2. Plant-Specific Failure Probabilities

This section provides plant-specific failure probabilities for the FTSO and IFRS failure modes. These are the two modes for which such variation was modeled. For all other RCIC failure modes, significant variation was not observed between plants.

The results for FTSO are presented by plant in Table C-3. The results for IFRS are presented by plant in Table C-4. As explained in Section C-1.1.2 above, each plant is modeled as being homogeneous, with a constant probability in time of FTSO failure or of restart. The probabilities themselves are assumed to differ from plant to plant. Table C-3 and Table C-4 provide the plant-specific raw failure data: failure counts, demand counts, probability estimates, and confidence intervals. The empirical Bayes distributions summarizing the uncertainty are tabulated. These distributions are obtained by a Bayesian update, as described in Section A-2.1.5 of Appendix A. 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 cases toward the general population.

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

Plant	*f*	*d*	90% conf. interval[a]	*a*	*b*	Empirical Bayes 90% interval[b]
Browns Ferry 2	0	3	(0.000, 0.000, 0.632)	0.60	18.63	(0.000, 0.031, 0.111)
Brunswick 1	0	8	(0.000, 0.000, 0.312)	0.58	22.39	(0.000, 0.025, 0.091)
Brunswick 2	0	15	(0.000, 0.000, 0.181)	0.55	26.75	(0.000, 0.020, 0.074)
Clinton	0	7	(0.000, 0.000, 0.348)	0.59	21.71	(0.000, 0.026, 0.094)
Cooper	0	14	(0.000, 0.000, 0.193)	0.55	26.16	(0.000, 0.021, 0.076)
Duane Arnold	0	9	(0.000, 0.000, 0.283)	0.58	23.06	(0.000, 0.024, 0.088)
Fermi 2	0	9	(0.000, 0.000, 0.283)	0.58	23.06	(0.000, 0.024, 0.088)
FitzPatrick	0	8	(0.000, 0.000, 0.312)	0.58	22.39	(0.000, 0.025, 0.091)
Grand Gulf	0	19	(0.000, 0.000, 0.146)	0.53	29.05	(0.000, 0.018, 0.067)
Hatch 1	1	17	(0.003, 0.059, 0.250)	1.51	30.50	(0.006, 0.047, 0.120)
Hatch 2	1	16	(0.003, 0.063, 0.264)	1.50	29.25	(0.006, 0.049, 0.124)
Hope Creek	0	13	(0.000, 0.000, 0.206)	0.56	25.56	(0.000, 0.021, 0.078)
LaSalle 1	0	6	(0.000, 0.000, 0.393)	0.59	20.99	(0.000, 0.027, 0.098)
LaSalle 2	0	7	(0.000, 0.000, 0.348)	0.59	21.71	(0.000, 0.026, 0.094)
Limerick 1	0	7	(0.000, 0.000, 0.348)	0.59	21.71	(0.000, 0.026, 0.094)
Limerick 2	0	5	(0.000, 0.000, 0.451)	0.60	20.25	(0.000, 0.029, 0.102)
Monticello	0	8	(0.000, 0.000, 0.312)	0.58	22.39	(0.000, 0.025, 0.091)
Nine Mile Pt. 2	1	11	(0.005, 0.091, 0.364)	1.37	22.67	(0.006, 0.057, 0.149)
Peach Bottom 2	0	6	(0.000, 0.000, 0.393)	0.59	20.99	(0.000, 0.027, 0.098)
Peach Bottom 3	0	9	(0.000, 0.000, 0.283)	0.58	23.06	(0.000, 0.024, 0.088)
Perry	1	14	(0.004, 0.071, 0.297)	1.46	26.69	(0.006, 0.052, 0.133)
Pilgrim	2	9	(0.041, 0.222, 0.550)	1.42	13.03	(0.011, 0.098, 0.247)
Quad Cities 1	0	6	(0.000, 0.000, 0.393)	0.59	20.99	(0.000, 0.027, 0.098)
Quad Cities 2	3	9	(0.098, 0.333, 0.655)	1.38	8.87	(0.015, 0.135, 0.336)
River Bend	0	8	(0.000, 0.000, 0.312)	0.58	22.39	(0.000, 0.025, 0.091)
Susquehanna 1	0	6	(0.000, 0.000, 0.393)	0.59	20.99	(0.000, 0.027, 0.098)
Susquehanna 2	0	6	(0.000, 0.000, 0.393)	0.59	20.99	(0.000, 0.027, 0.098)

Table C-3. (continued)

Plant	f	d	90% conf. interval[a]	a	b	Empirical Bayes 90% interval[b]
Vermont Yankee	1	6	(0.009, 0.167, 0.582)	1.15	15.61	(0.005, 0.069, 0.189)
Wash. Nuclear 2	0	13	(0.000, 0.000, 0.206)	0.56	25.56	(0.000, 0.021, 0.078)
Industry	10	274	(0.020, 0.036, 0.061)	0.66	17.51	(0.001, 0.037, 0.124)

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

b. The middle number in each triple is the Bayes mean, $a/(a+b)$, and the end numbers form a 90% interval, leaving 5% in each tail.

Table C-4. Probability of FRS, by plant.

Plant	f	d	90% conf. interval[a]	a	b	Empirical Bayes 90% interval[b]
Browns Ferry 2	0	0	—	0.88	2.47	(0.013, 0.263, 0.681)
Brunswick 1	1	3	(0.017, 0.333, 0.865)	1.74	4.14	(0.056, 0.296, 0.620)
Brunswick 2	2	7	(0.053, 0.286, 0.659)	2.78	7.21	(0.084, 0.278, 0.525)
Clinton	2	2	(0.224, 1.000, 1.000)	1.32	1.13	(0.093, 0.539, 0.946)
Cooper	0	3	(0.000, 0.000, 0.632)	0.68	4.22	(0.003, 0.139, 0.437)
Duane Arnold	0	3	(0.000, 0.000, 0.632)	0.68	4.22	(0.003, 0.139, 0.437)
Fermi 2	0	2	(0.000, 0.000, 0.776)	0.72	3.66	(0.004, 0.165, 0.497)
FitzPatrick	0	0	—	0.88	2.47	(0.013, 0.263, 0.681)
Grand Gulf	0	7	(0.000, 0.000, 0.348)	0.60	6.42	(0.001, 0.085, 0.292)
Hatch 1	4	6	(0.271, 0.667, 0.937)	3.33	3.05	(0.215, 0.522, 0.820)
Hatch 2	2	6	(0.063, 0.333, 0.729)	2.73	6.12	(0.093, 0.308, 0.574)
Hope Creek	1	5	(0.010, 0.200, 0.657)	1.80	6.19	(0.041, 0.225, 0.490)
LaSalle 1	0	1	(0.000, 0.000, 0.950)	0.77	3.03	(0.006, 0.203, 0.579)
LaSalle 2	1	1	(0.050, 1.000, 1.000)	1.13	1.48	(0.049, 0.433, 0.880)
Limerick 1	0	2	(0.000, 0.000, 0.776)	0.72	3.66	(0.004, 0.165, 0.497)
Limerick 2	0	1	(0.000, 0.000, 0.950)	0.77	3.03	(0.006, 0.203, 0.579)
Monticello	0	1	(0.000, 0.000, 0.950)	0.77	3.03	(0.006, 0.203, 0.579)
Nine Mile Pt. 2	0	4	(0.000, 0.000, 0.527)	0.65	4.77	(0.002, 0.120, 0.389)
Peach Bottom 2	0	1	(0.000, 0.000, 0.950)	0.77	3.03	(0.006, 0.203, 0.579)
Peach Bottom 3	0	4	(0.000, 0.000, 0.527)	0.65	4.77	(0.002, 0.120, 0.389)
Perry	0	5	(0.000, 0.000, 0.451)	0.63	5.32	(0.001, 0.106, 0.351)
Pilgrim	2	3	(0.135, 0.667, 0.983)	1.98	2.38	(0.116, 0.454, 0.818)
Quad Cities 1	0	0	—	0.88	2.47	(0.013, 0.263, 0.681)
Quad Cities 2	0	0	—	0.88	2.47	(0.013, 0.263, 0.681)
River Bend	0	0	—	0.88	2.47	(0.013, 0.263, 0.681)
Susquehanna 1	1	1	(0.050, 1.000, 1.000)	1.13	1.48	(0.049, 0.433, 0.880)
Susquehanna 2	0	0	—	0.88	2.47	(0.013, 0.263, 0.681)
Vermont Yankee	1	1	(0.050, 1.000, 1.000)	1.13	1.48	(0.049, 0.433, 0.880)
Wash. Nuclear 2	1	3	(0.017, 0.333, 0.865)	1.74	4.14	(0.056, 0.296, 0.620)
Industry	18	72	(0.168, 0.250, 0.348)	0.88	2.47	(0.013, 0.263, 0.681)

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

b. The middle number in each triple is the Bayes mean, $a/(a+b)$, and the end numbers form a 90% interval, leaving 5% in each tail.

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

The possibility of a trend in RCIC reliability performance with plant age as measured by a plant's low-power license date was investigated for each of the three unreliability models. The most significant trend was found for the short term mission unreliability model, so results for this case are displayed. No trends were found for the long term mission unreliability estimate (P-value = 0.07) or for the PRA mission unreliability estimate (P-value = 0.5).

Table C-5 shows the RCIC short term mission unreliability by plant, along with the plant low-power license date. The details of calculating the plant-specific unreliabilities deserve some attention. The unreliabilities from Figure 5 are not used, since the failure probabilities for four of the five failure modes in the model are generic, not plant specific The trend study estimates were obtained as described in Section A-2.1.4. First, the data for a failure mode were pooled and a diffuse prior with the mean (more specifically, a constrained noninformative prior) was formed for each failure mode. For each plant, each of these priors was updated with plant-specific failures and demands from the study period to obtain plant-specific posterior distributions for each failure mode. The resulting updated distributions were combined for each plant as described in Section A-2.2 to yield plant-specific unreliabilities for RCIC that were very sensitive to the plant data.

A simple approach for seeking trends is to plot the plant-specific unreliability against the plant low-power license date. Such a plot is shown in Figure 7 of the body of this report, with 90% uncertainty bars plotted vertically. The slope of the trend line was not statistically significant for the unreliabilities (P-value = 0.15). 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 in the next section. A straight line was fitted to the unreliability (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 regression confidence limits greater than zero. The regression-based confidence band shown as dashed lines on the plots applies to every point of the fitted line simultaneously; it is the band due to Working, Hotelling, and Scheffé, described in References C-1 and C-2 and in statistics books that treat linear regression.

The unreliability results used only those failures that occurred during unplanned demands and cyclic surveillance tests, and that were applicable to the short term mission. To make use of all the data, the plant-specific frequency of failures per operating year was estimated. Frequencies were also estimated for unplanned demand events. The simplest normalizing technique was used: the frequency for a plant was estimated as the quotient (number of events)/(number of operating years), with operating time estimated as described in Section A-1.3 of Appendix A. Frequencies were also estimated for the number of restarts per event (calculated as the number of restarts divided by the number of unplanned demands).

Table C-5. Plant-specific short-term mission unreliabilities, based on diffuse prior distributions, ordered by low-power license date.

Plant Name	Low-power License Date	90% Interval[a]
Monticello	09/08/70	(2.05E-03, 3.53E-02, 1.03E-01)
Quad Cities 1	10/01/71	(2.02E-03, 3.70E-02, 1.08E-01)
Quad Cities 2	03/21/72	(5.03E-03, 6.93E-02, 1.92E-01)
Pilgrim	09/15/72	(1.58E-02, 8.32E-02, 1.89E-01)
Vermont Yankee	02/28/73	(7.07E-03, 6.86E-02, 1.79E-01)
Peach Bottom 2	12/14/73	(2.00E-03, 3.68E-02, 1.08E-01)
Cooper	01/18/74	(2.07E-03, 3.05E-02, 8.66E-02)
Duane Arnold	02/22/74	(2.03E-03, 3.42E-02, 9.91E-02)
Peach Bottom 3	07/02/74	(2.79E-03, 3.44E-02, 9.47E-02)
Browns Ferry 2	08/02/74	(2.87E-03, 4.03E-02, 1.13E-01)
Hatch 1	10/13/74	(1.03E-02, 5.88E-02, 1.38E-01)
FitzPatrick	10/17/74	(2.05E-03, 3.44E-02, 9.96E-02)
Brunswick 2	12/27/74	(2.00E-03, 3.00E-02, 8.55E-02)
Brunswick 1	11/12/76	(2.02E-03, 3.48E-02, 1.01E-01)
Hatch 2	06/13/78	(1.05E-02, 6.02E-02, 1.41E-01)
LaSalle 1	04/17/82	(2.00E-03, 3.68E-02, 1.08E-01)
Grand Gulf	06/16/82	(6.39E-03, 4.49E-02, 1.11E-01)
Susquehanna 1	07/17/82	(2.00E-03, 3.68E-02, 1.08E-01)
LaSalle 2	12/16/83	(2.72E-03, 3.64E-02, 1.02E-01)
Wash. Nuclear 2	12/20/83	(2.06E-03, 3.16E-02, 9.02E-02)
Susquehanna 2	03/23/84	(2.01E-03, 3.66E-02, 1.07E-01)
Limerick 1	10/26/84	(2.71E-03, 3.62E-02, 1.01E-01)
Fermi 2	03/20/85	(2.05E-03, 3.37E-02, 9.73E-02)
River Bend	08/29/85	(2.06E-03, 3.48E-02, 1.01E-01)
Perry	03/18/86	(1.10E-02, 6.42E-02, 1.51E-01)
Hope Creek	04/11/86	(2.03E-03, 3.11E-02, 8.90E-02)
Clinton	09/29/86	(2.71E-03, 3.62E-02, 1.01E-01)
Nine Mile Pt. 2	10/31/86	(3.09E-03, 3.96E-02, 1.10E-01)
Limerick 2	07/10/89	(2.58E-03, 3.80E-02, 1.08E-01)

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.

As was done for Figure 7, a trend of failures was fitted to the frequency and to the log (frequency). An additional detail of the methodology for frequencies deserves mention. The log model, which avoids zero and negative regression lines and bounds, cannot be used directly when a frequency is zero. Rather than simply using an (arbitrary) fraction of a failure or demand divided by exposure time to estimate a non-zero frequency for these cases, all the data for a particular type of frequency were adjusted uniformly. The constrained noninformative prior gamma distribution described in Section A-3 was updated with plant-specific data, and the resulting plant-specific mean was used for the frequency. It was strictly positive, and therefore its logarithm was defined. For the RCIC failure and demand frequencies, this adjustment effectively added approximately 0.5 to each failure count and, depending on the frequency under consideration, from 0.4 and 0.8 years to each exposure time. For the restarts per

start, 0.5 restarts were effectively added to the restart count and 1.4 events were added to each total demand count. This process results also in the calculation of 90% Bayesian uncertainty bounds for each frequency; these bounds are shown in the plots as a matter of interest.

For log models, a refinement to the methodology helps stabilize the simultaneous confidence intervals on the trend lines. The method, described in the *Example 2: Poisson Regression* section of Ref. C-2, weights the log (frequency) inversely according to their variances.

No significant frequency trends with plant age were found. The data for failures are plotted in Section 4.3 of the main report. Use of log models was necessary to avoid negative regression prediction limits; thus, the fitted regression lines have a small curvature.

The frequency analyses did show significant differences among plants for all three frequencies: unplanned demands per year, failures per year, and restarts per start. Each chi-square test for differing occurrence frequencies across plants had a P-value less than 0.00005. Among failures, the lower Bayesian limit on the frequency lies above the fitted line for Pilgrim, LaSalle 1, Perry, and Quad Cities 1. Overall differences between plants are discussed in Section 4.3.

C-3. ANALYSIS BY YEAR, 1987–1993

The analyses described in Section C-2 were modified to see if there was a time trend during the period of the study. As in Section C-2, the analyses apply to the three unreliability analyses (short term, long term, and PRA-based missions), for unplanned demands per plant operating year and failures per operating year.

A significant trend was found for the short term unreliability analysis. The P-values for the tests of trends were, respectively, 0.03 for the short term mission, 0.73 for the long term mission, and 0.85 for the PRA mission. Since the lowest P-value among these models occurred for the short term mission, results are displayed just for this model.

Table C-6 and Figure 6 (in the main report) show the short term mission unreliability by year. The estimates are obtained in the same manner as described in Section C-2, except that the data used to update the constrained noninformative prior for each failure mode are pooled across plants for each calendar year instead of across calendar years for each plant. Similarly, the linear model method to test for a trend was the same as described in Section C-2, except that the time variable was calendar year instead of low-power license date. The logarithmic fit was selected in preference to the linear model in order to avoid negative lower limits from the regression, but the slope of the trend was not statistically significant in either case.

Rates for each calendar year were also analyzed by pooling the data from all the plants during each calendar year. The Bayesian adjustment described in Sections C-2 and A-3 was needed only for the restart mission frequencies for the calendar year data. Logarithmic models were selected for this situation and for the failure frequencies to ensure positive trend lines and bounds.

Table C-6. Unreliability (includes recovery) by year, based on constrained noninformative prior distributions and annual data.

Year	90% interval[a]
1987	(0.021, 0.063, 0.122)
1988	(0.007, 0.039, 0.091)
1989	(0.006, 0.042, 0.103)
1990	(0.013, 0.052, 0.111)
1991	(0.003, 0.029, 0.079)
1992	(0.005, 0.035, 0.088)
1993	(0.002, 0.026, 0.074)

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

The results of the frequency analyses are shown in Figures 13 and 14 of the main report. For the RCIC system, unplanned demand event frequencies were found to be significantly decreasing during the study period (P-value = 0.003). No trend was found among the failure frequencies (P-value = 0.67).

The frequency analysis did show significant differences among years for the overall unplanned demand frequency (P-value <0.00005). Forty-nine demands occurred in 1988 and thirty-three occurred in 1987, while only 12 occurred in 1993.

C-4. REFERENCES

C-1. M. E. Engelhardt, Modeling Patterns in Continuous Data: Linear and Related Models, DRAFT INEL-95/0120, April 1995.

C-2. Corwin L. Atwood, Modeling Patterns in Count Data Using Loglinear and Related Models, INEL-95/0121, December 1995.