High Pressure Coolant Injection (HPCI) System Risk-Based Inspection Guide For Browns Ferry Nuclear Power Station

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Prepared for
U.S. Nuclear Regulatory Commission

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High Pressure Coolant Injection (HPCI) System Risk-Based Inspection Guide For Browns Ferry Nuclear Power Station

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ABSTRACT

The High Pressure Coolant Injection (HPCI) system has been examined from a risk perspective. A System Risk-Based Inspection Guide (S-RIG) has been developed as an aid to HPCI system inspections at the Browns Ferry Nuclear Power Plant, Units 1, 2 and 3. The role of the HPCI system in mitigating accidents is discussed in this S-RIG, along with insights on identified risk-based failure modes which could prevent proper operation of the system.

The S-RIG provides a review of industry-wide operating experience, including plant-specific illustrative examples to augment the PRA and operational considerations in identifying a catalogue of basic PRA failure modes for the HPCI system. It is designed to be used as a reference for routine inspections, self-initiated safety system functional inspections (SSFIs), and the evaluation of risk significance of component failures at the nuclear power plant.

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EXECUTIVE SUMMARY

This System Risk-Based Inspection Guide has been developed as an aid to HPCI system inspections at the Browns Ferry Nuclear (BFN) Plant. The document presents a risk-based discussion of the role of the HPCI system in accident mitigation and provides a catalogue of PRA-based HPCI system failure modes (Sections 3 and 4). Most PRA oriented inspection plans contain these prerequisite information; however, the inspector(s) has to rely on his experience and knowledge of plant-specific and BWR plant operating histories to accomplish the inspection objectives. Thus, this system RIG integrates insights from industry-wide experience with PRA and other operational considerations to augment the catalogue of basic PRA-derived failure modes for use by the inspector(s).

Risk-based input and insights from the operating experience database have been combined to develop a set of composite rankings of failure modes for the HPCI system. Table 4-2 shows the ranking of these HPCI system failure modes. This information can be used to optimize NRC resources by properly allocating proactive inspection efforts based on risk considerations and industry experience. In this regard, the more important or unusual component faults in the HPCI system are reflected in the system walkdown checklist presented in Section 5. Along with the assessment of the operating experience discussed in Section 6, this checklist provides guidance on potential areas of NRC oversight both for routine inspections and the "post mortems" conducted after the occurrence of significant failures. Appendices A-1 and A-2 provide detailed information on selected failure events that were observed in the industry-wide operating experience. This information can also be utilized by the inspector(s) to have further insights on a particular component failure mode and provide the rationale for inspection emphasis.

A comparison of the distribution of HPCI system failure events between the BFN plant and industry-wide BWR operating experience is presented in Table 4-2. Although the plant specific operating experience data are limited (because the BFN plant units were in cold shutdown for about half of the evaluation period), the plant specific LER frequency for some HPCI system failure modes was higher than that observed in the industry-wide survey results. These component failures are candidates for greater attention in the inspection efforts and thus, the generic prioritization of plant components for inspection focus should be adjusted accordingly to reflect the observed distribution of failures. Because the distribution of plant specific component failures in the HPCI system is expected to vary in time (e.g., modifications may reduce or eliminate a number of chronic problems), the generic ranking of HPCI system failure modes developed in this report has not been revised to reflect the presently available BFN plant LER database.

As the BFN plant matures in its operating lifetime, the knowledge feedback of operational experience is assimilated by the utility's staff and reflected in the plant procedures. Therefore, the incidence of failure events such as inadvertent HPCI system isolations during the performance of surveillance and calibration activities is expected to decrease because of improved knowledge of the system operations. However, component failures due to aging-related causes are expected to become a significant contributor to the frequency of BFN plant HPCI system failures. Review of industry-wide operating experience has identified several HPCI system failure events due to component aging problems in the pump and turbine control equipment at a few older BWR plants (e.g., Duane Arnold, Hatch, Cooper, and Brunswick) including the Browns Ferry nuclear plant. It

is noted that there is a concerted effort at the BFN plant to upgrade the HPCI system control equipment that would preclude the effects of component obsolescence, improve system reliability and thus, enhance HPCI system availability.

Review of the BFN plant operational experience in this report included all HPCI system-related LERs generated from 1980 to mid 1992. Subsequently issued LERs can be correlated with the PRA-derived failure categories, and then used to update the distribution of plant specific HPCI system failures. A comparison of this updated database with the more static failure distribution of HPCI failure events for the entire population of BWR plants can provide insights on certain trends of recurrent problems that warrant additional inspection oversight as the plant ages.

Recommendations have been made throughout this document regarding the emphasis or focus of inspection activities for the HPCI system at the BFN plant. Some of these suggestions are generic in nature, but some recommendations related to specific maintenance, testing, or operational activities conducted at the BFN plant are made to assure that a highly reliable operation of the HPCI system is maintained. These recommendations could also be useful to the licensee in planning and conducting self-initiated safety system functional inspections (SSFIs) on various safety systems including the HPCI system to ensure functional adequacy and operational readiness of a plant system. Some of the specific recommendations for greater attention in future inspections are:

1. The inspector(s) should examine the surveillance and maintenance programs for the emergency diesel generators and the plant procedures for the recovery of either the 500 kV or 161 kV offsite power supply during a loss of offsite power event. In addition, the training program should be periodically reviewed to assure a continued awareness of temporary connections, various contingency measures, and procedures for successful DC load shedding required to cope with SBO-type conditions. [Page 3-2]
2. The plant licensee actions to monitor and control the temperature conditions in the HPCI room should be reviewed and the effects of loss of room cooling on long term operation of the HPCI system should be evaluated. It is noted that there are no room coolers in the BFN plant HPCI room. [Pages 3-3 and 6-19]
3. Within the context of using the HPCI system in an ATWS event, the capability of the licensee to perform the necessary bypasses of the system trip logic should be evaluated periodically. [Page 3-4]
4. The turbine exhaust rupture disks should be installed with a structural backing to prevent cyclic fatigue failures. [Page 6-7]
5. The inspector(s) should confirm that there is adequate oversight on the modifications, operations, maintenance and surveillances of the turbine speed control subsystem to ensure functional adequacy of the overall system. [Page 6-4]
6. Licensee responses to NRC Bulletin 88-04 should be reviewed to assess the adequacy of the design of the minimum flow bypass line. [Page 6-14]

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1. INTRODUCTION

1.1 Background

Probabilistic risk assessment (PRA) is a comprehensive, integrated analysis of the diverse aspects of design, operation, and maintenance of a plant to provide a snapshot of risks. A probabilistic risk analysis may reveal the features of the plant design that merit further attention and thus, provide a focus for improving safety. In a study sponsored by the U.S. Nuclear Regulatory Commission, Brookhaven National Laboratory (BNL) has developed and applied a methodology for providing plant specific risk-based inspection guidance for the High Pressure Coolant Injection (HPCI) system in boiling water reactor (BWR) plants that do not have a PRA study. This methodology uses insights from existing PRA studies and plant-specific operating experience for consideration in inspection planning at the nuclear power plant selected for study.

1.2 Purpose

This HPCI System Risk-Based Inspection Guide (S-RIG) has been developed as an aid to NRC inspection activities at the Browns Ferry Nuclear Power Station. The High Pressure Coolant Injection (HPCI) system has been examined from a risk perspective. Common BWR accident sequences that involve the HPCI system are described in Section 3 to provide a review of the system's accident mitigation function and to identify system unavailability combinations that can greatly increase risk exposure. Section 4 provides the description and prioritization of the PRA-based HPCI system failure modes for inspection purposes. In Section 5, risk significant failure modes are identified in a system walkdown guide for inspection emphasis. Results of a BWR operating experience review are presented in Section 6 along with additional information in related areas such as HPCI support systems, human errors, and system interactions that affect the availability of the HPCI system. A summary of insights from the Browns Ferry plant operating experience review is provided in Section 7.

1.3 Application to Inspections

This inspection guide can be used as a reference for routine inspections and for identifying the significance of component failures that occur at the Browns Ferry Nuclear Power Plant. The information presented in Sections 4 and 5 can be used to prioritize day-to-day inspection activities. This S-RIG is also useful for NRC inspection activities in response to unusual event occurrences resulting from system failures. The accident sequence descriptions presented in Section 3 together with the discussion of multiple system unavailability (Section 6), provide some insight into the combinations of system outages that can greatly increase risk. Within the context of the HPCI system, review of the operating experience data provides insights on some of the more unusual failure mechanisms (including corrective actions) that would be useful in the review of the licensee response to a system failure. Recurrent component failures identified in this system RIG can also be used for trending purposes to point out unique problems. Table 4-2 provides a summary of the industry wide distribution of HPCI failure events, and presents a comparison of the Browns Ferry HPCI system failure history with industry experience. Certain HPCI system failure modes (e.g., inverter trips or failures, turbine stop valve failures, turbine exhaust rupture disk failures, and CST/suppression pool switchover logic failures) appear to account for a large fraction of the HPCI

system failures at the Browns Ferry nuclear plant and therefore, are candidates for increased inspection surveillances. These problem areas should be reviewed periodically as additional and new data of plant-specific operating experience are compiled.

2. HPCI SYSTEM DESCRIPTION

At each Browns Ferry Nuclear Plant unit, the High Pressure Coolant Injection (HPCI) system is a single train system consisting of steam turbine-driven injection and booster pumps, a gland seal condenser, piping, valves, controls, and instrumentation. A simplified flow diagram of the system for Browns Ferry Nuclear Plant Unit 2 is shown in Figure 2-1. The system is designed to pump a minimum of 5000 gpm into the reactor vessel over a range of reactor pressures from 150 to 1120 psig when automatically activated by a low-low reactor water level (~ 45.0 inches) or high drywell pressure (2.45 psig) signal, or when manually initiated from the control room. Each automatic initiation signal is generated from a "one-out-of-two-twice" logic in which at least one division I logic channel and one division II logic channel in either the low reactor water level logic or the high drywell pressure logic must be actuated. Two sources of cooling water are available for the HPCI system. Initially, the HPCI pump takes suction from the condensate storage tank (CST) through a normally open motor-operated valve, 2-FCV-73-40. The pump suction automatically transfers to the suppression pool on low CST level or high suppression pool level. This transfer is accomplished by a signal that opens the suppression pool suction valves, 2-FCV-73-26 and 2-FCV-73-27. Once these valves are fully open, stem-mounted limit switches automatically actuates to close the CST suction valve. There is a 5-second time delay for the switchover on high suppression pool level conditions. Events that raise the suppression pool temperature above the HPCI system design limits of temperature for the suction source may require a manual suction transfer back to the CST.

Upon HPCI system initiation, the normally closed injection valve 2-FCV-73-44 automatically opens to allow water to be pumped into the reactor vessel through a series of check valves in the main feedwater line A. A minimum-flow bypass line is provided for pump protection. When the bypass valve 2-FCV-73-30 is open, flow is directed to the suppression pool. A full-flow test line is also provided to recirculate water back to the CST. The two isolation valves, 2-FCV-73-35 and 2-FCV-73-36, are equipped with interlocks to automatically close the test line (if open) upon the generation of an HPCI system initiation signal.

The HPCI pump turbine is driven by reactor steam. The inboard and outboard HPCI system isolation valves in the steam line to the HPCI turbine, 2-FCV-73-2 and 2-FCV-73-3, are normally open to keep the piping to the turbine in a hot and pressurized condition which permits rapid startup of the HPCI system. Upon receiving a signal from the HPCI system isolation logic, these valves will close and cannot be reopened until the isolation signal is cleared and the logic is reset. Inboard isolation valve 2-FCV-73-2 is powered from the 480 VAC Reactor MOV Board 2A and controlled by the isolation logic system A; while the outboard isolation valve 2-FCV-73-3 is powered from the 250 VDC Reactor MOV Board 2A and controlled by the isolation logic system B.

Steam is admitted to the HPCI pump turbine through steam supply valve 2-FCV-73-16, a turbine stop valve 2-FCV-73-18, and a turbine governor valve 2-FCV-73-19, all of which are normally closed and are opened by an HPCI system initiation signal. Exhaust steam from the turbine is discharged to the suppression pool, while condensed steam from the steam lines and leakage from the turbine gland seals are routed to a gland seal condenser.

Figure 2-1 Simplified HPCI System Flow Diagram

3. ACCIDENT SEQUENCE DISCUSSION

The role of the HPCI system in the prevention of reactor core damage provides valuable information that can be applied in the normal day-to-day inspection activities of the system. This information is readily available if a nuclear power plant has its own Probabilistic Risk Assessment (PRA) study. In addition to considerations of plant specific design and operating nuances, the risk information includes insights from the quantification and prioritization of postulated likelihood of accident sequences, system unavailabilities, and component risk importances.

Since most nuclear power plants do not currently have PRAs, the application of risk insights to support audit and inspection activities is less straightforward. Thus, eight representative BWR accident sequences were developed from the review of available PRAs of BWR nuclear plants to provide a risk perspective for use in NRC inspection activities¹. The contributions of these eight representative sequences account for an average of 87 percent of the estimated core damage frequency due to internal event initiators in seven BWR plants. Because of operational and design similarities, generic risk insights from the characterization of these representative accident scenarios can be applied to other BWR plants for risk based inspections. This information can be used to allocate inspection resources commensurate with risk importance. Since five of the eight representative sequences require the HPCI system to function for accident mitigation purposes, the generic risk information allows the inspector to focus attention on the important systems and plant components. These five accident sequences are discussed in the subsections below.

A PRA study of the Browns Ferry Unit 1 plant was performed as part of the NRC's Interim Reliability Evaluation Program (IREP) in 1982². Six of the eight dominant accident sequences identified in the study involve failure to remove long-term decay heat from the reactor, while the other two sequences involve an anticipated transient without a scram (ATWS) event. Thus, the results of this study indicate that the residual heat removal system is the most important system at the Browns Ferry plant. However, the IREP studies and other early PRAs (e.g. WASH-1400) have conservatively assumed no recovery of the power conversion system subsequent to the accident initiator and the loss of all water injection into the reactor core following containment failure. Furthermore, no credit was given for venting capability because most BWR plants at that time did not have procedures to facilitate such action. These assumptions resulted in the likelihood of one accident sequence (i.e., loss of decay heat removal) to dominate the core damage frequency estimates and minimize the importance of other accident progressions and mitigating systems. Therefore, insights from this PRA study were not utilized in the characterization of generic BWR accident sequences and were of limited use in the evaluation of operational readiness of the HPCI system. Notwithstanding these limitations, specific risk insights from the IREP study found to be applicable have been incorporated into the discussions on PRA-based failure modes presented in Section 6.1.

3.1 Loss of High Pressure Injection and Failure to Depressurize

This sequence is initiated by a general transient (such as turbine trip with subsequent MSIV closure, loss of main feedwater, inadvertent SRV opening with MSIV closure, or loss of DC power), a loss of offsite power, or a small break LOCA event. The reactor successfully scrams. The power conversion system, including the main condenser, is unavailable either as a direct result of the initiator or due to subsequent MSIV closure. The high pressure injection systems (HPCI/RCIC) fail to inject into the vessel. The major causes of HPCI/RCIC unavailability include

hardware failures (primarily turbine/pump faults, or pump discharge or steam turbine inlet valves failing to open) and system outages due to test or maintenance activities. The CRD hydraulic system can also be used as an alternate source of high pressure injection (HPI) at the Browns Ferry Nuclear Plant units in both normal and enhanced modes of operation. Failure of the second CRD pump during the enhanced mode of operation (which require two-pump injection flow) or unsuccessful flow control station valving prevents sufficient injection into the reactor pressure vessel (RPV). The operator attempts to manually depressurize the RPV, except that a common cause failure of the safety relief valves (SRVs) defeats both manual and automatic depressurization of the reactor vessel. The failure to depressurize the reactor vessel after HPI failure results in core damage due to a lack of vessel inventory makeup.

3.2 Station Blackout (SBO) with Intermediate Term Failure of High Pressure Injection

This sequence is initiated by a loss of offsite power (LOOP) event. The emergency diesel generators (EDGs) are unavailable, primarily due to hardware faults. A secondary contributor to EDG unavailability are outages for maintenance activities. Support system malfunctions include EDG room or battery/switchgear room HVAC failures, service water pump malfunctions, or EDG jacket cooler hardware failures. The HPCI and RCIC systems are initially available to provide reactor vessel inventory makeup.

The high pressure injection systems can provide inventory makeup until:

- the station batteries are depleted, or
- the system fails due to environmental conditions, i.e., high lube oil temperatures or high turbine exhaust pressure due to the high suppression pool temperature and pressure, or
- the RPV is depressurized wherein conditions can no longer support HPCI or RCIC system operation, or
- the HPCI system high area temperature logic isolates the system or long term exposure to high temperatures disables the turbine driven pump.

The Browns Ferry Unit 2 IPE analyses indicate that the LOOP scenario is the most important initiating event which results in the highest frequency accident sequences contributing to the overall plant core damage frequency (CDF)³. The total frequency of all LOOP-initiated accident sequences comprise about 69 percent of the Browns Ferry plant CDF. Of these accident scenarios, about 27 percent of the Browns Ferry plant CDF result from LOOP sequences involving station blackout (SBO). SBO coping measures include successful DC load shedding which allows the battery lifetime to be extended to 4 hours and thus, assure the continued operation of the HPCI or RCIC systems to provide a source of water to the reactor core during that time. Plant procedures also address the recovery of either the 500 kV or 161 kV offsite power supply within 6 hours to help reestablish water level control in the reactor vessel. In addition, the emergency procedures instruct the operators to utilize the residual heat removal service water (RHRSW) system (or the emergency equipment cooling water system as the backup) for water injection into the reactor vessel as a contingency measure if the SBO condition persists until decreasing reactor pressure (decay heat) can no longer support the HPCI or RCIC system operation. Once the reactor vessel is depressurized, these plant procedures guide the operators in establishing a "feed and bleed" path

from the suppression pool to the reactor vessel and back to the suppression pool via the safety relief valves (SRVs) with heat removal via RHR heat exchangers.

The reactor building environmental conditions can also impact long term HPCI system operation. The reactor building HVAC and HPCI room cooling are dependent on AC power. Although the high area temperature isolation logic is not operable during SBO conditions at the Browns Ferry plant when DC battery power is depleted, there is an environmental qualification concern (e.g., operability of instrumentation and controls) if the HPCI pump room temperature approaches beyond 129°F under worst case conditions. The HPCI pump room does not have any room coolers, but it is open to the adjacent RHR quadrangle area which is ventilated automatically by room coolers that are activated on high temperature in the area. Plant procedures (2-EOI-3) address proper operator response to lower any high temperature condition in the HPCI room. The plant activities to monitor and control high area temperature during a SBO event should be reviewed. The review should include an audit of any calculations necessary to establish a time frame for the implementation of these activities.

3.3 Station Blackout with Short Term Failure of High Pressure Injection

This SBO sequence is similar to the previous sequence except the high pressure injection systems fail early. The sources of emergency AC power, i.e., the emergency diesel generators (EDGs), fail primarily due to hardware failures. Secondary contributors are: output breaker failures and EDG unavailability due to test or maintenance activities. Support system malfunctions such as service water supply failures in the EDG jacket cooling water train, battery/switchgear room HVAC failures, or test and maintenance unavailability, are significant contributors to the loss of on-site emergency AC power. Station battery failures (including common mode) within 4 hours are an important contributor to this sequence, because the EDGs and HPI systems are dependent on DC power for instrumentation and control objectives.

This accident sequence is a major contributor to the overall core damage risk at the Browns Ferry plant, primarily due to the short term failures of HPI systems (e.g., HPCI, RCIC and CRDH systems) and failure to recover AC power within 6 hours that prevent the possibility of cooling via the suppression pool source. The Browns Ferry IPE analyses indicate that the importance of HPCI/RCIC unavailability is assessed to be 0.1125 i.e., about 11.25 percent of the plant CDF is contributed by accident sequences involving failure of the HPCI and RCIC systems. As such, the HPCI/RCIC unavailability estimates are a significant influence on the total plant core damage frequency.

3.4 ATWS with Failure of RPV Water Level Control at High Pressure

This sequence is initiated by a transient event with initial or subsequent MSIV closure and a failure of the reactor protection system to provide an automatic scram. Attempts to manually scram are not successful; however, the Standby Liquid Control System (SLCS) is initiated. The condenser and the feedwater system are unavailable. The BWR Owner's Group Emergency Procedure Guidelines (EPGs) recommend RPV water level reductions for control of reactor power below 5% and the characterization of this BWR representative sequence was based on that philosophy. As evidenced by the EOI Program Manual Section III relating EPGs for development of emergency operating instructions, ATWS mitigation procedures at Browns Ferry Unit 2 are consistent with the philosophy of the BWROG guidance document.

This sequence postulates a failure to ensure sufficient RPV makeup at high pressure to prevent core damage. There are two failure modes considered in this scenario:

1. The operator fails to control acceptable water level at high RPV pressure. This results in high reactor core power levels, continuous SRV discharges, and suppression pool heatup. After the suppression pool water reaches saturation, containment pressurization begins to occur. High pressure injection fails due to high suppression pool temperature prior to containment failure.
2. The high pressure injection (HPCI) system fails, primarily due to pump failure to start or as a result of testing and maintenance (T&M) unavailability. Failure of injection or minflow valves, inability of suction switchover, or loss of DC power are other potential system failures. HPCI pump failure to start or run, pump unavailability due to testing and maintenance activities, and Service Water EDG jacket cooler inlet or return valve failures are the major contributors to HPCI system failures.

The inability to maintain acceptable RPV water level above the top of the active fuel (TAF) requires manual emergency depressurization to allow the low pressure ECCS systems to inject water, and thus prevent the onset of core damage.

The continued operability of the HPCI system during an ATWS event is critical. Within the context of this accident sequence (i.e., time available for success), the licensee capability to achieve the HPCI pump suction transfer in time and perform logic bypasses of the high turbine exhaust pressure trip that causes a HPCI system isolation on high back pressure should be evaluated periodically. With regard to HPCI system availability, the remaining sections will provide discussions on system failures and availability evaluation.

3.5 Unisolated LOCA Outside Containment

The accident initiator in this sequence is a high pressure boundary failure outside containment with a failure to isolate the rupture. The piping failure is postulated in the following systems: main steam system (60%), feedwater system (12%), high pressure injection system (20%), and interfacing system piping lines (8%). The percentages in parentheses indicate the estimated relative contribution to core damage frequency due to piping failures of each system⁴.

An interfacing systems LOCA event is defined as the initial pressurization of a low pressure piping line which results in a pressure boundary failure, compounded by the failure to isolate the failed piping line. The failure is typically postulated in a low pressure portion of the low pressure core spray (LPCS) system, the LPCI system, shutdown cooling system, and (to a lesser extent), the HPCI or RCIC pump suction or the head spray line of RHR system.

The unisolated LOCA outside containment results in a rapid loss of the reactor coolant system (RCS) inventory and thus, eliminating the suppression pool as a long term source of RPV injection. Piping failures in the reactor building can also result in unfavorable environmental conditions for the Emergency Core Cooling Systems (ECCS). Unless the unaffected ECCS systems or the condensate system are available, long term RPV injection is suspect and core damage is likely.

There have been several HPCI pump suction overpressurization events, primarily during surveillance testing of the normally closed motor-operated HPCI injection valve 2-FCV-73-44⁵. This is of particular concern for the discharge configuration at the Browns Ferry plant that has a testable air-operated check valve in series with the normally closed MOV, because of the check valve's history of back leakage as observed in the industry-wide operating experience. The HPCI interfacing systems LOCA initiator seems to be less of a problem when the normally open valve 2-FCV-73-34 is closed prior to surveillance testing of the valve 2-FCV-73-44. However, some of the concerns regarding the previous test configuration are also valid here. There must be reasonable assurance that the normally closed 2-FCV-73-44 valve is leak tight during plant operation and prior to stroke testing, confirmation is necessary to assure that it is fully closed and will provide the necessary protection for the upstream piping. At the Browns Ferry plant, a one-inch relief valve 2-RFV-73-506 was installed in the HPCI booster pump suction piping to ensure the mitigation of overpressurization events. The valve is set to operate at 55 psig and is bench tested once per plant refueling cycle to comply with ASME Code Section XI requirements.

3.6 Overall Assessment of HPCI Importance in the Prevention of Core Damage

As previously stated, the high pressure injection function (HPCI/RCIC/CRD) is important for mitigation purposes in five of the eight representative BWR accident sequences. The various system failures and their risk importances for all eight accident sequences were prioritized by their contribution to overall core damage (using a normalized Fussell-Vesely importance measure). The HPI function, in aggregate, was assessed to fall in the high importance category. Other high risk important systems are the Emergency AC Power system and the Reactor Protection system (RPS). The HPCI system itself is considered to be of medium risk importance, because of the multiple systems (e.g., RCIC and CRD systems) that can successfully provide vessel inventory makeup at high pressure. However, the Browns Ferry plant IPE analyses indicate that the importance of the HPCI system was assessed to be 0.16, i.e. about 16 percent of the plant core damage frequency were contributed by the likelihood of accident sequences involving failure of the HPCI system. For comparison, other systems of medium risk importance are: the Standby Liquid Control, Automatic/Manual Depressurization, Service Water, and DC Power systems.

4. PRA-BASED HPCI FAILURE MODES

PRA models are often used for inspection purposes to prioritize systems, components, and human actions in plant operational activities from a risk perspective. This enables the inspection effort to be apportioned based on a core damage prevention measure called risk importance. Risk importance measures (e.g., Fussell-Vesely importance measure) can be used to determine the ranking of risk significant failure modes. A list of HPCI system failure modes for this system Risk-Based Inspection Guide (System RIG) was developed from a review of BWR plant specific RIGs⁶⁻¹⁰, and the PRA-Based Team Inspection Methodology¹. As presented in Table 4-1, the identified component failure modes are grouped by risk significance that was determined by PRA and other operational considerations. Table 4-2 provides a summary of the operating experience of the HPCI system for the industry and at the Browns Ferry Nuclear Plant with regard to these risk significant failure modes. Appendices A-1 and A-2 provide more detailed information on the failure events, and selected examples of other PRA-based HPCI system failure modes.

Due to the artifact of modeling, PRAs do not generally provide detailed guidance for inspection activities and are less helpful in the determination of specific failure modes or root causes of equipment failures. This makes it necessary for an inspector to draw on his experience, and a variety of information sources such as the plant operating history, Licensee Event Reports (LERs), NRC Bulletins, Information Notices and Generic Letters, INPO documents, and vendor information to conduct an inspection of the PRA-prioritized items. Information useful for prioritization of inspection efforts has been obtained by review of HPCI system operating experience at the Browns Ferry Nuclear Plant and other BWR plants to aggregate observed problems to the categories of PRA-derived failure modes. This information is used to develop the system walkdown checklist of risk significant components for inspection emphasis. The system walkdown checklist for use by the inspector(s) is presented in the next section. The results of the HPCI operating experience review are discussed in Section 6 with illustrative examples to show applicability to the PRA-based failure modes.

The survey of HPCI-related LERs generated at the Browns Ferry Nuclear Plant included all LERs documented between 1980 and 1992 for the 3 plant units. It is noted that Browns Ferry Plant Units 1 and 3 were in cold shutdown status throughout most of this period. Thus, the sample of HPCI-related LERs considered in this review was largely based on the operational history of the Browns Ferry Nuclear Plant Unit 2. Because the Browns Ferry Unit 2 was in operation for about half of the evaluation period, this review effectively included the HPCI-related LERs from the other plant units as well. As shown in Table 4-2, the plant specific LER frequency for several HPCI system failure modes is higher than that observed in the industry-wide survey results. The more frequent HPCI system failure modes observed at the Browns Ferry Nuclear Plant were:

1. HPCI Pump or Turbine failure to start or run due to:
 - i) turbine speed control faults,
 - ii) inverter trip or failures,
 - iii) turbine stop valve failures, or
 - iv) turbine exhaust rupture disk failures, and

2. CST/suppression pool switchover logic failures.

The survey of operating experience of the Browns Ferry Plant HPCI system is discussed in Section 6 with the focus on recurrent problems found in recently issued LERs.

Table 4-1 Summary of PRA-Based Failure Modes for the HPCI System

High Risk Importance

Pump or Turbine Fails to Start or Run*
System Unavailable Due to Test or Maintenance Activities*
Turbine Steam Inlet Valve FCV-73-16 Fails to Open
Pump Discharge Valve FCV-73-44 Fails to Open

Medium Risk Importance

CST/Suppression Pool Switchover Logic Fails*
Suppression Pool Suction Valves FCV-73-26 and FCV-73-27 Fail to Open*
Normally Open Pump Discharge Valve FCV-73-34 Fails Closed or is Plugged

Lower Risk Importance

CST Suction Line Check Valve CKV-73-505 Fails to Open
CST Suction Line Manual Valve HCV-2-705 Plugged
Normally Open CST Pump Suction Valve FCV-73-40 Fails Closed or is Plugged
Pump Discharge Check Valve FCV-73-45 Fails to Open
Suppression Pool Suction Line Check Valve CKV-73-517 Fails to Open
Normally Open Steam Line Containment Isolation Valve FCV-73-2 or FCV-73-3 Fails Closed*
Steam Line Drain Pot Malfunctions
Turbine Exhaust Line Faults, including:

- Normally Open Turbine Exhaust Valve FCV-73-64 is Plugged
- Turbine Exhaust Check Valve CKV-73-603 Fails to Open

Turbine Exhaust Line Vacuum Breaker Valves Fail to Operate
False High Steam Line Differential Pressure Signal
False High Area Temperature Isolation Signal
False Low Suction Pressure Trip
False High Turbine Exhaust Pressure Signal
System Actuation Logic Fails
Pump Suction Strainer Blockage
Minimum Flow Valve FCV-73-30 Fails to Open, Given Delayed Activation of Pump Discharge Valve FCV-73-44.

* Indicates a failure mode found in the Browns Ferry plant operating experience review discussed in Section 6.

Table 4-2 Browns Ferry Nuclear Plant HPCI System LER Survey Compared with Industry Experience

Failure Description	All BWRs (1985-1989)		Failure Ranking ²	Browns Ferry (1980-1992)		Comments
	# of Failures	Failure Contribution ¹ (%)		# of Failures ³	Failure Contribution (%)	
HPCI Pump or Turbine Fails to Start or Run						
Turbine speed control faults	16	11		4	15	4
Lube oil supply faults	11	7		1	4	
Turbine overspeed and reset problem	8	5		0	0	
Inverter trips or failures	7	4		4	15	4
Turbine stop valve failures	5	3		2	8	4
Turbine exhaust rupture disk failures	5	3		2	8	4
Flow controller failures	5	3		0	0	
Turbine control valve faults	3	2		1	4	
Loss of lube oil cooling	2	1		1	4	
Misc-valve high flow during testing	2	1		0	0	
Fails to start or run SUBTOTAL	64	40	1	15	62	
System unavailable due to T&M activities	43	27	2	6	23	

Table 4-2 (Cont'd)

Failure Description	All BWRs (1985-1989)		Failure Ranking ¹	Browns Ferry (1980-1992)		Comments
	# of Failures	Failure Contribution ¹ (%)		# of Failures ¹	Failure Contribution (%)	
False high steam line differential pressure signal	10	6	3	0	0	5.7
Turbine-steam inlet valve (FOI) fails to open	8	5	4	0	0	
Pump discharge valve (FOI) fails to open	8	5	5	0	0	
System interactions fail HPCI	3	2	6	1	4	11
System actuation logic fails	4	3	7	0	0	8
False high area temperature isolation signal	3	2	8	0	0	5.7
False low suction pressure trip	2	1	9	0	0	5.7
False high turbine exhaust signal	1	<1	10	0	0	5.7
Normal open turbine exhaust valve fails closed	1	<1	11	0	0	
CST Suppression pool switchover logic fails	1	<1	12	2	8	46.9

Table 4-2 (Cont'd)

Failure Description	All BWRs (1985-1989)		Failure Ranking	Browns Ferry (1980-1992)		Comments
	# of Failures	Failure Contribution (%)		# of Failures ³	Failure Contribution (%)	
Suppression pool suction valve (F142) fails to open	6	4	13	1	4	6.9
Minimum flow valve (F012) fails to open	5	3	14	0	0	6.10
Normal open steamline containment isolation valve fails closed	0	0	N/A	1	4	4

Table 4-2 Comments

1. Failure contribution is expressed as a percentage of all significant HPCI system failures identified by the Operating Experience Review.
2. Failure ranking is a subjective prioritization based on PRA and operational considerations, recovery potential, current accident management philosophy and conditional failures, as applicable.
3. Significant HPCI system failures at the Browns Ferry Nuclear Plant are determined from the review of all available LERs (1980 to 1992).
4. Although some caution is needed in making this observation because of the limited plant specific data, this failure mode seems to comprise a disproportionate fraction of the Browns Ferry HPCI system unavailability. This area is a candidate for enhanced inspection attention.
5. Failure importance was upgraded from the PRA-based ranking of Table 4-1.
6. Failure importance was downgraded from the PRA-based ranking of Table 4-1.
7. HPCI system isolation and trip logics are significant contributors to unavailability. The system can be isolated by a single malfunction, yet instrument surveillance intervals can be greater than that required for the more reliable actuation logic.
8. Unlike the system trip and isolation logic, the actuation logic arrangement (one out-of-two twice) diminishes the importance of a single instrument failure to reliable system operation. At least two low RPV level or two high drywell pressure sensors must fail to result in significant risk. As discussed in Section 6, system availability is more dependent on the reliability of control power.
9. The latest BWROG Emergency Procedure Guidelines deemphasize the importance of the suppression pool as an injection source during plant abnormal conditions.
10. Importance of failure mode is conditional on the delayed opening of the pump discharge line valve, FCV-73-44.
11. Unlike the rest of the failure modes listed herein, "Systems Interactions" is not a PRA-based failure mode. It was identified as a significant failure mechanism during the operating experience review and is discussed in Section 6.

5. HPCI SYSTEM WALKDOWN CHECKLIST BY RISK IMPORTANCE

Table 5-1 presents the HPCI system walkdown checklist for use by the inspector(s). This information allows the inspector to focus the inspection efforts on components that are important to system availability and operability. Equipment locations and power sources are identified to assist in the assessment of this system. The risk significance of the various components identified in this checklist have been determined by information in PRAs and other operational considerations.

Table 5-1 Browns Ferry Plant HPCI System Walkdown Checklist

Description	ID NO.	Location	Power Source and Location	Standby Position	Actual Position
A. Components of High Risk Significance					
Turbine Steam Isolation Valve	FCV-73-16	HPCI Room Reactor Bldg, Elev. 519'	250 VDC RMOV Board A, Panel/Breaker 3D	Closed	
Inboard Steam Isolation Valve	FCV-73-2	Drywell	480VDC RMOV Board A, Panel/Breaker 17E	Open	
Outboard Steam Isolation Valve	FCV-73-3	HPCI Room- Elev. 551'	250 VDC RMOV Board A, Panel/Breaker 11D1	Open	
Pump Inboard Discharge Valve	FCV-73-44	HPCI Room- Elev. 519'	250 VDC RMOV Board A, Panel/Breaker 7A	Closed	
B. Components of Medium Risk Significance					
CST Suction Isolation Valve	FCV-73-40	HPCI Room- Elev. 519'	250 VDC RMOV Board A, Panel/Breaker 1D2	Open	
Pump Outboard Discharge Valve	FCV-73-34	HPCI Room- Elev. 519'	250 VDC RMOV Board A, Panel/Breaker 5A	Open	
Pump Minimum Flow Valve	FCV-73-30	HPCI Room- Elev. 519'	250 VDC RMOV Board A, Panel/Breaker 8D	Closed	
Pump Suction From Suppression Pool (2 Valves)	FCV-73-26 and FCV-73-27	HPCI Room- Elev. 519'	250 VDC RMOV Board A, Panel/Breaker 4D and 9D	Closed	
Turbine Exhaust Valve to Suppression Pool	HCV-73-23	Torus Room- Elev. 519'	NA	Open	

Table 5-1 (Cont'd)

Description	ID NO.	Location	Power Source and Location	Standby Position	Actual Position
Full Flow Test Valves to CST	FCV-73-35 and FCV-73-36	HPCI Room- Elev. 519' and 541'	250 VDC RMOV Board A, Panel/Breaker 6A and Board B, Panel/Breaker 4A	Closed	

- Notes: 1. All circuit breakers should be in the closed (ON) position.
 2. These valves are included in the ASME Inservice Testing (IST) Program.

Additionally, some of these valves are required to be tested under the guidance of Generic Letter 89-10. Results of IST and Generic Letter 89-10 testing requirements may be reviewed to assure the adequacy of operational readiness of these valves.

6. OPERATING EXPERIENCE REVIEW

As previously stated, an operating experience review was performed to evaluate recent industry-wide operating experience of the HPCI system in BWR plants and categorize the various observed problems with PRA derived failure modes. Approximately 200 Licensee Event Reports (LERs) describing HPCI system failures that occurred in the period between 1985 to 1992 were reviewed for applicability to the PRA failure modes for the HPCI system. Sixty-two LERs did not have a corresponding failure mode. These LERs generally documented successful system challenges, administrative deviations, or seismic/equipment qualification concerns. The remaining 140 LERs documented 159 HPCI system faults or degradations. As presented in Table 6-1, these failures have been categorized by PRA failure modes to provide a relative indication of the contribution to all HPCI system faults. Each of the 14 PRA-based failure modes that has corresponding industry failures is discussed below. Selected LERs identified during the operating experience review are summarized to illustrate typical failure mechanisms and potential corrective actions. Where applicable, other sources of background information including NRC IE Bulletins, Information Notices, Inspection Reports, NUREGs, and AEOD Reports are cited. The Browns Ferry Nuclear (BFN) Plant HPCI system operating experience over the plant life is also integrated into the discussion of each HPCI failure mode.

**Table 6-1
HPCI Failure Summary**

Failure Number	Description	Total Failures*	HPCI Failure Contribution (%)
1	Pump or Turbine Fails to Start or Run	64	40
2	System Unavailable Due to Test or Maintenance Activities	43	27
3	False High Steam Line Differential Pressure Isolation Signal	10	6
4	Turbine Steam Inlet Valve (F001) Fails to Open	8	5
5	Pump Discharge Valve (F006) Fails to Open	8	5
6	Systems Interactions Fail HPCI System**	3	2
7	System Actuation Logic Fails	4	3
8	False High Area Temperature Isolation Signal	3	2
9	False Low Suction Pressure Trip	2	1
10	False High Turbine Exhaust Signal	1	<1
11	Normally Open Turbine Exhaust Valve Fails Closed	1	<1
12	CST/Suppression Pool Switchover Logic Fails	1	<1
13	Suppression Pool Suction Valve (F042) Fails to Open	6	4
14	Minimum Flow Valve (F012) Fails to Open	5	3
	Total	159	

* Identified during the HPCI System Operating Experience Review which examined HPCI LERs from 1985 to mid 1992.

** Non PRA-derived failure mode; operating experience is discussed in Section 6.

The search of LERs generated from the Browns Ferry Nuclear Plant Units 1, 2, and 3 (Docket numbers 50-259, 260, and 296, respectively) was conducted for the period between 1980 and 1992, and 67 LERs were found to be related to HPCI system problems. It is noted that the BFN plant units were in operation for about half of the evaluation period and thus, this evaluation effectively considers the operating experience of the BFN station as if it was a single nuclear power plant. Out of the 67 HPCI system-related LERs reviewed for the BFN plant, 26 LERs were found to fall within the set of PRA-based failure modes. The breakdown of the 26 LERs within each category of PRA-based failure modes is : 15 LERs were related to HPCI pump or turbine failures to start or run, six LERs were related to HPCI system unavailability due to testing and maintenance activities, two LERs described CST/suppression pool switchover logic failures, and each of the remaining LERs were related to events involving the suppression pool suction valve failure to open, steam line outboard isolation valve failing closed, or a system interactions problem failing the HPCI system. Based on the LER survey, specific component failures of importance that require attention at the BFN plant are turbine speed control faults, inverter failures, turbine stop valve failures, turbine exhaust rupture disk failures, and condensate storage tank level switch failures.

The information compiled in this section should be useful in more detailed reviews of the HPCI system, rather than routine operational checks. It may be used during programmatic inspections (such as maintenance program reviews) or in reactive inspections of HPCI system failures.

Illustrative examples of corresponding industry failures for the first failure mode, "HPCI Pump or Turbine Fails to Start or Run," are presented in Table A-1 along with details of the root cause, method of detection, corrective actions, and potential inspection areas that could identify and prevent similar problems. The examples of industry failures for the other PRA failure modes are discussed in Table A-2. The text provides additional information on the distribution of failure events within a particular failure mode.

6.1 HPCI System Failure Modes

HPCI Failure No. 1- Pump or Turbine Fails to Start or Run

The major contributor to HPCI system unavailability, both from risk and operational considerations, is the failure of the turbine driven pump to start or continue running. This failure mode includes dependent failures as a result of subtle interactions between various subsystems and components and thus, root cause analysis and component repair becomes a complex task. The concern on system interaction problems has been reflected in BWR plant PRAs by the assessment of various subsystem, or support system failures that cause this failure of the pump or turbine to start or run. However, the uncertainties associated with identifying system interaction problems have resulted in some confusion in the application of PRA insights for inspection activities. For the purposes of this study, this failure has been defined as the loss of functional capability of those components that directly support the operation of the pump or turbine. The basic event describing "HPCI Pump or Turbine Fails to Start or Run" accounted for 64 failures or 41% of the HPCI system faults in the industry-wide operating experience review. Table 6-2 shows the subcategories of failure mechanisms that may result in Failure No.1, and the number of events in each subcategory.

Table 6-2

HPCI Pump Turbine Fails to Start or Run - Failure Subcategories

Sub-category Description	LER Failures
A. Turbine speed control faults, including	
EG-M control box	6
Motor speed changer (EG-R actuator remote servo)	5
Resistor box	2
Ramp generator/signal converter box	1
Magnetic speed pickup cable	1
Speed control potentiometer	1
	16
B. Lube oil supply faults	11
C. Turbine overspeed and auto reset problems	8
D. Inverter trips or failures	7
E. Turbine stop valve failures	5
F. Turbine exhaust rupture disk failures	5
G. Flow controller failures	5
H. Turbine control valve faults	3
I. Loss of lube oil cooling	2
J. Miscellaneous: Valid high steam flow during testing	2
TOTAL	<u>64</u>

A. Turbine Speed Control Faults

The turbine speed is controlled automatically by a control system consisting of a flow controller and an electro-hydraulic turbine governor. As in most other plants, the BFN plant HPCI pump turbine has a Woodward governor control system. The turbine governor system receives the flow controller signal input and processes the electrical signal to effect hydraulic-mechanical motion to position the governor (control) valve. The system has a "ramp" generator which upon turbine start, will control the acceleration rate up to a speed relative to the flow controller output demand signal. The ramp generator is part of the ramp generator and signal converter (RGSC) box at the BFN plant and the "ramp" rate is adjustable.

Turbine speed control faults are a major contributor to the pump failure to start. The sixteen failures identified in the industry-wide LER survey include:

- six electro-mechanical governor (EGM) control box faults,
- two dropping resistor assembly (resistor box) failures,
- one ramp generator/signal converter box failure,
- one magnetic speed pickup cable malfunction,
- one speed control potentiometer problem, and
- five motor speed changer/electro-mechanical hydraulic (EG-R) actuator faults.

The LER survey for the BFN plant identified 4 LERs related to turbine speed control faults. In the first event (LER 259/80-079), an electrical ground occurred on the EGR actuator as a result of corrosion between the EGR actuator connector and connector pins. The electrical ground caused failure of the EGM output transistors Q9 & Q10, and resulted in turbine speed control problems. The second event (LER 260/83-009) was related to a HPCI pump turbine failure resulting from the erratic performance of the flow controller which was caused by trapped air in the hydraulic oil control system following maintenance repair work. In the third event (LER 260/84-003), the operator was unable to bring the speed of the HPCI turbine down to the required 2,400 RPM because of an erratic ramp generator/signal converter box adjustment. The fourth event (LER 260/85-015) was related to a design deficiency in the resistor box. A special test showed that AC output voltage from the dropping resistor box was insufficient when its input voltage was at the design minimum. The resistor box was modified to ensure that the EGM control box would receive the required AC voltage signal under worst case conditions.

As a result of the observed problems, significant hardware modifications of the HPCI system have been made at the BFN plant unit 2 to reduce the potential occurrence of turbine speed control faults. The HPCI governor control system has been redesigned and upgraded with new components, and the EGM control panel has been relocated from the turbine skid to the HPCI room wall to eliminate the vibration effects of the skid environment. A new overspeed test controller in place of the original bias speed setting potentiometer, and new and more reliable 24/48 Vdc power supplies for the control system were also installed. Other specific upgrades included the replacement of the RSGC box, EGM controller, speed sensor and cable assembly with new components, replacement of existing copper piping for auxiliary oil supply with stainless steel, and addition of seismic restraints to the turbine skid piping. In addition to hardware improvements, the system surveillances include functional testing of the EG-R assembly on a quarterly basis during the performance of the HPCI system flow rate test to assure reliable operation. Monthly inspections to verify the correctness of system oil pressures require the auxiliary oil pump to be cycled, and this operation results in cycling of the turbine stop valve and turbine control valve which further verifies the operability of the EG-R assembly. Furthermore, a tiered approach in the electrical maintenance procedures (ECI-2-073-GOV001, GOV002, and GOV003) provide an auditable process of governor control system checks and calibration.

The HPCI turbine speed control is a very complex area that requires specialized attention. EG-R actuator failures may increase as the HPCI system and speed control subsystem ages. Thus, the inspector(s) should confirm that there is adequate oversight on the modifications, operations, maintenance and surveillances of the turbine speed control subsystem to ensure functional adequacy of the HPCI system.

B. Lube Oil Supply Faults

This failure mode subcategory consists of eleven failures to provide sufficient lubricating oil to turbine components. As presented in Table A-1, most of the failure events are related to the auxiliary oil pump (AOP) faults which include two bearing failures and five auxiliary oil pump pressure switch faults. Three other events involving low bearing oil pressure events were attributed to valve mispositioning and oil contamination.

There was one LER event at the BFN plant describing a lube oil supply fault. In this event (LER 260/82-016), the HPCI lubricating oil reservoir was found to be almost empty because the reservoir drain valve was sufficiently open to drain most of the reservoir contents. This condition rendered the HPCI system inoperable. The cause of the problem was attributed to personnel error.

Current surveillance practices at the BFN plant preclude the occurrence of such an event. Daily shift walkthrough inspections require plant personnel to verify that the lube oil reservoir is not depleted through visual observation. Furthermore, the HPCI lube oil reservoir is sampled once a month to assure contamination free oil in the lube oil reservoir supply. If degraded oil samples are found, the oil is filtered to return it within specifications.

C. Turbine Overspeed and Auto Reset Problems

The mechanical overspeed trip function is set at 125 percent of the rated turbine speed. The displacement of the emergency governor weight lifts a ball tappet which displaces a piston that allows oil to be dumped through a port from the oil operated turbine stop valve 2-FCV-73-18. This allows the spring force acting on the piston inside the stop valve oil cylinder to close the stop valve. The overspeed hydraulic device is capable of automatic reset after a preset time delay.

In the industry-wide survey, overspeed and auto reset problems were found to have contributed to eight failures in the turbine driven pump failure category. Although the LER search did not identify any event involving turbine overspeed and auto reset problems at the BFN plant, the licensee personnel should be cognizant of the potential problems of turbine overspeed trips resulting in "lockout" conditions. Additional sources of information on turbine overspeed trips are NRC Information Notice 86-14,¹¹ 86-14 Supplements 1 and 2,¹² and AEOD Case Study Report C602.¹³

D. HPCI Inverter Trips or Failures

Control power supply for the BFN plant HPCI system was originally provided by the HPCI "Topaz" inverter that was powered from a 125 V DC bus. As a result of design modifications to have more reliable control power supplies for the HPCI system, the HPCI inverter was replaced with a direct connection to the Division II 120 Vac Uninterruptible Power Supply (UPS) system used by the analog trip system. The design change also added new 48 Vdc power supplies to provide reliable DC power to the governor control system. The present design of the HPCI system also include loss of power annunciator alarms in the main control room (MCR) for all HPCI control power supplies.

The LER survey for the BFN plant identified 4 LERs related to problems associated with the old "Topaz" inverters. In three failure events (LERs 259/85-006, 260/83-028 and 260/83-034), the HPCI system was declared inoperable as a result of blown inverter fuses. The fourth event (LER 260/83-046) was related to a failure of the inverter transformer which resulted in the HPCI system being declared inoperable. Although the HPCI inverter has been replaced with a direct connection to the Division II 120 Vac UPS system in the present design of the HPCI system, the licensee personnel should be cognizant of the impact of fuse problems on the reliability of control power supplies. An extensive fuse control program has been implemented at the BFN plant to control activities related to fuses. This program includes fuse coordination calculations for safety-related power supplies, updated fuse drawings, and new identification documentation for safety-related

fuses. Additional information on potential problems due to inadequate fuse control programs is provided in NRC Information Notice 91-51.¹¹

E. Turbine Stop Valve Failures

The turbine stop valve FCV-73-18 is located in the steam supply line near to the inlet connection of the turbine. The primary function of the valve is to close quickly and stop the flow of steam to the turbine when appropriately signaled. A secondary function of this hydraulically operated valve is to open slowly to provide a controlled rate of admission of steam to the turbine and its governing valve.

Review of the industry-wide operating experience indicated that there were 5 failures of the turbine stop valve. Since 1980, two reportable events involving HPCI turbine stop valve failures have occurred at the BFN plant. In the first event (LER 259/80-026), the HPCI turbine stop valve 1-FCV-73-18 would not open completely because of a worn out mechanical overspeed trip piston. In the second event (LER 260/82-012), the HPCI turbine stop valve 2-FCV-73-18 would not stay open because the Leespring did not compress adequately to allow the trip mechanism to remain in the reset position.

As part of a reliability-centered maintenance (RCM) program for the HPCI system at the BFN plant, the overspeed trip tappet is scheduled for maintenance inspections at every refueling outage. Based on vendor information (GE Services Information Letter) which identified potential binding problems, the tappet assembly is replaced with a new component design with improved performance reliability. The vendor has also recently verified that the turbine stop valve has the correct spring constant in the pilot valve spring. In addition, operability of the turbine stop valve is verified on a quarterly basis during the performance of the HPCI system flow rate surveillance test. During this test, the specified opening times of the turbine stop valve are verified and anomalous operation of the valve is noted for corrective actions.

F. Turbine Exhaust Rupture Disk Failures

The HPCI pump turbine has a set of two mechanical rupture diaphragms in series which protect the exhaust piping and turbine casing from overpressure conditions. When the inner disk ruptures, pressure switches initiate turbine trip and HPCI isolation signals. Low pressure steam flows past the ruptured diaphragm through a restriction orifice directly into the HPCI room. Rupture of the second disk would vent the turbine exhaust into the HPCI pump room without flow restriction. The nominal rupture pressure is approximately 175 psig.

Since 1980, there were two LER events related to turbine exhaust rupture disk failures at the BFN plant. In the first event (LER 260/80-032), failure of the teflon sheet portion of a rupture disc resulted in a HPCI turbine trip. The second event (LER 260/83-074) was related to the rupture of a turbine exhaust rupture disk which rendered the HPCI system inoperable soon after system initiation following a reactor scram.

In the IREP PRA study of the BFN plant, the dominant contributors to HPCI system unavailability were rupture disk failures. These failures accounted for about 31 and 45 % of HPCI system unavailability considered in the LOCA and transient initiated sequences, respectively. Thus, the installation of rupture disks with a structural backing (or the periodic inspection of the older

type design of disk) was recommended to prevent these cyclic fatigue failures. Presently, the BFN plant utilizes "Fike Metal Product" rupture discs to ensure that the turbine casing does not experience overpressurization during a transient event. These rupture discs are replaced at every five years to ensure satisfactory operation. Furthermore, design modifications and installation of new governor control system components eliminate governor control system startup transients which had caused the rupture disc failures.

G. Flow Controller Failures

The flow controller 2-FIC-73-33 in conjunction with the electro-hydraulic turbine governor controls turbine speed and pump flow rate. The flow controller senses pump discharge flow and outputs a 4 to 20 milliamp signal to the turbine governor to maintain a constant pump discharge flow rate over the pressure range of operation.

There were no LER events involving flow controller failures at the BFN plant.

H. Turbine Control Valve Faults

In the industry-wide operating experience review, three turbine control valve fault events were attributed to different root causes. At the BFN plant, one LER event (LER 260/83-028) described the HPCI turbine control valve failure to open due to a misadjusted rod. Potential failures of the turbine control valve can occur as a result of broken lifting beam bolts or broken steam control valve pilot (or poppet). NRC AEOD Study Report T906¹⁵ provides additional information on contributors to the bolt failures of HPCI Terry turbines. Presently, mechanical maintenance procedures (MMI-23) at the BFN plant include quality control inspections of all HPCI system maintenance work to preclude the occurrence of turbine control valve faults. In particular, these procedures have a QC signoff for verification of the cover nut torquing after maintenance on the turbine control valve.

I. Loss of Lube Oil Cooling

The loss of lube oil cooling can be caused by faults in the cooling water lines to and from the cooler, cooler leakage, or flow blockage. A prolonged loss of lube oil cooling can lead to turbine bearing failure.

In the LER survey of the BFN plant, there was one event (LER 259/80-055) in which the pressure control valve 1-PCV-73-43 was found to be stuck closed due to a loose valve guide and this resulted in the loss of lube oil cooling. Presently, the HPCI system flow rate surveillance test procedure requires that all turbine and pump skid temperatures to be recorded during the test performance for subsequent review to ensure adequate cooling is available to all system components including the pressure control valves under normal operating conditions.

J. Miscellaneous --- Valid High Steam Flow During Testing

Another potential system failure involves the practice of running the auxiliary oil pump to lubricate the turbine bearings or to clear an electrical ground in the system. In the Monticello plant, this practice was used in attempts to clear an electrical ground in the electro-hydraulic governor. A system test was initiated to confirm HPCI system operability when the electrical fault

could not be cleared. When the operator opened the turbine steam admission valve to simulate a cold quick start, the system isolated on high steam flow. The operation of the auxiliary oil pump caused the hydraulically operated turbine stop valve to move from its full closed to its full open position. When the stop valve moves from its fully closed position, it initiates a ramp generator response that provides the flow control signal to the turbine steam admission valve and thus, allowing it to move to the open position. Since the auxiliary oil pump had been running for some time, the ramp generator had timed out and a maximum steam flow demand signal was sent to the control valve. This prevented the turbine steam admission valve from restricting steam flow as it normally would during a turbine start, and this condition results in high steam flow and a valid system isolation.

Common practice in some plants include running the auxiliary pump periodically to keep the turbine bearings lubricated. When the auxiliary oil pump is running, the HPCI system will isolate if an automatic initiation signal is received at any time after the ramp generator has timed out, which occurs after approximately 10 to 15 seconds. The following corrective actions have been taken at the Monticello plant to address the problem:

- A modification has been approved that will eliminate ramp generator initiation while the auxiliary oil pump is running unless a valid initiation signal occurs.
- The HPCI system operating procedures have been revised to include caution statements addressing system inoperability when the auxiliary oil pump is running.
- The operating procedures utilized to verify system operability have been revised to include precautions about system status before and during the test. The control system ramp generator function during the opening of the steam admission valve is described in these procedures.

In summary, this is a significant concern because a common plant practice has the potential to disable the HPCI system. BFN plant operating procedures (BF-OI-73) address this problem¹⁶ by including a precautionary statement that if the auxiliary oil pump is started before the steam supply valve FCV-73-16 is open, the possibility of a turbine trip due to overspeed or HPCI isolation due to excessive steam flow exists.

HPCI Failure No. 2 - System Unavailability Due to Test or Maintenance Activities

In a probabilistic risk assessment (PRA), estimates of system unavailability are determined using a fault tree methodology. The fault tree is a diagrammatic representation of the known contributors to system unavailability. In addition to component failures, the system may not be functional due to testing or maintenance (T&M) activities. In a single train system such as the HPCI system, test and maintenance activities on one critical component may usually disable the entire system. It is important to keep the downtime of the HPCI system due to T&M activities as low as possible because of its direct contribution to system unavailability. In the BFN plant IPE analyses, the HPCI system unavailability was estimated to be $1.21\text{E-}5$ per year and the importance of HPCI system was determined to be 0.16, i.e., about 16 percent of the plant core damage frequency were contributed by the likelihood of accident sequences involving failure of the HPCI system. The earlier IREP PRA study indicated that routinely scheduled surveillance tests and maintenance account for over 25% of the HPCI system unavailability. This particular value was

significantly higher than the T&M contribution in the other plant systems analyzed. In the present IPE analyses, the treatment of T&M contributions in the HPCI/RCIC system models were conservative in that no credit was taken for the simultaneous performance of T&M procedures on the HPCI/RCIC systems. Each performance of T&M activities was assumed to occur separately which resulted in the cumulative effects of T&M impact on HPCI/RCIC system unavailability.

The root sources of excessive HPCI system unavailability due to T&M induced failures were examined as part of this operating experience review. In the industry-wide survey, forty-three examples of test or maintenance errors (27% of all HPCI system failures) were divided into three categories: 1) inadequate maintenance or insufficient post-maintenance testing, 2) human error that inadvertently disables the HPCI system, and 3) system inadvertently disabled during testing activity. Inadequate maintenance or insufficient post maintenance testing resulted in 22 HPCI system failures. The problems included valve packing leaks, misadjusted torque switch settings, miscalibrations of a steam line differential pressure instrument and an EGR actuator, improper connection of a gland exhaustor drain line to the tube (high pressure) side of the gland seal condenser, system adjustment without a retest, and a rag left in the turbine sump which disabled the shaft driven oil pump.

In the second T&M category consisting of 4 HPCI system failure events caused by human errors, pertinent examples include the disabling of the wrong HPCI system at a two unit site, mistakenly disabling the auxiliary oil pump due to a smoke odor in the HPCI room, and valving errors which subsequently caused a low pump suction trip or inadequate lube oil pressure at the pump. The final category, "system inadvertently disabled during testing," consists of thirteen personnel errors that temporarily disabled the HPCI system. These incidents include steam line containment isolation valve closure due to errors during testing of the isolation logic, a valve motor failure due to overheating caused by excessive stroking during a surveillance test, and an inverter trip caused by personnel error which resulted in a high voltage condition affecting both Channel C battery chargers. Unlike the first two categories, the majority of these failures have a high probability of recovery.

The search of HPCI system-related LERs identified 6 LERs generated at the BFN plant that resulted from events in which the HPCI system was unavailable due to maintenance and testing activities. In most of these events, the HPCI system was rendered inoperable during the performance of surveillance tests. One event (LER 259/82-032) occurred during testing activities on the 4 kV relays in which the power supply breakers for the train A RHIR and core spray motor driven pumps were racked out, and this resulted in the inoperability of both pumps and the HPCI system. Procedural deficiency and lack of communication were the causes of simultaneous unavailability of these safety-related equipment. The next event (LER 260/82-014) described surveillances not being performed due to personnel error after the HPCI system was made inoperable to allow the performance of circuit calibrations. A maintenance-induced failure event (LER 260/83-009) occurred when the HPCI turbine failed due to erratic operation of the flow controller which was caused by trapped air in the hydraulic oil control system following maintenance work. Two events (LERs 260/83-047 and 260/92-003) resulted from deficiencies in installation procedures. In the first case (LER 83-047), a wiring error resulted in the HPCI system being inoperable during a tachometer calibration activity. The second event (LER 92-003) was related to the inadvertent installation of a test plug that was 120 degrees out of orientation. During performance of the HPCI system functional test, the inboard and outboard steam isolation valves isolated as a result of concurrent heating and subsequent activation of three temperature detectors

which satisfied the logic for a Group 4 isolation. Corrective actions taken at the BFN plant include revising test procedures for safety related equipment to incorporate human factors considerations to prevent human errors during calibration and installation activities. The last T&M event (LER 296/85-003) was related to the HPCI system being declared inoperable for failing to reach rated flow in 25 seconds (actually took 35 seconds) as a result of an incorrectly set position of the limit switch which starts the HPCI auxiliary oil pump. A discrepancy in engineering drawings caused the craftsmen to incorrectly set the switch position. The in-service inspection (ISI) program per ASME Code Section XI recommendations at the BFN plant ensures that relevant HPCI system valves are checked to assure all limit switch settings are in agreement with valve stem position and correctly indicated in the main control room. In addition, the RCM program requires that the Limitorque operators of safety-related valves to be checked during a refueling outage to assure no signs of damage in the torque and limit switches.

In summary, the T&M contributions to HPCI system unavailability must be continuously monitored by the inspector(s) to assure it is as low as possible. The licensee should be administratively limiting the time that the HPCI system is in test or maintenance during normal plant operation. System restoration should be vigorously pursued such that the HPCI system should not be down for days when repair work can be reasonably accomplished in hours. Whenever feasible, portions of the system should be tested during outages. In addition, HPCI system unavailability can also be minimized by adequate root cause analysis and effective corrective action to avoid multiple system outages to address the same failure. Efficient work planning and good engineering practices could also prevent inadvertent or unnecessary removals from service and system isolations during calibration or surveillances. The licensee at the BFN plant has set the present unavailability goal of the Unit 2 HPCI system to be 0.016.

HPCI Failure No. 3 - False High Steam Line Differential Pressure Isolation Signal

The HPCI system is constantly monitored for leakage by transmitter devices sensing steam flow rate, steam pressure, area temperatures adjacent to HPCI steam lines and equipment, and high HPCI turbine exhaust pressure. The steam flow rate is monitored by two differential pressure switches located across two different elbows in the steam piping inside the primary containment. The flow measurement is derived by measuring differential pressure across the inside and outside radius of each elbow. If a leak is detected, the HPCI steam line is automatically isolated and the HPCI system isolation is annunciated in the main control room.

Over the 12 year review period, there were no LERs in this failure category identified for the BFN plant.

HPCI Failure No. 4 - Turbine Steam Inlet Valve FCV-73-16 Fails to Open

Motor operated valve FCV-73-16 is a normally closed, DC powered gate valve. This valve opens on an automatic or manual initiation signal, provided that the turbine exhaust valve is open, to admit reactor steam up to the turbine stop valve.

In the industry-wide survey, there were 8 failures of this valve to open on demand which comprise 5% of all HPCI system failures. Most of these failures were due to mechanical/thermal

binding problems due to insufficient stem lubrication, loose torque switch adjustment screws, and inadequate opening torque capability. There were no LERs in this failure category identified during the 12 year review period for the BFN plant.

HPCI Failure No. 5 - Pump Discharge Valve FCV-73-44 Fails to Open

Motor operated valve FCV-73-44 is a normally closed, DC powered gate valve that is automatically opened upon system initiation. The failure of this valve to open disables the HPCI system to inject water into the reactor vessel.

There have been 8 HPCI pump discharge valve failures documented in the industry-wide operating experience review which account for 5% of all system failures. Most of the valve failures were generic problems including valve motor failures, a ground of the DC control voltage at the torque switch, and inadequate torque problems due to the use of starting resistors in the valve motor circuitry.

The BFN plant did not have any reportable failures of the HPCI pump discharge valve FCV-73-44 over the 12 year review period.

HPCI Failure No. 6 - HPCI System Interactions

Systems interactions refer to unrelated system failures that can disable the HPCI system. Although there is no associated PRA-based failure category, the industry-wide operating experience review identified the following examples of system interactions that disabled the HPCI system:

- a) During a fire protection system surveillance test, approximately one gallon of water drained onto a battery powered motor control center (MCC) causing a circuit breaker overload trip and valve inoperability.
- b) A cracked flow control valve test coupling allowed water to be sprayed on a battery powered MCC and resulted in disabling a loss of power monitor on the main steam line drain. The HPCI system was disabled when the MCC was deenergized to allow inspection and drying of the components.
- c) An automatic sprinkler system in the HPCI room activated after a system test. The probable cause was buildup of steam vapor from the leakoff drain system that activated an ionization detector.
- d) Setpoint drift in a Fenwal temperature switch caused activation of a deluge system during a HPCI turbine overspeed test.

The LER survey identified one LER event at the BFN plant in which system interactions problems affected HPCI system operability. In this event (LER 259/82-032), the power supply breakers for train A RHR and core spray pump motors were racked out during the performance of a surveillance test on the 4 kV relays, and this resulted in both safety-related pumps and the HPCI system inoperable. Procedural deficiency and lack of communication were the causes of the simultaneous unavailability of these safety-related equipment. Operator training lessons at the BFN plant include examples and descriptions of consequences of support systems interactions that may

cause HPCI system inoperability. The training objectives of providing awareness of system interactions problems are further tested and reinforced by simulator training exercises which include proper diagnosis of the effects of the system interactions scenarios.

HPCI Failure No. 7 - System Actuation Logic Fails

Startup and operation of the HPCI system is automatically initiated upon detection of either low-low reactor vessel water level (- 45.0 inches decreasing) in the reactor vessel or high drywell pressure (2.45 psig, increasing). The HPCI system can also be manually initiated by arming and then depressing the manual initiation switch in the control room.

In the industry-wide survey, there were 4 LERs associated with this failure mode. These LERs illustrate that failure of the HPCI system actuation logic is more likely due to common causes such as the loss of electrical power. Unlike the HPCI system trip logic, the redundancy (one out of two twice design concept) and the diversity (low vessel level/high drywell pressure conditions) of the actuation logic make it less susceptible to the impact of individual sensor failures. Over the 12 year review period, there were no LERs in this failure category identified for the reactor level and containment pressurization instrumentation of the BFN plant HPCI system.

HPCI Failure No. 8 - False High Area Temperature Isolation Signal

The HPCI system is constantly monitored for leakage by transmitter devices sensing steam flow rate, steam pressure, and area temperatures adjacent to the steam line and equipment. If a leak is detected, the system is automatically isolated and alarmed in the control room. At the BFN plant Unit 2, the high HPCI system area temperature (indicative of a steam leak) is monitored by the temperature switch 2-TS-73-2A-S.

In the industry-wide survey, this category accounted for three HPCI system failures (i.e., about 2% of all failures). During the 12 year review period, there were no LERs identified for the BFN plant that were related to false high HPCI system area temperature isolation signals.

HPCI Failure No. 9 - False Low Suction Pressure Trips

The purpose of the low pump suction pressure trip is to prevent damage to the HPCI pumps due to loss of suction. At the BFN plant Unit 2, the pressure switch 2-PS-73-29 actuates to cause the turbine stop valve to close in the event that low HPCI pump suction pressure is sensed.

In the industry-wide survey, there were two occurrences of HPCI pump turbine trips that were attributed to false low suction pressure signals. However, the BFN plant has not experienced any HPCI system isolations due to false low pump suction pressure trips since 1980.

HPCI Failure No. 10 - False High Turbine Exhaust Pressure Signal

The high turbine exhaust pressure signal is one of several logic signals from the protective turbine trip circuitry that close the turbine stop valve and isolate the HPCI system. The high turbine exhaust pressure signal is generated by pressure switches PS-73-22A and PS-73-22B at the BFN plant, and is indicative of a turbine or a control system malfunction.

There was only one LER in this failure category identified in the industry-wide operating experience review. No LERs related to false high turbine exhaust pressure signals were found for the BFN plant during the review period since 1980.

HPCI Failure No. 11 - Normally Open Turbine Exhaust Valve Fails Closed

Failure of any one of the turbine exhaust valves to open would cause a turbine trip as a result of a valid high turbine exhaust signal. One BWR plant had experienced a failure of the turbine exhaust line swing check valve. The valve internals were found wedged in a MOV located downstream in the turbine exhaust line and this could potentially cause a turbine trip due to high exhaust pressure. The failure was attributed to the forceful cycling of the swing check discs under low flow conditions. Additional information on the background of such problems is provided in the NRC AEOD Report E402¹⁷ and Information Notice 82-26.¹⁸

At the BFN plant, no LERs were found within the review period that involved failure of normally open turbine exhaust valve HCV-73-23 to close.

HPCI Failure No. 12 - Condensate Storage Tank/Suppression Pool Switchover Logic Fails

In the standby mode, the HPCI pump suction is normally aligned to the condensate storage tank (CST). Upon a low CST level signal via level switch LS-73-56A and LS-73-56B, or a high suppression pool level signal via level switch LS-73-57A and LS-73-57B, the suppression pool suction valves FCV-73-26 and FCV-73-27 automatically open with subsequent closure of the CST suction valve FCV-73-40. System operation continues with the use of the HPCI booster pump to draw suction from the suppression pool.

This PRA-based HPCI failure mode has become less important as a result of changes in the BWR Emergency Procedure Guidelines which generally advocate the continued use of water sources that are external to the containment. This avoids potential ECCS degradation due to high suppression pool temperature (high HPCI lube oil temperature) while simultaneously increasing suppression pool mass. Thus, an HPCI pump suction transfer to the suppression pool is no longer greatly desirable and especially in decay heat removal accident sequences, the operator would likely bypass the switchover logic to maintain the CST suction source, or realign to the CST if a switchover to the pool had occurred. Therefore, the inspection focus should be on the continued viable option of the CST as an injection source during an accident sequence.

There were 2 LERs describing problems involving the CST/suppression pool switchover logic at the BFN plant since 1980. In the first event (LER 259/82-071), the condensate storage tank low level switches LS-73-56A and LS-73-56B failed to operate due to dirty and corroded activating plates of the level switches. The plate points were cleaned. The second event (LER 259/84-028) was related to the failure of the automatic CST/suppression pool transfer logic to perform its intended function during surveillance testing because of a dirty contact on the limit switch. Present surveillance practices at the BFN plant include testing and calibrating the CST low level and suppression pool high level transfer switches on a quarterly basis. During these surveillance inspections, the relays in the HPCI system logic are also actuated to satisfy overlap testing requirements which are used to demonstrate HPCI logic operability once per refueling outage.

HPCI Failure No. 13 - Suppression Pool Suction Line Valves FCV-73-26 or FCV-73-27 Fail to Open

At the BFN plant, there are two 250 VDC powered suppression pool HPCI pump suction valves, FCV-73-26 and FCV-73-27, with a check valve CKV-73-517 in between them and this valve arrangement is in series with a hand control valve HCV-73-25. In the standby mode, the HPCI system is initially aligned to the condensate storage tank (CST). The suppression pool suction valves are opened and the CST suction valve is closed on a CST low water level or a high suppression pool level signal. The importance of this failure mode has been diminished by the current emergency procedure guidelines which emphasize the continued use of external sources of water injection. This requires operator action to bypass the HPCI suppression pool switchover logic to prevent the opening of the suppression pool suction valves FCV-73-26 and FCV-73-27. This is especially true for the decay heat removal (non ATWS) sequence where it is likely that inventory makeup from the CST can be maintained.

In the industry-wide survey, there have been 6 failures of the suppression pool suction valve to open which represents about 4% of all HPCI system failures. All these failures occurred during system surveillances. For the BFN plant, one LER was identified that described the failure of the hand control valve in the suppression pool suction line. In this event (LER 259/87-027), the normally locked open hand control valve HCV-73-25 which isolates the suppression pool from the first motor operated suppression pool isolation valve FCV-73-26 during layup was found in a failed closed position (as observed through a borescope) with the stem separated from the valve disc. The failure was attributed to tensile overload on 3 of the 4 bolts which hold the key attachment between the shaft and the disc of the valve. The bolts were replaced with stainless steel bolts. Current surveillance practices at the BFN plant include verifying the normally open position of this valve. The RCM program schedule has recommendations to replace this valve with a newer design. As an interim measure, this valve is inspected at each refueling outage for signs of corrosion and appropriate maintenance actions are taken to correct any identified problems.

HPCI Failure No. 14 - Minimum Flow Valve FCV-73-30 Fails to Open

The minimum flow bypass line is provided for pump protection. The bypass valve, FCV-73-30, automatically opens on a low flow signal of 600 gpm or less flow when the pump discharge pressure is greater than 125 psig. When the bypass line is open, pump flow is directed to the suppression pool. The valve automatically closes on a high flow signal of 1200gpm or more flow. During an actual system demand, failure of the minimum flow valve to open is important only when the opening of the pump discharge valve FCV-73-44 is significantly delayed. In probabilistic terms, this combination of events is generally not risk significant. With regard to system operation and testing in the minimum flow mode, the licensee response to NRC Bulletin 88-04¹⁹ should be reviewed to determine the adequacy of the design of the minimum flow bypass line. Unless there is a design concern or a recurring problem with either component, inspection attention may be minimized in this area.

At the BFN plant, there were no LERs in this failure category identified over the 12 year review period. Although the HPCI minimum flow valve has not been prone to failures, current surveillance practices at the BFN plant include verifying proper operation of this valve during performance of valve stroke time testing and flowrate testing activities.

Other Failure Modes

The industry-wide Operating Experience Review did not identify any HPCI system failures for the following PRA-based failure modes:

- Normally Open Pump Discharge Valve FCV-73-34 Fails Closed or is Plugged
- Pump Discharge Check Valve FCV-73-45 Fails to Open
- CST Suction Line Check Valve CKV-73-505 Fails to Open
- CST Suction Line Manual Valve HCV-2-705 Plugged
- Normally Open CST Pump Suction Valve FCV-73-40 Fails Closed or Is Plugged
- Suppression Pool Suction Line Check Valve CKV-73-517 Fails to Open
- Normally Open Steam Line Containment Isolation Valve FCV-73-2 or FCV-73-3 Fails Closed
- Steam Line Drain Pot Malfunctions
- Turbine Exhaust Line Vacuum Breaker Valves Fail to Operate
- Suction Strainer Plugged

The PRA-based prioritization of HPCI failure modes have a good correlation with the actual industry-wide experience of HPCI system failures. With the exception of the first failure mode listed above for the pump discharge valve FCV-73-34, all of the HPCI faults listed above have been considered as "low importance" failure events in the PRA-based rankings of Section 4.

In the LER survey, one LER event involving failure of the steam line isolation valve was identified for the BFN plant. In this event (LER 296/84-013), the HPCI outboard steam line isolation valve FCV-73-3 could not be opened electrically because the motor pinion gears had been installed backwards. Current surveillance practices at the BFN plant include verifying proper operation of all HPCI system flow/pressure control valves (e.g., FCV-73-19, FCV-73-43, PCV-73-501, PCV-73-502, etc.) during the performance of HPCI system flow rate tests.

6.2 Site Visit Observations

During a plant site visit to the BFN plant, discussions on various aspects of operation, maintenance and surveillance of the HPCI system to ensure reliable system performance were held with licensee representatives. Recent or planned modifications to prevent or eliminate problems identified in previously issued LERs were discussed. The recent or planned modifications to upgrade the HPCI system at the BFN plant are:

- a) The governor control system has been redesigned and upgraded with new components such as a new overspeed test controller in place of the original bias speed setting potentiometer, new and more reliable 24/48 Vdc power supplies, and new replacement of the ramp generator/signal converter (RGSC) box, EGM controller, speed sensor and cable assembly;
- b) The EGM control panel has been relocated from the turbine skid to the HPCI room wall to eliminate the vibration effects of the skid environment as well as allowing ease of maintenance;
- c) Seismic restraints has been added to the turbine skid piping to improve the margin of safety and seismic qualifications;

- d) Existing copper piping for the auxiliary oil supply has been replaced with stainless steel to be compatible with correct material requirements;
- e) Control power supply from the HPCI "Topaz" inverter has been replaced with a direct connection to the Division II 120 Vac Uninterruptable Power Supply (UPS) system used by the analog trip system;
- f) A one-inch relief valve (2-RFV-73-506) has been installed in the HPCI booster pump suction piping to ensure the mitigation of overpressurization events; and
- g) The tappet assembly on the overspeed trip was being replaced with a new Dresser-Rand design based on the recommendation of GE Service Information Letter (SIL) No. 392, Revision 1.

In addition to the above modifications, the licensee have established a reliability-centered maintenance (RCM) program for maintenance of the HPCI system and a recommended surveillance program per ASME Section XI requirements to check limit switch settings of all relevant HPCI system valves. Furthermore, the licensee has instituted a performance monitoring program to assure contamination free oil in the lube oil reservoir supply and introduced requirements in mechanical maintenance procedures (MMI-23) to include quality control inspections of all pertinent HPCI system repair work. It is noted that there is a concerted effort at the BFN plant to upgrade the HPCI system control equipment that would preclude the effects of component obsolescence, improve system reliability and thus, enhance HPCI system availability.

6.3 Contribution of Human Errors to System Unavailability

The potential for human error exists for activities involving maintenance, calibration, surveillance, and operation of plant systems. In PRAs, the influence of operator error on plant risks is typically modeled both in fault trees (system failure diagrams) and in the event trees that delineate the postulated sequences. As such, these human errors are usually defined as gross actions that can cause complete failure of a system. Typical human errors considered in PRAs that affect HPCI system availability are:

- a) Failure to manually start the high pressure injection system after automatic injection fails,
- b) Operator failure to transfer pump suction from the CST to the suppression pool after a pump trip on low suction due to CST unavailability,
- c) Failure to provide makeup to the CST during an ATWS event,
- d) Failure to transfer pump suction from the suppression pool to the CST during an event in which high suppression pool temperatures are reached (e.g., during an ATWS event, or during a non-ATWS event where there is failure of suppression pool cooling),
- e) Failure to override the HPCI high-temperature isolation logic (for station blackout sequences),

- f) Miscalibration of HPCI system sensors that disables system actuation, causes system isolation on erroneous high RPV level indication, or results in false system isolation signals, and
- g) Failure to reset the HPCI system for operation after testing or maintenance.

Except for the last two listed items, all these human errors are either: (i) conditional errors, i.e., mistakes made within the context of an HPCI system failure or isolation (errors a and b), or (ii) event specific errors (items c, d and e). These types of human errors make direct observation of their occurrence unlikely. Therefore, the potential for these human errors can only be evaluated indirectly by a review of the licensee procedures and observation of operator performance at a simulator.

The last two types of human errors can occur during normal operation and thus, are more easily inspectable. NRC Resident Inspectors routinely examine surveillance, calibration and maintenance practices and procedures, and perform main control room and plant lineup verifications of ECCS. HPCI system operability is confirmed by checking the steam supply and exhaust lineup, pump suction and discharge lineups, and the control function settings (hand/auto station in automatic mode).

In addition to the examination of licensee practices and procedures, the application of insights from the review of industry-wide experience can help reduce a significant portion of the HPCI system unavailability due to human error contributions. In the reactive mode, a thorough root cause analysis and suitable corrective measures can prevent similar occurrences in the future.

In the LER survey of HPCI system-related failure events at the BFN plant, five LERs describing failure events caused by human errors were identified. These 5 LERs are briefly summarized below:

- (a) LER 259/85-056 described a configuration problem in which the normal and alternate control power supplies to the 4kV shutdown board "A" were found to be reversed as a result of a wiring error that was attributed to personnel error during the initial installation of the shutdown battery board.
- (b) LER 259/82-032 described the simultaneous unavailability of safety systems due to procedural deficiency and lack of communication, when the power supply breakers for train "A" RHR and core spray pump motors were racked out during the performance of a test on 4 kV relays which rendered the safety-related pumps and HPCI system inoperable.
- (c) LER 260/82-016 reported that the HPCI system was rendered inoperable when the HPCI system lubricating oil reservoir was found to be almost empty because the reservoir drain valve was opened 1 and 1/2 turns as a result of personnel error.
- (d) LER 260/83-028 described a HPCI turbine control valve failure to open because of a rod misadjustment.
- (e) LER 296/84-013 described the inability of HPCI outboard steam isolation valve FCV-73-3 to be opened electrically because the motor pinion gears had been installed backwards.

Present practices at the BFN plant include incorporating lessons learned from LER analyses into the training programs for maintenance and surveillance test personnel, and utilizing insights from root cause analyses to resolve a mixed spectrum of potential problems. A Site Standard Practice document (SSP-12.9) provides guidance for the performance of incident investigations and root cause analysis of significant and some non-significant human errors related to the operation, maintenance and surveillance of the HPCI system. This document also provides the requirement for mandatory training of at least one member of the incident investigation team in root cause analysis techniques. The implementation of this site procedure has proved to be useful in identifying and rectifying problems.

6.4 Additional System Considerations

The LER survey of industry-wide experience has identified several other HPCI system considerations that could impact the overall risk of a plant. These considerations are discussed in the following subsections with any related BFN plant experience.

6.4.1 LOCAs Outside Containment

Unlike the HPCI system failure modes discussed previously, that result in unavailability of the system for core damage mitigation purposes, failures in the HPCI system boundary can be potential initiators of a LOCA outside containment. The industry survey identified degradations of the steamline isolation function and pump suction line overpressurizations as potential causes. Examples of steam line isolation problems include:

- a steamline differential pressure transmitter with a non-conservative setting, and
- an inboard containment isolation valve that failed to close.

Examples of pump suction line overpressurizations include:

- a slow closure of the pump discharge check valve that caused a pressure surge after a turbine trip, and
- a water hammer caused by steam void collapse following system initiation after feedwater backleakage elevated the temperature in the pump discharge line. (NRC IN 89-36 provides a discussion on elevated temperatures in ECCS systems.²⁰)

At the BFN plant, the main control room has analog indicating loops to provide indication of the HPCI booster pump suction pressure (PI-73-28A) and the main pump discharge pressure (PI-73-31A). Backleakage from the feedwater system would cause these pressures to increase noticeably and the instrumentation would alert operators to respond to the potential overpressurization problem.

In general, the potential event of HPCI system LOCA outside containment is considered to be a small contributor to the total core damage likelihood. The diversity of the steam line break

detection logic and the downstream feedwater check valve reduce the potential for an unisolated LOCA outside containment. The examples presented above are potential areas for inspection to assure that plant design or operation does not increase the possible occurrence of this initiator.

6.4.2 Support Systems Required for HPCI System Operation

The high pressure coolant injection system is dependent on other systems (called support systems) for successful operation. These systems are:

DC Power	For system control, pump operation and valve movement.
Room Cooling	For HPCI pump room cooling to support long term operations. This function requires service water (for cooling) and AC power supply for the fan motor.
HPCI Actuation	RPV level and primary containment pressure instrumentation for system initiation and shutdown.

Review of the HPCI system operational history showed that the influence of reliable support systems on HPCI system availability was obviously significant. The loss or degradation of the DC battery or DC bus that provides control power to the HPCI system has a straightforward effect. Besides battery charger problems or inadvertent fuse openings, the unusual DC system problems included a battery degradation due to corrosion of the cell plates. The suspected cause was a galvanic reaction due to plate weld metal impurities. Another concern is insufficient voltage at the load centers during degraded voltage conditions which could trip the station inverters or fail MOVs (e.g., Browns Ferry 1, Brunswick 1 & 2 and Nine Mile Point 1 events). This problem would be of particular concern during a loss of offsite power or a station blackout event. A BFN plant LER (LER 259/85-032) reported the potential for electrical support system failures.

The effects of loss of HPCI room cooling on continued HPCI system operation are not very clear. Tolerable ambient conditions in the HPCI room is typically required to support long term HPCI system operation. Besides random failures which can occur at any time, there is one accident sequence specific effect that should be examined. During station blackout conditions, the HPCI room temperatures may increase substantially when continued HPCI system operation is most critical. At the BFN plant, the HPCI pump room does not have any room coolers. However, it is open to the adjacent RHR quadrangle area which is ventilated automatically by room coolers that are activated on high temperature in the area. Although there are plant procedures (2-EOI-3) to address proper operator response to lower any high temperature condition in the HPCI room, the licensee actions to preserve HPCI system operation should be examined. The licensee should have acceptable pump room and steam line temperature calculations, or have other proceduralized provisions (e.g., bypass high temperature isolation) to assure long term HPCI system operability.

The RPV level or high drywell pressure instrumentation is required for actuation of various ECCS systems including the HPCI system. The operating experience review did not have any pertinent examples of failures of the ECCS actuation logic which directly affected HPCI system operation. This is because the ECCS actuation instrumentation logic does not activate the HPCI system directly. The initiation signal to start the HPCI system automatically is relayed via the

Shared Actuation Instrumentation signals generated to actuate intermediate ECCS systems in response to plant abnormal conditions.

In summary, support system malfunctions sometimes can impact HPCI system operation in a subtle manner. Within the context of specific accident scenarios, the incipient failure of these support systems may render the front-line system inoperable. The inspector(s) should verify that licensee personnel are aware of these support system dependencies and confirm that compensating measures are adequate to address this concern. Presently, operator training lessons at the BFN plant include examples and descriptions of consequences of support system interaction problems that may cause HPCI system inoperability. Awareness of support systems interaction problems are further tested and reinforced by simulator training exercises to enhance proper diagnosis of the effects of the systems interaction scenarios.

6.4.3 Simultaneous Unavailability of Multiple Systems

Multiple system unavailability of certain functionally related systems is a major concern because of the increased risk associated with continued operation. Although standard technical specification 3.0.3 provides the operational constraints to limit the risk exposure somewhat, the licensee should avoid planned multiple system outages if possible.

Within the context of the accident sequences discussed previously (in Section 3), unavailability of certain combinations of systems results in a relatively large risk of core damage. For example, the HPCI system operating experience review found nine LERs that documented simultaneous unavailability of HPCI and RCIC systems. During such outage periods, the probability of core damage becomes very much higher due to the increased likelihoods of accident sequences in which HPCI and RCIC systems are required for mitigation purposes. This would include all of the accident scenarios described in the Accident Sequence Description except for the "Unisolated LOCA Outside Containment" sequence. Unavailability of the HPCI system and an emergency diesel generator together would have a similar impact on overall plant risk. Additionally, the simultaneous unavailability of the HPCI system and ADS (one LER describes this occurrence during logic testing) would have a significant impact on the progression of Sequence 1, "Loss of High Pressure Injection and Failure to Depressurize".

Although some of these LER examples of multiple system unavailability were due to random failures, the majority of such outages involve licensee decisions to disable a system for surveillance tests when another critical system is not operable. At the BFN plant, Technical Specification 3.5.e - items 2 & 3 forbid multiple systems to become simultaneously unavailable during normal plant operation.²¹ Plant procedures SSP-7.1 "Work Control" and SSP-7.2 "Outage Management" provide guidance to the Operations staff to ensure that Technical Specifications for the BFN plant units are maintained when plant conditions require outage work to be performed. If one system is out of service and another system unexpectedly becomes inoperable, the Operations Shift Supervisor is responsible for placing the plant in safe shutdown conditions per SSP 12.1 "Conduct of Operations" in conformance with Technical Specifications.

In the LER survey, two LERs were found to describe occurrences of simultaneous unavailability of HPCI and other safety systems at the BFN plant. In the first event (LER 259/82-032), the power supply breakers for the train "A" RHR and core spray pump motors were racked out during the performance of a surveillance test on 4 kV relays which rendered the safety pumps

and the HPCI system inoperable. The second event (LER 296/85-003) was related to the HPCI system being declared inoperable as a result of failing to reach rated flow in 25 seconds (actual time taken was 35 seconds) due to an incorrectly set limit switch which starts the HPCI auxiliary oil pump, and a failed restart of the RCIC pump during a subsequent RCIC pump operability performance test to satisfy technical specification requirements. The RCIC pump failed to restart because the limit torque operator of a motor-operated steam isolation valve would not reopen to allow steam supply to the pump turbine.

At the BFN plant, administrative control procedures prevent unavailability of multiple systems due to testing and maintenance activities. The operations staff is required to assure that no licensed conditions are violated when removing a system from service. Furthermore, all repair work or testing on a system must be approved by the operations staff in accordance with procedure SSP-7.1 "Work Control" and procedure SSP-8.1 "Conduct of Testing."

7. SUMMARY

This System Risk-Based Inspection Guide (System RIG) has been developed as an aid to HPCI system inspections at the Browns Ferry Nuclear Plant. The document presents a risk-based discussion of the role of the HPCI system in accident mitigation and provides a catalogue of PRA-based HPCI system failure modes. In addition, the system RIG uses information from industry operating experience, including illustrative examples, to augment the identification of the basic PRA failure modes. The risk-based input and insights from the operating experience database have been combined to develop a set of composite rankings of failure modes for the HPCI system. Table 4-2 shows the ranking of these HPCI system failure modes. This information can be used to optimize NRC resources by properly allocating proactive inspection efforts based on risk considerations and industry experience. In addition, important component faults are summarized in Section 6 and the discussions of risk implications provide insights both for routine inspections and the "post mortems" conducted after the occurrence of significant failures.

Review of the BFN plant HPCI system operational history has identified the following component failure modes that experienced a high frequency of occurrence:

- turbine speed control faults,
- inverter trips or failures,
- turbine stop valve failures,
- turbine exhaust rupture disk failures, and
- CST/suppression pool switchover logic failures.

In addition, there was a relatively large number of HPCI system failure events due to test and maintenance activities. The importance of keeping the HPCI system downtime due to T&M activities as low as reasonably possible is to minimize its direct contribution to system unavailability. These areas should be given further attention during routine inspections and specialized inspection activities in the future.

As the BFN plant matures in its operating lifetime, the incidence of inadvertent HPCI system isolations due to surveillance and calibration activities is expected to decrease because of improved knowledge of the system. However, component failures due to aging-related causes are expected to become a more significant contributor to the BFN plant HPCI system failure distribution. Review of industry-wide operating experience has identified several HPCI system failure events due to component aging problems in the pump and turbine control systems at a few older BWR plants including the Browns Ferry nuclear plant. It is noted that there is a concerted effort at the BFN plant to upgrade the HPCI system control equipment that would preclude the effects of component obsolescence, improve system reliability and thus, enhance HPCI system availability.

Recommendations have been made throughout this document regarding the emphasis or focus of inspection activities for the HPCI system at the BFN plant. Some of these suggestions are generic in nature, but some recommendations related to specific maintenance, testing, or operational activities conducted at the BFN plant are made to assure that a highly reliable operation of the HPCI system is maintained. These recommendations could also be useful to the licensee in planning and conducting self-initiated safety system functional inspections (SSFIs) on various safety systems including the HPCI system to ensure functional adequacy and operational readiness of a plant system.

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APPENDIX A-1

SUMMARY OF INDUSTRY SURVEY OF HPCI OPERATING EXPERIENCE

HPCI PUMP OR TURBINE FAILS TO START OR RUN

Table A-1 HPCI Pump or Turbine Fails to Start - Industry Survey Results

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
<p><u>TURBINE SPEED CONTROL FAULTS</u></p> <p>EGM control box malfunction</p>	Two similar failures attributed to aging effects due to long term energization and possibly elevated ambient temperatures. An EGM printed circuit board failed and caused a false high steam flow signal. The second failure involved the electronics in the control box chassis.	EGM printed circuit boards will be replaced at eight year intervals. Additional HPCI pump room cooling added.	Each of these EGM control box failures occurred at older plants and appear to be aging related.	
	EGM control box had a ground.	Two printed circuit boards replaced.		
	Miscalibration of null voltage settings.	Recalibration of voltage settings.		
	Failed transistor in the EGM control box.	Box replaced. Surveillance procedures being expanded to verify proper functioning of the output speed circuit.		
<p>Motor speed changer/EG-R actuator malfunctions.</p>	HPCI failed auto initiation surveillance because the electrical connections between the governor and the control valve electrohydraulic servo were in error.	Error was not detected during a previous test at 160 psig. Procedures revised to functionally test the governor control system during the low pressure surveillance testing.		
	Capacitor failure in motor gear unit.	Replaced capacitor	Failure may have been caused by excessive HPCI room temperature.	Ambient temperatures in equipment areas should be verified with specifications.
	Improper gapping and foreign accumulation on contacts.	Component replaced or serviced.		
	EG-R actuator grounded at pin connection due to the accumulation of corrosion products. There were three occurrences of this event that have been attributed to a design change in the actuator pin connections.	Corrosion products removed.		

Table A-1 (Cont'd)

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
Dropping resistor assembly problems.	Resistor box design deficiency-special test showed output voltage insufficient when input voltage at design minimum.	Resistor box modified to ensure EGM control box will receive required voltage under worst case conditions.		
Ramp generator/signal converter box.	Resistor Failure	Resistor component replaced		
Magnetic speed pickup cable.	Slow HPCI response time attributed incorrect turbine loop gain and ramp time settings.	Gain and time settings reset.	Settings had not been modified based on power ascension test program.	
Speed control potentiometer.	Cable damaged during HPCI maintenance preventing speed feedback to the speed controller.	Cable repaired.		
<u>LUBE OIL SUPPLY FAULTS</u> Auxiliary oil pump pressure switch fails.	Loose control room panel terminations	Repaired panel terminations.		
	Microswitch within pressure switch fails.	Microswitch replaced.	2 additional failures due to miscalibration, and one attributed to a piece of teflon tape that blocked sensing orifice of switch.	
	Loose hydraulic control system pressure switch contacting arm.	Component adjusted.		
	Pump bearing failure degraded pump performance/lower discharge pressure, bearing had been recently replaced-potential human error.	Pump replaced.	Similar event-pump motor bearing failure was possibly due to daily use to supply oil to turbine stop valve.	
Additional low bearing oil pressure occurrences.	Human error. All control valves mispositioned.	Valves correctly positioned, handles removed. Surveillance revised to check oil pressure during turbine test.	Two similar events have occurred at other plants.	
Lube oil contamination.	Paraffin in lube oil coated piston caused binding of hydraulic trip relay.	Piston cleaned.		The process of periodically sampling lube oil should be verified.

Table A-1 (Cont'd)

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
<u>TURBINE OVERSPEED AND AUTO RESET PROBLEMS</u> Electrical termination failures	Loose electrical termination on solenoid valve coil disabled the remote reset function. Failure attributed to normal HPCI vibration.	Wiring to the solenoids will be restrained to reduce strain on the terminations.	The corrective action for a similar earlier event apparently did not address the root cause of the failure.	
Overspeed trip device tapped binding.	Overspeed trip device tappet assembly head was binding in valve body. Polyurethane tappet, previously machined per GE guidance, had experienced additional growth.	Tappet remachined.	Similar occurrence at another plant.	
	Loose hydraulic control system pressure switch contactor arm.	Repaired contactor arm.	None.	
Drain port blocked.	Erratic stop valve operation. Blocked drain port in overspeed trip and auto reset piston assembly caused trip mechanism to cycle between tripped and normal positions.	Drain port cleared.	Additional information on turbine overspeed trips is provided in NRC Information Notice 86-14 and 86-14, Supp. 1.	
<u>INVERTER TRIPS OR FAILURES</u>	Inverter tripped and could not be reset due to a failed diode.	Replaced inverter.	See Ref. 16 for effects of inverter aging and preventative measures.	
	Inverter failed due to the failure of an internal capacitor.	Replaced inverter.	A similar event involving a ruptured capacitor occurred at another plant.	
Internal electronic faults	Inverter overheating due to a failed integral cooling fan.	Repaired or replaced cooling fan.		
	Inverter failure due to blown fuse.	Replaced fuse.		

Table A-1 (Cont'd)

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
Internal electronic faults (cont'd)	Inverter trip due to high voltage setpoint drift.	Equalize voltage was reduced allowing inverter to reset.		
<u>TURBINE STOP VALVE FAILURES</u> Control oil leaks.	Oil leak developed at pilot valve assembly/hydraulic cylinder flange bolts were loose.	Flange bolts torqued.	Similar event at another plant.	
Pilot oil trip solenoid valve.	Valve stuck open due to disintegration of diaphragm that caused valve plunger to stick above the seat.	Valve's expendable parts now scheduled for replacement at every third refueling outage.		
	Valve would not open due to excessive leakage of piston rings in hydraulic cylinder actuator.	Piston rings were fabricated from resin impregnated leather. Vendor recommended replacement every five years. Potential aging concern.	Further discussion in IE Circular 80-07.	
Mechanical valve failures.	Valve and actuator stems separated at split coupling. Balance chamber adjustment drift believed to have caused increased momentum and disk overtravel.	Balance chamber adjustment was performed in 1985 per GE SIL 352. Adjustment will be checked quarterly for a minimum of 3 quarters.	Similar failure occurred involving a loose valve position sensor bracket that caught on actuator housing when the valve opened. The valve failed in the open position.	Overstress and ultimate fracture will usually occur at the undercut on the coupling threads due to reducing cross section. Incipient stem failure may be indicated by circumferential cracks in threaded stem area.
<u>TURBINE EXHAUST RUPTURE DISK</u> Cyclic fatigue.	Inner rupture disk failed due to cyclic fatigue (alternating pressure and vacuum within the exhaust line). Vacuum occurs during cold quick starts with cold piping.	Both disks replaced with an improved design that has a structural backing to prevent flexing during exhaust line vacuum conditions.	Improved design appears to eliminate the cyclic fatigue failure mode.	AEOD Report E402 provides additional examples of turbine exhaust rupture disk failures.
Water hammer induced disk rupture.	Exhaust diaphragm ruptured by water carryover from exhaust line drain pot due to a blocked drain line.	Blocked line cleared; rupture disk replaced.	A similar event has occurred at another plant. Duration and frequency of exhaust line blowdown increased.	

Table A-1 (Cont'd)

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
<u>FLOW</u> <u>CONTROLLER</u> <u>FAILURES</u> Failure to control in automatic.	Defective amplifier card and solder joint attributed to aging.	Repairs performed.	Failures appear to be aging related, yet it appears some licensees do not intend to periodically replace sensitive equipment or otherwise address the root cause of these failures.	Ambient conditions in areas containing this equipment should be verified against specifications.
	Dropping resistor failed in the instrument amplifier circuitry due to normal heat of operation.	Resistors R26, R24, and zener diode C24 all appeared to be affected by ambient temperatures and were replaced.		
	Intermittent operation of internal switch contacts did not allow the controller to read the flow setpoint in auto.	The slight oxidized contacts were cleaned and lubricated. In the long term, permanent jumpers will be installed to bypass the switches.		
Gear train failure.	Loose fastener caused intermediate gear to unmesh which prevented adjustment of the controller setting.	Procedures will be revised to require a periodic check of the gear train and fasteners.		
Miscalibration	Flow controller indicated a flow of 400 gpm when system not in operation. Failure attributed to miscalibration.	Controller recalibrated.		
<u>TURBINE</u> <u>CONTROL VALVE</u> <u>FAULTS</u> Control oil leak.	Oil supply line nipple leaking because plant personnel stepped on line to gain access to control valve.	Nipple repaired; plant personnel informed of failure cause.		
	Six of the eight lifting beam bolts failed due to stress corrosion cracking of improperly heat treated bolts. The remaining two bolts were cracked.	Licensee to change thread lubricant; non-metal bearing petroleum jelly recommended.	Per AEOD Report T906, improper heat treatment and the use of a copper based anti-seizure compound were major contributors to this failure.	
Throttle valve lifting beam bolting failure.				

Table A-1 (Cont'd)

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
<u>LOSS OF LUBE OIL COOLING</u> PCV-F035 failures.	PCV_F035 had an incorrect diaphragm installed due to inadequate controls to update plant information with industry experience.	Formation of a procurement engineering group.	Additional LER reported a diaphragm failure resulting in a 5 gpm leak. No cause stated.	
<u>MISCELLANEOUS</u>	Used auxiliary oil pump to flush oil through the governor to clear a ground. Subsequently, system isolated on startup because the oil pump causes the stop and control valves to go full open.	A modification was proposed to eliminate ramp generator initiation on auxiliary oil pump startup, unless a valid initiation signal is present.	The periodic use of the auxiliary oil pump is a common practice that can disable the HPCI system.	Operating procedures should be reviewed to ensure that cautions identify HPCI system inoperability when the auxiliary oil pump is running.

APPENDIX A-2

SELECTED EXAMPLES OF ADDITIONAL HPCI FAILURE

MODES IDENTIFIED DURING INDUSTRY SURVEY

Table A-2 Summary of Illustrative Examples of Additional HPCI Failure Modes

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
HPCI Failure 3 - False High Steamline Differential Pressure Isolation Signal	Differential pressure transmitter failed due to inadequate connection of amplifier condition card was either incorrectly seated during installation or worked loose.	Amplifier card connection was secured.	Rosemount Transmitter	NRC Information Notice 82-16 provides additional information on steamline pressure measurement
	Miscalibration and a stuck pressure indicator disabled both divisions of high ΔP transmitters.	Wrong conversion value caused miscalibration and was corrected.	Rosemount Transmitter	
	Transmitter operating outside tolerances due to incorrect setpoint adjustment	Recalibrated transmitter	Conservatively narrow instrument tolerances were used during the setpoint adjustment. The instrument was a Rosemount Transmitter.	
	Setpoint drift cause spurious system isolations	Setpoint was adjusted.	Barton transmitter	Increased calibration frequency may be necessary.
HPCI Failure 4 - Turbine Steam Inlet Valve [F001] fails to open	Setpoint draft caused by moisture intrusion through the dial rod shaft seal.	Unknown	Barton transmitter	
	Mechanical/thermal binding of disk due to inadequate clearances.	Interim corrective action was drilling a hole in the valve disk. Double disks were to be installed during a failure refueling outage as a long term solution.	This failure was attributed to procedural and training inadequacies.	
	Thermal binding of disk	Replaced motor gears and installed larger power supply cable to motor.	The thermal binding can occur for ~2 hours after system is returned to service following a cooldown.	A four hour system warmup may be required by procedures to circumvent this problem.
	Motor failure	Surge protection added to shunt coil of DC motor control circuitry.	Motor failure caused by high voltage transient in shunt coil that occurred when supply breaker opened.	
	Motor failure.	Valve repaired and torque switch adjustment screws were correctly torqued.	Motor windings failed due when torque setting out of adjustment due to loose torque switch adjustment screws.	Other safety related MOV's were also affected. Procedures were revised and torque switch limiter plates were installed.

Table A-2 (Cont'd)

Failure Desc.	Root Cause	Corrective Measures	Comments	Inspection Guidance
HPCI Failure 4 - (cont'd)	Valve motor failure due to incorrect steam lubrication	Valve motor was replaced		
	Licensee review determined that valve might not open due to insufficient torque	Removed step starting resistors.	Other DC MOVs were also evaluated	INPO SER 25 SS and NRC Information Notice SS-72 provide further guidance
HPCI Failure 5 - Pump Discharge Valve [E006] Fails to Open	Mispositioned auxiliary contacts in starting time delay relay for valve motor	Replaced contacts		
	Valve motor failure	Valve motor replaced	Failure attributed to heat related breakdown of valve motor internals	
	Licensee review determined that valve may have insufficient torque to open	Step starting resistors had not been considered in the torque analyses and were removed	Potential problem may affect other DC MOVs	INPO SER 25 SS and NRC Information Notice provide additional guidance
HPCI Failure 7 - System Actuation Logic Fails	Fuse failure due to electrical grounding	Fuse replaced and ground corrected		
	System failed to actuate due to inadequate seal in time	Design modified	Further discussion in AFOD Report F-407	
HPCI Failure 8 - False High Area Temperature Isolation Signal	Failed power supply resistor	Resistor replaced		
	Failed temperature monitoring module	Module replaced	New model replacement considered	
	Design error	Minimum intake setpoint temperature was increased		
HPCI Failure 9 - False Low Suction Pressure Trip	Pressure switch isolation valve inadvertently closed	None	Isolated pressure switch actuated due to changing environmental conditions	
	Corrosion of pressure switch seals	Pressure switch replaced	Seal corrosion allowed moisture into casing and shorted wiring	
HPCI Failure 10 - False High Turbine Exhaust Pressure Signal				

Table A-2 (Cont'd)

Failure Desc	Root Cause	Corrective Measures	Comments	Inspection Guidance
HPCL Failure 11 - Normally Open Turbine Exhaust Valve Fails Closed	Exhaust line swing check valve failure blocked MOV	Check valve replaced	Failure of check valve was attributed to overstressed cycling due to high exhaust pressure.	References [21] and [22] provide further information.
HPCL Failure 12 - CST Suppression Pool Logic Fails	Level switches out of calibration	Switches replaced	Accumulation of foreign material on float caused failure.	
HPCL Failure 13 - Suppression Pool Section Line Valves Fail to Open	Motor failure. Winding insulation degraded due to high voltage transients	Replaced motor. Voltage surge protection added to circuitry.	High voltage transients occurred as supply breaker was opened	
	Torque switch out of adjustment	Recalibrated		
	Limit switch out of adjustment	Replaced limit switch.		
	Valve stem separated from disk	Valve repaired	Three bolts failed due to tensile overload. Other similar valves were inspected.	These valves were manufactured by Associated Control Equipment, Inc.
HPCL Failure 14 - Minimum Flow Valve Fails to Open	Valve inoperable due to damaged motor starter disconnect switch.	Switch replaced.	Damage resulted from overtravel of operating handle due to poor design.	Design changes may be required as a result of this failure.

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11. ABSTRACT (200 words or less)

The High Pressure Coolant Injection (HPCI) system has been examined from a risk perspective. A System Risk-Based Inspection Guide (S-RIG) has been developed as an aid to HPCI system inspections at the Browns Ferry Nuclear Power Plant, Units 1, 2 and 3. The role of the HPCI system in mitigating accidents is discussed in this S-RIG, along with insights on identified risk-based failure modes which could prevent proper operation of the system.

The S-RIG provides a review of industry-wide operating experience, including plant-specific illustrative examples to augment the PRA and operational considerations in identifying a catalogue of basic PRA failure modes for the HPCI system. It is designed to be used as a reference for routine inspections, self-initiated safety system functional inspections (SSFIs), and the evaluation of risk significance of component failures at the nuclear power plant.

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