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# Nuclear Plant Aging Research on High Pressure Injection Systems

Prepared by L. C. Meyer

**Idaho National Engineering Laboratory**
**EG&G Idaho, Inc.**

**Prepared for**
**U.S. Nuclear Regulatory Commission**

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Prepared by
L. C. Meyer

Idaho National Engineering Laboratory
Managed by the U.S. Department of Energy

EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

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# ABSTRACT

This report represents the results of a review of light water reactor High Pressure Injection System (HPIS) operating experiences reported in the Nuclear Power Experience Data Base, Licensee Event Reports (LER)s, Nuclear Plant Reliability Data System, and plant records. The purpose is to evaluate the potential significance of aging as a contributor to degradation of the High Pressure Injection System. Tables are presented that show the percentage of events for HPIS classified by cause, component, and subcomponents for PWRs. A representative Babcock and Wilcox plant was selected for detailed study. The U.S. Nuclear Regulatory Commission's Nuclear Plant Aging Research guidelines were followed in performing the detailed study that identifies materials susceptible to aging, stressors, environmental factors, and failure modes for the HPIS.

In addition to the engineering evaluation, the components that contributed to system unavailability were determined and the aging contribution to HPIS unavailability was evaluated. The unavailability assessment utilized an existing probabilistic risk assessment (PRA), the linear aging model, and generic failure data.

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# EXECUTIVE SUMMARY

Operating experience of nuclear power plants is evaluated to determine the significance of service wear on equipment due to aging and the possible impact of service wear on safety. The High Pressure Injection System (HPIS) and those portions of related systems needed for operation of the HPIS were selected for detailed study and emphasized in this report. This research is part of the U.S. Nuclear Regulatory Commission's (USNRC's) Nuclear Plant Aging Research (NPAR) Program and follows the NPAR guidelines.

The NPAR guidelines provided the framework through which the effect of aging on HPI was studied. The products asked for in the NPAR guidelines include: an identification of failure modes; a preliminary identification of failure causes due to aging and service wear degradation; and a review of current inspection, surveillance and monitoring methods, including manufacturer recommended surveillance and maintenance practices. Performance parameters or functional indicators potentially useful in detecting degradation are also identified and preliminary recommendations are made regarding inspection, surveillance, and monitoring methods.

A description of the HPIS for a Babcock and Wilcox PWR is presented based on information provided by a cooperating utility. The description provides a general understanding of a HPIS. A variety of designs exist from the various NSSS vendors. However, they are all similar in that they use borated water, generally inject into the cold-leg piping, utilize high head centrifugal motor driven pumps, have motor operated valves and check valves, and have similar operating environments.

There is some concern that the operational differences and variations in system boundaries would lead to different conclusions if each type of system were considered separately. However, this is not considered likely because of the similarity of equipment and environment.

The HPIS for the B&W type of system is part of the Emergency Core Cooling System (ECCS) and has two modes of operation under emergency conditions. The first is the high pressure injection mode that is necessary to prevent uncovering of the core for small LOCAs where high system pressure is maintained, and to delay uncovering of the core for intermediate size LOCAs. The second provides long-term core cooling following a LOCA using the high pressure recirculation mode. Part of the HPIS is also used during normal operation to provide reactor coolant pump seal cooling and to maintain the volume of the reactor coolant system within acceptable limits. The HPIS interfaces with many other systems in performing its functions, which include 1E electrical power, service water, instrument air, low pressure injection system, and the Engineered Safety Feature Actuating System.

In addition to the one plant that was studied in detail, generic data bases were reviewed for HPIS failures in PWRs. This review provided larger statistical bases for determining HPIS problems related to aging. Data sources used include the Nuclear Power Experience (NPE) data base (prior to 1986), Licensee Event Reports (LERs) (prior to 1984), Nuclear Plant Reliability Data System (NPRDS) (prior to 1986), and material from an operating nuclear plant supplied by a utility (including personnel interviews). The system boundaries as defined by each data base were used as reported.

A review of Nuclear Power Experience (NPE) shows that the most frequent cause of HPIS component failures is maintenance error, followed by design error, and mechanical disability. The four types of components with the highest frequency of failure for PWRs were valves-35%; I&C-19%; pumps-15%; and piping-7%.

Instrumentation and Control (I&C) failures included the sensors, electronics, and motor control centers for valves and pumps. Instrumentation accounted for 50% of the I&C failures, valve control 17%, pump control 9%, and the rest were miscellaneous control circuits.

HPI piping failures, after eliminating design, construction, and maintenance errors (which accounted for 37%), were primarily due to weld failures-15%, corrosion-7%, and vibration-5%. The rest of the events were spread over many causes. The HPI pipe sizes varied from 1 to 14 in., depending upon location. Failures were not dominated by any one particular size.

Command faults were the leading cause for valve failures, reported in LERs. They include electrical power or any support system that prevents the valve from performing its intended function. Mechanical parts failure, seat or disk failure problems, packing failures (leaks), and foreign material were the most frequent causes of the basic valve failures. There were 44 HPI pump failures reported in the LER data base. Out of these, 22 events were caused by control, maintenance, and design error. The remaining events found no single dominant cause of failure. Only nine failures of HPIS pumps were potentially aging related.

The NPRDS data followed the same component failure pattern as NPE. The aging fraction for HPI based on NPRDS data was 0.213, indicating 21.3% of system failures in the HPIS were aging related.

Plant data followed the same pattern as NPE for those events requiring an incident investigation report. Plant maintenance records listed many more events. While the top four components with the highest frequency of failure were the same, the order placed I&C first; pipe, supports, and nozzles second; then valves and pumps. These data indicate that many minor problems associated with I&C and pipe hangers received corrective maintenance before major failures occurred.

A review of the electrical standards identified that operational life is based on accelerated aging tests. As naturally aged component data becomes available, the standards should be updated. Standards for mechanical equipment are under review by ASME Section XI and are supported by the NPAR research where applicable.

The conclusions for the HPIS study are based on a review of one plant and generic information from the various data bases. The plant maintenance record contains many minor adjustments and repairs for I&C and pipe hangers, but most of the major components failures concerned valves and pumps. Serious piping problems concerning thermal sleeve and nozzle cracking were attributed to thermal fatigue. The utilities affected have taken corrective action by redesigning the thermal sleeves, using warm up lines and enhanced IS&M. Materials in seals and valve packing deteriorates with time and results in leaks. Borated water leaks are potentially serious because of the corrosive action of boric acid on carbon steel and potential for loss of pressure boundary.

Approximately 57% of the component failure lead to system degradation but, because of system redundancy, only 0.7% caused loss of system function. The failure modes that involve total loss of system function are, failure to inject cooling water for emergency operations, and failure to provide makeup water or seal cooling water for normal operations.

The specific problems related to aging were: (a) through-wall cracks occurring in the makeup nozzle and safety injection line elbow from thermal fatigue, (b) valves failing to operate due to boron crystallization, and (c) injection boron concentration diluted from leaking valves.

Inspection and surveillance review has identified that electrical measurements on pump motors and valve operators (for MOVs) could be used to detect aging. Also, that improved inservice testing of valves is needed to detect aging and assure operability with load. The detection of cracks caused by thermal fatigue requires enhanced ultrasonic testing methods. In addition, inspection of base metal in high-stress regions is needed to detect cracks in those areas.

The HPIS unavailability assessment identified that motor-operated valves contributed significantly to unavailability of the system for all three operating modes evaluated. The HPIS pumps were significant contributors to systems unavailability for the two of three pumps required mode and the recirculation mode of operation. The time dependant unavailability assessment showed that the HPI unavailability was only moderately affected by aging with a relatively small increase over the operating life.

# ACKNOWLEDGMENTS

The detailed systems studies are based on material supplied by the Duke Power Company, Charlotte, North Carolina.

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## TABLES

# ACRONYMS

| | |
|---|---|
| ANSI | American National Standards Institute |
| ASME | American Society of Mechanical Engineers |
| B&W | Babcock and Wilcox |
| BIT | Boron Injection Tank |
| BNL | Brookhaven National Laboratory |
| BWST | Borated Water Storage Tank |
| CE | Combustion Engineering |
| CFS | Core Flood System |
| CM | Corrective Maintenance |
| CVCS | Chemical Volume Control System |
| ECCS | Emergency Core Cooling System |
| EEI | Edison Electric Institute |
| ES | Engineered Safeguards |
| ESF | Engineered Safety Features |
| ESFAS | Engineered Safety Features Actuating System |
| gpm | gallons per minute |
| HHIS | High Head Injection System |
| HP | High Pressure |
| HPI | High Pressure Injection |
| HPIS | High Pressure Injection System |
| HPP | High Pressure Pump |
| HPRS | High Pressure Recirculation System |
| HPSW | High Pressure Service Water |
| I&C | Instrumentation and Control |
| IS&M | Inspection, Surveillance and Monitoring |
| IRRAS | Integrated Reliability and Risk Analysis System |

| | |
|---|---|
| 1E | Classification for electrical power for safety systems |
| IEEE | Institute of Electrical and Electronic Engineers |
| IGSCC | Intergranular Stress Corrosion Cracking |
| IIR | Incident Investigation Report |
| INEL | Idaho National Engineering Laboratory |
| IS&M | Inspection Surveillance and Monitoring |
| LCO | Limiting Condition for Operation |
| LDST | Let Down Storage Tank |
| LER | Licensee Event Report |
| LOCA | Loss of Coolant Accident |
| LP | Low Pressure |
| LPI | Low Pressure Injection |
| LPIS | Low Pressure Injection System |
| LPP | Low Pressure Pump |
| LPRS | Low Pressure Recirculation System |
| LPSW | Low Pressure Service Water |
| LW | Lower Bound |
| MCC | Motor Control Center |
| MIC | Microbial Influenced Corrosion |
| MU | Make Up |
| MOV | Motor Operated Valve |
| NPAR | Nuclear Plant Aging Research |
| NPRDS | Nuclear Plant Reliability Data Systems |
| NPE | Nuclear Power Experience |
| O&M | Operation and Maintenance |
| ORNL | Oak Ridge National Laboratory |
| PRA | Probabilistic Risk Assessment |

| | |
|---|---|
| PWR | Pressurized Water Reactor |
| RC | Reactor Coolant |
| RCP | Reactor Coolant Pump |
| RCS | Reactor Coolant System |
| RWST | Refueling Water Storage Tank |
| SI | System Injection |
| SWS | Service Water System |
| UHIS | Upper Head Injection System |
| UP | Upper Bound |
| USNRC | United States Nuclear Regulatory Commission |
| W | Westinghouse |

# NUCLEAR PLANT AGING RESEARCH ON HIGH PRESSURE INJECTION SYSTEMS

## INTRODUCTION

As part of its responsibilities to protect the public health and safety, the USNRC is concerned with the effect aging has on the safety of commercial nuclear power plants. To meet this responsibility, the USNRC has developed and implemented a hardware-oriented research program to investigate plant aging and the related degradation of components, systems, and structures. This program is called the Nuclear Plant Aging Research (NPAR) Program and is being conducted by the Electrical and Mechanical Engineering Branch of the Division of Engineering of the office of Nuclear Regulatory Research.[1] A complementary program focusing on pressure vessel, piping, steam generator materials problems, and nondestructive examination methods is being conducted by the Materials Engineering Branch of the Division of Engineering.

### Aging and Plant Safety

The NPAR Program is investigating how the aging of components, systems, and civil structures can affect the safe operation of nuclear power plants. The United States currently has approximately 100 commercial pressurized and boiling light water reactors in operation. In the context of NPAR, aging is defined as the "cumulative degradation that occurs with the passage of time in a component, system, or structure." The main concern of the NPAR program is that plant safety could be compromised if aging degradation is not detected and corrective action taken before there is a loss of the required functional capability in a component, system, or structure. Consequently, aging might result in a reduction in the safety level achieved by the defense-in-depth approach used to ensure the safety of domestic reactors. Defense-in-depth requires that the public is protected from the accidental release of fission products by a series of multiple barriers and engineered safety systems.

Operating plant experience provides examples where age induced degradation of a key component has led to a reduction in the capability of a barrier to prevent the release of fission products. These examples include degradation of valves and pipe cracks.

Age degradation can also cause a loss of operational readiness of engineered safety systems. The engineered safety systems are designed to mitigate the consequences of failure of a vital component, system, or physical barrier, such as a loss of main feedwater or a break in the primary system boundary. These systems are also designed to mitigate the effects of events ranging from anticipated operational transients such as loss of offsite power to low probability occurrences such as design basis seismic events. Failures have occurred in systems such as the auxiliary feedwater system and in the emergency diesel generators used to supply vital ac power to the 1E Power System.[a]

Aging can also lead to a higher probability of common mode failure. Aging can result in wide scale degradation of a physical barrier or to simultaneous degradation of redundant components. One example of this is a simultaneous degradation of the redundant valves designed to isolate the reactor coolant lines to a PWR. If this were to occur, a failure in the piping outside the containment could lead to an uncontrolled release of the primary coolant and radioactivity outside of the containment.

### NPAR Program Goals and Strategy

1. Identify and characterize aging and service wear effects associated with electrical and mechanical components, interfaces, and systems likely to impair plant safety.
2. Identify and recommend methods of inspection, surveillance, and condition monitoring of electrical and mechanical components, and systems that will be effective in detecting significant aging effects before loss of safety function so

a. 1E is the classification given for all the electrical power for nuclear plant safety systems.

that timely maintenance and repair or replacement can be implemented.

3. Identify and recommend acceptable maintenance practices that can be undertaken to mitigate the effects of aging and to diminish the rate and extent of degradation caused by aging and service wear.

The NPAR Program uses a two-phased approach to conduct aging research on the risk significant components and systems in light water reactors; as illustrated in Figure 1. The first stage, Phase I makes use of readily available information from: public and private data bases, vendor information, open literature, utility information, and expert opinion. The Phase I analysis includes a review of three elements:

1. The hardware design, operating environment, and performance requirements
2. A survey of operating experience
3. The current methods used for inspection, surveillance, monitoring, and maintenance and for qualifying end-of-life performance.

The results of the Phase I evaluation include an identification of actual and potential failure modes; a preliminary identification of failure causes due to aging and service wear degradation; and a review of current inspection, surveillance and monitoring practices, standards and guides. The Phase I evaluation is used to decide if a Phase II evaluation is warranted. If a Phase II evaluation is needed, recommendations are developed to identify the detailed engineering tests and analyses to be conducted in Phase II and which will result in improved industry standards, guides, and practices.

A Phase II assessment includes developing and validating advanced inspection, testing, monitoring and maintenance methods. This development includes both laboratory and field testing to verify candidate technologies. Phase II may also include examining and testing naturally aged components from operating power plants and developing service life prediction models.

With the completion of the Phase I and Phase II aging assessment research, a technical basis will be available for use in the regulatory process. The key end uses are shown in Figure 1. The uses envisioned for the NPAR program results include: implementing improved inspection, surveillance, maintenance, and monitoring methods; modifying present codes and standards; developing guidelines for plant life extension; and resolution of generic safety issues.

## Phase I Aging Assessment of a PWR High Pressure Injection System

This report describes the results of an in-depth Phase I evaluation of the High Pressure Injection Systems (HPIS) used in light water reactors.

The study was performed at the Idaho National Engineering Laboratory (INEL) and addresses the system aspects of the HPIS and the materials susceptible to aging in components associated with the HPIS. Certain components, such as valves and pumps, have been extensively studied at other national laboratories as part of the USNRC aging and equipment qualification programs.[2-4] Operating experience from the generic data bases and plant records on the HPIS are complemented by data from these component studies where applicable. Specifically, Phase I NPAR component studies on valves and pumps are being pursued at the Oak Ridge National Laboratory (ORNL). The valves are the HPIS component category with the most failures. Each motor operated valve and pump is controlled by a motor control center (MCC). The MCC (and electric motors in general) are currently being studied at the Brookhaven National Laboratory (BNL) as part of the NPAR program. Data from these component studies are also used in supporting the system studies. In addition, the Engineered Safety Feature Actuating System (ESFAS) aging study performed at the INEL is directly applicable to the HPIS because it provides the actuating signal for initiation of the HPIS operation under accident conditions.[5]

The strategy for this HPIS study follows the NPAR guidelines. Generic data bases are used to get statistical data on which HPIS components have experienced the most failures and the causes for failures. Plant specific data supplied by a cooperating utility includes design descriptions, drawings, maintenance records, and personnel interviews. (The plant specific data, of course, applies to one plant considered to be typical for those plants that use the HPI pumps for both normal operation to supply makeup water and for emergency injection.) Information sources used include: the Nuclear Power Experience (NPE) data base, Licensee Event Reports (LERs), Nuclear Plant Reliability Data System (NPRDS), 1E

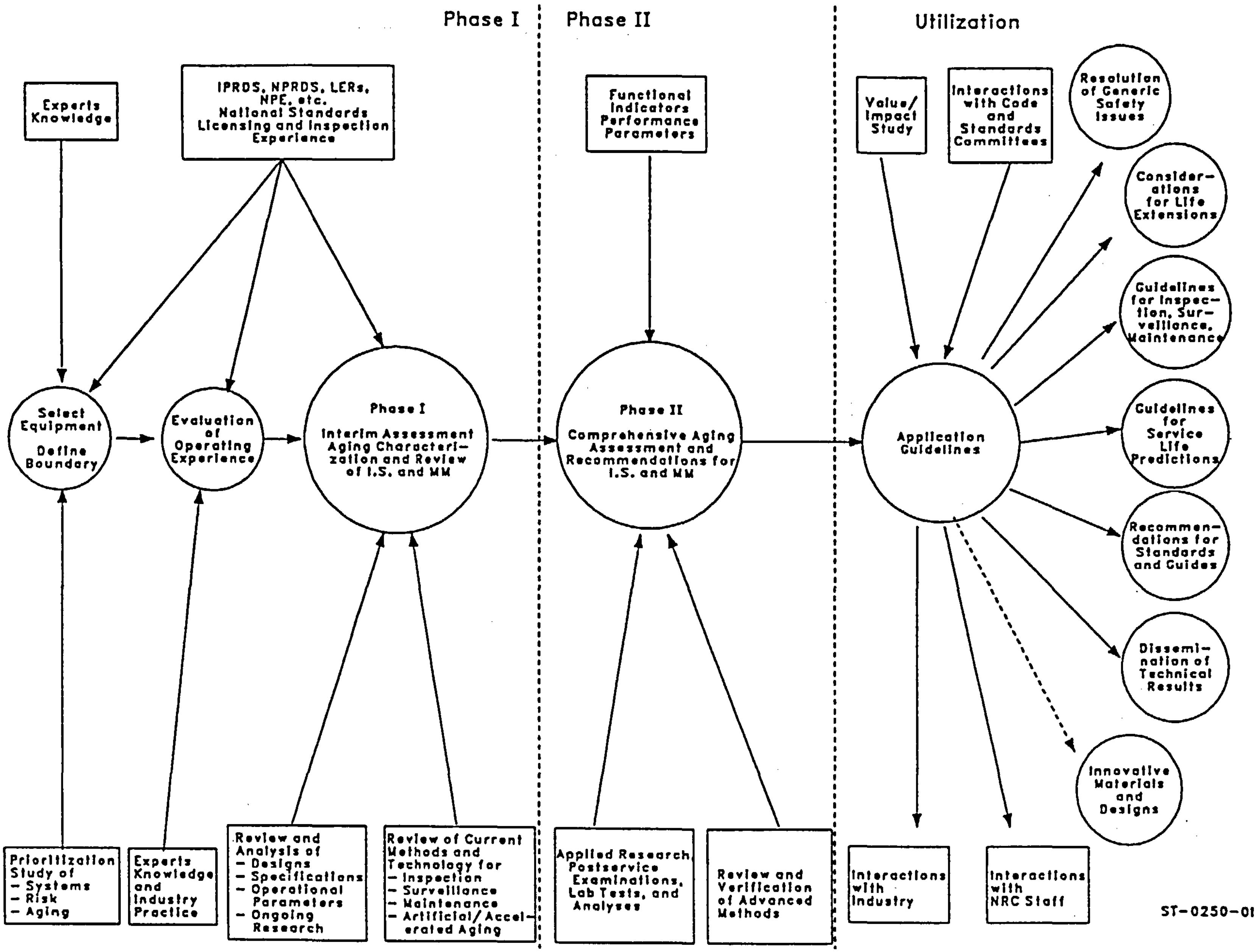


**Figure 1.** NPAR program strategy.

notices and bulletins, plant-design information and specifications, operation and maintenance (O&M) manuals and procedures, historical records, site-event records, and site interviews with maintenance personnel.

The specific objectives of this study are:

1. Evaluate the overall operating experience to determine if aging-related operational problems have developed.
2. Use specific examples from a representative Babcock and Wilcox (B&W) pressurized water reactor (PWR) to illustrate the functions of the HPIS and evaluate specific problems related to aging.
3. Perform screening type aging assessments of the impact of aging on operability. The assessment will focus on identifying:

    a. Failure modes and causes
    b. Materials susceptible to aging degradation
    c. Stressors during operation
    d. Functional indicators that would aid in failure prediction
    e. Methods for detection and control of aging degradation.

4. Review and provide recommendations for inspection, surveillance, and monitoring (IS&M), as well as advanced methods for IS&M.
5. Evaluate the role of maintenance in counteracting aging effects to include the following:

    a. Survey and evaluate currently used maintenance practices that counteract aging and service wear effects
    b. Evaluate relative benefits of preventive and corrective maintenance
    c. Identify potential mechanisms causing component system degradation through improper maintenance
    d. Provide recommendations for preferred maintenance practices.

6. Perform an unavailability assessment of the HPIS to determine which components contribute significantly to the HPIS unavailability and how aging affects unavailability.

Other work at the INEL related to this HPIS aging study includes the reactor protection system aging study,[5] the reported failure cause study of component failures for selected systems,[6] and the development of technical criteria for use in assessing the residual life of the major light water reactor components.[7] The reported failure cause work identified safety systems significantly affected by aging phenomenon (of which HPIS is included). Although many component failures were identified in the reported failure cause work, actual HPIS failure occurred as a result of only 0.7% of the component failures. This is due to control channel redundancy and priority maintenance.

The description of the HPIS for the representative PWR is given first. This is followed by a review of the operating experience section, which provides information from the various data bases. HPIS safety issues and potential aging problems are discussed next followed by aging assessments. Then a review of HPIS IS&M and the role of maintenance is discussed. A section on the HPIS unavailability assessment identifying risk significant components is the last section just before the conclusions.

# SYSTEM FUNCTIONAL DESCRIPTION

The HPIS along with the Low Pressure Injection System (LPIS) and the Core Flooding System (CFS) collectively form the overall Emergency Core Cooling System (ECCS), which is designed to prevent core damage from a loss-of-coolant accident (LOCA). High pressure injection is necessary to prevent uncovering of the core for small LOCAs, where high system pressure is maintained, and to delay uncovering of the core for intermediate sized LOCAs. The HPIS can also be used to cool the core following a non-LOCA reactor shutdown (e.g., transient). This mode of HPIS operation would be utilized only if normal and emergency secondary heat removal via the steam generators cannot be achieved.

Commercial nuclear power plants have various designs for HPIS in regard to boundaries, function, and terminology. A typical Westinghouse 4-loop plant uses accumulators [sometimes referred to as the Upper Head Injection System (UHIS)] as the immediate response system performing an ECCS function if the reactor coolant system (RCS) pressure drops. When system injection is called for, the boron injection tank (BIT) subsystem is valved into the charging system to supply borated water to the RCS. This BIT injection in independant of the UHIS and is a HPIS function performed by the charging system to supply borated water to the RCS. The system injection (SI) signal also starts the two HPIS pumps and aligns both the HPIS and charging systems to take suction from the refueling water storage tanks (RWST). The HPIS, sometimes referred to as the High Head Injection System (HHIS), injects borated water to the RCS after the system pressure drops to 1500 psi. Both the HPIS and charging system can be aligned to the residual heat removal system which takes suction from the containment sump.

Westinghouse 3-loop designs use an accumulator system for an immediate borated water injection system and uses three pumps that perform the high pressure injection function including the BIT insertion. One of the pumps is also used for normal charging. The charging and high pressure injection function is similar to the B&W system except that Westinghouse uses separate injection nozzles.

The Combustion Engineering designs have three HPIS pumps used in the emergency mode only and a separate charging system. The B&W system which is exampled in this report consists of three motor-driven high pressure centrifugal pumps, with two primary suction and discharge paths. One of the three pumps is also used for supplying makeup water during normal operation. The detailed system configuration is shown in Figure 2. The HPIS and related systems perform the following functions for the B&W type system:

1. Maintain the Reactor Coolant system (RCS) inventory during normal operation
2. Maintain proper RCS water chemistry and purity
3. Control RCS boric acid concentration
4. Provide fill and makeup for the core flood tanks
5. Provide seal injection water for the reactor coolant pumps
6. In the event of an RCS accident, provide high pressure injection of borated water for emergency core cooling and plant shutdown
7. Provide long term core cooling following a LOCA using the high pressure recirculation system and low pressure recirculation system.

The first four items can be combined into one system called the makeup and purification system to maintain the volume of the reactor coolant system (RCS) within acceptable limits during most modes of plant operation. It also recirculates reactor coolant for purification, addition of chemicals for the control of RCS corrosion, and the control of soluble boron concentration for long term reactivity control.

For the purpose of this report, the HPIS configured for the emergency injection mode will be of primary interest. However, parts of the system are shared for RC pump seal cooling, RC makeup and purification, as well as the high pressure recirculation mode. Each of these configurations is briefly discussed, as necessary, to cover the functions of the HPIS shared components.

## Makeup and Purification System

The makeup function is achieved primarily by a portion of the HPIS and the coolant storage and chemical addition systems. Makeup flow is supplied by either pump HPP-A or HPP-B (Figure 3) and is controlled automatically to balance normal leakage. Letdown flow from the RCS accommodates small increases in RCS volume due to inleakage from the seals of the reactor coolant pumps (RCPs) and variations in RCS temperature. The system was not designed for emergency

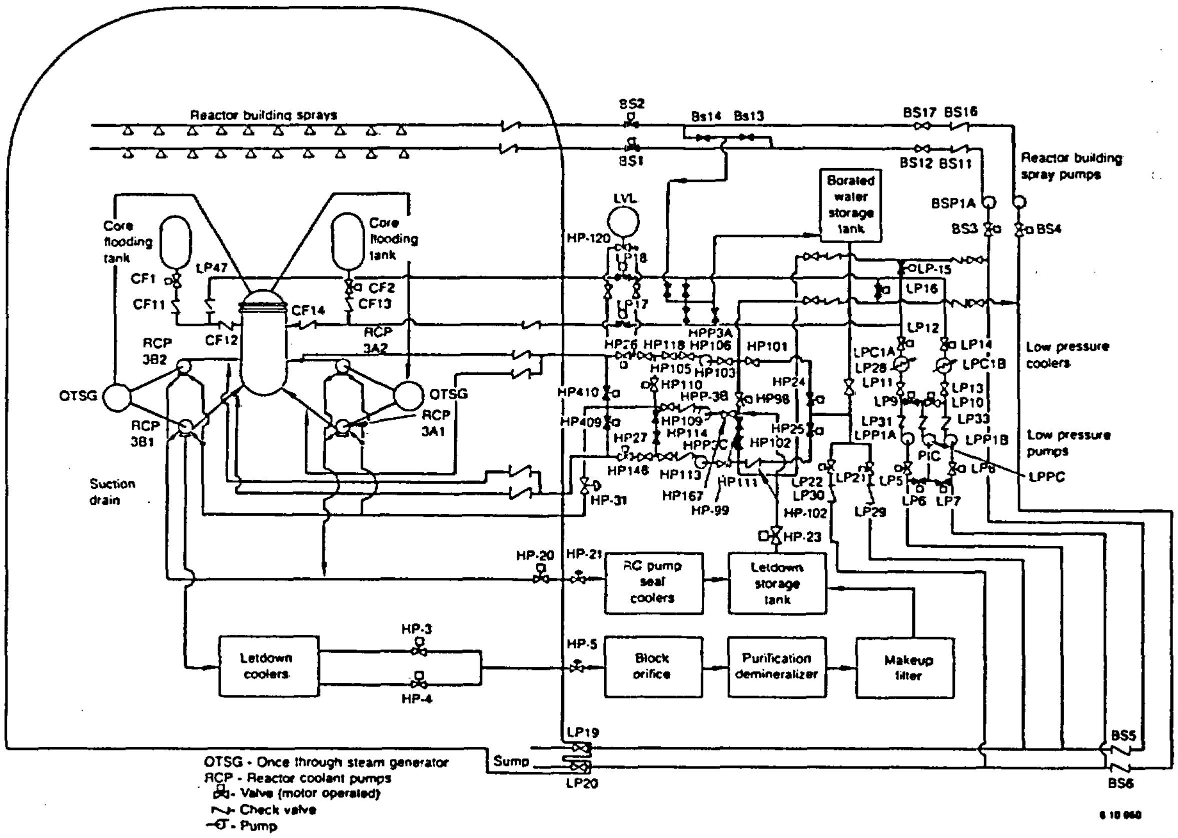


**Figure 2.** Emergency core cooling system.

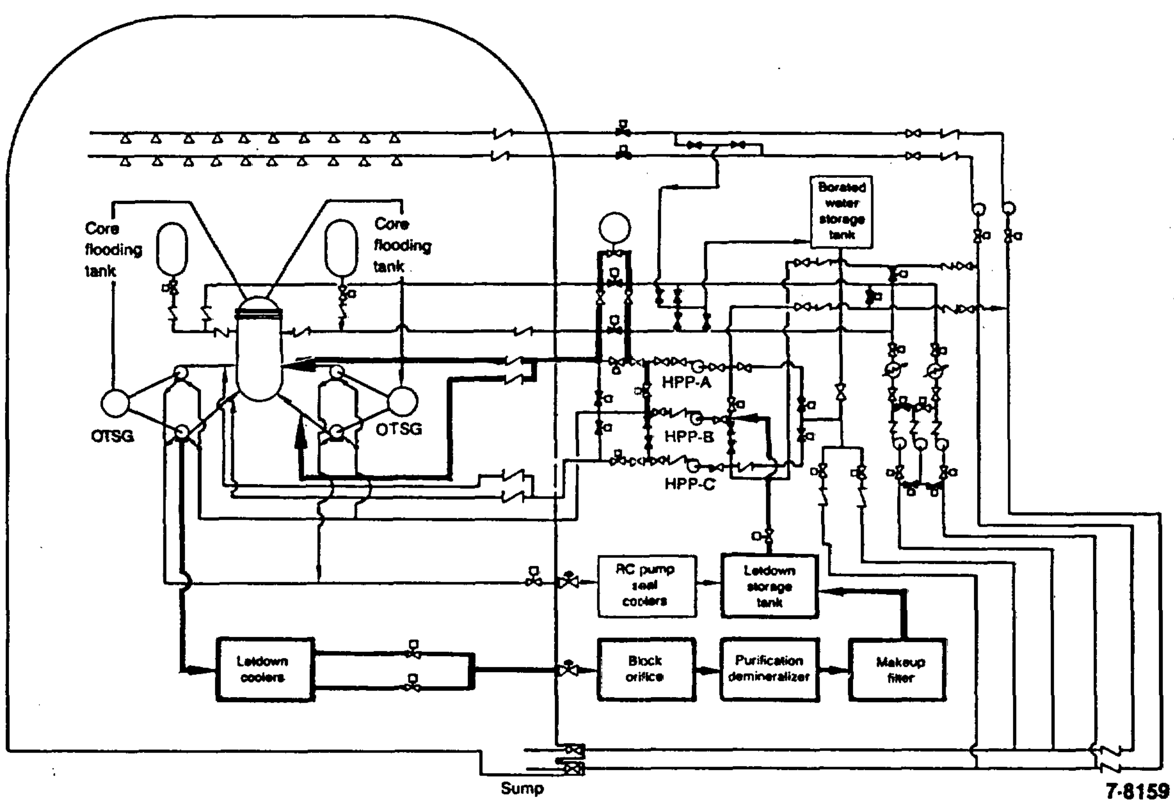


**Figure 3.** ECCS with makeup and purification system highlighted.

operation; however, it does provide RCS inventory control during most transient conditions other than loss-of-coolant accidents. If the system is not capable of meeting the requirements for inventory control after a reactor trip, manual action can be taken to start additional HPI pumps, establish additional discharge paths to the RCS, or align the borated water storage tank (BWST) for assurance of a sufficient suction source. Figure 3 highlights the ECCS makeup and purification system. More detail system information is given in Appendix A.

## Cooling System for RCP Seals

Seal injection flow is provided by the HPI pump operating to supply normal RCS makeup. These seals prevent the leakage of reactor coolant between the shaft and the housing of the RCPs. When the RCS is at a high temperature, the seals must be cooled to keep them from warping, to keep the seal faces from becoming cracked or eroded, and to prevent the O-rings from extruding. The interruption of cooling flow can result in seal damage, leading to increased RCS leakage or small break LOCA conditions.

The ECCS, with the Seal Cooling System highlighted, is shown in Figure 4. Details of the RCP seal cooling system are given in Appendix A.

## Emergency Injection Mode of the HPIS

The HPIS provides emergency core cooling in the event of a small break LOCA, and it also provides an alternative means of core heat removal if the ability to cool via the steam generators is lost. Figure 5 illustrates the HPIS configuration. For most event sequences, flow from one pump is sufficient; for special cases, two pumps may be required. The HPIS is capable of supplying flow at a relatively high RCS pressure, with a shutoff head of 2900 psig (other types of systems have shutoff heads less than normal system pressure). The emergency mode of operation is initiated if the RCS pressure decreases to 1500 psig or if Reactor Building pressure increases to 4 psig. Under these conditions, the following actions are automatically initiated:

1. Three isolation valves in the purification letdown line close (HP-3, HP-4, HP-5), and two isolation valves in the seal return line close (HP-20 and HP-21)
2. One inlet valve in each injection line opens (HP-26, HP-27, HP-409, and HP-410)
3. Two valves in the lines to the borated water storage tank outlet header open (HP-24 and HP-25)
4. All high pressure injection pumps start.

The emergency high pressure injection flow path is from the borated water storage tank through the high pressure injection pumps and into both reactor coolant loops. The emergency mode of operation will continue until manually terminated.

## High Pressure Recirculation Mode

The High Pressure Recirculation System (HPRS) is one of two systems designed for long-term core cooling following a LOCA. The other system is the Low Pressure Recirculation System (LPRS). After exhaustion of the BWST, the LPRS and HPRS are used to recirculate water from the containment sump to the RCS. If the LOCA is large enough, the RCS will be at a low enough pressure so that only the LPRS would be required. If the LOCA is small, however, the RCS will be at a pressure above the shutoff head of the LPRS pumps and the HPRS would be required. For small break LOCAs, the HPRS and the LPRS are both required, because the HPRS takes its suction from the discharge of the LPRS. This realignment is shown in Figure 6. In this configuration, the LPIS takes its suction from the reactor building sump through valves LP-19 and LP-20. The discharge for the HPRS is through the HPIS nozzles into the reactor coolant system.

Any one pump is capable of providing enough flow to prevent core damage for those smaller leak sizes that do not allow the RCS pressure to decrease rapidly enough to the point where only the LPRS is required. One high pressure line can deliver 450 gpm at 1800 psig reactor vessel pressure. One of the three high pressure pumps is normally in operation and a positive static head of water ensures that all pipe lines are filled with coolant. The high pressure lines contain thermal sleeves at their connections into the reactor coolant pipe to prevent thermal stressing at the pipe juncture.

All three pumps have self-contained lubrication and mechanical seal coolant systems tied in with the Low Pressure Service Water System (LPSW).

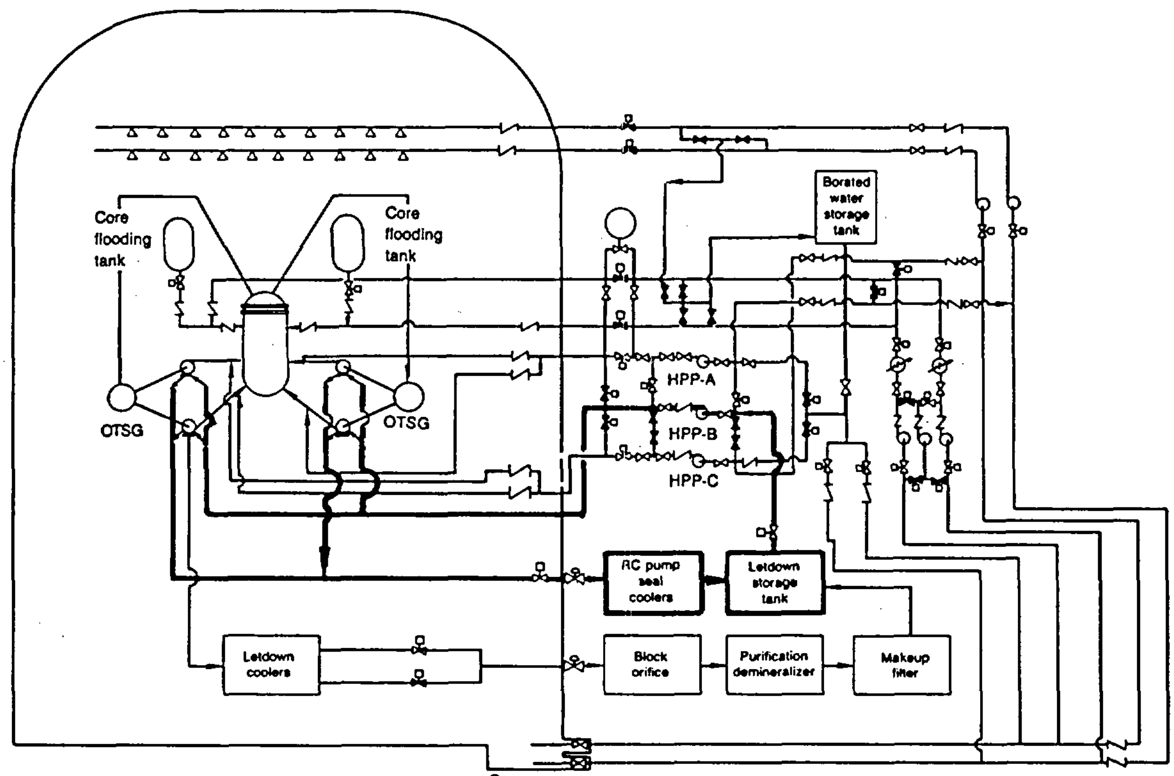


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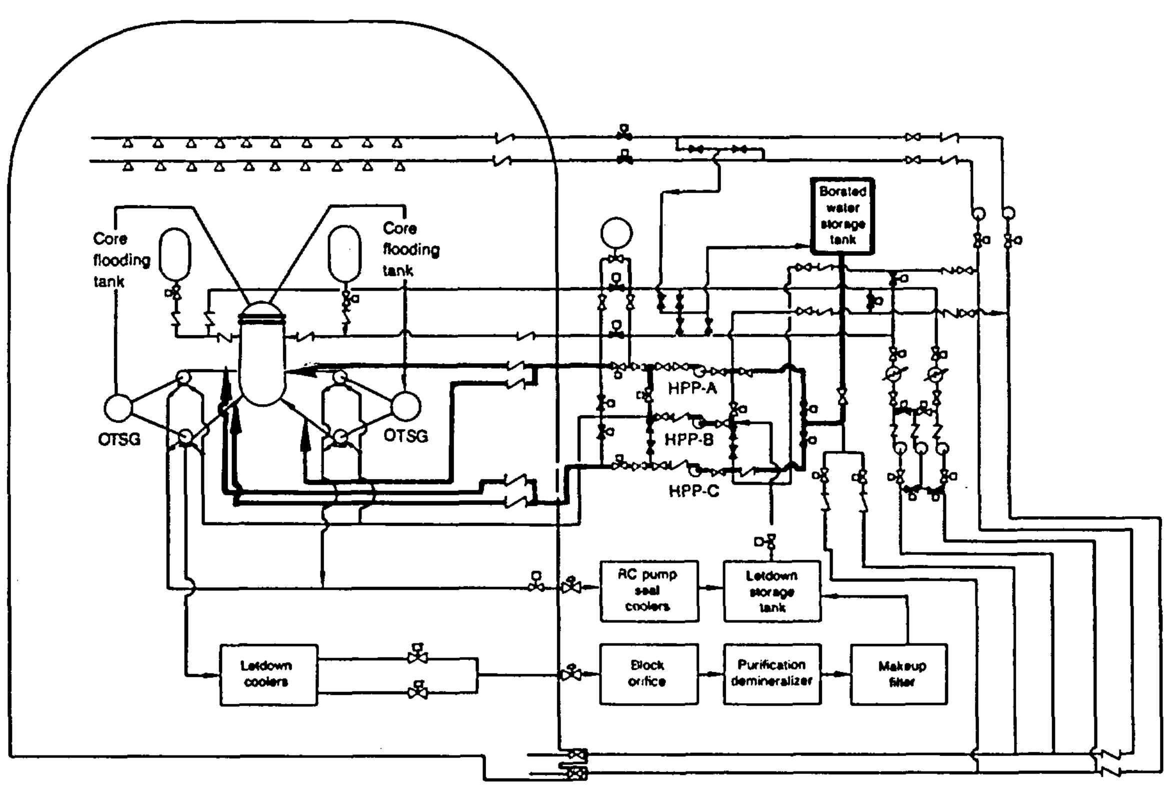
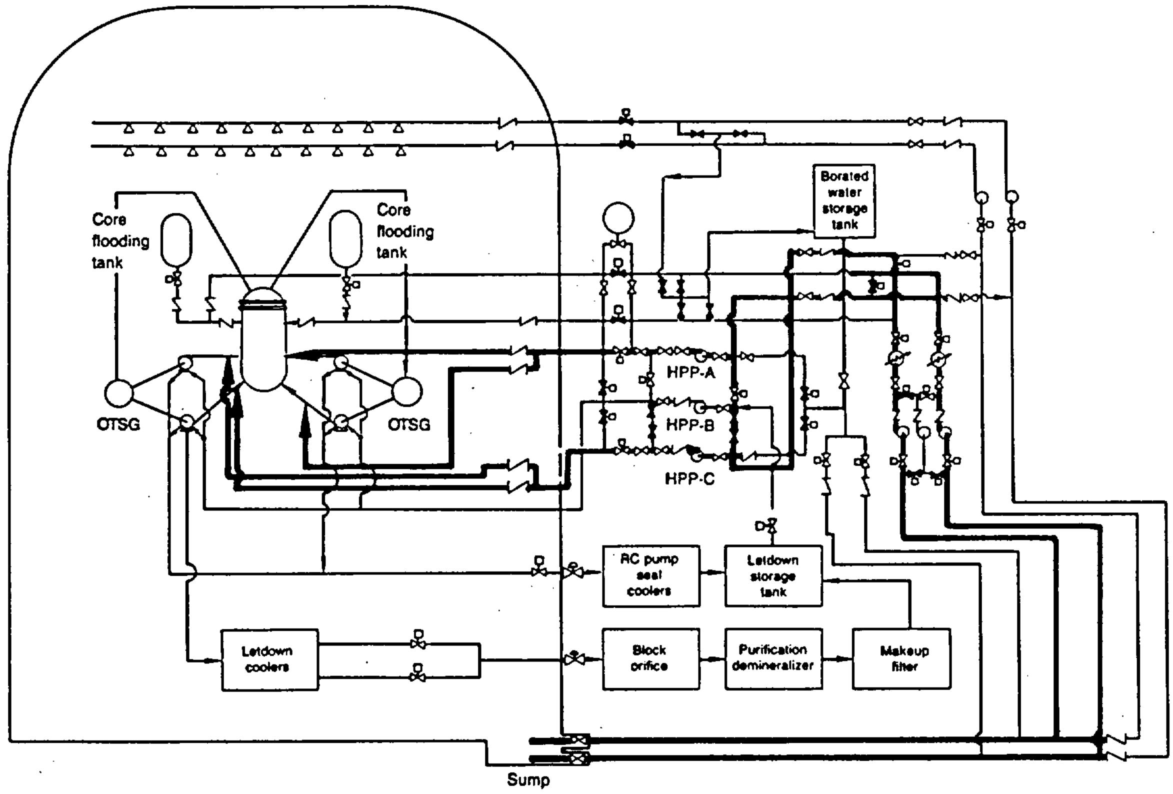
**Figure 4.** ECCS with RCP seal cooling system highlighted.




7-8157

**Figure 5.** ECCS with high pressure injection system highlighted.




7-8160

**Figure 6.** ECCS with high pressure recirculation system highlighted.

In the representative plant studied, the high pressure recirculation mode is manually initiated by the following operator actions:

1. BWST supply line valves HP-24, HP-25, LP-21, and LP-22 are closed when the BWST low level alarm notifies the operator. All high and low pressure ECCS pumps are also shut off at this point
2. Containment sump valves LP-19 and LP-20 are opened and the low pressure pumps LPPA and LPPB are restarted
3. Valves LP-15 and LP-16 are opened in order to divert a portion of the LPRS flow to the high pressure pumps that are also restarted.

Appendix B contains more information on the LPIS as it relates to the HPIS.

After initiating the HPRS, the operator continues to control the system in the recirculation mode. To aid the operator, the following system conditions are monitored and displayed in the control room: the reactor building sump level, the temperatures of water in the line from the sump to the low pressure pumps, the low pressure pump discharge pressure, the flows in the low pressure and high pressure supply lines to the reactor vessel, the level in the BWST, and all motor-operated valve positions.

## INTERFACES WITH SUPPORTING SYSTEMS

The supporting systems are those systems required for the HPIS to perform its function. Failure in a support system can affect the operation of HPIS.

### Electrical

Electric power is supplied to the three HPIS pumps by three independent 4160 volt buses. The motor-operated valves (MOVs) also require ac motive power. Emergency power is available to critical components in the event that the normal power source is lost. Control power for the HPI pumps is provided from the dc power system. Control power for all other electrical components is derived from the same source as the motive power. The HPIS components and their power supplies are listed in Appendix C.

Following a loss-of-coolant accident, assuming a simultaneous loss of normal power sources, the emergency power source and both the LPIS and HPIS will be in full operation within 25 seconds after actuation. All calculations for the representative plant studied have assumed a 25 second delay from receipt of the actuation signal to start of flow for both the HPI and LPI systems. Upon loss of normal power sources including the startup source and initiation of an engineered safeguards signal, the 4160 volt engineered safeguards power line is connected to the emergency power source. The emergency unit will start up and accelerate to full speed in 23 seconds or less. An analysis has shown that by energizing the HPI and LPI valves (which have opening times of 14 seconds and 15 seconds respectively at normal bus voltage) and pumps at less than 100% voltage and frequency, the design injection flow rate (HPI - 450 gpm, LPI - 3000 gpm) will be obtained within 25 seconds.

### Service Water

Cooling water for the HPI pump motors is provided by the LPSW system. Backup cooling flow can be made available by local manual action from the elevated storage tank of the high pressure service water system. The LPSW system also supplies cooling flow to the heat exchangers of the component cooling system.

### Instrument Air

The instrument air system supplies motive power to the number of valves required for HPIS to function in the normal makeup and RCP seal cooling modes. Upon loss of instrument air, all the pneumatic valves transfer to or remain in the closed position with the exception of control valve (3HP-31), which opens fully for seal injection flow to the RCPs.

### ECCS Pump Room Coolers

New plants (0-5 years old) for all four U.S. NSSS vendors have pump room coolers. Older plants (5-15 years old) may or may not have pump room coolers. Plants older than 15 years do not have them.

### Engineered Safety Features Actuating System

The HPIS is one of the Engineered Safeguards (ES) Systems that is automatically actuated by the ESFAS. The aging study on ESFAS is covered in Reference 5.

For normal operation, automatic control signals are supplied for two flow control valves. They are the normal makeup flow control valve, HP-120, and valve HP-31 for RC pump seal flow control (see Figure 2).

During emergency conditions ES signals are provided to components in the HPIS that must change state. The components required for function of the HPIS receive signals from the ESFAS when the RCS pressure is low (1500 psig), or when the reactor building pressure increases to 4 psig. The ES-actuated HPIS components as well as the ES channel doing the actuation are listed in Table 1. Appendix D describes the ESFAS system for the HPIS in greater detail.

**Table 1. HPIS components actuated by the engineered safety features actuating system**

| Component | ES Actuation Channel | Normal Channel | ES Status |
|---|---|---|---|
| Pump HPP-A | 1 | On/off | On |
| Pump HPP-B | 1 & 2 | On/off | On |
| Pump HPP-C | 2 | Off | On |
| MOV HP-24 | 1 | Closed | Open |
| MOV HP-25 | 2 | Closed | Open |
| MOV PH-26 | 1 | Closed | Open |
| MOV PH-27 | 2 | Open | Open |
| MOV HP-20 | 1 | Open | Closed |
| AOC HP-21 | 2 | Open | Closed |
| MOV HP-3 | 5 | Open | Closed |
| MOV HP-4 | 6 | Open | Closed |
| AOV HP-5 | 2 | Open | Closed |

## SYSTEM COMPONENTS AND HARDWARE

All HPIS piping and hardware components are made of stainless steel which is resistant to corrosion from boric acid used in the borated water. The major components are discussed in this section. More detailed aging related design information on these components is given in Appendix E.

### Valves

For the purposes of this report, a valve is defined as the valve body and all its internal parts, the valve operator (motor, solenoid, hand wheel, etc.), and any limit and torque switches mounted on the valve body or operator needed to make the valve function. The HPIS uses many types of valves and valve operators including motor-operated valves (MOV), pneumatic-operated valves, solenoid-operated valves, manual-operated valves, check valves, and safety relief valves. The component NPAR studies have extensively covered aging of valves (see References 2 and 3).

Valve failures and how they affect system operations is an important consideration in this research. The failure modes that can affect system operation include failure to open, failure to close, internal leakage, external leakage, and plugged. General failure mechanisms that exist independent of valve type include normal wear, excessive wear, corrosion, foreign material contamination, and excessive vibration. Control valves such as the HPI flow control valves can also have a failure mode in which they fail to operate as required. They are designed to constantly change position during operation. A system failure occurs when a valve has lost the ability to control system parameters.

Types of valves are discussed further in Appendix E and valve failures are covered in a later section on Operating Experience.

### Instrumentation and Control

In general, there are three variations of the engineered safeguards control stations as shown in Figure 7. The first station is a controller and monitor for a motor-operated valve automatically operated by an ESFAS signal. Feedback information on the valve position is provided by a limit switch. The second station is a pump motor control station that has inputs from either the ESFAS or main control room. Instrumentation for the HPI pumps includes local indication of pump discharge pressure and suction pressure. Discharge flow through the pump crossover lines, discharge pressure, and low pressure are also provided to the control room. The third type of control station is one that controls an air operated pilot valve to control the pneumatic valve. Two stations are shown on this drawing meaning that the valve can be controlled from two different locations. The "C" in the triangles on these drawings indicates computer monitoring for control room display.

The operator can override the automatic flow control on HPI by adjustment of the flow controller so the flow rate may be reduced to match the loss of coolant from the vessel when small line breaks occur.

**HPI Pump A Controls.** The HPI pump A is normally controlled from the control room with a manual four position (start-run-off-auto) switch. In the start position, power is supplied to the pump circuit breaker closing coil and pump starts. In auto position, the pump automatically starts on low seal injection flow, or loss of voltage on the main feeder bus as sensed by the main feeder Bus Monitor. When in the off position, the control switch energizes the circuit breaker trip coil and the pump motor is de-energized.

In the event of a reactor accident, the ESFAS channel 1 will automatically start HP injection pump A regardless of its manual control switch location. If the control switch was in the off position when the start occurred, the pump will continue to run after the ESFAS signal is reset until the manual pump control switch is cycled out of the off position and back.

After an ESFAS signal is initiated, the automatic control can be overridden by pressing the manual pushbutton in the control room. This override can be done only when a safeguards trip signal, or test signal is present. When in the manual mode, the pump control then functions as if no ESFAS signal is present. Control is returned to the automatic mode for safeguards when the auto pushbutton is operated in the control room or if the ESFAS trip signal is cleared at the safeguards cabinet.

**HPI Pump B Controls.** The controls for pump B are essentially the same as those provided for pump A except that in the event of an accident it receives an automatic start signal from both ESFAS channels 1

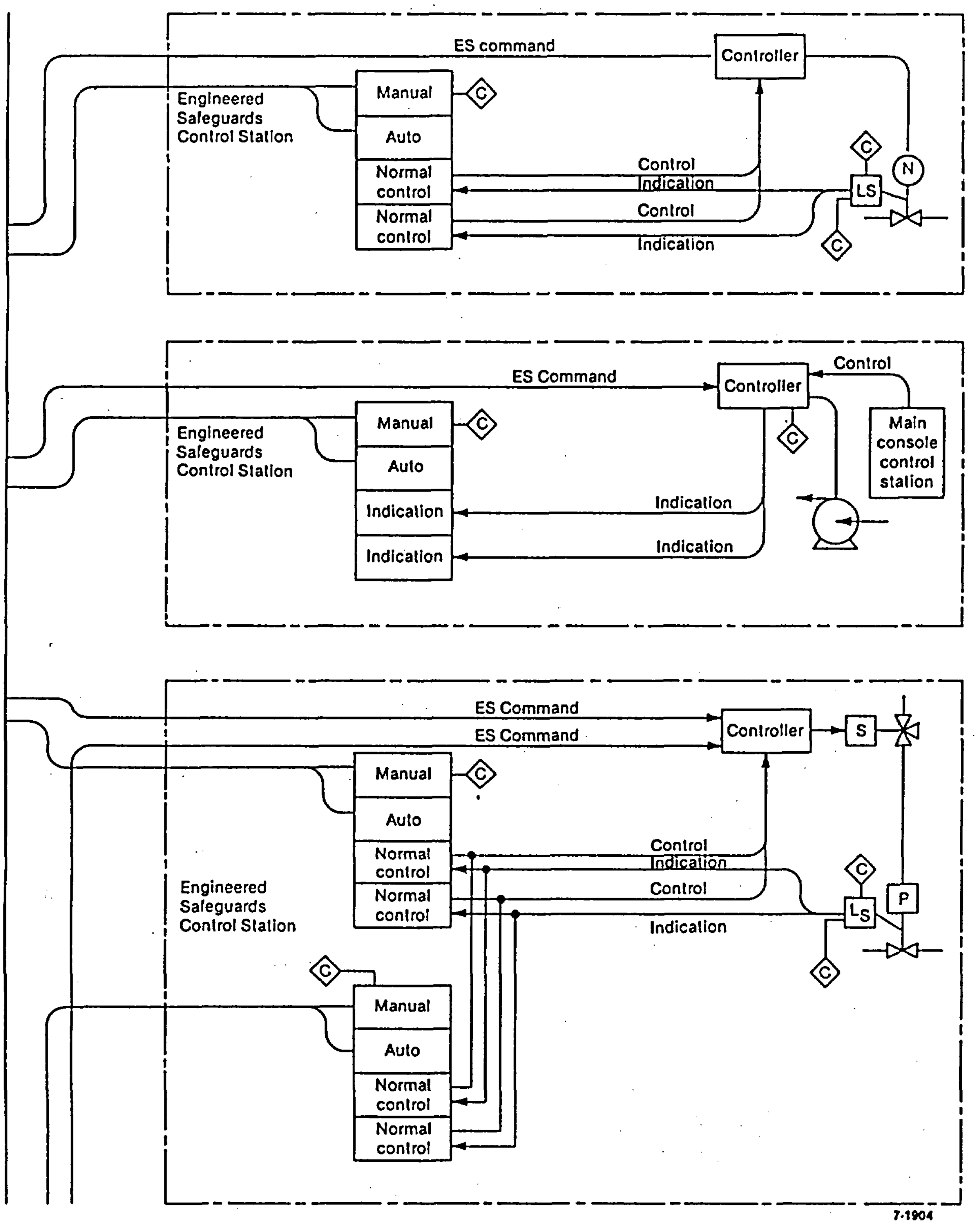



**Figure 7.** Representative ESF actuated systems.

and 2. In order to take manual control of pump B when an ESFAS signal is present, both channels 1 and 2 must be put into the manual mode.

**HPI Pump C Controls.** The controls for HPI pump C are essentially the same as for pump A except that pump C is not used for normal operation. In the event of a reactor accident, HPI pump C receives an automatic start signal from ESFAS channel 2.

**Motor-Operated Valves.** The ESFAS provides automatic operation for the valves listed in Table 1. After an ESFAS signal is initiated, the automatic control signal can be overridden by manual pushbutton. While in the manual mode the valve is controlled as if no ESFAS signal is present. Control is returned to the automatic mode for safeguards when the auto pushbutton is operated or when the ESFAS trip signal is cleared at the safeguards cabinet. Manual controls are provided in the control room and safeguards cabinet.

**Pneumatic-Operated Valves (HP-5 and HP-21).** The pneumatic-operated valves are controlled by a 125 Vac solenoid operated valve that controls the air line operating the pneumatic valve. Manual control is provided in the control room and automatic operation is provided by ESFAS channel 2. A manual override similar to the MOV and HPI pump controls is provided. Interlocks in the control circuit will close HP-5 in the event of an excessively high letdown temperature or low instrument air pressure. Similarly, valve HP-21 is interlocked to close on low instrument air or if all four of the individual RC pump seal return valves are closed.

## HPI Pumps

The HPI pumps are vertical multiple-stage-centrifugal pumps with mechanical seals. The wetted parts of the pumps are stainless steel. Figure 8 is a picture of a HPI pump. Operation of the HPI pumps requires lubricating oil cooling and pump seal cooling. The HPI pump cooling is accomplished via the LPSW systems where heat generated in the pump lubricating oil and seals is removed via heat exchangers. The HPI pump data is given in Appendix E.

## HPI Piping

The HPI piping is stainless steel and designed for normal operation. The normal operating system temperature and pressure requirements are greater than those encountered during emergency operation. Pipe sizes range from 1 to 14 in. Design pressures and temperatures for piping are given in Appendix E.

## Nozzles and Thermal Sleeves

The high pressure injection/makeup (HPI/MU) nozzles with thermal sleeves are located on all four cold legs of the reactor coolant piping. They provide emergency core cooling and normal makeup flow to the primary coolant system. In general, one or two of the lines are used for both HPI and MU, while the remaining nozzles are used for HPI alone. The thermal sleeves are incorporated into the nozzle assembly to provide a thermal barrier between the cold HPI/MU fluid and the hot HPIS nozzle. This prevents thermal shock and fatigue of the nozzle. See Appendix F for a discussion of nozzle cracking.

## Piping Penetrations

The reactor building penetrations for HPI lines associated with the representative plant studied include the following: the letdown from the reactor coolant system to the demineralizers is a 2.5 in. line with remotely controlled valves on the inside and outside of containment for isolation control; two (1 in.) nozzle warming lines with check valves for isolation control; a normal makeup inlet line (4 in.) having a check valve on the inside of containment; two seal injection lines that supply RC pump seal cooling (2.5 in.) with a check valve inside of containment; and the emergency injection line (4 in.) with a check valve on inside of containment. The penetrations must be able to maintain reactor building pressure seal. Reactor coolant isolation under accident conditions is maintained by valves on the inside and outside of the penetrations.

## Pipe Hangers

Pipe hangers are rigid carbon steel supports for the various HPI piping. Their purpose is to resist the dead weight loads of the piping and water.

## Snubbers

Snubbers move freely at low acceleration and lock up at higher acceleration, to provide support for seismic and other dynamic loads. They may be mechanical or hydraulic.

## Tanks

The borated water storage tank is the source of water for the emergency HPIS. It is a 350,000 gallon coated carbon steel tank. For the representative plant studied it is considered part of the low pressure injection system because it also supplies borated water for LPIS and containment spray systems.

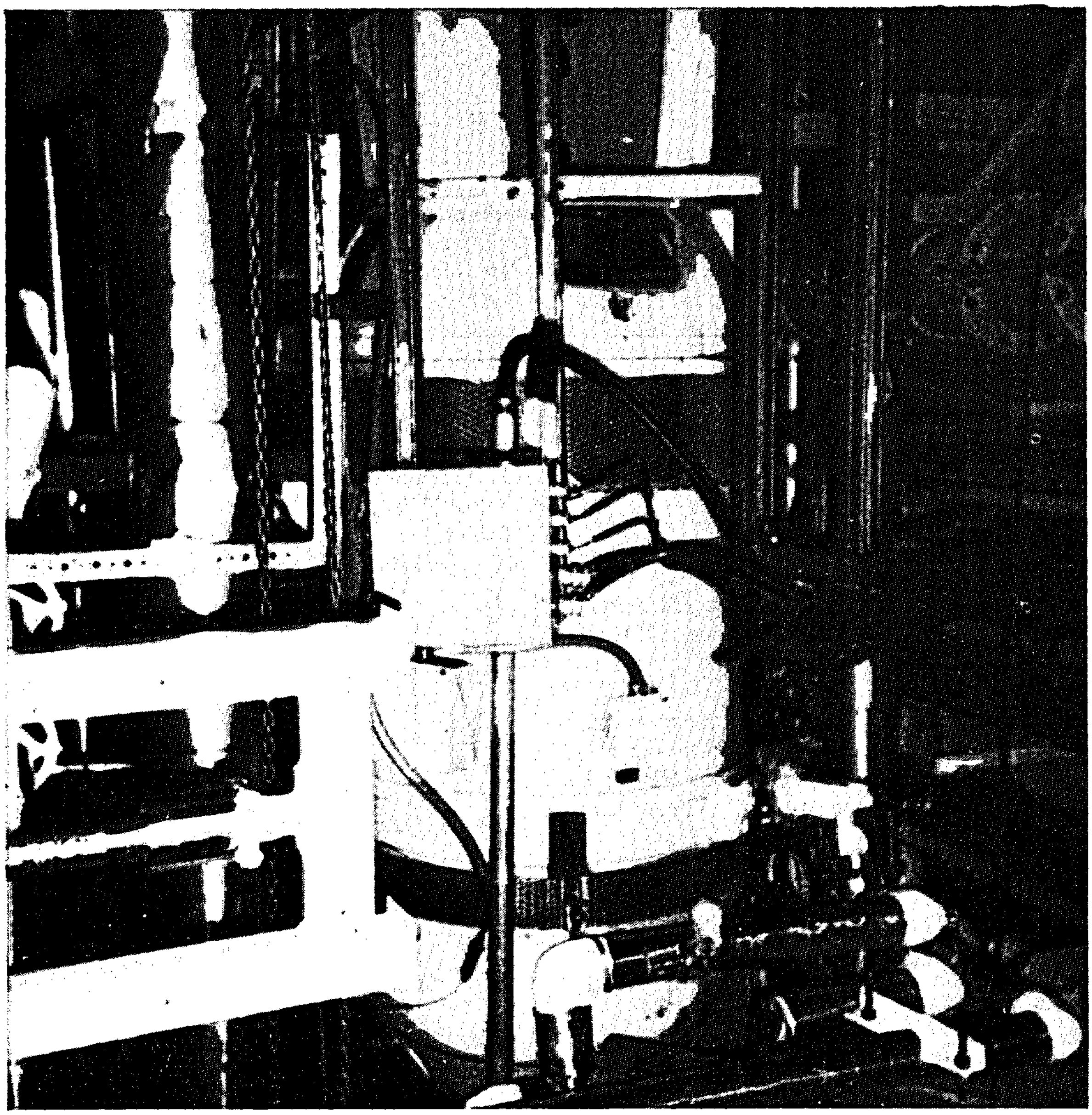


**Figure 8.** HPI pump.

# OPERATING EXPERIENCE

The HPIS operating experience is based on information from generic data bases, plant records from the representative PWR studied, and other sources such as USNRC information notices and bulletins for specific problems. Information was taken from the NPE, LER, and NPRDS generic data bases. These data bases were adequate for drawing general conclusions about the ECCS with emphasis on the HPIS. The system boundaries used were those indentified by these data bases. The discussion of each data base identifies the components or the subsystem covered by that data base. Although the components and subsystems that support the HPIS function are generally included as part of the HPIS, actual high pressure exists only in that part of the system from the HPI pumps to the injection nozzles. All the components that are included in the HPIS are important to its service and therefore, are included in this study.

## Nuclear Power Experience Data

The NPE automated retrieval system was developed and introduced by the S. M. Stoller Corporation at Boulder, Colorado. This system contains information on nuclear plant components available from the public domain. The index and key words are computerized, allowing a rapid search of the system for specific articles with titles and reference numbers to hard copy volumes. The system is updated quarterly and is a convenient source for obtaining generic information on problem areas. The NPE data is summarized in this section. More detailed data from NPE on the various HPI and associated ECCS components are given in Appendix G.

The NPE data base includes the following ECCS subsystems: safety injection, high head injection, upper head injection, boron injection, recirculation phase, containment spray, and accumulator tank. All the above systems are part of the HPIS except containment spray. The containment spray system could not be conveniently removed, thus, to indicate the data summaries from the NPE also include containment spray, they are called ECCS summaries. The components in these subsystems are similar in that they have similar operating environments and must be compatible with borated water.

For U.S. Nuclear Power Plants, from startup through 1986, there were 1552 articles on the ECCS for PWRs. Component failure events listed in order of frequency of occurrence for these PWRs is given in Table 2. Valve failures are listed most frequently (35%), followed by I&C (19%), pumps (15%), and pipes (7%). Pipes in this case include nozzles and penetrations.

The ECCS failure causes are listed in Table 3. The top three causes in order of frequency of occurrence were maintenance error, design error, and mechanical disability. This was followed with 4% each for local I&C, set point drift, chemistry out of spec, and subcomponent sticking. The failure causes that are considered potentially aging related and identified in Table 3 account for 28% of the failures. The cause is identified only as potentially aging related because the root cause can not always determined from the reported events.

After eliminating human and procedure errors, a breakdown of subcomponents causing ECCS failure is given in Table 4 for PWRs. Moving internal parts for valves, pumps, and motors accounted for 15% of the problems. Just a little over half of these were caused by valve stem or disc seating problems. Instrumentation accounted for 12% of failures and control 11% of failures. The drive sources for most of the valves and pumps are electric motors which accounted for 66% of drive/actuator failures.

**Table 2. ECCS component failure ranking (NPE)**

| Component | PWR (%) |
|---|---|
| Valves | 35 |
| Instrument and control | 19 |
| Pumps | 15 |
| Pipe | 7 |
| Electrical | 4 |
| Heat exchanger | 2 |
| Other | 18 |
| Number of events | 1,552 |

**Table 3. ECCS failure causes (NPE)**

| Cause | PWR (%) |
|---|---|
| Maintenance error | 28 |
| Design error | 13 |
| Mech. disability[a] | 10 |
| Local I&C failure[a] | 4 |
| Setpoint drift[a] | 4 |
| Chemistry out of spec | 4 |
| Sub-comp. sticking[a] | 4 |
| Short/ground[a] | 3 |
| Weld failure[a] | 3 |
| Blockage | 3 |
| Other | 24 |
| Number of events | 1,552 |

a. Potentially aging related failures in 28%.

**Table 4. Subcomponents causing ECCS system failures for PWRs (NPE)**

| Subcomponent | Percent | (a) | Subcomponent | Percent | (a) |
|---|---|---|---|---|---|
| Moving Internal | 15 | | Drive/Actuator | 8 | |
| Stem/disc seating | | (52) | Pneumatic air | | (10) |
| Blade/impeller | | (9) | Hydraulic | | (3) |
| Coupling shaft | | (16) | Motor | | (66) |
| Bearing/bushing | | (14) | Other | | (21) |
| Piston/diaphragm | | ( 9) | | | |
| Instrumentation | 12 | | Chemistry | 7 | |
| Bistables | | (33) | Relay/breakers | 6 | |
| Transmitters | | (25) | Wire cable | 5 | |
| Sense lines | | (25) | Connectors | 5 | |
| Indicator | | (17) | Seal/gasket | 5 | |
| | | | Fitting/flange | 4 | |
| Control | 11 | | External Support | 4 | |
| Limit SW | | (14) | Mounting/fastener | 4 | |
| Solenoid valve | | (11) | Body/casing | 2 | |
| Torque SW | | (23) | Other misc. | 12 | |
| Other | | (52) | | | |

a. Number in "parentheses" is % of number in left column heading.

Electrical subcomponents—relays, breakers, cable, and connectors—accounted for 16%.

## LER Data

The Code of Federal Regulations (10 CFR 50.72 for occurrences before 1984 and 10 CFR 50.73 for events after January 1, 1984) require nuclear power plants to report significant events to the USNRC. The pre-1984 LER data base has been used as a source of reliability data. Events reported to the LER system after January 1, 1984 are only those that are, or lead to, safety-significant events. If a component fails and can be replaced within the time constraint of the limiting condition for operation (LCO), no LER is required. This limited reporting would not be expected to provide an adequate representation of failure experience; therefore, only the LERs prior to 1984 were used in this aging study. Data from licensee event reports on HPI pumps and valves from LERs are presented in this section. The LER data covers HPI and CVCS valves and pumps for B&W, W, and CE plants.

**Pump Failures.** A total of 44 events associated with HPI pumps were reported in the LERs for all PWRs from January 1, 1972 to September 30, 1980.[8] For the HPI pumps, the leading failure cause was control malfunction with 14 failure events out of a total of 44. The next most frequent causes were maintenance and design error with four events each. This is followed by three events each for operation error, failed internals, and unknown. These HPI pump failure causes are summarized in Table 5.

The failure mode experienced most often was does not start for 24 of the 44 events. This was followed by does not continue to run (8 events) and loss of function (7 events). Most of the problems (25) were discovered by performance testing. Twelve were discovered by normal operations (See Table 6).

**System Pumps.** The system pump category covers all HPIS/CVCS pumps apart from the main HPI pumps, (i.e., charging pumps, makeup pumps, etc.). There were 130 events reported where the leading cause was seal or packing failure (29), followed by control malfunction (13), loss of pressure boundary (12), and drive train failure (9). Table 7 ranks these causes by number of events.

**Valves.** A summary of HPIS valve failure from LER data for 1976 through 1980 is given in Table 8.[9] About 42% of the valve failures were classified as potentially aging related. In this category, mechanical controls (parts failed or out of adjustment) were the most frequent with 8%, followed by seat or disk failure 6.9%, and packing failure 5%. It is interesting to note that command faults (faults due to power source, controls or supporting systems) caused 32% of HPIS valve failures. See Appendix G for additional LER data on valves.

## Nuclear Plant Reliability Data System

The NPRDS was developed by the Equipment Availability Task Force of the Edison Electric Institute (EEI) in the early 1970s under the direction of the American National Standards Institute (ANSI). The NPRDS was maintained by the Southwest Research Institute under contract to the EEI through 1981. Since January 1982, the NPRDS has been under the direction of the Institute of Nuclear Power Operation. The components covered in the NPRDS for HPIS are announciators, circuit breakers, safety function instruments, motors, pumps, valves, and valve operators. For Westinghouse plants upper head injection, the Boron Injection Tank along with associated valves is also included. For B&W plants, filters are included as well as letdown, purification, and also CVCS components common to the CVCS and HPIS systems.

The NPRDS data for all Westinghouse and Babcock and Wilcox plants were compiled for the HPIS and the aging fraction determined. Combustion Engineering data was unavailable from NPRDS at the time these data were compiled. Aging fraction is the ratio of aging-related failures to total number of failures. The B&W systems included in this sort were the letdown purification and makeup systems and high pressure injection system. The Westinghouse systems included were the High Pressure Injection System and Upper Head Injection Subsystem. The results of this sort are shown in Table 9. The overall aging fractions for 1036 failures is 0.213. This means that 21.3% of the failures were aging related. The HPIS components ordered by aging fractions for categories of design, aging, testing, and human is shown in Table 10. Valves caused the most failures, followed by valve operators and instrumentation. These

**Table 5. HPI pump failure causes (LER)**

| Item | Cause | Number of Events |
|---|---|---|
| 1 | Electrical/mechanical | 14 |
| 2 | Control malfunction maintenance error | 4 |
| 3 | Design error | 4 |
| 4 | Operation personnel error | 3 |
| 5 | Failed internals[a] | 3 |
| 6 | Unknown | 5 |
| 7 | Drive train failure[a] | 2 |
| 8 | Foreign material | 2 |
| 9 | Testing | 1 |
| 10 | Extreme environment | 1 |
| 11 | Loose fastener[a] | 1 |
| 12 | Loss of pressure boundary[a] | 1 |
| 13 | Improper clearance | 1 |
| 14 | Seal failure[a] | 1 |
| 15 | Bearing failure[a] | 1 |
| | Total | 44 |

a. Potentially aging related.

three categories accounted for approximately 77% of HPI component failures in HPIS.

The NPRDS system effect code identifies the effect on the system caused by the component failure. The codes were taken directly from the NPRDS failure records. The NPRDS has five system effect categories and are defined as follows:

- Loss of System Function—A component failure that, singularly results in the system being unable to perform its intended function (i.e., all trains, channels, etc., inoperable).
- Degraded System Operation—The system is capable of fulfilling its intended function, but some feature of the system is impaired.
- Loss of Redundancy—Loss of one system functional path.
- Loss of Subsystem/Channel—A partial loss of system functional path.
- System Function Unaffected—Failure did not affect the operation of the system.

The fractions for each system effect are shown in Table 9. Approximately 57% of the failures lead to system degradation, but only 0.7% caused a loss of system functions.

The motor-operated valve data from the nuclear plant reliability data system for Westinghouse plants had enough events (56) to show an aging trend (shown in Figure 9) when the data is plotted

## Table 6. Data on HPI and other chemical volume control pumps (CVCS/HPI) (LER Data)

| | (a) Mode | | | | | (b) Type of Event | | | | | | | (c) Activity | | | | | (d) Class | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pump type | U | A | B | C | D | R | C | S | T | U | V | N | M | N | R | T | U | D | T | U |
| HPI | 4 | 1 | 24 | 7 | 8 | 2 | 2 | 6 | 10 | 10 | 0 | 1 | 2 | 12 | 3 | 25 | 2 | 29 | 9 | 6 |
| All other CVCS/HPI pumps | 2 | 43 | 16 | 18 | 33 | 50 | 3 | 17 | 2 | 4 | 2 | 3 | 3 | 89 | 0 | 13 | 5 | 39 | 50 | 22 |

(a) Failure mode

| Code | Description |
|---|---|
| A | Leakage/rupture |
| B | Does not start |
| C | Loss of function |
| D | Does not continue to run |
| U | Unknown |

(c) Activity resulting in discovery

| Code | Description |
|---|---|
| M | During maintenance |
| N | During normal operations |
| R | During records review |
| T | During testing |
| U | Unknown |

(b) Type of Event

| Code | | |
|---|---|---|
| Failure | Command | Description |
| | S | Nonrecurring, not common cause |
| R | T | Recurring, not common cause |
| C | U | Nonlethal common cause |
| | V | Recurring nonlethal common cause |
| | N | Lethal common cause |

(d) Event Classification

| Code | Description |
|---|---|
| D | Demand |
| T | Time (continuous operation) |
| U | Unknown |

**Table 7. Cause for all system pump failures other than main HPI pumps (LERs)**

| Cause | Number of Events |
|---|---|
| Seal failure[a] | 29 |
| Control malfunction[a] | 13 |
| Loss of pressure boundary[a] | 12 |
| Drive train failure[a] | 9 |
| Maintenance personnel error | 7 |
| Failed internals[a] | 6 |
| Shaft/coupling failure[a] | 5 |
| Bearing failure[a] | 4 |
| Operating personnel error | 4 |
| Extreme environment | 3 |
| Excessive wear[a] | 1 |
| Other | 16 |
| Total | 109 |

a. Potentially aging related.

**Table 8. Summary of HPIS valve failures[a]**

| Failure Mechanisms | Percent |
|---|---|
| Potentially Aging Related | |
| Mechanical controls (Parts failed or out of adjustment) | 8 |
| Seat or disk failure | 6 |
| Packing failure | 5 |
| Pilot valve failure | 3 |
| Torque valve failure | 3 |
| Motor operator failure | 3 |
| Leaking/ruptured diaphragm | 3 |
| Normal wear | 3 |
| Seal gasket failure | 2 |
| Limit switch failure | 1 |
| Excessive wear | 1 |
| Solenoid failure | 1 |
| Corrosion | 1 |
| | 40 |
| All Other | |
| Command faults | 32 |
| Personnel operations | 6 |
| Personnel maintenance | 4 |
| Construction | 3 |
| Design | 3 |
| Other and unknown | 12 |
| | 60 |

a. Data source is LER.

**Table 9. High pressure injection system totals and fractions**

| | |
|---|---|
| **Failure Category Totals** | |
| Design failures | 122 |
| Aging failures | 221 |
| Test and maintenance failures | 83 |
| Human related failures | 27 |
| Other failures | 583 |
| Total | 1036 |
| **Failure Category Fractions** | |
| Design fraction | 0.118 |
| Aging fraction | 0.213 |
| Test and maintenance fraction | 0.080 |
| Human related fraction | 0.026 |
| Other fraction | 0.563 |
| **System Effect Totals** | |
| Loss of system function | 7 |
| Degraded system operation | 197 |
| Loss of redundancy | 138 |
| Loss of subsystem/channel | 251 |
| System function unaffected | 443 |
| Total | 1036 |
| **System Effect Fractions** | |
| Loss of system function fraction | 0.007 |
| Degraded system operation fraction | 0.190 |
| Loss of redundancy fraction | 0.133 |
| Loss of subsystem/channel fraction | 0.242 |
| System function unaffected fraction | 0.428 |

**Table 10. High pressure injection system component failure category fractions[a]**

| Component | Total | Design | Aging | Testing | Human | Other |
|---|---|---|---|---|---|---|
| Relay | 1 | — | 1.000 | — | — | — |
| Support | 32 | 0.156 | 0.375 | 0.031 | 0.031 | 0.406 |
| Filter | 6 | — | 0.333 | 0.500 | — | 0.167 |
| Heat exchanger | 9 | 0.444 | 0.333 | — | — | 0.222 |
| Valve | 307 | 0.127 | 0.326 | 0.085 | 0.020 | 0.443 |
| Pump | 86 | 0.105 | 0.314 | 0.116 | 0.047 | 0.419 |
| Instrumentation recorder | 18 | — | 0.278 | — | — | 0.722 |
| Valve operator | 161 | 0.081 | 0.211 | 0.143 | 0.031 | 0.534 |
| Circuit breaker | 43 | 0.163 | 0.209 | 0.070 | 0.047 | 0.512 |
| Instrumentation: transmitter | 141 | 0.106 | 0.113 | 0.071 | 0.007 | 0.702 |
| Heater | 36 | 0.111 | 0.111 | 0.111 | 0.167 | 0.500 |
| Instrumentation: controller | 19 | 0.158 | 0.105 | — | — | 0.737 |
| Instrumentation: switch | 153 | 0.124 | 0.039 | 0.007 | — | 0.830 |
| Accumulator | 4 | — | — | — | 0.250 | 0.750 |
| Motor | 9 | 0.111 | — | 0.111 | 0.111 | 0.667 |
| Pipe | 5 | 0.400 | — | 0.200 | — | 0.400 |
| Instrumentation: computation module | 6 | 0.167 | — | — | — | 0.833 |

a. Components ordered by aging fractions.

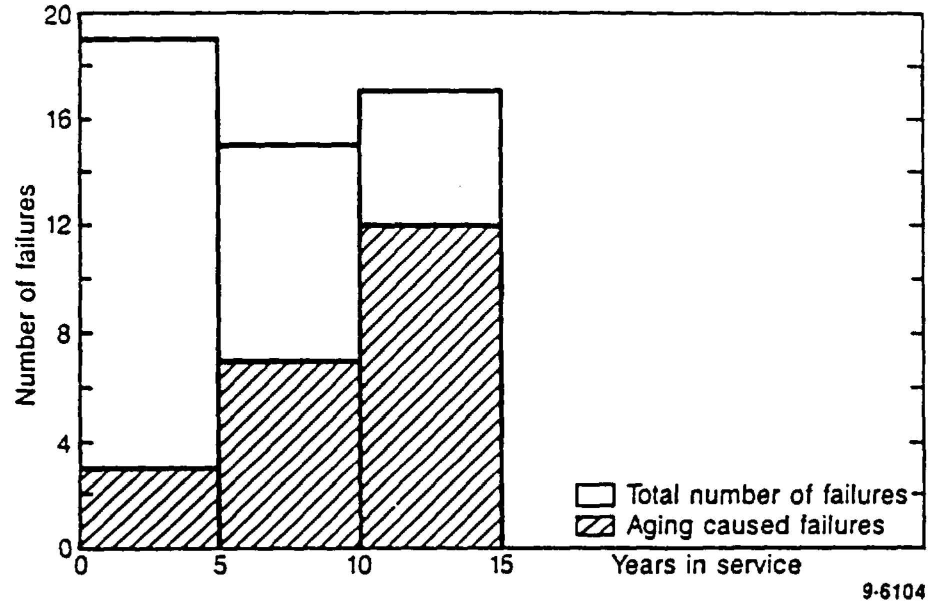



**Figure 9.** Failure data for HPIS motor-operated valves in 5-year increments (data from nuclear plant reliability data system).

in five-year increments. This also appears in Table 11 along with data for check valves, manual valves, and HPIS pumps. The check valves and manual valves showed no trend on aging failures. The HPIS pumps had a significant increase in the number of failures in the 10- to 14.9-year period for both aging and other causes.

## Plant Operating Experience from Site Visit and Personnel Interviews

An operating B&W plant was visited and site personnel interviewed. Included in the interviews were the HPI maintenance supervisor, I&C supervisors, and an electrical specialist. Detailed I&C drawings on HPIS were reviewed with plant personnel, as well as computer printouts of corrective maintenance (CM) requests, incident investigation reports (IIR), and test procedures for HPIS. All maintenance work is initiated with a maintenance work request and when the work is finished, a description of the problem and corrective action is written on the request sheet. These CM requests are then filed for record purposes.

**Nuclear Maintenance Data Base.** Corrective Maintenance summaries were taken from the Nuclear Maintenance Data Base. This plant data system summarizes all CM reports as a one-line summary, work required reference number, and date. Any channel or component found deficient during implementation of calibration and testing procedures would have a CM request written to correct the problem.

The CM request records were computerized by the utility starting October 23, 1980 and these were the ones reviewed. Microfilm records for CM before October 23, 1980, were not searched because of manhour and cost limitations.

The computerized maintenance records were reviewed and show that many potential problems are fixed before major system or channel failures occur. Thus, maintenance records reflect the incipient failures to some extent.

Data from the maintenance records are shown in Table 12. These data cover a period from May 1980

**Table 11. Component failures in 5-year increments[a]**

| Component | Failure Classification | Number of Failures 0-4.9 Years | 5-9.9 Years | 10-14.9 Years | Total |
|---|---|---|---|---|---|
| Motor-operated valve | Other | 16 | 8 | 5 | 29 |
| | Aging | 3 | 7 | 12 | 22 |
| | Total | 19 | 15 | 17 | 51 |
| CV | Other | 7 | 4 | 9 | 20 |
| | Aging | 2 | 1 | 2 | 5 |
| | Total | 9 | 5 | 11 | 25 |
| Manual valves | Other | 3 | 3 | 3 | 9 |
| | Aging | 1 | 4 | 2 | 7 |
| | Total | 4 | 7 | 5 | 16 |
| Pump (centrifugal) <500 gpm | Other | 4 | 7 | 14 | 25 |
| | Aging | 4 | 4 | 15 | 23 |
| | Total | 8 | 11 | 29 | 48 |

a. Data from the nuclear plant reliability data system; data for older Westinghouse plants.

to December 1986 and contain 356 records. Of these, 171 were routine maintenance items such as recorder paper problems, cleaning filter, etc. Instrumentation and Control were the largest category with 74 requests. Pipe-related maintenance items were the next largest category with 55 requests. They include flange leaks, hangers, pipe, penetration, and snubbers. These requests were followed by valves with 25 requests, control circuits with 21 requests, and pumps with 18 requests.

**Incident Investigation Reports.** Nonroutine events in the plant (including those that occurred during the precommercial operations phase) are evaluated. This evaluation may result in an incident investigation report (IIR) that captures the important details related to the event through interviews, analysis of logs, recorder strip charts, computer printouts, etc. IIRs are company proprietary and cover reportable events such as techical specification violations. The event may or may not require NRC notification. Hence, the LERs for the station are a subset of the IIRs. The IIRs were reviewed through April 1985.

Some observations based on sorts of the IIR data base are:

1. Better resolution of information in the coded fields than LERs and NPRDS failure reports
2. Precommercial operation events captured
3. Report event frequency relatively constant up to 1984
4. Coded reporting for LER tracking
5. Infant mortality observable in component failure searches.

A summary of IIR causes for HPIS failures are presented in Table 13. Procedure or personnel error and valve failure each accounted for 28% of the incidents, followed by I&C (17%), pumps (11%), nozzle (6%), and welds (5%). However, bacause there were only 17 events covering the HPIS over an 11-year period, the average for reportable events was relatively low at about 1.5 per year for the plant studied. Estimates indicate that about half of these events are potentially age related.

## Summary of Operating Experience

The information from the data bases indicate that approximately 57% of the failures lead to

**Table 12. HPI plant data**

| Item | Number of CM Requests | Sub breakdown of CM Requests |
|---|---|---|
| Routine Maintenance, Misc. | 171 | |
| Pipe Maintenance | 55 | |
| Flange leaks | | (22) |
| Hangers | | (17) |
| Pipe, penetration, orifice | | (12) |
| Snubbers | | (4) |
| Instrumentation and Control | 74 | |
| Sensors, monitors | | (38) |
| Sensing line leaks | | (15) |
| Valves | 25 | |
| Mechanical problems | | (12) |
| Packing replaced | | (11) |
| Valve operator | | (2) |
| Pumps | 18 | |
| Vibration | | (7) |
| Pump repair | | (4) |
| Mech. seals | | (4) |
| HPI pump repair | | (1) |
| Boron accumulation | | (1) |
| Pump motor | | (1) |
| Other | 13 | |
| Pump coolers | | (7) |
| Bolts | | (3) |
| Gaskets | | (3) |
| Total | 356 | |

**Table 13. IIR summary of causes for HPIS failures**

| Type of Event | Percent |
|---|---|
| Procedure/personnel error | 28 |
| Valve failure | 28 |
| I&C failure | 17 |
| Pumps failure | 11 |
| Nozzle/thermal sleeve failure | 6 |
| Weld failure | 5 |
| Other | 5 |
| Total | 100 |

system degradation, but only 0.7% of these failures caused a loss of system function. The data bases also showed that 21.3% of these failures were aging related.

The data bases are in agreement on the four most troublesome components in the HPIS. However, the CM data ranks them differently than the NPE, NPRDS, and IIRs. Valves have the most failure, followed by I&C, pumps and pipe related events. However, CM received the most requests for I&C problems, then pipe related problems, and finally, valves and pumps. These requests indicate more minor problems with I&C and pipe hanger adjustments etc., but the major reportable problems rank valves first in frequency of failure (see Table 14).

LER have frequency of occurrence similar to the NPE.

A summary of problems with the HPI system components is given next for each type of component.

**Piping.** Prior to 1982, there were no significant problems with piping cracks in HPI systems for PWRs. However, in March of 1982, cracks were identified in the thermal sleeve and safe end where a makeup/high pressure injection line joins the reactor coolant system at one B&W unit.[10] Subsequent investigations of these lines at four other B&W units revealed similar cracks. The apparent cause of the cracking was thermal fatigue. The injection lines for normal reactor coolant makeup are also part of the high pressure injection system at B&W plants. Because these plants do not have regenerative heat exchangers in the coolant makeup circuit, a potential existed for makeup temperatures to be substantially lower than the reactor coolant temperature. Temperature variations due to mixing in the high pressure system nozzle, coupled with hydraulic effects, were suspected to be the principle cause of failure.

Beginning in June, 1982, cracks were also identified in the thermal sleeve to nozzle connections of reactor coolant system branch pipes at several Westinghouse units. The cracking was discovered in the thermal sleeve retainer welds that attach the sleeve to the nozzle inlet. These cracking problems included:

1. Accumulator lines, pressurizer surge line, and charging line nozzles at one unit
2. Accumulator line nozzle at one unit
3. Safety injection and charging line nozzles at one unit

**Table 14. Data base ranking of most troublesome HPI components**

| Component | NPE | NPRDS | IIR | CM[a] |
|---|---|---|---|---|
| Valves | 1 | 1 | 1 | 3 |
| I&C | 2 | 2 | 2 | 1 |
| Pump | 3 | 3 | 3 | 4 |
| Pipe, supports, nozzles | 4 | 4 | 4 | 2 |

a. The CM has many requests for I&C problems and minor pipe problems which are repaired and are not reportable events.

4. Two accumulator lines, a safety injection cold leg injection line, and the charging line nozzles at one unit.

The failure mechanism was suspected to be fatigue induced by thermal cycling.

Most of the recent stainless steel pipe crack problems at PWRs have been fatigue related rather than corrosion related. In 1979, stress corrosion cracking was discovered in some safety system pipes containing stagnant borated water.[11] No losses due to this problem were reported in 1980-1986.

Cracks have also occurred due to vibration and dynamic loading (water hammer). Welds and flanges are connection stress points. Flange loosening accounted for 9% of all pipe problems in NPE data.

**Snubbers.** Snubbers perform a safety function by restraining the motion of attached systems or components under rapidly applied load conditions of earthquakes, pipe breaks, or severe hydraulic transients. LERs relating to malfunction of snubbers indicated the most frequent problem was seal leaks in hydraulic snubbers. Mechanical snubbers were subject to damage due to vibration. A phase 1 NPAR study has been conducted on snubbers.[12]

**Penetrations.** At least five piping penetrations are associated with the HPIS for the plant studied. Few problems have been found with penetrations. One estimate for penetration problems (Issue B-26, Reference 13) was one failure per year for all operating plants (71 at time of estimate). In that estimate, it was assumed that each plant had 40 penetrations. If five penetrations are associated with HPIS, then about every eight years a problem could be expected with an HPIS penetration in one of the 71 operating plants.

**Tanks.** Few tank problems have occurred. Most of the problems attributed to tanks in data bases involved boron concentrations or fluid levels that were out of specification. The only significant event was to replace a boric acid injection tank at a PWR.

**Pumps.** Most high pressure injection pump failures that are aging related involved seal, bearing, and shaft problems.

**Valves.** The type of component most often responsible for HPI failure was valves. This includes all types of valves and valve operators. Personnel error, operation, and maintenance were the primary causes overall. When these causes were removed, mechanical parts failure, packing leaks, and seat or disk failure were the most often mentioned causes related to aging and service wear.

**Chemistry Problems.** Corrosion in pipe weld heat zones due to contaminants and boric acid corrosion of ferritic metals are two failure causes related to chemistry and aging. Controlling boric acid concentrations is a safety related operational problem. See Appendix H for problems with borated water systems.

**Microbial Influenced Corrosion.** Many systems in the majority of nuclear plants appear to be susceptible to some form of microbial influenced corrosion (MIC). This is particularly true of standby systems where conditions exist for microbial growths. Stainless steel 304, 316, etc., have been affected by MIC as well as other metals. One utility experienced MIC in the HPI and LPI pump impeller blades after initial tests followed by a period of standby. Microorganisms have also been found in a borated water storage tank, but no degradation was reported.

# HPI SAFETY ISSUES AND POTENTIAL AGING PROBLEMS

The following is a review of system and personnel interaction safety issues[13] related to HPI and aging.

## Locking Out of HPIS Power-Operated Valves

The NRC staff positions BTP EISCB 18 and BTP RSB 6-11 require the physical locking out of electrical sources to specific motor-operated valves in the ECCS including HPIS and LPIS. This method protects against a single failure causing an undesirable component action. This assumption in the safety evaluation is that the component is then equivalent to a similar component that is not designed for electrical operation and can only be opened or closed by direct manual operation of the valve. Thus, no single failure (due to any cause including aging) can both restore power to the component and cause mechanical motion of the component. The probability of failures due to maintenance errors, electrical faults, and mechanical failures ($7 \times 10^{-7}$) was greater than the probability of the valve mispositioning coincident with a LOCA, and as a result of operator error ($4 \times 10^{-7}$). This was issue number B-8 in Reference 13, but was dropped as a safety issue because it is an acceptable approach to meet the single failure design criteria. However, this points out a design shortcoming when human interaction is required for initiating HPIS valve action.

## Inadvertent Actuation of Safety Injection in PWRs

Westinghouse and B&W plants had a high rate of spurious or inadvertent safety injections occurring. In the case of B&W reactors, the practice was to manually turn on one or more HPI pumps after a reactor scram to recover the pressurizer level. This practice contributed to the high rate of safety injections for these plants. This practice was stopped after the accident at the Three Mile Island plant because it was determined the HPI pumps were not needed to maintain pressurizer level. As a result, unneeded SI in B&W plants is now significantly lower. A possible reason for unneeded SIs in Westinghouse plants is their design requires more signals for initiating SI and thus more chances for spurious signals. Actuation of the SI is undesirable because it injects cold borated water into the reactor, thereby subjecting injection nozzles to thermal stresses and requiring removal of boron from the primary system before startup. Actuation was determined as not only an economic issue, but could possibly lead to a wrong response by an operator when SI is really needed. Operator response is carried as another issue and would include this one. This was issue 8, Reference 13. Inadvertent SI actuation due to this operating procedure was corrected by eliminating the procedure. However, maintenance personnel error and other operator procedures that could inadvertently initiate SI should continue to be reduced through design, training, and applicable updating procedures.

## Switch from HPI Mode to Recirculation Mode

The switchover from the HPI mode of operation to the recirculation mode for accident recovery requires realignment of a number of valves. The switchover can be achieved by a number of manual actions, by automatic actions, or a combination of both. The three switchover options (manual, automatic, and semiautomatic) are vulnerable with varying degrees to human errors, hardware failure, and common cause failures. Automatic system actuations reduce the impact of operator error in completing the switchover, but are subject to spurious actuations. Spurious switchover of HPI to HPR has the potential for pump damage as well as unacceptable safety consequences. This safety issue (No. 24) was scheduled for prioritization (Reference 13).

## High Pressure Recirculation System Failure Due To Containment Debris

In the recirculation mode the HPIS pumps take suction from the LPIS, which is taking suction from the containment sump. Any debris, paint flakes or loose material due to aging could potentially damage system components during the HPRS mode of operation. This is safety issue 28 (Reference 13), which has now been scheduled for prioritization.

## Failure of Demineralizer System and the Effect on HPIS

While the demineralizer system does not directly perform a safety function, a failure of the demineralizer system could impair the operation of the HPIS. In the plant studied, the demineralizer system has key components labeled as part of the HPIS to ensure prompt attention if failure occurs. In Reference 13, this problem is listed as issue 71 and is scheduled for prioritization. This is also true of other systems and is addressed in the next subsection on Systems Interaction.

## Systems Interaction

The HPIS interfaces with many other plant systems. They include 1E power, LPIS, RCS, service water systems, containment spray system, monitoring, and ESFAS. In addition, part of the HPIS is used for both normal operation and emergency operation. There are also HPI subsystems such as demineralizer, makeup/letdown system, chemical control, boron injection, lubrication of HPI pumps, pump seal cooling, and instrument air system. System interactions for HPI may be one study recommended for the Phase 2 aging study. Overall plant system interactions is also a Safety Issue (A-17, Reference 13). In addition, the performance of the HPIS equipment can be affected by the heating, ventilation, and air conditioning system.

# AGING ASSESSMENTS FOR THE HPIS

The third objective of the HPIS aging study was to perform screening type assessments of the impact of aging on operability of the HPIS. Subobjective (a), failure modes and causes, has already been covered in the discussion of operating experience. Based on the review of operating experience from generic data bases, safety issues, and plant data the remaining four subobjectives of objective 3 can be discussed. They include: (b) identification of materials susceptible to aging degradation, (c) stressors during operation, (d) functional indicators that would aid in failure prediction, and (e) methods for detection and control of aging degradation.

## Preliminary Identification of Susceptibility of Materials to Aging

The HPIS piping, pumps, and valves are all stainless steel which is compatible with boric acid. The BWST is carbon steel with a liner to protect against corrosion. Problems have occurred when leaks in connections or valves allowed borated water to come in contact with carbon steel components. Water evaporation results in a concentration of boric acid causing corrosion on carbon steel components.

The narrative descriptions in the NPE data base were reviewed to determine if failure occurred as a result of conditions specific to the HPIS. Several failures were reported that resulted from the charging of cold water into a hot system and from the handling of the water with a high boron concentration. The four most significant failures are discussed below.

High-pressure injection/makeup nozzles have developed through wall cracks. The cracks resulted from thermal fatigue. The thermal fatigue was caused by turbulent mixing of hot and cold coolant and thermal shock of the hot safe-end wall during normal makeup. All cracks were associated with loose thermal sleeves. Improved thermal sleeve design and increase in minimum continuous makeup flow to prevent thermal stratification have been employed for failure mitigation.

Elbows in the safety injection piping between the cold leg and the first check valve have developed through wall cracks. The cracks occurred in the heat-effected zone of the elbow weld, to the safety injection piping, and in the base metal of the elbow. The cracks resulted from high-cycle thermal fatigue caused by cold makeup water leaking through a closed globe valve at a pressure sufficient to open the check valve. Mitigation methods are being evaluated. Installation of a globe valve downstream of the check valve, rather than the existing valve, is being considered to isolate the injection line during normal makeup.

Motor-operated valves and check valves have failed to operate due to boron crystallization on the valve stems, in the valve packing, and in the valve body. The reason for crystallization was not always reported in the NPE, and investigations may not have identified the cause. However, most causes were reported as packing leaks. The valves were usually cleaned and placed back in service. One incident reported additional heat trace was added to prevent future failures.

Injection boron concentration has been diluted from leaking valves. Leaks have been reported for both check and globe valves. Dilution of the boron injection tanks for Westinghouse plants and safety injection tanks for combustion engineering plants have been reported. A few dilutions have been reported for the borated water storage tanks of the Babcock and Wilcox plants. Improved monitoring of the tanks and repair of the valve seats have been implemented as mitigation measures.

A microbe-caused-problem with stainless steel occurred in a plant when preliminary tests were conducted with water in the HPIS and allowed to stand before startup. During this standby period microorganisms caused corrosion on the pump impeller blades.

I&C and electronic components have been susceptible to catastrophic failure. Contact wear in switches and relays as well as corrosion on contacts are common aging effects on electrical components. Electrical insulation ages with thermal cycling.

## Stressors for HPIS

The HPIS is subject to many stressors during operation. They include stressors due to maintenance, operation, and testing; environmental stressors; electrical stressors on I&C; and mechanical stressors. Various types of stressors are identified in the following sections.

**Maintenance, Operations, and Testing Stressors.** Included in the maintenance, operations, and testing stressors are:

1. *Personnel error*—resulting in inadvertent SI actuation. If valves are not oriented properly, or pump suction unavailable, damage to components could result.
2. *Water hammer (dynamic loading)*—incidents have been attributed to pump startup with partially empty lines and rapid valve motion. Most damage has been relatively minor and involves pipe hangers and restraints.
3. *Thermal cycling*—due to cold water from the HPI system into the hot RC system. Also reactor heatup and cooldown causes thermal cycling.

**Environmental Stressors.** Included in the environmental stressors are:

1. *Temperature or pressures*—are environmental stressors
2. *Water chemistry incorrect*—impurities left from welding and boric acid crystals are examples of environmental stressors
3. *Vibration*—flow-induced vibration may have been a contributing factor in the thermal sleeve cracking in PWRs. Pumps can be a source of vibration if unbalanced. Many other potential sources of vibration exist in a nuclear plant. If the natural frequency of vibration of the connected piping is very nearly the same as the driving frequency of the pump, then there is the possibility of fatigue failures in the system, particularly at the nozzles where the stress will be highest. Vibration is detected on major rotating equipment by instrumentation, inservice inspection, or other visual means. Vibration problems, however, have to be resolved on a case by case basis
4. *Seismic stresses*—may cause relay chatter or fastener damage. Seismic stresses, however, are not due to recurrent conditions due to operations.

**Electrical Stressors.** The electrical stressors from switching transients and loading include:

1. *Transients affecting I&C*—transients can occur from HPIS operation, external electrical faults, and lightning.
2. *Low voltage affecting I&C*—abnormal voltage can occur from excessive loading, power supply drift, and set point adjustments.

**Mechanical Stressors.** Some mechanical stressors are as follows:

1. *Valve misadjustment*—limit switches, and torque switches out of adjustment, and mechanical adjustments can cause mechanical stress
2. *Pipe alignment*—any misalignment of piping can stress welds, connection, and flanges
3. *Vibration*—caused by motors and pumps.

## Functional Indicators that would Aid in Failure Prediction

Functional indicators include abnormal currents and voltages for I&C equipment and indicate a change from the normal expected values. Leaks in pipes, flanges, and nozzles indicate problems such as loose fasteners, cracked pipe, or corrosion. Visual indicators could include limit switch setting, boric acid crystals, or shaft wear. Unusual vibration or noise associated with motors, valves, and pumps could also be an indication of impending failure.

## Methods of Detection and Control of Aging Degradation

Any of the failure detection methods also apply to aging detection because aging is one of the mechanisms causing failure. Functional indicators observed during normal operations or testing is one means of detecting degradation. This detection includes the normal control room monitoring of gauges, charts, and computer printouts. For special problems or studies, additional condition monitoring such as vibration sensors, noise monitoring, or current and voltage signatures may be applied. During refueling outages, end-to-end operational checks and functional testing results are compared to previous baseline measurements. Any change from the baseline should be checked out for cause to determine if it is degradation due to aging.

Because equipment starts aging from the day it is manufactured, control of aging begins at that time through the management process. The management of the equipment in all phases of its life cycle includes attention to shipping and conditions of storage prior to installation. After installation, the management of the aging process is through inspection, surveillance, and monitoring with both preventive and corrective maintenance.

## Aging Assessment Summary

The aging assessment of the HPIS involves a number of factors including stressors, degradation mechanisms, and failure modes. A summary of these various factors in the aging process along with the inservice inspection methods is given in Table 15.

Stressors acting on the various components contribute to the aging process. Stressors associated with maintenance, operation, and testing include inadvertent HPIS actuation, water hammer, and thermal cycling. Environmental stresses include abnormal temperatures or pressures, incorrect water chemistry, boric acid crystals, and vibration. Electrical stresses include external environment of temperature, humidity and limited radiation, abnormal voltages, and electrical transients affecting I&C. Mechanical stresses include pipe misalignment, vibration, and dynamic loading from valves closing.

Degradation mechanisms for the HPIS passive components (piping, thermal sleeves, and nozzles) include fatigue, crack initiation and propagation, and thermal embrittlement. Valves are subjected to wear, foreign material, mechanical linkage problems, and seat or disk degradation. Motor operators have wear and loose connections as they age. Air-operated valves main degradation mechanism is due to contaminated air supply this contamination is moisture or oil in the air. For I&C, the degradation mechanisms are loose connections, corrosion of terminals, and catastrophic component failures. Pumps degrade through wear, vibration, and fatigue.

The potential failure modes for the HPIS valves and pumps are failure to operate when needed; inadvertent operation when not called for; and during operation, a failure to operate as required. Secondary modes would include leaks, blockage, or command faults. Piping and other passive components have failure modes of leaks, cracks, or loose parts. For I&C, the failure modes are opens, shorts, or failure to operate.

The inservice inspection methods for the HPIS components include visual inspection for leaks, volumetric inspection, and operational tests.

Materials in the HPIS susceptible to aging include seals, and packing material in pumps and valves. Carbon steel materials in other systems exposed to boric acid for some period of time will corrode. Electrical components in the I&C subsystem are subject to degradation of insulation, corrosion, and wear failures. The stainless steel piping ages from thermal fatigue and wear. Material wear in pumps, valves, and relay contacts is a normal aging process.

**Table 15. Summary of aging processes for HPIS**

| Major Component | Stressors | Degradation Mechanisms | Potential Failure Modes | ISI Methods |
|---|---|---|---|---|
| Nozzles and thermal sleeves | System operating transients, thermal cycling, vibration, water (hammer) | Fatigue crack initiation and propagation | Leaks through wall, loose parts | Visual inspection volumetric inspection |
| Valves | System operation transients, maintenance, and testing | Wear, foreign material, mechanical linkage faults | Leakage, fail to operate, blockage, command faults | Visual and operation tests |
| Air-operated valves | Contaminate air supply | Parts degradation by oil in air supply | Fail to operate | Visual and operational tests |
| I&C | Electrical transients, temperature maintenance, vibration | Corrosion, loose connections, failure (catastrophic) | Open, shorts, fail to operate | Testing |
| Pumps | Systems operating transients, thermal cycles | Wear, vibration, fatigue | Seal leaks, fail to start, fail to run | Testing, visual inspection |
| Pipe supports | Vibration, water hammer | Fatigue, loosening of connections | Breaking loose | Visual inspection |
| Piping | Vibration, water hammer, thermal cycles | Thermal fatigue abrasive wear | Through the wall leakage, or cracks | Visual inspection volumetric inspections |
| Motor operators for valves | Electrical transients, maintenance | Loose connections, wear | Fail to operate | Testing |

# REVIEW OF INSPECTION, SURVEILLANCE, AND TESTING

For the representative plant studied, the operability requirements of the HPIS are governed by the Standard Technical Specification. These specifications require that at least two HPI pumps be operable when the reactor is critical, and that two trains of the HPIS must be able to draw suction from the BWST and discharge to the RCS automatically upon ES actuation at power levels up to 60% full power. In addition, the remaining HPI pump and valves HP-409 and HP-410 must be operable and valves HP-99 and HP-100 must be open when the reactor is above 60% full power. Test or maintenance on any component is permitted provided that operability of the redundant component in the other train is demonstrated first, and subject to the following conditions:

1. If reactor power is less than 60%, the HPIS must be restored to the appropriate status identified above within 24-hours, or placed in hot shutdown within an additional 12 hours. If the HPIS cannot be restored within the following 24 hours, the reactor must be taken to cold shutdown within an additional 24-hour period.
2. If the power level is greater than 60%, the inoperable component must be restored within 72 hours, or power must be reduced to below 60% in another 12 hours.

The surveillance requirements in the Technical Specifications[14] and Section XI of the ASME Boiler and Pressure Vessel Code[15] comprise the testing requirements for the HPIS. Technical Specifications 4.5.1.1.1 requires that during each refueling outage the HPIS be tested to demonstrate that it responds correctly to an actuation signal. Individual components are required to be tested more frequently, as defined in Table 16.

Section XI of the ASME defines the inservice testing used by the plants. Pumps are tested quarterly unless a relief request is granted. For these tests, vibration, differential pressure, and flow are measured. Bearing temperatures are also measured but on a less frequent schedule. Vibration is an excellent indicator of pump degradation and is a good monitor for pump aging. Periodic measurements of the electrical characteristics of the motor are not required by Section XI. A check at one plant indicated that monitoring is not done. Pump vibration and performance are not sensitive measurements for electrical insulation and other motor electrical degradation. Electrical characteristic measurements would be required to detect such aging.

Valves are tested quarterly unless a relief request has been granted. For these tests, stroke time is measured, usually without differential pressure. The measurements are often made crudely using a stop watch. Such tests would not be effective as a monitor for aging. Periodic measurement of the electrical characteristic for motor operators is not required by Section XI. For resolution of IE Bulletin 85-03, most plants are using diagnostic equipment to verify torque switch setting. Although the use of this equipment often includes electrical measurements of the operator, the tests are usually only done once for verification and rarely repeated. For valve testing to be a useful monitor for aging, more accurate measurements of stroke time and periodic measurement of electrical characteristics of the motor operator will be needed.

Section XI also defines the inservice inspection for welds. Welds are to be inspected volumetrically each 10 years. The cracks in the HPI nozzles and elbows were detected by leaks, not by the ultrasonic inspection of the inservice inspection program. The ultrasonic techniques specified by Section XI were found to be inadequate to detect cracks resulting from thermal fatigue. The instrument gain had to be increased significantly and the 45-degree transducer had to be supplemented by a 60-degree shear wave transducer in order to detect the cracks. Also, one crack developed in the base metal of the elbow. Section XI only requires inspection of welds. Inspection of high-stress areas of base metal may be needed. See IE notices No. 88-01 and 88-02.[16,17]

Periodic testing standards are given in Part 3 of Table E-5 in Appendix E. The high pressure injection system will also be inspected periodically during normal operation for leaks from pump seals, valve packing, and flanged joints. Additional items inspected include heat exchangers and safety valves for leaks to atmosphere. Typical performance tests are given in Table 17.

The following specific performance tests are performed at the representative plant studied:

1. *High pressure injection valve verification—* Provides verification that each valve is in its correct position
2. *High pressure injection system leakage—* Periodically tests the High Pressure Injection System outside containment for leakage

**Table 16. Test frequency for HPIS components[a]**

| Component | Type of Test | Frequency |
|---|---|---|
| HPI pump 3A | Start, stop, and operating parameters | Monthly |
| HPI pump 3B | Start, stop, and operating parameters | Monthly |
| HPI pump 3C | Start, stop, and operating parameters | Monthly |
| MOV 3HP-3 | Stroke and leak | Quarterly |
| MOV 3HP-4 | Stroke and leak | Quarterly |
| MOV 3HP-5 | Stroke and leak | Cold SD |
| AOV 3HP-16 | Stroke | Quarterly |
| MOV 3HP-20 | Stroke and leak | Cold SD |
| AOV 3HP-21 | Stroke and leak | Cold SD |
| MOV 3HP-24 | Stroke | Quarterly |
| MOV 3HP-25 | Stroke | Quarterly |
| MOV 3HP-26 | Stroke and leak | Quarterly |
| MOV 3HP-27 | Stroke and leak | Quarterly |
| CV 3HP-101 | Check valve function and leak | Refueling SD |
| CV 3HP-102 | Check valve function and leak | Refueling SD |
| CV 3HP-105 | Check valve function and leak | Refueling SD |
| CV 3HP-109 | Check valve function and leak | Refueling SD |
| CV 3HP-113 | Check valve function and leak | Refueling SD |
| CV 3HP-126 | Check valve function and leak | Refueling SD |
| CV 3HP-127 | Check valve function and leak | Refueling SD |
| CV 3HP-152 | Check valve function and leak | Refueling SD |
| CV 3HP-153 | Check valve function and leak | Cold SD |
| CV 3HP-188 | Check valve function and leak | Refueling SD |
| CV-3HP-194 | Check valve function and leak | Cold SD |
| MOV 3CC-7 | Stroke and leak | Cold SD |
| AOV 3CC-8 | Stroke and leak | Cold SD |
| CV 3CC-20 | Check valve function and leak | Refueling SD |
| CV 3CC-24 | Check valve function and leak | Refueling SD |

a. Abbreviations: AOV, air-operated valve, SD, shutdown, CV, check valve.

**Table 17. HPIS performance testing**

| | |
|---|---|
| High pressure injection pumps | One of two pumps operates continuously. The other pump will be operated periodically |
| High pressure injection line valves | The remotely operated stop valves in each line are opened partially one at a time. The flow monitors will indicate flow through the lines |
| High pressure injection pump suction valves | The valves are opened and closed individually and console lights monitored to indicate valve position |
| Borated water storage tank outlet valves | The operational readiness of these valves is established in completing the pump operational test discussed above. During this test, each valve is tested separately |

3. *High pressure injection system performance test*—Demonstrates the operability of the HPI pumps in accordance with applicable ASME code and identifies potential problem areas as early as possible.
4. *High pressure injection system ES Test*—Demonstrates the HPI System is operable from an ES signal.
5. *High pressure injection pump venting*—Periodically vents the casings of nonoperating HP pumps to prevent gas buildups
6. *High pressure injection motor coolant flow test*—Periodically tests the cooling water flow through the HP pump motors to ensure adequate upper motor bearing cooling
7. *High pressure injection check valve functional test*—Demonstrates the operability of the HP System check valves.

Additional inspections for leaks, as well as functional tests may be performed periodically on major components if required by the utility. For example, after maintenance, functional tests may be necessary to verify operation. Monitoring consists of comparing the performance of similar channels and visual inspections for leaks in piping valves and pumps. Current maintenance practices by utilities follow recommendations by vendors for major components, such as valves and pumps. The Babcock & Wilcox plants that have experienced nozzle cracking have also indicated enhanced inspection and surveillance of the nozzle and associated piping welds.

Some utilities have used advanced I&C cable testing during refueling outages to establish baselines and obtain trending data on electrical equipment. One such system used primarily for cable and connection testing is the ECCAD system.[18] Another advanced surveillance system is the motor operated valve analysis and test system (MOVATS).[3] Since 1984, MOVATS has been used as a diagnostic tool for motor operated valves.

# ROLE OF MAINTENANCE IN COUNTERACTING AGING EFFECTS

## Present Regulations and Guidance

The current USNRC regulation approach to nuclear plant maintenance is embodied in requirements for quality assurance during design, construction, and operations consistent with the safety (10 CFR 50, Appendix B) and surveillance requirements that ensure necessary availability, and quality of systems and components is maintained (10 CFR 50.36). These rules and regulations provide no clear programmatic treatment of nuclear plant maintenance. Regulatory Guide 1.33, Revision 2[19] endorses ANSI N18.7-1976/ANS 3.2[20], which provides no specific guidance regarding maintenance, but covers administrative controls and quality assurance for the operational phase of nuclear power plants.

## Current Maintenance Practices

The representative plant studied follows manufacturer's recommendations for preventive maintenance on major components and plant specific procedures. For example, preventive maintenance on HPI pumps and system valves includes the following:

1. *High pressure injection pump*—In order to determine internal wear of the pump, periodic efficiency tests shall be performed. This efficiency shall be used as a comparison to initial efficiency.
2. *System valves*—Maintenance on remotely operated valves shall be in accordance with the vendor's recommendations. Manual valve maintenance shall include checking for packing leakage when the system is under pressure. Safety relief valve tests shall consist of in-place or bench testing of setpoints as appropriate.

Corrective maintenance is also minimized by observing good operating practices and precautions. For example, the following limits and precautions shall be followed to prevent component damage and abnormal aging.

**Normal Operation Precautions.** Prior to starting the high pressure injection pumps, particular attention must be given to the opening of all valves in the suction line and to proper venting of the pumps. Failure of suction could result in instant loss of the started pump. The minimum allowable flow of a pump is 30 gpm.

The HP pump can be started against shutoff head, but operation of the pump in this condition for over 30 seconds could cause the pump to overheat. The HP pump must be tripped if the motor bearing temperature exceeds 215°F.

The HP pumps must not be started with an open flow path to the RC pump seals. Injection seal flow is required to all RC pumps when the RC pressure and temperature are above 100 psig and 190°F.

The maximum flow through one letdown cooler shall not exceed 80 gpm. The maximum seal return temperature should not exceed 130°F to avoid damaging the demineralizer resins.

The maximum flow through one makeup filter shall not exceed 150 gpm. A maximum pressure drop of 30 psi should not be exceeded at any flow rate.

**High Pressure Injection Mode Precautions.** The same precautions apply during high pressure injection in regard to suction and discharge flow of the HP pumps as under normal operating conditions. The possibility of pump runout due to a line break on the discharge side must be considered. The maximum flow of 525 gpm must not be exceeded for any length of time because overheating of the motor may occur.

## Benefit of Preventive and Corrective Maintenance

Preventive maintenance should be performed on the basis of need because the adoption of arbitrary and frequent maintenance can be counter to safety. Preventive maintenance should be supported by technical evidence and reviewed periodically. The benefits from preventive maintenance include higher system availability, increased life, and higher reliability.

Corrective maintenance is usually performed on a priority basis and closely coordinated with testing. After corrective maintenance, the channel or system is usually tested to verify that it is functionally correct. Likewise, a component or system that fails a test will probably require adjustment or corrective maintenance. Thus, corrective maintenance is a necessary part of plant operations and keeps the HPIS functioning properly.

## Improper Maintenance

Excessive preventive maintenance can have a negative impact on safety and aging. Thirty-five percent of nuclear plant abnormal occurrences may be due to faulty maintenance and surveillance testing.[21] Human error during maintenance has involved the wrong unit or train and may increase the potential for equipment damage. In order for a preventive maintenance program to be effective it must apply to both equipment with detectable degradation effects, and methods of detecting degradation before failure. Only about 25% of equipment failures are preventable.[22] Examples of faulty maintenance include sticking control breakers because of lack of lubrication, maintenance on wrong train or component, and personnel errors.

## Recommendations for Preferred Maintenance Practices

For the HPIS, the preferred maintenance recommendation would be the maintenance practice recommended by the vendors for major components such as pumps and valves. In addition, an enhanced inspection program for leaks and cracks in piping and nozzles would be coordinated with corrective maintenance. A maintenance program takes into account many factors including safety, operations, economics, and availability. The interval for equipment maintenance frequency should take into account potential impending failures, their detection, and known equipment wearout regions. Reliability centered maintenance has been used in the aircraft industry and is being considered in some nuclear plants. When properly applied, reliability centered maintenance should enhance plant safety and reduce life cycle costs.

# CODES AND STANDARDS

Determining aging effects on equipment and life extension is a key part of the NPAR program. One of the outputs of the NPAR program is to recommend upgrades for old standards or recommend development of new ones. Electrical equipment issues relating to HPI equipment qualification and aging are addressed by the following documents.

NUREG 0588[23] requires that qualification programs for electrical equipment should identify materials susceptible to aging effects and establish a schedule for periodically replacing the equipment and material.

IEEE 323-1983,[24] the industry standard upon which the above requirements are based, includes a number of paragraphs addressing this issue. For example, Paragraph 6.4.2 on *Operating History* states that, in order to use operating history information for establishing qualification, a record or auditable data showing that equipment similar to that being qualified has been exposed to levels of environment at least as severe as those expected from all service conditions for which the equipment being qualified is required to function and that the equipment satisfactorily performed the functions required for the equipment being qualified. Those elements of required exposure not covered by operating history may be accounted for by testing.

Regulatory Guide 1.89[25] provides the guidelines for meeting the Equipment Qualification Rule and endorses IEEE 323-1974.

Data from naturally aged components or in-situ measurements should be used to verify, where possible, data from artificial aging of components used during equipment qualification.

The Standard Review Plan,[26] Section 3.11, "Environmental Qualification of Mechanical and Electrical Equipment," which provides guidance for USNRC staff in reviewing FSARs, includes requirements for maintenance/surveillance programs for equipment located in mild environments. Specifically, it is required that "the maintenance/surveillance program data shall be reviewed periodically (not more than every 18 months) to ensure that the design qualified life has not suffered thermal or cyclic degradation resulting from the accumulated stresses triggered by the abnormal environmental conditions and the normal wear due to its service condition. Engineering judgment shall be used to modify the replacement program and/or replace the equipment as deemed necessary." This SRP guideline should be considered for possible application in any new maintenance standard or guide for maintenance.

The HPIS regulatory requirements and guidelines are given in Appendix E.

The Board of Nuclear Codes and Standards has overall responsibility for codes and standards development covering nuclear plant life extension. The IEEE working group 3.4 is presently reviewing selected IEEE standards related to plant life extension and plans to develop a guideline document. The mechanical components are covered by ASME code including Sections III-C, VIII, and XI. The process of developing recommendations for requirements similar to the electrical equipment is an ongoing process as part of the NPAR program.

# HPIS AGING SYSTEM UNAVAILABILITY ASSESSMENT

The main objective of this unavailability assessment is to identify the components that contribute to HPIS unavailability, and determine if they change with time because of aging. Another objective is to determine the aging contribution to the HPIS unavailability for the three emergency modes of operation. These three operating modes are: (a) high-pressure injection with one of three HPI pumps [HPI(1) and HPI(2)] required, (b) high-pressure injection with two of three HPI pumps required and (c) the recirculation mode. A third objective is to identify the type of events that contribute to HPIS unavailability.

This aging assessment is based on the linear aging model[27] and uses data from the Probabilistic Risk Assessment (PRA)[28] for the representative plant studied and generic failure cause data on HPIS components from a composite of nine PWR plants that were at least 10 years old. This approach is an approximate method that uses PRA results (steady state models) to evaluate aging risk. The PRA results provided the system fault trees and baseline data for this study. The failure cause data is used to estimate the time dependent failure rates and the PRA is rerun at discrete times to provide the aging assessment. The software tool used for this work was the Integrated Reliability and Risk Analysis System (IRRAS).[29]

## PRA and Basic Event Data

The PRA for the representative plant used in this study, had been developed as part of a program to improve the PRA capability of the electric utility industry. This PRA was used for training personnel from seven utilities during the course of its development. The PRA results were also used as input to Living Schedules for plant modifications and to the Integrated Safety Assessment Program.

The results of the PRA showed that the system risk is dependant on support systems and events internal to the HPIS. Only the internal events were considered in this study.

The internal events included HPIS component failures, human errors in leaving components unavailable, and having a system's segment out for maintenance. The basic event data from the PRA for the hardware, human errors and maintenance are given in Appendix I. The basic event data were used to run the baseline calculations assumed to be for a plant with random nonaging failures.

## Failure Cause Data

The failure cause work[30] was used to evaluate the aging fraction (f) and the mean time to failure (T) for each of the major HPIS components. Although, Reference 30 does not report the specific data used in this evaluation, the files developed from the NPRDS data base as part of that work were accessed to obtain the information.

The upper and lower bounds were developed in Reference 30 to account for the uncertainty encountered in accurate identification of aging-related causes on the basis of the component failure descriptions. The categorization scheme defined when a failure should be classified as related to aging or nonaging. When insufficient information was contained in the failure description, the aging classification was unknown. These failures were then used to establish the upper and lower bounds for the aging-related failure-cause fractions. The upper bounds (UP) were calculated using the failures classified as unknown as aging-related failures, while the lower bounds (LW) are calculated using them as nonaging-related failures. Upper and lower bounds were developed for the data used in this report by the same method. The upper and lower bounds for f and T are included in the data shown in Table 18.

In Table 18, the first three to five letters and numbers identify the system and component numbers. The last three letters in the event name describe the following event codes:

| | |
|---|---|
| CVO | check valve fails to open |
| MVO | motor-operated valve fails to open |
| VVT | manual valve fails to open |
| PPS | pump fails to start |
| PPR | pump fails to run |
| AVO | air-operated valve fails to open |
| RVF | pump fails to start on low seal flow |
| FTT | flow transmitter fails high. |

## Methodology

The random nonaging failure rates from the PRA were used for the first five-year period. Aging data taken from the failure cause study were used to calculate a new failure rate for subsequent five-year periods. When the constant rate contributions are incorporated, the time dependent failure rate using the linear model is given by the equation:

## Table 18. HPIS data for the risk assessment, aging acceleration factors, and component unavailabilities in 5-year increments for upper and lower bounds

| | Aging Failure | Failure Fraction | | Mean Time To Failure (Years) | | Mission Time (Years) | Failure Rate Per Year | Aging Acceleration Factor | | Component Unavailability | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event Name | Data Used | FUP | FLW | TUP | TLW | M.T. | F.R. | AUP | ALW | P(5) | P(10)UP | P(10)LW | P(15)UP | P(15)LW | P(20)UP | P(20)LW | P(25)UP | P(25)LW | P(30)UP | P(30)LW | P(35)UP | P(35)LW | P(40)UP | P(40)LW |
| HP101CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 1.7E-04 | 3.0E-04 | 4.5E-05 | 8.7E-05 | 9.1E-05 | 8.8E-05 | 9.5E-05 | 8.8E-05 | 9.9E-05 | 8.9E-05 | 1.0E-04 | 8.9E-05 | 1.1E-04 | 9.0E-05 | 1.1E-04 | 9.1E095 | 1.2E-04 | 9.1E-05 |
| HP102CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 1.7E-04 | 3.0E-04 | 4.5E-05 | 8.7E-05 | 9.1E-05 | 8.8E-05 | 9.5E-05 | 8.8E-05 | 9.9E-05 | 8.9E-05 | 1.0E-04 | 8.9E-05 | 1.1E-04 | 9.0E-05 | 1.1E-04 | 9.1E095 | 1.2E-04 | 9.1E-05 |
| HP109CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 2.2E-03 | 3.8E-03 | 5.8E-04 | 8.7E-05 | 1.4E-04 | 9.5E-05 | 1.9E-04 | 1.0E-04 | 2.4E-04 | 1.1E-04 | 2.9E-04 | 1.2E-04 | 3.5E-04 | 1.3E-04 | 4.0E-04 | 1.3E-04 | 4.5E-04 | 1.4E-04 |
| HP113CVO | HPI CV | -0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 2.2E-03 | 3.8E-03 | 5.8E-04 | 8.7E-05 | 1.4E-04 | 9.5E-05 | 1.9E-04 | 1.0E-04 | 2.4E-04 | 1.1E-04 | 2.9E-04 | 1.2E-04 | 3.5E-04 | 1.3E-04 | 4.0E-04 | 1.3E-04 | 4.5E-04 | 1.4E-04 |
| HP152CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 2.0E-04 | 3.5E-04 | 5.3E-05 | 9.8E-05 | 1.0E-04 | 9.9E-05 | 1.1E-04 | 9.9E-05 | 1.1E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 |
| HP153CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 2.0E-04 | 3.5E-04 | 5.3E-05 | 9.8E-05 | 1.0E-04 | 9.9E-05 | 1.1E-04 | 9.9E-05 | 1.1E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 |
| HP188CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 2.0E-04 | 3.5E-04 | 5.3E-05 | 9.8E-05 | 1.0E-04 | 9.9E-05 | 1.1E-04 | 9.9E-05 | 1.1E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 |
| LP55CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 2.0E-04 | 3.5E-04 | 5.3E-05 | 9.8E-05 | 1.0E-04 | 9.9E-05 | 1.1E-04 | 9.9E-05 | 1.1E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 |
| LP57CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 2.0E-04 | 3.5E-04 | 5.3E-05 | 9.8E-05 | 1.0E-04 | 9.9E-05 | 1.1E-04 | 9.9E-05 | 1.1E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.2E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 | 1.3E-04 | 1.0E-04 |
| HP148VVT | HPI HCV | 0.83 | 0.61 | 8.20 | 8.82 | 1.0E-00 | 7.8E-04 | 6.2E-04 | 1.8E-04 | 3.9E-04 | 3.5E-03 | 1.3E-03 | 6.6E-03 | 2.2E-03 | 9.7E-03 | 3.2E-03 | 1.3E-02 | 4.1E-03 | 1.6E-02 | 5.0E-03 | 1.9E-02 | 5.9E-03 | 2.2E-02 | 5.8E-03 |
| LP54VVT | HPI HCV | 0.83 | 0.61 | 8.20 | 8.82 | 1.0E-00 | 7.8E-04 | 6.2E-04 | 1.8E-04 | 3.9E-04 | 3.5E-03 | 1.3E-03 | 6.6E-03 | 2.2E-03 | 9.7E-03 | 3.2E-03 | 1.3E-02 | 4.1E-03 | 1.6E-02 | 5.0E-03 | 1.9E-02 | 5.9E-03 | 2.2E-02 | 5.8E-03 |
| LP56VVT | HPI HCV | 0.83 | 0.61 | 8.20 | 8.82 | 1.0E-00 | 7.8E-04 | 6.2E-04 | 1.8E-04 | 3.9E-04 | 3.5E-03 | 1.3E-03 | 6.6E-03 | 2.2E-03 | 9.7E-03 | 3.2E-03 | 1.3E-02 | 4.1E-03 | 1.6E-02 | 5.0E-03 | 1.9E-02 | 5.9E-03 | 2.2E-02 | 5.8E-03 |
| HP24MVO | HPI MOV | 0.84 | 0.49 | 8.01 | 8.41 | 2.7E-03 | 4.9E-04 | 4.3E-02 | 7.5E-03 | 6.4E-03 | 7.0E-03 | 6.5E-03 | 7.6E-03 | 6.6E-03 | 8.1E-03 | 6.7E-03 | 8.7E-03 | 6.8E-03 | 9.3E-03 | 6.9E-03 | 9.9E-03 | 7.0E-03 | 1.0E-02 | 7.1E-03 |
| HP25MVO | HPI HCV | 0.84 | 0.49 | 8.01 | 8.41 | 2.7E-03 | 4.9E-04 | 4.3E-02 | 7.5E-03 | 6.4E-03 | 7.0E-03 | 6.5E-03 | 7.6E-03 | 6.6E-03 | 8.1E-03 | 6.7E-03 | 8.7E-03 | 6.8E-03 | 9.3E-03 | 6.9E-03 | 9.9E-03 | 7.0E-03 | 1.0E-02 | 7.1E-03 |
| HP26MVO | HPI HCV | 0.84 | 0.49 | 8.01 | 8.41 | 2.7E-03 | 4.9E-04 | 4.3E-02 | 7.5E-03 | 6.4E-03 | 7.0E-03 | 6.5E-03 | 7.6E-03 | 6.6E-03 | 8.1E-03 | 6.7E-03 | 8.7E-03 | 6.8E-03 | 9.3E-03 | 6.9E-03 | 9.9E-03 | 7.0E-03 | 1.0E-02 | 7.1E-03 |
| HP409MVO | HPI HCV | 0.84 | 0.49 | 8.01 | 8.41 | 2.7E-03 | 4.9E-04 | 4.3E-02 | 7.5E-03 | 6.4E-03 | 7.0E-03 | 6.5E-03 | 7.6E-03 | 6.6E-03 | 8.1E-03 | 6.7E-03 | 8.7E-03 | 6.8E-03 | 9.3E-03 | 6.9E-03 | 9.9E-03 | 7.0E-03 | 1.0E-02 | 7.1E-03 |
| HP410MVO | HPI HCV | 0.84 | 0.49 | 8.01 | 8.41 | 2.7E-03 | 4.9E-04 | 4.3E-02 | 7.5E-03 | 6.4E-03 | 7.0E-03 | 6.5E-03 | 7.6E-03 | 6.6E-03 | 8.1E-03 | 6.7E-03 | 8.7E-03 | 6.8E-03 | 9.3E-03 | 6.9E-03 | 9.9E-03 | 7.0E-03 | 1.0E-02 | 7.1E-03 |
| HPBPPS | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 2.1E-02 | 2.0E-02 | 5.5E-03 | 8.4E-04 | 1.1E-03 | 9.1E-04 | 1.4E-03 | 9.9E-04 | 1.5E-03 | 1.1E-03 | 1.9E-03 | 1.1E-03 | 2.2E-03 | 1.2E-03 | 2.4E-03 | 1.3E-03 | 2.7E-03 | 1.4E-03 |
| HPCPPS | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 2.1E-02 | 2.0E-02 | 5.5E-03 | 8.4E-04 | 1.1E-03 | 9.1E-04 | 1.4E-03 | 9.9E-04 | 1.5E-03 | 1.1E-03 | 1.9E-03 | 1.1E-03 | 2.2E-03 | 1.2E-03 | 2.4E-03 | 1.3E-03 | 2.7E-03 | 1.4E-03 |
| HPAPPR | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 7.4E-02 | 7.0E-02 | 1.9E-02 | 2.0E-04 | 1.1E-03 | 4.6E-04 | 2.1E-03 | 7.3E-04 | 3.0E-03 | 9.9E-04 | 4.0E-03 | 1.3E-03 | 4.9E-03 | 1.5E-03 | 5.9E-03 | 1.8E-03 | 6.8E-03 | 2.0E-03 |
| HPRAPPR | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 7.4E-01 | 7.0E-01 | 1.9E-01 | 2.0E-03 | 1.1E-02 | 4.6E-03 | 2.1E-02 | 7.3E-03 | 3.0E-02 | 9.9E-03 | 4.0E-02 | 1.3E-02 | 4.9E-02 | 1.5E-02 | 5.9E-02 | 1.8E-02 | 6.8E-02 | 2.0E-02 |
| HPBPPR | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 7.4E-02 | 7.0E-02 | 1.9E-02 | 2.0E-04 | 1.1E-03 | 4.6E-04 | 2.1E-03 | 7.3E-04 | 3.0E-03 | 9.9E-04 | 4.0E-03 | 1.3E-03 | 4.9E-03 | 1.5E-03 | 5.9E-03 | 1,8E-03 | 6.8E-03 | 2.0E-03 |
| HPRBPPR | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 7.4E-01 | 7.0E-01 | 1.9E-01 | 2.0E-03 | 1.1E-02 | 4.6E-03 | 2.1E-02 | 7.3E-03 | 3.0E-02 | 9.9E-03 | 4.0E-02 | 1.3E-02 | 4.9E-02 | 1.5E-02 | 5.9E-02 | 1.8E-02 | 6.8E-02 | 2.0E-02 |
| HPCPPR | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 7.4E-02 | 7.0E-02 | 1.9E-02 | 2.0E-04 | 1.1E-03 | 4.6E-04 | 2.1E-03 | 7.3E-04 | 3.0E-03 | 9.9E-04 | 4.0E-03 | 1.3E-03 | 4.9E-03 | 1.5E-03 | 5.9E-03 | 1.8E-03 | 6.8E-03 | 2.0E-03 |
| HPRCPPR | HPI MOP | 0.86 | 0.54 | 8.66 | 9.00 | 2.7E-03 | 7.4E-01 | 7.0E-01 | 1.9E-01 | 2.0E-03 | 1.1E-02 | 4.6E-03 | 2.1E-02 | 7.3E-03 | 3.0E-02 | 9.9E-03 | 4.0E-02 | 1.3E-02 | 4.9E-02 | 1.5E-02 | 5.9E-02 | 1.8E-02 | 6.8E-02 | 2.0E-02 |
| HP15AVO | HPI POV | 0.88 | 0.56 | 12.21 | 11.12 | 2.7E-03 | 1.2E-02 | 9.6E-03 | 1.8E-03 | 1.5E-03 | 1.7E-03 | 1.6E-03 | 1.9E-03 | 1.6E-03 | 2.0E-03 | 1.7E-03 | 2.1E-03 | 1.7E-03 | 2.2E-03 | 1.7E-03 | 2.4E-03 | 1.7E-03 | 2.5E-03 | 1.8E-03 |
| HP16AVO | HPI POV | 0.88 | 0.56 | 12.21 | 11.12 | 2.7E-03 | 1.2E-02 | 9.6E-03 | 1.8E-03 | 3.5E-03 | 3.6E-03 | 3.5E-03 | 3.8E-03 | 3.5E-03 | 3.9E-03 | 3.6E-03 | 4.0E-03 | 3.6E-03 | 4.1E-03 | 3.5E-03 | 4.3E-03 | 3.6E-03 | 4.4E-03 | 3.7E-03 |
| CS55CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 6.7E-04 | 1.2E-03 | 1.8E-04 | 8.7E-05 | 1.0E-04 | 8.9E-05 | 1.2E-04 | 9.2E-05 | 1.3E-04 | 9.4E-05 | 1.5E-04 | 9.7E-05 | 1.7E-04 | 9.9E-05 | 1.8E-04 | 1.0E-04 | 2.0E-04 | 1.0E-04 |
| CS56CVO | HPI CV | 0.90 | 0.63 | 6.88 | 8.58 | 2.7E-03 | 6.7E-04 | 1.2E-03 | 1.8E-04 | 8.7E-05 | 1.0E-04 | 8.9E-05 | 1.2E-04 | 9.2E-05 | 1.3E-04 | 9.4E-05 | 1.5E-04 | 9.7E-05 | 1.7E-04 | 9.9E-05 | 1.8E-04 | 1.0E-04 | 2.0E-04 | 1.0E-04 |
| HPRCBPPS | HPI MOP | 0.85 | 0.64 | 8.66 | 9.00 | 2.7E-03 | 6.5E-03 | 61E-03 | 1.7E-03 | 8.4E-04 | 9.2E-04 | 8.6E-04 | 1.0E-03 | 8.9E-04 | 1.1E-03 | 9.1E-04 | 1.2E-03 | 9.3E-04 | 1.3E-04 | 9.6E-04 | 1.3E-03 | 9.8E-04 | 1.4E-03 | 1.0E-03 |
| HPM53RVF | HPI MOP | 0.85 | 0.64 | 8.66 | 9.00 | 2.7E-03 | 3.7E-03 | 3.5E-03 | 9.7E-04 | 4.8E-04 | 5.3E-04 | 4.9E-04 | 5.7E-04 | 5.1E-04 | 6.2E-04 | 5.2E-04 | 6.7E-04 | 5.3E-04 | 7.2E-04 | 5.5E-04 | 7.6E-04 | 5.6E-04 | 8.1E-04 | 5.7E-04 |
| HP31FTT | HPI FT | 0.92 | 0.41 | 3.98 | 4.00 | 2.7E-03 | 1.1E-02 | 4.2E-02 | 2.5E-03 | 3.1E-05 | 6.0E-04 | 6.5E-05 | 1.2E-03 | 1.0E-04 | 1.7E-03 | 1.3E-04 | 2.3E-03 | 1.7E-04 | 2.9E-03 | 2.0E-04 | 3.5E-03 | 2.4E-04 | 4.0E-03 | 2.7E-04 |

$$\lambda_{(t)} = \lambda_o + at \quad (1)$$

where

| | | |
|---|---|---|
| $\lambda_{(t)}$ | = | time-dependent failure rate |
| $\lambda_o$ | = | random-only failure rate |
| a | = | aging failure acceleration parameter |
| t | = | time. |

The equation for aging acceleration parameter a based on the moments considerations from Reference 25 is

$$a = \left[\frac{4}{3}\left(\frac{f}{1 - f}\right)\left(\frac{\bar{\lambda}}{T}\right)\right] \quad (2)$$

where

| | | |
|---|---|---|
| $\frac{4}{3}$ | = | constant from the deviation |
| f | = | nonrandom fraction of failures of the component which are caused by aging mechanisms |
| T | = | average time to failure |
| $\lambda$ | = | mean failure rate. |

The time values shown in Table 18 are in years. The data that was in terms of hours was converted to years by using 8760 hours per year.

*Sample Calculation for (2)*

The event chosen for this example is the high pressure pump A fails to run (HPAPPR). The basic events are identified in Table I-1 of Appendix I.

The aging failure acceleration parameter is

| | | |
|---|---|---|
| $f_{up}$ | = | 0.86 |
| $T_{up}$ | = | 8.66 y |
| $\bar{\lambda}$ | = | $7.36 \times 10^{-2}$ y$^{-1}$ |

$$a_{up} = \frac{4}{3}\left[\left(\frac{0.86}{1 - 0.86}\right)\left(\frac{1}{8.66}\right)\right]7.36 \times 10^{-2}$$
$$= 6.961 \times 10^{-2}\ y^{-2}.$$

The computer calculations rounded off to $7.0 \times 10^{-2}\ y^{-2}$.

The calculations for probability of failure were then performed for 5-year increments of time using the following general equation

$$P_n = P_{n-1} + [(\Delta T)(a\tau)] \quad (3)$$

where

| | | |
|---|---|---|
| $P_n$ | = | new probability for the new 5-year increase |
| $P_{n-1}$ | = | probability for the previous 5-year increment |
| $\Delta T$ | = | five years |
| t | = | twenty-four hours (mission time) |
| a | = | acceleration parameter. |

*Example Calculations for $P_n$*
*Event HPAPPR*

| | | |
|---|---|---|
| $a_{up}$ | = | $7.0 \times 10^{-2}$ |
| $P_{n-1}$ | = | $P_5 = 2.0 \times 10^{-4}$ |
| $\Delta T$ | = | 5 years |
| $\tau$ | = | 24 hours = $2.7 \times 10^{-3}$ years |
| $P_{10\,up}$ | = | $2.0 \times 10^{-4} + [(5)(7.0 \times 10^{-2})(2.7 \times 10^{-3})]$ |
| | = | $1.145 \times 10^{-3}$. |

The computer calculations rounded off to $1.1 \times 10^{-3}$.

The probabilities identified under the P heading in Table 18 were calculated for each component event and for each 5-year increment. The base case [P(5)] values were taken directly from the PRA data. Each column of data was then used as input to the IRRAS program for the calculations that represent the time period for that column. Also shown in Table 18 are mission time, failure rate, calculated values for the aging failure acceleration parameters (both upper and lower bounds), and the component unavailabilities for each 5-year period up to 40 years. These were the basic data and intermediate calculated results for this aging risk evaluation.

The IRRAS software program was developed at the INEL to run on a personal computer. Version 2.0 was used for this analysis. The fault trees for the three cases modeled were loaded into the personal computer and the IRRAS program run to determine the cut-sets for the significant sequences. A minimal cut-set is defined as the smallest combination of component failures, which if they all occur, will cause the top event of the fault tree to occur.

The outputs that were selected from the IRRAS program were the minimum cut-set upper bound (which is the HPIS unavailability) and the Fussell-Vesely (F-V) importance measure. The F-V importance measure is a measure of contribution of the event to the system unavailability. A F-V importance value of 0.01 or greater was considered significant.

The Fussell-Vesely importance is determined by evaluating the sequence frequency with the basic event failure probability at its true value and again with the basic event failure probability set to zero. The difference between these two results is divided by the true minimal cut-set upper bound to obtain the Fussell-Vesely importance. In equation form this is

$$\text{F-V} = [F(x) - F(O)]/F(x) \qquad (4)$$

where

F-V = Fussell-Vesely importance

F(x) = minimal cut-set upper bound (sequence frequency) evaluated with the basic event failure probability at its true value

F(O) = minimal cut-set upper bound (sequence frequency) evaluated with the basic event failure probability set to zero.

## Assumptions

The assumptions made in performing this analysis are: (a) that all support systems such as 1E power, service water, and low pressure injection are always available; (b) that the probabilities for human error events and maintenance events remain constant for all time periods; (c) the PRA failure rates were the random failure rates and apply for the first 5-year interval at the representative plant; and (d) when not given in the PRA the mean failure rates were calculated by dividing the demand failure rate by the estimated time between demands.

In addition, the following modeling assumptions are from the PRA (Reference 28) for the three cases considered.

1. It was assumed that flow from the borated water storage tank (BWST) through either suction line (valves 3HP-24 or 3HP-25 in Figure 10) is sufficient for all three HPI pumps. The letdown storage tank (LDST), which provides HPI pump suction initially as the BWST valves open, was not assumed to be available for emergency HPI operation since makeup to the LDST is limited to less than 200 gpm. Furthermore, it was assumed that adequate NPSH to the three HPI pump exists with the LDST suction remaining open.
2. Between the discharges of pumps 3HP-P3B and 3HP-P3C there is an additional cross-connection that is not shown in Figure 10. This line contains two normally closed manual valves, and would serve only as a backup to the crossover lines containing motor-operated valves 3HP-409 and 3HP-410. Therefore, its availability was judged to have very little effect on HPIS reliability and was not modeled.
3. Each injection loop splits into two lines that provide flow to the cold legs downstream of the reactor-coolant pumps. For sequences that require flow from only one HPI pump, it was assumed that only one of the injection-line splits was needed. For sequences requiring the function of two pumps, at least two of the splits were assumed to be required.

## Components that Contribute Significantly to System Unavailability

The significant Fussell-Vesely importance measures calculated for the initial 5-year period and the 40-year period are summarized in Table 19 for each of the three operating modes. The values at 40 years

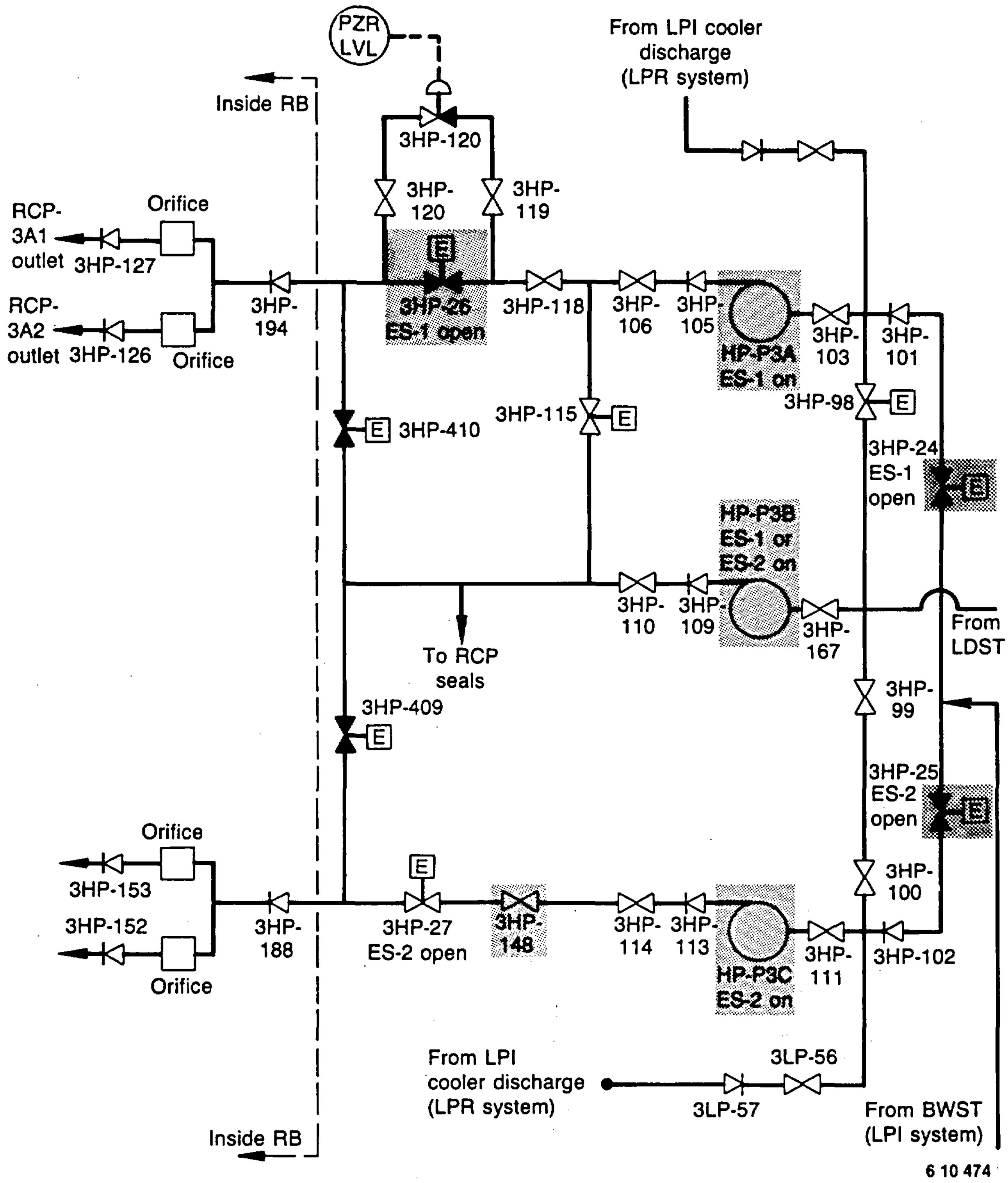



**Figure 10.** Components that contributed significantly to HPIS unavailability for emergency modes of operation.

**Table 19. Events with significant Fussell-Vesely importance measures**

| Event Name | HPI(1) 5 Year | HPI(1) 40-Year Mean | HPI(2) 5 Year | HPI(2) 40-Year Mean | Recirculation Mode 5 Year | Recirculation Mode 40-Year Mean |
|---|---|---|---|---|---|---|
| HP-24MVO | 0.4503 | 0.5673 | 0.2592 | 0.2006 | 0.1705 | 0.3352 |
| HP-25MVO | 0.4503 | 0.5673 | 0.2590 | 0.1956 | 0.1705 | 0.3352 |
| HP-26MVO | 0.0021 | 0.0163 | 0.3738 | 0.2325 | 0.3541 | 0.4848 |
| HP-CPPS | 0.0006 | 0.0021 | 0.0008 | 0.0290 | 0.0640 | 0.0223 |
| HP-148VVT | 0.0003 | 0.0149 | 0.0039 | 0.2016 | 0.0297 | 0.1054 |
| HP-CPPR | 0.0002 | 0.0046 | 0.0020 | 0.0615 | 0.0152 | 0.0318 |
| HP-APPR | <0.0001 | 0.0061 | 0.0020 | 0.0650 | — | — |
| HP-BPPR | <0.0001 | 0.0061 | 0.0055 | 0.2941 | — | — |
| HPRAPPR | — | — | — | — | 0.2166 | 0.4638 |
| HPRCPPR | — | — | — | — | 0.1524 | 0.3180 |

are the arithmetic mean of the upper and lower bound values at 40 years from the tables in Appendix I.

The motor-operated valves "failure to open" events, HP-24 MVO and HP-25 MVO, are significant for all three modes of operation for both 5 years and after 40 years aging. Event HP-26 MVO is significant for both the HPI(2) and recirculation operating modes (for both 5 and 40 years) and becomes significant for the HPI(1) operating mode after 40 years aging. All of the events listed for the recirculation mode are significant for both 5- and 40-year time periods. Event HP-148 VVT becomes significant for both HPI(1) and HPI(2) operating modes after aging 40 years. The pump events HPCPPS, HPCPPR, HPAPPR, and HPBPPR become significant after 40 years for the HPI(2) operating mode, but were not significant events at 5 years. This is an indication of the aging effect on the pumps.

The conclusions that can be drawn from the analysis of the F-V importance measure is that seven components involving 10 events were identified as contributing significantly to system unavailability for at least one operating mode and time period. The seven components are highlighted in Figure 10, and are motor-operated valves HP-24, HP-25, and HP-26; manual valve HP-148; and HPIS pumps A, B, and C.

## HPIS Unavailability

The cut set quantification reports were obtained from each run of the IRRAS program. The reports for the 5-year, 10-year, and 40-year runs are given in Appendix I. The HPIS unavailability for each operating mode modeled is given as the minimal cut-set (mincut) on the reports. These HPIS unavailabilities are summarized in Tables 20, 21, and 22 for three emergency operating modes. These tables present the mean, upper bound and lower bound for 5-year increments from 5 years to 40 years.

The HPIS mean unavailability for the three emergency operating modes are plotted in Figure 11. The one-of-three-pumps-required operating mode had an unavailability starting at 9.59E-5 at 5 years and increased to 1,353-4 at 40 years. The two-of-three-pumps-required operating mode has the highest HPIS unavailability starting at 1.720E-4 at 5 years and increased to 4.280 E-4 at 40 years. Similarly the recirculation mode

Table 20. Data for HPIS unavailability (one of three HPI pumps required)

| Year | Means | Upper Bound | Lower Bound |
|---|---|---|---|
| 5 | 9.59E – 5 | — | — |
| 10 | 1.011E – 4 | 1.048E – 4 | 9.737E – 5 |
| 15 | 1.067E – 4 | 1.146E – 4 | 9.886E – 5 |
| 20 | 1.120E – 4 | 1.235E – 4 | 1.004E – 4 |
| 25 | 1.184E – 4 | 1.348E – 4 | 1.019E – 4 |
| 30 | 1.254E – 4 | 1.472E – 4 | 1.035E – 4 |
| 35 | 1.328E – 4 | 1.604E – 4 | 1.051E – 4 |
| 40 | 1.353E – 4 | 1.639E – 4 | 1.067E – 4 |

Table 21. Data for HPIS unavailability (two of three HPI pumps required)

| Year | Means | Upper Bound | Lower Bound |
|---|---|---|---|
| 5 | 1.720E – 4 | — | — |
| 10 | 1.921E – 4 | 2.053E – 4 | 1.788E – 4 |
| 15 | 2.189E – 4 | 2.513E – 4 | 1.865E – 4 |
| 20 | 2.491E – 4 | 3.028E – 4 | 1.953E – 4 |
| 25 | 2.889E – 4 | 3.726E – 4 | 2.051E – 4 |
| 30 | 3.314E – 4 | 4.485E – 4 | 2.142E – 4 |
| 35 | 3.823E – 4 | 5.386E – 4 | 2.260E – 4 |
| 40 | 4.280E – 4 | 6.194E – 4 | 2.365E – 4 |

Table 22. Data for HPIS unavailability (recirculation mode)

| Year | Means | Upper Bound | Lower Bound |
|---|---|---|---|
| 5 | 8.401E−7 | — | — |
| 10 | 2.0E−6 | 2.716E−6 | 1.339E−6 |
| 15 | 3.5E−6 | 5.105E−6 | 1.868E−6 |
| 20 | 5.0E−6 | 7.553E−6 | 2.405E−6 |
| 25 | 6.8E−6 | 1.067E−5 | 3.029E−6 |
| 30 | 8.7E−6 | 1.394E−5 | 3.485E−6 |
| 35 | 1.1E−5 | 1.785E−5 | 4.130E−6 |
| 40 | 1.27E−5 | 2.072E−5 | 4.614 E−6 |

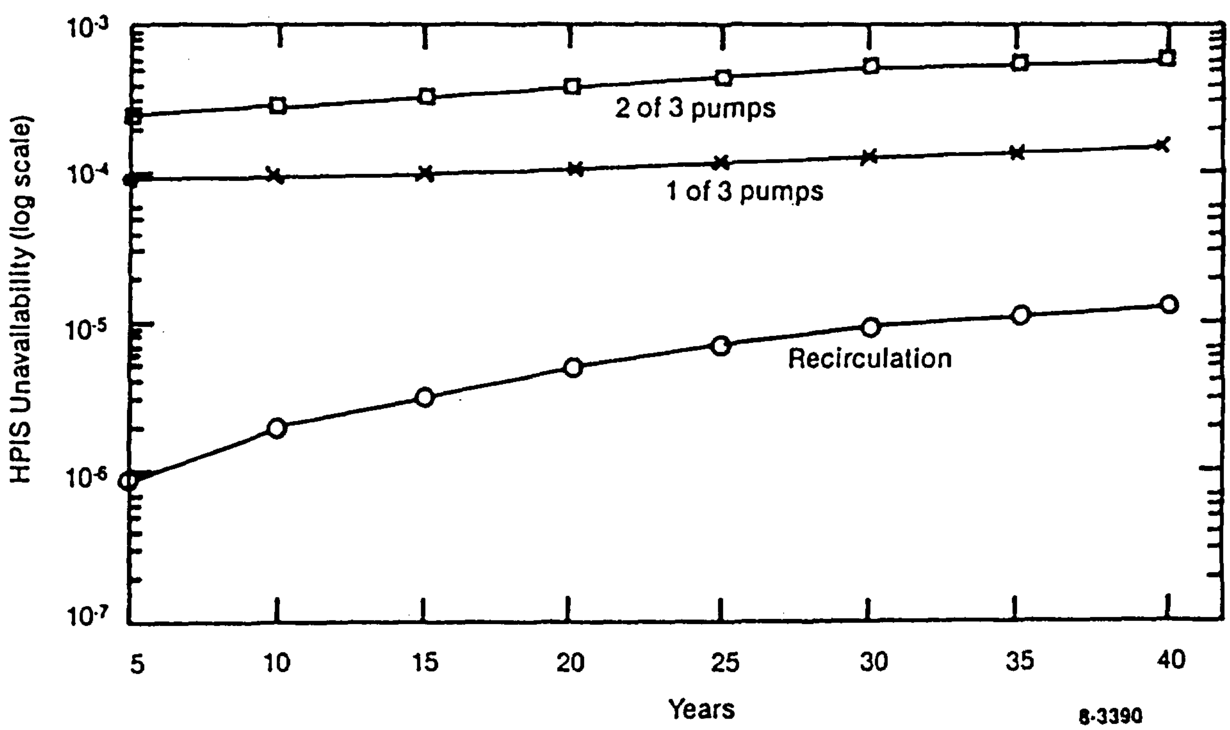



Figure 11. HPIS unavailability vs years showing the effect of aging for the three emergency operating modes.

HPIS unavailability started lower at 8.401E-7 at 5 years and increased to 1.27E-5 at 40 years. The recirculation mode had the greatest increase, but was still an order of magnitude less than the injection modes. Normally changes in unavailability at less than an order of magnitude are not important in final PRA results. Based on that assumption, the computed change for the two HPI modes would not be expected to change the results of the full plant PRA significantly. For the recirculation mode, the change is more than an order of magnitude but even with the change the unavailability remains very low. A cursory review of the representative plant PRA indicated that loss of HPI in the recirculation mode from failure of components does not appear in any of the important event sequences and, therefore, a significant change would not be expected in the full plant PRA.

## Estimate for Types of Events That Cause HPIS Unavailability

An estimate of the contribution of the types of events to the system unavailability was obtained by summing all the F-V importance values for a particular event type for a given time period and dividing by the sum of all the F-V importance values for that same time period. Because of truncation error and the possibility that some of the events may be included more than once in different cut-set combinations, this result will only be a rough estimate of the contribution of each type of event to the HPIS unavailability. The results are shown in Table 23.

As demonstrated by the values in Table 23, the motor-operated valves failure to open is the type of event with the highest probability of contributing to HPIS unavailability for the two HPIS, injection modes of operation. For these same two modes of operation the human error events have the second highest probability followed by the events associated with maintenance. The change in probabilities from 5 years to 40 years may vary either up or down depending on how the cut-sets combine. The most noteable probability increase with age was for the manual valves and pumps in the HPI (two of three pumps) mode. The manual valves probability increased from 1.4% to 21% and the HPIS pumps increased from 0.2% to 9.3%.

For the recirculation mode the maintenance events were the most significant, 41% at 5 years, but dropped to only 7.5% at 40 years. All the other events showed an increased with age between 5 years and 40 years. The motor-operated valves continued to be a contributor with 20% at 5 years and 39% at 40 years.

In general, all the component events had an increase in unavailability over the 40-year period for all three operating modes, except for motor-operated valve in the HPI (two of three pumps) mode, which decreased, and the check valves in the HPI (one of three pumps) mode, which had no change.

**Table 23. Probability for type of events causing HPIS unavailability**

| Event Type | Percent Contribution to HPIS Unavailability | | | | | |
|---|---|---|---|---|---|---|
| | HPI (1 of 3 pumps) | | HPI (2 of 3 pumps) | | Recirculation Mode | |
| | 5 yr | 40-yr Mean | 5 yr | 40-yr Mean | 5 yr | 40-yr Mean |
| Human error | 35 | 26 | 39 | 20 | 25 | 27 |
| Segment of system out of service for maintenance | 5 | 5 | 10 | 20 | 41 | 7.5 |
| Motor-operated valves failure to open | 59 | 66 | 49 | 30 | 20 | 39 |
| Check valves failure to open | 0.8 | 0.8 | 0.4 | 0.5 | 0 | 0 |
| Manual valves failure to transfer | 0.05 | 0.8 | 1.4 | 21 | 13 | 22 |
| HPIS pumps failure to run or failure to start | 0.02 | 0.7 | 0.2 | 9.3 | 0.9 | 3.9 |

# CONCLUSIONS

The conclusions for the HPIS aging research are based on a detailed study of one plant and supplemented by information from generic data bases. Experience from the generic data bases shows that the motor-operated valves were the most troublesome components. Some failures and aging mechanisms are not being detected by current inspection and surveillance methods. The study indicates that aging causes only a moderate increase in system unavailability and that motor-operated valves are the components that contribute most often to the system unavailability. Conclusions for the specific study objective are presented in the following sections.

## Operating Experience

The HPIS operating experience was evaluated by reviewing generic data bases and plant specific data. The operating experience from the NPRDS, covering B&W and Westinghouse plants, indicated that approximately 57% of the component failures lead to system degradation, but because of system redunancy, only 0.7% of HPIS component failures caused loss of system function. The data also showed that 21.3% of these failures were aging related.

The NPE data covering all PWRs were reviewed and four types of components were identified as having the highest frequency of failure. They were valves-35%, I&C-19%, pumps-15%, and piping-7%. Both NPRDS and LERS had the same relative ranking for these components. The corrective maintenance ranked I&C and piping failures higher than valve and pump failures because of many subcomponents failures that were repaired on these particular components.

The conclusion for the data base reviews is that a significant number of HPIS component failures have been aging related. The term "aging related" is used because the information given in data bases often requires further analysis to determine extent of aging contribution to the failure. The conclusions for specific problems related to aging are summerized in following sections.

## Specific Problems Related to Aging

Problems with boric acid systems have occurred. Leaks of borated water onto carbon steel caused corrosion of the carbon steel. Such corrosion can occur at a rate greater than 1 in. per year as proven by both laboratory tests and plant experience. Boric acid crystals have caused blockage and in one instance precipitated out in an HPI pump causing it to malfunction. The latter was due to an internal valve leak.

The thermal sleeve and nozzle cracking problem experienced in B&W plants in 1982 was attributed to thermal fatigue. Thermal cycling occurred when the makeup flow cycled on and off and when system injection flow occurred. The problem was corrected at the representative plant studies by redesign of the thermal sleeve and maintaining a continuous small makeup flow. An augmented inservice inspection plan was also implemented.

The HPIS interacts with many of the other reactor systems. This makes it particularly vulnerable to common mode failures when a problem in another system can prevent HPIS from performing its function. For example, HPI pump seal cooling is supplied by the service water system. The HPI itself supplies RC pump seal cooling and RC makeup water during normal operation.

IEEE 323-1974 was the industry standard used to address HPI electrical equipment qualification and makes reference to the use of historical data and the analysis of failures and trends. The design and maintenance data should be reviewed periodically (approximately 18 months) to ensure that the design qualified life has not suffered. The review should include thermal or cyclic degradation resulting from accumulated stresses triggered by abnormal environmental conditions and the normal wear due to its service condition.

Problems with the ECCS piping cracks have occurred at Farley-2 and Tihange-1. These two plants were Westinghouse plants utilizing the high pressure injection pumps for both charging during normal operation and injecting emergency core coolant during a LOCA. The pipe cracking was attributed to thermal fatigue that occurred because the failure of valves in the safety injection system allowed relatively cold water to flow back into the primary system.

The B&W system that has the dual purpose HPIS pump would potentially have the same problem. The difference in the B&W system is that it uses the same nozzle for makeup and injection.

## Aging Assessment

The aging assessment of the impact of aging on HPIS operability involves a number of factors including the identification of stressors, degradation mechanisms, and failure modes. The various potential electrical, mechanical, and environmental stressors were indentified and degradation mechanisms determined for both passive and active components. These factors were summarized in Table 15 along with the various failure modes and ISI methods.

Materials in the HPIS susceptible to aging include seals and packing material in pumps and valves. Carbon steel materials in other systems exposed to boric acid for some period of time will corrode. Electrical components in the I&C subsystem are subject to degradation of insulation, corrosion, and wear failures. The stainless steel piping ages from thermal fatigue. However, material wear in pumps, valves, and relay contacts is a normal aging process.

## Inspection, Surveillance, and Monitoring

The surveillance requirements in the technical specifications for a plant and the ASME Boiler and Pressure Code comprise the testing requirements for the HPIS. Additional inspections for leaks may be performed periodically along with functional tests on major HPIS components if required by the utility. For example, after maintenance, functional tests may be necessary to verify operation.

Included in the surveillance methods are visual inspections, operational testing, and calibrations for the HPIS as a system. Individual components may have additional tests. For example, the limitorque valve operators require periodic 18-month inspections as part of routine maintenance for cleaning and lubrication. Rotork valve operators are qualified for 40-year life or 2000 open-close cycles, therefore, no preventive maintenance program is recommended. Rotork ensures reliability by carefully sealing out the environment during installation. Routine maintenance of inner parts is deemed likely to cause defective sealing and, should be avoided. The exception is that seals and lubricants subjected to radiation and heat aging must be replaced based on the qualified life.

Some advanced methods for IS&M on mitigating IGSCC in piping developed by EPRI have included stress improvement methods, alternate materials, and improved water chemistry. Another advanced monitoring method developed by the INEL for cable monitoring is the ECCAD system. This technology has been transferred to industry and at least two operating utilities have used the system. Another advanced surveillance system is the motor-operated valve analysis and test system (MOVATS). Since 1984, the MOVATS system has been used as a diagnostic tool for motor-operated valves.

## Maintenance

Maintenance practices for major HPIS components follow vendor's recommendations closely, in addition to plant specific maintenance procedures. Corrective maintenance is minimized by observing good operating practices and precautions. The benefits of preventive maintenance include higher system availability, increased life, and higher reliability.

In general, up to 35% of nuclear plant abnormal occurrences may be due to faulty maintenance and surveillance testing. In order for preventive maintenance to be effective, it must be applied to equipment that has degradation effects that are detectable. Also, methods of detecting degradation must be available.

For the HPIS, the recommendation is to continue the maintenance recommended by the vendors for major components such as pumps and valves. In addition, an enhanced inspection program for detecting pipe leaks and cracks (including nozzles) using advanced monitoring methods should be implemented.

## HPIS Unavailability Assessment

This HPIS aging system unavailability assessment demonstrates the linear aging model technique using failure cause data can be used to update a representative plant PRA with time to calculate the change of unavailability as the system ages. This approach, as presented, is suitable for exploratory investigations and identification of components that contribute significantly to system unavailability. The results of this assessment apply to the plant studied and only to other plants of the same design configuration. More advanced aging reliability models with better methods of verifying that failure data exhibits aging and for calculating the time dependent failure rates are being developed.

Seven components involving 10 events were identified as risk significant for the HPIS by the Fussell Vesely measure. These events were motor-operated valves HP-24, HP-25, and HP-26; failure to operate, HPIS pumps A, B, and C; failure to start or run, and manual valve HP-148; failing to transfer.

The HPIS unavailability increased over the aging period modeled from 5 to 40 years for all three emergency operating modes. Even after the increases, the unavailabilities of the system are not much higher for the high pressure injection modes and the full plant PRA would not be expected to change significantly. For the recirculation mode, the unavailability increased significantly, but even after the increase, the value remained very low. A cursory review of the representative plant PRA indicated this change would not be expected to change the results of the full plant PRA.

The equipment failures that have the highest contribution to HPIS unavailability are the motor-operated valves failure to open.

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# APPENDIX A

## REACTOR COOLANT MAKEUP SYSTEM, PURIFICATION SYSTEM, AND COOLANT INJECTION AND RETURN FOR RC PUMP SEALS

# APPENDIX A

# REACTOR COOLANT MAKEUP SYSTEM, PURIFICATION SYSTEM, AND COOLANT INJECTION AND RETURN FOR RC PUMP SEALS

The part of the HPIS used during both normal and emergency operation is shown in Figure A-1. During normal operation, the High Pressure Injection system receives reactor coolant as letdown water for purification and chemistry control. The letdown water is cooled in one or both of the parallel connected letdown coolers in order to prevent damage to the purification system ion exchange resins. Cooling water for the letdown coolers is provided by the Component Cooling system. The cooled letdown is routed through the N16 Decay Tank, which provides sufficient flow delay to allow for decay of radioactive nitrogen-16. The RC makeup system is shown in Figure A-2. (The N-16 decay tank is not shown on Figure A-2.)

Flow from the decay tank to the purification system is controlled by a fixed block orifice. In the event additional flow is necessary, an orifice bypass valve is provided.

In the purification system, the letdown stream enters the purification demineralizer through the purification demineralizer supply header, and leaves through the purification demineralizer discharge header. A valve is provided between the supply and discharge headers to allow the demineralizer to be bypassed if necessary. A three-way valve in the discharge header allows the demineralizer discharge to be directed to either the letdown filters or the debarking demineralizer supply header. From the debarking demineralizer supply header, the letdown can be sent to the Coolant Treatment system or through the debarking demineralizer. The debarking demineralizer effluent is sent via the debarking demineralizer discharge header to the letdown filters.

Feed and bleed controls allow batch addition of demineralized water and/or concentrated boric acid for control of RC system boric acid concentration and restores the letdown storage tank level as necessary. The makeup batch enters the system upstream of the letdown filters.

Letdown from the purification system and/or makeup from the Coolant Treatment system passes through one or both of the two parallel connected letdown filters to the letdown storage tank.

Downstream from the letdown filters, return water from the reactor coolant pump seals is supplied to the letdown storage tank. The seal return water is taken from each of the four RC pumps and is cooled by one or both of the parallel connect RC seal return coolers before entering the letdown storage tank. The seal return and injection system is shown in Figure A-3.

The letdown storage tank serves as the normal suction source for the HP injection pumps; however, during safety injection, the borated water storage tank is automatically connected as an additional source. These sources provide injection water until RC system pressure is low enough for low pressure injection.

The three high pressure injection pumps are connected in parallel with cross connecting suction and discharge headers thus enabling any pump to supply any discharge line. During normal operation, only one pump is required for normal makeup and reactor coolant pump seal injection. A second pump serves as a backup for normal operation. All three HPI pumps are started automatically by a signal from the engineered safeguards system in the event of a low RC system pressure or a high reactor building pressure condition.

Three principal flow paths are provided from the HPI pump discharge header: an injection line to reactor coolant Loop A, a reactor coolant pump seal injection line, and an injection line to reactor coolant loop B. Normally HPI pump A or B is operated to supply makeup flow to RC loop A and RC pump seal injection flow; pump C is used only for injection to loop B in the event of an accident. An additional emergency cross connect line is provided from the HPI pump discharge header to both RC loops as a backup for safety injection.

The water supplied for reactor coolant pump seal injection is routed through the two parallel connected seal filters before being distributed to the four reactor coolant pumps.

## Description of Components

**Letdown Coolers.** The letdown coolers are of the shell and spiral tube type with a shell material of carbon steel and a tube material of stainless steel. The two letdown coolers are installed in

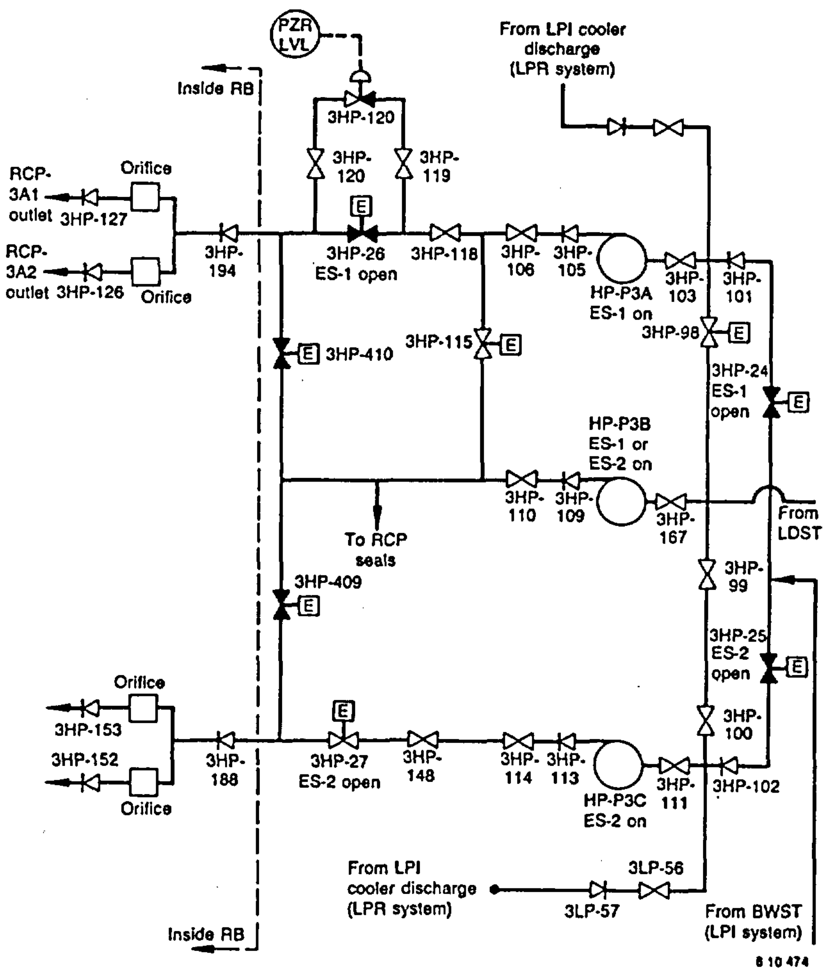



**Figure A-1.** Part of the HPIS used during normal and emergency operations.

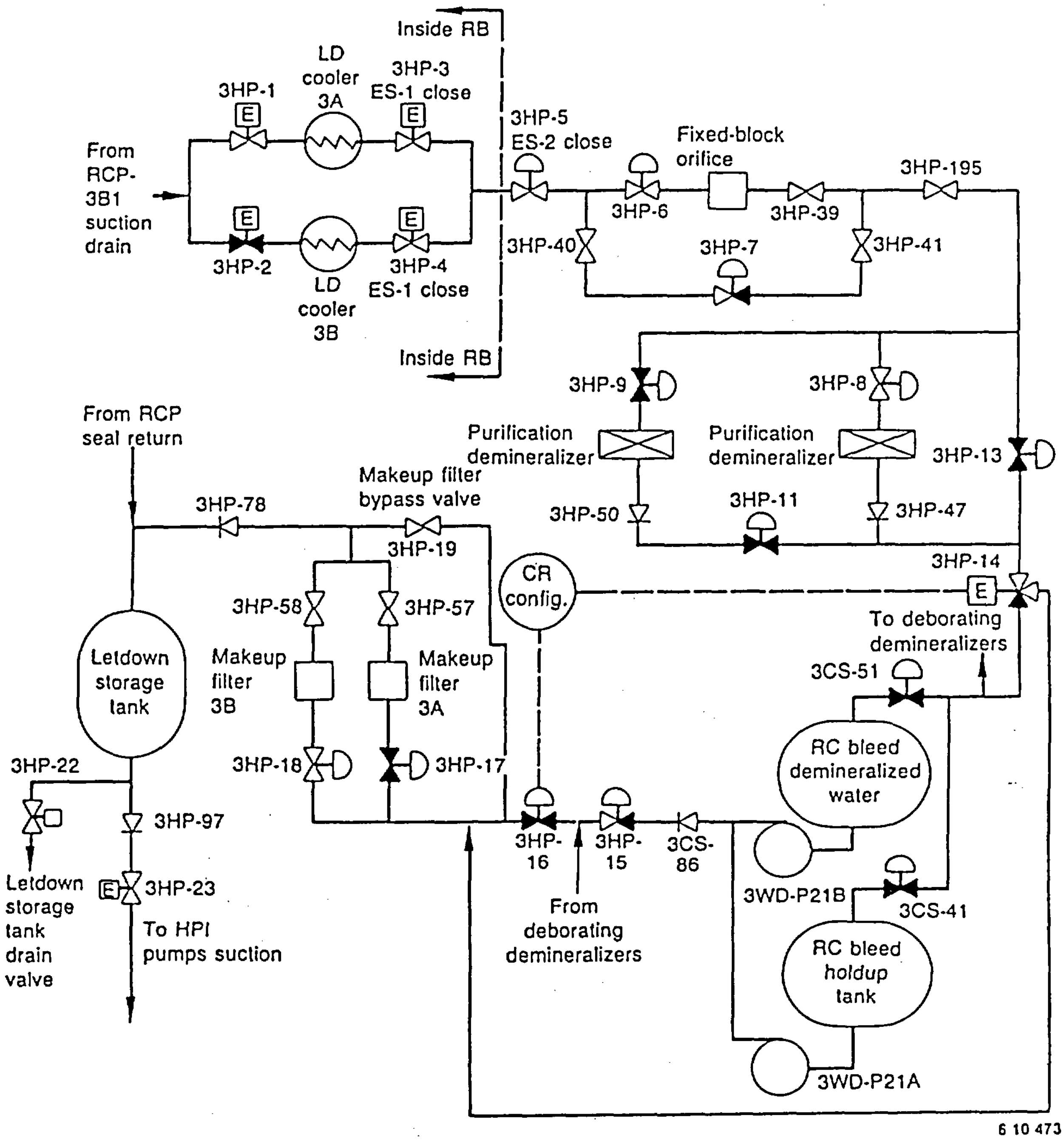



**Figure A-2.** Reactor coolant makeup and purification system.

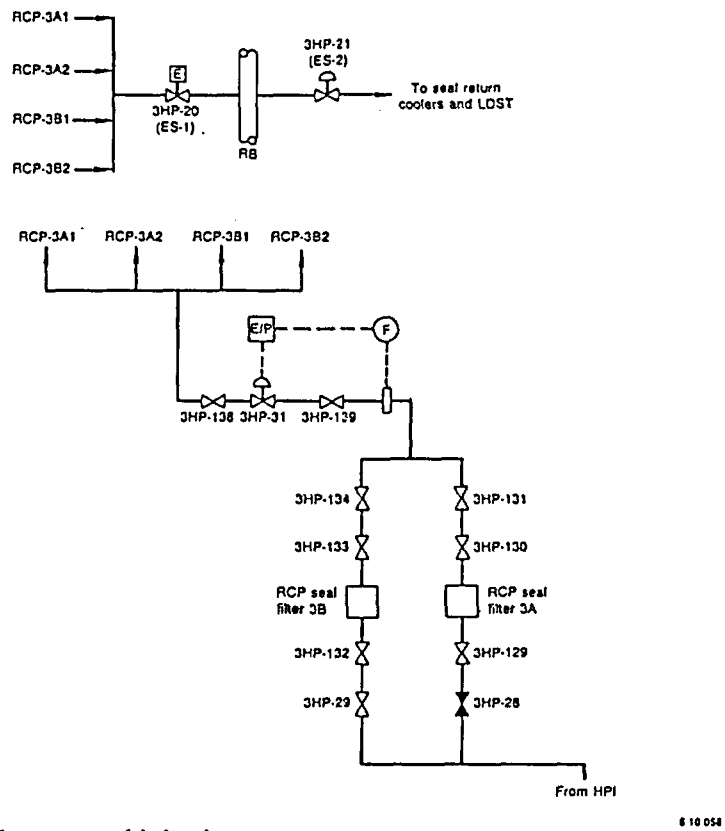



**Figure A-3.** RC pump seal return and injection system.

parallel with one normally in use and the second as a spare. For maximum letdown flow, both coolers are required.

**Seal Return Coolers.** The seal return coolers are of the shell and tube type with carbon steel as the shell material and stainless steel as the tube material. Of the two coolers installed in parallel, one is normally in operation.

**Makeup Filters.** The material of all wetted parts of the filter vessel is stainless steel. The filter elements themselves are of depth type design. The materials are wound cotton around a stainless steel core. Two makeup filters are installed in parallel with one normally in use.

**Reactor Coolant Pump Seal Filters.** The filter assembly consists of the filter vessel and one element. The filter vessel is of the in-line type with flanged ends. The element is pleated stainless steel. One of the two filters is required during normal operation. A bypass line is installed around the filters.

**Letdown Storage Tank.** The total volume of the stainless steel letdown storage tank is 600 $ft^3$. The water content under steady state conditions is about 350 $ft^3$ while the rest is gas space. The tank is equipped with a manway, 4-in. inlet and outlet connections, a 1-in. relief valve connection, a 1-in. vent connection, two 3/4-in. sampling connections (one in the gas space, the other in the water space), a 1-in. inlet connection for $H_2$ and $N_2$ and connections for level, pressure, and temperature indication.

The inlet connects to a nozzle that sprays the incoming water into the gas space. For hydrogen and nitrogen addition, a ring header in the water space is provided.

**Purification Demineralizers.** The purification demineralizers function is to purify the portion of the reactor coolant let down through the letdown coolers. Each demineralizer is sized for a flow rate of 70 gpm.

The inlet flow is distributed in an inlet header. The outlet is equipped with a similar header having a 110 mesh stainless steel screen to contain the resin beads. The vessel contains a manway, a resin inlet, resin outlet, and a vent connection to the high activity waste tank in addition to the water inlet and outlet. The material of all parts wetted by the process fluid is 304 stainless steel.

At the inlet line of each demineralizer, a small capacity relief valve is installed in order to prevent pressure buildup during ambient temperature changes in the event that the demineralizer is isolated. The reactor coolant quality specifications are given in Table A-1.

**Deborating Demineralizers.** The debarking demineralizers are used to reduce the boron concentration in the reactor coolant during the latter part of the core lifetime when the boron concentration must be lower. Each demineralizer is sized for a 70 gpm flow rate, the same as the purification demineralizers.

## Component Data

Letdown Cooler

| | |
|---|---|
| Type | Shell and spiral tube |
| Heat Transferred, Btu/hr | $16.0 \times 10^6$ |
| Letdown Flow, lb/hr | $3.5 \times 10^4$ |
| Letdown Cooler Inlet/Outlet Temperature, °F | 555/120 |
| Material, shell/tube | CS/SS |
| Design Pressure, psig | 2,500 |
| Design Temperature, °F | 600 |
| Component Cooling Water Flow (ea.), lb/hr | $2 \times 10^5$ |
| Code | ASME Sec. III-C & VIII |

Reactor Coolant Pump Seal Return Cooler

| | |
|---|---|
| Type | Shell and tube |
| Heat Transferred, Btu/hr | $2.2 \times 10^6$ |
| Seal Return Flow, lb/hr | $1.25 \times 10^5$ |
| Seal Return Temperature Change, °F | 145 x 127 |
| Material, shell/tube | CS/SS |
| Design Pressure, psig | 150 |
| Design Temperature, °F | 200 |
| Recirculated Cooling Water Flow (ea.), lb/hr | $1.25 \times 10^5$ |
| Code | ASME Sec. III-C & VIII |

Letdown Storage Tank

| | |
|---|---|
| Volume, $ft^3$ | 600 |
| Design Pressure, psig | 100 |
| Design Temperature, °F | 200 |
| Material | SS |
| Code | ASME Sec. III-C |

Purification Demineralizer

| | |
|---|---|
| Type | Mixed bed, boric acid saturated |
| Material | SS |
| Volume, $ft^3$ | 85 |
| Flow, gal/min | 70 |
| Vessel Design Pressure, psig | 150 |
| Vessel Design Temperature, °F | 200 |
| Code | ASME Sec. III-C |

Letdown Filter

| | |
|---|---|
| Design Flow Rate, gal/min | 80 |
| Material | SS |
| Design Temperature | 200 |
| Design Pressure | 150 |
| Code | ASME Sec. III-C |

**Table A-1. Reactor coolant quality**

| | |
|---|---|
| Total solids, including dissolved and undissolved material, but excluding $^7LiOH$ and $H_3BO_3$ (max), ppm | 1.0 |
| Boron (max), ppm | 2,270 |
| Lithium as $^7Li$, ppm (when required for pH adjustment) | 0.5-2.0[a] |
| pH at 77°F | 4.8-8.5[b] |
| Dissolved oxygen as $O_2$ | —[c] |
| Chlorides as $Cl^-$ (max), ppm | 0.15 |
| Hydrogen as $H_2$, std cc/L $H_2O$ | 15-40 |
| Fluorides as $Fl^-$ (max), ppm | 0.15 |

a. Equivalent range as $^7LiOH$ is 1.455 to 5.82 ppm.

b. Equivalent pH at 600°F is 6.8 to 7.8.

c. With proper $H_2O$ specification at critical condition, dissolved $O_2$ is assumed not to be present.

# APPENDIX B

## LOW PRESSURE INJECTION SYSTEM INTERFACE WITH HPI

# APPENDIX B

## LOW PRESSURE INJECTION SYSTEM INTERFACE WITH HPI

The LPI system is connected to the HPI system in two respects: (a) Under accident conditions they both take their suction from the borated water storage tank (the reactor building spray system also takes suction from the BWST), and (b) for high pressure recirculation mode of operation, the HPIS takes suction from the LPIS output.

The HPRS mode is initiated when the BWST borated water is depleted and conditions require high pressure recirculation. Both HPI and LPI pumps are shut down if operating and the LPI valves are reconfigured by opening the two valves of the reactor building emergency sump (valves LP-19 and LP-20), starting at least one LPI pump, closing valves LP-21 and LP-22 from the BWST, and opening valves LP-15 and LP-16 to the suction of the HPI pumps.

# APPENDIX C

# ELECTRICAL POWER REQUIREMENTS FOR HPIS COMPONENTS

# APPENDIX C

## ELECTRICAL POWER REQUIREMENTS FOR HPIS COMPONENTS

The voltage requirements for the various valves and HPI pumps are given in Table C-1. The 1E safety power system supplies the power for the HPI components. Grid voltage is regulated to + 10%. Each plant must decide what voltage degradation represents an acceptable level.

Table C-1. HPIS pumps and valve electrical power requirements

| Description | | Voltage Requirement |
|---|---|---|
| HPI Pump A[a] | | 4 kV |
| HPI Pump B[a] | | 4 kV |
| HPI Pump C[a] | | 4 kV |
| HP-1, | Letdown cooler A inlet isolation valve | 208 V |
| HP-2, | Letdown cooler B inlet isolation valve | 208 V |
| HP-3, | Letdown cooler A outlet valve | 208 V |
| HP-4, | Letdown cooler B outlet valve | 208 V |
| HP-5, | Letdown isolation valve | 125 Vdc |
| HP-6, | Letdown orifice inlet valve | 208/120 Vac |
| HP-8, | Purification demineralizer inlet valve | 208/120 Vac |
| HP-9, | Spare purification demineralizer inlet valve | 208/120 Vac |
| HP-11, | Spare purification demineralizer outlet valve | 208/120 Vac |
| HP-13, | Purification demineralizer bypass valve | 208/120 Vac |
| HP-14, | Bleed control valve | 208 V |
| HP-16, | Makeup isolation valve | 208 V |
| HP-17, | Makeup filter isolation valve | 208/120 Vac |
| HP-18, | Makeup filter isolation valve | 208/120 Vac |
| HP-19, | Makeup filter bypass valve | 208/120 ac |
| HP-20, | RC pump seal return valve | 208 V |
| HP-21, | RC pump seal return isolation valve | 125 Vdc |
| HP-22, | Letdown storage tank drain valve | 208/120 Vac |
| HP-23, | HPI pump suction valve | 208 V |
| HP-24, | Borated water to HPI pump A valve | 208 V |
| HP-25, | Borated water to HPI pump C valve | 208 V |
| HP-26, | HPI to loop A reactor inlet valve | 208 V |
| HP-27, | HPI to loop B reactor inlet valve | 208 V |
| HP-98, | HPI pumps suction crossover valve | 208 V |
| HP-115, | HPI pumps discharge crossover valve | 208 V |
| HP-226, | RC pump A2 seal return isolation valve | 208 V |
| HP-228, | RC pump A1 seal return isolation valve | 208 V |
| HP-230, | RC pump B2 seal return isolation valve | 208 V |
| HP-232, | RC pump B1 seal return isolation valve | 208 V |
| HP-409, | HPI isolation from HPI pump crossover valve | 600 V |
| HP-410, | HPI isolation from HPI pump crossover valve | 600V |
| GWD-19, | Letdown storage tank vent valve | 208/120 Vac |

a. In the event of a loss of 4 kV power, emergency power can be provided to one HPI pump from the auxiliary service water switchgear.

# APPENDIX D

# ENGINEERED SAFETY FEATURES ACTUATING SYSTEMS FOR HPIS

# APPENDIX D

# ENGINEERED SAFETY FEATURES ACTUATING SYSTEMS FOR HPIS

The HPIS is one of the Engineered Safeguards Systems that is automatically actuated by the Engineered Safety Feature Actuating System (ESFAS). The other safeguards systems actuated by ESFAS include the low-pressure injection system, reactor building isolation, reactor building cooling system, and the reactor building spray system.

The generic ESFAS diagram for a representative B&W plant is shown in Figure D-1. Figure D-1 is presented to illustrate the interconnections between major ESFAS subsystems. The three blocks on the left side of Figure D-1 are identical analog subsystems that receive pressure transducer inputs. The output lines from the analog subsystems go to the two identical center logic subsystems where the *two out of three* logic decides whether an ESF system is actuated. On the right side of the figure are the five ESF actuated systems. Although only the HPIS will be addressed in detail in this report, the other systems are covered only to show system interactions. The simplified one-line diagram for initiation of the High Pressure Injection (HPI) systems (ESFAS channels 1 and 2) is shown in Figure D-2, along with the related aging data for the various components. A detailed discussion of ESFAS is covered in Reference D-1.

In case of a LOCA, the HPIS will be initiated when the RC pressure drops to 1550 psig. If the high pressure injection channels fail to maintain RC pressure and it continues to decrease, then at 600 psig the core flooding system will automatically dump water into the core. This will happen automatically, with no means for manual control. If the RC pressure continues to drop, at 550 psig the low pressure injection channels (3 and 4) will be actuated in the same manner as the high pressure channels. Anytime there is a large RC leak or rupture, the coolant will flash to steam as it escapes from the system. This will cause the building pressure to increase. When the building pressure increases to 3.0 psig, the building cooling and isolation channels will be actuated as well as high and low pressure injection channels if they have not already been actuated.

The ESFAS Unit Control Module provides the output contacts to drive the final actuating device control circuitry. Interfacing capability is also provided to allow manual control of the final device after safety action has been initiated. If the remotely mounted manual control equipment is activated before safety action is initiated, the system safety function will not be inhibited.

The engineered safeguards for actuated devices on ESFAS channels 1 and 2 are shown in Table D-1, they include HPI pumps, valves, and IE power breakers and busses.

Electrical power for operating the HPIS control relays is taken from the power source for the associated device. Loss of power, a relay, or a device does not impair system functions because there is a second redundant device for each required function.

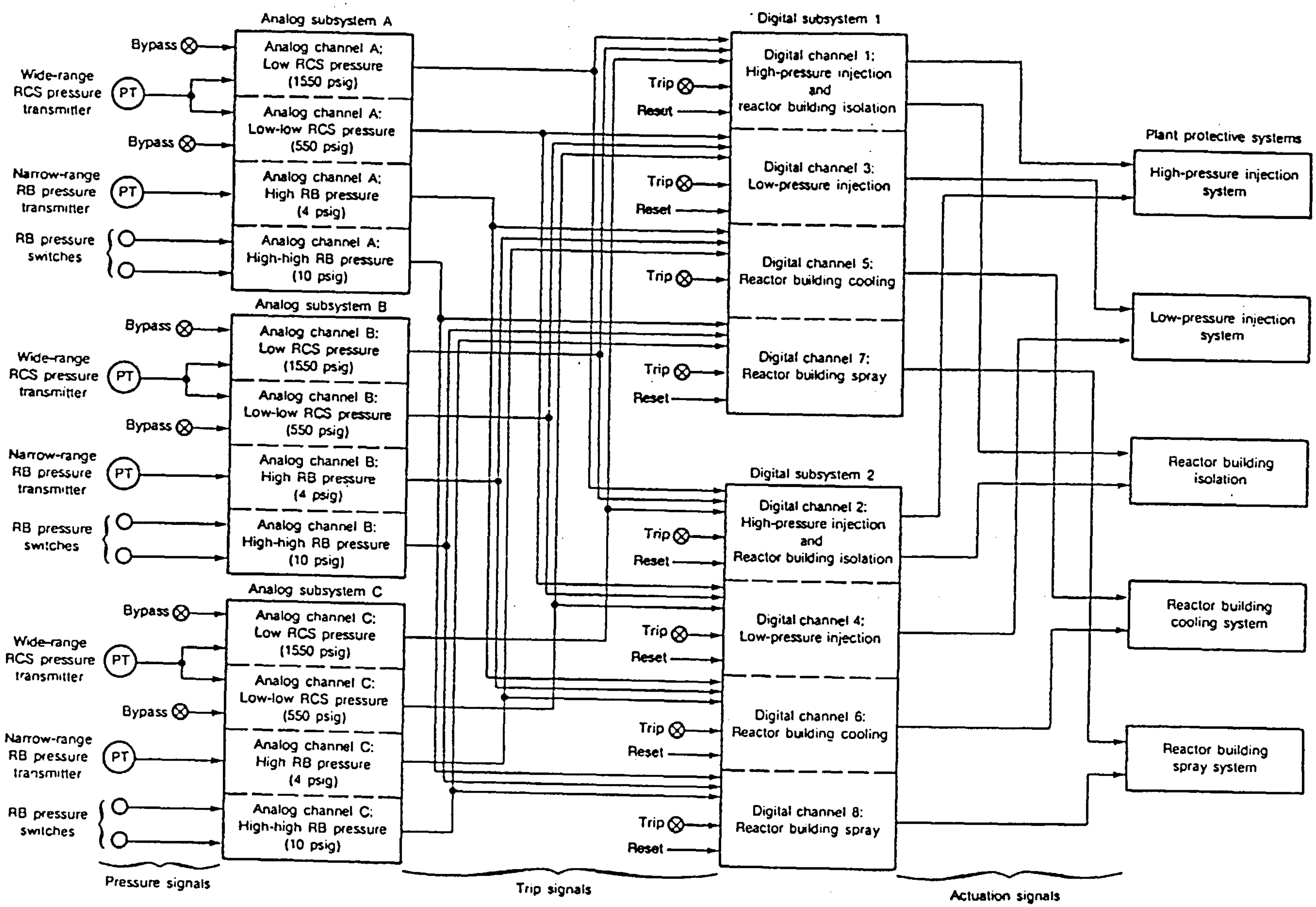
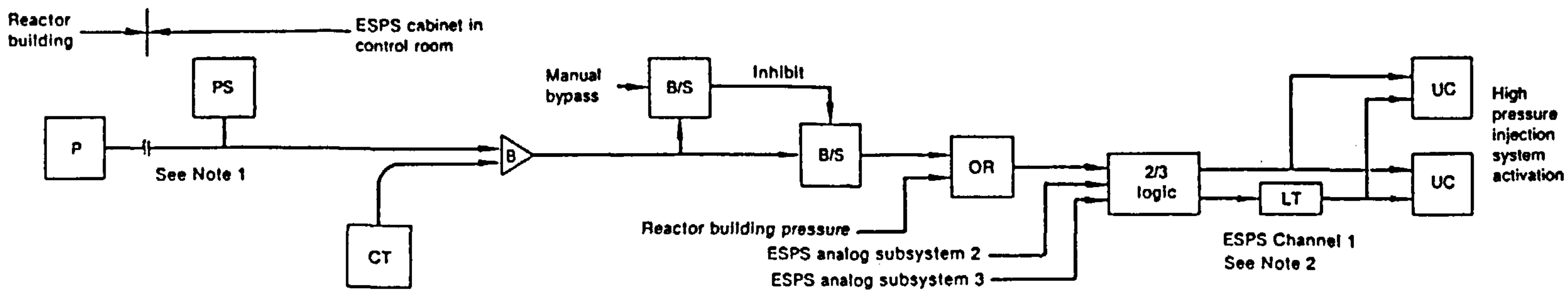



**Figure D-1.** Engineered safeguard system.




| Component | Reactor coolant pressure transmitter | Instrument power supply | Calibrate test | Buffer amplifier | Bistable | Bistable | OR logic | 2/3 logic | Logic test | Unit control | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Environment Temperature | 120°F average | 50 to 80°F | | | | | | | | | |
| Radiation | 3 x $10^4$ RAD | N/A | | | | | | | | | |
| Interfaces | Pressure TAP | 110V power and module interlock | | | | | | | | | |
| EQ | 10 year life | 40 years | | | | | | | | | |
| Testing | Monthly Funtional test, response time test at 18 months | | | | | | | | | | |
| Calibration | 18 months or refueling | 18 months | | | | | | | | | |
| Maintenance | | 18 months | | | | | | | | | |
| Signal | 0 to 2000 PSI | 4-20 ma | | 0 to 10 Vdc | | | | | | | |
| Physical data | | | | | | | | | | | |
| Stressors | See Note 1 | | | | | | | | | | |
| Indicators of degradation | Drift, moisture intrusion, wearout, failure, signal variance from similar channels | Drift, failure, contact resistance change, binding or bent parts | | | | | | | | | |

6 2729

Note 1: The transmitter, cable, reactor building penetration, terminal strip and connectors are identical to that of the RPS RC pressure channel

Note 2: The low pressure injection is identical.

**Figure D-2.** ESFAS channel for initiating the high pressure injection with related aging and engineering data.

**Table D-1. Engineered safeguards actuated devices for Channels 1 and 2**

| Devices | Channel 1 | Channel 2 | Channels 1 and 2 |
|---|---|---|---|
| HPI pumps and valves | HP-PA<br>HP-24<br>HP-26<br>HP-3<br>HP-4<br>HP-20 | HP-PC<br>HP-25<br>HP-27<br>HP-5<br>HP-21<br>Emergency power source start (Channel B) | HP-PB |
| Electrical power sources and Equipment | Emergency power source start (Channel A)<br>LOAD SHED & STBY. BKR. 1<br>Standby BUS FEED BKR. 1 | Emergency power source start (Channel B)<br>LOAD SHED & STBY. BKR. 2<br>Standby BUS FEED BKR. 2 | |

# REFERENCES

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# APPENDIX E

# COMPONENT DESIGN INFORMATION

# APPENDIX E

# COMPONENT DESIGN INFORMATION

## Piping

The high pressure injection and low pressure injection lines are designed for normal operating conditions. The normal operating system temperature and pressure requirements are greater than those encountered during emergency operation. The low pressure injection system piping and valves are subjected to more severe conditions during decay heat removal operation than during emergency operation and, therefore, operate well within the design conditions. Table E-1 gives the design pressure and temperatures of these systems. To ensure system integrity, major piping has welded connections except where flanges are dictated for maintenance reasons. All piping for the HPI system is stainless steel. Pipe sizes include 1, 2 1/2, 4, 6, 8, and 14 in.

Generic guidance is needed for predicting and mitigating and the effects of piping damage due to flow-assisted erosion, corrosion, or cavitation. Results from the Surry-2 rupture on feedwater pipes show that erosion and corrosion can occur in single-phase flow. What lessons from that incident can be applied to HPI piping is not yet known. Some factors that can effect piping damage include pipe design, fluid dynamics, piping material, and water chemistry.

## HPI Pumps

Each HPI pump can deliver 450 gpm at 1700 psig reactor vessel pressure. Water is drawn through a single suction header from the BWST and pumped through injection lines that enter the reactor building on opposite sides. Each injection line splits into two lines inside the reactor building, but outside the secondary missile shield, to provide four injection paths to the RCS cold legs. The four

**Table E-1. Engineered safeguards piping design conditions**

| | Temperature (°F) | Pressure (psig) |
|---|---|---|
| High Pressure Injection System | | |
| From the pump discharge to upstream of the stop check valves inside the secondary shielding. | 200 | 3,050 |
| High pressure injection pump. | 200/150 | 2,800/3,050 |
| From upstream of the stop check valves to the reactor inlet line. | 650 | 2,500 |
| Low Pressure Injection System (Portion used with HPI) | | |
| From the borated water storage tank to upstream of the borated water storage tank outlet valves. | 150 | Static |
| From upstream of the borated water storage tank outlet valve to upstream of the electric motor operated valves in the borated water feed lines. | 200 | 100 |

connections are located between the reactor coolant pump discharge and the reactor inlet nozzles.

Operation of the HPIS pumps requires lubrication oil cooling and pump seal cooling. Charging pump cooling is accomplished via the Low Pressure Service Water (LPSW) System where heat generated in the pump lubricating oil and seals is removed via heat exchangers and transferred to ultimate heat sink. Electrical power is supplied by three independent 4160 V buses to the three HPI pumps. After receiving an actuation signal, the HPI pumps can reach full speed within six seconds. The HPI pump data are given in Table E-2 and the HPI pump characteristics curves of total dynamic head and net position suction head are shown in Figure E-1. The HPI pumps are vertical stage-centrifugal pumps with mechanical seals. The wetted parts of the pumps are stainless steel.

## Valves

All remotely operated valves in the Emergency Core Cooling Systems are manufactured and inspected in accordance with the intent of the ASME Nuclear Power Piping Code B31.7. Liquid penetrant, radiography, ultrasonic, and hydrotesting are performed as the code classification requires.

The seats and discs of these valves are manufactured from materials free from galling and seizing. All valve material is certified to be in accordance with ASTM specifications. All remotely operated valves in these systems are of the backseating type and equipped with stem leak-off provisions.

The valves and their design conditions are listed in Table E-3. Actual system operating conditions are significantly less severe than design conditions shown in Table E-3.

1. *Tank Problems* — While there have been a number of events at PWRs involving tanks with boron concentrations or fluid levels that were out of specification, most of these events did not result in an outage or derating. The only significant event was an outage to replace a boric acid injection tank at a PWR. The borated water storage tank (BWST) is the primary water source for the HPI during the HPI emergency operation mode. A single header connects the borated water supply to the charging pump. The pumps take suction from the 350,000 gallon BWST ($\sim$2000 ppm boron). Specifications for the BWST are given in Table E-4.

Table E-5 gives the regulatory requirements and guidelines for the design equipment qualification and testing of the HPIS.

**Table E-2. High pressure injection pump data**

| | |
|---|---|
| Type | Vertical, multistage, centrifugal mechanical seal |
| Capacity, gal/min | (See Figure E-1) |
| Head, ft $H_2O$ (at sp. gr. = 1) | (See Figure E-1) |
| Motor horsepower, nameplate hp | 600 |
| Pump material | SS wetted parts |
| Design pressure, psig | 2,800/3,050 |
| Design temperature,°F | 200/150 |

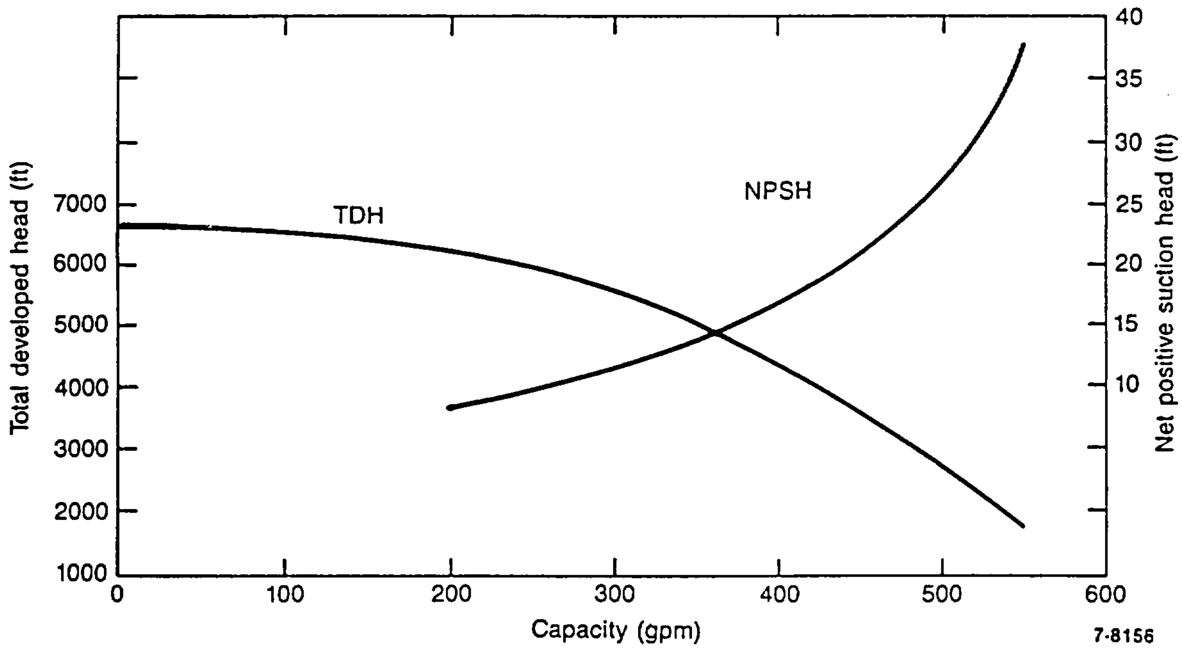


**Figure E-1.** HPI pump characteristics.

## Table E-3. Active—HPIS and LPIS reactor coolant pressure boundary valves

| Valve Number | System | Service | Size (in.) | System Design Rating | System Condition During Operation | Type | Motor Operator Type | Valve Movement |
|---|---|---|---|---|---|---|---|---|
| HP-3 | High pressure injection | Letdown cooler outlet | 2-1/2 | 2500 psig 650xF | 2170 psig 135xF 40-100 gpm | Globe | Limitorque SMB-00-15 | Full open to Full close |
| HP-4 | High pressure injection | Letdown cooler outlet | 2-1/2 | 2500 psig 650xF | 2170 psig 135xF 40-100 gpm | Globe | Limitorque SMB-00-15 | Full open to Full close |
| HP-5 | High pressure injection | Letdown line RB isolation | 2-1/2 | 2500 psig 200xF | 1270 psig 2950 psig 40-140 gpm | Globe | Sheffer Piston | Full open to Full close |
| HP-26 | High pressure injection | HP inj RB isolation | 4 | 3050 psig 200xF | 2200-2950 psig 120-245xF 450 gpm | Globe | Limitorque SMB-1-25 | Full close to Full open |
| HP-27 | High pressure injection | HP inj RB isolation | 4 | 3050 psig 200xF | 2200-2950 psig 450 gpm 120-245xF | Globe | Limitorque SMB-1-25 | Full close to Full open |
| LP-17 LP-18 | Low pressure injection | LP inj RB isolation | 10 | 2500 psig 300xF | 255 psig 280xF 3000 gpm | Gate | Limitorque SMB-4-100 | Full close to Full open |

## Table E-4. Borated water storage tank

| | |
|---|---|
| Capacity, gal | 388,000 |
| Material | Carbon steel/coated inside |
| Design pressure, psig | Atmospheric |
| Design temperature, °F | 150 |
| Code | AWWA D-100 |

Table E-5. HPIS regulatory requirements and guidelines

| Criteria | Title | Applicability HPIS | Remarks |
|---|---|---|---|
| Part 1 | Design | | |
| 1. — | ASME boiler and pressure vessel Code, Section III-C, VIII, and XI | R[a] | Life extension under review in ASME Section XI |
| 2. General Design Criteria (GDC), Appendix A to 10 CFR Part 50 | | | |
| b. GDC 2 | Design basis for protection against natural phenomena | R | — |
| c. GDC 4 | Environmental and missile design basis | R | — |
| d. GDC 13 | Instrumentation and control | R | — |
| e. GDC 19 | Control room | R | — |
| j. GDC 24 | Separation of protection and control systems | R | — |
| 3. Regulatory Guides (RG) | | | |
| c. RG 1.53 | Application of the single-failure criterion to nuclear power plant protection systems | G[b] | — |
| d. RG 1.62 | Manual initiation of protection actions | G | — |
| e. RG 1.75 | Physical independence of electric systems | G | — |
| f. RG 1.89 | Environmental qualification of electrical equipment for nuclear power plants | G | Positions on end of life and maintenance |

Table E-5. (continued)

| Criteria | Title | Applicability HPIS | Remarks |
|---|---|---|---|
| 3. Regulatory Guides (RG) (continued) | | | |
| g. RG 1.105 | Instrument spands and setpoints | G | Aging should be taken into account |
| h. RG 1.118 | Periodic testing of electric power and protection systems | G | May require updating to take into account studies on increasing surveillance intervals |
| 6. IEEE Standards | | | |
| a. 279-1971 | Criteria for protection system for nuclear power generating stations | R | — |
| b. 379-1977 | Application of the single failure criteria to NPGS Class IE systems | R | — |
| Part 2 | Electrical equipment qualification | | |
| 1. 10 CFR 50.49 | — | R | All replacement equipment purchased after 2/22/83 |
| 2. IEEE-323-1974 | General guide for qualifying Class IE electrical equipment for nuclear power generating stations (1971) | R | All replacement equipment purchased after 2/22/83 |
| 3. IEEE 344-1975 | Recommended practices for seismic qualification of Class IE electrical equipment for nuclear power generating stations | R | Seismic qualification |
| 4. Regulatory Guide 1.89 | Environmental qualification of electric equipment for nuclear power plants | G | Verify with naturally aged components |

**Table E-5. (continued)**

| Criteria | Title | Applicability HPIS | Remarks |
|---|---|---|---|
| 5. NUREG-0588 | Interim staff position on Environmental qualification of safety-related electrical equipment | G | Update using naturally aged component data |
| Part 3 | Testing requirements | | |
| 1. Standard Technical Specifications Section 3/4.5 and 4.5.11.1 | — | R | — |
| 2. IEEE-Std 338-1977 | Criteria for periodic testing of nuclear power generating station safety systems | R | — |
| 3. Regulatory Guide 1.68 | Initial test programs for water-cooled nuclear power plants | R | — |

a. R = required.

b. G = guideline.

# APPENDIX F

# MAKEUP/HPI NOZZLE CRACKING

# APPENDIX F

# MAKEUP/HPI NOZZLE CRACKING

## Makeup Nozzles

The 2.5-in. high pressure injection connections with thermal sleeves are located on all four cold legs of the reactor coolant piping. The four HPI/MU nozzles (one per cold leg) are used to: (a) provide a coolant source for emergency core cooling, and (b) supply normal makeup (purification flow) to the primary system. In general, one or two of the nozzles are used for both HPI and MU, while the remaining nozzles are used for HPI alone.

The incorporation of a thermal sleeve into a nozzle assembly is a common practice in the nuclear industry to provide a thermal barrier between the cold HPI/MU fluid and the hot high pressure injection nozzle. This helps prevent thermal shock and fatigue of the nozzle. The purpose of the safe-end is to make the field weld easier (pipe to safe-end) by allowing similar metals to be welded. The dissimilar metal weld between the safe-end and the nozzle can then be made under controlled conditions in the vendor's shop. The use of the safe-end also eliminates the need to do any post-weld heat treating in the field. Failures in these HPI/MU nozzles may preclude the proper functioning of the ECCS and/or the normal fluid makeup of the primary system.

## Make-Up Nozzle Cracking Problem

Cracks were found in the normal makeup high pressure injection (MU/HPI) nozzles of several B&W plants[F-1] following an inspection of the eight B&W plants licensed to operate. These cracks appeared to be directly related to loose or missing thermal sleeves. As a result, a B&W Owners' Group Task Force was established to identify the cause of the failures and recommend modifications to eliminate future failures.

The B&W Task Force completed a generic investigation of the MU/HPI nozzle component cracking problem and has a report on the findings of that investigation (Reference F-2). The report presents relevant facts and probable failure scenarios, as well as recommended modifications to thermal sleeve designs, makeup system operating conditions, and ISI plans. Failure analysis indicated that the cracks were initiated on the inside diameter and were propagated by thermal fatigue. Inspections at Midland have also shown that gaps may be present between the thermal sleeve and safe-end in the contact expansion joint. These findings along with stress analysis and testing have implicated insufficient contact expansion of the thermal sleeves as the most probable root cause of the failures.

## Possible Solutions

As a result of their investigation, B&W made the following recommendations[F-1] for solving the problem:

1. Reroll the upstream end of the thermal sleeve when inspections indicate that a gap exists, or repair and/or replace damaged components
2. Maintain a continuous MU flow greater than 1.5 gpm
3. Implement an augmented ISI plan
4. Perform a detailed stress analysis of a nozzle with a modified thermal sleeve design to justify long term operation.

The NRC staff reviewed and evaluated the recommendations of the Task Force and supported all four recommendations. The makeup HPI nozzle is shown in Figure F-1 with both the old and new design.

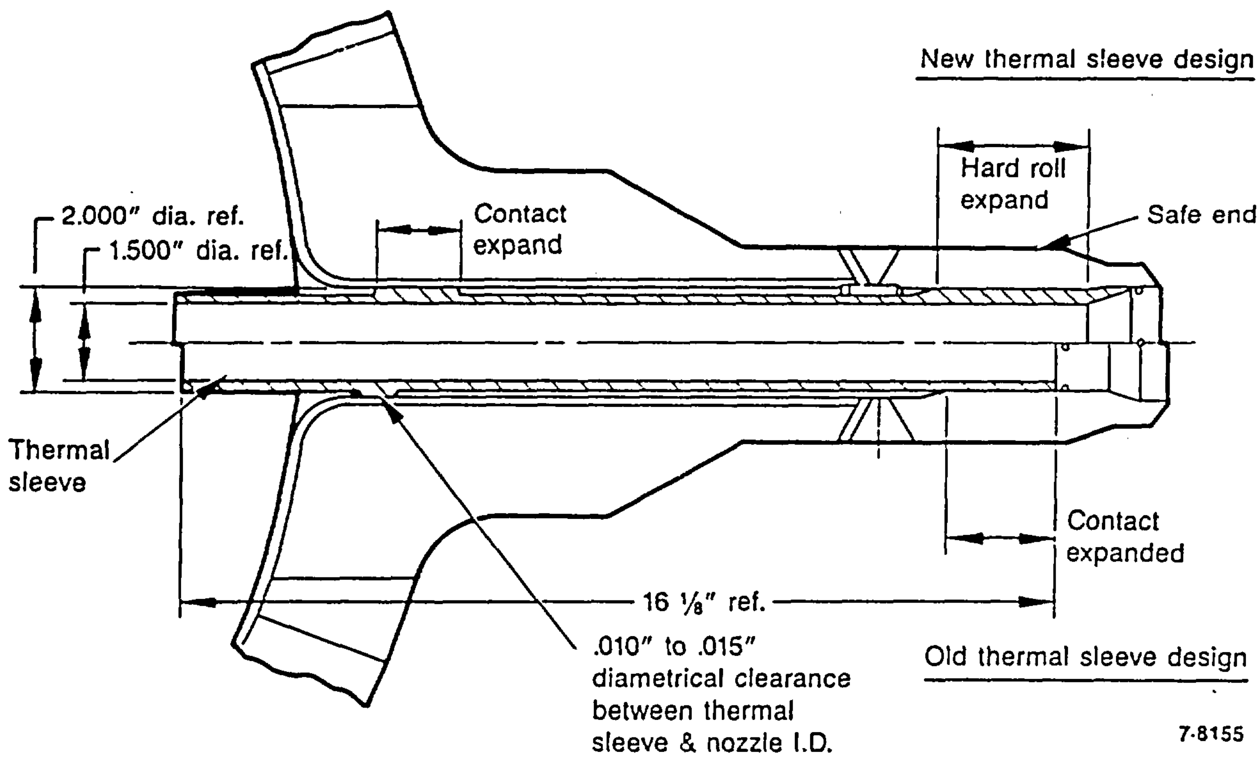


**Figure F-1.** Makeup HPI nozzle (new and old design).

# REFERENCES

F-1. "Make-Up Nozzle Cracking in Babcock and Wilcox (B&W) Plants," *A Prioritization of Generic Safety Issues*, NUREG 0933, Issue 69, December 1983.

F-2. *177 Fuel Assembly Owners' Group Safe End Task Force Report on Generic Investigation of HPI/MU Nozzle Component Cracking*, B&W Document No. 77-1140611-00, Babcock and Wilcox Company, 1983.

# APPENDIX G

# OPERATING EXPERIENCE DATA

# APPENDIX G

# OPERATING EXPERIENCE DATA

## Nuclear Power Experience Data for HPIS

The NPE data includes the following ESF systems under the heading Systems Injections Recirculation and Containment Spray. Valves, pipes, and many of the major components will be similar for these systems. The NPE data base could not be sorted on subsystems to eliminate containment spray events. Because of the similarity of components that handle borated water, this should not significantly affect the conclusions.

PWRs:

safety injection (SI)
high head injection (HHI)
(a.k.a. upper head inj - UHI)
boron injection
recirculation phase
containment spray
accumulator tank system

For all U.S. Nuclear Power Plants, from startup through 1986, there were 1552 articles in NPE on HPIS for PWRs. The ranking for frequency of HPI valve failures by function is given in Table G-1. The majority of valve failures (60%) were for stop (on/off) valves. Table G-2 gives a similar ranking for type of I&C channel failures. About half are for instrumentation. A sub-breakdown is shown in parentheses for various types of measurements.

**Table G-1. Valve failure ranking by function (NPE)**

| Valve Function | PWR (%) |
|---|---|
| Stop (on/off) | 60 |
| Check | 12 |
| Control | 8 |
| Containment isolation | 8 |
| Relief | 4 |
| Other | 8 |
| No. of events | 537 |

**Table G-2. I&C failures for HPI (NPE)**

| Component | PWR (%) | Instrumentation (%) |
|---|---|---|
| Control | 39 | |
| Valves | | (17) |
| Pumps | | ( 9) |
| Electrical and Miscellaneous | | (13) |
| Instrumentation | 50 | |
| Level | | (16) |
| Pressure | | (32) |
| Flow | | (18) |
| Heat Tracing | | ( 1) |
| Temperature | | ( 8) |
| Other | | (26) |
| Misc. and other | 11 | |
| | 100 | |

NOTE: Numbers in parentheses are a percentage breakdown for instrumentation channels for all instrumentation failures.

Based on data from NPE, the causes for pipe failures are given in Table G-3. Design error, construction error, and maintenance error are the leading causes for pipe failures. Pipe support (including snubbers) failure causes are broken down in Table G-4. Maintenance error, design error, water

**Table G-3. Causes for pipe failures (NPE)**

| Cause | Percent |
|---|---|
| Design construction error | 23 |
| Weld failure | 15 |
| Maintenance error | 14 |
| Corrosion | 7 |
| Vibration | 5 |
| Blockage | 4 |
| Mechanical disability | 4 |
| Water hammer | 3 |
| Foreign material | 3 |
| Environmental effects | 2 |
| Other | 20 |
| | 100 |

hammer, and mechanical disability are the leading causes for pipe support failures.

In the NPE data base, the heading tanks include I&C as well as valves associated with the tanks. Percentage of problems associated with tank subcomponents are shown in Table G-5 based on 194 articles.

**Table G-4. Causes for pipe support failures (NPE)**

| Item | Percent |
|---|---|
| Maintenance error | 23 |
| Design construction error | 20 |
| Water hammer | 20 |
| Mechanical disability | 13 |
| Vibration | 6 |
| Wearout | 4 |
| Weld failure | 3 |
| Corrosion | 2 |
| Broken part/damage | 2 |
| Environment | 2 |
| Fatigue | 1 |
| Other | 4 |
| | 100 |

## LER Data on Valves

The LER data for valves for the HPI and make up system is shown in Table G-6.[G-1] Command faults are those faults occurring in the control, power, or other support system that prevents the valve from performing its intended function. This data covered years 1976 through 1980.

**Table G-5. Subcomponents involved in tank problems (NPE)**

| Item | Percent |
|---|---|
| Water chemistry | 34 |
| I&C | 25 |
| Valve moving internals | 17 |
| Seals, gaskets, packing | 3 |
| Valve operators | 2 |
| Fittings, flanges | 2 |
| Other | 17 |
| | 100 |

**Table G-6. Summary of valve failures and command faults for HPIS AND CVCS (LERs)**

| | PWR | | | | | |
|---|---|---|---|---|---|---|
| | Failures | | Command Faults | | Total | |
| System | No. | Percent | No. | Percent | No. | Percent |
| High pressure coolant injection | 48 | 5 | 26 | 8 | 74 | 6 |
| Chemical volume control (makeup) | 92 | 10 | 11 | 3 | 103 | 8 |

# REFERENCES

G-1. W. H. Hubble and C. Miller, *Data Summaries of Licensee Event Reports of Valves at U.S. Commercial Nuclear Power Plants*, EGG-EA-5125 NUREG/CR-1363, October 1982.

# APPENDIX H

# PROBLEMS WITH BORATED WATER SYSTEMS

# APPENDIX H

## PROBLEMS WITH BORATED WATER SYSTEMS

A number of cracking incidents were experienced in safety-related stainless steel piping systems and portions of systems containing oxygenated, stagnant, or essentially stagnant borated water during the period from November 1974 to February 1977. Metallurgical investigations revealed these cracks occurred in the weld heat affected zone of type 304 stainless steel material. The cracks initiated on the ID surface and propagated in a mode typical of stress corrosion cracking. Analysis indicated the probable corrosives to be chloride and oxygen contamination in the affected systems. Cracks were also found as a result of local boric acid buildup and confirmed by liquid penetrant tests. Conclusions were drawn that cracking incidents were due to IGSCC originating in the pipe ID. The cracking was localized to the heat affected zone where type 304 stainless steel is sensitized to during welding. More information can be found in the IE Information Notice 79-19 on this problem. No problems were reported in 1980-82.

For the PWR plant used in the detailed HPI study, the system operation procedures stated a concern that following initial high pressure injection and HPI recirculation boron may plate out in the core and block cooling channels. Therefore, at a predetermined time, HPI flow is realigned from cold leg injection to hot leg injection. This reverses flow direction through the core and dissolves any crystallized boron.

On April 20, 1987, the NRC Information Notice No. 86-109 alerted recipients of possible degradation of the reactor coolant system pressure boundary resulting from boric acid corrosion. The boric acid corrosion of ferritic steel components in the RCS was first noticed at Arkansas One when inspecting HPI nozzles and safe ends as a follow-up to the thermal stress cracking problem in 1982. Boric acid will rapidly corrode ferritic (carbon) steel components if a small leak occurs near a hot surface. The boric acid solution will boil and concentrate, becoming more acidic and more corrosive. In addition, the evaporation of the water will cause the boric acid crystals to accumulate at that point. Other plants have experienced boric acid corrosion of ferritic steel due to leakage of borated water. One involved threaded fasteners and is discussed in IE Notice 82-02.

The boric acid corrosion is most active where the metal surface is cool enough to remain wet. If the surface were hot enough to dry out, the loss of electrolyte would slow the corrosion rate. Laboratory tests and plant experience have shown corrosion rates of > 1-in. depth per year in ferritic steel (Reference Article 522 VII Safety System, A ECCS NPE).

Many PWRs have no positive means of detecting boron dilution during cold shutdown. There have been 25 reported instances (Issue 22, NUREG-0933) of inadvertent boron dilution during maintenance and refueling. Although none have occurred, the possibility of an inadvertent criticality is a paramount safety concern. Although undesirable, the consequences of an unmitigated boron dilution event is not severe enough to warrant backfit of additional protective features at operating plants. Such an event at an operating plant would represent a breakdown in a licensee's ability to control its plant.

If there is no clear indication of boric acid leakage to bolts, boric acid corrosion of bolts could go undetected until failure of the bolts. Present ISI procedures do not require mandatory visual inspection of bolts and UT inspections are not required on pressure-retaining bolts of less than 2 in. in diameter. This problem was listed as safety issue 29, NUREG-0933 and given a high priority ranking for resolution.

The most recent alert to boric acid problems is from NRC information notices 86-108 supplement 1, "Degradation of Reactor Coolant System Pressure Boundary Resulting from Boric Acid Corrosion." In this instance, about 500 lb of boric acid crystals were found on the RV head as a result of a small leak in an instrument tube seal.

The loss of safety injection capability has occurred at two plants[H-1] as a result of common mode failure of SI pumps from crystallization of boric acid. In one instance, leaky valves in the discharge line of the boron injection tank (BIT) enabled concentrated boric acid to flow through the low pressure discharge line (SI pump suction) and to precipitate in pumps not heat traced. In the other case, boric acid crystallization blockage occurred between the boric acid storage tank (BAST) and the charging pump. Solidified boric acid has also blocked mixing tank pumps[H-2] and level indicator failures have occurred due to blocked sensing lines.

# REFERENCES

H-1. Nuclear Power Experience Article, PWR 7A489.

H-2. Nuclear Power Experience Article, PWR7A497.

# APPENDIX I

# HPIS RISK ASSESSMENT DATA SUMMARIES

# APPENDIX I

## HPIS RISK ASSESSMENT DATA SUMMARIES

This appendix contains the baseline data from the PRA[I-1] in Tables I-1, I-2, and I-3. The description of each event is given in these tables.

Fault tree importance measures for the three cases studied are given in Tables I-4 through I-18. These are direct printouts from the IRRAS Program for the 5-year, 10-year upper and lower bounds, and 40-year upper and lower bounds.

The fault tree cut set quantification reports for the three cases are given in Tables I-19 through I-33 for the same time periods as the importance measures. The top of this display gives the family and fault tree names along with the minimal cut set upper bound value as calculated by the point estimate quantification. The lower portion showed the quantified minimal cut sets. The first column gave the ranking of the cut sets according to the probability. The second column indicated an approximate percentage contribution of the cut set to the minimal cut set upper bound. The third column gave the frequency of each individual cut set and the last column gave a listing of the basic events making up each cut set.

The code for the fault tree heading on Tables I-4 through I-33 identifies the mode of operation that applies for the table.

HPI is for the injection that requires one of three pumps.

HP201 is for the injection mode that requires two of three pumps.

HPR1 is for the recirculation mode.

**Table I-1. Basic events for the high-pressure injection/recirculation system: hardware**

| Event Name | Description[a,b] | Mean Unavailability[c] | Mean Failure Rate ($yr^{-1}$) |
|---|---|---|---|
| HP101CVO | Tilting-disk check valve 3HP-101 fails to open on demand | 8.7 – 5 | 1.7 – 4 |
| HP102CVO | Tilting-disk check valve 3HP-102 fails to open on demand | 8.7 – 5 | 1.7 – 4 |
| HP109CVO | Tilting-disk check valve 3HP-109 fails to open on demand | 8.7 – 5 | 2.2 – 3 |
| HP113CVO | Tilting-disk check valve 3HP-113 fails to open on demand | 8.7 – 5 | 2.2 – 3 |
| HP152CVO | Stop check valve 3HP-152 fails to open on demand | 9.8 – 5 | 2.0 – 4 |
| HP153CVO | Stop check valve 3HP-153 fails to open on demand | 9.8 – 5 | 2.0 – 4 |
| HP188CVO | Swing check valve 3HP-188 fails to open on demand | 9.8 – 5 | 2.0 – 4 |
| LP55CVO | Swing check valve 3LP-55 fails to open on demand | 9.8 – 5 | 2.0 – 4 |
| LP57CVO | Swing check valve 3LP-57 fails to open on demand | 9.8 – 5 | 2.0 – 4 |
| HP148VVT | Manual valve 3HP-148 transfers closed | 3.9 – 4 | 7.8 – 4 |
| LP54VVT | Manual valve 3LP-54 transfers closed | 3.9 – 4 | 7.8 – 4 |
| LP56VVT | Manual valve 3LP-56 transfers closed | 3.9 – 4 | 7.8 – 4 |
| HP24MVO | MOV 3HP-24 fails to open on demand | 6.4 – 3 | 4.9 – 2 |
| HP25MVO | MOV 3HP-25 fails to open on demand | 6.4 – 3 | 4.9 – 2 |

Table I-1. (continued)

| Event Name | Description[a,b] | Mean Unavailability[c] | Mean Failure Rate ($yr^{-1}$) |
|---|---|---|---|
| HP26MVO | MOV 3HP-26 fails to open on demand | 6.4 – 3 | 4.9 – 2 |
| HP409MVO | MOV 3HP-409 fails to open on demand | 6.4 – 3 | 4.9 – 2 |
| HP410MVO | MOV 3HP-410 fails to open on demand | 6.4 – 3 | 4.9 – 2 |
| HPBPPS | Pump HP-P3B fails to start on demand[d] | 8.4 – 4 | 2.1 – 2 |
| HPCPPS | Pump HP-P3C fails to start on demand | 8.4 – 4 | 2.1 – 2 |
| HPAPPR | Pump HP-P3A fails to run[e] | 2.0 – 4 | 7.4 – 2 |
| HPRAPPR | Pump HP-P3A fails to run during recirculation[e] | 2.0 – 3 | 7.4 + 1 |
| HPBPPR | Pump HP-P3B fails to run | 2.0 – 4 | 7.4 – 2 |
| HPRBPPR | Pump HP-P3B fails to run during recirculation[e] | 2.0 – 3 | 7.4 – 1 |
| HPCPPR | Pump HP-P3C fails to run | 2.0 – 4 | 7.4 – 2 |
| HPRCPPR | Pump HP-P3C fails to run during recirculation[e] | 2.0 – 3 | 7.4 – 1 |
| HP15AVO | AOV valve 3HP-15 fails to open on demand[f] | 1.6 – 3 | 1.2 – 2 |
| HP16AVO | Piston-operated valve 3HP-6 fails to open on demand[d] | 3.5 – 3 | 1.2 – 2 |
| HP120UCF | AOV 3HP-120 control signal fails low[g] | 1.7 – 4 | 6.2 – 2 |
| HP120EPF | AOV 3HP-120 E/P module output fails low[h] | 4.6 – 5 | 1.7 – 2 |

Table I-1. (continued)

| Event Name | Description[a,b] | Mean Unavailability[c] | Mean Failure Rate ($yr^{-1}$) |
|---|---|---|---|
| HP120VPF | AOV 3HP-120 pneumatic positioner output fails low[h] | 4.6 – 5 | 1.7 – 2 |
| CS55CVO | Tilting-disk check valve 3CS-55 fails to open on demand[i] | 8.7 – 5 | 6.7 – 4 |
| CS86CVO | Tilting-disk check valve 3CS-36 fails to open on demand[f] | 8.7 – 5 | 6.7 – 4 |
| HPRCBPPS | RC bleed-transfer pump 3B fails to start on demand[j] | 8.4 – 4 | 6.5 – 3 |
| HPM53RVF | Pump HP-P3B fails to start on low seal flow[k] | 4.8 – 4 | 3.7 – 3 |
| HP31FTT | Flow transmitter controlling AOV 3HP-31 output fails high[k] | 3.1 – 5 | 1.1 – 2 |
| HP31UCT | AOV 3HP-31 control signal to E/P module fails high[l] | 6.0 – 4 | 2.2 – 1 |
| HP31VPT | Valve positioner output for AOV 3HP-31 fails high[k] | 4.6 – 5 | 1.7 – 2 |
| HP31EPT | Output fails high from E/P module for AOV-HP-31[k] | 4.6 – 5 | 1.7 – 2 |
| CC24CVO | Swing check valve 3CC-24 fails to open on demand | 9.8 – 5 | 2.0 – 4 |
| CC14CVO | Tilting-disk check valve 3CC-14 fails to open on demand | 8.7 – 5 | 1.7 – 4 |
| CC20CVO | Swing check valve 3CC-20 fails to open on demand | 9.8 – 5 | 2.0 – 4 |
| CCBPPS | Pump CC-P3B fails to start on demand[m] | 8.4 – 4 | 6.5 – 3 |
| CCBLSF | Pump CC-P3B fails to actuate on low CC flow[k] | 2.4 – 4 | 1.8 – 3 |

Table I-1. (continued)

| Event Name | Description[a,b] | Mean Unavailability[c] | Mean Failure Rate ($yr^{-1}$) |
|---|---|---|---|
| CCAPPR | Pump CC-P3A fails to run | 2.0 − 4 | 1.8 − 1 |
| CCABPSF | Limit switch for valve 3CC-7 or 3CC-8 opens, causing interlock to fail[n] | 2.3 − 4 | 8.2 − 2 |

a. Events used in the RISK Assessment

b. Abbreviations and acronyms: MOV, motor-operated valve; AOV, air-operated valve; RC, reactor coolant.

c. Unavailability" as used here includes contributions from all failure modes of interest. For some events there is more than one failure mode of interest, and the mean unavailability is the sum of the contributions from each failure mode, using an appropriate mean failure rate and duration.

d. Failure rate multiplied by 10 due to pumping sump water.

e. Pump is run for normal makeup; 1 month is maximum.

f. Cycled during operation.

g. Controls continuously; level transmitter failure rate x 10.

h. Controls continuously (generic data).

i. Also cycled during operation.

j. Also operated during operation; used data for HPI pumps.

k. OPRA generic data.

l. OPRA generic data x 5 for five modules in series.

m. Used data for HPI pumps.

n. OPRA generic data x 2 for two limit switches.

## Table I-2. Basic events for the high-pressure injection/recirculation system: human errors

| Event Name | Description[a] | Event Type[b] | Mean Unavailability[c] |
|---|---|---|---|
| HP2425MVH | MOVs 3HP-24 and 3HP-25 left unavailable | U | 5.0 – 5 |
| HP26MVCH | MOV 3HP-26 left unavailable | U | 1.5 – 4 |
| HP27MVH | MOV 3HP-27 left unavailable | U | 1.5 – 4 |
| HP409MVH | MOV 3HP-409 left unavailable | U | 2.9 – 4 |
| HP410MVH | MOV 3HP-410 left unavailable | U | 2.9 – 4 |
| HPSEGOH | Manual valves 3HP-33 or 3HP-100 left closed inadvertently | U | 2.2 – 4 |
| HP418VVH | Manual valve 3HP-148 left closed inadvertently | U | 6.1 – 4 |
| HPBCPPH | Pumps HP-P3B and HP-P3C left unavailable | U | 1.5 – 4 |
| HP24MVH | Operator fails to open MOV 3HP-24 | OF(Recovery) | 1.0 – 2<br>1.0 |
| HP25MVH | Operator fails to open MOV 3HP-25 | OF(Recovery) | 1.0 – 2<br>1.0 |
| HP26MVH | Operator fails to open MOV 3HP-26 | OF(Recovery) | 1.0 – 2<br>1.0 |
| HPCROSSH | Operator fails to open HPI crossover valves, 3HP-409, 3HP-H10 | OF(Recovery) | 1.0 – 2 |
| HPBPPH | Operator fails to start pump HP-P3B | OF(Recovery) | 1.0 – 2<br>1.0 |
| HPCPPH | Operator fails to start pump HP-P3C | OF(Recovery) | 1.0 – 2<br>1.0 |
| HPLDSTH | Operator fails to initiate letdown storage tank | OF | 1.0 – 2 |
| HPRCPH | Operator fails to trip RCPs on loss of cooling flow | OF | 1.0 – 2 |

a. Abbreviations and acronyms: MOV, motor-operated valve; RCP, reactor coolant pump.

b. Definition of event types; U, unavailability error; OF, "operator fails to" error.

c. Mean unavailability consists of all human-error contributions for a particular event.

**Table I-3. Basic events for the high-pressure injection/recirculation system: maintenance**

| Event Name | Mean Unavailability | Components in Maintenance Block |
|---|---|---|
| HP26MVM | 2.7 – 4 | MOV 3HP-26 |
| HP409MVM | 2.7 – 4 | MOV 3HP-409 |
| HP410MVM | 2.7 – 4 | MOV 3HP-410 |
| HPSEGKM | 1.5 – 3 | Pump HP-P3a; manual valves 3HP-106 and 3HP-103; check valve 3HP-105 |
| HPSEGMM | 1.5 – 3 | Pump HP-P3B; manual valves 3HP-107 and 3HP-110; check valve 3HP-109 |
| HPSEGHM | 6.1 – 4 | Pump HP-P3C; MOV 3HP-27; manual valves 3HP-111, 3HP-14 and 3HP-148; check valve 3HP-113 |
| HPSEGPM | 2.6 – 4 | MOV 3HP-24; check valve 3HP-101 |
| HPSEGQM | 2.6 – 4 | MOV 3HP-25; check valve 3HP-102 |

**Table I-4. Fault tree HPI importance measures report (5 year)**

Family: HPI
Fault Tree: HPI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HP2425MVH | 5.000E−005 | 5.213E−001 | 2.089E+000 | 1.043E+004 |
| HP24MVO | 6.400E−003 | 4.503E−001 | 1.819E+000 | 7.088E+001 |
| HP25MVO | 6.400E−003 | 4.502E−001 | 1.819E+000 | 7.087E+001 |
| HPSEGQM | 2.600E−004 | 3.523E−002 | 1.037E+000 | 6.861E+001 |
| HPSEGHM | 6.100E−004 | 2.046E−002 | 1.021E+000 | 1.699E+000 |
| HPSEGPM | 2.600E−004 | 1.757E−002 | 1.018E+000 | 6.856E+001 |
| HP101CVO | 8.700E−005 | 6.121E−003 | 1.006E+000 | 7.132E+001 |
| HP102CVO | 8.700E−005 | 6.120E−003 | 1.006E+000 | 7.131E+001 |
| HPSEGKM | 1.500E−003 | 2.816E−003 | 1.003E+000 | 2.585E+000 |
| HPSEGMM | 1.500E−003 | 2.815E−003 | 1.003E+000 | 1.005E+000 |
| HPBCPPH | 1.500E−004 | 2.451E−003 | 1.002E+000 | 1.734E+001 |
| HPCROSSH | 1.000E−002 | 2.212E−003 | 1.002E+000 | 1.219E+000 |
| HP26MVO | 6.400E−003 | 2.145E−003 | 1.002E+000 | 1.333E+000 |
| HPCPPS | 8.400E−004 | 6.308E−004 | 1.001E+000 | 1.750E+000 |
| HP148VVH | 6.100E−004 | 4.581E−004 | 1.000E+000 | 1.750E+000 |
| HP148VVT | 3.900E−004 | 2.929E−004 | 1.000E+000 | 1.751E+000 |
| HPCPPR | 2.000E−004 | 1.502E−004 | 1.000E+000 | 1.751E+000 |
| HP188CVO | 9.800E−005 | 1.162E−004 | 1.000E+000 | 2.186E+000 |
| HP27MVH | 1.500E−004 | 1.126E−004 | 1.000E+000 | 1.751E+000 |
| HP26MVM | 2.700E−004 | 7.322E−005 | 1.000E+000 | 1.271E+000 |
| HP113CVO | 8.700E−005 | 6.533E−005 | 1.000E+000 | 1.751E+000 |
| HP410MVO | 6.400E−003 | 5.414E−005 | 1.000E+000 | 1.008E+000 |
| HP26MVCH | 1.500E−004 | 5.027E−005 | 1.000E+000 | 1.335E+000 |
| HPSEGOH | 2.200E−004 | 4.772E−005 | 1.000E+000 | 1.217E+000 |
| HPBPPS | 8.400E−004 | 2.990E−005 | 1.000E+000 | 1.036E+000 |
| HPAPPR | 2.000E−004 | 9.328E−006 | 1.000E+000 | 1.047E+000 |
| HP409MVO | 6.400E−003 | 9.167E−006 | 1.000E+000 | 1.001E+000 |
| HPBPPR | 2.000E−004 | 8.384E−006 | 1.000E+000 | 1.042E+000 |
| HP109CVO | 8.700E−005 | 3.097E−006 | 1.000E+000 | 1.036E+000 |
| HP410MVM | 2.700E−004 | 2.284E−006 | 1.000E+000 | 1.008E+000 |
| HP409MVH | 2.900E−004 | 4.154E−007 | 1.000E+000 | 1.001E+000 |
| HP409MVM | 2.700E−004 | 3.867E−007 | 1.000E+000 | 1.001E+000 |
| HP152CVO | 9.800E−005 | 1.137E−008 | 1.000E+000 | 1.000E+000 |
| HP153CVO | 9.800E−005 | 1.137E−008 | 1.000E+000 | 1.000E+000 |

**Table I-5. Fault tree HPI importance measures report (10 year upper bound)**

Family: HPI
Fault Tree: HPI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HP24MVO | 7.000E – 003 | 4.911E – 001 | 1.965E + 000 | 7.064E + 001 |
| HP25MVO | 7.000E – 003 | 4.909E – 001 | 1.964E + 000 | 7.062E + 001 |
| HP2425MVH | 5.000E – 005 | 4.771E – 001 | 1.912E + 000 | 9.542E + 003 |
| HPSEGQM | 2.600E – 004 | 3.535E – 002 | 1.037E + 000 | 6.863E + 001 |
| HPSEGHM | 6.100E – 004 | 2.066E – 002 | 1.021E + 000 | 1.710E + 000 |
| HPSEGPM | 2.600E – 004 | 1.758E – 002 | 1.018E + 000 | 6.858E + 001 |
| HP101CVO | 9.100E – 005 | 6.383E – 003 | 1.006E + 000 | 7.112E + 001 |
| HP102CVO | 9.100E – 005 | 6.382E – 003 | 1.006E + 000 | 7.110E + 001 |
| HPCROSSH | 1.000E – 002 | 5.265E – 003 | 1.005E + 000 | 1.521E + 000 |
| HP26MVO | 7.000E – 003 | 5.058E – 003 | 1.005E + 000 | 1.717E + 000 |
| HPSEGKM | 1.500E – 003 | 2.905E – 003 | 1.003E + 000 | 2.574E + 000 |
| HPSEGMM | 1.500E – 003 | 2.902E – 003 | 1.003E + 000 | 1.071E + 000 |
| HP148VVT | 3.500E – 003 | 2.758E – 003 | 1.003E + 000 | 1.785E + 000 |
| HPBCPPH | 1.500E – 004 | 2.258E – 003 | 1.002E + 000 | 1.605E + 001 |
| HPCPPR | 1.100E – 003 | 8.667E – 004 | 1.001E + 000 | 1.787E + 000 |
| HPCPPS | 1.100E – 003 | 8.667E – 004 | 1.001E + 000 | 1.787E + 000 |
| HP148VVH | 6.100E – 004 | 4.806E – 004 | 1.000E + 000 | 1.787E + 000 |
| HPAPPR | 1.100E – 003 | 1.936E – 004 | 1.000E + 000 | 1.176E + 000 |
| HPBPPR | 1.100E – 003 | 1.887E – 004 | 1.000E + 000 | 1.171E + 000 |
| HP26MVM | 2.700E – 004 | 1.792E – 004 | 1.000E + 000 | 1.663E + 000 |
| HP188CVO | 1.000E – 004 | 1.224E – 004 | 1.000E + 000 | 2.224E + 000 |
| HP27MVH | 1.500E – 004 | 1.182E – 004 | 1.000E + 000 | 1.788E + 000 |
| HPSEGOH | 2.200E – 004 | 1.145E – 004 | 1.000E + 000 | 1.520E + 000 |
| HP113CVO | 1.400E – 004 | 1.103E – 004 | 1.000E + 000 | 1.788E + 000 |
| HP26MVCH | 1.500E – 004 | 1.084E – 004 | 1.000E + 000 | 1.722E + 000 |
| HPBPPS | 1.100E – 003 | 1.038E – 004 | 1.000E + 000 | 1.094E + 000 |
| HP410MVO | 7.000E – 003 | 7.704E – 005 | 1.000E + 000 | 1.011E + 000 |
| HP409MVO | 7.000E – 003 | 2.649E – 005 | 1.000E + 000 | 1.004E + 000 |
| HP109CVO | 1.400E – 004 | 1.322E – 005 | 1.000E + 000 | 1.094E + 000 |
| HP410MVM | 2.700E – 004 | 2.972E – 006 | 1.000E + 000 | 1.011E + 000 |
| HP409MVH | 2.900E – 004 | 1.097E – 006 | 1.000E + 000 | 1.004E + 000 |
| HP409MVM | 2.700E – 004 | 1.022E – 006 | 1.000E + 000 | 1.004E + 000 |
| HP153CVO | 1.000E – 004 | 1.221E – 008 | 1.000E + 000 | 1.000E + 000 |
| HP152CVO | 1.000E – 004 | 1.221E – 008 | 1.000E + 000 | 1.000E + 000 |

**Table I-6. Fault tree HPI importance measures report (10 year lower bound)**

Family: HPI
Fault Tree: HPI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HP2425MVH | 5.000E−005 | 5.135E−001 | 2.055E+000 | 1.027E+004 |
| HP24MVO | 6.500E−003 | 4.572E−001 | 1.842E+000 | 7.085E+001 |
| HP25MVO | 6.500E−003 | 4.571E−001 | 1.842E+000 | 7.084E+001 |
| HPSEGQM | 2.600E−004 | 3.527E−002 | 1.037E+000 | 6.863E+001 |
| HPSEGHM | 6.100E−004 | 2.052E−002 | 1.021E+000 | 1.701E+000 |
| HPSEGPM | 2.600E−004 | 1.758E−002 | 1.018E+000 | 6.858E+001 |
| HP101CVO | 8.800E−005 | 6.189E−003 | 1.006E+000 | 7.130E+001 |
| HP102CVO | 8.800E−005 | 6.188E−003 | 1.006E+000 | 7.129E+001 |
| HPCROSSH | 1.000E−002 | 3.098E−003 | 1.003E+000 | 1.307E+000 |
| HP26MVO | 6.500E−003 | 2.984E−003 | 1.003E+000 | 1.456E+000 |
| HPSEGKM | 1.500E−003 | 2.840E−003 | 1.003E+000 | 2.588E+000 |
| HPSEGMM | 1.500E−003 | 2.839E−003 | 1.003E+000 | 1.017E+000 |
| HPBCPPH | 1.500E−004 | 2.417E−003 | 1.002E+000 | 1.711E+001 |
| HP148VVT | 1.300E−003 | 9.896E−004 | 1.001E+000 | 1.760E+000 |
| HPCPPS | 9.100E−004 | 6.927E−004 | 1.001E+000 | 1.761E+000 |
| HP148VVH | 6.100E−004 | 4.643E−004 | 1.000E+000 | 1.761E+000 |
| HPCPPR | 4.600E−004 | 3.502E−004 | 1.000E+000 | 1.761E+000 |
| HP188CVO | 9.900E−005 | 1.181E−004 | 1.000E+000 | 2.192E+000 |
| HP27MVH | 1.500E−004 | 1.142E−004 | 1.000E+000 | 1.761E+000 |
| HP26MVM | 2.700E−004 | 1.069E−004 | 1.000E+000 | 1.396E+000 |
| HP113CVO | 9.500E−005 | 7.231E−005 | 1.000E+000 | 1.761E+000 |
| HP26MVCH | 1.500E−004 | 6.887E−005 | 1.000E+000 | 1.459E+000 |
| HPSEGOH | 2.200E−004 | 6.705E−005 | 1.000E+000 | 1.305E+000 |
| HP410MVO | 6.500E−003 | 5.962E−005 | 1.000E+000 | 1.009E+000 |
| HPBPPS | 9.100E−004 | 4.937E−005 | 1.000E+000 | 1.054E+000 |
| HPAPPR | 4.600E−004 | 3.641E−005 | 1.000E+000 | 1.079E+000 |
| HPBPPR | 4.600E−004 | 3.426E−005 | 1.000E+000 | 1.074E+000 |
| HP409MVO | 6.500E−003 | 1.335E−005 | 1.000E+000 | 1.002E+000 |
| HP109CVO | 9.500E−005 | 5.154E−006 | 1.000E+000 | 1.054E+000 |
| HP410MVM | 2.700E−004 | 2.477E−006 | 1.000E+000 | 1.009E+000 |
| HP409MVH | 2.900E−004 | 5.958E−007 | 1.000E+000 | 1.002E+000 |
| HP409MVM | 2.700E−004 | 5.547E−007 | 1.000E+000 | 1.002E+000 |
| HP152CVO | 9.900E−005 | 1.167E−008 | 1.000E+000 | 1.000E+000 |
| HP153CVO | 9.900E−005 | 1.167E−008 | 1.000E+000 | 1.000E+000 |

**Table I-7. Fault tree HPI importance measures report (40 year upper bound)**

Family: HPI
Fault Tree: HPI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HP24MVO | 1.000E-002 | 6.338E-001 | 2.730E+000 | 6.372E+001 |
| HP25MVO | 1.000E-002 | 6.333E-001 | 2.727E+000 | 6.367E+001 |
| HP2425MVH | 5.000E-005 | 3.050E-001 | 1.439E+000 | 6.102E+003 |
| HPSEGQM | 2.600E-004 | 3.265E-002 | 1.034E+000 | 6.272E+001 |
| HP148VVT | 2.200E-002 | 2.402E-002 | 1.025E+000 | 2.068E+000 |
| HPSEGHM | 6.100E-004 | 2.354E-002 | 1.024E+000 | 1.918E+000 |
| HPCROSSH | 1.000E-002 | 2.135E-002 | 1.022E+000 | 3.113E+000 |
| HP26MVO | 1.000E-002 | 2.080E-002 | 1.021E+000 | 3.059E+000 |
| HPSEGPM | 2.600E-004 | 1.605E-002 | 1.016E+000 | 6.270E+001 |
| HPAPPR | 6.800E-003 | 1.150E-002 | 1.012E+000 | 2.679E+000 |
| HPBPPR | 6.800E-003 | 1.147E-002 | 1.012E+000 | 2.676E+000 |
| HP101CVO | 1.200E-004 | 7.604E-003 | 1.008E+000 | 6.434E+001 |
| HP102CVO | 1.200E-004 | 7.599E-003 | 1.008E+000 | 6.429E+001 |
| HPCPPR | 6.800E-003 | 7.424E-003 | 1.007E+000 | 2.084E+000 |
| HPSEGKM | 1.500E-003 | 6.959E-003 | 1.007E+000 | 3.900E+000 |
| HPSEGMM | 1.500E-003 | 6.943E-003 | 1.007E+000 | 2.358E+000 |
| HPCPPS | 2.700E-003 | 2.948E-003 | 1.003E+000 | 2.089E+000 |
| HPBCPPH | 1.500E-004 | 1.529E-003 | 1.002E+000 | 1.119E+001 |
| HPBPPS | 2.700E-003 | 8.121E-004 | 1.001E+000 | 1.300E+000 |
| HP148VVH | 6.100E-004 | 6.660E-004 | 1.001E+000 | 2.091E+000 |
| HP26MVM | 2.700E-004 | 5.510E-004 | 1.001E+000 | 3.040E+000 |
| HP113CVO | 4.500E-004 | 4.913E-004 | 1.000E+000 | 2.091E+000 |
| HPSEGOH | 2.200E-004 | 4.685E-004 | 1.000E+000 | 3.129E+000 |
| HP26MVCH | 1.500E-004 | 3.120E-004 | 1.000E+000 | 3.080E+000 |
| HP410MVO | 1.000E-002 | 3.072E-004 | 1.000E+000 | 1.030E+000 |
| HP409MVO | 1.000E-002 | 2.190E-004 | 1.000E+000 | 1.022E+000 |
| HP188CVO | 1.300E-004 | 1.687E-004 | 1.000E+000 | 2.297E+000 |
| HP27MVH | 1.500E-004 | 1.638E-004 | 1.000E+000 | 2.092E+000 |
| HP109CVO | 4.500E-004 | 1.353E-004 | 1.000E+000 | 1.301E+000 |
| HP410MVM | 2.700E-004 | 8.295E-006 | 1.000E+000 | 1.031E+000 |
| HP409MVH | 2.900E-004 | 6.351E-006 | 1.000E+000 | 1.022E+000 |
| HP409MVM | 2.700E-004 | 5.913E-006 | 1.000E+000 | 1.022E+000 |
| HP152CVO | 1.300E-004 | 2.176E-008 | 1.000E+000 | 1.000E+000 |
| HP153CVO | 1.300E-004 | 2.176E-008 | 1.000E+000 | 1.000E+000 |

**Table I-8. Fault tree HPI importance measures report (40 year lower bound)**

Family: HPI
Fault Tree: HPI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HP24MVO | 7.100E−003 | 4.958E−001 | 1.983E+000 | 7.031E+001 |
| HP25MVO | 7.100E−003 | 4.956E−001 | 1.982E+000 | 7.028E+001 |
| HP2425MVH | 5.000E−005 | 4.684E−001 | 1.881E+000 | 9.369E+003 |
| HPSEGQM | 2.600E−004 | 3.531E−002 | 1.037E+000 | 6.834E+001 |
| HPSEGHM | 6.100E−004 | 2.121E−002 | 1.022E+000 | 1.733E+000 |
| HPSEGPM | 2.600E−004 | 1.751E−002 | 1.018E+000 | 6.830E+001 |
| HPCROSSH | 1.000E−002 | 8.410E−003 | 1.008E+000 | 1.833E+000 |
| HP26MVO | 7.100E−003 | 8.048E−003 | 1.008E+000 | 2.125E+000 |
| HP101CVO | 9.100E−005 | 6.354E−003 | 1.006E+000 | 7.079E+001 |
| HP102CVO | 9.100E−005 | 6.352E−003 | 1.006E+000 | 7.077E+001 |
| HP148VVT | 6.800E−003 | 5.705E−003 | 1.006E+000 | 1.833E+000 |
| HPSEGKM | 1.500E−003 | 3.422E−003 | 1.003E+000 | 2.770E+000 |
| HPSEGMM | 1.500E−003 | 3.417E−003 | 1.003E+000 | 1.210E+000 |
| HPBCPPH | 1.500E−004 | 2.226E−003 | 1.002E+000 | 1.584E+001 |
| HPCPPR | 2.000E−003 | 1.678E−003 | 1.002E+000 | 1.837E+000 |
| HPCPPS | 1.400E−003 | 1.175E−003 | 1.001E+000 | 1.838E+000 |
| HPAPPR | 2.000E−003 | 7.648E−004 | 1.001E+000 | 1.382E+000 |
| HPBPPR | 2.000E−003 | 7.558E−004 | 1.001E+000 | 1.377E+000 |
| HP148VVH | 6.100E−004 | 5.118E−004 | 1.001E+000 | 1.838E+000 |
| HP26MVM | 2.700E−004 | 2.903E−004 | 1.000E+000 | 2.075E+000 |
| HPBPPS | 1.400E−003 | 2.184E−004 | 1.000E+000 | 1.156E+000 |
| HPSEGOH | 2.200E−004 | 1.831E−004 | 1.000E+000 | 1.832E+000 |
| HP26MVCH | 1.500E−004 | 1.700E−004 | 1.000E+000 | 2.133E+000 |
| HP27MVH | 1.500E−004 | 1.258E−004 | 1.000E+000 | 1.839E+000 |
| HP188CVO | 1.000E−004 | 1.226E−004 | 1.000E+000 | 2.226E+000 |
| HP113CVO | 1.400E−004 | 1.175E−004 | 1.000E+000 | 1.839E+000 |
| HP410MVO | 7.100E−003 | 9.537E−005 | 1.000E+000 | 1.013E+000 |
| HP409MVO | 7.100E−003 | 4.373E−005 | 1.000E+000 | 1.006E+000 |
| HP109CVO | 1.400E−004 | 2.184E−005 | 1.000E+000 | 1.156E+000 |
| HP410MVM | 2.700E−004 | 3.627E−006 | 1.000E+000 | 1.013E+000 |
| HP409MVH | 2.900E−004 | 1.786E−006 | 1.000E+000 | 1.006E+000 |
| HP409MVM | 2.700E−004 | 1.663E−006 | 1.000E+000 | 1.006E+000 |
| HP152CVO | 1.000E−004 | 1.223E−008 | 1.000E+000 | 1.000E+000 |
| HP153CVO | 1.000E−004 | 1.223E−008 | 1.000E+000 | 1.000E+000 |

**Table I-9. Fault tree HP201 importance measures report (5 year)**

Family: HPI
Fault Tree: HP201
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPCROSSH | 1.000E−002 | 3.967E−001 | 1.657E+000 | 4.025E+001 |
| HP26MVO | 6.400E−003 | 3.738E−001 | 1.597E+000 | 5.902E+001 |
| HP2425MVH | 5.000E−005 | 2.906E−001 | 1.410E+000 | 5.813E+003 |
| HP24MVO | 6.400E−003 | 2.592E−001 | 1.350E+000 | 4.122E+001 |
| HP25MVO | 6.400E−003 | 2.510E−001 | 1.335E+000 | 3.995E+001 |
| HPSEGHM | 6.100E−004 | 5.964E−002 | 1.063E+000 | 2.178E+000 |
| HPSEGQM | 2.600E−004 | 3.568E−002 | 1.037E+000 | 3.869E+001 |
| HPSEGKM | 1.500E−003 | 3.509E−002 | 1.036E+000 | 8.642E+000 |
| HPSEGMM | 1.500E−003 | 3.376E−002 | 1.035E+000 | 1.622E+001 |
| HP26MVM | 2.700E−004 | 1.575E−002 | 1.016E+000 | 5.933E+001 |
| HPSEGPM | 2.600E−004 | 1.013E−002 | 1.010E+000 | 3.993E+001 |
| HP26MVCH | 1.500E−004 | 8.760E−003 | 1.009E+000 | 5.939E+001 |
| HPSEGOH | 2.200E−004 | 8.642E−003 | 1.009E+000 | 4.026E+001 |
| HPCPPS | 8.400E−004 | 8.432E−003 | 1.009E+000 | 1.103E+001 |
| HPBPPS | 8.400E−004 | 7.326E−003 | 1.007E+000 | 9.714E+000 |
| HP148VVH | 6.100E−004 | 6.123E−003 | 1.006E+000 | 1.103E+001 |
| HPBPPR | 2.000E−004 | 5.505E−003 | 1.006E+000 | 2.847E+001 |
| HP148VVT | 3.900E−004 | 3.915E−003 | 1.004E+000 | 1.103E+001 |
| HP101CVO | 8.700E−005 | 3.523E−003 | 1.004E+000 | 4.147E+001 |
| HP102CVO | 8.700E−005 | 3.412E−003 | 1.003E+000 | 4.020E+001 |
| HPBCPPH | 1.500E−004 | 2.790E−003 | 1.003E+000 | 1.958E+001 |
| HPAPPR | 2.000E−004 | 2.036E−003 | 1.002E+000 | 1.118E+001 |
| HPCPPR | 2.000E−004 | 2.008E−003 | 1.002E+000 | 1.103E+001 |
| HP409MVO | 6.400E−003 | 1.854E−003 | 1.002E+000 | 1.288E+000 |
| HP410MVO | 6.400E−003 | 1.798E−003 | 1.002E+000 | 1.279E+000 |
| HP27MVH | 1.500E−004 | 1.506E−003 | 1.002E+000 | 1.103E+001 |
| HP113CVO | 8.700E−005 | 8.733E−004 | 1.001E+000 | 1.104E+001 |
| HP109CVO | 8.700E−005 | 7.588E−004 | 1.001E+000 | 9.721E+000 |
| HP409MVH | 2.900E−004 | 8.401E−005 | 1.000E+000 | 1.290E+000 |
| HP409MVM | 2.700E−004 | 7.821E−005 | 1.000E+000 | 1.290E+000 |
| HP410MVM | 2.700E−004 | 7.584E−005 | 1.000E+000 | 1.281E+000 |
| HP188CVO | 9.800E−005 | 6.516E−005 | 1.000E+000 | 1.665E+000 |
| HP153CVO | 9.800E−005 | 6.363E−009 | 1.000E+000 | 1.000E+000 |
| HP152CVO | 9.800E−005 | 6.363E−009 | 1.000E+000 | 1.000E+000 |

**Table I-10. Fault tree HP201 importance measures report (10 year upper bound)**

Family: HPI
Fault Tree: HP201
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPCROSSH | 1.000E−002 | 3.622E−001 | 1.568E+000 | 3.685E+001 |
| HP26MVO | 7.000E−003 | 3.428E−001 | 1.522E+000 | 4.963E+001 |
| HP24MVO | 7.000E−003 | 2.581E−001 | 1.348E+000 | 3.759E+001 |
| HP25MVO | 7.000E−003 | 2.506E−001 | 1.334E+000 | 3.654E+001 |
| HP2425MVH | 5.000E−005 | 2.435E−001 | 1.322E+000 | 4.871E+003 |
| HPSEGHM | 6.100E−004 | 1.009E−001 | 1.112E+000 | 6.431E+000 |
| HPSEGKM | 1.500E−003 | 7.965E−002 | 1.087E+000 | 1.369E+001 |
| HPSEGMM | 1.500E−003 | 7.848E−002 | 1.085E+000 | 3.900E+001 |
| HPBPPR | 1.100E−003 | 5.335E−002 | 1.056E+000 | 4.925E+001 |
| HP148VVT | 3.500E−003 | 4.507E−002 | 1.047E+000 | 1.382E+001 |
| HPSEGQM | 2.600E−004 | 3.144E−002 | 1.032E+000 | 3.552E+001 |
| HPAPPR | 1.100E−003 | 1.462E−002 | 1.015E+000 | 1.427E+001 |
| HPCPPR | 1.100E−003 | 1.417E−002 | 1.014E+000 | 1.385E+001 |
| HPCPPS | 1.100E−003 | 1.417E−002 | 1.014E+000 | 1.385E+001 |
| HP26MVM | 2.700E−004 | 1.321E−002 | 1.013E+000 | 4.991E+001 |
| HPSEGPM | 2.600E−004 | 9.249E−003 | 1.009E+000 | 3.655E+001 |
| HPBPPS | 1.100E−003 | 8.080E−003 | 1.008E+000 | 8.337E+000 |
| HPSEGOH | 2.200E−004 | 7.896E−003 | 1.008E+000 | 3.687E+001 |
| HP148VVH | 6.100E−004 | 7.855E−003 | 1.008E+000 | 1.386E+001 |
| HP26MVCH | 1.500E−004 | 7.345E−003 | 1.007E+000 | 4.996E+001 |
| HP101CVO | 9.100E−005 | 3.355E−003 | 1.003E+000 | 3.785E+001 |
| HP102CVO | 9.100E−005 | 3.258E−003 | 1.003E+000 | 3.678E+001 |
| HPBCPPH | 1.500E−004 | 3.007E−003 | 1.003E+000 | 2.101E+001 |
| HP409MVO | 7.000E−003 | 2.469E−003 | 1.002E+000 | 1.350E+000 |
| HP410MVO | 7.000E−003 | 1.951E−003 | 1.002E+000 | 1.277E+000 |
| HP27MVH | 1.500E−004 | 1.932E−003 | 1.002E+000 | 1.387E+001 |
| HP113CVO | 1.400E−004 | 1.803E−003 | 1.002E+000 | 1.387E+001 |
| HP109CVO | 1.400E−004 | 1.028E−003 | 1.001E+000 | 8.344E+000 |
| HP409MVH | 2.900E−004 | 1.023E−004 | 1.000E+000 | 1.353E+000 |
| HP409MVM | 2.700E−004 | 9.524E−005 | 1.000E+000 | 1.353E+000 |
| HP188CVO | 1.000E−004 | 7.990E−005 | 1.000E+000 | 1.799E+000 |
| HP410MVM | 2.700E−004 | 7.524E−005 | 1.000E+000 | 1.279E+000 |
| HP153CVO | 1.000E−004 | 7.908E−009 | 1.000E+000 | 1.000E+000 |
| HP152CVO | 1.000E−004 | 7.908E−009 | 1.000E+000 | 1.000E+000 |

**Table I-11. Fault tree HP201 importance measures report (10 year lower bound)**

Family: HPI
Fault Tree: HP201
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPCROSSH | 1.000E−002 | 3.874E−001 | 1.632E+000 | 3.934E+001 |
| HP26MVO | 6.500E−003 | 3.653E−001 | 1.576E+000 | 5.683E+001 |
| HP2425MVH | 5.000E−005 | 2.796E−001 | 1.388E+000 | 5.593E+003 |
| HP24MVO | 6.500E−003 | 2.569E−001 | 1.346E+000 | 4.025E+001 |
| HP25MVO | 6.500E−003 | 2.489E−001 | 1.331E+000 | 3.904E+001 |
| HPSEGHM | 6.100E−004 | 7.407E−002 | 1.080E+000 | 3.607E+000 |
| HPSEGKM | 1.500E−003 | 5.031E−002 | 1.053E+000 | 1.036E+001 |
| HPSEGMM | 1.500E−003 | 4.902E−002 | 1.052E+000 | 2.402E+001 |
| HPSEGQM | 2.600E−004 | 3.463E−002 | 1.036E+000 | 3.783E+001 |
| HPBPPR | 4.600E−004 | 1.606E−002 | 1.016E+000 | 3.581E+001 |
| HP26MVM | 2.700E−004 | 1.516E−002 | 1.015E+000 | 5.713E+001 |
| HP148VVT | 1.300E−003 | 1.448E−002 | 1.015E+000 | 1.212E+001 |
| HPCPPS | 9.100E−004 | 1.014E−002 | 1.010E+000 | 1.212E+001 |
| HPSEGPM | 2.600E−004 | 9.890E−003 | 1.010E+000 | 3.902E+001 |
| HPSEGOH | 2.200E−004 | 8.442E−003 | 1.009E+000 | 3.935E+001 |
| HP26MVCH | 1.500E−004 | 8.429E−003 | 1.009E+000 | 5.718E+001 |
| HPBPPS | 9.100E−004 | 7.648E−003 | 1.008E+000 | 9.397E+000 |
| HP148VVH | 6.100E−004 | 6.795E−003 | 1.007E+000 | 1.213E+001 |
| HPAPPR | 4.600E−004 | 5.231E−003 | 1.005E+000 | 1.236E+001 |
| HPCPPR | 4.600E−004 | 5.124E−003 | 1.005E+000 | 1.213E+001 |
| HP101CVO | 8.800E−005 | 3.478E−003 | 1.003E+000 | 4.050E+001 |
| HP102CVO | 8.800E−005 | 3.370E−003 | 1.003E+000 | 3.928E+001 |
| HPBCPPH | 1.500E−004 | 2.906E−003 | 1.003E+000 | 2.035E+001 |
| HP409MVO | 6.500E−003 | 1.981E−003 | 1.002E+000 | 1.303E+000 |
| HP410MVO | 6.500E−003 | 1.810E−003 | 1.002E+000 | 1.277E+000 |
| HP27MVH | 1.500E−004 | 1.671E−003 | 1.002E+000 | 1.213E+001 |
| HP113CVO | 9.500E−005 | 1.058E−003 | 1.001E+000 | 1.213E+001 |
| HP109CVO | 9.500E−005 | 7.984E−004 | 1.001E+000 | 9.403E+000 |
| HP409MVH | 2.900E−004 | 8.836E−005 | 1.000E+000 | 1.305E+000 |
| HP409MVM | 2.700E−004 | 8.227E−005 | 1.000E+000 | 1.305E+000 |
| HP410MVM | 2.700E−004 | 7.517E−005 | 1.000E+000 | 1.278E+000 |
| HP188CVO | 9.900E−005 | 7.026E−005 | 1.000E+000 | 1.710E+000 |
| HP153CVO | 9.900E−005 | 6.912E−009 | 1.000E+000 | 1.000E+000 |
| HP152CVO | 9.900E−005 | 6.912E−009 | 1.000E+000 | 1.000E+000 |

**Table I-12. Fault tree HP201 importance measures report (40 year upper bound)**

Family: HPI
Fault Tree: HP201
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPBPPR | 6.800E-003 | 4.584E-001 | 1.846E+000 | 6.703E+001 |
| HP148VVT | 2.200E-002 | 3.008E-001 | 1.430E+000 | 1.435E+001 |
| HPCROSSH | 1.000E-002 | 1.726E-001 | 1.209E+000 | 1.808E+001 |
| HP24MVO | 1.000E-002 | 1.710E-001 | 1.206E+000 | 1.792E+001 |
| HP25MVO | 1.000E-002 | 1.675E-001 | 1.201E+000 | 1.758E+001 |
| HP26MVO | 1.000E-002 | 1.632E-001 | 1.195E+000 | 1.715E+001 |
| HPSEGHM | 6.100E-004 | 1.370E-001 | 1.159E+000 | 1.216E+001 |
| HPSEGKM | 1.500E-003 | 1.289E-001 | 1.148E+000 | 1.848E+001 |
| HPSEGMM | 1.500E-003 | 1.283E-001 | 1.147E+000 | 6.398E+001 |
| HPAPPR | 6.800E-003 | 9.870E-002 | 1.110E+000 | 1.539E+001 |
| HPCPPR | 6.800E-003 | 9.296E-002 | 1.102E+000 | 1.456E+001 |
| HP2425MVH | 5.000E-005 | 8.068E-002 | 1.088E+000 | 1.614E+003 |
| HPCPPS | 2.700E-003 | 3.691E-002 | 1.038E+000 | 1.462E+001 |
| HPSEGQM | 2.600E-004 | 1.298E-002 | 1.013E+000 | 1.732E+001 |
| HP148VVH | 6.100E-004 | 8.339E-003 | 1.008E+000 | 1.464E+001 |
| HPBPPS | 2.700E-003 | 6.779E-003 | 1.007E+000 | 3.504E+000 |
| HP409MVO | 1.000E-002 | 6.224E-003 | 1.006E+000 | 1.616E+000 |
| HP113CVO | 4.500E-004 | 6.152E-003 | 1.006E+000 | 1.465E+001 |
| HP26MVM | 2.700E-004 | 4.401E-003 | 1.004E+000 | 1.729E+001 |
| HPSEGPM | 2.600E-004 | 4.334E-003 | 1.004E+000 | 1.766E+001 |
| HPSEGOH | 2.200E-004 | 3.716E-003 | 1.004E+000 | 1.788E+001 |
| HP26MVCH | 1.500E-004 | 2.447E-003 | 1.002E+000 | 1.731E+001 |
| HPBCPPH | 1.500E-004 | 2.405E-003 | 1.002E+000 | 1.699E+001 |
| HP101CVO | 1.200E-004 | 2.052E-003 | 1.002E+000 | 1.809E+001 |
| HP27MVH | 1.500E-004 | 2.051E-003 | 1.002E+000 | 1.465E+001 |
| HP102CVO | 1.200E-004 | 2.010E-003 | 1.002E+000 | 1.774E+001 |
| HP410MVO | 1.000E-002 | 1.861E-003 | 1.002E+000 | 1.184E+000 |
| HP109CVO | 4.500E-004 | 1.130E-003 | 1.001E+000 | 3.509E+000 |
| HP409MVH | 2.900E-004 | 1.805E-004 | 1.000E+000 | 1.622E+000 |
| HP409MVM | 2.700E-004 | 1.680E-004 | 1.000E+000 | 1.622E+000 |
| HP188CVO | 1.300E-004 | 1.119E-004 | 1.000E+000 | 1.860E+000 |
| HP410MVM | 2.700E-004 | 5.024E-005 | 1.000E+000 | 1.186E+000 |
| HP152CVO | 1.300E-004 | 1.428E-008 | 1.000E+000 | 1.000E+000 |
| HP153CVO | 1.300E-004 | 1.428E-008 | 1.000E+000 | 1.000E+000 |

**Table I-13. Fault tree HP201 importance measures report (40 year lower bound)**

Family: HPI
Fault Tree: HP201
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPCROSSH | 1.000E−002 | 3.196E−001 | 1.470E+000 | 3.263E+001 |
| HP26MVO | 7.100E−003 | 3.018E−001 | 1.432E+000 | 4.321E+001 |
| HP24MVO | 7.100E−003 | 2.302E−001 | 1.299E+000 | 3.318E+001 |
| HP25MVO | 7.100E−003 | 2.236E−001 | 1.288E+000 | 3.226E+001 |
| HP2425MVH | 5.000E−005 | 2.113E−001 | 1.268E+000 | 4.228E+003 |
| HPSEGHM | 6.100E−004 | 1.323E−001 | 1.153E+000 | 9.572E+000 |
| HPBPPR | 2.000E−003 | 1.298E−001 | 1.149E+000 | 6.542E+001 |
| HPSEGKM | 1.500E−003 | 1.138E−001 | 1.128E+000 | 1.744E+001 |
| HPSEGMM | 1.500E−003 | 1.127E−001 | 1.127E+000 | 5.657E+001 |
| HP148VVT | 6.800E−003 | 1.024E−001 | 1.114E+000 | 1.594E+001 |
| HPAPPR | 2.000E−003 | 3.137E−002 | 1.032E+000 | 1.664E+001 |
| HPCPPR | 2.000E−003 | 3.010E−002 | 1.031E+000 | 1.601E+001 |
| HPSEGQM | 2.600E−004 | 2.751E−002 | 1.028E+000 | 3.139E+001 |
| HPCPPS | 1.400E−003 | 2.107E−002 | 1.022E+000 | 1.602E+001 |
| HP26MVM | 2.700E−004 | 1.147E−002 | 1.012E+000 | 4.346E+001 |
| HP148VVH | 6.100E−004 | 9.182E−003 | 1.009E+000 | 1.603E+001 |
| HPBPPS | 1.400E−003 | 8.974E−003 | 1.009E+000 | 7.401E+000 |
| HPSEGPM | 2.600E−004 | 8.137E−003 | 1.008E+000 | 3.228E+001 |
| HPSEGOH | 2.200E−004 | 6.953E−003 | 1.007E+000 | 3.259E+001 |
| HP26MVCH | 1.500E−004 | 6.377E−003 | 1.006E+000 | 4.350E+001 |
| HPBCPPH | 1.500E−004 | 3.191E−003 | 1.003E+000 | 2.223E+001 |
| HP101CVO | 9.100E−005 | 2.951E−003 | 1.003E+000 | 3.340E+001 |
| HP409MVO | 7.100E−003 | 2.895E−003 | 1.003E+000 | 1.405E+000 |
| HP102CVO | 9.100E−005 | 2.866E−003 | 1.003E+000 | 3.248E+001 |
| HP27MVH | 1.500E−004 | 2.258E−003 | 1.002E+000 | 1.604E+001 |
| HP113CVO | 1.400E−004 | 2.107E−003 | 1.002E+000 | 1.604E+001 |
| HP410MVO | 7.100E−003 | 1.771E−003 | 1.002E+000 | 1.248E+000 |
| HP109CVO | 1.400E−004 | 8.974E−004 | 1.001E+000 | 7.409E+000 |
| HP409MVH | 2.900E−004 | 1.182E−004 | 1.000E+000 | 1.408E+000 |
| HP409MVM | 2.700E−004 | 1.101E−004 | 1.000E+000 | 1.408E+000 |
| HP188CVO | 1.000E−004 | 8.655E−005 | 1.000E+000 | 1.865E+000 |
| HP410MVM | 2.700E−004 | 6.733E−005 | 1.000E+000 | 1.249E+000 |
| HP153CVO | 1.000E−004 | 8.529E−009 | 1.000E+000 | 1.000E+000 |
| HP152CVO | 1.000E−004 | 8.529E−009 | 1.000E+000 | 1.000E+000 |

**Table I-14. Fault tree HPRI importance measures report (5 year)**

Family: HPI
Fault Tree: HPRI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPSEGMM | 1.500E−003 | 4.757E−001 | 1.907E+000 | 1.001E+000 |
| HPSEGKM | 1.500E−003 | 4.757E−001 | 1.907E+000 | 2.868E+002 |
| HPSEGHM | 6.100E−004 | 4.757E−001 | 1.907E+000 | 7.691E+001 |
| HP26MVO | 6.400E−003 | 3.541E−001 | 1.548E+000 | 5.597E+001 |
| HPCROSSH | 1.000E−002 | 3.541E−001 | 1.548E+000 | 3.606E+001 |
| HPBCPPH | 1.500E−004 | 2.673E−001 | 1.365E+000 | 1.783E+003 |
| HPRAPPR | 2.000E−003 | 2.166E−001 | 1.276E+000 | 1.091E+002 |
| HP2425MVH | 5.000E−005 | 2.081E−001 | 1.263E+000 | 4.160E+003 |
| HP25MVO | 6.400E−003 | 1.705E−001 | 1.206E+000 | 2.747E+001 |
| HP24MVO | 6.400E−003 | 1.705E−001 | 1.206E+000 | 2.747E+001 |
| HPRCPPR | 2.000E−003 | 1.524E−001 | 1.180E+000 | 7.703E+001 |
| HPCPPS | 8.400E−004 | 6.399E−002 | 1.068E+000 | 7.712E+001 |
| HP148VVH | 6.100E−004 | 4.647E−002 | 1.049E+000 | 7.714E+001 |
| HP148VVT | 3.900E−004 | 2.971E−002 | 1.031E+000 | 7.715E+001 |
| HPCPPR | 2.000E−004 | 1.524E−002 | 1.015E+000 | 7.717E+001 |

**Table I-15. Fault tree HPRI importance measures report (10 year upper bound)**

Family: HPI
Fault Tree: HPRI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPCROSSH | 1.000E−002 | 4.618E−001 | 1.858E+000 | 4.672E+001 |
| HP26MVO | 7.000E−003 | 4.618E−001 | 1.858E+000 | 6.651E+001 |
| HPRAPPR | 1.100E−002 | 4.010E−001 | 1.669E+000 | 3.705E+001 |
| HPRCPPR | 1.100E−002 | 2.835E−001 | 1.396E+000 | 2.649E+001 |
| HP2425MVH | 5.000E−005 | 2.301E−001 | 1.299E+000 | 4.596E+003 |
| HP25MVO | 7.000E−003 | 2.255E−001 | 1.291E+000 | 3.298E+001 |
| HP24MVO | 7.000E−003 | 2.255E−001 | 1.291E+000 | 3.298E+001 |
| HPSEGKM | 1.500E−003 | 1.529E−001 | 1.181E+000 | 9.234E+001 |
| HPSEGMM | 1.500E−003 | 1.529E−001 | 1.181E+000 | 1.000E+000 |
| HPSEGHM | 6.100E−004 | 1.529E−001 | 1.181E+000 | 2.668E+001 |
| HP148VVT | 3.500E−003 | 9.021E−002 | 1.099E+000 | 2.668E+001 |
| HPBCPPH | 1.500E−004 | 8.267E−002 | 1.090E+000 | 5.520E+002 |
| HPCPPS | 1.100E−003 | 2.835E−002 | 1.029E+000 | 2.674E+001 |
| HPCPPR | 1.100E−003 | 2.835E−002 | 1.029E+000 | 2.674E+001 |
| HP148VVH | 6.100E−004 | 1.572E−002 | 1.016E+000 | 2.676E+001 |

**Table I-16. Fault tree HPRI importance measures report (10 year lower bound)**

Family: HPI
Fault Tree: HPRI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPCROSSH | 1.000E−002 | 4.121E−001 | 1.701E+000 | 4.180E+001 |
| HP26MVO | 6.500E−003 | 4.121E−001 | 1.701E+000 | 6.399E+001 |
| HPRAPPR | 4.600E−003 | 3.170E−001 | 1.464E+000 | 6.959E+001 |
| HPSEGHM | 6.100E−004 | 3.004E−001 | 1.429E+000 | 4.938E+001 |
| HPSEGKM | 1.500E−003 | 3.004E−001 | 1.429E+000 | 1.813E+002 |
| HPSEGMM | 1.500E−003 | 3.004E−001 | 1.429E+000 | 1.000E+000 |
| HP2425MVH | 5.000E−005 | 2.277E−001 | 1.295E+000 | 4.550E+003 |
| HPRCPPR | 4.600E−003 | 2.234E−001 | 1.288E+000 | 4.933E+001 |
| HP25MVO | 6.500E−003 | 1.924E−001 | 1.238E+000 | 3.041E+001 |
| HP24MVO | 6.500E−003 | 1.924E−001 | 1.238E+000 | 3.041E+001 |
| HPBCPPH | 1.500E−004 | 1.677E−001 | 1.202E+000 | 1.119E+003 |
| HP148VVT | 1.300E−003 | 6.312E−002 | 1.067E+000 | 4.949E+001 |
| HPCPPS | 9.100E−004 | 4.418E−002 | 1.046E+000 | 4.951E+001 |
| HP148VVH | 6.100E−004 | 2.962E−002 | 1.031E+000 | 4.953E+001 |
| HPCPPR | 4.600E−004 | 2.234E−002 | 1.023E+000 | 4.953E+001 |

**Table I-17. Fault tree HPRI importance measures report (40 year upper bound)**

Family: HPI
Fault Tree: HPRI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPRAPPR | 6.800E−002 | 4.923E−001 | 1.969E+000 | 7.747E+000 |
| HP26MVO | 1.000E−002 | 4.861E−001 | 1.946E+000 | 4.911E+001 |
| HPCROSSH | 1.000E−002 | 4.861E−001 | 1.946E+000 | 4.911E+001 |
| HP25MVO | 1.000E−002 | 3.354E−001 | 1.505E+000 | 3.420E+001 |
| HP24MVO | 1.000E−002 | 3.354E−001 | 1.505E+000 | 3.420E+001 |
| HPRCPPR | 6.800E−002 | 3.282E−001 | 1.488E+000 | 5.498E+000 |
| HP2425MVH | 5.000E−005 | 1.677E−001 | 1.201E+000 | 3.350E+003 |
| HP148VVT | 2.200E−002 | 1.062E−001 | 1.119E+000 | 5.720E+000 |
| HPCPPR | 6.800E−003 | 3.282E−002 | 1.034E+000 | 5.793E+000 |
| HPSEGMM | 1.500E−003 | 2.461E−002 | 1.025E+000 | 1.000E+000 |
| HPSEGKM | 1.500E−003 | 2.461E−002 | 1.025E+000 | 1.542E+001 |
| HPSEGHM | 6.100E−004 | 2.461E−002 | 1.025E+000 | 5.809E+000 |
| HPCPPS | 2.700E−003 | 1.303E−002 | 1.013E+000 | 5.813E+000 |
| HPBCPPH | 1.500E−004 | 1.084E−002 | 1.011E+000 | 7.323E+001 |
| HP148VVH | 6.100E−004 | 2.944E−003 | 1.003E+000 | 5.823E+000 |

**Table I-18. Fault tree HPRI importance measures report (40 year lower bound)**

Family: HPI
Fault Tree: HPRI
(Sorted by Fussell-Vesely)

| Event Name | Probability of Failure | Fussell-Vesely Importance | Risk Reduction Ratio | Risk Achievement Ratio |
|---|---|---|---|---|
| HPCROSSH | 1.000E−002 | 4.835E−001 | 1.936E+000 | 4.886E+001 |
| HP26MVO | 7.100E−003 | 4.835E−001 | 1.936E+000 | 6.861E+001 |
| HPRAPPR | 2.000E−002 | 4.353E−001 | 1.771E+000 | 2.233E+001 |
| HPRCPPR | 2.000E−002 | 3.078E−001 | 1.445E+000 | 1.608E+001 |
| HP25MVO | 7.100E−003 | 2.349E−001 | 1.307E+000 | 3.385E+001 |
| HP24MVO | 7.100E−003 | 2.349E−001 | 1.307E+000 | 3.385E+001 |
| HP2425MVH | 5.000E−005 | 2.330E−001 | 1.304E+000 | 4.654E+003 |
| HP148VVT | 6.800E−003 | 1.046E−001 | 1.117E+000 | 1.628E+001 |
| HPSEGMM | 1.500E−003 | 9.060E−002 | 1.100E+000 | 1.000E+000 |
| HPSEGKM | 1.500E−003 | 9.060E−002 | 1.100E+000 | 5.508E+001 |
| HPSEGHM | 6.100E−004 | 9.060E−002 | 1.100E+000 | 1.633E+001 |
| HPBCPPH | 1.500E−004 | 4.866E−002 | 1.051E+000 | 3.254E+002 |
| HPCPPR | 2.000E−003 | 3.078E−002 | 1.032E+000 | 1.636E+001 |
| HPCPPS | 1.400E−003 | 2.154E−002 | 1.022E+000 | 1.637E+001 |
| HP148VVH | 6.100E−004 | 9.387E−003 | 1.009E+000 | 1.638E+001 |

**Table I-19. Fault tree HPI cut sets quantification report (5 year)**

Family: HPI
Fault Tree: HPI
Mincut Upper Bound 9.590E – 005

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 52.1 | 52.1 | 5.0E – 005 | HP2425MVH |
| 2 | 94.8 | 42.7 | 4.1E – 005 | HP24MVO, HP25MVO |
| 3 | 96.6 | 1.7 | 1.7E – 006 | HP24MVO, HPSEGQM |
| 4 | 98.3 | 1.7 | 1.7E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 5 | 98.9 | .6 | 5.6E – 007 | HP102CVO, HP24MVO |
| 6 | 99.5 | .6 | 5.6E – 007 | HP101CVO, HP25MVO |
| 7 | 99.7 | .2 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 8 | 99.8 | .1 | 5.4E – 008 | HP26MVO, HPCPPS, HPCROSSH |
| 9 | 99.8 | .0 | 3.9E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 10 | 99.9 | .0 | 3.9E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 11 | 99.9 | .0 | 2.5E – 008 | HP148VVT, HP26MVO, HPCROSSH |
| 12 | 99.9 | .0 | 2.3E – 008 | HP101CVO, HPSEGQM |
| 13 | 99.9 | .0 | 2.3E – 008 | HP102CVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 14 | 99.9 | .0 | 1.3E – 008 | HP26MVO, HPCPPR, HPCROSSH |

**Table I-20. Fault tree HPI cut sets quantification report (10 year upper bound)**

Family: HPI
Fault Tree: HPI
Mincut Upper Bound 1.048E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 47.7 | 47.7 | 5.0E – 005 | HP2425MVH |
| 2 | 94.5 | 46.8 | 4.9E – 005 | HP24MVO, HP25MVO |
| 3 | 96.2 | 1.7 | 1.8E – 006 | HP24MVO, HPSEGQM |
| 4 | 97.9 | 1.7 | 1.8E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 5 | 98.5 | .6 | 6.4E – 007 | HP102CVO, HP24MVO |
| 6 | 99.2 | .6 | 6.4E – 007 | HP101CVO, HP25MVO |
| 7 | 99.4 | .2 | 2.4E – 007 | HP148VVT, HP26MVO, HPCROSSH |
| 8 | 99.6 | .2 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 9 | 99.7 | .1 | 7.7E – 008 | HP26MVO, HPCPPR, HPCROSSH |
| 10 | 99.7 | .1 | 7.7E – 008 | HP26MVO, HPCPPS, HPCROSSH |
| 11 | 99.8 | .0 | 4.3E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 12 | 99.8 | .0 | 4.3E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 13 | 99.9 | .0 | 2.4E – 008 | HP101CVO, HPSEGQM |
| 14 | 99.9 | .0 | 2.4E – 008 | HP102CVO, /HPSEGHM, HPSEGPM, /HPSEGQM |

**Table I-21. Fault tree HPI cut sets quantification report (10 year lower bound)**

Family: HPI
Fault Tree: HPI
Mincut Upper Bound 9.737E – 005

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 51.4 | 51.4 | 5.0E – 005 | HP2425MVH |
| 2 | 94.7 | 43.4 | 4.2E – 005 | HP24MVO, HP25MVO |
| 3 | 96.5 | 1.7 | 1.7E – 006 | HP24MVO, HPSEGQM |
| 4 | 98.2 | 1.7 | 1.7E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 5 | 98.8 | .6 | 5.7E – 007 | HP101CVO, HP25MVO |
| 6 | 99.4 | .6 | 5.7E – 007 | HP102CVO, HP24MVO |
| 7 | 99.6 | .2 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 8 | 99.7 | .1 | 8.5E – 008 | HP148VVT, HP26MVO, HPCROSSH |
| 9 | 99.8 | .1 | 5.9E – 008 | HP26MVO, HPCPPS, HPCROSSH |
| 10 | 99.8 | .0 | 4.0E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 11 | 99.8 | .0 | 4.0E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 12 | 99.9 | .0 | 3.0E – 008 | HP26MVO, HPCPPR, HPCROSSH |
| 13 | 99.9 | .0 | 2.3E – 008 | HP101CVO, HPSEGQM |
| 14 | 99.9 | .0 | 2.3E – 008 | HP102CVO, /HPSEGHM, HPSEGPM, /HPSEGQM |

Table I-22. Fault tree HPI cut sets quantification report (40 year upper bound)

Family: HPI
Fault Tree: HPI
Mincut Upper Bound 1.639E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 61.0 | 61.0 | 1.0E – 004 | HP24MVO, HP25MVO |
| 2 | 91.5 | 30.5 | 5.0E – 005 | HP2425MVH |
| 3 | 93.1 | 1.6 | 2.6E – 006 | HP24MVO, HPSEGQM |
| 4 | 94.7 | 1.6 | 2.6E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 5 | 96.0 | 1.3 | 2.2E – 006 | HP148VVT, HP26MVO, HPCROSSH |
| 6 | 96.8 | .7 | 1.2E – 006 | HP101CVO, HP25MVO |
| 7 | 97.5 | .7 | 1.2E – 006 | HP102CVO, HP24MVO |
| 8 | 98.1 | .6 | 1.0E – 006 | HP148VVT, HPAPPR, HPBPPR |
| 9 | 98.5 | .4 | 6.8E – 007 | HP26MVO, HPCPPR, HPCROSSH |
| 10 | 98.7 | .2 | 3.1E – 007 | HPAPPR, HPBPPR, HPCPPR |
| 11 | 98.9 | .2 | 2.7E – 007 | HP26MVO, HPCPPS, HPCROSSH |
| 12 | 99.0 | .1 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 13 | 99.2 | .1 | 2.2E – 007 | HP148VVT, HPAPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 14 | 99.3 | .1 | 2.2E – 007 | HP148VVT, HPBPPR, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 15 | 99.4 | .1 | 1.2E – 007 | HPAPPR, HPBPPR, HPCPPS |
| 16 | 99.4 | .1 | 8.9E – 008 | HP148VVT, HPBPPS, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 17 | 99.5 | .0 | 6.9E – 008 | HPAPPR, HPCPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 18 | 99.5 | .0 | 6.9E – 008 | HPBPPR, HPCPPR, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 19 | 99.6 | .0 | 6.1E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 20 | 99.6 | .0 | 6.1E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 21 | 99.6 | .0 | 5.9E – 008 | HP148VVT, HP26MVM, HPCROSSH, /HPSEGHM, /HPSEGQM |
| 22 | 99.7 | .0 | 4.8E – 008 | HP148VVT, HP24MVO, HPSEGOH |
| 23 | 99.7 | .0 | 4.5E – 008 | HP113CVO, HP26MVO, HPCROSSH |
| 24 | 99.7 | .0 | 3.3E – 008 | HP148VVT, HP26MVCH, HPCROSSH |
| 25 | 99.7 | .0 | 3.1E – 008 | HP101CVO, HPSEGQM |
| 26 | 99.7 | .0 | 3.1E – 008 | HP102CVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 27 | 99.8 | .0 | 2.8E – 008 | HP148VVH, HPAPPR, HPBPPR |
| 28 | 99.8 | .0 | 2.8E – 008 | HPAPPR, HPBPPR, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 29 | 99.8 | .0 | 2.7E – 008 | HPAPPR, HPCPPS, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 30 | 99.8 | .0 | 2.7E – 008 | HPBPPS, HPCPPR, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 31 | 99.8 | .0 | 2.7E – 008 | HPBPPR, HPCPPS, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 32 | 99.8 | .0 | 2.2E – 008 | HP148VVT, HP26MVO, HP409MVO, HP410MVO |
| 33 | 99.9 | .0 | 2.1E – 008 | HP113CVO, HPAPPR, HPBPPR |
| 34 | 99.9 | .0 | 1.8E – 008 | HP26MVM, HPCPPR, HPCROSSH, /HPSEGHM, /HPSEGQM |
| 35 | 99.9 | .0 | 1.5E – 008 | HP26MVO, HPBCPPH, HPCROSSH |
| 36 | 99.9 | .0 | 1.5E – 008 | HP26MVO, HP27MVH, HPCROSSH |
| 37 | 99.9 | .0 | 1.5E – 008 | HP24MVO, HPCPPR, HPSEGOH |

**Table I-23. Fault tree HPI cut sets quantification report (40 year lower bound)**

Family: HPI
Fault Tree: HPI
Mincut Upper Bound 1.067E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 47.2 | 47.2 | 5.0E – 005 | HP24MVO, HP25MVO |
| 2 | 94.1 | 46.9 | 5.0E – 005 | HP2425MVH |
| 3 | 95.8 | 1.7 | 1.8E – 006 | HP24MVO, HPSEGQM |
| 4 | 97.6 | 1.7 | 1.8E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 5 | 98.2 | .6 | 6.5E – 007 | HP101CVO, HP25MVO |
| 6 | 98.8 | .6 | 6.5E – 007 | HP102CVO, HP24MVO |
| 7 | 99.2 | .5 | 4.8E – 007 | HP148VVT, HP26MVO, HPCROSSH |
| 8 | 99.4 | .2 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 9 | 99.6 | .1 | 1.4E – 007 | HP26MVO, HPCPPR, HPCROSSH |
| 10 | 99.7 | .1 | 1.0E – 007 | HP26MVO, HPCPPS, HPCROSSH |
| 11 | 99.7 | .0 | 4.3E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 12 | 99.7 | .0 | 4.3E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 13 | 99.8 | .0 | 2.7E – 008 | HP148VVT, HPAPPR, HPBPPR |
| 14 | 99.8 | .0 | 2.4E – 008 | HP101CVO, HPSEGQM |

**Table I-24. Fault tree HP201 cut sets quantification report (5 year)**

Family: HPI
Fault Tree: HP201
Mincut Upper Bound 1.720E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 37.2 | 37.2 | 6.4E – 005 | HP26MVO, HPCROSSH |
| 2 | 66.3 | 29.1 | 5.0E – 005 | HP2425MVH |
| 3 | 90.1 | 23.8 | 4.1E – 005 | HP24MVO, HP25MVO |
| 4 | 91.7 | 1.6 | 2.7E – 006 | HP26MVM, HPCROSSH, /HPSEGHM, /HPSEGQM |
| 5 | 92.6 | 1.0 | 1.7E – 006 | HP24MVO, HPSEGQM |
| 6 | 93.6 | 1.0 | 1.7E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 7 | 94.5 | .9 | 1.5E – 006 | HP26MVCH, HPCROSSH |
| 8 | 95.3 | .8 | 1.4E – 006 | HP24MVO, HPSEGOH |
| 9 | 96.0 | .7 | 1.3E – 006 | HPCPPS, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 10 | 96.7 | .7 | 1.3E – 006 | HPBPPS, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 11 | 97.3 | .5 | 9.1E – 007 | HP148VVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 12 | 97.6 | .3 | 5.8E – 007 | HP148VVT, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 13 | 97.9 | .3 | 5.6E – 007 | HP102CVO, HP24MVO |
| 14 | 98.3 | .3 | 5.6E – 007 | HP101CVO, HP25MVO |

**Table I-25. Fault tree HP201 cut sets quantification report (10 year upper bound)**

Family: HPI
Fault Tree: HP201
Mincut Upper Bound 2.053E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 34.1 | 34.1 | 7.0E – 005 | HP26MVO, HPCROSSH |
| 2 | 58.5 | 24.4 | 5.0E – 005 | HP2425MVH |
| 3 | 82.3 | 23.9 | 4.9E – 005 | HP24MVO, HP25MVO |
| 4 | 84.9 | 2.6 | 5.2E – 006 | HP148VVT, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 5 | 86.7 | 1.9 | 3.8E – 006 | HP148VVT, HPBPPR |
| 6 | 88.1 | 1.3 | 2.7E – 006 | HP26MVM, HPCROSSH, /HPSEGHM, /HPSEGQM |
| 7 | 88.9 | .9 | 1.8E – 006 | HP24MVO, HPSEGQM |
| 8 | 89.8 | .9 | 1.8E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 9 | 90.6 | .8 | 1.6E – 006 | HPCPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 10 | 91.4 | .8 | 1.6E – 006 | HPBPPR, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 11 | 92.2 | .8 | 1.6E – 006 | HPCPPS, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 12 | 93.0 | .8 | 1.6E – 006 | HPAPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 13 | 93.8 | .8 | 1.6E – 006 | HPBPPS, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 14 | 94.6 | .8 | 1.5E – 006 | HP24MVO, HPSEGOH |
| 15 | 95.3 | .7 | 1.5E – 006 | HP26MVCH, HPCROSSH |
| 16 | 95.9 | .6 | 1.2E – 006 | HPAPPR, HPBPPR |
| 17 | 96.5 | .6 | 1.2E – 006 | HPBPPR, HPCPPR |
| 18 | 97.1 | .6 | 1.2E – 006 | HPBPPR, HPCPPS |
| 19 | 97.5 | .4 | 9.1E – 007 | HP148VVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 20 | 97.9 | .3 | 6.7E – 007 | HP148VVH, HPBPPR |
| 21 | 98.2 | .3 | 6.7E – 007 | HPBPPR, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 22 | 98.5 | .3 | 6.4E – 007 | HP102CVO, HP24MVO |
| 23 | 98.8 | .3 | 6.4E – 007 | HP101CVO, HP25MVO |
| 24 | 99.0 | .2 | 3.4E – 007 | HP26MVO, HP409MVO, HP410MVO |
| 25 | 99.1 | .1 | 2.3E – 007 | HPBCPPH, HPSEGKM |
| 26 | 99.2 | .1 | 2.2E – 007 | HPBCPPH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 27 | 99.3 | .1 | 2.2E – 007 | HP27MVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 28 | 99.4 | .1 | 2.1E – 007 | HP109CVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 29 | 99.5 | .1 | 2.1E – 007 | HP113CVO, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 30 | 99.6 | .1 | 1.7E – 007 | HP27MVH, HPBPPR |
| 31 | 99.7 | .1 | 1.7E – 007 | HPBCPPH, HPBPPR |
| 32 | 99.7 | .1 | 1.5E – 007 | HP113CVO, HPBPPR |
| 33 | 99.8 | .0 | 5.7E – 008 | /HPSEGHM, HPSEGOH, HPSEGPM, /HPSEGQM |
| 34 | 99.8 | .0 | 5.2E – 008 | HP148VVT, HPCROSSH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 35 | 99.8 | .0 | 3.9E – 008 | HP148VVT, HPAPPR, HPCROSSH |
| 36 | 99.8 | .0 | 3.7E – 008 | HP148VVT, HP409MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 37 | 99.8 | .0 | 2.7E – 008 | HP148VVT, HP409MVO, HPAPPR |
| 38 | 99.9 | .0 | 2.4E – 008 | HP101CVO, HPSEGQM |

**Table I-26. Fault tree HP201 cut sets quantification report (10 year lower bound)**

Family: HPI
Fault Tree: HP201
Mincut Upper Bound 1.788E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 36.4 | 36.4 | 6.5E – 005 | HP26MVO, HPCROSSH |
| 2 | 64.3 | 28.0 | 5.0E – 005 | HP2425MVH |
| 3 | 87.9 | 23.6 | 4.2E – 005 | HP24MVO, HP25MVO |
| 4 | 89.5 | 1.5 | 2.7E – 006 | HP26MVM, HPCROSSH, /HPSEGHM, /HPSEGQM |
| 5 | 90.5 | 1.1 | 1.9E – 006 | HP148VVT, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 6 | 91.5 | .9 | 1.7E – 006 | HP24MVO, HPSEGQM |
| 7 | 92.4 | .9 | 1.7E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 8 | 93.3 | .8 | 1.5E – 006 | HP26MVCH, HPCROSSH |
| 9 | 94.1 | .8 | 1.4E – 006 | HP24MVO, HPSEGOH |
| 10 | 94.8 | .8 | 1.4E – 006 | HPBPPS, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 11 | 95.6 | .8 | 1.4E – 006 | HPCPPS, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 12 | 96.1 | .5 | 9.1E – 007 | HP148VVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 13 | 96.5 | .4 | 6.9E – 007 | HPBPPR, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 14 | 96.9 | .4 | 6.9E – 007 | HPCPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 15 | 97.3 | .4 | 6.9E – 007 | HPAPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 16 | 97.6 | .3 | 6.0E – 007 | HP148VVT, HPBPPR |
| 17 | 97.9 | .3 | 5.7E – 007 | HP101CVO, HP25MVO |
| 18 | 98.2 | .3 | 5.7E – 007 | HP102CVO, HP24MVO |
| 19 | 98.5 | .2 | 4.2E – 007 | HPBPPR, HPCPPS |
| 20 | 98.6 | .2 | 2.8E – 007 | HP148VVH, HPBPPR |
| 21 | 98.8 | .2 | 2.8E – 007 | HPBPPR, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 22 | 98.9 | .2 | 2.7E – 007 | HP26MVO, HP409MVO, HP410MVO |
| 23 | 99.1 | .1 | 2.3E – 007 | HPBCPPH, HPSEGKM |
| 24 | 99.2 | .1 | 2.2E – 007 | HPBCPPH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 25 | 99.3 | .1 | 2.2E – 007 | HP27MVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 26 | 99.4 | .1 | 2.1E – 007 | HPAPPR, HPBPPR |
| 27 | 99.6 | .1 | 2.1E – 007 | HPBPPR, HPCPPR |
| 28 | 99.6 | .1 | 1.4E – 007 | HP113CVO, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 29 | 99.7 | .1 | 1.4E – 007 | HP109CVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 30 | 99.7 | .0 | 6.9E – 008 | HP27MVH, HPBPPR |
| 31 | 99.8 | .0 | 6.9E – 008 | HPBCPPH, HPBPPR |
| 32 | 99.8 | .0 | 5.7E – 008 | /HPSEGHM, HPSEGOH, HPSEGPM, /HPSEGQM |
| 33 | 99.8 | .0 | 4.4E – 008 | HP113CVO, HPBPPR |
| 34 | 99.9 | .0 | 2.3E – 008 | HP101CVO, HPSEGQM |
| 35 | 99.9 | .0 | 2.3E – 008 | HP102CVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 36 | 99.9 | .0 | 1.9E – 008 | HP148VVT, HPCROSSH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 37 | 99.9 | .0 | 1.9E – 008 | HP101CVO, HPSEGOH |
| 38 | 99.9 | .0 | 1.4E – 008 | HPCPPS, HPCROSSH, /HPSEGHM, HPSEGKM, /HPSEGMM |

**Table I-27. Fault tree HP201 cut sets quantification report (40 year upper bound)**

Family: HPI
Fault Tree: HP201
Mincut Upper Bound 6.194E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 24.2 | 24.2 | 1.5E – 004 | HP148VVT, HPBPPR |
| 2 | 40.3 | 16.1 | 1.0E – 004 | HP24MVO, HP25MVO |
| 3 | 56.4 | 16.1 | 1.0E – 004 | HP26MVO, HPCROSSH |
| 4 | 64.5 | 8.1 | 5.0E – 005 | HP2425MVH |
| 5 | 72.0 | 7.5 | 4.6E – 005 | HPBPPR, HPCPPR |
| 6 | 79.4 | 7.5 | 4.6E – 005 | HPAPPR, HPBPPR |
| 7 | 84.8 | 5.3 | 3.3E – 005 | HP148VVT, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 8 | 87.7 | 3.0 | 1.8E – 005 | HPBPPR, HPCPPS |
| 9 | 89.4 | 1.6 | 1.0E – 005 | HPCPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 10 | 91.0 | 1.6 | 1.0E – 005 | HPBPPR, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 11 | 92.7 | 1.6 | 1.0E – 005 | HPAPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 12 | 93.3 | .7 | 4.1E – 006 | HP148VVH, HPBPPR |
| 13 | 94.0 | .7 | 4.1E – 006 | HPBPPR, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 14 | 94.6 | .7 | 4.0E – 006 | HPCPPS, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 15 | 95.3 | .7 | 4.0E – 006 | HPBPPS, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 16 | 95.8 | .5 | 3.1E – 006 | HP113CVO, HPBPPR |
| 17 | 96.2 | .4 | 2.7E – 006 | HP26MVM, HPCROSSH, /HPSEGHM, /HPSEGQM |
| 18 | 96.6 | .4 | 2.6E – 006 | HP24MVO, HPSEGQM |
| 19 | 97.1 | .4 | 2.6E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 20 | 97.4 | .4 | 2.2E – 006 | HP24MVO, HPSEGOH |
| 21 | 97.7 | .2 | 1.5E – 006 | HP26MVCH, HPCROSSH |
| 22 | 97.9 | .2 | 1.5E – 006 | HP148VVT, HP409MVO, HPAPPR |
| 23 | 98.1 | .2 | 1.5E – 006 | HP148VVT, HPAPPR, HPCROSSH |
| 24 | 98.3 | .2 | 1.2E – 006 | HP102CVO, HP24MVO |
| 25 | 98.5 | .2 | 1.2E – 006 | HP101CVO, HP25MVO |
| 26 | 98.7 | .2 | 1.0E – 006 | HPBCPPH, HPBPPR |
| 27 | 98.9 | .2 | 1.0E – 006 | HP27MVH, HPBPPR |
| 28 | 99.0 | .2 | 1.0E – 006 | HP26MVO, HP409MVO, HP410MVO |
| 29 | 99.2 | .1 | 9.1E – 007 | HP148VVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 30 | 99.3 | .1 | 6.7E – 007 | HP113CVO, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 31 | 99.4 | .1 | 6.7E – 007 | HP109CVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 32 | 99.5 | .1 | 4.6E – 007 | HP409MVO, HPAPPR, HPCPPR |
| 33 | 99.5 | .1 | 4.6E – 007 | HPAPPR, HPCPPR, HPCROSSH |
| 34 | 99.6 | .1 | 3.3E – 007 | HP148VVT, HPCROSSH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 35 | 99.6 | .1 | 3.3E – 007 | HP148VVT, HP409MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 36 | 99.7 | .0 | 2.3E – 007 | HPBCPPH, HPSEGKM |
| 37 | 99.7 | .0 | 2.2E – 007 | HP27MVH, /HPSEGHM, /HPSEGKM, HPSEGMM |

**Table I-28. Fault tree HP201 cut sets quantification report (40 year lower bound)**

Family: HPI
Fault Tree: HP201
Mincut Upper Bound 2.365E – 004

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 30.0 | 30.0 | 7.1E – 005 | HP26MVO, HPCROSSH |
| 2 | 51.3 | 21.3 | 5.0E – 005 | HP24MVO, HP25MVO |
| 3 | 72.5 | 21.1 | 5.0E – 005 | HP2425MVH |
| 4 | 78.2 | 5.8 | 1.4E – 005 | HP148VVT, HPBPPR |
| 5 | 82.5 | 4.3 | 1.0E – 005 | HP148VVT, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 6 | 84.2 | 1.7 | 4.0E – 006 | HPBPPR, HPCPPR |
| 7 | 85.9 | 1.7 | 4.0E – 006 | HPAPPR, HPBPPR |
| 8 | 87.2 | 1.3 | 3.0E – 006 | HPBPPR, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 9 | 88.4 | 1.3 | 3.0E – 006 | HPAPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 10 | 89.7 | 1.3 | 3.0E – 006 | HPCPPR, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 11 | 90.9 | 1.2 | 2.8E – 006 | HPBPPR, HPCPPS |
| 12 | 92.0 | 1.1 | 2.7E – 006 | HP26MVM, HPCROSSH, /HPSEGHM, /HPSEGQM |
| 13 | 92.9 | .9 | 2.1E – 006 | HPBPPS, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 14 | 93.8 | .9 | 2.1E – 006 | HPCPPS, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 15 | 94.6 | .8 | 1.8E – 006 | HP24MVO, HPSEGQM |
| 16 | 95.4 | .8 | 1.8E – 006 | HP25MVO, /HPSEGHM, HPSEGPM, /HPSEGQM |
| 17 | 96.0 | .7 | 1.6E – 006 | HP24MVO, HPSEGOH |
| 18 | 96.7 | .6 | 1.5E – 006 | HP26MVCH, HPCROSSH |
| 19 | 97.2 | .5 | 1.2E – 006 | HP148VVH, HPBPPR |
| 20 | 97.7 | .5 | 1.2E – 006 | HPBPPR, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 21 | 98.1 | .4 | 9.1E – 007 | HP148VVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 22 | 98.4 | .3 | 6.5E – 007 | HP101CVO, HP25MVO |
| 23 | 98.6 | .3 | 6.5E – 007 | HP102CVO, HP24MVO |
| 24 | 98.8 | .2 | 3.6E – 007 | HP26MVO, HP409MVO, HP410MVO |
| 25 | 98.9 | .1 | 3.0E – 007 | HP27MVH, HPBPPR |
| 26 | 99.0 | .1 | 3.0E – 007 | HPBCPPH, HPBPPR |
| 27 | 99.2 | .1 | 2.8E – 007 | HP113CVO, HPBPPR |
| 28 | 99.2 | .1 | 2.3E – 007 | HPBCPPH, HPSEGKM |
| 29 | 99.3 | .1 | 2.2E – 007 | HPBCPPH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 30 | 99.4 | .1 | 2.2E – 007 | HP27MVH, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 31 | 99.5 | .1 | 2.1E – 007 | HP113CVO, /HPSEGHM, /HPSEGKM, HPSEGMM |
| 32 | 99.6 | .1 | 2.1E – 007 | HP109CVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 33 | 99.7 | .1 | 1.4E – 007 | HP148VVT, HPAPPR, HPCROSSH |
| 34 | 99.7 | .0 | 1.0E – 007 | HP148VVT, HPCROSSH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 35 | 99.8 | .0 | 1.0E – 007 | HP148VVT, HP409MVO, HPAPPR |
| 36 | 99.8 | .0 | 7.2E – 008 | HP148VVT, HP409MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 37 | 99.8 | .0 | 5.7E – 008 | /HPSEGHM, HPSEGOH, HPSEGPM, /HPSEGQM |
| 38 | 99.8 | .0 | 4.0E – 008 | HPAPPR, HPCPPR, HPCROSSH |

**Table I-29. Fault tree HPRI cut sets quantification report (5 year)**

Family: HPI
Fault Tree: HPRI
Mincut Upper Bound 8.401E – 005

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 26.7 | 26.7 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 2 | 42.0 | 15.2 | 1.3E – 007 | HP26MVO, HPCROSSH, HPRCPPR |
| 3 | 53.9 | 11.9 | 1.0E – 007 | HP2425MVH, HPRAPPR |
| 4 | 63.6 | 9.8 | 8.2E – 008 | HP24MVO, HP25MVO, HPRAPPR |
| 5 | 72.5 | 8.9 | 7.5E – 008 | HP2425MVH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 6 | 79.8 | 7.3 | 6.1E – 008 | HP24MVO, HP25MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 7 | 86.2 | 6.4 | 5.4E – 008 | HP26MVO, HPCPPS, HPCROSSH |
| 8 | 90.9 | 4.6 | 3.9E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 9 | 95.5 | 4.6 | 3.9E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 10 | 98.5 | 3.0 | 2.5E – 008 | HP148VVT, HP26MVO, HPCROSSH |
| 11 | 100.0 | 1.5 | 1.3E – 008 | HP26MVO, HPCPPR, HPCROSSH |

**Table I-30. Fault tree HPRI cut sets quantification report (10 year upper bound)**

Family: HPI
Fault Tree: HPRI
Mincut Upper Bound 2.716E – 006

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 28.4 | 28.4 | 7.7E – 007 | HP26MVO, HPCROSSH, HPRCPPR |
| 2 | 48.6 | 20.3 | 5.5E – 007 | HP2425MVH, HPRAPPR |
| 3 | 68.4 | 19.8 | 5.4E – 007 | HP24MVO, HP25MVO, HPRAPPR |
| 4 | 77.5 | 9.0 | 2.4E – 007 | HP148VVT, HP26MVO, HPCROSSH |
| 5 | 85.7 | 8.3 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 6 | 88.6 | 2.8 | 7.7E – 008 | HP26MVO, HPCPPR, HPCROSSH |
| 7 | 91.4 | 2.8 | 7.7E – 008 | HP26MVO, HPCPPS, HPCROSSH |
| 8 | 94.2 | 2.8 | 7.5E – 008 | HP2425MVH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 9 | 96.9 | 2.7 | 7.3E – 008 | HP24MVO, HP25MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 10 | 98.4 | 1.6 | 4.3E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 11 | 100.0 | 1.6 | 4.3E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |

**Table I-31. Fault tree HPRI cut sets quantification report (10 year lower bound)**

Family: HPI
Fault Tree: HPRI
Mincut Upper Bound 1.339E – 006

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 22.3 | 22.3 | 3.0E – 007 | HP26MVO, HPCROSSH, HPRCPPR |
| 2 | 39.5 | 17.2 | 2.3E – 007 | HP2425MVH, HPRAPPR |
| 3 | 56.3 | 16.8 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 4 | 70.8 | 14.5 | 1.9E – 007 | HP24MVO, HP25MVO, HPRAPPR |
| 5 | 77.1 | 6.3 | 8.5E – 008 | HP148VVT, HP26MVO, HPCROSSH |
| 6 | 82.7 | 5.6 | 7.5E – 008 | HP2425MVH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 7 | 87.4 | 4.7 | 6.3E – 008 | HP24MVO, HP25MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 8 | 91.8 | 4.4 | 5.9E – 008 | HP26MVO, HPCPPS, HPCROSSH |
| 9 | 94.8 | 3.0 | 4.0E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 10 | 97.7 | 3.0 | 4.0E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |
| 11 | 100.0 | 2.2 | 3.0E – 008 | HP26MVO, HPCPPR, HPCROSSH |

**Table I-32. Fault tree HPRI cut sets quantification report (40 year upper bound)**

Family: HPI
Fault Tree: HPRI
Mincut Upper Bound 2.072E – 005

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 32.8 | 32.8 | 6.8E – 006 | HP26MVO, HPCROSSH, HPRCPPR |
| 2 | 65.6 | 32.8 | 6.8E – 006 | HP24MVO, HP25MVO, HPRAPPR |
| 3 | 82.0 | 16.4 | 3.4E – 006 | HP2425MVH, HPRAPPR |
| 4 | 92.7 | 10.6 | 2.2E – 006 | HP148VVT, HP26MVO, HPCROSSH |
| 5 | 95.9 | 3.3 | 6.8E – 007 | HP26MVO, HPCPPR, HPCROSSH |
| 6 | 97.2 | 1.3 | 2.7E – 007 | HP26MVO, HPCPPS, HPCROSSH |
| 7 | 98.3 | 1.1 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 8 | 99.1 | .7 | 1.5E – 007 | HP24MVO, HP25MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 9 | 99.4 | .4 | 7.5E – 008 | HP2425MVH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 10 | 99.7 | .3 | 6.1E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 11 | 100.0 | .3 | 6.1E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |

**Table I-33. Fault tree HPRI cut sets quantification report (40 year lower bound)**

Family: HPI
Fault Tree: HPRI
Mincut Upper Bound 4.614E – 006

| Cut No. | % Total | % Cut Set | Freq. | Cut Sets |
|---|---|---|---|---|
| 1 | 30.8 | 30.8 | 1.4E – 006 | HP26MVO, HPCROSSH, HPRCPPR |
| 2 | 52.6 | 21.9 | 1.0E – 006 | HP24MVO, HP25MVO, HPRAPPR |
| 3 | 74.3 | 21.7 | 1.0E – 006 | HP2425MVH, HPRAPPR |
| 4 | 84.8 | 10.5 | 4.8E – 007 | HP148VVT, HP26MVO, HPCROSSH |
| 5 | 89.6 | 4.9 | 2.2E – 007 | HPBCPPH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 6 | 92.7 | 3.1 | 1.4E – 007 | HP26MVO, HPCPPR, HPCROSSH |
| 7 | 94.9 | 2.2 | 1.0E – 007 | HP26MVO, HPCPPS, HPCROSSH |
| 8 | 96.5 | 1.6 | 7.5E – 008 | HP24MVO, HP25MVO, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 9 | 98.1 | 1.6 | 7.5E – 008 | HP2425MVH, /HPSEGHM, HPSEGKM, /HPSEGMM |
| 10 | 99.1 | .9 | 4.3E – 008 | HP148VVH, HP26MVO, HPCROSSH |
| 11 | 100.0 | .9 | 4.3E – 008 | HP26MVO, HPCROSSH, HPSEGHM, /HPSEGKM, /HPSEGMM |

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11. ABSTRACT *(200 words or less)*

This report represents the results of a review of light water reactor High Pressure Injection System (HPIS) operating experiences reported in the Nuclear Power Experience Data Base, Licensee Event Reports (LER)s, Nuclear Plant Reliability Data System, and plant records. The purpose is to evaluate the potential significance of aging as a contributor to degradation of the High Pressure Injection System. Tables are presented that show the percentage of events for HPIS classified by cause, component, and subcomponents for PWRs. A representative Babcock and Wilcox plant was selected for detailed study. The U.S. Nuclear Regulatory Commission's Nuclear Plant Aging Research guidelines were followed in performing the detailed study that identifies materials susceptible to aging, stressors, environmental factors, and failure modes for the HPIS.

In addition to the engineering evaluation, the components that contributed to system unavailability were determined and the aging contribution to HPIS unavailability was evaluated. The unavailability assessment utilized an existing probabilistic risk assessment (PRA), the linear aging model, and generic failure data.

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