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...g Assessment of BWR ...dby Liquid Control Systems

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Pacific Northwest Laboratory
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Aging Assessment of BWR Standby Liquid Control Systems

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Abstract

Pacific Northwest Laboratory conducted a Phase I aging assessment of the standby liquid control (SLC) system used in boiling-water reactors. The study was based on detailed reviews of SLC system component and operating experience information obtained from the Nuclear Plant Reliability Database System, the Nuclear Document System, Licensee Event Reports, and other databases. Sources on sodium pentaborate, borates, and boric acid, as well as the effects of environment and corrosion in the SLC system were also reviewed to characterize chemical properties and corrosion characteristics of borated solutions.

Relatively few SLC component failures were attributed to sodium pentaborate buildup or corrosion. The leading aging degradation concern to date appears to be setpoint drift in relief valves, which has been discovered during routine surveillance and is thought to be caused by mechanical wear. A higher setpoint results in loss of system overpressure protection, and a decrease in setpoint results in a reduction of boron injection rate. Degradation was also observed in pump seals and internal valves, which could prevent the pumps from operating as required by the technical specifications. In general, however, the results of the Phase I study indicate that age-related degradation of SLC systems has not been serious.

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Summary

Pacific Northwest Laboratory (PNL), in support of the U.S. Nuclear Regulatory Commission (NRC) and its Nuclear Plant Aging Research (NPAR) Program, conducted a Phase I study to determine the effects of age-related degradation on the standby liquid control (SLC) system used in boiling-water reactors (BWRs). The goal of this study was to develop an overview of the aging characteristics of SLC systems in sufficient depth to assess whether further research is needed to detect and manage aging degradation. The scope of this evaluation encompassed all SLC system designs found in commercial BWRs.

The SLC system is safety-related because it provides backup capability for reactivity control in the event that the normal operating systems fail. Based on calculations performed to determine the relative importance of reactor protection systems, the safety importance of the SLC system, as measured by core-melt frequency, is eighth of approximately thirty reactor protection systems. Additionally, guidance is provided from several NRC Regulatory Guides that help to establish the safety significance of the SLC system.

The study of the SLC system involved reviews of information on SLC system components and operating experience, which were obtained from the Nuclear Plant Reliability Database System, the Nuclear Document System, Licensee Event Reports, NRC Generic Issues, and other databases. Sources on sodium pentaborate, borates, and boric acid, and the effects of environment and corrosion in the SLC system were also reviewed to characterize chemical properties and corrosion characteristics of borated solutions. Characterizing the sodium pentaborate solution provides a useful basis for assessing potential aging mechanisms in SLC systems.

Relatively few SLC system failures were connected to sodium pentaborate buildup or corrosion of valve internals. Current industry experience on corrosion in SLC systems indicates that there is no unpredicted corrosion of components in contact with the sodium pentaborate solution because the solution provides a mild environment. Additionally, intergranular stress corrosion cracking (IGSCC) of the type that occurred in pressurized-water reactor (PWR) spent fuel storage pools is not expected to occur in SLC components. Higher pH levels in the sodium pentaborate solutions is one of the mitigating factors compared to the lower pH levels in the boric acid chemistries of spent fuel pools.

The results of the Phase I study indicate that the aging mechanisms active in the SLC system result in the failure of only a few specific components. A review of reported incidents indicates that the system relief valves (SRVs) are the major component affecting the operation of the system. The SRVs are susceptible to setpoint drift, which has been discovered during routine surveillance. Though the root cause of relief valve failures was not always determined, the majority of the reported failures were attributed to mechanical wear. Instances of degradation of pump seals, internal valves, and packing were also identified. This degradation could prevent the SLC pumps from operating as required by the technical specifications.

Although most SLC system components are being evaluated in other studies, insights obtained from this investigation suggest opportunities for improved aging management to minimize the risk of component corrosion in the presence of sodium pentaborate, specifically the risk of IGSCC.

The following are practices which, if implemented, would further minimize the risk of failures caused by IGSCC:

(1) The contaminant level of chloride and sulfate should be independently evaluated, to verify the certification values received from the Borax and boric acid vendor, before addition of the chemicals to the SLC system storage tank.

(2) The concentration of contaminant chlorides and sulfates in the SLC storage tank should be monitored periodically to determine whether concentrations are at levels that could contribute to IGSCC.

(3) Selected, specific nondestructive evaluations should be conducted to detect whether IGSCC is occurring, particularly in weld heat-affected zones.

In general, the results of the Phase I study indicate that age-related degradation of SLC systems has not been serious. Deterioration of relief valve performance has been the leading SLC system aging degradation problem; therefore, further study of relief valves is recommended. If the study were conducted, the principal aging vulnerabilities of the SLC system would be addressed, and a separate Phase II aging study of SLC systems would not be necessary.

Glossary

BIT	boron injection temperature
BWR	boiling-water reactor
DES	Division of Engineering Safety
EOP	emergency operating procedure
FSP	fuel storage pool
HAZ	heat-affected zones
IGSCC	intergranular stress corrosion cracking
LER	License Event Reports
NPAR	Nuclear Plant Aging Research
NPRDS	Nuclear Plant Reliability Database System
NRC	Nuclear Regulatory Commission
NUDOCS/AD	Nuclear Documentation System
PNL	Pacific Northwest Laboratory
PWR	pressurized-water reactor
RES	Office of Nuclear Regulatory Research
RPV	reactor pressure vessel
SLC	standby liquid control
SRV	system relief valve

1 Introduction

The U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), Division of Engineering Safety (DES), is implementing the Nuclear Plant Aging Research (NPAR) program plan (US NRC 1991) to resolve technical safety issues related to the aging of commercial nuclear power plants. NPAR aging assessments involve identifying and characterizing material and component degradation during service.

The NPAR aging assessments are being conducted to:

- identify and characterize aging effects that could cause degradation and thereby impair plant safety
- identify methods of inspection, surveillance, and monitoring that will ensure timely detection of significant aging degradation before loss of safety function
- evaluate the effectiveness of storage, maintenance, and replacement practices in mitigating the rate and extent of aging degradation.

In support of the NPAR Program, Pacific Northwest Laboratory PNL[1] conducted a Phase I aging assessment of the standby liquid control (SLC) system used in commercial boiling-water reactors (BWRs). The objective of this investigation was to evaluate the SLC system to determine if further aging research is needed to detect and mitigate degradation due to aging mechanisms such as corrosion and mechanical wear. This preliminary investigation comprised reviews of information on SLC system events and component aging phenomena.

1.1 Overview of SLC System

The SLC system is unique to General Electric BWR designs. The SLC system is a backup reactivity control system and is maintained in an operable status whenever a control rod is removed from a loaded reactor core. In this mode, the SLC system performs a safety-related function. Two of the design-basis requirements for the SLC system are as follows:

- Backup capability for reactivity control is provided, independent of normal reactivity control, to facilitate shut down of the reactor if normal reactivity control becomes inoperative.
- The system has the capacity for controlling the reactivity difference between the steady-state rated operating condition and the cold shutdown condition, including shutdown margin, to ensure complete shutdown from the most reactive condition at any time in core life.

1.2 Safety Significance of the SLC System

The SLC system is important to safety because it provides backup capability for reactivity control in the event of failure of the normal operating systems. When initiated, the SLC system injects neutron absorbing sodium pentaborate solution into the reactor vessel to shut down the reactor, independent of any control rod motion, and maintains the reactor in a subcritical condition. The following two subsections address the safety ranking and classification of the SLC system.

1.2.1 Risk Analysis

In a study by Vo et al. (1990), risk analysis calculations were performed to determine the relative importance of each reactor protection system. The initial order of ranking was determined by the Birnbaum Importance Measure, i.e., the change in risk that is associated with a total system failure leading to core melt. The SLC system importance to safety as measured by core-melt frequency was eighth out of approximately thirty reactor protection systems. This initial ranking can also be used as an indicator of the SLC system relative importance within the NPAR program aging assessments.

[1]PNL is operated for the Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

1.2.2 Regulatory Guidance

The NRC has developed regulatory guides that designate the relative importance of systems and components to ensure their adequacy, availability, and capability to perform their intended functions. The following regulatory guides support the safety significance of the SLC system:

- NRC Regulatory Guide 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants." (US NRC 1978a) This regulatory guide classifies the SLC system as a "System Required for Safe Shutdown." The explosive (squib) valves, valves and piping between the isolation valves, and the reactor pressure vessel are classified as Safety Class 1.

- NRC Regulatory Guide 1.26, "Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants." (US NRC 1976) This regulatory guide classifies the SLC system explosive valves, valves, and piping between the isolation valves and the reactor pressure vessel as Quality Group "A".

- NRC Regulatory Guide 1.29, "Seismic Design Classification." (US NRC 1978b) This regulatory guide classifies the SLC system as Seismic Category I.

1.3 Scope of Evaluation

The scope of this evaluation encompasses all SLC systems found in commercial BWRs. Because of differences in nuclear plant design and product lines, SLC system nomenclature and component makeup differ from plant to plant. Regardless of the nomenclature and physical design variations, the system that provides the functional purpose indicated for the SLC system is included in the scope of this evaluation. A simplified one-line diagram of the SLC system, that illustrates the scope of this evaluation, is shown in Figure 1.1.

The following items were excluded from the final SLC system evaluation. They were, however, examined for significance to the components included in the evaluation.

- electrical breakers
- motor control centers
- cables
- pump motors
- motor operators for valves
- pipe supports
- snubbers.

These components are being evaluated under separate NPAR program aging assessments.

1.4 Scope of Report

Section 2.0 of this report describes the important components of the SLC system, the various operation modes, and system differences reflecting the design of a particular BWR facility. Sections 3.0 and 4.0 present the SLC aging assessment methodology and results. Section 5.0 characterizes technical information on sodium pentaborate solutions and describes the use of sodium pentaborate in the SLC system and the chemical properties of the solution. Section 6.0 discusses corrosion and corrosion-related failures in the SLC system environments. Section 7.0 presents the conclusions and recommendations based on the results of the SLC system aging assessment.

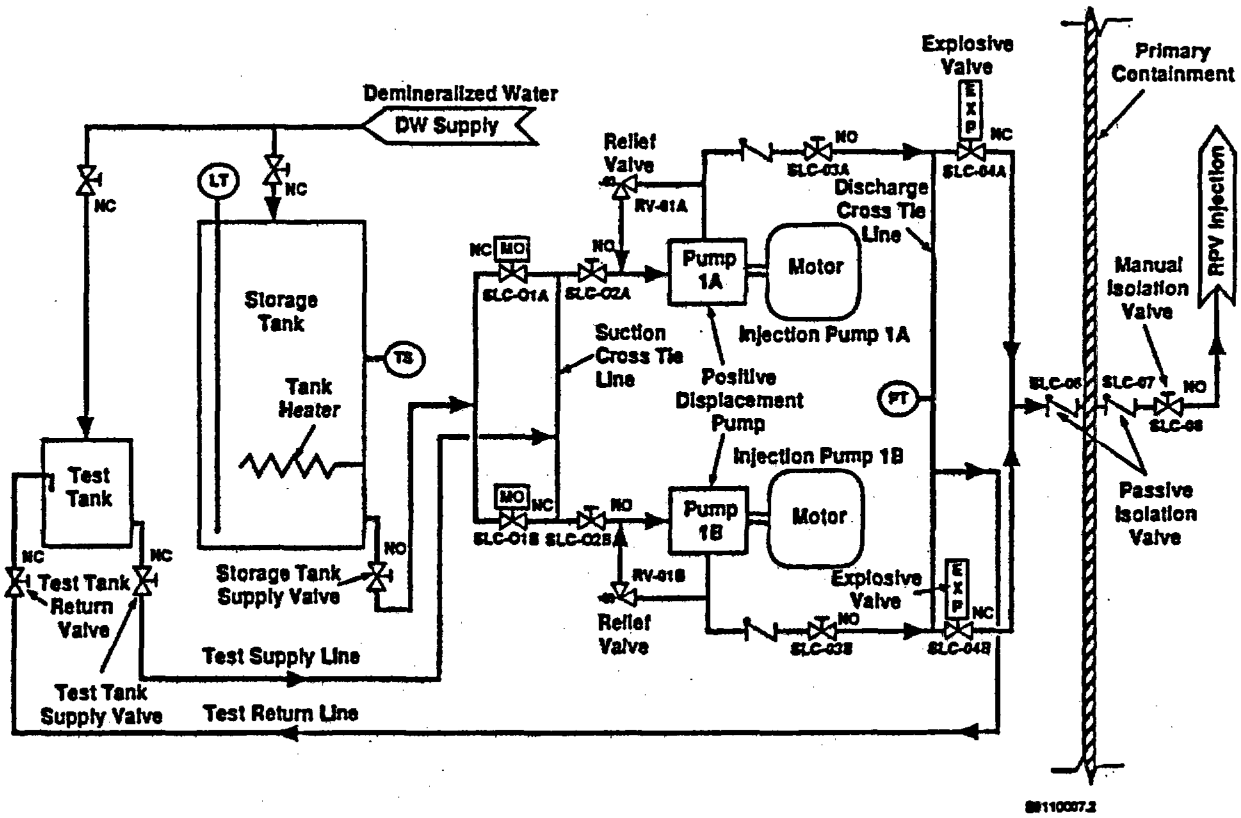

Figure 1.1 Standby liquid control system schematic

2 SLC System Description

The SLC system described in this section represents systems at typical BWR facilities. The system differences that may be encountered at different facilities are discussed in Section 2.5.

The SLC system shown in Figure 1.1 consists of a heated storage tank, two 100% capacity pumps, two motor operated suction valves, two explosive actuated discharge valves, and the necessary valves and associated piping to inject the sodium pentaborate into the reactor vessel. In addition, the system includes a test tank with the necessary valves and piping to adequately test system performance by injecting demineralized water instead of sodium pentaborate into the reactor pressure vessel (RPV).

The SLC system is manually initiated from the control room according to the facility emergency operating procedures (EOP) when conditions exist that prompt the operators to take action to assure control of core reactivity. Several BWR facilities also incorporate a logic circuit to automatically start the SLC system at predetermined conditions.

The SLC system is relatively slow compared to other shutdown systems; it takes approximately two hours to inject sufficient sodium pentaborate to shut down the reactor. The system cannot be considered as a backup to the control rods for accidents requiring a rapid shutdown or reactor scram. The SLC does have the capacity to shut down the reactor with adequate margin to control the reactivity difference between the steady-state rated operating condition and the cold shutdown condition. This margin of control is ensured during the period of the core life when reactivity is greatest, and takes into account dilution by the reactor recirculation system and non-homogenous mixing.

2.1 Description of SLC Components

The SLC components shown in Figure 1.1 are described in functional sequence, starting from the sodium pentaborate storage tank to the point at which the sodium pentaborate is injected into the RPV.

2.1.1 Storage Tank

The storage tank is stainless steel with about a 5200 gallon capacity. It is equipped with an overflow line at about the 5150 gallon level. An internal air sparger is used to mix the solution. The pump suction piping enters the side of the tank to prevent plugging of the suction line.

2.1.2 Tank Heaters

Heaters in the tank maintain the solution temperature in the 21 to 30°C (70 to 86°F) range to keep the sodium pentaborate in solution. Additional heaters are also installed in the tank to permit heating the contents to about 65°C (150°F) for preparation of the sodium pentaborate solution.

2.1.3 Pump Suction Valves (SLC-01A, -01B)

There are two motor-operated suction valves. These valves are normally closed to prevent inadvertent injection of the sodium pentaborate into the RPV during system testing. Both valves open on system initiation and each valve is interlocked with the pump so that the pump will not start until one of the valves is fully open. These valves are also interlocked with the test tank supply valve so that the pump suction valves do not open if the test tank supply valve is open. Heat tracing on the pump suction line between the storage tank and the SLC-01 pump suction valves keeps the solution in the lines from crystallizing during stagnant operation. The suction line to each pump is cross-connected to allow both suction valves to supply both injection pumps.

2.1.4 Injection Pumps (1A, 1B)

There are two 100% capacity pumps. These pumps are positive displacement type with motors rated at about 40 hp. Each pump is rated at 43 gpm at 1250 psig. The pumps are interlocked so that they will not start unless one of the two pump suction valves (SLC-01A or 01B) is fully open or the test tank supply valve is open. The local pump start switch bypasses the pump start interlocks.

2.1.5 Relief Valves (RV-01A, -01B)

Each pump discharge is protected with a relief valve that discharges back to the pump suction line. The setpoint for the relief valve is 1400 psig. A check valve downstream of the relief valve connection on each pump discharge line prevents the sodium pentaborate solution from bypassing through the idle pump or through the relief valve in the event that it opens below setpoint.

2.1.6 Injection Valves (SLC-04A, -04B)

The discharge line from each pump has an associated explosive actuated valve. During system initiation the explosive valve receives an open signal that causes the charges to explode. The explosion forces a ram to extend and shear off the top of the sealing end cap within the valve. The ram and cap form in a shape that prevents flow blockage. The explosive charge circuitry is monitored continuously for continuity by a small current. The discharge lines from each pump are cross connected at a point just upstream of the injection valves to allow both injection valves to discharge for either injection pump.

2.1.7 Containment Isolation Valves (SLC-06, -07, -08)

Passive isolation of the SLC system is provided by two in-line check valves in series, one inside containment (SLC-07) and one outside containment (SLC-06). Vent valves between the two check valves allow detection of a leaking check valve. A manual isolation valve (SLC-08) located downstream of the inside containment check valve is a maintenance valve. It is normally locked open.

2.1.8 Injection Sparger

The injection sparger penetrates the RPV at the bottom head near the edge of the core below the core plate. It is a tube-in-tube design with the inner tube being used for sodium pentaborate injection. The end of the inner tube is perforated to allow better distribution of the sodium pentaborate during injection. The injection sparger is also used for other RPV functions and instrumentation such as:

- detecting breaks in high pressure core spray lines
- jet pump differential pressure tap
- measuring the core differential pressure
- measuring the bottom head drain flow to the reactor water cleanup system
- control rod drive water and cooling water differential pressure tap.

2.1.9 Test Tank

The SLC system is provided with a test tank that is normally filled with demineralized water. The tank is stainless steel and holds about 210 gallons. The test tank is used to flush and to performance test the SLC system. The tank is piped to the suction of the SLC pumps and is provided with a manual isolation valve. The SLC pump discharge is also piped to the test tank and is controlled by two manual isolation valves in series.

2.1.10 Neutron Absorber

Sodium pentaborate solution is used as the reactivity control agent because boron-10 has a high absorption cross section for thermal neutrons (Walker et al. 1983). The limits for temperature, tank level, and concentration ensure that the minimum shutdown requirement of 660 ppm boron concentration within the 50- to 125-minute period is met. The boron reactivity control limits are summarized as follows:

- 660 ppm boron concentration is used to shut down the reactor; 185 ppm is added for non-homogenous mixing; 250 ppm is added for residual heat removal shutdown cooling dilution, which yield a total boron concentration of 1095 ppm
- the temperature should be maintained above 10°C (50°F) to ensure that the solute remains in solution

- 125 minutes maximum to ensure that the sodium pentaborate is injected fast enough to overcome cooldown and xenon depletion reactivity effects

- 50 minutes minimum to ensure that there are no power oscillations caused by high boron concentrations cycling in and out of the core due to poor mixing

- the concentration and volume limits are generally applied within an operating envelope. Operating within the envelope ensures that limits a, c, and d above are met.

2.2 Verifying System Performance

Adequate performance of the SLC system is verified by several methods. The following are examples of verifications that are required by technical specifications:

- periodic verification of sodium pentaborate solution volume, concentration, and temperature

- periodic verification of heat trace temperature

- periodic system performance check by recirculating demineralized water from/to the test tank

- continuity check circuitry for the explosive valves

- initiation of SLC injection, including the explosive valve and performance check, while injecting demineralized water from the test tank into the RPV

- verification of ASME Boiler Code Section XI requirements for minimum flow and pressure

- verification that the heat-traced piping between the storage tank and the RPV is unblocked

- verification that the tank heaters are functioning properly

- verification of the relief valve set point.

2.3 System Operation

The SLC system operates in a variety of modes. These modes are described in the following subsections.

2.3.1 Standby Mode

The SLC system must be maintained in an operational standby status when there is fuel in the reactor vessel and the control rods are removed. The time that the SLC system can be out of service during operation is limited by technical specifications. The system is in standby when the valves are in the following lineup:

- pump suction valves (SLC-01A, -01B) CLOSED

- test tank supply valve CLOSED

- injection valves (SLC-04A, -04B) CLOSED

- injection valve continuity lights ON

The SLC solution temperature, concentration, and tank level also have limits that determine if the SLC is operable in standby.

2.3.2 Injection Mode

The SLC system is initiated with keylocked switches. Each switch controls one 100% capacity pump subsystem. When the switch for Pump 1A is placed in the RUN position, the following actions occur:

(1) the pump suction valve (SLC-01A) opens

(2) both explosive pump discharge valves (SLC-04A, -04B) actuate and open

(3) the reactor water cleanup system is isolated

(4) the SLC Pump 1A starts when the suction valve is full open.

The SLC storage tank level is monitored during injection by the control room operators to ensure that the solution is being injected into the RPV. Reactor power and other complementary plant parameters are monitored closely to track decreasing power. When the reactor is confirmed to be shutdown or the SLC tank level is at zero and further injection is not required, the switch is placed in the STOP position.

2.3.3 Recirculation Test Mode

The recirculation test mode allows operators to verify proper operation of the SLC system pumps without injecting solution into the reactor. This test can be performed during reactor operation or shutdown periods. The recirculation test mode allows the system to be lined up to the test tank so that demineralized water can be recirculated from the tank, to the pumps, and back to the tank.

2.3.4 Simulated Injection Test Mode

This mode is performed periodically during reactor shutdown conditions. The procedure is to align the suction flow path of the SLC pumps to the test tank, then to activate the system with the control switch. The following automatic actions are verified: the proper system valves open, the SLC pumps start, and demineralized water is injected into the RPV. In this way pump discharge capacity and explosive valve performance can be verified. Typically, one explosive valve is fired each year, alternating every year. This test and replacement cycle appears adequate to address explosive valve aging concerns.

2.4 SLC Emergency Operating Procedures

2.4.1 System Initiation

The SLC system is manually initiated in accordance with EOPs when plant conditions require injection. With the reactor at full power and with heat being added to the suppression pool, it is possible that the heat capacity limit could be exceeded. The heat capacity limit is based upon not exceeding the design containment pressure or the design suppression pool temperature if an emergency RPV blowdown occurs.

The boron injection temperature (BIT) limit is defined by a curve (Figure 2.1) with reactor power on the x-axis and suppression pool temperature as the y-axis. The BIT curve is used by the operators to determine the conditions at which SLC injection must be initiated to ensure that injection of the hot shutdown weight of boron can be completed before the heat capacity limit is exceeded.

If the shaded area of the BIT curve is entered, the SLC system must be activated. It is important to point out that if an anticipated transient without a scram event is in progress and even though the suppression pool temperature is less than the BIT, the operator may initiate the SLC in anticipation of exceeding the BIT limit. The operator is guided to start SLC injection as soon as possible if insertion of the control rods, by any means, is unsuccessful.

2.4.2 EOP Contingency

The BWR emergency operating procedures utilize the SLC system as a low priority source of makeup water to the reactor pressure vessel. During emergency conditions in which adequate high pressure makeup water is

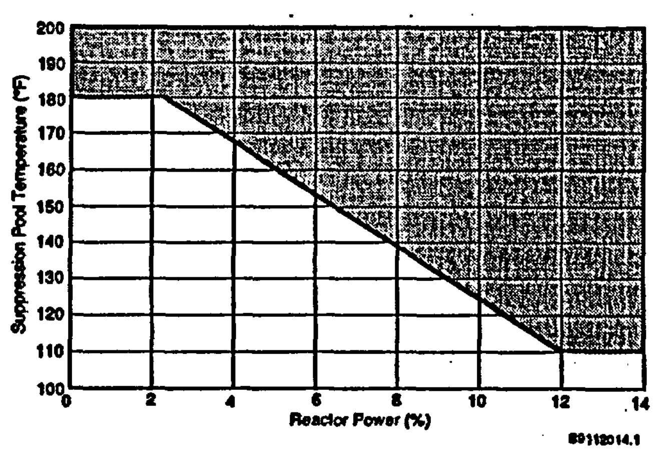

Figure 2.1 Boron injection temperature curve

not available, a contingency action may be required to use the SLC system as a source of makeup water to the RPV. The procedure to implement this contingency action is to manually valve in the test tank to the SLC pump suction, as would be performed for the simulated injection test mode. The system is then activated so that demineralized water from the test tank is injected into the RPV. The demineralized water fill valve is throttled open to keep the tank full.

2.5 System Differences

The SLC system components, operating procedures, and boron concentrations can differ depending on the design of a BWR facility. These differences are as follows:

- Boron-10 content can vary from natural (19.9 atom percent) to as high as 54.5 atom percent.
- Some facilities require that both SLC pumps be started and inject solution to meet the minimum shutdown criteria.
- Some facilities utilize automatic initiation logic circuits to activate the SLC system.
- Some facilities have manual suction valves that remain open instead of motor-operated suction valves that are maintained closed and are automatically opened when the system is initiated.
- Some facilities have a head tank that maintains a volume of demineralized water at an elevation higher than the storage tank level to ensure that the lines between the pump suction valves (SLC-01A, -01B) and the pump suction remain full of water and are free of sodium pentaborate solution. This helps prevent line plugging caused by crystallization of the sodium pentaborate if the pump suction valves leak.
- Some facilities have accumulators on the pump discharge lines to dampen the pressure pulsation from operation of the positive displacement pumps.
- Some facilities inject the sodium pentaborate solution into the high pressure core spray injection line at a point just downstream of the inboard isolation valve.

2.6 System Operating History

Most BWR safety systems are multipurpose, that is, they have more than one mode of operation. However, the SLC system and its components have one major purpose: to inject neutron absorbing solution (poison) into the reactor. Some facility emergency operating procedures list the SLC system as an alternative method of high pressure injection. However, the SLC system is a low priority high pressure source, because it has such a low flow rate. Since this system has never been called into emergency service to serve its intended purpose, the SLC system's entire operating history is recorded in its testing and maintenance records.

3 Aging Assessment Methodology

3.1 Database Review

Part of the preliminary aging assessment of the SLC system involved a review of industry and regulatory databases for SLC system operating experience. The databases consulted for this study were as follows:

- Nuclear Plant Reliability Database System (NPRDS)
- Nuclear Documentation System (NUDOCS/AD)/Licensee Event Reports (LERs)
- NRC Generic Issues.

These databases were evaluated to determine if system components evidenced age-related degradation. Those instances where aging degradation was evident were evaluated to determine whether or not the aging effects would cause the SLC system to fail when required to operate during an emergency. The results are presented in Section 4.0.

3.2 Characterization of Sodium Pentaborate Effects

Characterizing sodium pentaborate effects involved literature searches, including a review of publications on the subject of sodium pentaborate, borates and boric acid. The emphasis was to describe the chemical properties and corrosion characteristics of borated solutions. Findings from the literature searches are presented in Sections 5.0 and 6.0.

4 Results of Database Review

4.1 Databases

The NPRDS contained 510 operating records related to the SLC system. Each record provided a description of the event, the cause, the resolution, or what was done to repair the problem.

The NUDOCS/AD database had 122 LERs that applied to the SLC system.

4.2 Screening Database Results

The database information was screened to segregate instances of aging degradation from immediate damage due to operator error (procedural error), maintenance error (e.g., failure to tighten connections), abuse (e.g., valves broken by unknown causes) and design error (upgrading required to meet system demands). Normal aging degradation, produced by error-free preservice and operating conditions (Grant and Miller 1992), was typically detected during testing and operator rounds.

Once the age-related failures were identified, it was determined whether the failure, if undetected, would hinder the operation of the SLC system during critical need. The original NPRDS and LER files were then condensed to 110 records.

4.3 Preliminary Results

The reliability of the SLC system components was assessed based on the screened database information. The four components that evidenced aging degradation were the relief valves, accumulators, pumps, and the SLC system instrumentation. The nature of the degradation and the potential effects on operation of the SLC system are summarized in Table 4.1 and discussed in the following sections.

4.3.1 Relief Valves

The system relief valves were the most troublesome component identified in the final 110 records. Relief valve failure was noted 84 times. Relief valve failure is considered to affect SLC system operation in two ways. First, if the relief valve does not open during operation the system could lose its over-pressure protection capability. The system requires over-pressure protection because positive displacement pumps have the capability to easily damage the system if a vent path does not exist. Second, if the valves leak by or lift early, the system could bypass its injection flow back to the pump suction or the storage tank and thereby reduce the boron injection rate in times of critical need.

The root cause of the failure of the relief valves was difficult to assess from the descriptions given in the databases. Fifty-five of the failures were attributed to setpoint drift due to mechanical wear. Eight of the failures could be connected to sodium pentaborate build up. Only two failures were related to corrosion of the valve internals.

4.3.2 Accumulators

The system accumulators were found to maintain operational integrity during service. Although the accumulators were subject to age-related degradation, the impact of the degradation was not considered detrimental to SLC system operation during critical need. In most cases, the degradation was identified through a partial or complete loss of the nitrogen blanket pressure. Loss of nitrogen pressure was caused by valve wear and failure of the gas bladder. Even though the pressure was lost, the accumulators stayed intact and would still pass flow when needed.

4.3.3 Pumps

Twelve records showed that pump failures would have hindered SLC system operation. Most of the failures resulted from the aging degradation of seals and internal check valves. These failures typically prevented the pump from operating within technical specifications for a given flow at a given pressure. These failures were found during surveillance testing. Packing leaks are

Table 4.1 Effects of SLC component degradation

SLC component	Identified form(s) of degradation	Potential effect(s) on operation
Relief valves	55 valve failures attributed to setpoint drift, probably caused by mechanical wear; 8 failures attributed to sodium pentaborate buildup; 2 failures related to corrosion of valve internals.	Relief valve failure could hinder SLC operation; higher valve setpoint results in a loss of system over-pressure protection; a decrease in setpoint could reduce the rate of boron injection.
Accumulators	Instances of partial or complete loss of nitrogen blanket noted.	Degradation effects minimal; accumulator would function properly during critical need.
Pumps	Degradation of seals and internal valves identified; packing leaks also noted.	Degradation could prevent pumps from operating within technical specifications.
Instrumentation	Some degradation noted.	Minimal effects; instruments are not necessary for system operation during critical need.

considered an aging effect, but failure of packing has not been considered a critical issue that would hinder the operation of the SLC system during critical need.

4.3.4 Instrumentation

The instrumentation required to monitor the system, such as component status lights, tank level and temperature gages, and system pressure, flow, and explosive valve continuity gages, is subject to aging but is not necessary for system operation during critical need.

4.4 Summary of Database Review

Information from the maintenance data base, NPRDS, has shown that the SLC system relief valves are the most troublesome system component that could affect system operation during critical need. However, the validity of the data base depends on the participation from utilities and the accuracy of the information provided by the utilities. Discussions with component repair vendors could be valuable in determining the root cause of the relief valve failures.

5 Sodium Pentaborate Characterization

This section summarizes the information obtained during a literature review of the characteristics of the sodium pentaborate used in the SLC system. Characterizing the sodium pentaborate solution provides a useful basis for assessing potential aging mechanisms in the SLC system.

5.1 Use of Sodium Pentaborate

The amount of sodium pentaborate available for injection into the RPV depends on the volume of stored solution, the usable volume of the storage tank, and the inventory of boron-10 isotope in the solution. The minimum required concentration of sodium pentaborate in solution depends on two factors: 1) the pumping capacity, and 2) the volume of solution for injection. With two pumps available and a capacity of 5000 gallons of solution, the sodium pentaborate concentration in weight percent can range from about 10% to about 24%. The normal concentration is about 12%, which corresponds to about 4300 gallons of solution to provide sufficient boron for reactivity control.

The maximum concentration of sodium pentaborate in solution is limited by the saturation point in water. The saturation point depends on the solution temperature and the ratio of Borax to boric acid. For example, at a solution temperature of 30°C (86°F) the saturation concentration can be as high as 14% by weight. An increase of dissolved boron, compared to boric acid dissolved in water alone or Borax dissolved in water alone, is attributed to the formation of the polyborate ion.

5.2 Preparation

The chemical formula for sodium pentaborate decahydrate is $Na_2O \cdot 5B_2O_3 \cdot 10H_2O$. It is formed when Borax ($Na_2B_4O_7$) and boric acid (H_3BO_3) are mixed with water. This reaction occurs when the molar ratio of Na_2O/B_2O_3 is equal to about 0.2 (Kirk-Othmer 1964, p. 85). Heat is released when boric acid and borate solutions are mixed, indicating that the formation of the polyborates is exothermic (Kirk-Othmer 1964, p. 79).

The formation of sodium pentaborate depends on the relative amounts of the reactants and the temperature. For example, at 30°C (86°F) with a mole ratio of 0.27, a new polyborate, $2Na_2O \cdot 5.1B_2O_3 \cdot 7H_2O$, begins to form. The same compound begins to form at 5°C (41°F) with a mole ratio of 0.22.

5.3 Properties

5.3.1 Nuclear Properties

There are two naturally occurring isotopes of boron. The boron-10 proportion is 19% to 20%, and that of boron-11 is 80% to 81%. The boron-10 isotope is of particular importance in the operation of nuclear reactors because it has a large cross section for thermal neutron capture. Most BWR facilities use boron with naturally occurring isotope concentrations. Some BWR facilities are using boron with a boron-10 enrichment up to 54 atom percent.

5.3.2 Chemical Properties

5.3.2.1 Solubility

Sodium pentaborate is much more soluble than the individual Borax or boric acid compounds. When Borax is added to a saturated boric acid solution or boric acid is added to a saturated Borax solution, the solubility, measured as percent B_2O_3 (borate) in solution, increases markedly. For example, at 30°C (86°F), the saturation limit for dissolved borate, Borax, or boric acid in water alone is $<4\%$; a mixture of Borax and boric acid can be as high as 14% (Nies and Cambell 1964). The increase is evidence of the formation of the polyborate ions in solution. Polymerization removes from solution some of the boric acid molecules and borate ions that are in equilibrium with the solids. More Borax and boric acid can therefore dissolve (Nies and Cambell 1964).

The solubility of sodium pentaborate also increases with increasing temperature. Solubility, expressed in units of percent anhydrous salt by weight, increases from 6.28% at 0°C (32°F) to 50.30% at 100°C (212°F). The temperature of the SLC storage tank is normally maintained at about 30°C (86°F), which results in a 13.75 wt% solution (weight of sodium pentaborate per 100 wt of saturated solution) (Nies and Cambell p. 100, Table VI). The solubility of the B_2O_3 at 30°C ranges from about 11.5% to 14.5%, corresponding to molar ratios of 0.19 to 0.25 (Nies and Cambell 1964, p. 82, Figure 5). The sodium pentaborate concentration is normally kept at about 12%. This is less than the saturation limit for 30°C (86°F).

Note that the sodium pentaborate concentration examples given in the previous paragraph use the anhydrous salt form (molecular weight is 410 wt/mole) for determining the weight percent. Industry experts state that the standard calculation of weight percent of sodium pentaborate in solution uses the decahydrate salt form (molecular weight is 590 wt/mole). Therefore, 13.75% sodium pentaborate by weight per 100 wt of solution would yield 3.63% boron if anhydrous sodium pentaborate is used and 2.52% boron if sodium pentaborate decahydrate is used. This difference is significant because 1095 ppm boron is required to be converted into weight percent of sodium pentaborate (decahydrate) in solution.

5.3.2.2 pH Characteristics of Sodium Pentaborate Solutions

The pH values of aqueous solutions of sodium pentaborate at 20°C (68°F) as a function of weight percent are (Kirk-Othmer 1964, p. 85):

Wt %	pH
0.5%	8.5
1.0%	8.4
2.0%	8.2
3.0%	8.0
5.0%	7.7
10.0%	7.1
14.0%	6.8

Based upon the 13.75 wt% given above, the pH should be in the range from 7.1 to 6.8, adjusted for temperature. In general the pH is near neutral.

5.3.2.3 Stability

At 100°C (212°F) crystalline sodium pentaborate, the decahydrate, was found to decompose to form the dihydrate and a solution of 58% NaB_5O_8 (US NRC 1978a). This is not expected to be a problem because sodium pentaborate is batch mixed from Borax and boric acid as needed; the mixture is not stored in crystalline form.

If hot sodium pentaborate solutions are agitated for some time, the compound $2Na_2O{\cdot}9B_2O_3{\cdot}11H_2O$ will crystallize if seed crystals are present (US NRC 1978a). This process only occurs at temperatures near boiling and thus is not expected to be a problem because the storage tank solution is maintained at about 30°C (86°F).

Sodium pentaborate solution when left undisturbed for long periods (more than one week) will stratify into concentration gradients (US NRC 1986). The SLC storage tank is routinely agitated. This practice maintains the tank solution well mixed to prevent concentration stratification.

5.3.2.4 Environmental Conditions: Borated Section of SLC Systems

General Electric specifications for boric acid indicate that the purity limit of the granular boric acid must be 99.90% by weight. The chloride impurity limit is 0.0001% by weight.

The US BORAX Service Bulletin No. 1179 identifies Borax as a corrosion inhibitor. The bulletin states that "The buffering action of Borax (5 molar or 10 molar) maintains pH above 7, where acidic compounds cannot form." The bulletin further states that "Borax inhibits corrosion by minimizing the rate of oxidation at the surface of the metal and is classified as an anodic inhibitor."

The US BORAX Service Bulletin No. BX-21 states that anodic inhibition is "...accomplished by growing an oxide film on the surface of the metal. This phenomenon is called passivation and is actually a form of controlled general corrosion." The bulletin further states that Borax is a "nonoxidizing anodic inhibitor because [it] has insufficient oxidizing power of [its] own to effect passivation (i.e. oxygen must be present)."

The portion of the SLC system in contact with the sodium pentaborate solution is the storage tank to the pump suction valves (SLC-01). The concentration of chlorides and sulfates is the maximum stated in the material specification for the boric acid. The environmental conditions in the borated sections of SLC systems are as follows:

Temperature	
Normal	21-30°C (70-86°F)
Mixing	65°C (150°F) (storage tank only)
Pressure	<10 psig
pH	>6.8
Chlorides	<0.0001% by weight (<1 ppm)
Sulfates	<0.0002% by weight (<2 ppm)
Oxygen	saturated

These conditions appear to be less aggressive than the conditions that cause degradation of stainless steels (see following section).

6 Corrosion in SLC System Environments

To assess the potential for corrosion of SLC system components to develop, it is necessary to define the material and environmental factors and to assess their relationship to known corrosion regimes. The failure databases do not reveal specific failures in SLC systems that are attributed to corrosion. However, it is important to consider whether corrosion can be expected to emerge as service life is extended.

6.1 SLC System Environments and Materials

The principal environments in typical SLC systems are as follows:

- aerated sodium pentaborate solution at 65°C (150°F) during mixing and 21-30°C (70-86°F) during static operation in the tank and heat-traced lines
- deionized water (aerated) in the test circuits and tank at ambient temperatures
- exterior surfaces of stainless steel pipes, valve bodies, and tanks exposed to air in the temperature range 10 to 30°C (50 to 86°F).

The principal material in the SLC system tanks and pipes is stainless steel. The specific types have not been surveyed in detail, but both normal grades (e.g., alloy 304) and low-carbon grades (e.g., 316L) are represented.

The SLC system resides at low pressures and temperatures in normal operation (see Section 5.3.2). It operates static except during runs in the test circuit.

The factors that contribute to corrosion of stainless steels include: a contaminated environment, corrosion-prone (e.g., sensitized) microstructures, and, in the case of stress-assisted phenomena, high stress levels.

Because the SLC system is safety-related, high-integrity weld procedures would have been required, suggesting that high levels of sensitization would not be expected in weld heat-affected zones. Stress levels in SLC system components have not been characterized specifically, but their effects, if present, seem to be mitigated by other favorable factors considered below.

6.2 Assessment of Expected Corrosion Characteristics

Stainless steels are generally not prone to serious corrosion in deionized water under conditions that exist in the SLC system. Also, the SLC-air-side environments appear to be benign for stainless steels unless contaminants foreign to normal conditions are introduced.

The principal corrosion consideration in the SLC system focuses on the portion of the system that is in contact with borated solutions.

6.2.1 Corrosion-Induced Failures of Stainless Steel in Aerated, Borated Solutions

6.2.1.1 Documented Failures

There have been numerous failures of stainless steel in borated solutions at low temperatures [20-40°C (68-104°F)]. The failures are illustrated by two cases cited below. The first involved failure of the piping in the fuel storage pool cooling system, in a standby loop; the second involved separation of the upper end fitting from an irradiated fuel assembly in a spent fuel storage pool (FSP).

6.2.1.2 Three Mile Island 1 Fuel Pool Piping

At the Three Mile Island Unit 1 fuel storage pool, cooling loop A, nine sections of pipe from the fuel pool were observed to have small through-wall cracks in weld heat-affected zones (HAZ). The failures occurred in the redundant section of the pool coolant system (loop A), which remained stagnant for most of the time from commissioning in 1974 to observation of the cracks in 1979. A study (Bruemmer and Johnson 1984) indicated that sulfur and chlorine were present in the fracture area in a weld heat-affected zone, and the HAZ material was sensitized.

6.2.1.3 Prairie Island 1 Fuel Assembly End Fitting Separation

The upper end fitting (nozzle) separated from an irradiated Prairie Island Unit 1 fuel assembly during handling in the spent fuel pool in December 1981. The suspected failure mode of the Type 304 stainless steel sleeves in the Prairie Island-1 fuel assembly was IGSCC, which occurred while the fuel assembly was stored in the FSP (Bailey and Johnson 1983). The stainless steel guide tubes were sensitized when the upper tie plate assembly was heat treated. Bulges that joined these guide tubes to the Zircaloy tubes were a potential source of stress. A contaminant which might have contributed to the IGSCC was not identified but was speculated to be this sulfate. The NRC is treating this failure as an isolated case.

6.2.2 Failure Study Conclusions and Recommendations

A study by Jones et al. (1981) indicated that Type 304 stainless steel is susceptible to intergranular stress corrosion cracking (IGSCC) under fuel pool conditions. There have been, however, "... no IGSCC failures observed at 32°C (90°F) in borated water without [chloride ion] additions," addressing laboratory tests (Jones et al. 1981).

Johnson et al. (1981) state that crack initiation in Type 304 stainless steel in boric acid at 40°C (104°F) is a significant step in the fracture process. The study suggests that several factors be avoided when using Type 304 stainless steel in FSP: 1) carbon concentrations should be kept below 0.07 wt%; 2) weld preparation grinding should be done with care; 3) weld heat should be minimized; and 4) system impurities such as chlorides and thiosulfates should be minimized.

The study by Jones et al. (1981) concludes that "high carbon (0.07%) 304SS can be sensitized sufficiently by welding or heat treating (24 hrs at 620°C) to cause IGSCC at 32°C (90°F) in borated water containing 15 ppm [chloride ion]."

6.3 Comparison of FSP and SLC System Conditions

The following table summarizes information comparing FSP and SLC system conditions.

Condition	FSP	SLC
Temperature, °C	20-50°C (68-122°F)	21-30°C (20-68°F)
Pressure	static head of pool	static head of storage tank
Oxygen	saturated	saturated
pH	4.5	>6.8
Chlorides, ppm	<0.15	<1.0
Sulfates, ppm	?	<2.0

The similarities between the FSP and SLC system conditions are stated below:

- both involve borated chemistries
- both involve oxygenated conditions
- both operate in similar temperature and pressure regimes
- both operate under stagnant conditions
- both have stainless steel as the principal material of construction.

The literature suggests that stress corrosion cracking generally occurs more aggressively at low pH in low-temperature aqueous environments, although there are variations, particularly as temperatures increase (Theus and Staehle 1973).

Tyfield (1982) indicates that oxide film breakdown has an induction time that appears to be extended by increasing pH and borate content and decreasing chloride and temperature.

The testing that is required by technical specifications for the SLC borated solution addresses only the concentration of the sodium pentaborate and in some cases the atom percent of boron-10. It does not address the concentration of chlorides or of sulfates. Therefore, it is recommended that the concentrations of the contaminant chlorides and sulfates in the SLC storage tank be monitored as a basis to control susceptibility to stress corrosion cracking.

The main potential sources of contaminants in the SLC solution are the bulk chemicals, boric acid and Borax. The contaminant level of chloride and sulfate ions should be evaluated periodically, to verify original certifications, before addition to the storage tank.

Key differences between the FSP and SLC are as follows:

- The source of boron in the SLC system is sodium pentaborate; in the FSP system, the boron source is boric acid.
- The pH of the FSP solution is typically ~4.5; in the SLC solution the pH is near neutral (~7.0).

The higher pH in the SLC system would be expected to mitigate IGSCC of stainless steel. Higher weld integrity is another potentially favorable factor that has not been investigated systematically.

In summary, the current industry experience on corrosion in SLC systems indicates that there is no unpredicted corrosion of components in contact with the sodium pentaborate solution. This result is expected because the components are subject to relatively mild conditions: low levels of chloride, higher pH range, low temperature, and low pressure. The types of failures experienced in PWR fuel storage pools are not expected to occur in SLC system materials, based on the less aggressive conditions. However, selected monitoring of SLC system components for IGSCC is recommended, particularly at locations that may have been subject to sensitization (weld heat-affected zones).

7 Conclusions and Recommendations

The SLC system is unique to BWRs and is designed to provide alternative reactivity control in the event that control rods can not be inserted into the reactor core. The SLC system is a stand-alone system and is rarely operated except to perform required surveillances and inspections for technical specification compliance.

A survey of reported incidents related to the aging of the SLC system indicates that degradation of system relief valves (SRVs) could prevent the valves from opening properly and thus reduce the boron injection rate. The relief valves have experienced setpoint drift, which has been discovered during routine surveillances and is likely attributed to mechanical wear. Therefore, additional study of the SLC relief valves is recommended. A minimum relief valve testing interval of every refueling outage is also recommended.

Degradation of SLC pump seals and pump internals as well as packing leaks were also noted; this could prevent the pumps from operating within technical specifications. Additionally, degradation of accumulators has occurred resulting in partial or complete loss of the nitrogen blanket.

The SLC sodium pentaborate solution provides a mild environment with respect to age-related degradation. The intergranular stress corrosion cracking (IGSCC) that occurs in PWR fuel storage pools is not expected to occur in SLC systems. Industry experience and expert opinion suggest that the SLC system is less vulnerable to IGSCC than the boric acid conditions that have resulted in IGSCC in other systems.

The following are practices which, if implemented, would further minimize the risk of failures due to IGS-CC:

(1) The contaminant level of chloride and sulfate should be independently evaluated, to verify the certification values received from the Borax and boric acid vendor, before addition of the chemicals to the SLC system storage tank.

(2) The concentration of contaminant chlorides and sulfates in the SLC storage tank should be monitored periodically to determine whether concentrations are at levels that could contribute to IGSCC.

(3) Selected, specific nondestructive evaluations should be conducted to detect whether IGSCC is occurring, particularly in weld heat-affected zones.

In summary, the effects of age-related degradation on the SLC system have been minimal. Deterioration of system relief valve performance has been the most significant aging problem. Additional study of the SLC relief valves and testing of the valves during every refueling outage is recommended. If the NPAR safety relief valve study were conducted, then the principal vulnerabilities of the SLC system would be addressed, and a separate NPAR Phase II aging study of the SLC system would not be necessary.

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Pacific Northwest Laboratory conducted a Phase I aging assessment of the standby liquid control (SLC) system used in boiling-water reactors. The study was based on detailed reviews of SLC system component and operating experience information obtained from the Nuclear Plant Reliability Database System, the Nuclear Document System, Licensee Event Reports, and other databases. Sources on sodium pentaborate, borates, and boric acid, as well as the effects of environment and corrosion in the SLC system were also reviewed to characterize chemical properties and corrosion characteristics of borated solutions.

Relatively few SLC component failures were attributed to sodium pentaborate buildup or corrosion. The leading aging degradation concern to date appears to be setpoint drift in relief valves, which has been discovered during routine surveillance and is thought to be caused by mechanical wear. A higher setpoint results in loss of system overpressure protection, and a decrease in setpoint results in a reduction of boron injection rate. Degradation was also observed in pump seals and internal valves, which could prevent the pumps from operating as required by the technical specifications. In general, however, the results of the Phase I study indicate that age-related degradation of SLC systems has not been serious.

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