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Generic Assessment for Optimized Reactor Coolant System Hydrogen of a Four-loop Westinghouse Pressurized Water Reactor

2011 TECHNICAL REPORT

Generic Assessment for Optimized Reactor Coolant System Hydrogen of a Four-Loop Westinghouse Pressurized Water Reactor

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EPRI Project Manager
C. Haas

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ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Westinghouse Electric Company LLC
1000 Westinghouse Drive
Cranberry Township, PA 16066

Principal Investigators
G. Corpora
T. Jaeger
R. Mangerie
K. Slaby
J. Stevens

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ABSTRACT

The Chemistry, Fuel Reliability, and Material Reliability Programs at the Electric Power Research Institute (EPRI) have developed a comprehensive elevated reactor coolant system (RCS) hydrogen program that is focused on qualification of plant operation with dissolved hydrogen concentration in the RCS greater than 50 standard cubic centimeters per kilogram (scc/kg) (1.38 in.^{3}/lb$_m$), up to 60 scc/kg (1.66 in.^{3}/lb$_m$), to mitigate primary water stress corrosion cracking (PWSCC) in nickel-based alloys. Currently, the industry-wide RCS upper limit on dissolved hydrogen is set at 50 scc/kg (1.38 in.^{3}/lb$_m$), and the industry-wide cycle-average RCS hydrogen concentration is 34 scc/kg (0.94 in.^{3}/lb$_m$) . Six plants worldwide report operation with a cycle-average RCS hydrogen concentration greater than 45 scc/kg (1.25 in.^{3}/lb$_m$).

The current *EPRI Pressurized Water Reactor (PWR) Primary Water Chemistry Guidelines* (Revision 6) allow for power operation of plants with RCS hydrogen maintained between 25–50 scc/kg (0.69-1.38 in.^{3}/lb$_m$). This report investigates the effects on a typical PWR of increasing the RCS dissolved hydrogen concentration from 25–50 scc/kg (0.69-1.38 in.^{3}/lb$_m$) to as high as 80 scc/kg (2.21 in.^{3}/lb$_m$). The effects on RCS systems, components, materials, instrumentation, and plant operations have been evaluated and are documented here.

The results of the evaluations indicate that a significant increase in dissolved hydrogen concentration up to 80 scc/kg (2.21 in.^{3}/lb$_m$) is feasible during normal plant power operations, with the maximum hydrogen concentration being dependent upon and limited by the desired margin between the volume control tank normal operating pressure and the tank relief valve setpoint. A lesser increase in dissolved hydrogen concentration to 60 scc/kg (1.66 in.^{3}/lb$_m$) maximum would have correspondingly reduced impacts on systems, components, materials, instrumentation, and plant operations as compared to the current operating parameters. Either increase above the current maximum operating range would require similar evaluations and changes to be approved prior to implementation of increased RCS hydrogen concentration.

Keywords

Hydrogen
PWSCC
Reactor coolant pump
Reactor coolant system
Volume control tank

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1
INTRODUCTION

1.1 Background

The Electric Power Research Institute (EPRI) currently has a long-term program to investigate the possible benefits of changes to the hydrogen concentration in the reactor coolant system (RCS) with regard to ameliorating the occurrence of primary water stress corrosion cracking (PWSCC) of nickel-based alloys. EPRI published a report in 2006 which determined that significant benefits in material integrity and longevity can be derived from an increase in RCS dissolved hydrogen concentration up to 80 scc/kg [1]. These benefits were associated with reducing PWSCC growth rates for nickel-based alloys. However, the ability of the affected plant systems and equipment to accommodate the increased dissolved hydrogen concentration had not yet been investigated.

In 2007, Westinghouse participated on an expert panel to assess the feasibility of operating Westinghouse and Combustion Engineering plants with high and low concentrations of dissolved hydrogen in the RCS [8]. The EPRI report specifically focused on operating pressurized water reactors (PWRs) at elevated RCS hydrogen concentrations above the current operating range of 25–50 standard cubic centimeters per kilogram (scc/kg), that is, concentrations at or above 50 scc/kg, up to 80 scc/kg. As part of the 2007 assessment, Westinghouse also performed an impact review of the increased range of RCS dissolved hydrogen concentration, summarizing additional plant system and equipment safety assessments that would need to be performed [21]. The results of this review are contained in Appendix B.

Several functional areas were categorized as impacted, several as not directly impacted, and others as not impacted by the proposed increase in RCS hydrogen concentration. In summary,

- Impacted areas would require additional evaluation, analysis, and effort.
- Not directly impacted areas might or might not require additional evaluation, analysis, and effort.
- Not impacted areas were not expected to require additional evaluation, analysis, or effort.

This functional area categorization was used as the basis for determining which systems and equipment should be evaluated for impacts from the proposed increase in RCS hydrogen concentration.

1.2 Objective

The objective of the system and equipment assessments was to evaluate those functional areas that have been identified as being impacted by increasing the RCS hydrogen concentration up to 80 scc/kg. If it became apparent during the performance of the evaluations that system or component difficulties arose with respect to RCS dissolved hydrogen at 80 scc/kg, Westinghouse would promptly notify and consult with EPRI to determine a path forward in this event, possibly with a sensitivity analysis approach on interim hydrogen values between 50–80 scc/kg. This contingency was further defined by EPRI in 2010, with direction to focus on a reduced maximum concentration of 60 scc/kg should the original maximum concentration of 80 scc/kg be problematic for any system or component under evaluation [22].

1.3 Approach

The assessments performed by Westinghouse typically used Byron Unit 1 as the reference Westinghouse nuclear steam supply system (NSSS) study plant. Where possible, generic statements regarding the applicability of the results to other Westinghouse- and Combustion Engineering– (CE-) designed NSSS are provided in this report. This does not preclude performance of plant-specific assessments for any plant designs, but was intended to provide a confidence level for additional evaluations associated with this topic.

1.4 Scope of Work

Note: Nuclear fuel and fuel assembly impacts from increased RCS hydrogen concentration are addressed separately under an EPRI Fuel Reliability Program and are not included with the scope of work described in this report.

The following scope of work used a previous submittal to EPRI from Westinghouse [21] and a prioritization of the initial, most critically perceived tasks to be performed first.

The first system and component evaluations included the following:

- Fluid systems technical evaluation and assessment
  - Determine if the existing chemical and volume control system (CVCS) volume control tank can operate at the increased pressure required to maintain the increased RCS hydrogen concentration.
  - Determine reactor coolant pump (RCP) number 1 seal backpressure.
- Reactor coolant pump seals evaluation and assessment
  - Determine the effect or impact of lower number 1 seal pressure drop, higher number 2 seal pressure drop.

Based upon the results of the first set of evaluations, subsequent evaluations would consider the effects of increasing the volume control tank (VCT) pressure from 20–30 psig to a pressure value sufficient to maintain a dissolved hydrogen concentration in the RCS up to 80 scc/kg. This would include gas pressure regulator setpoints, relief valve performance due to increased backpressure from the VCT, and flow performance of systems injection into the VCT discharge, which must overcome additional backpressure. The second set of system and component evaluations included the following:

- RCS
  - Evaluate the effect of additional hydrogen released to containment post-accident.
  - Evaluate the effect of additional hydrogen discharged to the pressurizer relief tank from the pressurizer safety valve and power-operated relief valve leakage.
- CVCS

- Confirm the adequacy of the existing VCT relief valve for the higher set pressure.
- Confirm the adequacy or re-specify the VCT hydrogen supply regulator sizing and set pressure.
- Confirm the adequacy or re-specify the VCT burp regulator sizing and set pressure (older vintage plants).
- Confirm the adequacy or re-specify the VCT purge regulator sizing and set pressure (newer vintage plants – part of waste gas system).
- Confirm the adequacy or re-specify the VCT gas sample regulator sizing and set pressure.
- Evaluate the letdown line pressure control valve performance with additional backpressure.
- Evaluate the letdown line relief valve performance with additional backpressure.
- Evaluate the excess letdown line control valve performance with additional backpressure.
- Evaluate the RCP seal return line relief valve performance and set pressure with additional backpressure.
- Re-analyze the emergency boration flowpath with additional backpressure.
- Re-analyze the makeup system (boric acid and makeup water) control valves with additional backpressure.
- Evaluate the increased potential for voids in the centrifugal charging pump suction.
- Evaluate the charging pump miniflow orifice performance with additional backpressure.

· Boron recycle system

Calculate additional hydrogen released to the recycle holdup tanks from the letdown flow.

· Instrumentation and Controls (I&C)

Determine the adequacy or re-specify the existing pressure instruments in lines connected to the VCT.

· Materials evaluation

Evaluate the effects of increased hydrogen on selected component materials:

1. Perform a literature review to define the current state of knowledge regarding the effect of hydrogen on properties of these materials. In particular, define:
   - The fracture toughness change with hydrogen concentration either in the environment or in the material
   - Whether the material is subject to subcritical crack growth in hydrogen
2. Perform a cursory review of the material performance in liquids with dissolved hydrogen.
3. Perform a review of the material performance in gas phase hydrogen.

4. Summarize the material's expected performance in the increased hydrogen concentration condition, including plausible variations over the anticipated conditions.
5. Based on the literature review results, perform a qualitative assessment on the potential for hydrogen-induced degradation of materials.

- RCP #1 and #2 seal tests

  These proof-of-principle tests were intended to replicate the change in the RCP seal differential pressure that would be required to operate at the elevated RCS hydrogen concentrations of interest for this project.

  1. Conduct a special test of a #1 ring and runner seal assembly with an increased differential pressure. The #1 seal test included a baseline test using standard parameters and a primary test for elevated backpressure.
  2. Conduct a special test of a No. 2 seal ring and runner with an increased differential pressure.

1.5 Document Overview

Westinghouse performed generic evaluations of affected systems, components, and typical operating practices. The selected reference plant was Byron Unit 1, which is a typical Westinghouse NSSS four-loop PWR. However, application of the concepts and conclusions contained here are deemed appropriate for other NSSS designs (for example, CE NSSS designs) even though the component descriptions, functions, and setpoints may vary slightly from one plant to another. Where appropriate, specific differences in these designs are mentioned or supported with additional detail.

1.6 Conversion Factors

Table 1-1 lists the measurements used in this report, along with conversion factors to convert them between English unit measurements and International System of Units (SI) measurements.

Table 1-1
Conversion Factors

English to SI Units	SI to English Units
Area	
1 ft^2 = 0.0929 m^2	1 m^2 = 10.76 ft^2
Length	
1 inch = 25.4 mm or 2.54 cm 1 ft = 0.3048 m or 30.48 cm	1 mm = 0.03937 inch 1 m = 3.281 ft
Mass and Density	
1 lb_m = 0.4536 kg 1 lb_m/ft^3 = 0.06234 kg/m^3	1 kg = 2.2046 lb_m 1 kg/m^3 = 16.02 lb_m/ft^3
Pressure	
1 lb/in^2 = 1 psi 1 psi = 6.8948 kPa Std. Atm. Pressure = 14.696 psi	1 N/m^2 = 1 Pa 1 kPa = 0.145 psi Std. atm pressure = 1.01325 bar 1 bar = 1 x 10^5 Pa
Temperature	
°F = (°C x 9/5) +32	°C = (°F -32) x 5/9
Volume	
1 ft^3 = 0.02832 m^3 1 gallon (US) = 3.785 L 1 ft^3 = 7.4805 gallons (US)	1 m^3 = 35.31 ft^3 1 L = 0.2642 gallon (US) 1 m^3 = 1000 L 1 scc/kg = cc (STP)/kg H_2O 1 cc = 0.001 L STP = 273K (0°C) and 1 atm pressure
Weight	
1 lb = 0.454 kg	1 kg = 2.205 lb_m

2
EQUIPMENT EVALUATIONS

This section is devoted to addressing system components that are routinely exposed to fluid containing high dissolved hydrogen concentrations during normal plant operations. These components are sensitive to these increased concentrations primarily because of the potential for more gas coming out of solution. These components include the VCT, RCP seals, and charging pumps. Other components are not addressed because they are not expected to be affected by any dissolved hydrogen concentration:

- Piping – The pipe itself is affected only by fluid pressure and temperature. Effects on materials are addressed in Section 7.
- Manual and control valves – Isolation and control functions are not affected by fluid composition. Effects on materials are addressed in Section7.
- Pressure vessels, such as filters, heat exchangers, and demineralizers – Like piping, they are affected only by fluid pressure and temperature. Effects on materials are addressed in Section 7.
- Residual heat removal (RHR) pump and heat exchanger – This system is aligned with the RCS for two reasons: During normal plant cooldown, the RCS is typically degassed down to 15 scc/kg prior to reactor shutdown, so there is no effect of increased hydrogen concentration during power operation. During safety injection operation, the RHR pump takes suction from the atmospherically vented refueling water storage tank (RWST). Other safety injection–type pumps are not affected since they also take suction from the RWST.

2.1 Volume Control Tank (VCT)

One of the key components in the overall systems evaluation is the VCT, which performs the following functions:

- Provides suction head for the charging pumps
- Provides a gas space during plant operation to allow a hydrogen blanket to dissolve hydrogen into the liquid space or a nitrogen blanket during shutdown conditions
- Provides makeup and surge volume for the RCS

As a result of the second function, the VCT gas space creates a backpressure for the following:

- RCP No. 1 seals (for the CE NSSS, between the vapor seal and preceding stage seal)
- Reactor makeup subsystem (including primary water and boric acid)
- Nitrogen and hydrogen supply regulators
- Letdown line
- Excess letdown line (enters RCP seal leakoff line) (not applicable to CE NSSS)

- RCP seal leakoff line and letdown line relief valves

Under current operating conditions, the typical normal VCT pressure is in the range of 20–30 psig. This provides a liquid dissolved hydrogen concentration of 25–35 scc/kg. A VCT high-pressure alarm is typically set at 67 psig, and the VCT relief valve is set for 75 psig Thus, a significant operating margin currently exists.

Westinghouse plant designs are equipped with VCTs with a total tank volume of 300 ft^3, 400 ft^3, or 600 ft^3, depending on the specific plant design. To accommodate the proposed operating conditions, a structural analysis [2] was performed. The purpose of the analysis was to determine the maximum internal pressure that the 300 $ft^3$and 400 ft^3 tank designs can withstand.

Maximum internal pressure is determined by demonstrating that American Society of Mechanical Engineers (ASME) Code criteria impacted by pressure are satisfied. First, the maximum allowable internal pressure was calculated using the minimum thickness of the shell and head. The nozzle reinforcements on the 400 ft^3 tank were then checked to determine if they were sufficient given this new internal pressure. Finally, the local stresses in the nozzle attachments under the new pressure are calculated. The completed analysis shows that 90 psig is the maximum acceptable internal pressure.

The maximum allowable internal pressure for the 300 ft^3 tank is then calculated using the minimum thickness of its shell and head. Since the resulting pressure is higher than the allowable internal pressure for the 400 ft^3 tank and the nozzle geometry is the same, the 400 ft^3 tank is the limiting case. The only exception to the nozzle geometry is the addition of a 1" N_2 and hydrogen supply nozzle in the 300 ft^3 tank that is not found in the 400 ft^3 design. To address this difference, its nozzle reinforcements and local stresses were evaluated and were found to be acceptable.

After accounting for an additional 10% safety factor, the final allowable internal pressure was calculated to be 80 psig. The existing relief valve could therefore be reset for 80 psig (see Section 5).

The Westinghouse 600 ft^3 VCT design has a design pressure of 85 psig and is, therefore, bounded by the above analysis.

2.1.1 CE NSSS Volume Control Tanks

The VCTs in the CE NSSS fleet range in internal volume from 386 ft^3 to 683 ft^3 with a design pressure of 75 psig. Although no structural analyses have been performed, it is expected that a design pressure of 80 psig could be justified for each tank design similar to that discussed above.

An additional requirement for the CE NSSS VCT is to provide water for RCS contraction upon a reactor trip (with the VCT in the normal operating band) beyond that not accounted for by the change in the pressurizer level program. Also a requirement of the VCT is to accept RCS expansion water in going from 0% to 100% power beyond that not accounted for by the change in the pressurizer level program without exceeding the VCT design pressure. If the hydrogen overpressure is raised substantially closer to the VCT design pressure, there will be less operating margin to accept an influx of fluid into the VCT during start or design transients. Accordingly, each plant will need to review plant operating procedures (that is, to determine initial levels) and re-evaluate VCT setpoints with respect to design basis transients. It is noted that it may be possible to vent (or partially vent depending on existing valve capacity) the VCT to the gas waste system to accommodate such an in-surge; however, this would result in unnecessary use of additional hydrogen and increased demand on the waste system. During the startup scenario, it may also be possible to procedurally limit the VCT overpressure until after the plant heat-up, or lower VCT level prior to the heat-up in order to preclude an overpressure condition.

2.2 Westinghouse NSSS Reactor Coolant Pump Seals

The Westinghouse NSSS Pump Shaft Sealing system employs three stages of seals that operate in series to reduce the RCS pressure from 2250 psia to containment ambient pressure [3]. See Figure 2-1. Injection water at slightly higher pressure than the RCS pressure is injected into the RCP at an axial location within the pump between the thermal barrier heat exchanger (TBHx) and the No. 1 seal. The total injection flow, which exceeds the No. 1 seal leak rate, supplies the seal with cool, filtered water. The seal injection water then flows either through the No. 1 seal as leakoff flow or down past the TBHx and joins the RCS flow circulating through the pump.

The majority of the pressure drop occurs across the No. 1 seal, where the pressure is reduced from RCS pressure to slightly above VCT pressure. The majority of the flow past the No. 1 seal is diverted by the No. 2 seal to the seal return heat exchanger and then to the VCT discharge. The VCT pressure influences the backpressure to the No. 1 seal leakoff and the No. 2 seal inlet pressure. The differential pressure across the No. 2 seal is normally controlled by the VCT pressure on the inlet side of the seal and by the No. 3 seal standpipe static head at the discharge of the seal. The majority of the flow past the No. 2 seal is diverted to the reactor coolant drain tank (RCDT) by the No. 3 seal. For pumps using a bellows-style or cartridge conversion single nose No. 3 seal, the ΔP is controlled by the static head in the No. 3 seal standpipe at the inlet and containment atmospheric pressure on the discharge.

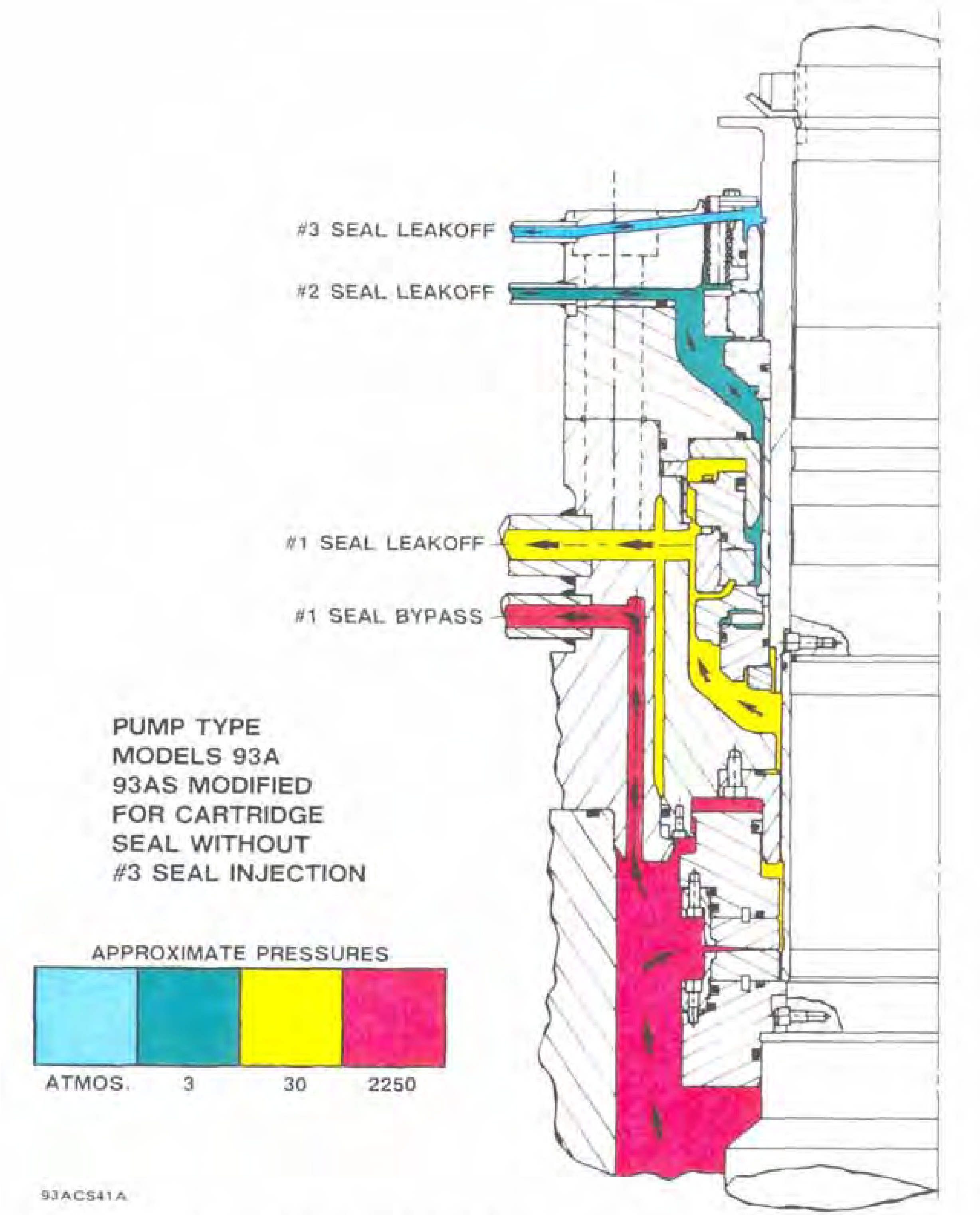


Fig. II-1, 93ACSC Single-Dam Seals

Figure 2-1
Westinghouse RCP Seal Diagram with Flow Paths

2.2.1 Seal Backpressure

Backpressure on the RCP No. 1 seals consists of:

- VCT overpressure
- Head loss from the seal leakoff line and charging pump miniflow piping to the VCT
- Elevation head from the RCP No. 1 seal leakoff to the VCT normal operating level elevation

As discussed in the next section, VCT overpressure is expected to be in the range of 63–66 psig, depending upon VCT temperature, to achieve 80 scc hydrogen/kg in the RCS. Head losses due to friction are typically small, in the range of 5–10 psi. Data from Byron Unit 2 shows that the elevation head is ~35 ft. (15 psig), depending upon actual VCT level. Thus, the backpressure on the RCP No. 1 seals is expected to be as shown in Table 2-1.

Table 2-1
RCP No. 1 Seals Expected Backpressure

	Reference Plant	RCS H_2 Increase to 60 scc/kg	RCS H_2 Increase to 80 scc/kg
Component	**Pressure**	**Pressure**	**Pressure**
VCT overpressure	20–30 psig	43–46 psig*	62–66 psig*
Head loss	5–10 psi	5–10 psi	5–10 psi
Elevation head	15 psi	15 psi	15 psi
RCP No. 1 seal backpressure	40–55 psig	63–71 psig	83–91 psig

*See Section 3, below

The No. 1 seal is a hydrodynamic seal designed and tested to function with a ΔP of approximately 200–2250 psi. The typical leak rate of the No. 1 seal is between 1.5–3.0 gallons per minute (gpm) (at 2250 psi ΔP) with typical alarm set points of 1 and 5 gpm. Increasing the VCT pressure will effectively reduce the ΔP under which the No. 1 seal will operate. This would have a tendency to reduce the No. 1 seal leak rate. Based on the calculated future VCT pressure, the ΔP of the No. 1 seal will be reduced by approximately 28–51 psi. This would result in a very small reduction (estimated to be less than 0.1 gpm) in the No. 1 seal leak rate. This reduction is not significant and would not pose a problem for continued operation of the seal. However, experience has shown a much greater than linear impact on No. 1 seal leakoff rates when VCT pressure is adjusted. Therefore, those plants operating with a relatively low leakoff flow rate will have difficulty meeting minimum leakoff flow limits with increased VCT backpressure.

Backpressure on the No. 2 seals is provided by the RCDT. In older plant designs, the RCDT is vented continuously to the waste gas system vent header, which operates at 0–2 psig. In newer plant designs, the RCDT is vented to the waste gas system via a pressure regulator, which opens at 6 psig. Operation of either design is not affected by an increase in the RCS hydrogen concentration. Because more hydrogen will be released into the RCDT under the new VCT conditions, the tank will be vented more often. Typical No. 2 seal leakoff flow is 0.05 gpm per RCP. At 30 scc/kg, the hydrogen release rate would be 0.0008 SCFM for a four-loop plant, assuming all the hydrogen is released. At 80 scc/kg, the release rate would be 0.002 SCFM.

In the low-pressure or normal mode of operation, the No. 2 seal operates with a differential pressure of approximately 30 psi across the face. The forward pressure on the seal is normally determined by the VCT pressure (typically, 30 psig) and the backpressure determined by the head of water above the No. 2 seal leakoff connection and/or pressure in the RCDT. When functioning as designed in the low-pressure mode, the No. 2 seal will typically leak at a negligible rate and any flow through the seal passes to the RCDT. As a result of this very low leak rate through the No. 2 seal, the indicated leakage on the No. 1 seal flow meter typically represents the total flow passing through the No. 1 seal.

With the increase in VCT pressure, the ΔP on the No. 2 seal will be increased by approximately 20–35 psi. Based on this increased seal ΔP, the predicted maximum leak rate for the No. 2 seal will be approximately 0.026 gpm. This value is still well below the maximum No. 2 seal leak rate of 0.5 gpm for normal plant operation.

The No. 3 seal in either the bellows or cartridge arrangement should not be affected by the increased hydrogen concentration or the increased VCT pressure.

A review of RCP seal failure causes was performed and the predominant failure mechanisms are listed below [23]:

- Debris or foreign material exclusion (FME)
- Maintenance related
- Operational related
- Manufacturing related
- Design inadequacies
- Age degradation
- Unknown

Of the previous list, operational, design, and age could possibly be affected by the VCT pressure increase. Westinghouse does not believe the increase in VCT pressure would increase the instances of these types of failures. Westinghouse believes that a full qualification program should be considered to determine whether design inadequacies and age degradation could be factors in the long-term operation of the seals at the increased VCT pressure.

Most RCP seal components are functionally tested in full-scale test fixtures. Final acceptance is based on satisfactory test results using typical plant parameters. If utilities implement changes to the typical VCT pressures, the parts supplier should be notified so that this change can be incorporated into their testing procedures.

2.2.2 Hydrogen Gas Accumulation in Seal Assembly

The process of seal injection water passing through the No. 1 and No. 2 seals results in an increase in the water temperature. During this time, the fluid pressure is also drastically reduced by the No. 1 seal and slightly more by the No. 2 seal (the No. 2 seal discharge pressure is less than the VCT pressure). This phenomenon could result in some amount of hydrogen coming out of solution at the exit of the No. 2 seal. Over time, the gas collects and forms a bubble and free surface as the circulating water is thrown to the outside of the internal volume of the enclosure by the centrifugal action of the rotation. See Figure 2-2 and Westinghouse internal letter, "Evaluation of Impact of Increased Dissolved Hydrogen on RCP Seal Performance" [3]. The long-term impact of gas accumulation in the seal is not known. Long-term testing would provide better information on the seal performance.

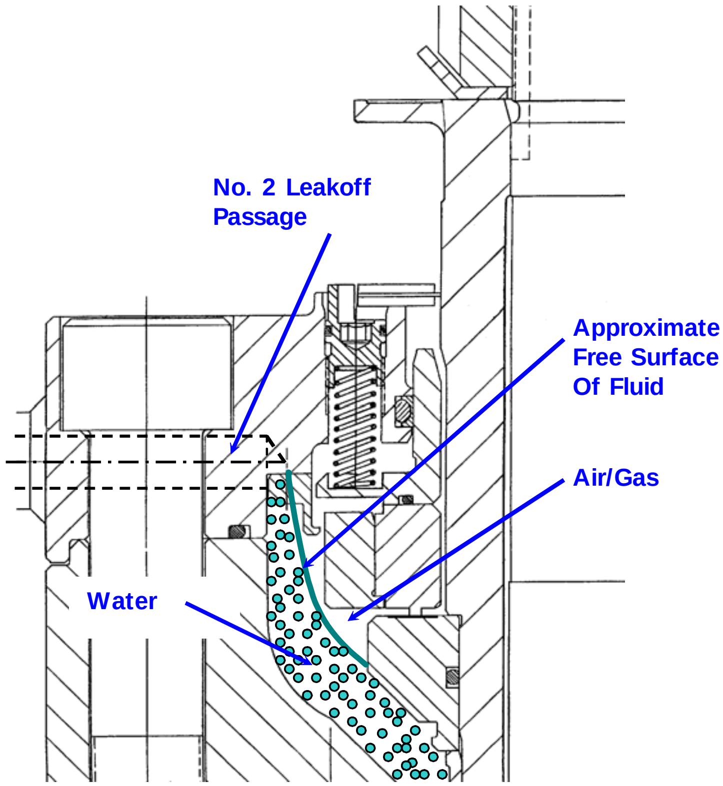


Figure 2-2
RCP No. 2 Seal Discharge Chamber to the No. 3 Seal

As a result of the increased dissolved hydrogen concentration, additional hydrogen would be released to the containment. In the Byron/Braidwood designs, No. 3 seal leakoffs are routed to the containment floor drain sump. The typical No. 3 seal leakoff rate is approximately 400 cc/hour of coolant per RCP. At 80 cc hydrogen/kg, the hydrogen release rate would be 32,000 cc/hour or 0.0015 scfm per RCP. This compares to 12,000 cc/hour, or 0.00056 scfm per RCP at 30 scc/kg.

2.2.3 Seal Testing

2.2.3.1 Description of the No. 1 Seal Tests

The No. 1 seal is a film-riding hydrostatic seal designed and tested to function with a ΔP of approximately 200–2250 psi. The typical leak rate of the No. 1 seal is 1.5–3.0 gpm (at 2250 psi ΔP) with typical alarm setpoints of 1 and 5 gpm. Increasing the VCT pressure will effectively reduce the ΔP under which the No. 1 Seal will operate. This would have a tendency to reduce the No. 1 seal leak rate [5].

The special No. 1 seal tests were performed in the Westinghouse/Stein No. 1 seal developmental test loop. Two tests were done—one at the normal VCT backpressure of 30 psig and one using an increased backpressure of 55 psig. It is noted that the increased backpressure tests were planned to be done at 65 psig, but this pressure was unable to be achieved with the current test equipment. It was deemed acceptable to perform the increased backpressure tests at 55 psig. This testing pressure is nearly double the normal pressure and, for this "proof of concept" test, was deemed acceptable to show any abnormal behavior of the seal with increasing seal back pressure.

The No. 1 seal test procedure followed the requirements of the Westinghouse test specification for seal mockup production testing. This production test specification includes the following tests:

- Static cold low-pressure test
- Dynamic cold low-pressure test
- Dynamic cold high-pressure test
- Thermal performance test
- Pressure hysteresis test
- Cooldown and cold testing

This set of tests is designed to test the No. 1 seals in conditions representative of plant startup, shutdown, and normal operation. This set of tests was performed at the normal, as well as the increased, backpressure. In addition to these production tests, a continuous steady-state test of 8 hours was performed at normal operating pressure and temperature conditions. During this additional test, the first 4 hours were run with 30-psig backpressure, and the last 4 hours were run with 55-psig backpressure.

2.2.3.2 Results of the No. 1 Seal Tests

During all of the normal and increased backpressure testing, the No. 1 seals performed within the production acceptance criteria. During the additional steady-state testing, the average No. 1 seal leak rate was 0.2–0.4 gpm lower for the period of increased seal backpressure.

2.2.3.3 Description of the No. 2 Seal Tests

The No. 2 seal is a face-riding seal designed to operate with minimal leakage, with a differential pressure of approximately 30 psig across the face. The forward pressure on the seal is normally determined by the VCT pressure (typically, 30 psig), and the backpressure is determined by the head of water above the No. 2 seal leakoff connection and/or pressure in the RCDT. With the increase in VCT pressure, the ΔP on the No. 2 seal will be increased by approximately 20–35 psi. Based on this increased seal ΔP, it is predicted that the leak rate for the No. 2 seal will also increase [5].

The special No. 2 seal tests were performed at the Curtis Wright Electro-Mechanical Division facility using the production model 93A-1 test loop. The tests were performed in accordance with a Westinghouse test specification at the normal VCT back pressure of 30 psig and again at the increased backpressure of 60 psig. It is noted that the increased backpressure tests were planned to be done at 65 psig, but the tests were completed at 60 psig. It was deemed acceptable to perform the increased backpressure tests at 60 psig. This testing pressure is nearly double the normal pressure and, for the proof of concept test, was deemed acceptable to show any abnormal behavior of the seal with increasing seal back pressure.

The No. 2 seals were tested at various temperatures and pressures under static and dynamic conditions. These tests are designed to represent plant conditions at startup, shutdown and normal conditions. After completion of the normal VCT pressure tests, the test seals were measured and inspected for wear. Before starting the increased VCT pressure tests, the seals were relapped to a ‘new’ condition. After completion of the increased VCT pressure tests, the seals were again measured and inspected.

2.2.3.4 Results of the No. 2 Seal Tests

During all of the normal and increased backpressure testing, the No. 2 seals performed within the production acceptance criteria. The No. 2 seals showed no signs of abnormal or excessive wear in the post-test inspection and measurements. During the normal backpressure tests, the approximate average No. 2 seal leak rate was 0.036–0.043 gph. During the increased backpressure tests, the approximate average No. 2 seal leak rate was 0.104–0.221 gph. For this test, the increase in No. 2 seal leak rate was expected to increase with increased VCT pressure, as the VCT pressure is the No. 2 seal inlet pressure.

2.2.3.5 Conclusions

During the increased VCT pressure testing, both the Westinghouse No. 1 and No. 2 seals performed within the normal limits established by the current production testing requirement. These tests are not considered a qualification program, but merely a proof test. The current utility inspection intervals can be as long as six years; therefore, longer duration tests should be considered. The current design configuration has millions of hours of operation and hundreds of inspections have been done by utilities. A qualification program would involve design calculations as well as long-term tests. Long-term testing may lead to design modifications to support inspection intervals from six to twelve years. Test facilities, procedures, and drawings may also need modification.

2.3 CE NSSS Reactor Coolant Pump Seals

The CE NSSS pump shaft sealing systems use several basic types of seal designs. The early CE NSSSs employ RCPs designed by Byron-Jackson (BJ) and currently incorporate four-stage seals designed by BJ or Sulzer. The later CE NSSSs employ RCPs designed by KSB and currently incorporate three-stage seals designed by Sulzer.

All CE NSSS RCP seal designs require that a small amount of leakage be permitted to pass through the seals. This seal leakage serves two purposes: (1) to provide cooling and lubrication to the moving parts within the RCP seal cartridge and (2) to establish a pressure breakdown to limit the pressure loss across any single seal stage during normal operation. Seal cooling is necessary to ensure long life of the elastomers and associated seal components. Although the various seal designs exhibit differences in configuration, the general functional design of the seals is similar. In these designs, the RCS leakage (or RCS leakage as supplemented via a seal injection system) is cooled upon entry into and during the various stages of the seal cartridge via the component cooling water system (or equivalent system). There are two distinct flow paths for this leakage as further described below, one across the seal faces and the other bypassing around the seal faces.

A typical shaft seal assembly consists of three or four mechanical stages based on an injection-less, hydrodynamic seal design. Each stage has one stationary seal face mounted on the pump housing and one rotating seal face mounted on the pump shaft to form a very small hydraulic leakage gap between the two seal ring faces (that is, the primary seal). The hydrodynamic force generated by the pressure gradient across the seal gap acts to balance the closing forces provided by hydraulic and spring load forces, and a very thin film of primary fluid maintains cooling and lubrication between the rotating and stationary faces. That gap is maintained by a balance of forces that can be influenced by the fluid conditions in the seal stage cavities. Were it not for this leakage across the seal faces that allow the seal faces to ride on an extremely thin film of fluid, the rotating parts would be in hard contact with the mating stationary parts, and a large amount of heat would be generated. The severe wear would result in rapid degradation of the seals. In all designs, the primary seals limit the amount of leakage across the seal faces to values of approximately 1 gph.

The remainder of the RCS leakage, typically defined as RCP seal controlled bleed-off, passes through several pressure breakdown devices (PBDs), one in parallel with each set of seal faces except for the last stage, which acts as the vapor seal. The PBDs consist of coiled tubes that offer resistance to fluid flow and are staged so that each seal stage will take a proportionate part of the system pressure to establish the required pressure gradient across each seal stage. In the four-stage seal design, the first three seal stages each take approximately one-third of the system pressure, and the fourth vapor stage operates at a low pressure of approximately 25–100 psig. In the three-stage seal design, the stage breakdown is 43%, 43%, and 14% of the system pressure. The controlled bleed-off between the vapor seal and previous stage seal is returned to the VCT. Any leakage past the vapor stage cavity passes through a gravity drain line and on to the reactor drain system. All RCP seal stages are designed to seal at 2500 psig with the pump stationary. Controlled bleed-off flows bypassing the seal faces are established based on the design of the pressure breakdown or seal staging devices. Typical operational controlled bleed-off leakage is around 1–1.5 gpm for the four-stage seal designs and 3–4 gpm for the three-stage seal design.

2.3.1 Seal Backpressure

As discussed above, the seal designs are such that each seal stage takes a proportionate part of the RCS pressure to establish the pressure gradient across each seal. An assumed 50 psi increase in the VCT hydrogen overpressure will result in additional 50 psi backpressure superimposed between the RCP vapor seal and the adjacent stage seal. Accordingly, there will be a 50 psi lower total required pressure drop across the set of seals (that is, reactor pressure minus new higher VCT backpressure) and, thus, across each individual seal.

As such, each seal stage will have a lower differential pressure by approximately 7–21 psid, depending on the seal design. The magnitude of this differential pressure gradient change is well within current operating design limits (that is, RCS pressure change ±100 psi would result in greater differences in the seal pressure gradient). Accordingly, there is no expected impact on the CE NSSS RCP seals as a result of the maximum proposed increase in the VCT pressure and its resulting superimposed backpressure on the controlled bleed-off line.

2.3.2 Hydrogen Gas Accumulation in Seal Assembly

For the CE NSSS pump seal designs, an increased reactor coolant dissolved hydrogen concentration as a result of increased hydrogen overpressure in the VCT up to 80 cc (STP)/kg (H_2O) is not expected to present any new normal operation concerns because the RCS seal leakage (controlled bleed-off flow) from the seal cavity between the last two seals is returned to the VCT. As such, the pressure head in this seal cavity must be greater than the VCT overpressure, and the hydrogen will remain dissolved in the controlled bleed-off water returned to the VCT. However, it is noted that in the event the vapor seal has leakage and a gravity drain design is employed, the hydrogen release to the containment would be greater than the current dissolved hydrogen concentration and would continue to increase with an increasing leak rate. This would not be an issue for those designs where leakage is collected via a drain system that uses a collection tank with an overpressure cover gas, but may still slightly increase the demand on the gas waste system.

2.4 Positive Displacement Charging Pumps

Positive displacement pumps are used in many of the chemical and volume control system (CVCS) charging systems where their suction piping is connected to the VCT as its primary source of water. Accordingly, the impact of an increase in the dissolved hydrogen concentration must be evaluated with respect to both net positive suction head (NPSH) and pump performance issues. Historically, even at the current dissolved hydrogen concentrations, numerous events have occurred that have resulted in reduced pump performance and even in complete failure to start (gas binding). Although these events have resulted in lessons learned to mitigate future instances, sufficient concern still exists that warrants further discussion and caution in proceeding with an increased dissolved hydrogen concentration in the VCT beyond that which current operational experience has demonstrated to provide acceptable performance. These concerns are presented below and should be addressed on a plant-specific basis:

- Hydrogen gas bubbles accumulate in the charging pump suction lines, specifically in high points and/or dead piping legs that exist during normal power operation, such as lines connected to alternative makeup or borated water sources. Procedures should be in place to vent potential gas void areas periodically. Evaluations should be performed to ensure that conditions exist in all sections of suction piping and charging pump cavities so that hydrogen remains dissolved in the fluid. This may be part of a plant’s gas intrusion program.
- The impact of gas binding on a specific pump design should be demonstrated not to result in pump damage so that, when vented, the pump can continue to perform its design basis function. Several evaluations have been performed which indicate that gas binding does not result in pump damage, and the pump will continue to operate normally once vented.
- Cracked charging pump blocks have been an issue in the industry. The cracked blocks, for at least one manufacturer, have been attributed to cumulative fatigue due to internal pump

pressures in excess of 5500 psi. Therefore, it can only be assumed that internal pressures were being developed in excess of 5500 psi. One possible mechanism that can generate such internal pressure spikes is the presence of gas bubbles in the pumping chamber during the compression stroke, where pressures two to three times the discharge backpressure were observed. It is noted that generation of this phenomenon is configuration-specific and may not be able to be reproduced *in situ* when attempted in the plant. However, even though it may not be possible to reproduce such an event *in situ*, certain optimum conditions may develop during long-term normal operation that can momentarily support such conditions. The fact is that blocks have cracked when analysis says it should not have cracked in the absence of a material defect at the crack initiation point and without such pressure spikes.

The point to be made here is that alternative block designs can improve block performance (fatigue life under higher internal pressure) and should be evaluated for use if the VCT overpressure is to be substantially increased. Example design changes include increasing the corner radii at intersection of the plunger bores and valve bores, alternative block materials such as 17-4 PH, 15-5 PH, or PH13-8Mo, and shot peening at the intersection of plunger bores and valve bores.

- If the VCT overpressure is increased, the dissolved gas in the fluid increases. When this fluid pressure is subsequently reduced in the pump suction headers due to elevation head and line losses, the risk and amount of these gases collecting and forming a bubble (a gas intrusion or accumulation issue) increases. When bubbles enter a positive displacement pump pressure chamber, there is a potential for excessive pressure spikes (due to collapsing the bubble) greater than they were designed for, relative to cumulative fatigue usage. Thus, there is an increased risk for cumulative fatigue and shortened life. There is no requirement to redesign the pumps. Gas intrusion and accumulation practices should be evaluated, or a way to prevent it might be a more appropriate consequence of an increase in VCT overpressure. However, it should be noted that charging pump blocks have undergone such improvements, which are today being used by many utilities. These improvements do not preclude such failure but, in general, have exhibited improved life. There is no direct correlation between the VCT overpressure value and the magnitude of the internal pressure spikes that can develop; it is the volume of gas bubbles that reach the charging pumps that is a concern.

  For those plants that have an extremely low charging pump suction pressure allowing bubble formation or those plants that have a design where gas can collect, this may be the biggest concern. This could occur during normal operation and/or during gravity feed boration, depending on each plant’s design. It is probably not as much of an issue for plants where positive displacement pumps are not normally running. The gas intrusion or accumulation efforts should address this issue of an added source of gas.

- Several plants that have both positive displacement and centrifugal charging pumps have established administrative limits to prevent operation of positive displacement pumps when the VCT overpressure is above a certain threshold. This threshold would typically be based upon operational experience where the pumps had demonstrated acceptable or unacceptable pump performance.

- Some plants (for example, CE NSSS SYS80 plants) incorporated a high-pressure hydrogen injection line downstream of the charging pumps. It might be desirable to consider using this injection point periodically to supplement the dissolved hydrogen from the VCT instead of increasing the VCT overpressure beyond that known to provide acceptable operating conditions for the charging pumps. This may also avoid necessary modifications that would be required to support a dissolved hydrogen concentration as high as 80 scc/kg. For plants that do not have an existing high-pressure connection, evaluate the possibility of using an existing vent, drain, or test connection in the charging line for this purpose. The pros and cons of using high-pressure hydrogen injection should be evaluated.

- Several plants were designed with a charging pump bypass system where a bypass line from the charging pump discharge to the VCT is installed with a motor-operated isolation valve. The bypass line is normally open when the corresponding charging pump is off and slowly closes over a 150-second stroke when the pump is turned on. This design function is to minimize thermal gradients during charging transients to reduce the fatigue life of the charging nozzle and other components. This design adds an additional path where hydrogen could collect in the charging pump discharge. Adequate procedures should be in place to vent this piping and charging pumps.

3
PLANT OPERATIONS

This section addresses changes to day-to-day plant operations at power conditions and plant procedures when operating at elevated dissolved hydrogen concentrations. A comparison of typical current operating values versus revised values at the new conditions is presented. Finally, a markup of a typical plant procedure for elevated dissolved hydrogen concentrations is included.

Based on Henry's Law at 100°F, a hydrogen pressure of approximately 64 psig in the VCT would be required to provide the target dissolved hydrogen concentration of 80 scc/kg (see Appendix A).

Table 3-1
VCT Pressure to Achieve 60 scc/kg and 80 scc/kg at Various VCT Temperatures

VCT Temperature (°F)	VCT Pressure for 60 scc/kg (psig)	VCT Pressure for 80 scc/kg (psig)
90	43.30	62.64
100	44.24	63.89
110	44.93	64.81
120	45.51	65.59

Thus, an increased dissolved hydrogen concentration via the VCT is feasible, but the exact value will depend upon the degree of operating margin desired by the plant. An example follows in Table 3-2.

Table 3-2
Sample Pressures and Operating Margins

	Pressure (psig)			
	Current Plants	Increased H_2 to 60 scc/kg No VCT RV Change	Increased H_2 to 80 scc/kg No VCT RV Change	Increased H_2 to 80 scc/kg with VCT RV Change
VCT Relief Valve (RV) Setpoint	75	75	75	80
Max. Operating/Alarm	67	67	67	75
Normal Operating	30	44*	64*	64*
Operating Margin to Alarm	37	23	3	11

*At 100°F

During normal power operations, VCT pressure fluctuations are relatively small. RCS leakage over a period of time causes the VCT level to drop, reducing pressure slightly. Eventually, the makeup system actuates on the low VCT level. The water addition increases the level and may increase the pressure slightly. In preparation for plant shutdown, RCS hydrogen concentration is reduced to 5 scc/kg at < 24 hours before reactor shutdown, which is achieved by venting the VCT to about 15 psig. (Note that plant shutdown is not impacted by this proposed increase except that it may take longer to degas to the shutdown concentration level.) The VCT would be vented to the waste gas system, and the VCT is burped by raising the VCT level and then allowing the level to drop while adding N_2. In theory, VCT pressure should not change, but some fluctuation may occur, depending upon the response time of the supply and venting gas pressure regulators during the burping process. Therefore, each plant should determine the maximum operating VCT pressure (and associated RCS dissolved hydrogen concentration) by subtracting a comfortable operating margin from the new (or existing) relief valve setpoint.

Alternatively, the relief valve setpoint can remain the same, and the maximum operating pressure can be reduced. This will avoid possible costs due to relief valve setpoint adjustment (spring and other part replacements, bench testing). Table 3-3 can be used to determine the dissolved hydrogen concentration at other pressures at a nominal 100°F (see Appendix A).

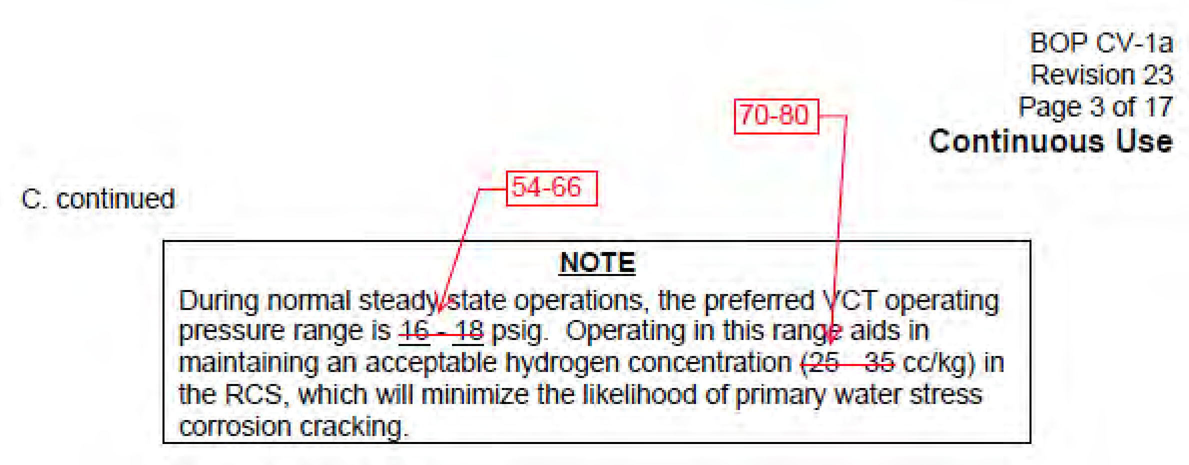
Table 3-3
VCT Pressure to Achieve Various RCS Hydrogen Concentrations at T_{VCT} = 100°F

VCT Pressure (psig)	RCS Dissolved Hydrogen (scc/kg)
63.89	80
58.97	75
54.06	70
49.15	65
44.24	60

3.1 Plant Procedure Changes

Procedures are often written to allow maximum flexibility for the operator to set valves or instruments within a broad band to accommodate nuances in operating conditions. The following are two examples of existing plant procedures that address VCT operating pressure, with suggested modifications for the new operating conditions:

Example 1:



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C. continued

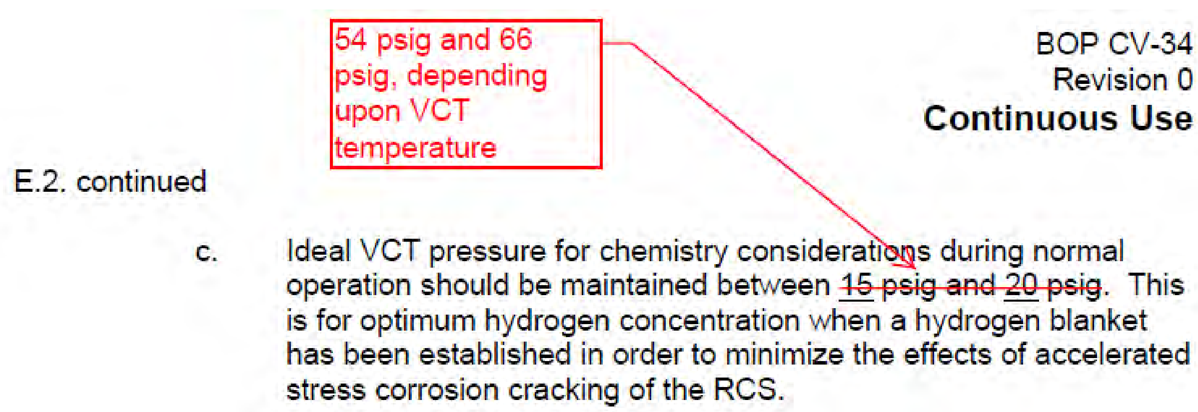
70-80

54-66

NOTE

During normal steady state operations, the preferred VCT operating pressure range is ~~16 - 18~~ psig. Operating in this range aids in maintaining an acceptable hydrogen concentration (~~25 – 35~~ cc/kg) in the RCS, which will minimize the likelihood of primary water stress corrosion cracking.

Example 2:



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Continuous Use

E.2. continued

54 psig and 66 psig, depending upon VCT temperature

c. Ideal VCT pressure for chemistry considerations during normal operation should be maintained between ~~15 psig and 20 psig~~. This is for optimum hydrogen concentration when a hydrogen blanket has been established in order to minimize the effects of accelerated stress corrosion cracking of the RCS.

4
REACTOR COOLANT SYSTEM-RELATED EVALUATIONS

With higher dissolved hydrogen concentrations, the RCS fluid will release more hydrogen when depressurized locally through valve leakage to the pressurizer relief tank and globally to the containment atmosphere post-accident.

4.1 Post-Accident Hydrogen

4.1.1 Description

Following a major loss of coolant accident (LOCA), the containment structure will be isolated for a considerable period of time to prevent the release of radioactive fission products to the environment. Since hydrogen gas can be generated inside the sealed containment after the LOCA, a potential hazard could be created by the accumulation of hydrogen gas if the period of isolation is sufficiently long and no means are provided for hydrogen removal. Since hydrogen is a combustible gas, the hydrogen concentration inside the containment should not exceed the lower flammability limit for air or steam-air mixtures.

Based on plant operating parameters and on containment conditions prior to and following the accident, a history of the post-accident hydrogen generation and accumulation can be calculated using a Westinghouse-developed computer code. The code determines the total amount of hydrogen generation and the hydrogen concentration in containment, based on calculations of the amounts of hydrogen produced from core radiolysis, sump radiolysis, aluminum and zinc corrosion, and zirconium-water reactions. The hydrogen released from the initial RCS inventory, which is based upon the pre-accident RCS hydrogen concentration, is also included in the calculation and is assumed to be immediately released at accident initiation.

A few minutes following the accident, the largest contributor to the post-LOCA hydrogen concentration is typically the hydrogen produced from the fuel assembly cladding–zinc-water reaction, with the other, albeit smaller, contributor being the RCS dissolved hydrogen. Further, the relative contribution of the RCS dissolved hydrogen decreases with time as hydrogen continues to be produced from radiolysis and the corrosion of materials.

The plant operating parameters considered in a post-LOCA hydrogen analysis include a conservative assumption that the maximum hydrogen concentration in the RCS prior to the accident is 50 scc/kg. The results of the post-LOCA hydrogen analysis are typically documented in Section 6.2.5 of the Updated Final Safety Analysis Report (UFSAR). Therefore, UFSAR revisions would likely be required to address the change in initial concentrations.

There have not been any recent post-LOCA hydrogen generation analyses for the reference plant, Byron, because the hydrogen recombiners are no longer credited in the UFSAR, so that a post-LOCA hydrogen generation analysis is not required. This UFSAR change is consistent with an August 2003 change to the requirements relative to post-accident hydrogen controls set forth in

10CFR50.44. Therefore, another Westinghouse four-loop plant was selected to provide a more quantitative assessment as discussed below.

4.1.2 Impact of Increasing RCS Dissolved Hydrogen Concentration

To assess the impact of increasing the RCS hydrogen concentration from 50 to 80 scc/kg, the analyses performed for a Westinghouse four-loop plant were repeated with an initial RCS inventory of hydrogen of both 50 scc/kg and 80 scc/kg. The largest impact was immediately following the accident, when the total amount of hydrogen was determined to be approximately 7% higher for the initial RCS inventory of 80 scc/kg. After one day, the difference decreased to approximately 1.5%; by six days following the accident, the difference decreased to less than 1%.

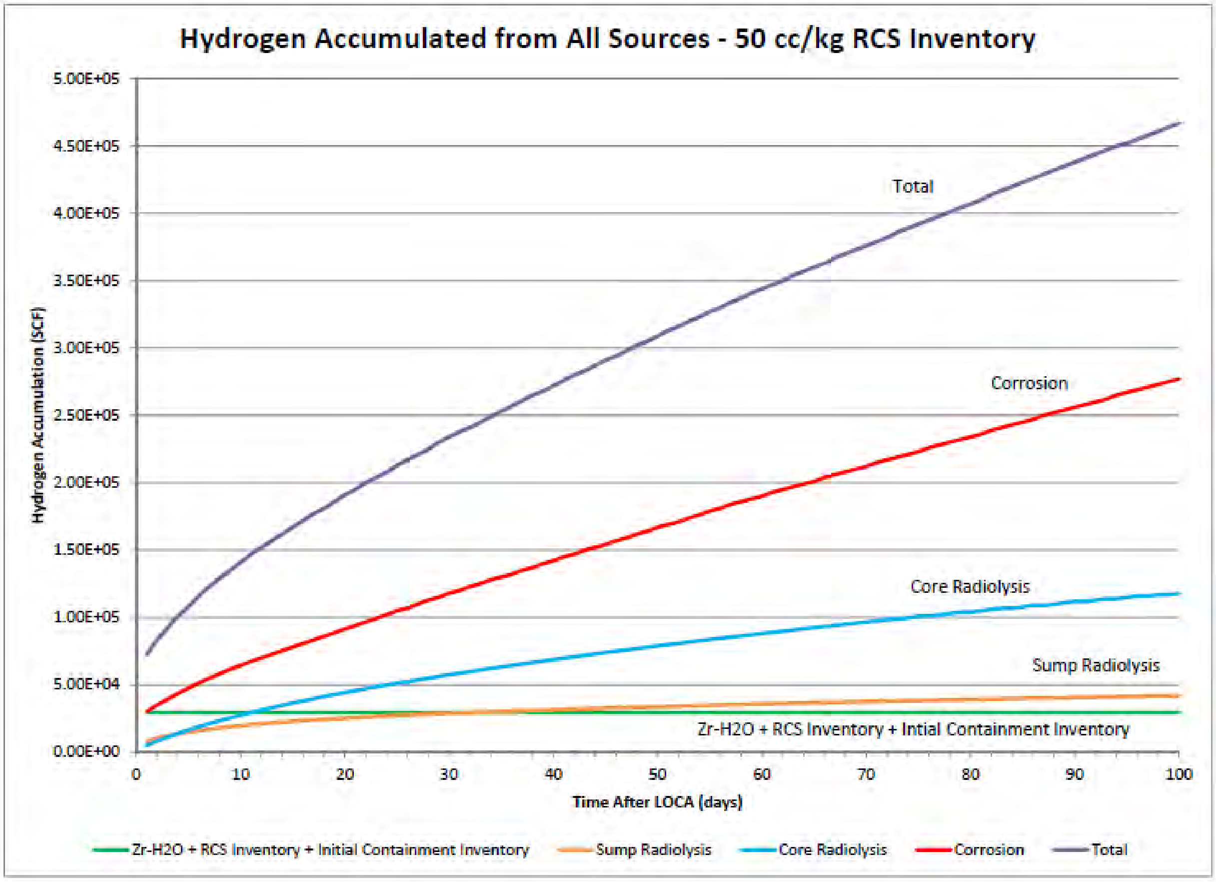

Figure 4-1
Base Case Post-Accident Containment H_2 Inventory

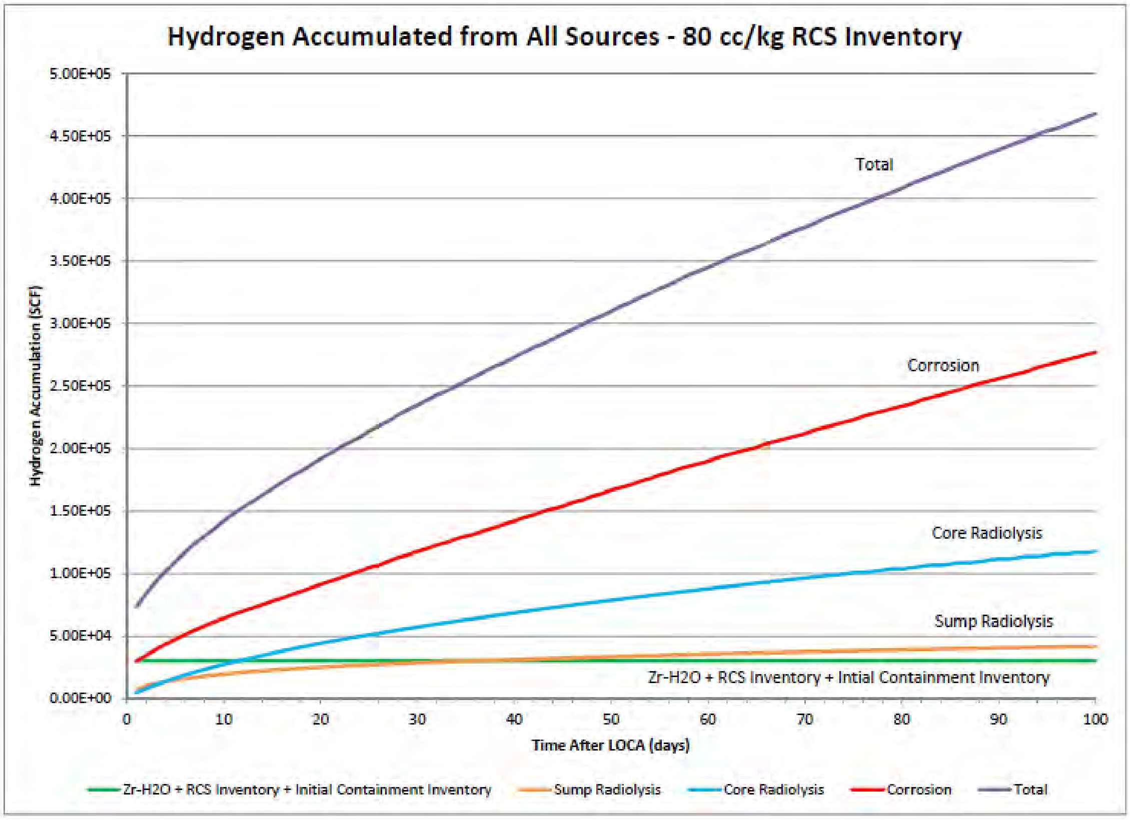

Figure 4-2
High H_2 Case Post-Accident Containment H_2 Inventory

Typically, the calculated peak hydrogen concentration in containment occurs several days following a LOCA. Because the relative contribution of the RCS dissolved hydrogen decreases with time as hydrogen continues to be produced from radiolysis and the corrosion of materials, the increased RCS dissolved hydrogen concentration has a negligible contribution to the calculated peak hydrogen concentration in containment.

As shown in Figures 4-1 and 4-2, increasing the maximum RCS hydrogen concentration from 50 scc/kg to 80 scc/kg has a negligible impact on the total amount of hydrogen generated and the hydrogen concentration in containment following a LOCA.

4.2 Pressurizer Valve Leakage

4.2.1 Description

The pressurizer operates at 2235- psig saturated water conditions. The gas space is mostly steam with some hydrogen. Two sets of valves are available for pressure control and overpressure protection and are connected to the gas space portion of the pressurizer. Two parallel power-operated relief valves open at slightly above normal operating pressure, and two parallel spring-loaded safety valves open at the pressurizer design pressure. Both sets of valves relieve into a quench tank, the pressurizer relief tank (PRT), which is maintained at a nominal 3 psig. Thus, any gas leaking past the valves will collect in the PRT. This leakage is detected by an increase in PRT level and/or pressure.

Hydrogen accumulates in the pressurizer gas space because there is a small, continuous flow of reactor coolant that bypasses the spray valves and enters the pressurizer. Since the flow comes from a higher pressure source (the RCS cold leg) to a lower pressure and higher temperature destination (pressurizer), some hydrogen is released. It eventually redissolves in the pressurizer liquid and returns to the RCS via the pressurizer surge line.

4.2.2 Impact of Increasing RCS Dissolved Hydrogen Concentration

Boiling in the pressurizer effectively strips all of the hydrogen from the coolant within the pressurizer. The vapor space will contain more noncondensable hydrogen, which could make pressurizer pressure control more difficult (that is, a "harder bubble"). Accordingly, the pressurizer may warrant intermittent venting during operation at the higher hydrogen concentrations. In addition, the rate of pressure decrease via spray as a response to a pressure increase due to a transient will be somewhat slower as the gas space hydrogen content increases (that is, less steam).

If the coolant entering the pressurizer via the spray valve bypass has an increased hydrogen concentration, then additional hydrogen will be released to the gas space, and the concentration of hydrogen in the gas space will increase accordingly. The effect on valve leakage is that more hydrogen will be released to the PRT, assuming that the leak rate does not change. Therefore, additional monitoring of PRT pressure and additional PRT gas space sampling will be required during periods of pressurizer valve leakage. Finally, a greater demand will be placed on the waste gas system due to additional venting.

Another effect of higher RCS hydrogen concentration is an accumulation of gas impurities. Gas supplied from bottles or a bulk supply is not 100% pure. The current Westinghouse specification is 99.95% (by volume) pure. The change in impurity volume is illustrated by the example below:

Initial charge of hydrogen to establish 80 scc/kg:

Typical RCS four-loop water mass including letdown/charging ~ 600,000 lb. (hot) = 2.727E05 kg

RCS dissolved hydrogen = 2.727E05 kg x 80 scc/kg = 2.182E07 cc = 770 SCF

VCT hydrogen gas volume @ 60 psig: (75 psia/15 psia) 200 ft^3 = 1000 SCF (Assume that the VCT is one-half full.)

Pressurizer gas space: Assume that the level = 60% and 1% of the gas space is hydrogen:

40% x 1800 ft^3 x (2250 psia/15 psia) x 1% = 1080 SCF

Total hydrogen = 770 + 1000 + 1080 = 2850 SCF

Impurities = 0.05% x 2850 ft^3 = 1.4 SCF

At 30 scc/kg:

RCS dissolved hydrogen = 2.727E05 kg x 30 scc/kg = 8.181E06 cc = 289 SCF

VCT hydrogen gas volume @30 psig: (45 psia/15 psia) 200 ft^3 = 600 SCF (Assume that the VCT is one-half full.)

Pressurizer gas space: Assume level = 60% and 1% of gas space is hydrogen:

40% x 1800 ft^3 x (2250 psia/15 psia) x 1% = 1080 SCF

Total hydrogen = 289 + 600 + 1080 = 1969 SCF

Impurities = 0.05% x 1969 ft^3 = 1.0 SCF

This volume of impurities is small relative to the ingress of noncondensables from other sources such as makeup water.

5
CHEMICAL AND VOLUME CONTROL SYSTEM-RELATED EVALUATIONS

This section contains descriptions of critical components in the chemical and volume control system (CVCS) that are directly affected by the increased dissolved H_2 concentration. The components include control and relief valves, orifices, pumps, as well as subsystems. Note that the VCT is addressed in Section 2.

5.1 VCT Relief Valve

5.1.1 Description

The VCT relief valve is currently set for the VCT design pressure of 75 psig. It is designed to relieve flow resulting from a loss of charging flow while maintaining the letdown flow, plus maximum makeup flow, excess letdown flow, and seal return flow.

5.1.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

While not absolutely required, an increase in VCT design pressure from 75 to 80 psig will provide additional operating margin (see Section 3) with an increased normal operating VCT pressure. An increase in set pressure will increase the pressure drop across the relief valve orifice and, therefore, flow capacity. Consequently, the existing capacity will be bounded.

One vendor that supplies many relief valves for applications in nuclear plants indicated that the existing valve spring and washers must be replaced to reset the relieving setpoint. In addition, the vendor must create a new documentation package for this set pressure change, which will include a new drawing that is a modification to the existing drawing. In addition, a design or seismic report for the higher pressure loading will be required. Finally, the vendor will typically revise its test procedure and applicable documents to reflect the 80-psig set pressure. These documents will need to be reviewed and approved.

5.2 VCT Hydrogen Supply Regulator

5.2.1 Description

This regulator provides a hydrogen overpressure in the VCT gas space, which is the governing factor that determines the RCS dissolved hydrogen concentration based on Henry's law (See Section 3). Once the desired pressure is established, the valve closes during normal power operation until the VCT level decreases sufficiently to require makeup or when a VCT "burping" operation is performed. VCT "burping" is performed periodically to refresh the VCT gas inventory and during startup conditions to replace the nitrogen cover gas used during shutdown with a hydrogen blanket. The VCT level is manually raised by throttling charging flow, and then the level is reduced, at which point the regulator opens to maintain the prescribed downstream pressure setpoint. The maximum regulator flow is designed to match the maximum letdown/charging rate so that if letdown flow is lost, charging pump NPSH can be maintained for a short time.

5.2.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The regulator downstream setpoint would be increased from the current typical values in the range of 20–30 psig to 58–67 psig (see Section 3), based upon the desired dissolved hydrogen concentration and operating margin between the set pressure and the VCT relief valve setpoint. The valve is designed for an inlet pressure of 100 psig, so a higher setpoint is feasible, but may require that the integral controller (Fisher "Wizard Controller" design) be replaced with one having a larger range, for example, 0–100 psig versus 0–60 psig.

Regarding valve sizing, to maintain the same design flow rate with a reduced ΔP, the required maximum flow coefficient of the valve C_v would have to increase. However, an investigation of the charging pump NPSH requirements shows that the sizing basis of the regulator is very conservative. The valve is sized so that there is no pressure reduction (from an assumed 15 psig) in the VCT during a draindown event. There is typically more than adequate NPSH available to the charging pumps even at 0 psig VCT pressure due to elevation head. Thus, with 60 psig in the VCT and no makeup gas flow, the VCT pressure would drop to 23 psig, assuming that the tank was initially about half full during a draindown event. The final pressure still provides adequate NPSH to the charging pumps. Therefore, no change to the valve trim is recommended.

The CE NSSS plants have hydrogen supply regulators with inlet design pressures ranging from 70–150 psig. These hydrogen supply regulators are self-contained regulators that do not have external controllers. The required capacities also varied between the various plants, but were typically specified as a maximum required capacity. Therefore, each plant would require evaluation for the new conditions, but capacity is not expected to be a significant issue since a momentary decrease in VCT pressure during a transient event is not critical to maintaining dissolved hydrogen concentration and charging pump NPSH is typically provided by the VCT low-low water level and does not rely on the VCT overpressure. The only issue here might be hydrogen bubble formation in the charging pump suction header during the reduced pressure condition, which is addressed separately.

5.3 VCT to Waste Gas Header Pressure Control Valve

5.3.1 Description

In certain Westinghouse plant designs, this regulator maintains sufficient backpressure on the VCT to prevent depressurization during VCT venting evolutions. Once the desired pressure is established, the flow path is typically closed during power operation until a VCT "burping" operation is performed. This occurs during: 1) normal operation to increase the hydrogen purity, 2) plant startup when the nitrogen overpressure is replaced with a hydrogen blanket and 3) plant shutdown when the hydrogen overpressure is replaced with a nitrogen blanket. The VCT level is manually raised by throttling charging flow. The normally closed isolation valve upstream of the backpressure regulator is opened, and as the VCT gas space is compressed, the increased pressure exceeds the regulator setpoint, so the regulator opens to maintain the backpressure setpoint. The maximum regulator flow is designed to match the maximum flow of the waste gas system compressor that received the vent flow.

5.3.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The regulator setpoint would be increased from the current typical values in the range of 20–30 psig to 58–67 psig (see Section 3), based upon the desired operating margin between the set pressure and the VCT relief valve setpoint. The valve is designed for an inlet pressure of 100 psig, so a higher setpoint is feasible, but may require that the integral controller (Fisher “Wizard Controller” design) be replaced with one having a larger range, for example, 0–100 psig versus 0–60 psig.

This valve is not applicable to CE NSSS designs.

5.4 VCT Purge Regulator

5.4.1 Description

In certain Westinghouse plant designs, there is no VCT burp regulator, as described previously. There is instead a regulator in the VCT vent line, which maintains a constant downstream pressure to a flow control valve in the waste gas system to establish a small, continuous VCT gas space purge.

5.4.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The regulator downstream setpoint of 13 psig would not be affected. The purge regulator is already sized for an upstream pressure of 60 psig in the VCT. However, if the VCT is operated slightly above 60 psig as described in Section 3, some adjustment of the purge regulator and/or downstream flow control valve may be required.

For some CE NSSS designs, this pressure regulator valve has a design pressure of 75 psig, and is set to regulate downstream pressure in the range of 3–5 psig, establishing a continuous purge to the gas waste system when it is not isolated. If the VCT design pressure is changed to a value greater than 75 psig, it may be necessary to replace this valve or to ensure that it is qualified at the new design conditions. For several plants, a second regulator valve is used in the same line to maintain the VCT at the desired overpressure. This valve was originally specified for set pressures between 15 and 50 psig and will require evaluation for higher set pressures.

5.5 VCT Gas Sample Regulator

5.5.1 Description

This regulator provides a constant downstream pressure with varying VCT pressure to supply the waste gas analyzer package with a tiny flow on demand.

5.5.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The regulator downstream setpoint of 2 psig would not be affected. A higher inlet pressure from the VCT will result in the valve throttling down more to maintain downstream pressure. Since the flow requirement is so small, the valve may have difficulty providing steady control.

There is no equivalent valve in the CE NSSS CVCS scope, but there may be a similar valve in the gas analyzer system.

5.6 Letdown Line Pressure Control Valve

5.6.1 Description

In Westinghouse plant designs, letdown flow is reduced in pressure from approximately 2200 psig to less than 600 psig using special orifices. Subsequently, the letdown line pressure control valve further reduces the pressure from about 350 psig to less than 150 psig. The control valve maintains a constant upstream pressure setpoint with varying letdown flow and VCT backpressure.

5.6.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The regulator upstream setpoint would not be affected. Assuming a constant letdown flow, the regulator would operate at a more open position with increased VCT backpressure. At 120 gpm maximum letdown flow, the operating valve C_v is approximately 7, assuming a ΔP of about 250 psig. An increase of 30 psig backpressure from the VCT would increase the C_v to about 8. The valve control range is from 2 to 40. Therefore, very little impact on valve operation is expected. Feedback from Byron indicates that the valve is only about 35% open at maximum letdown flow.

For CE NSSS plants, the equivalent valve is called the letdown backpressure control valve. Its purpose is to provide sufficient backpressure to maintain the fluid between the letdown flow control valves and the letdown backpressure control valve in a sub-cooled condition to prevent flashing in the letdown flow control valves and letdown heat exchanger (intermediate section of letdown piping). The original design setpoint was conservatively set at 460 psig; however, some plants have modified this setpoint to a lower value as part of optimizing flow or pressure control. Based on actual increased backpressure from the VCT, the above modification by some plants and upon actual valve C_v versus valve travel capability, each plant would have to determine whether the their respective valves are suited for operation at the new conditions; however, unless already operating at maximum valve travel, the existing valves are likely to be acceptable. Based upon the VCT backpressure and the head loss in the other letdown components, it is expected that the hydrogen will remain dissolved at the valve outlet, and cavitation would not be expected.

5.7 Letdown Flow Control Valve

5.7.1 Description

In CE NSSS plant designs, letdown flow is controlled to match charging flow or as necessary to maintain pressurizer level within its program limits and where pressure is reduced from approximately 2100–2250 psig to the letdown backpressure control set pressure (typically in the range of 350–460 psig).

5.7.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

As a result of the letdown backpressure control valve maintaining an upstream pressure that is unaffected by a VCT backpressure change, the letdown valves will see the same operating conditions. As such, the only possible impact on these valves might be if the increased dissolved hydrogen results in a reduced vapor pressure at the valve outlet sufficient to initiate cavitation. This may happen if the valves were already operating near their cavitation limit and should be evaluated.

5.8 Letdown Line Relief Valve

5.8.1 Description

This relief valve protects equipment downstream of the letdown pressure control valve and discharges to the VCT. It is set for 230–300 psig, depending upon the plant design, and assumes a backpressure (VCT) of 75 psig. Design flow is 200 gpm.

5.8.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The design backpressure is the current VCT relief valve setpoint of 75 psig. If this setpoint is increased to 80 psig, the maximum flow through the letdown line relief valve would decrease. However, since the design flow of 200 gpm exceeds maximum letdown flow of 120 gpm, there is adequate margin for flow even with a slightly increased backpressure. Therefore, there is no effect on this relief valve operation.

The CE NSSS equivalent valve is called the low-pressure letdown relief valve and discharges to an auxiliary building drain tank (for example, equipment drain tank, holdup tank). It is set at 200 psig at minimum 180-gpm design flow (some plants have a design flow as high as 325 gpm). The CE NSSS design also has a relief valve in the intermediate section of the letdown line called the intermediate-pressure letdown relief valve and discharges to the same auxiliary building drain tank. It is set at 600 psig at minimum 180-gpm design flow (some plants have a design flow as high as 325 gpm). Neither of these valves should be impacted by an increase in the VCT overpressure unless the pressure drop at maximum letdown flow in the downstream letdown components is already causing the letdown line to be operating near the relief valve setpoint. If this should be the case, then the entire letdown line and components downstream of the letdown backpressure control valve would require evaluation for a change in design pressure. In this case, it would probably be prudent to evaluate a lower VCT overpressure rather than a system design pressure change.

5.9 Excess Letdown Line Control Valve

5.9.1 Description

This flow control valve reduces excess letdown pressure during power operation from approximately 2200 psig to less than 150 psig. Alternatively, excess letdown can be used to supplement normal letdown flow when the RCS is at low pressure (approximately 400 psig). The control valve is used to set the design flow rate of 25 gpm.

5.9.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

Due to the large design ΔP across the valve, a slight increase in VCT backpressure is not expected to affect valve operation. At the design flow of 25 gpm and a nominal ΔP of 2170 psi, the operating C_v is approximately 0.537. An increase in VCT backpressure of 30 psi will only change the C_v to 0.540. During low RCS pressure operation, the VCT will be at low pressure for either shutdown or startup conditions. Therefore, a negligible impact on valve operation is expected.

This valve is not applicable to CE NSSS designs.

5.10 RCP Seal Return Line Relief Valve

5.10.1 Description

This valve protects the seal return header at a 150-psig set pressure. The typical operating pressure is slightly less than the RCP No. 1 seal backpressure, which was estimated in Table 2-1 to be 40–55 psig.

The relief valve relieves to the VCT and is designed for 53-psig backpressure.

5.10.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

In Table 2-1, the new backpressure on the No. 1 seal is estimated to be 76–84 psig, which is well below the relief valve setpoint of 150 psig. However, an increase in backpressure from the VCT will reduce the flow capability of the valve during relieving conditions. The valve was originally sized based upon the miniflow from three centrifugal charging pumps at 60 gpm each plus margin. The size J orifice is capable of relieving approximately 362 gpm with a ΔP of ~100 psi (150-psig set pressure – 53-psig backpressure). In the worst case of the VCT reaching its relief valve setpoint of 75 psig, the ΔP would be 75 psi, and the required flow capacity of the seal return line relief valve would be approximately 314 gpm. The Byron design (and most Westinghouse four-loop plants) has two centrifugal charging pumps, so the required flow is only 120 gpm. Since there is significant flow capacity margin, this relief valve should not be affected by the increased VCT backpressure.

For the CE NSSS design, this valve ensures continued seal controlled bleed-off in the event that the normal path to the VCT is isolated. The design pressure is at reactor coolant design pressure of 2485 psig with a set pressure range of 150–225 psig, depending on the plant. The capacity is in the range of 20–22 gpm, which is just above the flow rate required for the excess flow check valve to close. During normal operation, the VCT will provide backpressure to the seal return header; however, even at 80 psig in the VCT and additional line pressure drop, the return header will be well below the relief setpoint. The relief valve discharges to a reactor building drain tank (for example, reactor drain tank, quench tank); therefore, the VCT overpressure will not impact the relief capacity.

5.11 Emergency Boration

5.11.1 Description

The flow path from the discharge of the boric acid pumps directly to the charging pump suction is referred to as the *emergency boration path*. It is used to expedite RCS boration for core reactivity control or to establish shutdown margin by bypassing the normal makeup flow path in which a control valve limits boric acid flow to 35 gpm. Slightly higher flow rates are possible through the emergency boration flow path.

5.11.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

A higher VCT backpressure will reduce emergency boration flow. The degree of reduction is a function of boric acid pump performance, elevation head, and frictional losses. A generic quantitative assessment cannot be made. Consequently, each plant will have to evaluate the effect of increased VCT pressure on emergency boration flow and verify that the impact is acceptable prior to increasing the VCT pressure control band.

The emergency boration flow rate with an increased VCT pressure will be verified by periodic surveillance testing. In a planned shutdown, when maximum boration is desired, VCT pressure could be reduced to increase boration flow because degassing operations are part of the shutdown sequence.

Several plants, during the construction phase, identified concerns regarding allowable head losses in pipe connected to the VCT (normal makeup) due to excessively large pressure drops at 120 gpm in the 2-inch pipe when the VCT overpressure was high. These plants may not be able to achieve design flows with increased VCT overpressure.

For CE NSSS designs, both the normal makeup and emergency boration flow paths are capable of supplying the total charging pump flow at current VCT operating conditions. If the VCT overpressure is substantially increased, the operating point will move up on the boric acid pump head curve resulting in lower flow. Since each plant and each pump have a specific curve, each plant must be evaluated separately. In the event that emergency boration is initiated coincident with a safety injection actuation signal (SIAS), the VCT will be isolated, eliminating the VCT overpressure (that is, emergency boration will be the same as current design). Likewise, boration would be the same as current design if the VCT outlet isolation valve is closed after the boration path is opened. Therefore, required design emergency boration flow could be obtained by ensuring that procedures make the appropriate valve alignment. However, normal makeup water flow, borated water flow, and/or blended flow to the VCT can be impacted by increased VCT overpressure and should be evaluated or tested as discussed above.

5.12 Makeup System

5.12.1 Description

The chemical and volume control system makeup system consists of control valves and logic to provide primary makeup water (PMW) and boric acid flow, either independently or as a blended flow, to the RCS via the charging pumps. The makeup system can be operated manually or automatically, as chosen by the operator. Because the VCT is aligned during makeup, its backpressure affects the operation of the PMW and boric acid flow control valves.

5.12.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

An increase in VCT pressure would result in an increase in the control valve operating C_v. However, both the PMW and boric acid control valves have a wide C_v range and, in general, would not be greatly affected by an increase in VCT backpressure. The PMW system is typically sized and provided by the architect engineer, so its capacity is dependent upon plant-specific layout and PMW pump design. The boric acid transfer pump is supplied by Westinghouse, so there are design calculations available to assess the impact of the VCT pressure increase.

Generic calculations for the boric acid flow control valve show that a maximum backpressure of 60 psig was assumed for the valve sizing. Therefore, there is no effect expected due to increased VCT backpressure. Westinghouse calculations on the PMW system for Byron were reviewed, and it was determined that with 60 psig in the VCT, a valve C_v of 30.4 would be required to provide 120 gpm. The maximum C_v of the valve originally provided by Westinghouse was 35.4.

In this particular case, no changes to the valve trim would be required. There are time delay alarms in the makeup control system to indicate that the programmed flow rate is not obtained. These time delay setpoints may require adjustments, with the appropriate evaluation, to prevent erroneous alarms due to the higher backpressure in the VCT.

Several plants, during the construction phase, identified concerns regarding allowable head losses in pipe connected to the VCT due to excessively large pressure drops at 120 gpm in the 2-inch pipe when the VCT overpressure was high. These plants may not be able to achieve design flows with increased VCT overpressure.

For the CE NSSS design, also see the discussion for emergency boration.

5.13 Charging Pumps Suction Relief Valve

5.13.1 Description

This is thermal relief valve designed to protect the 150 psig charging pump suction header piping from overpressure during the recirculation mode of safety injection, when hot fluid from the containment sump is aligned to the charging pumps. During normal power operation, the operating pressure is equal to VCT overpressure plus elevation head minus system losses.

5.13.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

During the accident mode of operation, the VCT is isolated from the charging pumps by redundant motor-operated valves, so there is no effect on valve operation from increased RCS hydrogen concentration. In addition, the valve discharges to the recycle holdup tanks, not the VCT. Normal pressure at this relief valve is expected to be less than 100 psig, so no effect on valve operation is expected.

5.14 Charging Pump Miniflow Orifice

5.14.1 Description

One centrifugal pump is normally in operation with the miniflow orifice aligned to the VCT. The orifice typically provides 60 gpm at the shutoff head (~6000 ft = 2609 psi) of the pump.

5.14.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

Since the VCT provides both a suction boost and a backpressure on the miniflow orifice, there is no change in ΔP and, therefore, no change in miniflow. However, additional hydrogen may be evolved from the miniflow fluid at the orifice due to the higher inlet dissolved hydrogen concentration. This free hydrogen gas will be purged back to the VCT through the miniflow line, but could also collect in the charging pump suction piping. See the information on gas voids below.

This valve is not typically used for CE NSSS designs.

5.15 Letdown Flow Stripper

5.15.1 Description

Some plants use a full letdown flow stripper to remove dissolved hydrogen and fission gases from the letdown flow. The stripped gases are sent to the waste gas system, which may be of the compressed storage or charcoal adsorption type.

5.15.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The operation of the stripper would not be affected. However, with a higher dissolved hydrogen concentration in the letdown flow, a higher stripped gas flow rate would result. This higher flow input will not affect a compressed storage–type gas system. For a charcoal adsorption system, a higher flow would theoretically shorten the decay time of the key fission gases, Krypton-85 and Xe-133. Again, in theory, this would increase the number of curies in fission gases released to the environment. Historically, due to good fuel performance (that is, few leaking fuel elements), very small amounts of fission gases are generated, so the impact is expected to be minimal. In addition, there may be some inherent margin in the charcoal system design. The plant would have to review the system design basis to determine the actual impact.

Several plants use an in-line (letdown line) degasifier upstream of the VCT to continuously de-gas the RCS. This process effectively removes all of the hydrogen prior to entering the VCT, the liquid in the VCT must then re-absorb hydrogen at the desired concentration prior to exiting the VCT. Experience has shown that there may be some concern that the fluid may not remain in the VCT long enough to reach dissolved hydrogen equilibrium, even at the current hydrogen concentration. Accordingly, this configuration may warrant additional evaluation or testing to demonstrate that acceptable dissolved hydrogen can be maintained at the higher desired hydrogen concentration.

5.16 Gas Voids

5.16.1 Description

Pursuant to Generic Letter 2008-01 [4], plants are required to monitor and/or vent high points in the suction of safety injection system pump suction piping. The VCT is currently pressurized to 20–30 psig. Therefore, if there is any leakage in downstream interconnecting piping though valves to lower pressure piping, hydrogen will evolve and collect in piping high points.

5.16.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

Because the charging pump is used for safety injection and because pockets of gas accumulation have been found in piping adjacent to the pump suction piping, the introduction of additional dissolved hydrogen will exacerbate existing problems. When the charging system is aligned to take suction from the VCT during normal operation, the suction piping and miniflow lines for the charging pumps become filled with fluid that is saturated with hydrogen. It has been seen in plant gas intrusion evaluations that, during this flow alignment, the charging pump miniflow has the potential to strip hydrogen gas out of solution and cause it to collect in suction piping that is common to both the normal charging and safety injection alignment.

Because this gas is under VCT pressure during normal charging alignment, the gas bubble has the potential to expand when the suction alignment is transferred from the normal charging function to the safety injection function, with cooler fluid being provided by the refueling water storage tank (RWST). This expansion would be dictated by the difference in pressure on the bubble caused by the VCT versus the elevation head of the RWST. If the VCT pressure were assumed to be doubled from 30 psig to 60 psig, this could cause a change to the effect on the bubble when switching the suction path from the VCT to the RWST. Three examples can explain this effect. It is assumed that, due to the piping configuration, there is a location that could physically collect a maximum of 1 ft^3 of gas.

Example 1

If the VCT pressure is initially 30 psig and the RWST elevation head is equivalent to a pressure that is approximately equal to 30 psig, a doubling of VCT pressure would increase the void as follows:

In original case:

$$P_1V_1 = P_2V_2$$

Where:

$P_1 =$	VCT pressure during normal charging mode	(psia)
$V_1 =$	Volume of void during normal charging mode	(ft^3)
$P_2 =$	Pressure equivalent to the RWST elevation head	(psia)
$V_2 =$	Volume of void after the switchover to safety injection mode	(ft^3)

So in this case, since P1 equals P2, there would be no change in the void size prior to the safety injection mode.

In the increased pressure case:

$$75 \text{ psia} * 1 \text{ ft}^3 = 45 \text{ psia} * V_2$$

$$V_2 = 1.7 \text{ ft}^3$$

In this case, the effect of nearly doubling the VCT pressure would be to double the potential void that could be introduced to the suction of the charging pump.

Example 2

If the VCT pressure is initially 30 psig and the RWST elevation head is equivalent to a pressure that is approximately equal to 40 psig, a doubling of VCT pressure would increase the void as follows:

In the original case:

$$45 \text{ psia} * 1 \text{ ft}^3 = 55 \text{ psia} * V_2$$

$$V_2 = 0.82 \text{ ft}^3$$

In the increased pressure case:

$75 \text{ psia} * 1 \text{ ft}^3 = 55 \text{ psia} * V_2$

$V_2 = 1.4 \text{ ft}^3$

In this case, the effect of doubling the VCT pressure would also be to nearly double the potential void that could be introduced to the suction of the charging pump. As also seen, the original case would have produced a benefit in switchover to RWST injection (that is, a reduction in the size of the void), whereas doubling the VCT pressure now causes an increase in the size of the void.

5.17 Centrifugal Charging Pump

5.17.1 Description

The centrifugal charging pump uses the VCT as a surge tank for normal operation and the RWST for safety injection for most plants.

5.17.2 Impact of Increasing the RCS Dissolved Hydrogen Concentration

Higher hydrogen concentrations in the suction fluid will result in more hydrogen released in local lower pressure spots within the pump. However, a significant elevation head provided by the VCT more than offsets frictional losses from the VCT to the pump suction, which tends to keep the hydrogen in solution. Other effects include additional hydrogen released downstream of the pump miniflow orifice and greater potential for formation of gas voids in the pump suction piping, both of which have been addressed previously in this section.

6
BORON RECYCLE SYSTEM-RELATED EVALUATIONS

Letdown flow is diverted from the VCT to large holdup tanks to maintain RCS inventory or during changes in RCS boron concentration when either boric acid or clean makeup water is added. The letdown flow dissolved hydrogen concentration is the same as that of the RCS since the VCT is bypassed. The holdup tanks are atmospheric tanks that have a diaphragm or a nitrogen cover gas at 1–2 psig. The pressure of the letdown flow at the point of diversion is close to that of the VCT (20–30 psig). Therefore, when the letdown enters the atmospheric holdup tanks, hydrogen is released.

For holdup tank designs that have a diaphragm, the gas space above the liquid (and under the diaphragm) is 100% hydrogen. Therefore, the dissolved hydrogen in the liquid is according to Henry's law at the prevailing temperature (about 17 scc/kg at 115°F). For the nitrogen cover gas holdup tank design, the gas space hydrogen concentration is high, but not 100%, so the liquid concentration will be somewhat less than 17 scc/kg.

6.1 Hydrogen Released to the Recycle Holdup Tanks

6.1.1 Impact of Increasing the RCS Dissolved Hydrogen Concentration

The hydrogen release rate into the holdup tanks would be:

Letdown flow x (RCS hydrogen concentration – 17 scc/kg)

Typically, this rate would be:

120 gpm x 8.3 lb/gal. x 1 kg/2.2 lb x (30 scc/kg – 17 scc/kg) = 5885 cc/min. = 0.21 scfm

At the maximum RCS hydrogen concentration, the rate increases to:

120 gpm x 8.3 lb/gal. x 1 kg/2.2 lb x (80 scc/kg – 17 scc/kg) = 28,521 cc/min. = 1.01 scfm

The letdown orifices at the Byron plants allow a maximum of 132 gpm flow. At this flow, the hydrogen release rates at 30 and 80 scc/kg are 0.23 and 1.11 scfm, respectively.

For the tanks with a diaphragm, assuming that the letdown input frequency is the same, the diaphragm bubble would have to be vented to the waste gas system approximately five times more often. Since this venting is administrative, it would require additional operator attention. However, the venting operation would not change. For tanks with a nitrogen cover gas, the tank gas space pressure would increase, sending a hydrogen/nitrogen mixture to the waste gas system more often. This venting process is automatic and would not require additional operator attention. For both types of holdup tank designs, there would be additional input to the waste gas system at the higher RCS hydrogen concentration. Note that oxygen intrusion into the holdup tank and the waste gas system remains a concern to prevent explosive mixtures since there is expected to be a larger inventory of hydrogen that accumulates in those locations..

7
MATERIALS EVALUATIONS

7.1 Introduction

Current EPRI studies have shown a trend of improved material performance for increasing levels of hydrogen in the coolant. These studies have focused on the effects related to primary water stress corrosion cracking [8]. By increasing the hydrogen content in the aqueous matrix, that is, the PWR coolant, it is possible to reduce the propensity of surface corrosion associated with free oxygen concentrations. This improvement is accomplished by a chemical mechanism where free oxygen reacts with hydrogen and is removed from the matrix. These EPRI studies do not explicitly take into account all embrittlement mechanisms of interest. An assessment was performed to evaluate the impacts of increased hydrogen concentration on materials in contact with primary coolant, including the susceptibility of such materials to hydrogen embrittlement [9].

Hydrogen embrittlement refers to the loss of fracture toughness in materials when exposed to hydrogen. While there are several postulated mechanisms for hydrogen embrittlement, the general concept is based on the penetration of atomic or ionic hydrogen at the surface of a material. Absorbed hydrogen migrates along the interstitial sites of the metal lattice and collects in regions of lattice dilation. Lattice dilation occurs due to manufacturing defects related to precipitates, dislocations, and inclusions or in regions of localized stresses. This directed diffusion results in a concentration of hydrogen within dilated regions where combination with other atomic hydrogen or compounds within the material occurs. The products of such reactions are generally stable molecules and are too large to readily diffuse further in the material. The resulting accumulation of gas pockets results in localized internal pressures and additional material stress. When a new crack tip forms within the region, cracking propagates and reduces local stresses, resulting in additional local lattice dilation. This cycle can continue until the component fractures or until local stresses are reduced such that hydrogen concentration equilibrates [7].

The mechanism for hydrogen embrittlement is favored in locations with high concentrations of gaseous or aqueous hydrogen and under conditions that support diffusion at the material interface, which generally include elevated pressures, generally greater than 1500 psia, and lower temperatures, generally less than 300°F, with the greatest susceptibility at near-room-temperature conditions [6]. Therefore, piping and valves in the discharge of the centrifugal charging pumps were reviewed to determine which materials make up the wetted surfaces. These components are typically at 2300–2600 psig and 100°F–130°F. As part of this evaluation, an index of components and typical materials has been identified in these regions of interest to establish a database of materials in contact with primary coolant in typical PWRs at susceptible locations. Several materials that have been determined to be in contact with the hydrogen-charged reactor coolant are identified in Tables 7-1 and 7-2 for the reference plant (Byron).

Table 7-1
Components and Materials Exposed to High Dissolved Hydrogen

Component*	ID	SA-182 Gr F316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 420
PI-118 isolation (8798A)	¾-T78	X						X					
PI-119 isolation (8798B)	¾-T78	X						X					
Miniflow check valves (8480A,B)	2-C78	X						X			X		
Miniflow orifices	ORCP												
Charging check valve (8481A,B)	4-C78	X	X			X		X					
Charging isolation (8485A,B)	4-G78	X		X				X	X	X			
Charging isolation (8387A,B)	3-T78	X		X			X		X				
FCV-121 isolation (8483A,B)	3-G78	X		X				X	X	X			
Charging flow control (FCV-121)	3-RA78DG	X			X				X			X	X
PD pump isolation (8388)	3-T78	X		X			X		X				
PI-117 isolation (8390)	¾-T78	X						X					
FT-121 isolation (8404A,B)	¾-T78	X						X					
Loop fill isolation (8345)	2-T78	X						X					
FT-139 isolation (8347A,B)	¾-T78	X						X					
Loop fill control (HCV-184)	2-RA78RE	X			X				X			X	
Loop fill isolation (8346)	2-T78	X						X					
HCV-182 bypass (8403)	3-T78	X		X			X		X				
HCV-182 isolation (8402A,B)	3-G78	X		X				X	X	X			
Charging flow (HCV-182)	3-RA78DG	X			X				X			X	X
Charging isolation (8105, 8106)	3-GM78FN	X		X				X	X	X			

Table 7-1 (continued)
Components and Materials Exposed to High Dissolved Hydrogen

Component*	ID	SA-182 Gr F316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 420
Charging check valve (8381)	3-C78	X	X			X		X					
Regen HX isolation (8324A,B)	3-IA78RG	X			X			X	X			X	
PI-120 isolation (8380)	¾-T78	X						X					
SWI filter isolation (8384A,B)	2-T78	X						X					
SWI filter vent (8385A,B)	¾-T78	X						X					
SWI filter drain (8386A,B)	¾-T78	X						X					
SWI filter isolation (8382A,B)	2-T78	X						X					
FT-142, 143, 144, 145 isolation (8370A,B; 8371A,B)	¾-T78	X						X					
SWI throttle (8369A,B,C,D)	1-R78PA	X										X	X
SWI isolation (8355A,B,C,D)	2-TM78FN	X							X				
SWI check valve (8368A,B,C,D)	2-C78	X						X			X		
SWI isolation (8352A,B,C,D)	2-T78	X						X					
SWI check valve (8367A,B,C,D)	2-C88	X						X			X		
SWI check valve (8372A,B,C,D)	2-C88	X						X			X		
SWI drain (8364A,B,C,D)	¾-T78	X						X					

Table 7-1 (continued)
Components and Materials Exposed to High Dissolved Hydrogen

Component*	ID	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel X718	Incone l X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/ Braided Asbestos/ SS Asbestos
PI-118 Isolation (8798A)	¾-T78				X	X		X	X			
PI-119 Isolation (8798B)	¾-T78				X	X		X	X			
Miniflow check valves (8480A,B)	2-C78				X	X			X			
Miniflow orifices	ORCP											
Charging check valve (8481A,B)	4-C78						X			X		
Charging isolation (8485A,B)	4-G78						X					
Charging isolation (8387A,B)	3-T78											X
FCV-121 isolation (8483A,B)	3-G78						X					
Charging flow control (FCV-121)	3-RA78DG	X	X	X	X							X
PD pump isolation (8388)	3-T78											X
PI-117 Isolation (8390)	¾-T78				X	X		X	X			
FT-121 isolation (8404A,B)	¾-T78				X	X		X	X			
Loop fill isolation (8345)	2-T78				X	X		X	X			
FT-139 isolation (8347A,B)	¾-T78				X	X		X	X			
Loop Fill control (HCV-184)	2-RA78RE	X	X	X	X							X
Loop fill isolation (8346)	2-T78				X	X		X	X			
HCV-182 bypass (8403)	3-T78											X
HCV-182 isolation (8402A,B)	3-G78						X					
Charging flow (HCV-182)	3-RA78DG	X	X	X	X							X

Table 7-1 (continued)
Components and Materials Exposed to High Dissolved Hydrogen

Component*	ID	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel X718	Incone I X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/ Braided Asbestos/ SS Asbestos
Charging isolation (8105, 8106)	3-GM78FN						X					
Charging check valve (8381)	3-C78						X			X		
Regen HX isolation (8324A,B)	3-IA78RG	X	X	X	X							X
PI-120 isolation (8380)	¾-T78				X	X		X	X			
SWI filter isolation (8384A,B)	2-T78				X	X		X	X			
SWI filter vent (8385A,B)	¾-T78				X	X		X	X			
SWI filter drain (8386A,B)	¾-T78				X	X		X	X			
SWI filter isolation (8382A,B)	2-T78				X	X		X	X			
FT-142, 143, 144, 145 isolation (8370A,B; 8371A,B)	¾-T78				X	X		X	X			
SWI throttle (8369A,B,C,D)	1-R78PA				X							X
SWI isolation (8355A,B,C,D)	2-TM78FN										X	X
SWI check valve (8368A,B,C,D)	2-C78				X	X			X			
SWI isolation (8352A,B,C,D)	2-T78				X	X		X	X			
SWI check valve (8367A,B,C,D)	2-C88				X	X			X			
SWI check valve (8372A,B,C,D)	2-C88				X	X			X			
SWI drain (8364A,B,C,D)	¾-T78				X	X		X	X			

* FCV = flow control valve FT = flow transmitter HCV = hand control valve PD = positive displacement PI = pressure indicator SWI = seal water injection

Location numbers are for the reference plant (Byron).

Table 7-2
RCP Seal Components and Materials Exposed to High Dissolved Hydrogen

Part Name	Part Composition
No. 3 seal runner	304 stainless steel, chrome carbide
No. 3 seal ring assembly	304 stainless steel, 347 stainless steel, carbon graphite
No. 3 seal springs	316 stainless steel
No. 3 end closure	304 stainless steel
No. 3 seal spacer	304 stainless steel
No. 3 double dam cart. seal	Tetralon 720, ethylene propylene diene monomer (EPDM)

Note: The equipment listed is based on the reference plant; however, with respect to other plants, it is expected that the materials identified are representative of those used by most valve manufacturers. As such, unless the materials evaluation identifies a specific material that is adversely impacted by the higher dissolved hydrogen concentration, it is deemed unnecessary for individual plants to perform such an evaluation.

Following identification of these materials, the hydrogen compatibility of each has been evaluated based on a review of openly available literature. This evaluation specifically targets changes in fracture toughness and smooth tensile properties related to increased hydrogen concentration in the environment, as well as the available literature concerning subcritical crack growth in hydrogen environments. The expected performance of the material in the increased hydrogen concentration condition, including plausible variations over the anticipated conditions, is then summarized.

It should be noted that, as hydrogen embrittlement has not been evaluated specifically for PWR chemistry and materials in previous work, this study cannot demonstrate definitively that hydrogen embrittlement is or is not a concern with respect to a change in hydrogen concentration. Also, the effects of hydrogen embrittlement are not sufficiently differentiable from normal PWSCC to conclude definitively that this effect has never occurred in a PWR, based on operating experience. However, the fact remains that this mechanism has not been specifically identified in PWR operating experience, and the conditions under which hydrogen embrittlement occur do differ somewhat from normal PWSCC. Also, while it is possible that some combination of hydrogen embrittlement and intergranular stress corrosion cracking (IGSCC) may be accelerated in a higher concentration hydrogen environment, the increases being considered in this study are modest and should not result in significant changes in material properties [8].

If hydrogen concentration is increased in PWRs, it is recommended that this effect be evaluated to confirm the expectations as outlined here. This could be accomplished by performing testing on components replaced as a part of typical in-service maintenance, especially those components that are constructed of the susceptible materials explicitly identified as a part of this report. The following evaluation identifies the subcomponents containing those materials that are most susceptible. Furthermore, cases where subcomponents constructed of such materials can also be reasonably extracted for such testing are identified.

7.2 Evaluation

7.2.1 Identification of Susceptible Material Parts for Westinghouse and CE Design NSSS

Materials of interest in this study were identified by determining which components that are in contact with the reactor coolant fluid were most likely to be at risk for hydrogen embrittlement. Since high-pressure, low-temperature conditions have been shown to be conducive to the hydrogen embrittlement processes, specific regions under these conditions were identified, including the charging system, reactor coolant pump (RCP) seals, and line isolation points. The components identified in these systems in contact with the hydrogen-charged coolant include isolation valves, check valves, pump mini-flow components, flow-control valves, and pump seals. A table of identified components and corresponding materials for typical Westinghouse and CE design plants was developed (Table 7-1). This evaluation takes this process a step further to determine the specific subcomponent parts versus material. This was accomplished via a detailed review of component drawings and specifications. A summary of this breakdown is presented in Table 7-3.

Table 7-3
Component Materials for Typical Westinghouse and CE Design NSSS

Component	SA-182 Gr F316	SA-182 Gr F304	SA-403 Gr WP 304	SA-403 Gr WP 316	SA-376 TP 304	SA-376 TP 316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/Braided Asbestos/SS Asbestos
Miniflow check valves (8480 A,B) SWI check valve (8368A,B,C, D)	Body, cover											Disc			Gasket							Disc cap	Pin			Spring			
Charging check valve (8481 A,B)	Body, disc, seat ring						Bonnet			Disc arm		Lock pin, disc arm pin, disc arm collar, disc arm anti-rotation pin												Pivot pin			Bearing block		(4)
Charging isolation (8485 A,B) HCV-182 isolation (8402 A,B)	Body, disc, seat ring, bonnet							(1)				Backseat, lantern ring, pin (for disc pin), lock ring & lock pin (for stem pin)	Stem, bearing block, disc to stem link	Disc guide										Stem pin, disc pin					(4)

Table 7-3 (continued)
Component Materials for Typical Westinghouse and CE Design NSSS

Component	SA-182 Gr F316	SA-182 Gr F304	SA-403 Gr WP 304	SA-403 Gr WP 316	SA-376 TP 304	SA-376 TP 316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/Braided Asbestos/SS Asbestos
Charging isolation (8387 A,B) PD pump isolation (8388) HCV-182 bypass (8403)	Body, bonnet, disc							(1)			(10)		Stem (2)															Seat, back-seat & disc over-lay	(5), (6)
FCV-121 isolation (8483 A,B)	Body, disc, seat ring, bonnet							(1)				Backseat, lantern ring, pin (for disc pin), lock ring & lock pin (for stem pin)	Stem, bearing block, disc to stem link	Disc guide										Stem pin, disc pin					(4)
Charging flow control (FCV-121)	Body, bonnet								(1)			Disc	Plug			Stem		Trim (3)		Roll pin	(10)	Guide bushing, cage spacer, seat ring							(7)

Table 7-3 (continued)
Component Materials for Typical Westinghouse and CE Design NSSS

Component	SA-182 Gr F316	SA-182 Gr F304	SA-403 Gr WP 304	SA-403 Gr WP 316	SA-376 TP 304	SA-376 TP 316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/Braided Asbestos/SS Asbestos
PI-118 isolation (7869A) PI-119 isolation (8769B) PI-117 isolation (8390) FT-121 isolation (8404 A,B) FT-139 isolation (8347 A,B) PI-120 isolation (8380) SWI filter vent (8385 A,B) SWI filter drain (8386 A,B) (8370 A,B; 8371 A,B)	Body											Disc, bonnet					Stem, stem head					Disc cap, spring guide (cond. H1100)	Disc pin		Diaphragm	Spring		Disc & seat over-lay	(8)

Table 7-3 (continued)
Component Materials for Typical Westinghouse and CE Design NSSS

Component	SA-182 Gr F316	SA-182 Gr F304	SA-403 Gr WP 304	SA-403 Gr WP 316	SA-376 TP 304	SA-376 TP 316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/Braided Asbestos/SS Asbestos
FT-142, 143, 144, 145 isolation SWI drain (8364A,B,C, D)																													
Loop fill isolation (8345) Loop fill isolation (8346) SWI filter isolation (8384 A,B) SWI filter isolation (8382 A,B) SWI isolation (8352A,B,C, D)	Body											Disc, bonnet					Stem, stem head					Disc cap, spring guide (cond. H1100)	Disc pin		Diaphragm	Spring		Disc & seat over-lay	(8)
Loop fill control (HCV-184)	Body, bonnet								(1)				Cage, plug			Stem		Trim (3)	Cage spacer	Roll pin	(10)	Guide bushing, seat ring							(7)

Table 7-3 (continued)
Component Materials for Typical Westinghouse and CE Design NSSS

Component	SA-182 Gr F316	SA-182 Gr F304	SA-403 Gr WP 304	SA-403 Gr WP 316	SA-376 TP 304	SA-376 TP 316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/Braided Asbestos/SS Asbestos
Charging flow (HCV-182)	Body, bonnet								(1)				Cage, plug			Stem		Trim (3)	Cage spacer	Roll pin	(10)	Guide bushing, seat ring							(7)
Charging isolation (8105, 8106)	Body, seat ring, disc, bonnet							(1)				Backseat, lantern ring, pin (for disc pin), lock ring & lock pin (for stem pin)	Stem, disc to stem link, bearing block	Disc guide										Stem pin, disc pin					(4)
Charging check valve (8381)	Body, disc, seat ring						Bonnet			Disc arm		Lock pin, disc arm pin, disc arm collar, disc arm anti-rotation pin												Pivot pin			Bearing block		(4)
Regen HX isolation (8324 A,B)	Body, bonnet								(1)			Disc, plug	Cage			Stem		Trim (3)	Cage spacer	Roll pin	(10)	Guide bushing, seat ring						Plug facing	(7)
SWI throttle (8369A,B,C, D)	Body, bonnet															Stem		Cage, plug, plug roll pin & key				Guide bushing							(9)

Table 7-3 (continued)
Component Materials for Typical Westinghouse and CE Design NSSS

Component	SA-182 Gr F316	SA-182 Gr F304	SA-403 Gr WP 304	SA-403 Gr WP 316	SA-376 TP 304	SA-376 TP 316	SA-240 Type 316	SA-312 Type 304	SA-312 Type 316	SA-351 CF8M	SA-479 Type 304	SA-479 Type 316	SA-564 Type 630	AMS 5344 17-4PH	ASTM A177 Type 304	ASTM A276 Type 316	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A312 Type 304	ASTM A479 Type 302	ASTM A479 Type 304	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B	Stellite No 6	Asbestos/Braided Asbestos/SS Asbestos
SWI isolation (8355A,B,C, D)	Body, bonnet												Stem (2)															Seat & back-seat over-lay, disc	(5), (6)
SWI check valve (8367A,B,C, D) SWI check valve (8372A,B,C, D)	Body, cover											Disc			Gasket							Disc cap (cond. H1100)	Pin			Spring			
Pipe ¾"–8"					X	X																							
Fittings 3"–8"			X	X																									
Fittings $\leq$ 2"	X	X																											
Flanges	X																												
Miniflow Orifices							X																						
RCP seal (11)																													

Notes: (1) Leakoff pipe or leakoff nipple (This component operates at low pressure.) (2) Hardened material (3) Trim cylinder assembly (4) Gasket (304 stainless steel/asbestos) (5) Packing ring (Crane 187-I braided asbestos) (6) Spiral wound gasket (Flexitalic ML-G21032-TY1 stainless steel and asbestos) (7) Outer trim, inner trim & body gaskets (stainless steel & asbestos) (8) Packing ring (Crane 187I braided asbestos with Inconel wire) (9) Bonnet and trim gaskets (stainless steel and asbestos) (10) Lantern ring (This component operates at low pressure.) (11) The RCP No. 3 seal components contain various 304, 316, and 347 type stainless steels and other non-metallic parts that are at low temperature but are also at low pressure [20].

7.2.2 Identification of the Limiting Susceptible Materials and Subcomponents

The subcomponent material matrix in Table 7-3 was reviewed to identify the most limiting materials that are subject to conditions conducive to hydrogen embrittlement effects. These materials were then evaluated to determine a qualitative expectation concerning performance at elevated hydrogen conditions as described in Table 7-4. As previously mentioned, this effect has not been documented in the industry specifically, and, as such, it is not feasible to demonstrate that there is no impact due to the proposed change. However, based on operating experience where this effect has not been specifically observed, it is unlikely that there will be a significant impact due to the minor increase in hydrogen concentration proposed.

Table 7-4
Summary of Results for Individual Materials Evaluated in Tables 7-1, 7-2, and 7-3

Class of Materials	Summary
Austenitic stainless steels (SS)	Austenitic SSs generally demonstrate high levels of resistance to hydrogen effects. Cold working may increase their sensitivity slightly.
Type 302	No data are available specific to Type 302, but its metastable austenitic structure is less susceptible than martensitic steels to hydrogen effects. Martensite formation may occur under stress and in the cold-worked condition, resulting in minor increases to hydrogen sensitivity.
Type 303	Type 303 is very similar to Type 302, but exhibits inferior corrosion resistance. No data are available specific to Type 303, but its metastable austenitic structure is less susceptible than martensitic steels to hydrogen effects. Martensite formation may occur under stress and in the cold-worked condition, resulting in minor increases in hydrogen sensitivity.
Type 304	Type 304 is generally resistant to hydrogen effects. This material has a metastable austenitic structure similar to Types 302 and 303, which results in some martensite formation under stress or in the cold worked condition. This structure is largely immune to tensile strength reduction in the presence of hydrogen, but does demonstrate a minor reduction in ductility properties for such conditions.
Type 316	Type 316 is a stable austenitic structure and is not significantly impacted by the presence of hydrogen. Type 316 is the most common material.
Martensitic steels	Martensitic steels are more susceptible to hydrogen embrittlement than austenitic steels. Based on current research, it is expected that this effect is benign under the expected plant conditions, a theory supported by current operational experience. If the hydrogen levels are increased, it is recommended that this effect be tracked by performing testing on components replaced as a part of typical in-service maintenance.
Type 420	No data are available on Type 420 stainless steels. However, this material is sufficiently analogous to other types of martensitic steels and can be evaluated based on the generic recommendations provided.

Table 7-4 (continued)
Summary of Results for Individual Materials Evaluated in Tables 7-1, 7-2, and 7-3

Class of Materials	Summary
Type 17-4PH	Some hydrogen sensitivity in Type 17-4PH SS is expected due to its martensitic structure and the lack of tensile and ductile property data for hydrogen effects. It is noted that H1100 is the most likely condition for this steel in PWRs which is less sensitive to hydrogen effects than higher strength conditions.
Nickel alloys	Some hydrogen sensitivity is expected in nickel alloys, as data show that they are significantly embrittled by hydrogen under high-pressure hydrogen gas.
Alloy 718	The tensile strength of Alloy 718 is relatively insensitive to hydrogen effects in its unnotched form, but is affected in the notched form. Alloy 718 also undergoes a large change in reduction in area and elongation properties when exposed to hydrogen. Some hydrogen sensitivity is expected, specifically for conditions supporting aqueous hydrogen exposure.
Inconel X-750	Inconel X-750 is susceptible to low-temperature crack propagation (LTCP) in the presence of a pre-existing crack. Some hydrogen sensitivity is expected, and the limited data do not permit a full assessment of the effect of increasing hydrogen. However, based on current research, it is expected that this effect is benign under the expected plant conditions, a theory supported by current operational experience.
Other Materials	
Stellite No. 6	No hydrogen embrittlement data were found for Stellite No. 6, and no sufficiently analogous material has been identified to use as comparison. However, the applications for Stellite No. 6 are generally not consistent with a structural function and, therefore, are of limited concern with respect to this effect.
Braided Asbestos/SS Asbestos	No hydrogen embrittlement data were found for asbestos alloys. Non-metallic asbestos is not impacted by hydrogen effects, and stainless steels asbestos should be considered based on the type of stainless steel it is composed of, using the appropriate results noted above.

Given the fact that the most limiting materials and components have been identified as a part of this study, it is established that an improved state of knowledge with respect to hydrogen embrittlement could be achieved by evaluating these limiting components following an increase in primary coolant hydrogen concentration. Therefore, this evaluation for limiting material has been extended to recommend suitable parts for removal, replacement, or periodic testing for the purpose of establishing or trending the extent of hydrogen embrittlement that might actually be occurring at the specified low-temperature, high-pressure operating conditions. This selection was based on the following criteria:

1. The selected materials and parts should be reasonably suitable for extraction from the system at a pre-defined periodic frequency. Valve non-pressure boundary internal parts are deemed most suitable as these parts can be, and typically are, considered consumable parts over the life of the valve and can be extracted or replaced during routine valve maintenance. These parts are also constructed of the materials targeted as being the most susceptible or that have little or no data in Item 3 below. It is also noted that the pressure boundary parts (for

example, valve body, valve bonnet, piping, and fittings), for the most part, are constructed of the 304 and 316 type austenitic stainless steels, which provide a high resistance to hydrogen embrittlement.

2. The selected materials and parts should be those that are subjected to hydrogen under low-temperature, high-pressure conditions. The charging system between the charging pump discharge and regenerative heat exchanger meets this condition.
3. The selected materials and parts should be those that are most susceptible to hydrogen embrittlement over those less susceptible (see Table 7-4). It was concluded that hydrogen embrittlement is a highly material-specific effect. Austenitic stainless steels are found to be less significantly impacted by hydrogen embrittlement, while martensitic steels and nickel alloys are more sensitive to such effects.[1] As a note, no data specific to either Stellite- or asbestos-based material were found in this study. While asbestos can be evaluated based on the material type used in its construction, no such analogous material was identified for Stellites.

In addition to the above criteria, the following exceptions are noted:

1. Components and parts that are nonmetallic or a combination of metallic and nonmetallic parts (for example, gaskets or packing) are excluded from consideration for testing, primarily because there are no established test standards. These parts are consumable parts and typically are periodically replaced during maintenance, and functionally, they do not perform in a structural fashion where a reduction in tensile strength or ductility is paramount.
2. Several parts in Table 7-2 were identified as not being at a high-pressure condition (for example, valve leak off pipe or nipples, packing gland parts, lantern rings, and RCP No. 3 seals); therefore, they were excluded from consideration.
3. In most applications of Stellite #6, the material is applied as a hard-facing or overlay onto another material (for example, valve stem and seat surfaces) to minimize erosion and corrosion wear. The hard-facing or overlay does not provide any structural function in which its failure would result in any detrimental consequence other than minor seat leakage. Routine valve maintenance would appropriately address this degradation. Further, it is not clear if current test practices for determining tensile strength and ductility are appropriate when the material is applied as an overlay onto another material, especially if pre-stressed or pre-cracked samples are desired. Therefore, Stellite, when used as an overlay, is excluded from consideration. However, Stellite material in other applications (for example, hinge pin bearing block) is considered.

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[1] It is noted that the data presented are specifically considered at extremely limiting, worst-case conditions for hydrogen embrittlement, and the impact of very high pressure, high-concentration gaseous hydrogen is much greater than that of the modest increase in aqueous hydrogen concentration proposed as a part of this study. Therefore, it is expected that an increase of hydrogen concentration from 25–50 cc/kg to 50–80 cc/kg will not have a significant impact on either the tensile strength or ductility of the materials in contact with the low-temperature, high-pressure RCS process fluid. The resistance of austenitic stainless steels to the hydrogen embrittlement phenomenon is clearly demonstrated, and even metastable austenitic steels, while susceptible to α' martensite formation (and, therefore, hydrogen embrittlement), will be largely unaffected by hydrogen embrittlement, especially considering the small change in exposure concentration. Therefore, changing the amount of hydrogen in the RCS is expected to have little or no detrimental effect.

Using the above criteria and exceptions, the materials and parts from the reference plant that are considered appropriate for hydrogen embrittlement trending consideration are summarized in Table 7-5. It is noted that these recommendations are based on a reference plant and that not all plants will have these materials and parts as indicated here due to differences in construction vintage, design, procurement, and plant-specific tag numbers. However, it is probable that each plant will find some of the same identified materials in other manufacturers’ components (for example, internals of other plant-specific valves) because vendor fabrication practices use the same industry standards and material specifications.

Table 7-5
Recommended Materials and Parts for Hydrogen Embrittlement Trending

Component	SA-564 Type 630	AMS 5344 17-4PH	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A479 Type 302	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B
Miniflow check valves (8480A,B) SWI check valve (8368A,B,C,D)						Disc cap	Pin			Spring	
Charging check valve (8481 A,B)								Pivot pin			Bearing block
Charging isolation (8485 A,B) HCV-182 isolation (8402 A,B)	Stem, bearing block, disc to stem link	Disc guide						Stem pin, disc pin			
Charging ISOLATION (8387 A,B) PD pump isolation (8388) HCV-182 bypass (8403)	Stem										
FCV-121 isolation (8483 A,B)	Stem, bearing block, disc to stem link	Disc guide						Stem pin, disc pin			
Charging flow control (FCV-121)	Plug			Trim cylinder assembly	Roll pin	Guide bushing, cage spacer, seat ring					
PI-118 isolation (7869A) PI-119 isolation (8769B) PI-117 isolation (8390) FT-121 isolation (8404 A,B) FT-139 isolation (8347 A,B) PI-120 isolation (8380) SWI filter vent (8385 A,B) SWI filter drain (8386 A,B) FT-142, 143, 144, 145 isolation (8370 A,B; 8371 A,B) SWI drain (8364A,B,C,D)			STEM, stem head			Disc cap, spring guide	Disc pin		Diaphragm	Spring	
Loop fill isolation (8345) Loop fill isolation (8346) SWI filter isolation (8384 A,B) SWI filter isolation (8382 A,B) SWI isolation (8352A,B,C,D)			Stem, stem head			Disc cap, spring guide	Disc pin		Diaphragm	Spring	
Loop fill control (HCV-184)	Cage, plug			Trim cylinder assembly	Roll pin	Guide bushing, seat ring					
Charging flow (HCV-182)	Cage, plug			Trim cylinder assembly	Roll pin	Guide bushing, seat ring					
Charging isolation (8105, 8106)	Stem, disc to stem link, bearing block	Disc guide						Stem pin, disc pin			

Table 7-5 (continued)
Recommended Materials and Parts for Hydrogen Embrittlement Trending

Component	SA-564 Type 630	AMS 5344 17-4PH	ASTM A276 Type 410	ASTM A276 Type 420	ASTM A479 Type 302	ASTM A564 Gr 630	ASTM A581 Type 303	ASTM A637 Gr 718	Inconel Alloy 718	Inconel X750	RDT M7-7T Stellite 6B
Charging check valve (8381)								Pivot pin			Bearing block
Regenerative heat exchanger isolation (8324 A,B)	Cage			Trim cylinder assembly	Roll pin	Guide bushing, seat ring					
SWI throttle (8369A,B,C,D)				Cage, plug, plug roll pin, plug key		Guide bushing					
SWI isolation (8355A,B,C,D)	Stem										
SWI check valve (8367A,B,C,D) SWI check valve (8372A,B,C,D)						Disc cap	Pin			Spring	

7.2.3 Recommended Hydrogen Embrittlement Testing Practices

The testing for hydrogen embrittlement and fatigue evaluation should be performed under near-to-actual operating conditions (that is, cyclic loads, actual hydrogen concentration, and high-pressure, low-temperature process conditions) encountered in the CVCS charging system and RCS, rather than at excessive hydrogen concentrations that attempt to predict degradation using accelerated techniques. Accelerated testing is of particular concern since it is expected that such testing will not provide results that support appropriate extrapolation to existing plant conditions and will not, therefore, provide an appropriate basis. The accelerated test data generally referenced as a part of this study did not provide satisfactory resolution with respect to lower concentration hydrogen conditions to quantify longer-term, less-accelerated effects using standard methods.

Consequently, it is recommended that testing should be performed on components, as discussed above, based on the expected limited impact of this effect for the proposed concentration change. It is expected that collection and testing of parts and samples in Table 7-5 could begin in the near term based on long-term operation at the current plant hydrogen concentration to determine if any degradation has occurred. Based on the plants' varied operating lives, there should be available sufficient samples with varied cumulative fatigue usage under high-pressure low-temperature hydrogen exposure of varying hydrogen concentrations to develop a database and, therefore, provide further assurance that hydrogen embrittlement at 50–80 cc/kg is not an industry issue.

In order to facilitate comparison of hydrogen embrittlement degradation results throughout the industry and support development of an industry materials database, a common testing practice is required. It is further suggested that testing be performed by one common entity as a way to establish consistent testing of all collected samples and parts. A review of industry papers was performed as a part of this study to determine general practices with respect to establishing the current state of knowledge for hydrogen embrittlement. Although all the previous tests performed for the purpose of hydrogen embrittlement evaluation were not always performed so that test-to-test comparisons could be made, Sandia National Laboratories [10] summarized the mechanical properties that are commonly used to quantify the susceptibility to hydrogen embrittlement. Suggested tests are summarized below and in Table 7-6; however, refer to Sandia report SAND2008-1163 [10] for a more detailed discussion.

Table 7-6
Recommended Test Methods for Hydrogen Embrittlement Trending

Test	Method/Guidance
Tensile Properties	ASTM E8 [12] ASTM G129 [13] ASTM E602 [14] ASTM G142 [15]
Fracture Mechanics	ASTM E1820 [16] ASTM E1681 [17] ASME VIII, Division 3, Article KD-10 [19]
Fatigue	ASTM E647 [20]

7.2.4 Tensile Properties

Tensile properties characterize deformation and fracture in the hydrogen environment. The susceptibility to hydrogen-assisted fracture is sensitive to strain rate. Both smooth and notched tensile properties are reported, based on cylindrical test specimens. Smooth tensile properties (for example, yield strength, tensile strength, uniform and total elongation, reduction of area, and relative reduction in area) are reported in accordance with the terminology in ASTM E6 [11] and performed in accordance with the standard test methods in ASTM E8 [12] and standard practice in ASTM G129 [13]. Notched tensile properties (for example, notched tensile strength, reduction of area, and elastic stress concentration factor) are reported in accordance with ASTM E602 [14]. A standard notched tensile geometry for testing in high-pressure hydrogen is provided in ASTM G142 [15].

7.2.5 Fracture Mechanics

Fracture toughness testing of materials is performed using pre-cracked specimens subjected to a constant displacement rate to yield a measure of both the fracture initiation and crack propagation resistances. The displacement rate can affect the results, so standard test specimen geometries and procedures are required as outlined in ASTM E1820 [16] and ASTM E1681 [17]. Fatigue and fracture testing terminology is provided in ASTM E1823 [18] with additional test method guidance provided in ASME VIII, Division 3, Article KD-10 [19].

7.2.6 Fatigue

Fatigue, the result of cyclic loading, is one of the most probable failure mechanisms, but it has not been extensively studied in the presence of high-pressure hydrogen. Therefore, more effort must be directed at measuring fatigue properties under high-pressure hydrogen cyclic loading conditions. Both frequency of the load cycle and ratio of the minimum-to-maximum loads have been shown to affect fatigue properties. Since fatigue testing on smooth cylindrical specimens does not separate fatigue crack initiation and propagation, pre-cracked specimens are tested using the methods in ASTM E647 [20] to generate plots of fatigue crack growth as a function of stress intensity factor range.

While not recommended, if it were desirable to perform generic testing for this effect, it is recommended that testing be performed to reflect appropriate condition-specific hydrogen levels in a low-temperature, high-pressure aqueous environment to maximize the effect of hydrogen embrittlement. Because other means of acceleration may inhibit making appropriate extrapolations with respect to hydrogen embrittlement, it is recommended that the use of pre-stressed or pre-cracked samples be considered to ensure the presence of observable embrittlement phenomena since preliminary research indicates a slow rate under the expected conditions.

7.3 Conclusions and Recommendations

Specific materials commonly contained in PWRs, and the subsequent impact of hydrogen on these materials, were identified. These materials are summarized in Table 7-3, including the components that are composed of these materials. Based on current research, it is expected that the effect of hydrogen embrittlement is benign for these components under the expected plant conditions, a theory supported by current operational experience. Furthermore, it is expected that an increase of hydrogen concentration from 25–50 cc/kg to 50–80 cc/kg will not have a significant impact on either the tensile strength or ductility of the materials in contact with the low-temperature, high-pressure RCS process fluid. Therefore, changing the amount of hydrogen in the RCS is expected to have little or no detrimental effect.

If hydrogen levels are increased per the study findings, it is recommended that the effect of hydrogen embrittlement, previously not considered within the industry, be evaluated by performing testing on subcomponents replaced as a part of typical in-service maintenance, specifically those components that are constructed of the most susceptible materials as identified in Table 7-4. As there is no finding that concludes that such an effect is of significant consequence, sampling of the various material types is suggested only on an as-needed maintenance replacement basis to develop appropriate data, should such questions arise in the future. A compilation of the industry samplings should provide a sufficient size database to confirm the expectations with respect to long-term hydrogen embrittlement effects in PWRs for the susceptible materials identified in this study; that is, that hydrogen embrittlement is not a significant contributor to material issues in PWRs at the current or newly proposed operating conditions.

The testing recommended is considered in further detail to ensure that, should such an approach be adopted, there is consistency within the industry. As such, this evaluation (see Table 7-3) provides a further material breakdown at the subcomponent level. From this subcomponent material matrix, certain parts are selected or recommended for periodic testing for the purpose of establishing or trending the extent of hydrogen embrittlement that may actually be occurring under actual operating conditions. The selected materials and parts are summarized in Table 7-5, and recommended testing procedures and techniques are summarized in Table 7-6.

8
INSTRUMENTATION & CONTROL

Temperature instruments are inherently not affected by fluid composition. Flow instruments typically have a relatively small pressure drop, so gas evolution is relatively small. Pressure instruments are indirectly affected by the increased hydrogen concentration in that the VCT and downstream instruments may be out of range due to the increased VCT pressure, so they are evaluated in this section. Finally, level instruments with condensate pots have the potential for collecting noncondensables, so they are also with the scope of this section.

8.1 Pressure Instruments

Only a few instruments are potentially affected by the increase in normal VCT pressure. They are summarized below for the reference plant (Byron):

Table 8-1
Instrumentation Potentially Affected by Increased RCS Dissolved Hydrogen

Channel Number	Description	Current Range (psig)	Typical Reading (psig)	Anticipated Reading (psig)	Recommended Range
PIA-115	VCT pressure	28" Hg Vac - 75 psig	20–30	50–60	0–100 psig*
PI-117	PD pump discharge pressure	0–3000	2600	2630	No change
PI-118	Centrifugal charging pump 1 discharge pressure	0–3000	2600	2630	No change
PI-119	Centrifugal charging pump 2 discharge pressure	0–3000	2600	2630	No change
PI-120	Charging header pressure	0–3000	2500	2530	No change
PI-186	PD pump suction pressure	0–150	30–40	60–70	No change
PI-187	Centrifugal charging pump 1 suction pressure	0–150	30–40	60–70	No change
PI-188	Centrifugal charging pump 2 suction pressure	0–150	30–40	60–70	No change

*Due to the small increase in expected operating pressure, only the VCT pressure instrument should be considered for modification and only if the relief valve setpoint increases from 75 to 80 psig.

Table 8-2
CE NSSS Instrumentation (Typical) Potentially Affected by Increased RCS Dissolved Hydrogen

Channel Number	Description	Current Range (psig)	Typical Reading (psig)	Anticipated Reading (psig)	Recommended Range
P-225	VCT pressure	0 psia–75 psig	15–35 max range 15–50	50–60	0–100 psig*
PS-216 or PS-224X	Pump suction pressure switch	10 psia-120 psig	NA	NA	No change
PS-217 or PS-224Y	Pump suction pressure switch	10 psia-120 psig	NA	NA	No change
PS-218 or PS-2218 or PS-224Z	Pump suction pressure switch	10 psia-120 psig	NA	NA	No change
P-212	Charging pump discharge pressure	0–3000	2300-2485	2300-2485	No change
P-215	RCP controlled bleed-off pressure	0–300	25–175	25–175	No change
P-220	Letdown line pressure	0–200	40–95	40–120	No change

* Due to the small increase in expected operating pressure, the VCT pressure instrument needs to be considered for modification only if the relief valve setpoint is increased from 75 to 80 psig.

8.2 Pressurizer Level Condensate Pots

In the 1990s, problems were reported with condensate pots due to the accumulation of noncondensables. These problems included:

1. Level indication error during normal operation due to insufficient condensation
2. Misindication during pressure transients due to dissolved gases that come out of solution in the reference leg
3. Nozzle cracking due to thermal fatigue caused by a large ΔT between the pot and the pressurizer
4. Condensate pot cracking
5. Thermal stresses in the piping connecting the pot to the process piping

New pot designs have eliminated these problems. However, if accumulation of noncondensables in condensate pots remains a problem, higher RCS dissolved hydrogen concentrations will result in higher pressurizer steam and liquid hydrogen concentrations and will exacerbate the problems. It is recommended that the condensate pot design and layout be reviewed to ensure proper operation.

9
EVALUATION INPUTS TO A 10 CFR 50.59 SCREEN

The current generic assessments indicate a number of items that could potentially cause an adverse affect to a structure, system, or component (SSC) design function as described in the Final Safety Analysis Report (FSAR). Quantitative evaluations will need to be completed on a plant-specific basis prior to performing a plant-specific 50.59 screening evaluation for the proposed increase in RCS hydrogen concentration. This includes, but is not limited to, a specific evaluation of these identified items and issues:

- Longer duration RCP seal qualification tests will need to be completed prior to implementing the change.
- Pressurizer response and control following a transient will need to be evaluated for the potential effects of an increased hydrogen concentration in the pressurizer gas space.
- The VCT relief valve will need to be evaluated for modification.
- Various regulator setpoints will require changes from their current values.
- Letdown flow control valves (CE NSSS) will need to be evaluated for potential cavitation.
- The effect of increased VCT pressure on emergency boration flow will need to be evaluated.
- Hydrogen volume and holdup time impacts on the waste gas handling system will need to be evaluated.
- Gas void impacts will need to be evaluated, such as the potential for increased gas void size and increased gas generation and collection in the charging pump suction, which could render the pump incapable of performing its required safety function.

A review of the Byron Technical Specifications (TS), contained within the Technical Requirements Manual [25] and TS Bases [26], indicated that no changes are required to either document as a result of this proposed change. In addition, this proposed change does not impact the Facility Operating License Appendix B, Environmental Protection Plan [27]. It should also be noted that any reference to the *EPRI Pressurized Water Reactor Primary Water Chemistry Guidelines* [28] contained within the Technical Requirements Manual should be confirmed to be consistent with the Guidelines document prior to implementation.

Each of the 10 CFR 50.59 screening topics must be answered on a plant-specific basis to determine if a 10 CFR 50.59 evaluation must also be performed.

A review of the Byron Final Safety Analysis Report [24] identified typical sections that will need to be reviewed for potential changes, including:

- 5.2.3.2.1 Chemistry of Reactor Coolant
- 5.4.1.3.10 (RCP) Shaft Seal Leakage

- 9.3.4.1.2.1 Charging, Letdown, and Seal Water System
- 9.3.4.1.2.2 Reactor Coolant Purification and Chemistry Control System
- 9.3.4.1.2.5 Component Description - Volume Control Tank
- 9.3.4.1.2.6 System Operation - Reactor Startup & Cold Shutdown

10
CONCLUSIONS AND RECOMMENDATIONS

1. Increased RCS dissolved hydrogen concentration is feasible for typical NSSS systems and components. The acceptability of the specified hydrogen concentration up to a maximum of 80 scc/kg is dependent upon the following considerations and should be evaluated on a plant-specific basis:
   a. VCT relief valve setpoint (that is, existing 75 psig, or increased to 80 psig)
   b. Typical VCT operating temperature, as it affects the solubility of hydrogen in the reactor coolant
   c. Desired margin between the relief valve setpoint and the normal operating pressure, considering normal transients, based on operating experience
   d. Actual benefit realized in reducing primary water stress corrosion cracking for a given dissolved hydrogen concentration versus the cost of required modification or procedure changes and the risk associated with hydrogen embrittlement issues
2. The required VCT operating pressures to provide 80 scc hydrogen/kg based on Henry's Law and assuming 90% hydrogen in the gas space are:

Table 10-1
VCT Pressure to Achieve 60 scc/kg and 80 scc/kg Hydrogen

VCT Temperature (°F)	RCS H_2 60 scc/kg Pressure (psig)	RCS H_2 80 scc/kg Pressure (psig)
90	43.30	62.64
100	44.24	63.89
110	44.93	64.81
120	45.51	65.59

3. RCP No. 1 seal backpressure is acceptable. For replacement seals, Westinghouse will perform the usual qualification tests, but at the new operating conditions. Note that the CE NSSS specification already specifies seals for operation up to 100 scc (STP)/kg (H_2O) and at the increased VCT backpressure conditions.
4. For Westinghouse RCPs, an increase in VCT backpressure results in a very small reduction (estimated to be less than 0.1gpm) in the No. 1 seal leak rate. This reduction is not significant and would not pose a problem for continued operation of the seal.

5. For Westinghouse RCPs, with the increase in VCT pressure, the ΔP on the No. 2 seal will be increased by approximately 20–35 psi. Based on this increased seal ΔP, the predicted maximum leak rate for the No. 2 seal will be approximately 0.026 gpm, which is still well below the maximum allowable No. 2 seal leak rate of 0.5 gpm. Westinghouse recommends that a long-term qualification program be completed before changing the VCT pressure.
6. For Westinghouse RCPs, the No. 3 seal in either the bellows or cartridge arrangement should not be affected by the increased hydrogen concentration or the increased VCT pressure.
7. During the increased VCT pressure testing, both the Westinghouse RCP No. 1 and No. 2 seals performed within the normal limits established by the current production testing requirement. The current utility inspection intervals can be as long as six years; therefore, longer duration tests should be considered.
8. Prior to operation at the VCT pressure range needed to maintain an elevated RCS dissolved hydrogen concentration, customers should notify Westinghouse to allow time to modify the current RCP seal production test facilities and test procedures and to create specific parts drawings.
9. For the Westinghouse NSSS, based on structural analysis, the existing VCT design pressure can be increased from 75 to 80 psig. Therefore, the VCT relief valve setpoint can be increased from 75 to 80 psig. It is expected that the same could be performed for CE NSSS designs.
10. The additional hydrogen released post-accident into containment has a negligible effect on the containment analysis. This should be confirmed for the CE NSSS.
11. Additional monitoring of PRT pressure and additional PRT gas space sampling will be required during periods of pressurizer valve leakage. This applies to the reactor drain tank (or quench tank in CE NSSS designs).
12. Accumulation of hydrogen impurities will be noticeable in the long term in the gas spaces of vessels containing reactor coolant, that is, VCT and pressurizer.
13. If the VCT relief valve setpoint is increased from 75 to 80 psig, the existing valve spring and washers must be replaced, and the valve vendor must provide new documentation, which must be approved to support the change.
14. The VCT hydrogen supply regulator may require a larger controller range, for example, 0–100 psig.
15. The burp regulator may require that the controller be replaced with one having a larger range, for example, 0–100 psig versus 0–60 psig.
16. For plants with a VCT purge regulator in the vent line to the waste gas system, some adjustment of the purge regulator and/or downstream flow control valve may be required if the VCT is operated above 60 psig.
17. The VCT gas sample regulator may require adjustment due to the increased throttling requirements from the increased VCT supply pressure.
18. Very little impact is expected on the letdown pressure control valves or letdown flow control valves, as applicable. However, the valves should be evaluated for potential cavitation at the valve outlet if internal pressures drop sufficiently low.

19. No impact is expected on the letdown line relief valve.
20. A negligible effect is expected on the excess letdown line control valve, as applicable.
21. No effect is expected on the RCP seal return line relief valve.
22. Increased VCT backpressure may reduce flow in the emergency boration flow path. This must be determined on a plant-specific basis due to variations in boric acid pump performance and piping layout.
23. No effect on the boric acid flow control valve in the makeup system is expected. The additional backpressure in the VCT should be evaluated with respect to line losses and pump head delivery curve performance. A slower response in obtaining desired flow rates is expected. Therefore, there may be a need to adjust time delays in the makeup control system to prevent alarms for flow deviations.
24. While the PMW flow control valve in the makeup system has a wide range of operability, the performance is very layout-dependent. A plant-specific evaluation should be performed for each application. A slower response in obtaining desired flow rates is expected. Therefore, there may be a need to adjust time delays in the makeup control system to prevent alarms for flow deviations.
25. No effect is expected on the charging pump suction relief valve.
26. The charging pump miniflow is not affected, but additional hydrogen may be evolved from the miniflow fluid due to the higher inlet dissolved hydrogen concentration.
27. Plants with a full letdown flow stripper will experience an increased hydrogen flow rate to the waste gas system. This will reduce fission gas delay time in charcoal adsorption systems. The exact effect should be evaluated on a plant-specific basis.
28. Because pockets of hydrogen have been found in piping adjacent to the charging pump suction piping, introduction of additional dissolved hydrogen will exacerbate existing problems with gas voids. Evaluations and more frequent monitoring of individual piping segments would be required. The release rate of hydrogen into the recycle holdup tanks will increase from 0.2 to 1 scfm when letdown is diverted from the VCT. For plants with holdup tank diaphragms, the venting frequency must increase. For plants in which the holdup tanks vent directly to the waste gas system, there is no effect. In all cases, additional hydrogen must be treated in the waste gas system.
29. In general, materials in components that are most susceptible to hydrogen embrittlement (high pressure/low temperature) are not expected to be impacted by the increased hydrogen concentration. However, additional testing is recommended for materials for which no data were available.
30. Positive displacement charging pumps may be adversely impacted at the higher hydrogen concentrations and should be evaluated with respect to adequate venting procedures and frequency thereof.
31. The impact of instrument accuracy should be included in the plant-specific evaluations.

32. Due to the small increase in expected operating pressure, only the VCT pressure instrument should be considered for modification and only if the relief valve setpoint increases from 75 to 80 psig.

33. Pressurizer level instrument condensate pot designs should be reviewed to ensure adequate venting of noncondensables during normal operation and pressure transients.

11
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A
HYDROGEN SOLUBILITY

The VCT has a gas space with a hydrogen overpressure maintained by a pressure control valve (See Section 5). This overpressure allows hydrogen to dissolve in the liquid space and reach equilibrium according to Henry's Law. The VCT hydrogen pressure required to achieve a dissolved hydrogen concentration of 80 scc/kg in the reactor coolant is calculated in this appendix.

Henry's Law: x = yP/H

x = mole fraction (MF) of hydrogen in the liquid phase at equilibrium

y = MF of hydrogen in the gas phase at equilibrium

P = total absolute pressure of the gas phase (atm.)

H = Henry's Law constant at a specified temperature (atm/MF)

Using the target value of 80 scc/kg:

$$\frac{\text{80 cc hydrogen x (1 ft}^3\text{/28,320 cc) x (1 lb-mole/359 ft}^3\text{)}}{\text{1000 g H}_2\text{O x (1 lb/454g.) x (1 lb-mole/18 lb.)}} = 6.43E-05 = x$$

Table A-1
Vapor Pressure at Various VCT Temperatures

T	VP
(°F)	(psia)
90	0.7
100	0.95
110	1.27
120	1.69

From the International Critical Tables:

Table A-2
Henry's Law Constant at Various VCT Temperatures

T	H	T	T	Interpolated	Interpolated
(°C)	(x E07)	(°C)	(°F)	H(mmHg/MF)	H(atm/MF)
30	5.54	32.2	90	5.580E+07	7.342E+04
35	5.63				
35	5.63	37.8	100	5.669E+07	7.459E+04
40	5.7				
40	5.7	43	110	5.736E+07	7.547E+04
45	5.76				
45	5.76	49	120	5.792E+07	7.621E+04
50	5.8				

y = hydrogen gas space MF

While the VCT gas space is mostly hydrogen, it also contains water vapor (See Table A-1, above), nitrogen, and some helium. Based on operating experience, a total mole/volume fraction of 0.90 is representative of reality.

Re-arranging Henry's Law yields: P = xH/y

P = 77.34 psia @ 90°F = 62.64 psig

Now, using H from Table A-2, Table A-1 can be expanded to determine P as follows:

Table A-3
Required VCT Pressure to Achieve 80 scc/kg at Various VCT Temperatures

T	H	x	y	P	P	P
(°F)	(ATM/MF)			(ATM)	(psia)	(psig)
90	7.342E+04	6.43E-05	0.90	5.26	77.34	62.64
100	7.459E+04	6.43E-05	0.90	5.35	78.59	63.89
110	7.547E+04	6.43E-05	0.90	5.41	79.51	64.81
120	7.621E+04	6.43E-05	0.90	5.46	80.29	65.59

NOTE: Instrument accuracy is not included.

For other concentrations at 100°F, for example:

75 scc/kg: P = 75/80 x 78.59 = 73.67 psia = 58.97 psig

70 scc/kg: P = 70/80 x 78.59 = 68.76 psia = 54.06 psig

65 scc/kg: P = 65/80 x 78.59 = 63.85 psia = 49.15 psig

60 scc/kg: P = 60/80 x 78.59 = 58.94 psia = 44.24 psig

B
NSD-EPRI-07-27

To assess effects on associated and related plant operations and conditions, Westinghouse has applied an impact review process with the intention of assisting EPRI in determining impacts on plants should the new operating band be applied. For the purposes of this review, representative and generic U.S.-based operating plant work activities were assumed to bound the scope of this evaluation (note, international and future plant, as well as Licensee/Owner based, requirements were not explicitly included).

Tables B-1 and B-2 below list the Westinghouse Engineering Groups and Functional Areas assessed and results of the impact process review of the increased range of RCS dissolved hydrogen concentration. As can be noted in Table 1, each area is categorized as "Impacted" or "Not Directly Impacted" and includes explanatory notation while Table 2 list those areas "Not Impacted."

Several functional areas have been categorized as Impacted, several as Not Directly Impacted and several more as Not Impacted. Function areas falling into the category of Not Directly Impacted result from dependency of inputs from impacted functional areas.

> {For example, some analyses are not directly impacted by the defined hydrogen change but may be dependent on inputs from impacted functional areas. Should, upon further investigation/evaluation/tests/analysis, it be determined that the impacted functional areas have insignificant (or no) impact to the system capabilities, no further need for the "Not Directly Impacted" analyses would be expected. However in the event of analysis of record impacts, further analysis evaluations of the "Not Directly Impacted" areas would be expected.}

As a result,

a) Impacted areas would require additional evaluation, analysis and effort, while

b) Not Directly Impacted may or may not require additional evaluation, analysis and effort, and

c) Not Impacted areas are not expected to require additional evaluation, analysis or effort.

Based on a collective review of Table 1 results and findings, Westinghouse expects subsequent industry efforts prior to any final recommendation associated with this change and any eventual implementation would proceed on a case by case, plant-specific basis.

Table B-1
Impacted and Not Directly Impacted Functional Areas

Impacted Functional Areas	
Nuclear Fuels	Nuclear Fuel Rod Design and Fuel Mechanical Assembly Design would require analysis and evaluation (reference Westinghouse input to "Assessment of the Effect of Elevated Reactor Coolant Hydrogen on the Performance of PWR Zirconium-Based Alloys, 1013522, Technical Update, December 2006, EPRI Project Manager A. Yilmazbayhan)
Fluid Systems	Increased upper limit of 80 cc/kg hydrogen dissolved in the reactor coolant will require a significant increase in the partial pressure of hydrogen in the Chemical Volume and Control System Volume Control Tank (VCT) gas space. Effects on Reactor Coolant, Chemical Volume and Control, Emergency Core Cooling Systems, Boron Recycle, Liquid Waste Processing and Gaseous Waste Processing Systems would require analysis and evaluation.
Reactor Coolant Pump	Effects on Reactor Coolant Pump Number 1 Seal would require analysis and evaluation
Safety & Systems Analysis	Instrumentation systems would require analysis and evaluation (review to ensure proper reference leg operation, with respect to potential of dissolved gases come out of solution and causing improper indication during pressure transients; also conventional condensate pots should be reviewed for any sensitivity to accumulation of non condensable gases)
Materials Center	Material Assessment
Not Directly Impacted Functional Areas	
LOCA Analysis - Small Break/Large Break (App. K & Best Estimate)	Dependent on Fluid System results; if no impact to ECCS flows, no impact
LOCA Analysis - LOCA Related (Hot leg switchover/Long Term core cooling)	Dependent on Fluid System results; if no impact to ECCS flows, no impact
LOCA Forces	Dependent on Fluid System results; if no impact to ECCS flows and fluid properties, no impact
Plant Operations - Reactor Engineering	No impact, as long as 25 cc/kg minimum dissolved Hydrogen is permissible at beginning of cycle
Uncertainties-Reactor Protection System, Engineered Safety Feature Actuation System-ICO/Setpoints	No impact as long as no safety analysis changes required. Also the effect of increased Hydrogen concentration on issues in NRC-IN 92-54 and GL 92-04 should be evaluated
Reactor Vessel Structural	Dependent on Fluid System and LOCA Forces results; if no impact to LOCA loads, no impact
Reactor Vessel Internal	Dependent on Fluid System and LOCA Forces results; if no impact to LOCA hydraulic forces, no impact
Reactor Vessel Supports	Dependent on Fluid System and LOCA Forces results; if no impact to LOCA hydraulic forces, no impact
Ice Containment - Mechanical Design	Dependent on Fluid System and LOCA Forces results; if no impact to ECCS Flows/performance nor LOCA forces, no impact

Table B-2
Not Impacted Functional Areas

Mechanical & Systems
Technical Specifications
Instrumentation & Control (I&C) Systems/ Equipment Qualification (EQ)
Equipment Design/Aging Management
LOCA Long Term / Short Term Mass and Energy (M&E;Containment Integrity)
Main Steam Line Break Inside/Outside Containment M&E-Dose Steam Release (Containment Integrity)
Radiological / Doses
Transient Analysis
Steam Generator Tube Rupture
Probability Risk Assessment
Emergency Operating Procedures
Plant Operations - Shutdown Safety/Natural Circulation
Design Transients/Control System - Cold Overpressure Mitigation System/Margin To Trip
NSSS-BOP/Auxiliary Equipment Design Transients
Auxiliary Equipment
Performance Capability Working Group, NSSS design parameters
Fluences/Heat Generation/Sources
Steam Generators Design & Analysis
Pressurizer Design & Analysis
Leak Before Break/NSSS Supports
Reactor Vessel Supports
Control Rod Drive Mechanisms
Reactor Vessel Integrity
Reactor Coolant Loop Piping
RCS Chemistry
Reactor Vessel Head /Simplified Head Design
Project Scheduling
Hydrogen Generation

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com