H-1-BB-MEE-1878

Hope Creek 'B' Recirculation Pump Vibration Analysis

Revision 1
December 16, 2004

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1.0 REVISION SUMMARY

Revision #	Description
0	Original Issue
1	- Revised the description of the Hope Creek Reactor Recirculation pumps from 2nd Generation to 1st Generation reactor recirculation pumps. - In section 4.5 the Hope Creek Reactor Recirculation pumps' deviation from their best efficiency point was changed from 2% to 15%. - Added new paragraph (4) to section 4.6 to provide mechanical seal failure information. - No revision bars were used.

2.0 PURPOSE

The purpose of this engineering evaluation is to document the analysis associated with the following 'B' Reactor Recirculation pump reliably concerns:

1) The probability of a shaft cracking event in light of the industry concern on shaft cracking of Byron-Jackson reactor recirculation pumps.
2) The reliability of the pump's mechanical seal.
3) The pump's elevated shaft vibrations.

3.0 SCOPE

This evaluation reviews 'B' Reactor Recirculation pump's design, its current condition, and its history. The review of the industry concern for reactor recirculation pumps is limited to only pumps originally manufactured by Byron-Jackson. The industry as described in this evaluation is limited to the reactor recirculation pump associated with stations that are members of the Boiling Water Reactor Owners Group (BWROG).

4.0 DISCUSSION

4.1 Design Information:

Reactor Recirculation Pumps:

The Hope Creek Reactor Recirculation pumps are Byron-Jackson (now Flowserve) Type DVSS, size 28x28x35, vertical, single stage pumps. Byron-Jackson and Flowserve have made a series of modifications on the reactor recirculation pumps since they were first manufactured. The different style pumps are referred to as 1st, 2nd, 3rd, and 4th Generation reactor recirculation pumps. The 1st and 2nd Generation pumps have no significant technical differences, but were manufactured at different times and have been classified into two different groups. The 3rd Generation was a significant change. The shafts are hollow vice solid, and they are made of a harder metal. The 4th Generation is also a significant change. The 4th Generation reactor recirculation pump was specifically designed to prevent any shaft cracking concerns. The Hope Creek reactor recirculation pumps are classified as 1st Generation reactor recirculation pumps. They are powered by General Electric (GE) variable speed (1400-1680 rpm), 7500 HP motors. See Attachment 8.1 for a diagram of the pump.

Hope Creek Station has two reactor recirculation pumps. The pumps take suction from the reactor cavity, and provide the motive force for the jet pumps to recirculate the reactor coolant water.

The reactor recirculation pump shafts are made of 304 Stainless Steel with a yield stress of 39 ksi and an ultimate tensile stress of 80 ksi. The shaft is 59 inches long, with various diameters between 4 and 7.9 inches.

The pump and motor shafts are connected by a three piece coupling assembly. The assembly includes a motor hub, which is attached to the end of the motor shaft; a pump hub, which is attached to the end of the pump shaft; and a spacer piece to connect the two hubs. The flanged surfaces between the hubs and spacer contain rabbet fits to ensure a precision assembly of the coupling. The three piece coupling assembly allows mechanical seal replacement without motor removal. The rabbet fits of the flanged faces ensure the precision alignment of the coupling.

To maintain the pump's mechanical seal cool, the pumps have an integral heat exchanger is attached to the pump cover housing. Water from the housing is circulated through coils of the heat exchanger by an auxiliary impeller attached to the pump shaft located directly below the mechanical seal. Reactor Auxiliaries Cooling (RAC) water circulates around the cooling coils to remove the heat from the seal purge water.

Each of the Hope Creek reactor recirculation pumps has a Reactor Recirculation Pump Mechanical Seal Purge system. The purpose of the seal purge system is to provide clean cool water to the mechanical seals, and to keep particulate in the Reactor Coolant System

(RCS) water from entering the mechanical seal cavities and damaging the seal faces. The systems use cool (90-140°F) and filtered (50 micron) water from the Control Rod Drive (CRD) system and inject it into the mechanical seal cartridge on the high pressure side of the first stage seal faces. Once inside the seal cavity the water travels in two directions. Most of the water passes through the controlled leak-by past the first stage seal faces, into the cavity under the second stage seal faces, through the second stage controlled leak-by, and out the first stage leak-off line. The remainder of the water descends down the reactor recirculation pump shaft through the annulus between the pump shaft and the pump casing. In this region the relatively cool seal purge water mixes with and seals out the hot RCS water that is rising up the shaft.

The pumps' performance is monitored by trending the following:

(a) Pump Shaft vibration - (H1BB –1BBVT-7910A/B1/2) Two proximity probes (X & Y directions) are mounted on the pump shaft/coupling to detect shaft radial vibration. The vibration information is indicated in the control room to permit continuous monitoring by the operators, and is alarmed (11 mils) to prompt the operators of transient conditions. In addition, the vibration data is downloaded monthly into the ADRE system, (MP# HC650050) to permit evaluation of the pump phase angles and vibration orbital plots for indications of shaft cracking. See Attachment 8.2 for 'B' Reactor Recirculation pump's vibration performance over the last four cycles.
(b) Pump Axial vibration - (H1BB –1BBVT-7910A/B4) One velocity meter is installed on the upper edge of the motor upper bearing to detect axial movement. The vibration information is indicated in the control room to permit continuous monitoring by the operators, and is alarmed (7 mils) to prompt the operators of transient conditions.

Reactor Recirculation Pump Mechanical Seals:

The Hope Creek Reactor Recirculation pumps utilize a Flowserve N-7500, two stage, cartridge mechanical seal. The sealing faces are made of a carbon stationary face and a silicon carbide rotating face. Either stage of the mechanical seal is capable of withstanding full system pressure and permitting continued pump operation. The mechanical seals were first installed in November 1997 via DCP 4EO-3635. The previous mechanical seals, Borg-Warner, two stage, cartridge mechanical seal assembly, were too vulnerable to failure from inadequate venting. (PIR 961118205)

Each set of sealing faces leaks just enough water to lubricate the faces. The first stage seal faces have 1000 psig from the RCS on the high pressure side and 500 psig on the low pressure side. The 500 psig is created by the controlled leak-by flow of approximately 0.75 gpm from the high pressure side of the first set of sealing faces, through the pressure breakdown coil to the cavity between the two sets of sealing faces. The controlled leak-by flow is directed to the plant equipment drains via the second pressure breakdown coil and the seal staging-flow leak-off line. The second stage seal has 500 psig on the high pressure side and is vented to atmosphere on the low pressure side. The low pressure side is vented via an opening on the top of the mechanical seal housing, and by the second stage leak-off line that directs leakage to the plant's equipment drain system.

The mechanical seal performance is trended by monitoring the following:

(a) First stage seal pressure - (H1BB –1BBPT-N006A/B-B31) This pressure indication closely follows RCS pressure. A reduction in the first stage seal pressure would indicate a failure of the first stage sealing faces. See Attachment 8.2 for 'B' Reactor Recirculation pump's first stage seal pressure performance over the last four cycles.
(b) Second stage seal pressure - (H1BB –1BBPT-N005A/B-B31) This pressure is one half of RCS pressure (500 psig). A reduction in the second stage seal pressure would indicate excessive leak-by the second stage sealing faces. An increase in the second stage seal pressure would indicate excessive leak-by of the first stage sealing faces. This indication is the primary indication of the condition of the mechanical seal assembly. Acceptable seal performance is indicated by second stage seal pressures of 450-550 psig. See Attachment 8.2 for 'B' Reactor Recirculation pump's second stage seal pressure performance over the last four cycles.
(c) First & Second stage seal cavity temperature - (H1BB -1BBTE-3834/6A/B-B31) The cavity temperature is an indication of the stress on the mechanical seal. In the case of degraded mechanical seals, sudden changes in seal cavity temperature will result in changes, normally increases, in seal leak-off.
(d) First & Second stage seal leak-off alarms - (H1BB –1BBFSH-N002/7A/B-B31) Both the first and second stage seal leak-off lines have control room alarms to indicate excessive seal leak-off.

4.2 <u>Reactor Recirculation Pump Shaft Cracking Discussion</u>:

In the 1980's, Byron-Jackson (now Flowserve) began to identify cracks in the pump shafts, and in the heat exchanger covers of their reactor recirculation pumps during periodic inspections. The initial investigation indicated that all Byron-Jackson reactor recirculation pumps were susceptible to the cracking, and General Electric (GE) issued several Service Information Letters (SIL) discussing this issue. (References 11-21)

The cracks that have been found in integral pump heat exchanger covers in the industry are typically less than 0.3 inch deep. No cracks have been identified in either of the Hope Creek reactor recirculation pumps. These cracks have a potential for eventual seepage of reactor coolant into the Reactor Auxiliary Cooling (RAC) System. SIL 459 recommends monitoring the RAC system for possible contamination. The Hope Creek RAC system contains radiation monitor H1SP -1SPRI-2534 to monitor for possible contamination. To date, there is no evidence of RAC system contamination caused by reactor recirculation pump heat exchanger cover cracks either at Hope Creek station or any other station in the industry. Therefore, the remainder of this discussion will focus only on pump shaft cracking.

Flowserve has performed considerable investigation and testing associated with this shaft cracking issue and has determined the initiation mechanism for the cracking. The initiation of the cracks is due to thermal cyclic fatigue caused by mixing of the cold seal purge system water (90-140°F) and the hot reactor coolant water (545°F) in the thermal mixing region. The initial thermal cracks are axial in orientation and vary in depth from a few thousandths of an inch to 0.3 inches. The cracks appear on the threaded portion of the shaft from approximately one inch above the thermal barrier to one inch below the thermal barrier. See Attachment 8.3 for a drawing of the location of the shaft cracks. The severity of the thermal cracks is governed by the interacting effects of time in service, and the temperature and flow rate of the seal purge system. Through their testing and evaluation, Flowserve determined that a purge flow of 1.9 gpm would be sufficient to maintain the mechanical seal in a cool and clean environment, and minimize the adverse affects of the cold seal purge water on the pump shaft. Based on these findings, Hope Creek Station adjusted seal purge flow to 1.5-2.5 gpm. This band is within the acceptable tolerance around the calculated 1.9 gpm. The Flowserve calculations found that the recommended lower seal purge flow resulted in smaller thermal crack depths. At lower flow rates, the hot RCS water penetrates further up the pump shaft before encountering the cold seal purge flow. Since the RCS water travels a further distance over a longer period of time, the temperature gradient area is extended and the thermal stresses on the shaft are lower.

Over time, the axial thermal cracks can transition into circumferential cracks. As the crack becomes deeper, the thermal stresses become less and the crack self-arrests. See Attachment 8.4 for a Crack Growth Prediction graph. The horizontal line across the bottom of the graph represents the growth rate of thermally initiated cracks over the life of the plant. This thermal cracking alone is not detrimental to the pump. The three vertical lines represent the crack growth rate of circumferential cracks under three different assumed mechanical loads sufficient to continue crack propagation. Circumferential cracks propagating under mechanical loading, propagate much faster than axial cracks, and can result in shaft failure. The line to the left represents pumps with higher levels of mechanical loading. The amount of time between when the crack departs from the thermal crack progression line until the shaft fails is calculated to be one to two years, for pumps that have high mechanical loading. However, there is no empirical data to confirm that estimate. GE and Flowserve found in their investigations that the amount of shaft mechanical loading being experienced by any particular pump is difficult to quantify. They have been unable to develop a methodology to definitively quantify shaft mechanical loading. The loading is a function of the forces on the shaft, which include shaft torque, radial impeller thrust, pump vibrations, and residual loads from initial pump installation tolerances. Of these forces the radial impeller thrust is considered the largest. A pump that is operating close to its design flow rate will have the minimal radial thrust possible for its design. None of the shaft crack failure analyses, shaft cracking testing, or industry operating experience has identified elevated vibrations as a significant contributor. The exact cause of the high mechanical loading that led to the two shaft cracks at Grand Gulf in 1989 and 1990 has not been determined

Flowserve has reported that historically, all 1st, 2nd & 3rd Generation reactor recirculation pumps that have been inspected have had some degree of thermal cracking. Four circumferential cracks have been identified on reactor recirculation pumps in the BWROG. All of these pumps were 3rd Generation reactor recirculation pumps at Grand Gulf station. Two of the four shaft cracks were detected while the pump was in service. Both were in the same pump one cycle apart. The first shaft failed after a relatively short operating life of 27,000 hours. The shaft was replaced with the same design, and the new shaft failed during its first operating cycle after 11,000 hours of operation. After both failures, the station's other reactor recirculation pump shaft was inspected and both times found to be also cracked. The station now prevents future shaft cracking failures by the use of sacrificial shaft sleeves, which protect the shaft from the thermal stress cracking, and must be periodically replaced.

The upgraded 4th Generation reactor recirculation pump was designed to solve the shaft cracking issue. These pumps were developed by Flowserve and several Japanese utilities as a corrective action to the shaft cracking concern. In addition to other upgrades, the 4th Generation reactor recirculation pumps have a cooler to cool the hot RCS water rising up the shaft, and a heater to warm the cold seal purge water descending down the shaft. A total of 82 of the 4th Generation reactor recirculation pumps have been installed worldwide (13 in the BWROG) over the last ten years with no identified concerns to date. Two 4th Generation reactor recirculation pumps were removed and inspected after two years of service and there were no detectable cracking either visually or through NDE. Neither GE nor Flowserve has issued any recommendations for periodic inspections for 4th Generation reactor recirculation pumps.

4.3 'B' Reactor Recirculation Pump History:

In 1997, the Hope Creek reactor recirculation pumps reached 80,000 hours of operation. The GE SIL 459, which provides recommendations to minimize the consequences of reactor recirculation pump shaft cracking recommends inspecting the pumps after 80,000 hours of operation. Hope Creek station evaluated the condition of the Hope Creek reactor recirculation pumps, and the latest data available in the industry in regards to reactor recirculation pump shaft cracking. It was concluded that pump inspections were not required at that time. The reasons for their decision are documented in reference 30.

During the six outages since then, the station has systematically troubleshot and repaired various component parts associated with 'B' Reactor Recirculation pump toward the goal of reducing the pump's vibration level, and improving its mechanical seal reliability. A summary of all the actions associated with the pump's elevated vibration levels is found in the 'B' Reactor Recirculation pump technical issues review worksheets in Attachment 8.8. The following is a summary of the outage related actions and their results.

RF07 September 1997

Outage Goals:

(a) Upgrade the mechanical seal assembly to an updated design to improve mechanical seal reliability.
(b) Correct an initial installation error, which resulted in the second stage seal leak-off draining to drywell floor drains vice drywell equipment drains.

'B' Reactor Recirculation Pump Outage work:

(1) Replaced mechanical seal with the upgraded Flowserve N7500 mechanical seal due to elevated leakage from the previous mechanical seal.
    DCP# 4EO-3625
    WO# 961118205
(2) Rerouted the second stage leak-off line to permit the leak-off to properly gravity drain into the equipment drains instead of overflowing the mechanical seal vent and draining to the drywell floor drains.
    DCP# 4EC-3458
    WO# 970321117 / 961227088

Results:

(a) The N7500 has been a reliable mechanical seal; however, additional improvements were required in the station's procedure for filling and venting the mechanical seal.
(b) The second stage leak-off lines were improved, but continued to slope incorrectly allowing the second stage seal leak-off draining to drywell floor drains vice drywell equipment drains.

RF08 February 1999

No 'B' Reactor Recirculation pump work.

Cycle 9 March 1999-April 2000

'B' Reactor Recirculation Pump Performance:

(1) Mechanical seal failed due to inadequate venting during RF08. Replaced mechanical seal with rebuilt mechanical seal (ser# 342886) in August 1999.
    WO# 961118205
(2) Replacement mechanical seal (ser# 342886) has slowly degrading second stage seal pressure and elevated leak-off levels. See Attachment 8.2 for Cycle 9 pump and mechanical seal performance graphs.

RF09 April 2000

Outage Goals:

(a) Correct the motor to pump alignment, which is the most common cause of elevated vibrations.
(b) Correct the pump imbalance, which is another common cause of elevated vibrations.

'B' Reactor Recirculation Pump Outage work:

(1) Replaced mechanical seal with rebuild mechanical seal (ser# 324023) due to the elevated leak-off and degraded second stage seal pressure.
WO# 60004748
(2) Corrected motor to pump misalignment. Purchased an alignment tool to permit technicians to rotate the motor uncoupled to facilitate an accurate motor to pump alignment. Removed 30 mils of interference from the motor stand and installed 20 mils of shims under the motor to obtain the proper alignment.
WO# 60004748
(3) Inspected lower motor bearing to verify any possible damage from the pump's several years of operations with elevated vibration levels. The bearing was found to be in like new condition.
WO# 60004748
(4) Inadvertently swapped the X & Y vibration probes during the reinstallation. This is a data trending concern only, and was corrected by annotating the change in the vibration database.
CR# 70043098
(5) Installed a balance weight on the pump coupling to reduce pump imbalance. (1X vibration component)
WO# 60004748

Results:

(a) The motor to pump alignment was greatly improved. This was seen in the pump vibration orbital plots, which indicated no misalignment. Throughout all the remaining troubleshooting and maintenance, no additional motor moves were required.
(b) The balance weights were not successful in lowering the vibration levels. In Cycle 10 vibration levels rose. After two balance weight changes during Cycle 10, engineering concluded that 'B' Reactor Recirculation pump did not have an imbalance, and the balance weight was removed during RF10.

Cycle 10 May 2000-November 2001

'B' Reactor Recirculation Pump Performance:

(1) Pump vibration were elevated over Cycle 9. In April 2001, during a forced outage, the balance weight was moved to a new location; however, vibration levels rose again. See Attachment 8.2 for Cycle 10 pump performance graphs.
WO# 60018593

(2) Mechanical seal (ser# 324023) performed satisfactorily throughout the cycle. See Attachment 8.2 for Cycle 10 mechanical seal performance graphs.

RF10 November 2001

Outage Goals:

(a) The motor to pump alignment was corrected in RF09. The goal in RF10 was to verify the concentricity and proper fit of the pump coupling pieces to ensure that imperfections in the coupling stack-up was not contributing to the elevated vibrations.

'B' Reactor Recirculation Pump Outage work:

(1) Replaced mechanical seal with rebuilt mechanical seal (ser# 342886) as conservative action to ensure maximum reliability during Cycle 11.
WO# 60014335

(2) Inspected lower motor bearing to ensure no bearing wear from operating at elevated vibrations during Cycle 10. The bearing was found it to be in like new condition
WO# 60014335

(3) Corrected internal fit of coupling spacer lower flange rabbet fit. Oversized the ID of the fit by 4 mils. This provided the coupling spacer the movement necessary to improve the coupling stack-up, and reduced the coupling runout from 8 mils to 4 mils. However, the oversized fit will make it difficult for technicians to repeat this improved stack-up.
WO# 60014335

(4) Moved the balance weight and increased its size. Upon initial start of the pump, vibration levels continued to be very elevated. Removed balance weight since it was apparent that the pump's large 1X vibration component was not an imbalance that could be reduced with a balance weight.
WO# 60014335

(5) During the initial pump startup, measured vibration levels at several locations on the pump coupling and associated shafts. Found the vibration levels at the lower spacer flange were significantly higher than any other location. Concluded that the OD of the lower spacer flange was out of round producing a false 1X vibration reading. Relocated the pump vibration probes to the pump hub flange to improve accuracy. See Attachment 8.5 for additional details on the shaft vibration probe move.
DCP# 80036347

Results:

(a) The coupling spool piece lower rabbet fit was found to be non-concentric, and repaired by enlarging the rabbet fit area to permit the spool piece to be moved into proper concentric alignment with the pump hub. This corrected the coupling stack-up concern and reduced the coupling runout from 8 mils to 4 mils. However, the enlarged rabbet fit would make repeatability of the improved stack-up difficult since the technicians would be required to realign the coupling spool piece during every future pump coupling evolution.
(b) It was also determined during this outage that the large 1X vibration component was not due to imbalance, and the balance weight was removed.
(c) The immediate impact of moving the vibration proximity probes could not be determined since the vibration levels were also affected by the removal of the balance weight, and the improvement of the coupling stack-up. Later troubleshooting in RF12, found that the coupling spool piece lower flange OD (old vibration probe location) and the pump hub OD (new vibration probe location) were both round to within 1 mil. Therefore, the movement of the vibration probes had no actual affect on 'B' Reactor Recirculation pump vibration levels.

Cycle 11 November 2001-April 2003

'B' Reactor Recirculation Pump Performance:

(1) Pump vibration levels were significantly lower than during Cycle 10 and steady throughout the cycle. See Attachment 8.2 for Cycle 11 pump performance graphs.
(2) Early in the cycle, the 'B' Reactor Recirculation pump seal purge system relief valve (F025B) began to leak past its seat diverting all the seal purge flow away from 'B Reactor Recirculation pump mechanical seal.
(3) Mechanical seal (ser# 342886) failed due to high leakage and 2nd stage seal pressure oscillations after 17 months of operation. See Attachment 8.2 for Cycle 11 mechanical seal performance graphs.

(4) Planned Outage, March 2003:
- Outage goals:
  (a) Replace the mechanical seal.
  (b) Repair the leaking seal purge relief valve.
- Replaced mechanical seal with rebuilt mechanical seal (ser# 324023) due to excessive leak-off, and second stage seal pressure oscillations.
  WO# 60027904
- Replaced the purge system leaking relief valves, and returned seal purge system to service.
  WO# 60036091
- Results:
  (a) The mechanical seal was replaced, but inadequate venting caused in initial second stage seal pressure oscillation.
  (b) The seal purge system has remained in service continuously during Cycle 12, and the mechanical seal removed during RF12 had no indication of any debris related scoring on the seal faces.

(5) Mechanical seal (ser# 324023) second stage seal pressure began to steadily immediately after the pump was returned to service, and continued to decrease until RF11. See Attachment 8.2 for Cycle 11 mechanical seal performance graphs.

RF11 April-May 2003

No 'B' Reactor Recirculation pump work.

Cycle 12 June 2003-November 2004

'B' Reactor Recirculation Pump Performance:

(1) Pump vibration levels were steady, and slightly elevated over Cycle 11. The overall magnitude of the vibration was steady at 7-8 mils prior to the March 2003 planned outage and steady at 9-10 mils after the planned outage. The vibration spectrum indicated a 1X vibration magnitude of 5 mils and a phase angle of 269°, and the 2X magnitude of 0.84 mils and a phase angle of 284°. After the planned outage the vibration levels were steady at 9-10 mils. The vibration spectrum indicated 1X vibration magnitude of 7.5 mils and a phase angle of 292°, and the 2X magnitude of 0.82 mils and a phase angle of 270°. The variation in the 5X vibration was within the normal data scatter. The change in magnitude and phase angle indicated a change in the pump coupling stack-up. During the planned outage, the pump was uncoupled to replace the mechanical seal. The replacement of the mechanical seal did not affect vibration levels; however, the uncoupling and re-coupling of the pump and motor would. During this process the pump hub is removed and reinstalled. Any variation in the position of the pump hub would translate into a change in vibration levels. In addition, the lower rabbet fit of the coupling spacer was repaired during RF10. The resulting rabbet fit was 4 mils

oversized. This resulting in a relatively "loose" fit of the spacer to the pump hub. In this condition, the pump can be properly coupled, but repeatability to the as-found pump alignment would be very difficult. See Attachment 8.2 for Cycle 11 pump performance graphs to see the March 2003 step increase in vibration level.

(2) A root cause analysis was performed on the low reliability of the 'B' Reactor Recirculation pump mechanical seals. It concluded that the most likely causes of the low reliability of the mechanical seals was due to a possible bow in the pump shaft, and low reliability of the seal purge system.
CR# 70029861

(3) Mechanical seal (ser# 324023) performed satisfactorily during Cycle 12. The second stage seal pressure degraded for the first two months of Cycle 12, but then returned to 500 psig and remained steady for the remainder of the cycle. The RF12 mechanical seal inspection (ser# 324023) found that the dip in second stage seal pressure to be due to damage to the second stage carbon face from inadequate venting. See Attachment 8.2 for Cycle 12 mechanical seal performance graphs.

RF12 November-December 2004

Outage Goals:

(a) Complete the multi-outage evaluation of the pump components parts to repair all possible contributors to the elevated vibration levels. This final step was shaft runout readings to attempt to detect the presence of a bow in the shaft. Upon completion of this troubleshooting, all possible external data will have been collected, and the only remaining actions to lower the 'B' Reactor Recirculation pump vibration levels will be to replace the pump if necessary.
(b) Refurbish the pump coupling to restore the rabbet fit enlarged in RF10.
(c) Inspect the mechanical seal used in Cycle 12 to determine the cause of the initial second stage seal pressure oscillation, and take corrective actions prior to the start of Cycle 13.
(d) Reroute the second stage seal leak-off lines modified in RF07 to again achieve proper drainage from those lines.
(e) Improve vibration monitoring through additional instrumentation.

'B' Reactor Recirculation Pump Outage work:

(1) Replaced mechanical seal (ser# 324023) due to the initial second stage seal pressure oscillation. Install new mechanical seal assembly (ser# RLSA05447).
WO# 60036037

(2) Performed shaft runout troubleshooter to determine the condition of the pump shaft, and determined the following:
- The section of shaft that runs through the pump stuffing box, and interacts with the mechanical seal has consistent runout.
- The shaft contains a bow below the stuffing box, most likely in the thermal mixing region.
- 'B' Reactor Recirculation pump has relatively elevated vibration levels, but they do not adversely affect the performance or short term reliability of 'B' Reactor Recirculation pump.

  WO# 60036037
  CR# 70042434

(3) Inspected the mechanical seal from Cycle 12, (ser# 324023) with the vendor present, and found indications of inadequate venting, but no indications of vibration induced damage.

  CR# 70042730

(4) Reviewed and revised the operating procedure for the Reactor Recirculation system to prevent any future reactor recirculation pump mechanical seal venting concerns.

  CR# 70042730

(5) Rerouted the second stage leak-off line to permit the leak-off to properly gravity drain into the equipment drains instead of overflowing the mechanical seal vent and draining to the drywell floor drains. This is a repeat of DCP 4EC-3458 which rerouted the leak-off lines during RF07.

  DCP# 80064196 / 80062466
  WO# 60040177

(6) Installed five (5) new vibration points on 'B' Reactor Recirculation pump motor.
- Three accelerometers (X, Y & Z directions) at the top of the motor.
- Two accelerometers (X & Y directions) at the bottom of the motor.

  DCP 80062466

(7) Refurbished the pump coupling assembly to reduce its contributions to the overall vibration levels of the pump:
- Performed chrome buildup to restore the coupling spacer lower internal fit, which was oversized in RF10.

  PO# 4500275004
- Weighed the coupling bolts and matched their weights to within 0.5 grams.

  WO# 60036037
- Skim cut and polished the pump hub flange OD (location of vibration probes).

  WO# 60036037
- Corrected balance of coupling assembly.

  WO# 60049960

Results:

(a) The shaft runout measurements determined that the shaft has a bow, but were unable to accurately quantify the size of the bow; however, it was estimated to 5-10 mils.
(b) The coupling spool piece fit well into the pump hub, and no alignment of the coupling pieces was required. The results of the coupling balancing and other actions will not be determined until after the pump is placed in service.
(c) The disassembled mechanical seal inspection detected inadequate venting of the mechanical seal. Actions were added to the RF12 outage scope to revise the operations procedure for filling and venting the mechanical seal to ensure no future inadequate venting concerns.
(d) The results of the rerouted second stage seal leak-off lines will not be known until the pump is placed in service.
(e) Potential for improved vibration monitoring.

4.4 Industry Comparisons:

For the purposes of this evaluation, the industry is defined as the population of United States nuclear power plants belonging to the Boiling Water Reactor Owners Group (BWROG), as listed on Attachment 8.6. This group represents 35 nuclear power plants having a combined total of 77 installed reactor recirculation pumps. Of these plants, eight plants use Sulzer-Bingham reactor recirculation pumps, which are a different design; therefore, their 16 pumps are removed from the population.

Replacement Status:

Of the 61 Byron-Jackson (Flowserve) reactor recirculation pumps installed, 13 have been replaced with 4th Generation reactor recirculation pumps and no longer have a shaft cracking concern. Two additional 4th Generation reactor recirculation pumps are scheduled to be installed in 2005. The Hope Creek 'B' Reactor Recirculation pump is scheduled to be replaced with a 4th Generation reactor recirculation pump in April 2006. At that time 'B' Reactor Recirculation pump will be the 16th of the 61 susceptible Byron-Jackson reactor recirculation pump to permanently resolve the shaft cracking issue.

Industry Reactor Recirculation Pump Age:

The age of each of the 61 Byron-Jackson reactor recirculation pump are graphically displayed on the pump age graph in Attachment 8.7. The Hope Creek reactor recirculation pumps are exactly in the middle of the industry for the age of their reactor recirculation pumps.

Industry Reactor Recirculation Pump Vibration Levels:

The vibration levels for stations that maintain continuous vibration monitoring of their reactor recirculation pumps is graphed in Attachment 8.7. This data was obtained by phone calls placed to the respective station during November 2004. Several stations, in the BWROG only measure reactor recirculation pump shaft vibrations upon initial startup after maintenance; therefore, their pumps are not included on the vibration graph. This graph indicates that 'B' Reactor Recirculation pump vibration levels are high when compared to the mean (7.1 mils), but they are not the highest in the industry and they are well below the vendor specified limit of 25 mils.

4.5 Evaluation of Current Condition of 'B' Recirculation Pump:

Reactor Recirculation Pump Evaluation:

A certain level of vibrations is normal for all rotating equipment depending upon the use and design of the equipment. The 'B' Reactor Recirculation pump vibrations levels are elevated when compared to the same design pumps in similar applications. The pump's vibration spectrum is made up of frequencies peaks at 1X, 2X, and 5X the running speed of the pump.

The 1X frequency is the predominant component. There are several factors that contribute to the 1X vibration component. The shaft runout readings taken during RF12, and the observations from previous disassembled mechanical seal inspections indicate that 'B'. Reactor Recirculation pump has a bow in the shaft. The bow is one contributor to the elevated vibrations levels. The fit of the coupling pieces is another contributor to the 1X component. The pump coupling fits were verified and the coupling spool piece lower flange rabbet fit repaired during RF10. However, the repair oversized the rabbet fit making future pump coupling stack-ups difficult. This was seen after the mechanical seal was replaced in March 2003 when the vibration levels had a step increase due to changes in the coupling stack-up alignment. During RF12, the rabbet fit was restored to its proper dimensions to assist the technicians in future pump alignments and to ensure repeatable vibration levels. Additional inputs to the 1X vibration component are imbalance and misalignment. The motor to pump alignment was corrected in RF09, and pump vibration orbital readings indicate good motor to pump alignment. However, any improvement in the vibration level due to the alignment correction could not be determined, because the vibration weight was also added during RF10, and it resulted in a large increase in the vibration level. Several attempts were made with balance weights during Cycle 10 to correct a possible pump imbalance. Each attempt only elevated pump vibrations confirming that the pump imbalance is not a contributor to the elevated vibration levels. All balance weights were removed during RF10.

The 2X frequency component is small compared to the 1X component, and its magnitude has been steady for several years. A 2X frequency component along with a large 1X component is an indication of a bow in the shaft. The steady magnitude of the 2X over the last seven years is an indication that the bow is not degrading. A 2X frequency component is also an indication of misalignment. 'B' Reactor Recirculation pump does not have any misalignment. Pump misalignment indications would also have a 3X component, which is not present in the pump, and the magnitude of the 2X component would be equal to or larger than the 1X component, which is not the case.

The 5X frequency component is vane passing vibration, and is a result of the pump's five vane impeller. This component is not a indication of the condition of the pump.

The development of the shaft bow was independent of the mechanisms that initiate reactor recirculation pump shaft cracking. Shaft bows can develop when residual stresses, left in the shaft from initial fabrication and welding, are relieved either through normal pump vibration or uneven operating temperature gradients on the shaft. The presence of the bow does not increase the probability of the initiation of a shaft crack, which is caused by the thermal mixing of water in the annulus area below the pump stuffing box.

The mechanical loadings of concern for shaft crack growth are cyclic. The bow motion giving rise to 1X vibration puts a load on the shaft in one direction, and that load rotates with the shaft providing a constant not a cyclic load on the shaft. This is of no concern for crack growth because it is not cyclic. The bow may increase other, non-1X vibrations slightly, but these are not likely to increase the fluctuating mechanical loading significantly. There is currently no method to definitively determine the amount of mechanical loading necessary to propagate a thermal crack beyond the point where it would arrest considering only the thermal stresses. Therefore, it can not be definitively determined how close or far 'B' Reactor Recirculation pump is from having any of its thermal cracks transition into mechanical loading propagated circumferential cracks. This is the same situation for any non-4th Generation reactor recirculation pump. However, the Hope Creek Reactor Recirculation pumps operate in a band of 44,000 - 45,000 gpm with a best efficiency point of 39,000 gpm. This represents a 15% deviation from the best efficiency point and indicates a nominal loading increase on the Hope Creek reactor recirculation pumps. Note that other, later BWRs using constant-speed pumps and throttle flow control are likely subjecting their pumps to significantly higher radial loads. The fact that they have had successful operation provides some additional confidence that mechanical growth of the thermal cracking is unlikely to be a problem at Hope Creek.

There is also no proven predictive maintenance techniques to detect a crack in an installed shaft. Ultrasonic (UT) testing has been performed with mixed results at several stations. There are several factors contributing to lack of acceptable results from UT testing. First, neither Hope Creek or any other station with their original reactor recirculation pumps have baseline UT testing data to use as a reference. Second, the 1st Generation reactor recirculation pumps were not designed with UT holes in the shaft to permit accurate UT testing. Only top of the shaft down UT testing is possible, and this method of UT testing can only detect circumferential cracks. Top of the shaft down UT testing can only detect the shaft directly under the detector. The top of the Hope Creek reactor recirculation pumps is four inches in diameter. The section of the shaft that is susceptible to shaft cracking is 7.9 inches in diameter. In order for a crack to be detected by UT testing it would have to propagate to a depth of two inches.

Therefore, shaft cracking is a risk accepted by all stations that have not yet installed 4th Generation reactor recirculation pumps. It is for this reason GE SIL 459 recommended vibration monitoring and an inspection of reactor recirculation pumps after 80,000 hours of operations or approximately 10 years. The 80,000 hour inspection interval was developed in 1987 less than 18 months after the first report of reactor recirculation pump shaft cracking. The number was developed based on the initial theories of the cause of the shaft cracking and projections based on the very limited empirical data available at the time. The extensive testing and calculations performed by Flowserve were performed after SIL 459 was issued. The final conclusions on the thermal cracking projections and mechanical loads required to transition the crack into a circumferential crack were different than the initial theories and projections. Attachment 8.4 contains a graph, which graphically displays the crack depth as a function of the time in service from the pump and the mechanical loads on the shaft. Although the mechanical loads of a particular pump can not be determined, the graph displays that, regardless of the mechanical loads on the shaft, the time between the cracks departure from the expected thermal crack propagation line to the ultimate shaft failure is a period of 1-2 years, for pump with high mechanical loading. A station performing an 80,000 hour pump inspection would observe the expected shaft thermal cracks. However, unless the inspection happens to be performed during the brief interval between the cracks departure from the thermal crack propagation line and the shaft's failure, the station will be unable to detect the difference between a thermal crack with 10 years left from a thermal crack with 10 days left. As a reactor recirculation pump shaft cracking detection technique, the 80,000 hour inspection window has only a 10-20% chance of being useful. The data collected as part of the Industry Comparison section of this evaluation found no report of any BWROG station performing a reactor recirculation pump inspection since 1984, which was three years prior to the issuance of SIL 459.

Because the cost of removing a reactor recirculation pump is very high, there are no stations in the BWROG that inspect their reactor recirculation pumps on an 80,000 hour interval. Only one station periodically inspects their reactor recirculation pumps. That station has 3rd Generation reactor recirculation pumps with sacrificial shaft sleeves to protect their shafts from shaft cracking. Their periodic inspections is to replace the shaft sleeves, not to perform the 80,000 hour SIL 459 inspection. Since 1994, the industry practice has been to replace reactor recirculation pumps with the new 4th Generation reactor recirculation pumps whenever pump degradation or life cycle management concerns dedicated a need to replace a reactor recirculation pump.

The risk of a reactor recirculation pump shaft cracking failure in any given operating cycle cannot be determined with certainty. The initiating mechanism for shaft cracks is known, and cannot be avoided with the 1st Generation reactor recirculation pumps installed in Hope Creek station. Industry experience indicates that there are almost certainly thermal stress cracks on both reactor recirculation pump shafts. Experience to-date in the industry suggests that the thermal cracks are likely self-arresting and not detrimental to the operation or reliability of the reactor recirculation pump absent additional mechanical loading. The important factors in the transition of the benign thermal stress cracks to mechanically-driven cracks are time in service and mechanical loading. There is no methodology in the industry to determine the mechanical loading on a particular reactor recirculation pump, and no methodology to quantify the amount of mechanical loading required to transition a thermal stress crack into a mechanical loading propagated circumferential crack with sufficient accuracy to be a useful predictive tool. Therefore, the only methodology to assess the risk of a reactor recirculation pump shaft cracking failure is by evaluating a reactor recirculation pump's time in service against industry operating experience for the same amount of time in service.

To date there have been no shaft cracking failures in any 1st Generation reactor recirculation pumps. The Hope Creek reactor recirculation pumps have not yet reached the average age of the 13 reactor recirculation pumps in the BWROG that have been replaced. Hope Creek's reactor recirculation pumps are in the middle of the industry for time in service, and less than half of the time in service for the oldest ten pumps. The vibration levels of 'B' Reactor Recirculation pump are high compared to the other BWROG pumps; however, vibration level is not a major contributor to the mechanical loading that causes the benign thermal stress cracks from becoming circumferential cracks. Therefore, the risk of operating 'B' Reactor Recirculation pump for another cycle is equivalent to or less than the risk of any other BWR, which is operating without 4th Generation reactor recirculation pumps.

Reactor Recirculation Pump Mechanical Seal Evaluation:

The 'B' Reactor Recirculation pump mechanical seal has been replaced five times in the last six years. Of those five mechanical seal assemblies, none failed due to high vibration.

(a) Two of the mechanical seals displayed signs of inadequate venting: One, was replaced midway through Cycle 9, and the other operated satisfactorily throughout Cycle 12.
(b) One of the mechanical seals was replaced midway through Cycle 11 due to excessive leakage caused by particulate contamination from extended operations without the seal purge system. This mechanical seal was in service during Cycle 11, which was the cycle with the lowest pump vibration levels.
(c) One of the mechanical seals displayed elevated leakage, and lowering second stage seal pressure. These are indications of second stage seal leakage; however, no disassembled seal inspection results are available to determine the cause of the leakage.

(d) The fifth mechanical seal was in service during Cycle 10, which was the cycle with the highest vibration levels, and that mechanical seal performed satisfactorily throughout the cycle. The disassembled seal inspection identified no abnormal wear of the mechanical seal components.

The only mechanical seal assembly degradation related to either vibration or the shaft bow was fretting observed on the interior of the mechanical seal shaft sleeve. This fretting has been noted on both of mechanical seal assemblies which have been installed into 'B' Reactor Recirculation pump. (Ser#'s 342886 and 324023) Neither the fretting nor the relative motion between the shaft and sleeve that caused the fretting are detrimental to the mechanical seal. Measurements of the ID of the shaft sleeve found it to be within specification. However, continued fretting could cause looseness between the shaft and sleeve, which would be detrimental to the reliability of the mechanical seal.

With the exception of the step increase after the March 2003 outage, when the pump was uncoupled and re-coupled, the vibration levels have been steady for the last three years. Steady vibration levels indicate that the pump is not degrading. Rising vibration levels indicate degradation of the pump such as bearing wear, looseness in the pump coupling, a degrading shaft bow, or a growing shaft crack. Vibration trending is used to monitor for indications of this degradation; however, the actual vibration levels are not a concern until they cause collateral damage to other pump components. The first component likely to be adversely affected by rising vibrations is the mechanical seal. This is where the stationary and rotating components of the pump come into direct contact. Elevated vibration leads to excessive wear on the carbon seal face and eventual leakage. The pump vendor specifies a pump vibration limit of 25 mils. If the pump vibrations reach this level the pump should be removed from service to prevent damage to the mechanical seal. During Cycle 12, 'B' Reactor Recirculation pump vibration levels were steady at 8-10 mils with spikes up to 11 mils. This is well within the vendor's specifications. Any increase in pump vibration level will decrease the life expectancy of the mechanical seal. The vibration levels on 'B' Reactor Recirculation pump could reduce the life expectancy of the mechanical seal, but not in the short term. The results of the most recent disassembled mechanical seal inspections confirm the pump's vibrations levels do not damage the mechanical seal over an 18 month period.

4.6 Accident Safety Analysis:

The analysis of the reactor recirculation pump shaft cracking issue indicates that cracks are initiated due to thermal stresses on the shaft. The thermal cracks can be axial or circumferential, but are self-arresting and are not, by themselves detrimental to the operation or the reliability of the reactor recirculation pump. The thermal cracks grow slowly unless and until they reach a depth that pump mechanical loading causes the crack to propagate mechanically. This mechanical loading propagated circumferential crack could lead to shaft failure. The amount of time after the crack departs from the thermal crack propagation line until the shaft fails is not known. Estimates of this time period vary from one to two years. During most of this period the cracks are indistinguishable from self-arrested thermal cracks. At some point the crack becomes large enough to cause a change in the pump's vibration signature. This is believed to happen in days to weeks prior to shaft failure, but there is little empirical data to confirm this estimate. The phase angle of the vibrations is expected to change, and the 2X running speed vibration magnitude is expected to rise. The Hope Creek vibration program periodically monitors the reactor recirculation pump phase angles to catch this phase shift before it becomes a challenge to the operating crew.

Eventually, the crack size grows to the point where shaft failure will occur. As the crack grows to this point vibration should increase significantly. The Hope Creek control room operators receive indication of this event by a visual and audible alarm set at 11 mils for radial vibration and 7 mils for axial vibration. The operators procedural guidance in the event of an alarm (HC.OP-AR.ZZ-0008(Q)) provides guidance to lower pump speed to reduce vibration levels. If this is not successful the procedure sets danger limits of 21 mils for radial and 11 mils for axial vibrations to remove the pump from service. The basis for these set points are provided in Reference 34. In each of the reactor recirculation pump shaft cracking events, which have occurred to members of the BWROG, the vibration levels rose above the station's alarm setpoint, and held for several days while the station analyzed the situation and performed a controlled plant shutdown. This industry operating experience shows that the final phase of shaft crack propagation provides a definitive indication to the operators and sufficient time to perform a controlled plant shutdown.

A shaft cracking failure of a Hope Creek reactor recirculation pump is not expected. However, in the unlikely event of a failure, the consequences of that accident have been analyzed in the Hope Creek UFSAR accident analysis section 15.3.4:

1) The breaking of the shaft of a reactor recirculation pump is considered a design basis accident (DBA). It has been evaluated as a very mild accident in relation to other DBAs, such as a loss-of-coolant accident (LOCA). The analysis was been conducted with consideration to a single or double loop operation. The postulated event is bounded by the more limiting case of a reactor recirculation pump seizure.

2) A postulated instantaneous break of the pump motor shaft of one reactor recirculation pump will cause the core flow to decrease rapidly, resulting in water level swell in the reactor vessel. When the vessel water level reaches the high water level setpoint, L8, main turbine trip and feedwater pump trip will be initiated. Subsequently, reactor scram and the remaining recirculation pump trip (RPT) will be initiated due to the turbine trip. Eventually, the vessel water level will be controlled by high pressure coolant injection (HPCI) and reactor core isolation cooling (RCIC) flow.

3) The severity of this pump shaft break is bounded by the pump shaft seizure event, which is evaluated separately. In either of the two events, the recirculation drive flow of the affected loop decreases rapidly. In the case of the pump shaft seizure event, the loop flow decreases faster than the normal flow coast down, as a result of the large hydraulic

resistance introduced by the stopped rotor. For the pump shaft break event, the hydraulic resistance caused by the broken pump shaft is less than that of the stopped rotor for the pump shaft seizure event. Therefore, the core flow decrease following a pump shaft break effect is slower than the pump shaft seizure event. Thus, it can be concluded that the potential effects of the hypothetical pump shaft break event are bounded by the effects of the pump shaft seizure event.

4) In the event of a shaft shear, a mechanical seal failure is expected. A breakdown orifice is provided in the pump casing to reduce leakage in the event of a gross failure of both shaft seals. The GE pump purchase specification requires the pump design limit leakage thorough this breakdown orifice to 50 gpm, which is bounded by our loss of coolant accident analysis.

5.0 CONCLUSION / RECOMMENDATION

1) The 'B' Reactor Recirculation pump has elevated vibrations when compared to the industry average for reactor recirculation pumps. These vibration levels are not detrimental to the operation or reliability of the pump.

Over the last four refueling outages, troubleshooting activities on 'B' Reactor Pump have confirmed or refuted each of the possible inputs to pump shaft vibration. The final conclusion for the source of the elevated vibrations is a bow in the pump shaft, and inconsistencies in the pump coupling stack-up. The pump's vibration levels during the last cycle, 8-10 mils with spikes up to 11 mils, is well below the vendors vibration limit of 25 mils. Any shaft vibrations reduces the life expectancy of the pump's mechanical seal; however, this level of reduction would not adversely affect an 18 month operating cycle. The disassembled seal inspections performed on the mechanical seals used in 'B' Reactor Recirculation over the last three cycles found that the mechanical seals experienced no vibration related damage during their 18 months of operation.

2) 'B' Reactor Recirculation pump has minimal risk of a shaft cracking event during Cycle 13.

The risk of a reactor recirculation pump shaft cracking event during any given cycle can not be quantified. Actions can be taken to reduce the thermal and mechanical stress on the shaft such as reducing seal purge flow rate and operating the pump close to its design flow point. Both of these actions are controlled by operating procedures, but the two controlling parameters for a shaft cracking event are pump mechanical loading and pump time in service. The mechanical loading on 'B' Reactor Recirculation pump or any other reactor recirculation pump is not known. The mechanical loading that will cause a thermal crack to depart from the thermal crack propagation line is not known. Therefore, this parameter can not be use to access the risk of operating 'B' Reactor Recirculation pump for another cycle. The pump time in service is the only parameter that can be used to access the risk. There are currently 29 reactor recirculation pumps in the BWROG, which have been in service longer than 'B' Reactor Recirculation. On third of these pumps have twice as much in service time as 'B' Reactor Recirculation pump. This industry operating experience provides sufficient data to conclude that the risk of a shaft cracking event during Cycle 13 is minimal.

5.1 Independent Assessment :

A team of six engineers from Sargent & Lundy performed an independent assessment on the Hope Creek Reactor Recirculation system and pump vibration issues. Reference 31 is a copy of the entire assessment team report. The assessment team derived the following conclusions on 'B' Reactor Recirculation pump:

1) The operations of 'B' Reactor Recirculation pump does not appear to be impaired by its vibration levels.
2) The vibration data does not indicate signs of a degrading condition for either reactor recirculation pump. The shaft displacement is consistent with an unbalanced or a bent shaft.
3) It is likely that the 'B' Reactor Recirculation pump can operate in its present configuration until RF13, which is expected to occur after 18 months of operation.

6.0 REFERENCES:

Technical Documents

1) An Advanced Design Main Coolant Pump for BWR Plants, S. Gopalakrishnan, BW/IP International Pump Division, March 1996
2) Analytical Investigation of Thermal Cracking in Reactor Recirculating Pumps, S. Gopalakrishnan, BW/IP International Pump Division, October 1992
3) Crack Propatation in Main Coolant Pumps, S. Gopalakrishnan, BW/IP International Pump Division
4) Evaluation of Main Coolant Pump Shaft Cracking, EPRI, 1992

Vendor Manuals

5) VTD PN1-B31-C001-0124 Reactor Recirculation Pump Vendor Manual
6) VTD PN1-B31-C001-0119 Reactor Recirculation Pump Motor Vendor Manual
7) VTD 322556 N7500 Mechanical Seal Instruction Manual

General Electric Service Information Letters

8) GE RICSIL 003 Dated 05/21/86
9) GE SIL 459 Dated 12/15/87
10) GE SIL 459S1 Dated 03/23/90
11) GE SIL 459S2 Dated 10/21/91
12) GE SIL 459S3 Dated 08/31/93
13) GE SIL 203 Dated 10/29/76
14) GE SIL 203S1 Dated 03/80
15) GE SIL 511 Dated 04/30/90
16) GE RICSIL 028 Dated 09/07/88
17) GE RICSIL 029 Dated 09/13/88
18) GE RICSIL 043 Dated 06/16/89

Operating Experience

19) OE 3351 Grand Gulf 1 Shaft Failure Dated 05/11/89
20) OE 3365 Grand Gulf 1 Shaft Failure Dated 05/23/89
21) OE 3557 Grand Gulf 1 Shaft Failure Dated 09/20/89

Miscellaneous References

22) P&ID M-13-1 Reactor Auxiliaries Cooling System, Revision 32
23) P&ID M-43-1 Reactor Recirculation System, Revision 27
24) Operations Procedure HC.OP-AR.ZZ-0008(Q), Revision 25
25) Operations Procedure HC.OP-SO.BB-0002(Q), Revision 50
26) Hope Creek UFSAR Section 15.3.3 Reactor Recirculation Pump Seizure
27) Hope Creek UFSAR Section 15.3.4 Reactor Recirculation Pump Shaft Break

28) Flowserve TechNote No. 9309-08-022
29) 'B' Reactor Recirculation pump vibration history
30) Mark Bezilla letter dated 06/12/97, ser# GMHC-97-021
31) Independent Assessment of Reactor Recirculation System and Pump Vibration Issues, By Sargent & Lundy, Dated 11/12/04
32) SL1 Root Cause Report 70029861
33) Mechanical Seal Reports
34) Engineering Calculation SC-BB-0522

Personal Interviews

- AK Singh PHD Sargent & Lundy
- Dave Cagley General Electric
- Willard Roit General Electric
- Dave Zagres Flowserve
- Randy Decker Flowserve

7.0 EFFECTS ON OTHER TECHNICAL DOCUMENTS:

None

8.0 ATTACHMENTS:

Attached

9.0 SIGNATURES:

Preparer Peter Koppel 12/16/04 [signature]

Peer Reviewer George Seibold 12/16/04 Per telecom [initials]

Verifier Tom Greene 12/16/04 Per telecom [initials]

Preparer's Supervisor Steve Robitzski 12/16/04 [signature]

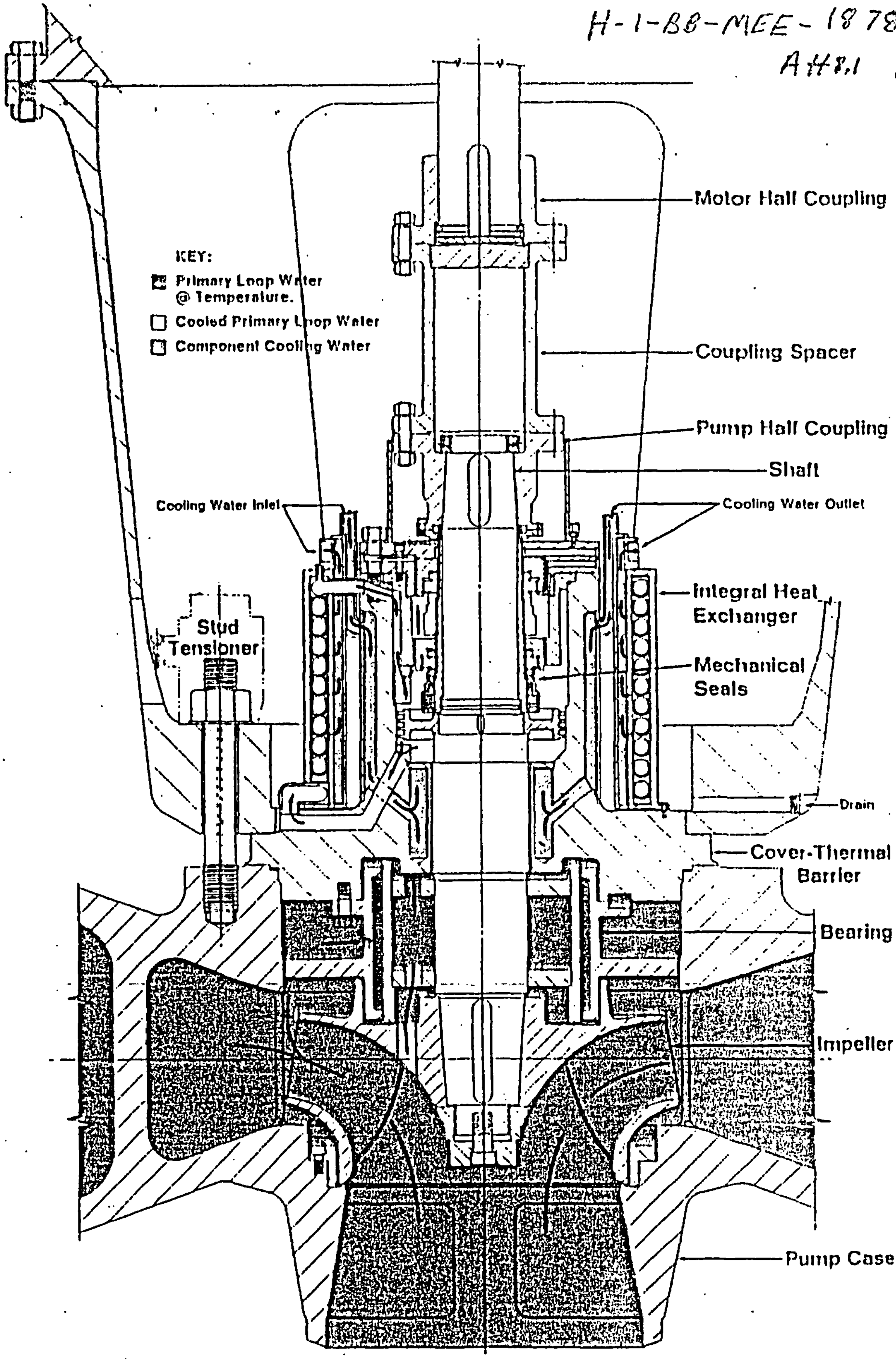
Programmatic Manager Steve Robitzski 12/16/04 [signature]

EE No.: H-1-BB-MEE-1878 Rev. No. 1 Date: 12/16/04

ATTACHMENT 8.1

Pump Drawing

Byron-Jackson (now Flowserve) Type DVSS, size 28x28x35, vertical, single stage pump



REACTOR RECIRCULATION PUMP

BW/IP International, Inc.
Pump Division

8020 2 12/89
PRINTED IN U.S.A.

ATTACHMENT 8.2

Pump / Mechanical Seal Parameter Trending Graphs

The attached graphs represent the history of the following 'B' Reactor Recirculation pump / mechanical seal parameters over the last four fuel cycles. (Cycle 9-12)

First Stage Seal Pressure

Detector: H1BB –1BBPT-N006B-B31 Computer Point: HC.A2591

Second Stage Seal Pressure

Detector: H1BB –1BBPT-N005B-B31 Computer Point: HC.A2592

Radial Shaft Vibrations

Detector: H1BB –1BBVT-7910B1 Computer Point: HC.A2603

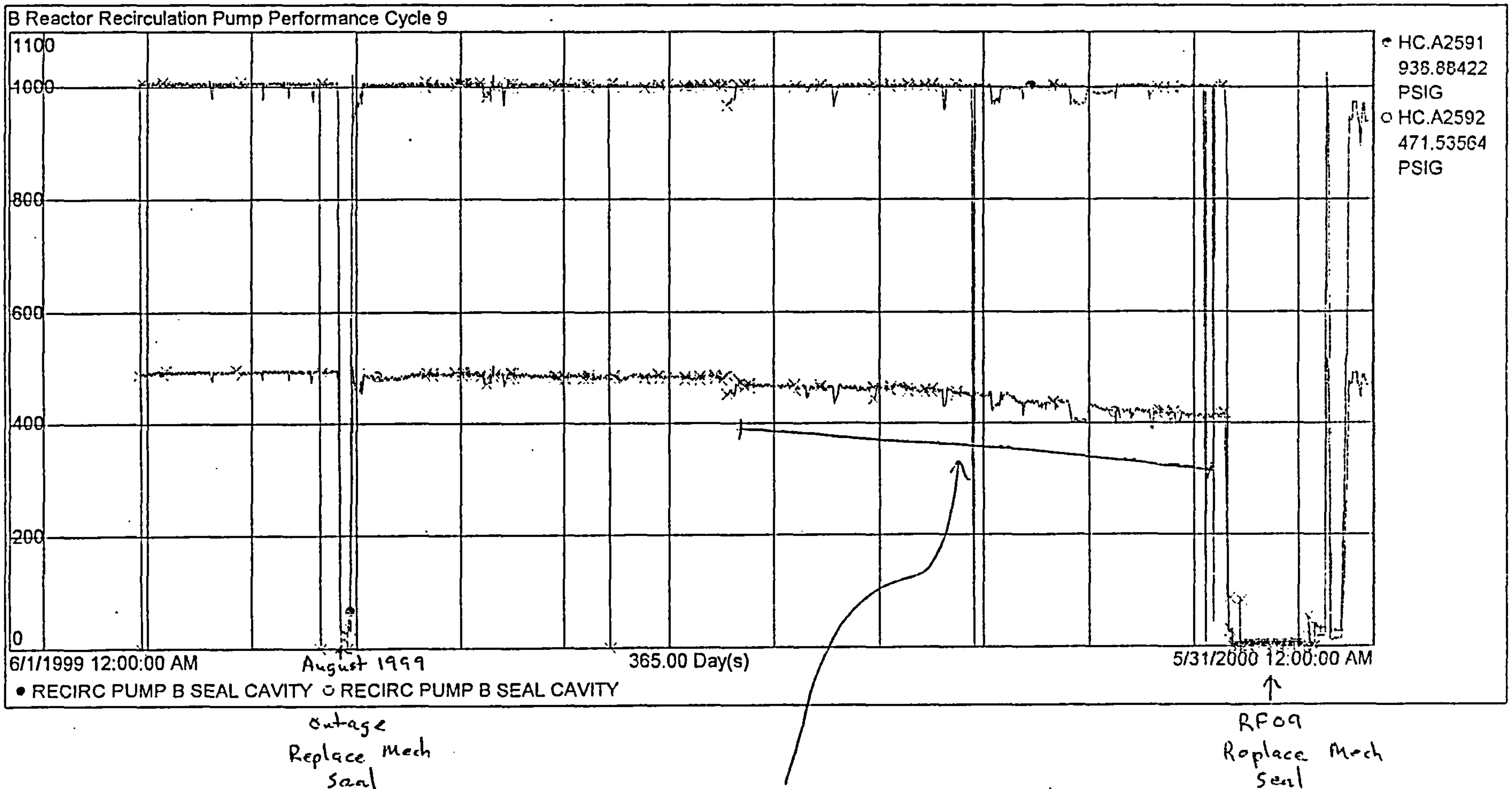
Drywell Floor Drain Leakage

Detector Computer Point: HC.A9314

Cycle 9

H-1-BB-MEE-1878-1
Att 8.2 pg 2

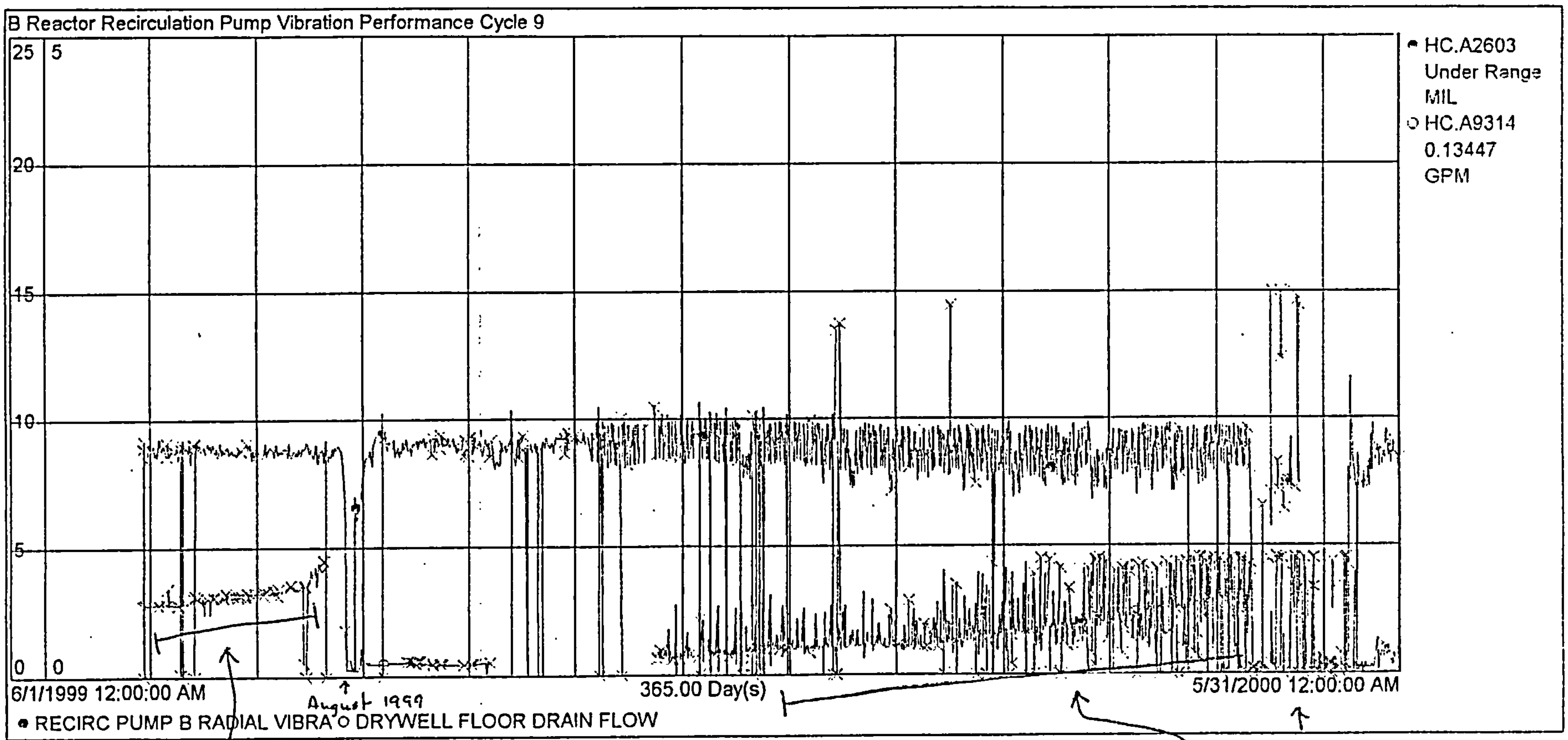
First and Second Stage Mechanical Seal Pressures



Cycle 9

H-1-BB-MEE-1878-1
ATT 8.2 Pg 3

Reactor Recirculation Pump Radial Vibrations and Drywell Floor Drain Leakage



Outage Replace Mech Seal

Vibrations Steady (8-10mils) for entire Cycle

RF09 Replace Mech Seal

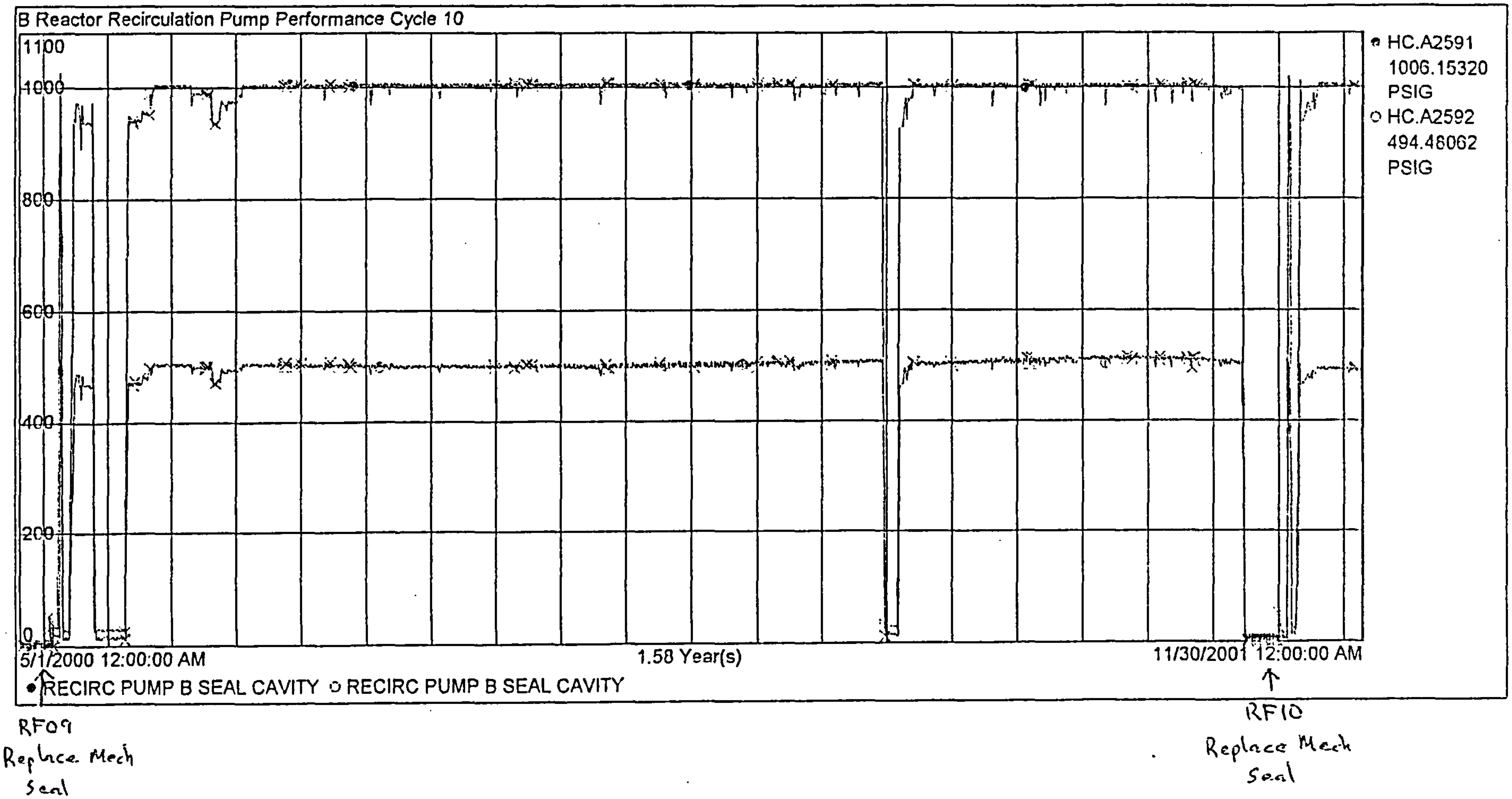
Elevated leakage due to inadequate seal venting

Second Seal Stage Seal leakage

Cycle 10

H-1-BB-MEE-1878-1
Att 8.2 pg 4

First and Second stage Mechanical Seal Pressures

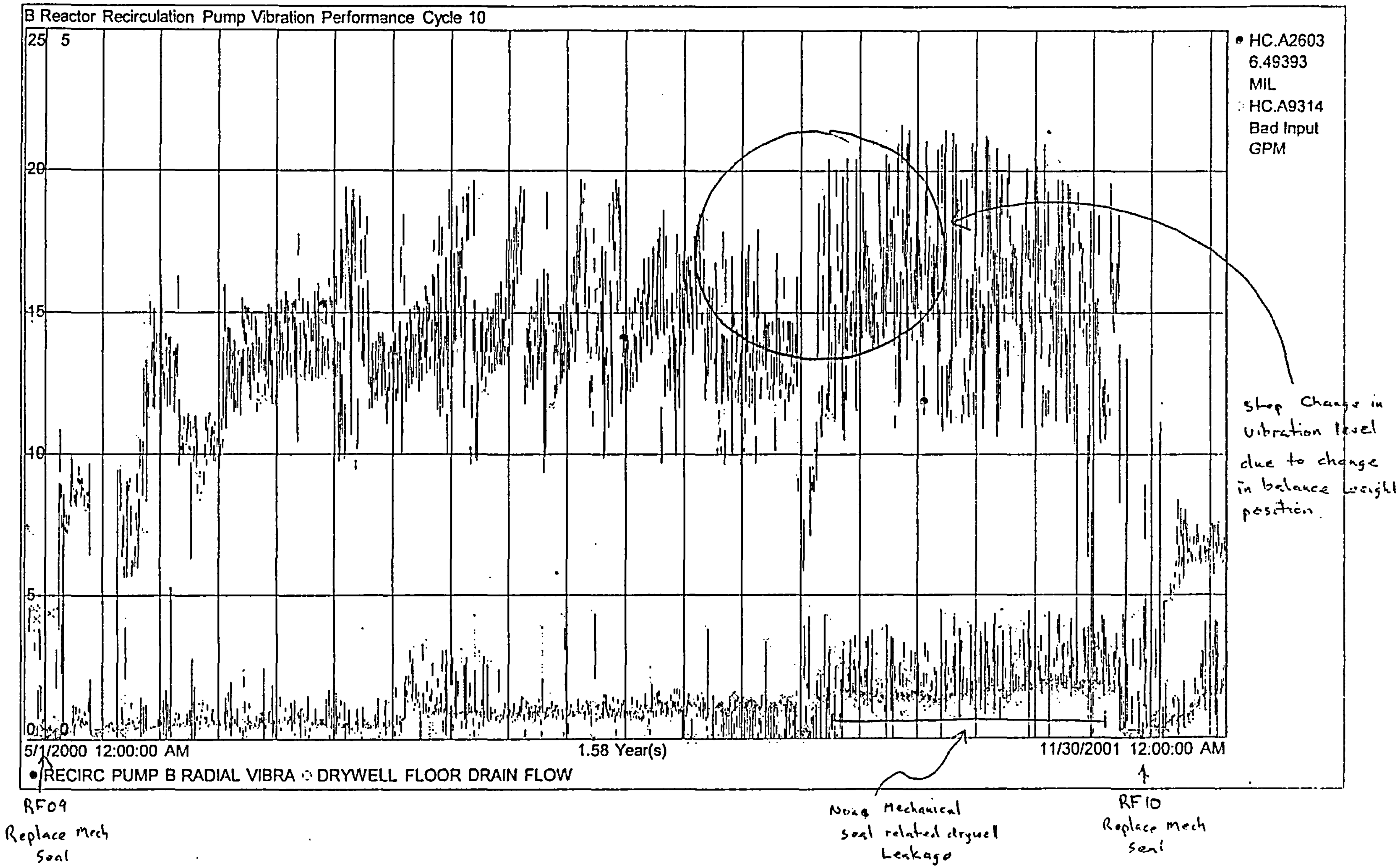


Satisfactory first and second stage mechanical seal pressures over entire cycle.

Cycle 10

H-1-BB-MEE-1878-1
A# 8.2 pg 5

Reactor Recirculation Pump Radial Vibrations and Drywell Floor Drain Leakage

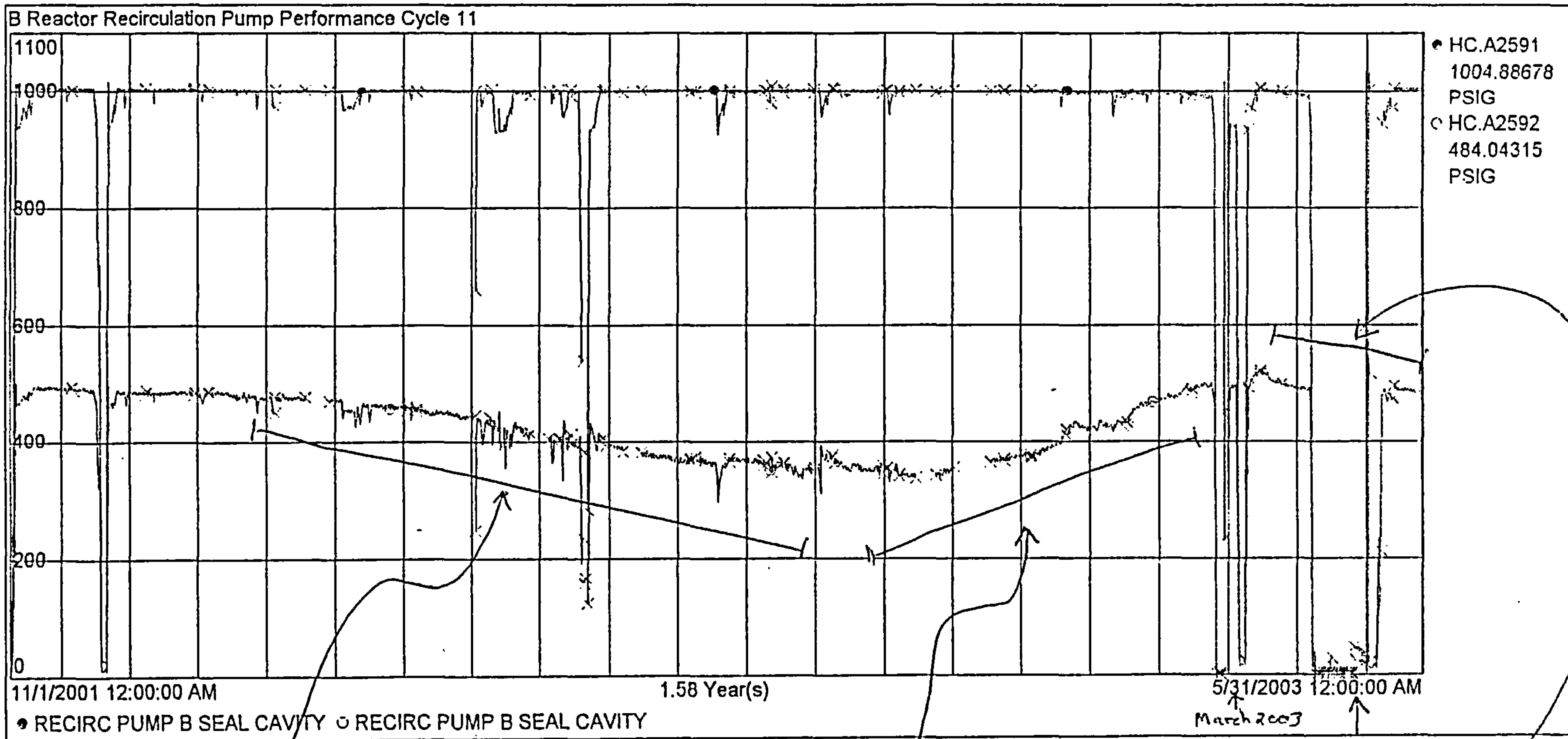


Elevated Vibrations throughout the Cycle due to the balance weight installed during RF09 and moved in April 2001.

Cycle 11

H-1-BB-MEE-1878-1
Att 8.2 Pg 6

First and Second Stage Mechanical Seal Pressures



Outage
Replace Mech Seal

RF11
No Pump work

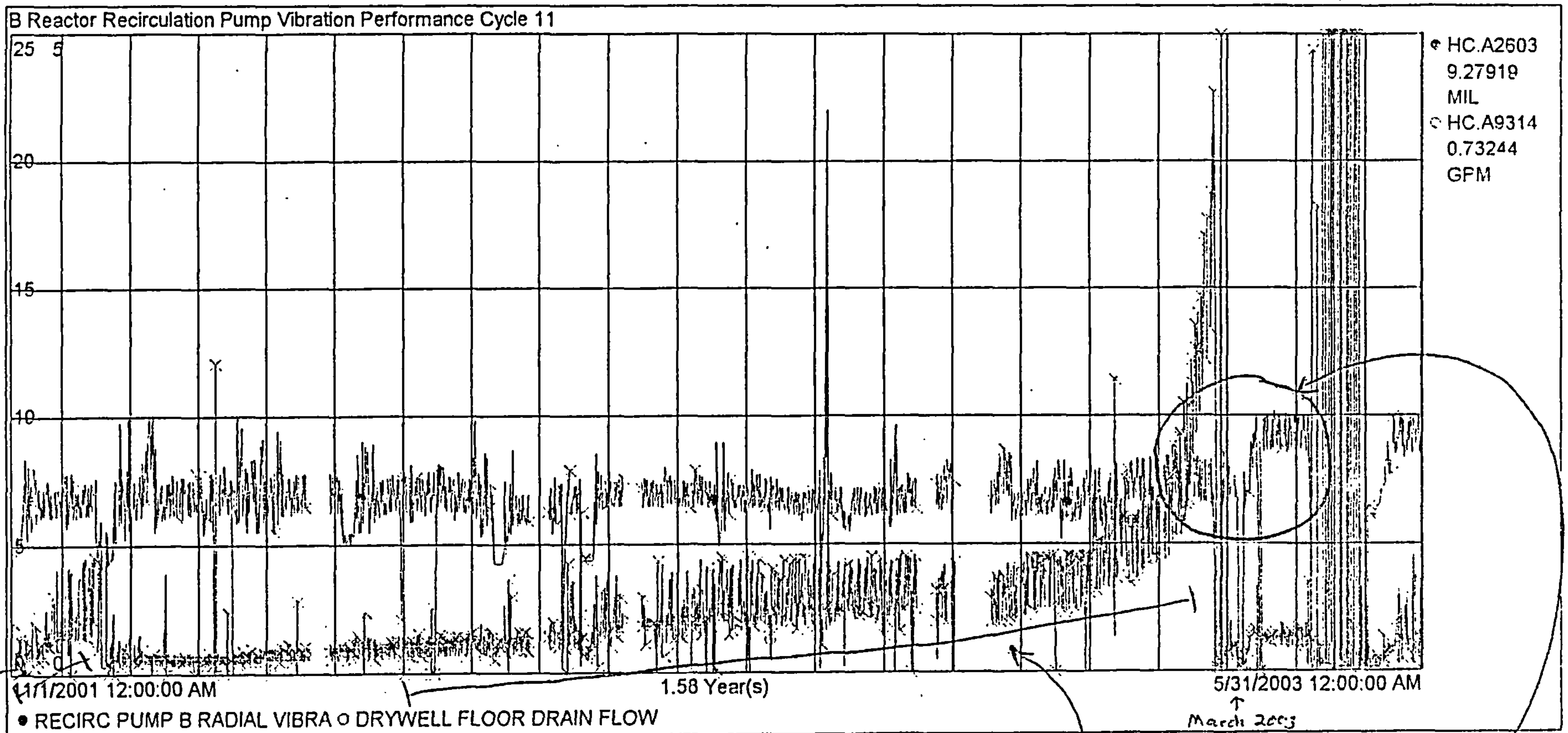
Second stage Seal leaking due to scoring on seal faces

First Stage Seal leaking due to scoring on Seal faces. The first stage leakage is greater than the second stage leakage

Second Stage Seal leaking due to inadequate venting

Cycle 11

Reactor Recirculation Pump Radial Vibrations and Drywell Floor Drain Leakage



March 2003 outage Replace Mech Seal

RF11 No Pump work

Vibrations steady (6-8mils) until March 2003 Mech Seal Replacement

Vibrations steady (8-10mils) After March 2003 Mech Seal Replacement

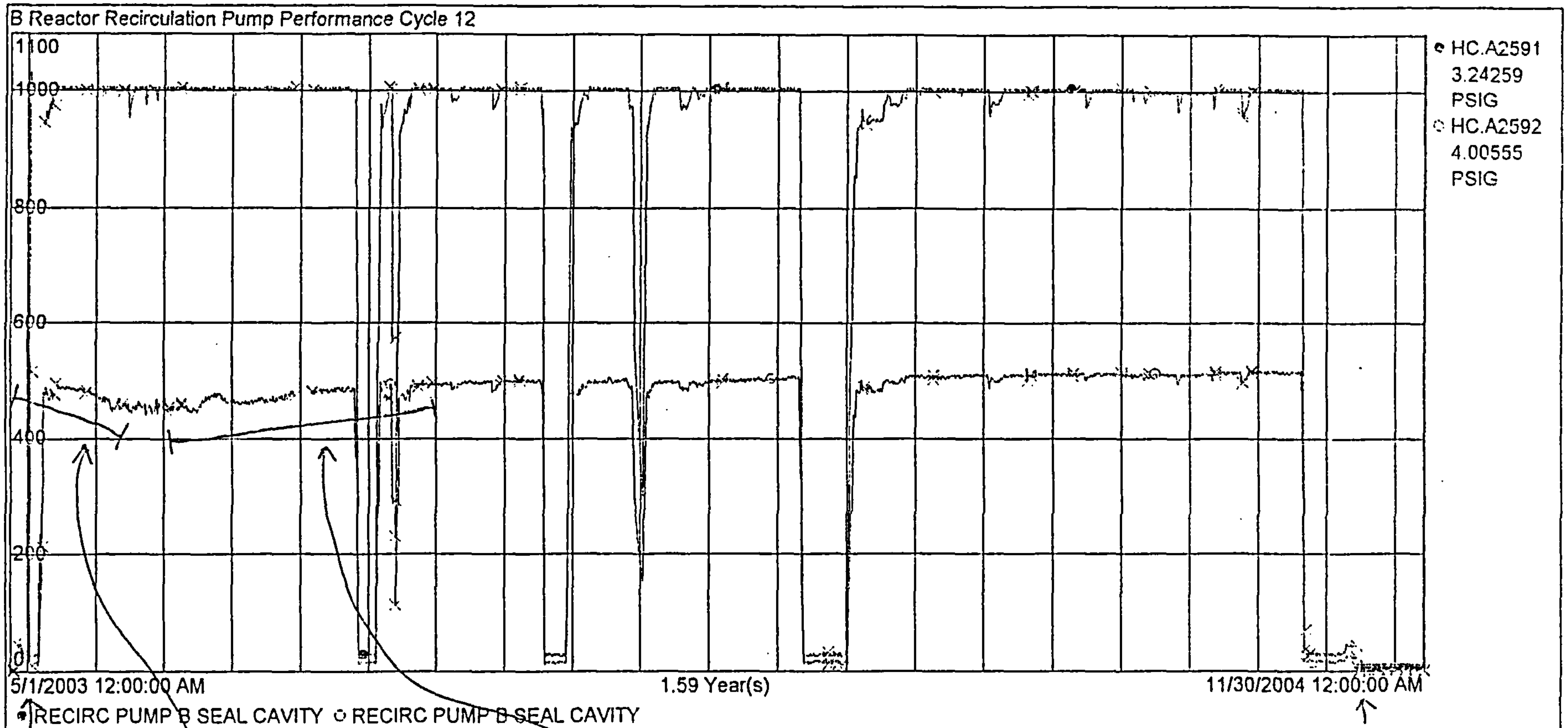
None mechanical seal related drywell leakage

Elevated leakage due to mechanical seal leakage from scoring on the seal faces.

Step change in vibration level due to change in coupling stack-up.

Cycle 12

First and Second Stage Mechanical Seal Pressures



RF11
No Pump work

RF12

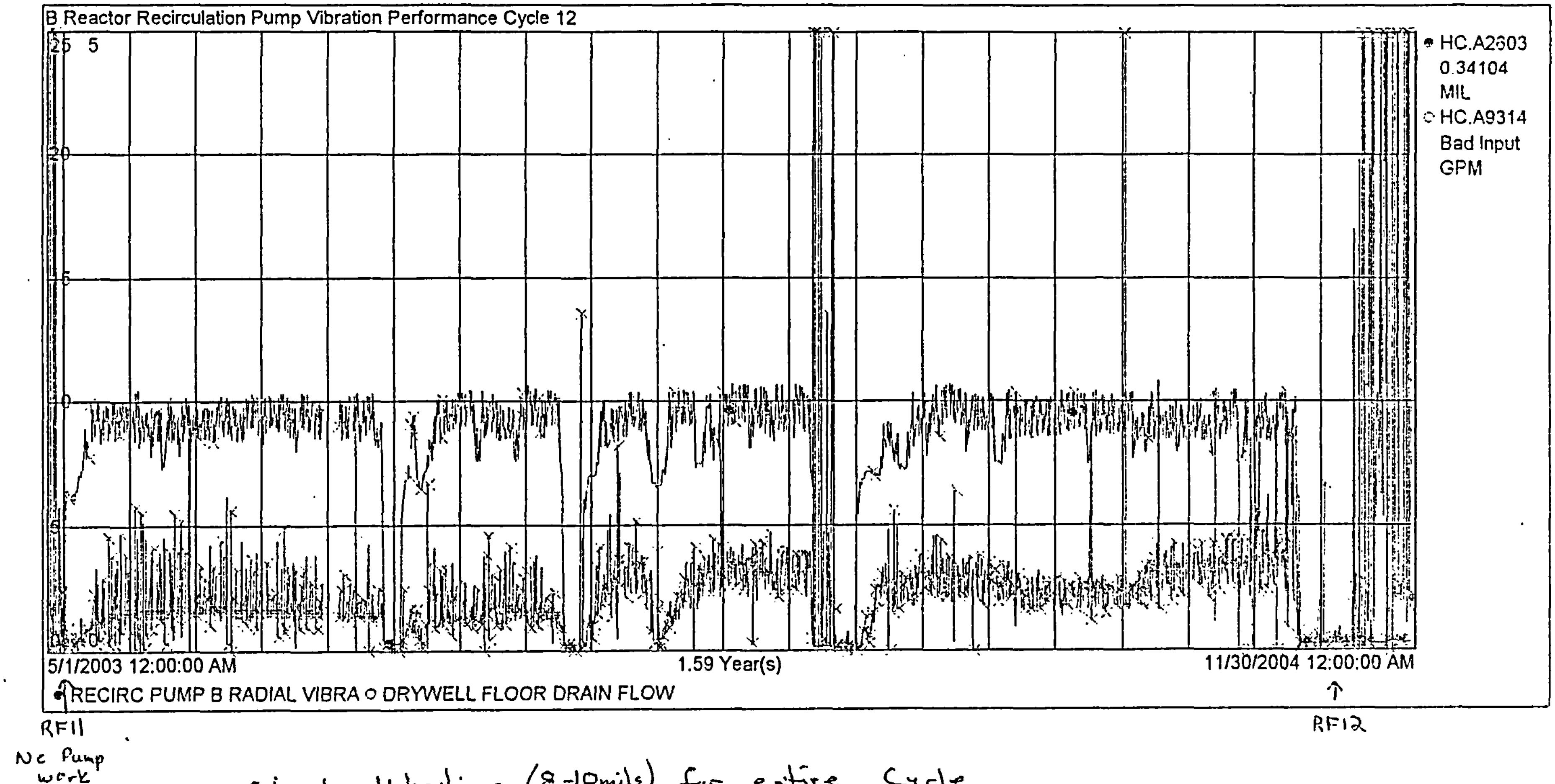
Second stage Seal leakage due to carbon seal face damage caused by inadequate venting.

Second Stage Seal leakage improved due to laping of carbon face by the Silicon Carbide hard face.

Cycle 12

H-1-BB-MEE-1878-1
Att 8.2 Pg 9

Reactor Recirculation Pump Radial Vibrations and Drywell Floor Drain Leakage

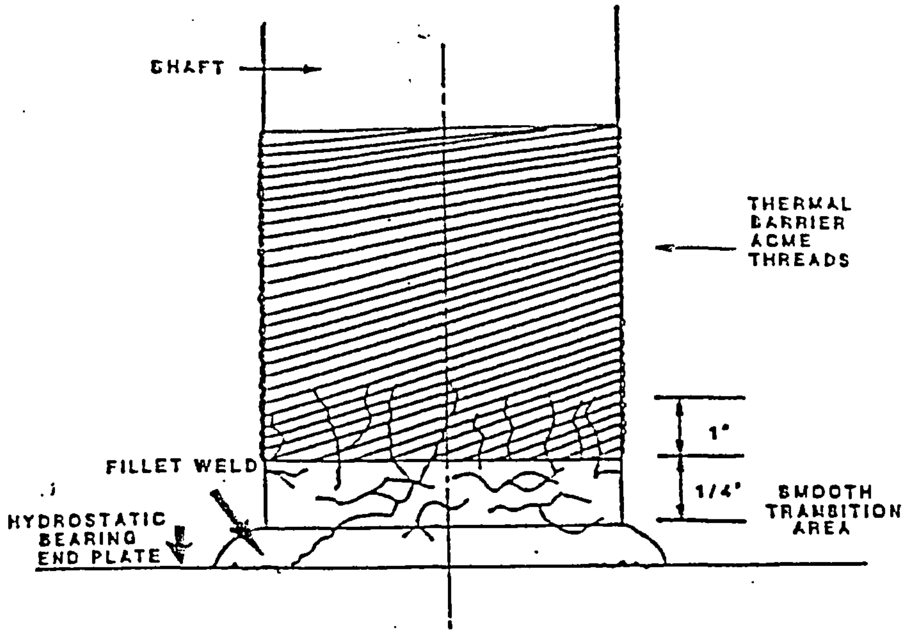


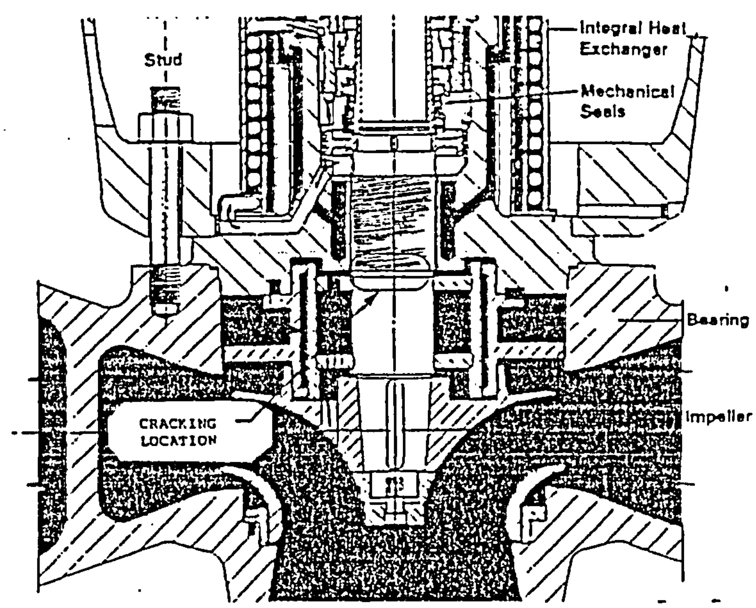
Steady Vibrations (8-10mils) for entire Cycle

No Seal leakage great enough to affect drywell floor drain leakage levels

ATTACHMENT 8.3

Location of Reactor Recirculation Pump Shaft Cracks

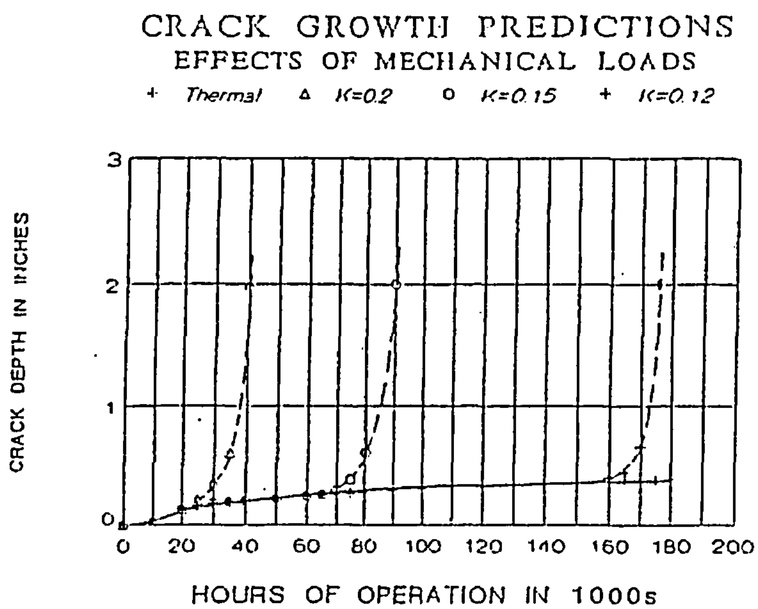




References:
1) Crack Propatation in Main Coolant Pumps, S. Gopalakrishnan, BW/IP International Pump Division
2) Evaluation of Main Coolant Pump Shaft Cracking, EPRI, 1992

ATTACHMENT 8.4

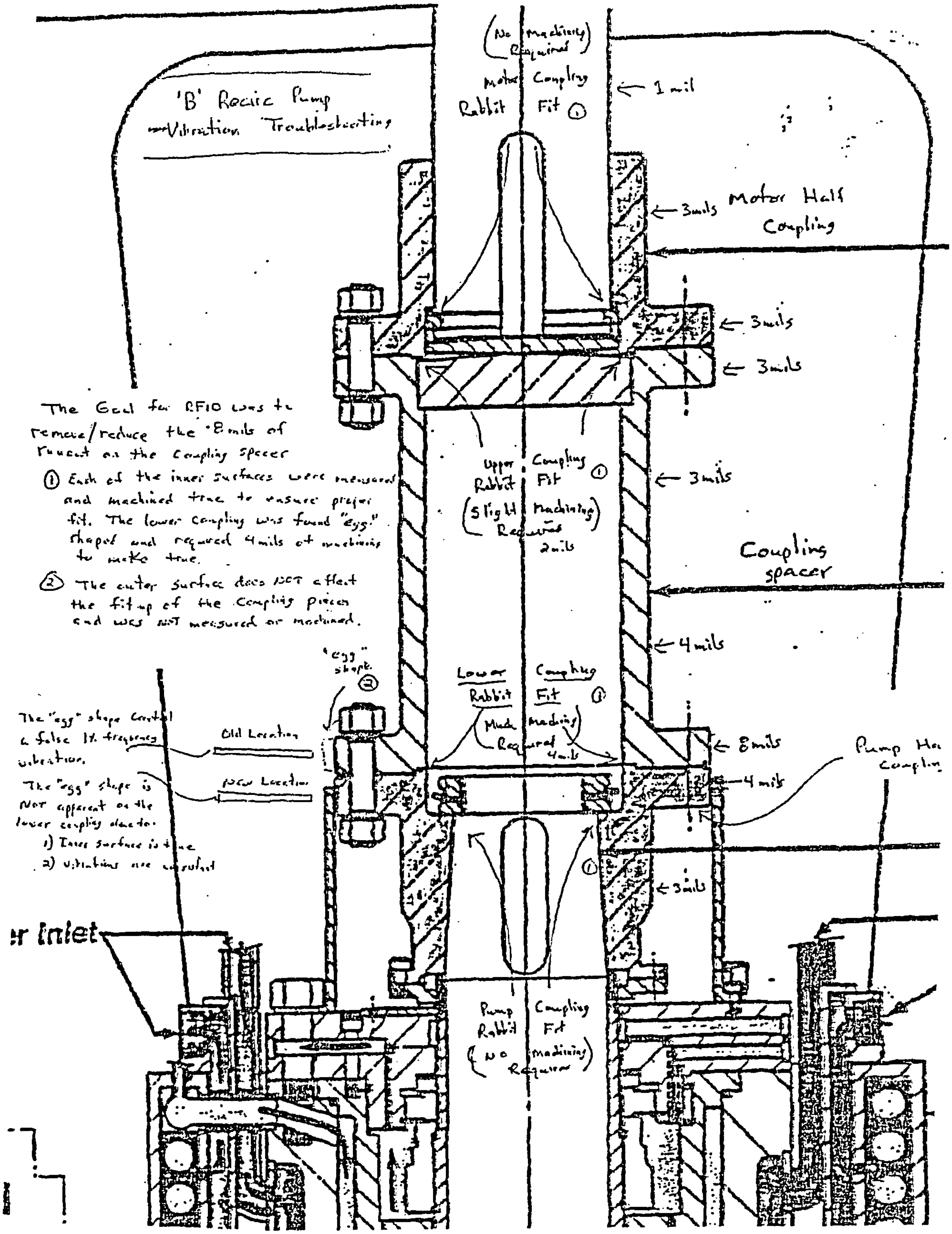
Shaft Crack Growth Prediction Graphs



Reference: 1) Crack Propatation in Main Coolant Pumps, S. Gopalakrishnan, BW/IP International Pump Division pg 1

ATTACHMENT 8.5

RF10 'B' Reactor Recirculation Pump Coupling Maintenance / Troubleshooting Summary



ATTACHMENT 8.6

Boiling Water Reactor Owners Group (BWROG) Members

Station	# pumps	Manufacturer
1) Browns Ferry 1&2&3	6 pumps	Byron-Jackson
2) Brunswick 1&2	4 pumps	Sulzer-Bingham
3) Clinton	2 pumps	Sulzer-Bingham
4) Columbia Power Station	2 pumps	Sulzer-Bingham
5) Cooper	2 pumps	Byron-Jackson
6) Dresden 2&3	4 pumps	Byron-Jackson
7) Duane Arnold	2 pumps	Byron-Jackson
8) Fermi 2	2 pumps	Byron-Jackson
9) Grand Gulf	3 pumps	Byron-Jackson
10) Hatch 1& 2	4 pumps	Byron-Jackson
11) Hope Creek	2 pumps	Byron-Jackson
12) John Fitzpatrick	2 pumps	Byron-Jackson
13) LaSalle 1&2	4 pumps	Sulzer-Bingham
14) Limerick 1&2	4 pumps	Byron-Jackson
15) Milestone 1	2 pumps	Byron-Jackson
16) Monticello	2 pumps	Sulzer-Bingham
17) Nine Mile Point 2	5 pumps	Byron-Jackson
18) Oyster Creek	5 pumps	Byron-Jackson
19) Peach Bottom 2&3	4 pumps	Byron-Jackson
20) Perry	2 pumps	Byron-Jackson
21) Pilgrim	2 pumps	Byron-Jackson
22) Quad Cities 1&2	4 pumps	Byron-Jackson
23) River Bend	2 pumps	Sulzer-Bingham
24) Susquehanna 1&2	4 pumps	Byron-Jackson
25) Vermont Yankee	2 pumps	Byron-Jackson

ATTACHMENT 8.7

Industry Comparison Graphs

Industry Reactor Recirculation Pump Age -

This graph represents each of the 61 Byron-Jackson Reactor Recirculation pumps in the BWROG, and their time in service. The following color code applies:

1st Generation Pumps	Yellow
2nd Generation Pumps	Green
3rd Generation Pumps	Red
4th Generation Pumps	Blue

Industry Reactor Recirculation Pump Current Shaft Vibration -

This graph represents the current vibration level for each of the reactor recirculation pump in the BWROG that have continuous vibration indication.

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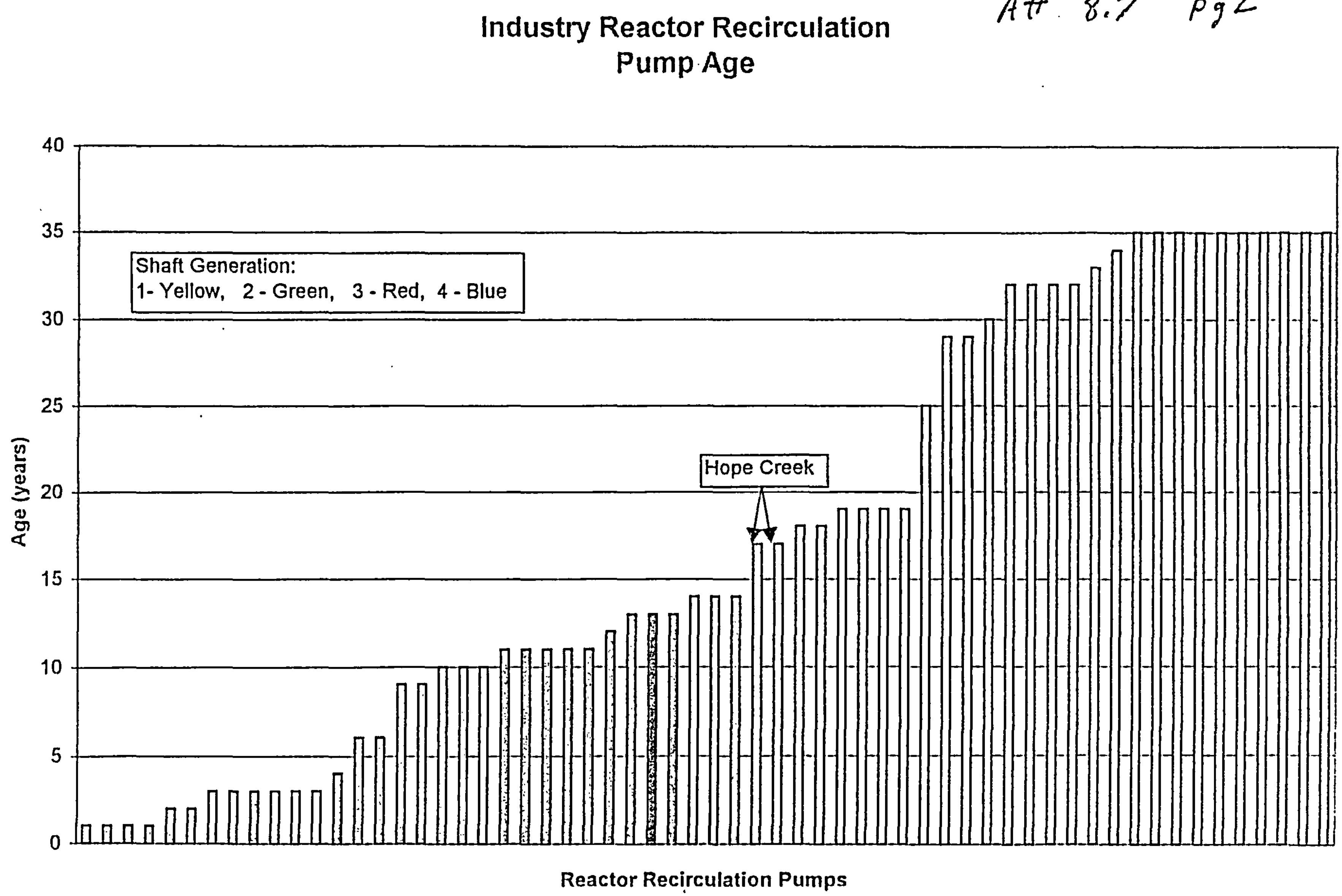

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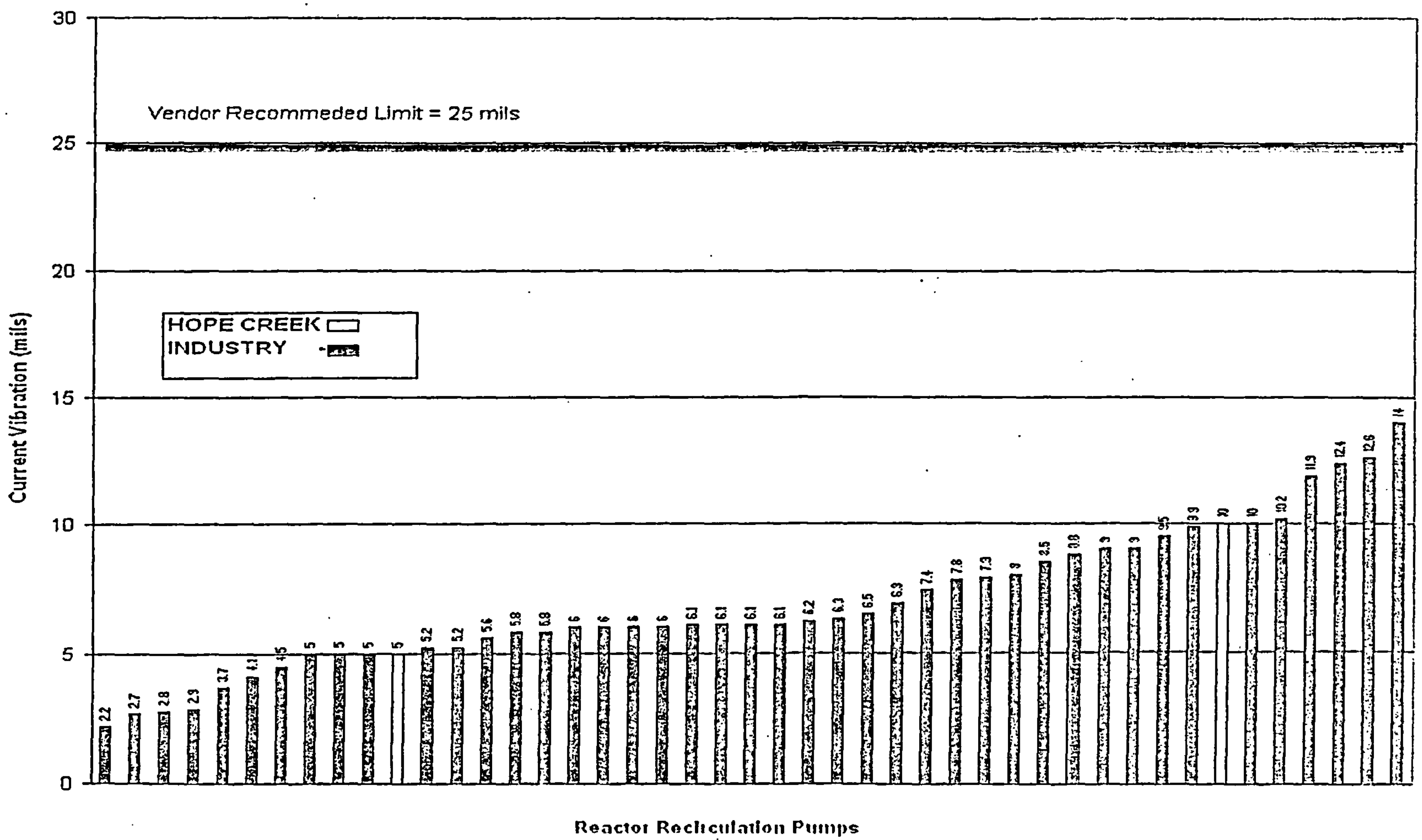
Industry Reactor Recirculation Pump



Note: For Information Only

ATTACHMENT 8.8

'B' Reactor Recirculation Pump Technical Issues Review

Note: Engineering Technical Issue review documentation is stored on a station computer shared drive in the following location:

M: Shared / Technical Issues / 3. Hope Creek Tech Issues / B Rx Recirc Pump vibs 11-04

The technical issues review process is a continual process. As new information becomes available, the technical issues review documentation is updated. The attached technical issue review worksheets are as of 12/10/04.

FORM 1 - TECHNICAL ISSUE FACT SHEET

Title of Issue: 'B' Reactor Recirculation Pump Vibrations Order #: 70042434

Responsible Engineer: Peter Koppel x2835 Last revised: 11/15/04

Problem Statement:

'B' Reactor Recirculation Pump has historically had higher vibration levels than 'A' Reactor Recirculation pump, and higher than the industry average.

Goals:

1) Determine cause of the elevated vibration levels.
2) Determine short term and long term corrective actions to address the elevated vibration levels.

Design Information and References:

1) PN1-B31-C001-0124 Pump Vendor Manual
2) PN1-B31-C001-0119 Motor Vendor Manual
3) 322556 Mechanical Seal Vendor Manual
4) PN1-B31-C001 Pump & Motor Drawing
5) SL1 70029861
6) McGraw-Hill Pump Handbook (page 2.425)

Licensing Basis Information and References:

Facts/Assumptions and Sources/Reference Documents:

Operating Experience/History and Sources:

A search was performed of all six of the INPO OE databases for various variations of "Reactor Recirculation Pumps/Vibrations/Shafts." OE documents were only found on the general search under Reactor Recirculation Pumps. A total of 300 OE documents were found. A review of approximately 50% of the Reactor Recirculation Pump OE documents found none associated with reactor recirculation pump vibrations. There were numerous documents regarding plant transients caused by faulty reactor recirculation pump controls; and several documents regarding reactor recirculation pump trips due to loss of power; however, the majority of the OE documents described plant trips for reasons other than the reactor recirculation pumps, which resulted in reactor recirculation pump trips. There was no additional information in the INPO OE database to assist in the 'B' Reactor Recirculation pump high vibration investigation.

Cause(s):

1) "Bow" in thermal mixing region of 'B' Rx Recirc pump shaft.

FORM 1 - TECHNICAL ISSUE FACT SHEET

2) Indication inaccuracy due to non-concentricity in the OD of the flange where the vibration indications were being collected. (Corrected RF10)
3) Inaccurate installation of balance weights. (Corrected RF10)
4) Motor to Pump misalignment. (Corrected RF09)

Solution Strategy:

1) RF12 - Perform all possible repairs, short of pump replacement, to lower 'B' Rx Recirc. pump vibration levels.
2) RF13 - Replace 'B' Rx Recirc. pump.
   Install improved filters on Rx Recirc purge system.

Action Plan:

ITEM	DESCRIPTION	PERSON RESPONSIBLE	STATUS	DUE DATE
1.	RF12 Refurbish/Replace 'B' Rx Recirc pump coupling			
2.	RF12 Install upgraded wavey face mechanical seal			
	Issue DCP			
	Obtain wavey face seal rebuild kit			
	Rebuild 'B' Rx Recirc pump mechanical seal			
3.	RF13 Replace 'B' Rx Recric pump			
	Perform pre-RF13 containtment walkdowns			
	Obtain PHPC/RAC/PRB approval			
	Contingency to replace coupling if pump replacement is not approved.			
	Replace 'B" Rx Recirc pump			
4.	RF13 Install improved Rx Recirc purge system filtration			
	Obtain PHPC/RAC/PRB approval		Complete	
	Prepare DCP			
	Install purge system filter			
5.				

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FORM 4 - CAUSE EVALUATION SHEET

Issue Description: 'B' Reactor Recirculation Pump Vibrations — Order #: 70042434

POSSIBLE CAUSE	Existing data that supports this as the cause. / Existing data that tends to disprove this as the cause.	Data required to prove or disprove this cause.	Cause / Contributor Y / N Explain if Yes	Explains All Symptoms? Y / N / NA Explain if No.
1) MISALIGNMENT OF MOTOR / PUMP	**Supports:** RF09: 60004748 - As-Found Alignment readings Face Reading 4 mils Rim Reading 15 mils RF11: 70029861 - The Root Cause evaluation noted scratches on the interior of the stuffing box, and on the outer edge of the auxiliary impeller. **Disproves:** RF09: 60004748 - Purchased alignment tool to lift motor off thrust bearing and improve alignment capabilities. - Ground 0.030 inches from one side of motor stand to facilitate aligning motor over pump. - Installed 0.020 inches of shims under motor base to correct coupling face readings. - Resulting vibration orbital readings were greatly improved, with almost no 2x vibration frequency readings. RF12: 60036037 - As-Found Alignment readings Rim Reading 2 mils	None	No	Yes

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FORM 4 - CAUSE EVALUATION SHEET

Issue Description: 'B' Reactor Recirculation Pump Vibrations   Order #: 70042434

POSSIBLE CAUSE	Existing data that supports this as the cause. / Existing data that tends to disprove this as the cause.	Data required to prove or disprove this cause.	Cause / Contributor Y / N Explain if Yes	Explains All Symptoms? Y / N / NA Explain if No.
2) MISALIGNMENT OF COUPLING TRAIN	**Supports:** RF10: 60014335 - Coupling spacer repairs changed the coupling spacer from its OEM supplied condition. - The machining of the coupling created a maintenance workaround making future alignments more difficult. **Disproves:** RF10: 60014335 - Measured ID of upper and lower rabbit fits. Found the lower fit to be 0.004 inches out of round. RF12: 60036037 - As found coupling stack-up readings.....	None	No	Yes

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FORM 4 - CAUSE EVALUATION SHEET

Issue Description: 'B' Reactor Recirculation Pump Vibrations

Order #: 70042434

POSSIBLE CAUSE	Existing data that supports this as the cause. / Existing data that tends to disprove this as the cause.	Data required to prove or disprove this cause.	Cause / Contributor Y / N Explain if Yes	Explains All Symptoms? Y / N / NA Explain if No.
3) BOWED OR BENT PUMP SHAFT	RF11: 70029861 - SL1 Root Cause on the Cycle 11 mechanical seal failure concluded two causes, one of which was a bow in the pump shaft. RF12: 60036037 - Performed pump shaft runout measurements in the pump stuffing box, and made the following conclusions: 1) The section of shaft in the stuffing box has constant and concentric 5 mils runout, which is not detrimental to the shaft. 2) The shaft has a bow, most likely in the Thermal Mixing Region, and it is 5-10 mils. 3) The bow causes increased pump vibration, but the vibration level (10-12 mil) is not detrimental to the mechanical seal. (25 mils limit)	Remove pump shaft and measure the shaft runout.	Yes	No, This cause does not explain the 11 mils of vibration reduction after RF10, and does not explain the poor mechanical seal reliability
	- Vibration spectrum does not indicate a large 2x frequency, which would be an indication of bow in shaft.			
4) MOTOR THRUST BEARING CLEARANCE		None	No	Yes
	RF12: 60036037 - Thrust bearing radial thrust measurements indicate 0.010 inches of bearing clearance. - Specification is 0.007 – 0.010 inches			

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FORM 4 - CAUSE EVALUATION SHEET

Issue Description: 'B' Reactor Recirculation Pump Vibrations — Order #: 70042434

POSSIBLE CAUSE	Existing data that supports this as the cause. / Existing data that tends to disprove this as the cause.	Data required to prove or disprove this cause.	Cause / Contributor Y / N Explain if Yes	Explains All Symptoms? Y / N / NA Explain if No.
5) MOTOR RADIAL BEARING CLEARANCE	*(supports)*: — *(disproves)*: RF09: 60004748 - Removed and inspected the lower radial bearing and found it to be in like new condition. RF12: 60036037 - Lower motor shaft thrust measurements indicate 0.88888 of bearing clearance. - Specification is 0.010 - 0.013 inches	None	No	Yes
6) ALIGNMENT / THERMAL DISTROTION CAUSED BY PUMP AND MOTOR SUPPORTS	*(supports)*: RF12: - Visual inspection of 'A' and 'B' strut pin-to-pin offset shows differences. A has pin-to-pin offset of 3/8 inch and B has pin-to-pin offset of 1 ¾ inch. - Specification is 3 inches +/- 2 inches, B pump strut is within cold setting specification. *(disproves)*: 'A' Rx Recirc pump does not have high vibration	Civil Engineering analysis		

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FORM 4 - CAUSE EVALUATION SHEET

Issue Description: 'B' Reactor Recirculation Pump Vibrations

Order #: 70042434

POSSIBLE CAUSE	Existing data that supports this as the cause. / Existing data that tends to disprove this as the cause.	Data required to prove or disprove this cause.	Cause / Contributor Y / N Explain if Yes	Explains All Symptoms? Y / N / NA Explain if No.
7) INACCURATE INDICATION	RF09: 60004748 - Removed and inspected the lower radial bearing and found it to be in like new condition. Vibration levels of 12 mils would cause accelerated wear of the lower motor radial bearing. - Pump vibration levels were 21-23 mils during Cycle 10. RF10: 60014335 - Measured 8 mils of vibration with a hand held probe on the lower coupling spacer hub. All other areas of the coupling and shafts were ≤ 4 mils. - Moved the shaft vibration probes from the lower spacer hub to the pump hub, which resulted in vibration levels of 10 mils. - The vibration levels remained steady for all of Cycle 11. RF11: 6000 - After the mechanical seal was replaced, the vibration level rose to 12 mils and remained steady for all of Cycle 12.	Properly install vibration probe after the RF12 mechanical seal replacement.	Yes	No, Approximately 4 mils of the 21 mils of elevated vibrations was corrected by moving the vibration probe.

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FORM 4 - CAUSE EVALUATION SHEET

Issue Description: 'B' Reactor Recirculation Pump Vibrations

Order #: 70042434

POSSIBLE CAUSE	Existing data that supports this as the cause.	Existing data that tends to disprove this as the cause.	Data required to prove or disprove this cause.	Cause / Contributor Y / N Explain if Yes	Explains All Symptoms? Y / N / NA Explain if No.
8) MOTOR AND PUMP TIPPING		RF12: 60036037 - Measured the stuffing box with a machinist level and			
9) OIL WHRIL		The vibration frequency spectrum has almost no < 1X frequencies, which is the primary indication of Oil Whril	None	No	Yes
10) COCKED COUPLING					
11) ROTATING ASSEMBLY IMBALANCE	The predominate vibration frequency is 1X, which is a possible of imbalance.	Cycle 10: 60004748/60014335/60018593/ - Three different balance weights of various masses were installed at different times and different locations. Each balance weight installation increased the 1X frequency component.	None	No	Yes
12) MECHANICAL SEAL RUB	Cycle 12: 70029861 - Root Cause analysis reported circumferential scratches 360° around the interior of the stuffing box in the area of the auxiliary impeller.		None	No	Yes

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FORM 4 - CAUSE EVALUATION SHEET

Issue Description: 'B' Reactor Recirculation Pump Vibrations

Order #: 70042434

POSSIBLE CAUSE	Existing data that supports this as the cause. / Existing data that tends to disprove this as the cause.	Data required to prove or disprove this cause.	Cause / Contributor Y / N Explain if Yes	Explains All Symptoms? Y / N / NA Explain if No.
	- There is almost no <1X frequency component, which is an indication of a rub. RF09/RF10/RF11/RF12 - Each of the mechanical seals removed was inspected and none of the inspections noted any indications of a rub from the pump shaft. RF12: 60036037 - Shaft runout readings taken with the pump shaft coupled found a consistent and concentric 5 mils of shaft runout in the stuffing box area. This is insufficient for the shaft to encounter any mechanical seal components. RF12: 60036037 - *Observations inside* the *stuffing* box found that the circumferential scratches on the interior of the stuffing box did not extend 360° around the interior of the stuffing box. In addition, the scratches appeared worn over, with an oxide layer on them, and no fresh metal visible.			