BRUCE NGS A UNIT 4 PREHEATER DIVIDER PLATE FAILURE

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INTRODUCTION

On May 19, 1995, without any prior operational indications, Bruce A discovered preheater divider plate damage in Unit 4 that had the potential to have a major impact on the continued safe operation of the station. Further investigations indicated that Unit 4 may have been operating with this damage for as long as ten years.

In the two months following this discovery, Bruce A:

- procured and replaced the 4 divider plates
- located most of the missing pieces
- retrieved pieces from the PHT system
- investigated historical operational information
- performed detailed analytical investigations
- investigated root cause
- performed in-situ and mock-up testing
- updated operational procedures
- installed DP monitoring equipment

This work culminated in a letter to the AECB, dated July 17, 1995, providing information & assuring continued safe operation of Bruce A.

Integral to the planning of the work were the Job Safety Analysis (JSA's), Radiation Safety Analysis (RSA's) and ALARA reviews. Ensuring (despite the hurried nature of the work), there were no serious injuries or radiological over-exposures.

Approximately 14,000 hours of direct field labour was associated with the divider plate work on Unit 4.

The total dose incurred as a result of all the field work was approximately 33 rem.

The total cost to the Corporation was a one month delay in the Unit 4 restart, $1,600,000 of direct charges, unaccounted costs as a result of additional outage and technical support, and a 75% power limit on all Bruce A Units until the Units preheaters are inspected, and any necessary repairs completed.

An integrated Team, focused on the job at hand, was the key ingredient in taking this work from a standing start to a safe and successful completion. All involved, combined with their different talents and skills, ensured all the preheater related work was performed such that Unit 4 continued to proceed towards a timely return to service.

Work is still continuing on the Root Cause Determination (RCD) and the actions needed to prevent recurrence.

1.0 PREHEATER DESIGN

The preheater divider plate is a carbon steel "board and batten" design bolted together. There are eight main "division plates", the longitudinal edges of which are secured by seven "clamping bars" and fifty eight 5/8" diameter bolts. These division plates are approximately 1-1/2" thick, and vary in width. The clamping bars are approximately 2-3/4" wide and 1/2" thick and are located on the "hot" or inlet side of the divider plate. The outer edges of the division plates are stepped to match the step in the seat bar which is welded to the preheater shell and to the tubesheet. Holding the assembly in place, against the seat bar, are eleven "clamping dogs" across the shell of the preheater, and nine clamping dogs at the tubesheet. These require a total of forty 5/8" diameter bolts to secure the assembly. The dogs are all 6" x 2-1/2" x 1" and are located on the "cold" or outlet side of the divider plate. Overall, the preheater divider plate is approximately 67" across the base and 34" at its maximum height. All bolts are held in place with locking tabs that are welded to the applicable component (clamping bars or clamping dogs).

2.0 SYSTEM LAYOUT

The Main Heat Transport System (HTS) is a closed loop system arranged for constant bi-directional flow through the reactor core. Major components of the HTS include 4 motor-driven pumps, 8 boilers, 4 preheaters, a reactor inner core, and a reactor outer core.

The 200 reactor outer core channels are fed directly from the 4 circulating pumps, which draw coolant

from the boiler outlets. The 280 inner zone channels are fed by coolant which passes from the pumps through the preheaters (half of this inner zone flow bypasses the preheater), heating the feedwater and cooling the Heat Transport fluid going to the inner zone channels

There are 2 preheater designs, a Type "A" and a Type "B". These two types are simply mirror images of each other.

3.0 DAMAGE DISCOVERY

As part of the Unit 4 outage, planned maintenance activities included preheater manway gasket repairs. These repairs, which involved opening the preheater manways, were in progress, and already completed on 2 of the 4 preheaters. During the repairs to preheater 3 (HX3) manway gaskets (Friday, May 19th, 1995), the mechanics noticed some loose parts laying on the tubesheet. A complete inspection of HX3 revealed substantial damage to HX3's divider plate. This discovery led to a complete inspection of all four Unit 4 preheater divider plates, including the ones for which the manway gasket repairs had already been completed. At that time, the Unit 4 outage was scheduled to be complete in a months time

The inspections identified considerable damage to the divider plates in 3 preheaters (HX1, HX2 & HX3). In total, 5 clamping dogs, 13 locking tabs and 20 bolts were unaccounted for from three preheaters. All damage indicated a that a pressure differential had occurred in the direction opposite to normal operations. Preheater 4 (HX4) had no signs of damage. All preheater divider plates were video-taped for future reference and analysis.

Preheater 1 was the most severely damaged, with 5 clamping dogs dislodged from their position at the top of the divider plate, and 5 division plates in the centre of the divider plate "leaning" towards the inlet side of the preheater, revealing a gap of approximately 6" in the top of the divider plate. One of the five dislodged clamping dogs was still jammed between a division plate and the top of the preheater shell. A total of 4 clamping dogs and 12 bolts or bolt heads were unaccounted for in preheater 1 (6 bolts from the Cold leg and 6 bolts from the Hot leg)

In preheater 2, four clamping dogs were dislodged from the bottom of the divider plate. These dogs were all found on the tubesheet and some with broken bolts still attached. Unlike HX1, the division plates were not bent or leaning. The number of bolts or bolt heads unaccounted for in HX2 totaled 1 from the Hot leg.

In preheater 3, the damage was similar to preheater 1, only not as severe. Four division plates in the centre of the HX3 divider plate assembly had leaned towards the inlet side of the preheater approximately 2" to 3". Three clamping dogs at the top of these division plates had dislodged, two of which were still in the preheater and jammed between the division plates and the preheater shell. A total of 1 clamping dog and 7 bolts or bolt heads were missing from preheater 3 (2 bolts from the Cold leg and 5 bolts from the Hot leg).

4.0 FIELD ACTIVITIES

4.1 Inspections & Retrievals

All loose (unattached) parts were retrieved from the tubesheet area and the tubesheet was vacuumed and visually inspected for damage. There were no signs of damage to the tubesheets

Due to the mirror image design of the system, the preheaters were inspected to ensure they were not originally installed in the opposite locations. Although inconceivable, the inspection was performed and verified the correct orientation of the preheaters.

The Reactor Inner Zone Inlet Headers (RIZIH's) were remote visually inspected using a remote operated vehicle (ROVVER). As a precautionary measure, these inspections were closely monitored by the control room operators to ensure the channels were not affected by ROVVER blocking a feeder inlet. All 5 missing dogs were located in the RIZIH's as anticipated (4 in the west RIZIH & 1 in the east RIZIH with a bolt attached)

Simultaneously, with the ROVVER inspections, ultrasonics (UT) were being performed on the outside of the RIZIH's. The UT unit consisted of a multi-transducer head with an auto-couplant feed to help reduce inspection time in the feeder cabinets. These inspections also proved to be successful in confirming the locations of the dogs.

Two fuel channels were CIGAR'ed, based on historical fueling information where pieces of what may have been locking tabs, were found ejected into the Spent Fuel Bay.

All 280 inner zone inlet endfittings were radiographed at the feeder connection in an attempt to locate the 19 missing bolts and 13 locking tabs. This was successful in locating 16 bolts and it was not clear if any of the missing locking tabs were located. The information obtained from these inspections proved to be very useful in reaffirming the safety of the reactor for continued operation. Out of the 280 inner zone inlet

end-fittings, 14 were found to have 1 or 2 bolts in them for a total of 16 out of 19 bolts located. The remaining 3 bolts and locking tabs are believed to be lodged in the annular space between the end-fittings and the liner tubes. This is not considered to be detrimental to the safe operation of the Unit.

4.2 Divider Plate Replacement

By May 31, the divider plate replacement and loose parts retrieval was planned and assigned to the Building Trades through the Purchase Service Agreement. The work was expected to take 18 days of the outage critical path and cause SLAR (Spacer Location and Re-location) to be interrupted early. The work would have to continue 24 hours a day until complete.

By June 18, twenty additional boilermakers were hired on and trained. A total of 46 boilermakers (some staff already hired for boiler work) were trained for this work. The training activities took approximately 5 days to complete and involved the use of a preheater head mockup.

After placing the order on May 31, the first divider plate was picked up and delivered by Ontario Hydro personnel on June 16.

On June 19, SLAR was halted to allow the divider plate work to commence to completion.

By June 23, most of the divider plates were removed and the Design authority provided the approvals to proceed with "replacement-in-kind". This approval was timed perfectly with the delivery of the remaining 3 divider plates (received on June 23).

As a result of being able to inspect on June 7 to 9, all loose parts in the RIZIH's were removed during the week on June 19. This was much quicker than anticipated and therefore did not hinder the divider plate replacement work.

The divider plate seat bar, in preheater 1, was found to be badly damaged as a result of the failed divider plate. The damage had to be ground out, re-welded and ground flush. The seat bar is not part of the vessel pressure boundary.

All 4 divider plate replacements were complete by June 29 reducing the time on outage critical path from the planned 18 days to 13 days. When this duration is added to the additional CIGAR'ing, end-fitting radiography and preheater box-up performed as a direct result of the divider plate damage, the Unit 4 outage experienced an approximate one month delay in restart.

4.3 Radiological Hazards

Due to the location of the work, significant radiological hazards were encountered as follows:

- 10 to 20 mrem/hr general gamma.
- 400 mrem/hr in the heads prior to shielding.
- <180 mrem/hr in the heads after shielding.
- up to 10 mrem/hr loose contamination.
- high hazard particles (>25 R/hr contact dose rate).
- 100 - 150 MPCa's tritium at the work locations.

The preliminary inspection of the heads identified up to 300,000 CPM of loose contamination with some minor hot spots of up to 1500 mrem/hr. Per above, the actual hazard was much higher than anticipated and required rigourous contamination control. For similar work in future Units, the use of power washers would have to be considered prior to preparing the heads for entry.

The tritium was less than anticipated as a result of the air movers and the high usage of breathing air (for plastic suits) keeping the preheater area continually purged.

Dedicated radiological safety personnel (greenmen) used for the duration of the job greatly helped to ensure the safety of the workers and minimize and control the radiological hazards.

In order to minimize the radiological hazards in the preheater heads, a combined gasket/shielding of the tubesheet was installed – this greatly reduced the tritium and general gamma coming from the tubesheet.

4.4 Additional Radiological Information

This section has been divided in parts that reflect the actual work performed as anticipated during the pre-job ALARA planning.

a) Preliminary Inspections (June 7 to 9)

This included RIZIH inspections (by ultrasonics & ROVVER), shielding and gasket installation in the HX1 and the cold legs of HX2 and 4, partial divider plate removal for research and general vault preparations for the remainder of the work to commence on June 19.

dose estimate: 8825 mrem
actual: 3133 mrem

Comments: The work in the preheater heads went from an estimated 200 min. to 27 min. The ultrasonic activity in the feeder cabinets was also reduced. Both items led to the overall reduction of dose for the work and support activities. The ROVVER camera inspections proved to be very successful in quickly locating the pieces in the headers.

b) Replacements and Retrievals (June 19 to 29)

This included the retrieval of divider plate dogs from the inlet headers, the remainder of the shielding and gasket installations, full preheater head inspections, seat bar repairs in HX1, high hazard work in HX1, divider plate removals and reinstallations in all four preheaters.

dose estimate: 106 rem
actual: 17 rem

Comments: The estimates were performed given the worst-case scenario and the actual work went very well with less staff and 75% of the time anticipated. The actual time spent in the preheater heads was also much less than anticipated due to extensive mockup training for all personnel doing the work. It was anticipated that some decontaminating and component modifications would be performed in the vault, however, the use of a tented area outside Airlock 5 and a glove box allowed a considerable amount of this work to be performed outside of the vault. The ROVVER camera retrievals were very successful and the pieces were removed from the headers in less than half the time anticipated.

c) E/F Radiography (July 3, 4 & 10 to 12)

This involved only the radiography performed on all the inlet endfittings of the reactor inner zone. This work commenced on both reactor faces simultaneously while working off small (8' by 10') reactor face platforms.

dose estimate: 6.5 rem
actual: 13 rem

Comments: Due to physical constraints caused by the use of the small reactor face platforms and the requirement to perform two radiographs for each endfitting, the estimated duration for this work doubled (went from 3 shifts to 6 shifts). Also, it was not anticipated that tape on the endfittings would have to be cleaned or that a radiography tool (tungsten collimator) would be dropped in the endfitting area and would have to be located and retrieved with the help of a remote camera. Seven of the radiographers received close to 1 rem each.

5.0 ROOT CAUSE DETERMINATION

While the repairs and replacement of the preheater divider plates was underway, investigations proceeded to uncover the Root Cause for the damage. Evidence was gathered from a myriad of sources in order to arrive at the cause of the divider plates failure.

Investigation of the Root Cause for this damage is still continuing and a final report is expected in 1996. Data gathered to date includes.

5.1 Physical Evidence

Some bolts and division plate sections were sent for analysis. The analysis pointed to a single, abrupt, overloading event, that occurred some time ago. Further analysis estimates the damage to have happened approximately 40,000 (± 20,000) operating hours ago (5 to 10 years).

Checks of Unit 4 boiler divider plates were also performed and did not indicate any signs of damage. This is pertinent to the Root Cause Determination for two reasons. One is that the boiler divider plates are of a similar design and the other is that the two divider plates reside on different sides of the main PHT pumps. This leads toward a conclusion that the initiating event is related to the pumps (i.e. a similar design upstream of the pumps experienced no damage).

5.2 Testing

A test was performed, using a hydraulic jack to load a division plate clamped in a fashion similar to the actual preheater divider plates. This test gave failure loads, for the divider plates bolts, that correspond to a steadily applied pressure of approximately 250 psig. Note that this pressure loading is opposite to the normal operating pressure differential for the divider plates. This test correlates with the engineering analysis that postulated the required pressure differentials to be in the order of 220 psig.

5.3 Engineering Analysis

A number of possible Level B transients were investigated (SOPHT analysis of pump trips, loss of Class IV power, etc.), but these were not considered to be a plausible source of the large reverse pressure differential thought to have been experienced by the damaged divider plates.

Water hammer-type loads were also considered as a possible source for the large pressure differential. This scenario involves trapped gas in the preheater when the heat transport pumps are started up after a shutdown where the HTS had been drained for maintenance. This water hammer could then be caused by incomplete venting of the preheater, or by a redistribution of gas trapped in the boilers, perhaps due to a failed pump start.

An investigation based on heat balance data suggests an abrupt anomaly in Unit 4 preheater performance circa Spring 1986. This corresponds with the time frame indicated by the physical investigations performed on the divider plate parts.

5.4 Historical Data

All four preheaters in Unit 4 were visually examined in 1981, and were damage free. In addition, HX4 was

opened and examined in 1993, to look for possible divider plate damage which could be causing high RIZIH temperatures. As confirmed previously in this paper, though, the divider plate in HX4 was not found to be damaged in 1995.

During the 1980's, the time that both the analysis of the broken bolts and the review of Unit 4 preheater performance points to as a possible timeframe for the damage to have occurred, the startup procedures were changed from starting 1 pump at a time to starting 3 pumps simultaneously, and the 4th after that. It is known that starting a single pump results in reverse flow. It is possible that, during the time that the "single pump start" startup procedures were in effect, a reverse pulse, which was created due to an air pocket, damaged the preheater divider plates.

Investigations of fueling historical records indicated no Channel Outlet Temperature (COT) alarms reached the alarm level, but a close look at the reports has confirmed that at least 2 bolt tabs or pieces of bolt tabs were observed during refueling operations.

6.0 SAFEGUARDS

To assess the effect of bolt segments located at the entrance of an inlet end-fitting on channel flow, pressure drop, and dryout characteristics, tests were performed at Sheridan Park Experimental Laboratories (SPEL) to determine the incremental change in end-fitting differential pressure as a function of mass flowrate for a varying number of preheater bolts. The effect of varying bolt size was also studied. The results of these tests demonstrated that for configurations consisting of two bolts or less, the incremental change in end-fitting differential pressure was limited to well below 100 kPa at 25 kg/s of D_2O. In terms of the impact on Bruce A channel flows, this magnitude of incremental pressure drop corresponds to a flow reduction of less than 4% of nominal flow. This range of flow reduction was found to have no impact on the current maximum channel power limits in the range of 0% to 75% of full power. The decrease in critical channel power was also found to be less than 2% for both inner and outer zone channels.

The results of the safety assessment demonstrated that Unit 4 can operate safely within the range of 0% to 75% of full power. Nominal setpoints and limits on SDS1 and SDS2 trip parameters as well as maximum channel power were shown to be adequate and post trip fuel cooling remains unaffected by the presence of bolt segments.

In the absence of a definitive Root Cause for the damage to the Unit 4 preheater divider plates, a number of actions have been implemented to more closely monitor the condition of the divider plates, and also to prevent potential damage causes.

- During Unit 4 power runup, the COT's on the fourteen affected channels were monitored to ensure that there is no gross flow blockage in them. There were no indications of blockage.
- Pressure differential A/I's have been installed in Unit 4. These A/I's are connected to the existing preheater instrument tubing. They allow monitoring of the pressure differential across each of the four Unit 4 preheater divider plates. These A/I's are to be read during normal operational transients and also during Heat Transport upset Conditions (Pump Trip, Pump Restart, etc.). The startup readings for Unit 4 indicated pressure differential from 170 to 188 kPa (A/I's are set to alarm at 100 kPa falling).
- More stringent procedures have been put in place for operating units when recovering from a PHT pump trip. Under these conditions, the Unit is now taken out of service, and the Duty Manager contacted.

7.0 FUTURE

Analytical work, to more precisely determine the cause of the failures, is currently in progress. The impact of loose parts in the HTS is being analyzed separately. Both of these items have the potential of requiring a divider plate re-design, however, this is on hold pending the completion of the Root Cause Determination.

All Preheaters at Bruce A will be inspected for damage at the first planned outage opportunity. These inspections will become part of a preheater inspection program for Bruce A. It is anticipated that the Unit 1 inspection findings will be available for the conference presentation.

It is anticipated that the loose parts located in the Unit 4 endfittings, by radiography, will be removed during the next planned outage (currently 1997). The associated endfittings will also be inspected for signs of fretting damage. During the 1997 outage, the unit 4 preheater divider plates will also be re-inspected.

The impact of a LOCA on the boiler divider plates is currently being assessed, although, this is not thought to have any impact on the preheater divider plate design.

8.0 CONCLUSION

Fortunately, the preheater divider plate failures in Unit 4 did not progress to the point of affecting the safe operation of the Unit, and their efficient replacement represents somewhat of a maintenance success story. This incident, however, has uncovered serious gaps in Bruce A's plant surveillance and In-Service Inspection Programs.

In addition to the inspections planned for all preheaters at Bruce A as a result of this incident, a comprehensive preheater divider plate inspection program will be implemented to ensure that adequate inspections are regularly performed and reported for the life of the Station.

While the measures to prevent recurrence of the event that led to the partial failure are not yet fully known, some interim measures have been implemented to:

- prevent recurrence of the known likely scenarios currently under study.
- provide "baseline data" for the pressure differential across the intact Unit 4 preheater divider plates.
- provide indication of full or partial failure of the Unit 4 divider plates through Control Room Annunciations.
- provide operational data for input to the root cause investigations.

As Bruce A Units go through planned outages, inspections will be performed, and interim or final (if RCD is completed) measures will be implemented to provide reasonable assurance that damage will not re-occur and/or any initiating event will be recorded.