Bruce B Fuelling-With-Flow Operations: Fuel Damage Investigation

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ABSTRACT

This paper summarizes the fuel bundle damage characterization done by Nuclear Safety Solutions Limited (NSS) and the out-reactor flow visualization tests done at Atomic Energy of Canada Limited (AECL) to reproduce the damage observed on irradiated fuel bundles. The bearing pad damage mechanism was identified and the tests showed that a minor change to the fuelling sequence would eliminate the mechanical interaction. The change was implemented in January 2005. Since then, the bearing pad damage appears to have been greatly reduced based on the small number of discharged bundles inspected to date.

1 BACKGROUND

The Bruce A and B fuel channels were designed to support the 13 bundle fuel string with a four-finger latch cage located downstream of the pressure tube. The fuelling machines performed Fuelling-Against-Flow (FAF) operations using fuel carriers to transport fuel bundles to and from the reactor core. The FAF operations resulted in low burnup fuel bundles at the flow outlet end of the fuel string and high burnup bundles at the inlet.

In 1993, all Bruce units were derated, because of power pulse considerations during a postulated inlet header break accident in which the flow reversal was predicted to result in a sudden reactivity increase as low burnup bundles with excess reactivity shift towards the centre of the core. This phenomenon does not occur in CANDU reactors that Fuel-With-Flow (FWF) because the low burnup bundles located near the flow inlet end of the channel shift away from the core centre during accident-induced flow reversal.

Subsequent to the identification of this postulated event, plans were developed to return all Bruce units to pre-derated conditions. There were three major changes introduced: gap management[1] with long bundles; reversing the fuelling direction from FAF to FWF; and introducing a new improved fuel design that offers a low coolant void reactivity. These changes addressed safety issues associated with postulated accidents and required modifications to the fuel, fuel channel, fuel handling components and fuelling operations. The resulting hardware changes incorporated the following several improvements:

a) Flow straighteners were installed in most inlet shield plugs in the inner zones of the Bruce cores to reduce the bundle vibration in acoustically active fuel channels.

b) New outlet shield plugs with extension pieces replaced old ones to provide support of the fuel bundle endplates. This reduced the risk of bundle endplate cracking particularly associated with latches, i.e., dampening axial vibration of non-outer fuel elements in acoustically active fuel channels; and prevented flow induced endplate "doming" when non-outer fuel elements were supported.

c) In the gap management scheme, long fuel bundles (about three per cent longer) were loaded into some channels to reduce the distance the fuel string would shift during postulated accidents involving flow reversal.

d) The 13th bundle was removed from all fuel strings to increase the distance between the inlet shield plug and fuel string. This eliminated the pressure tube fretting near the rolled joint regions of the pressure tube.

e) A nosepiece was added to the fuel carriers to open the fuel latch and facilitate bundle removal from the downstream endfitting as part of FWF operations. The fuelling machine operating sequence was also changed.

By 2002, Bruce B Unit 6 had undergone most of the above changes and had reordered the fuel bundles in the core. FWF operations commenced in July 2002 and soon thereafter the coolant gamma activity levels of both fission products and activation products increased. The presence of fission product indicated fuel defects in the core whereas the presence of activation products indicated the physical loss of material within the primary circuit. Subsequent fuel inspections in the fuel bay confirmed that all four Bruce B units were experiencing a higher than normal number of fuel defects. Discharged bundles showed evidence of widespread debris fretting and previously unseen mechanical damage of bearing pads. Further examination of fuel carriers and

[1] While operating under FAF, the gap caused by elongating irradiated fuel channels was managed to reduce the distance the fuel string would shift during postulated accidents involving flow reversal.

fuel channel liners revealed unexpected mechanical interaction between the two components. The debris generation from the mechanical interactions is believed partly responsible for the fuel defects.

Bruce Power set up a team of industry experts from across the CANDU fuel industry to investigate the damage mechanism and to provide solutions to the problem. Ontario Power Generation Inspection and Maintenance Services (OPG/IMS) from and NSS expanded the Bruce B fuel surveillance program in an attempt to characterize the mechanical interaction damage on discharged fuel bundles. Kinectrics with input from General Electric Canada performed the liner and carrier damage assessments. AECL's Chalk River Laboratories performed hot cell examinations of the irradiated liners and latches from the Bruce reactors.

The experts reviewed the results of these assessments and postulated several damage mechanisms that related fuel/carrier and liner damage. CANTECH modeled the fuel bundle and latch interactions, which formed the basis for an out-reactor investigation test aimed at reproducing the damage observed on the bearing pads.

2 ASSESSMENT OF FUEL INSPECTION RESULTS (2003)

The following observations are based on the initial results from bundles discharged in 2003. Ten defective fuel bundles had been discharged from Bruce B units in 2003 which was more than the eight experienced in the previous five years of operation. Debris fretting was confirmed to be the cause of eight of the 10 defects: the remaining two defects had unknown causes. In 2003, there was also a seven-fold increase in the number of bundles with debris indications and a 100-fold increases in bundles with mechanical interactions. The mechanical interactions were, for the most part; scrape marks on bearing pads[2], and to a lesser extent, scratches on the endplates. A few bundles also had endcap damage and broken assembly welds.

There were 47 bundles with mechanical damage to 117 bearing pads (about 2.5 bearing pads per bundle). Of these bundles, 44 were discharged using FWF and flow defuelling operations. Both operations involved discharging irradiated bundles, two at a time, through the latch, and into the fuel carrier parked at the downstream endfitting. The downstream bundle in each pair had

2 The Bruce bundle has 5 bearing pad planes, 3 bearing pads on each outer element, for a total of 54 bearing pads:

- 18 centre pads located at the midplane of the bundle on each outer element;
- 18 inboard pads located near the 2 quarter planes of the bundle; 9 on odd numbered outer elements at monogrammed end of the bundle and 9 on the even numbered elements at the other end; and
- 18 outboard pads located near the ends of the bundle; 9 on even numbered outer elements at monogrammed end of the bundle and 9 on the odd numbered elements at the other end.

almost three times the damage as the upstream bundle and 50 per cent of all bearing pad damage for both bundles occurred at the centre bearing pads which represents one third of all pads.

Generally, there were four bearing pad damage categories identified, see examples in Figure 1:

- small corner dig or small nicks on one side of the bearing pads near its bearing surface;
- corner chip same location as above, but bearing pad material appears to have been removed.
- impact angle 90^{o} scraping or material loss across the leading edge of the bearing pad near its bearing surface.
- deep gouges or scrapes along the entire bearing surface of the bearing pads.

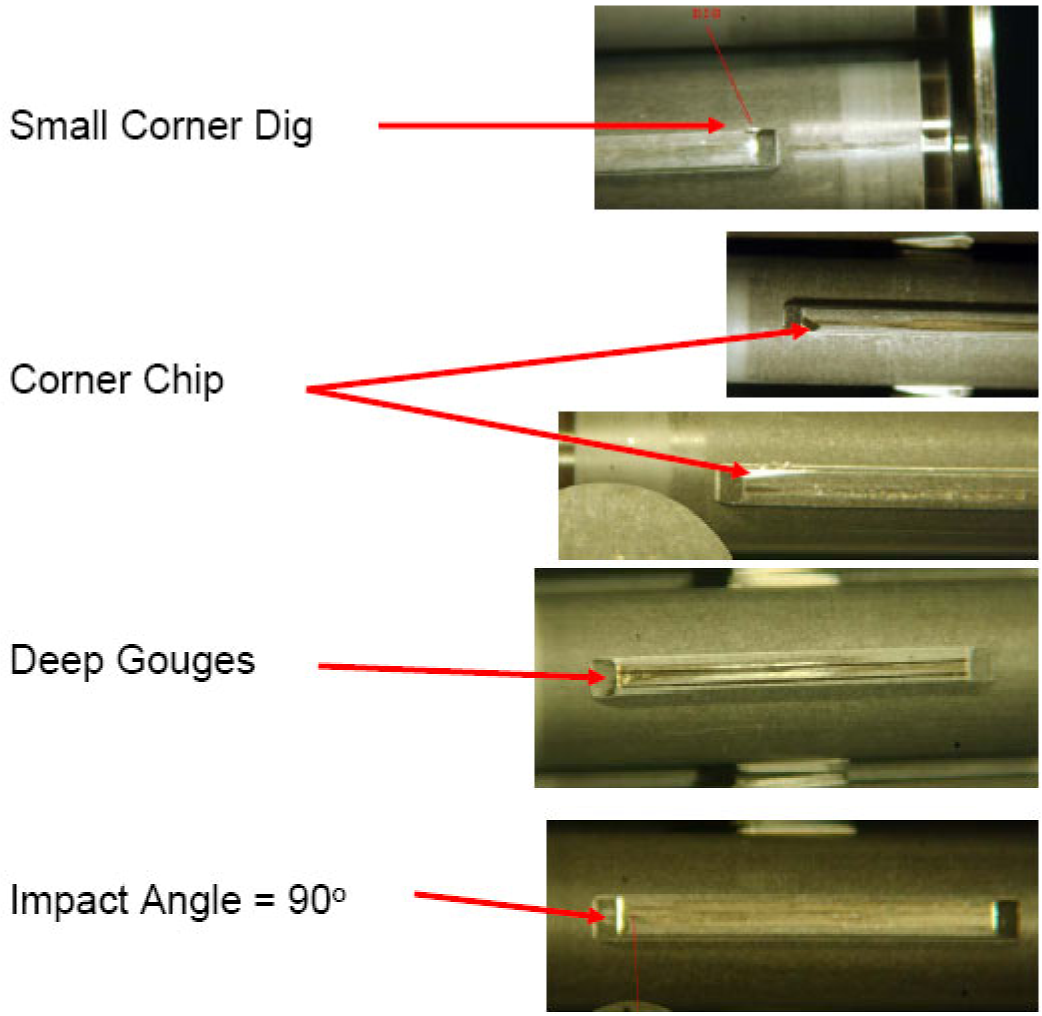


FIGURE 1: BEARING PAD DAMAGE CATEGORIES

Also, four FWF carriers had been examined at Bruce B by Kinectrics. The outer surfaces, which contact the endfitting liners, showed evidence of galling damage.

By 2004, significant evidence pointed to interference problems during refuelling operations involving irradiated fuel bundle transfer through latches and into the fuel carriers at the downstream end of the channels.

3 PRE-TEST EVALUATION

Various mechanisms were proposed, most of which were thought to be related to the fuel carrier and fuel bundle interference since the both components showed signs of damage after FWF operations started. The observed damage appeared to support various theories. During the initial stages of the investigation several damage scenarios were suggested. The most credible theories included:

Theory 1 The bearing pads were nicked by the latch fingers that were not completely opened by the carrier nosepiece (see Figure 2 and 3a),

Theory 2 The bearing pads were impacted on the carrier nosepiece which was not completely inserted or was tilted while parked inside the latch cage (see Figure 3c), and

Theory 3 The bearing pads were scraping along the latch cut out (see Figure 3b).

Latch Penetration = 0.5 mm

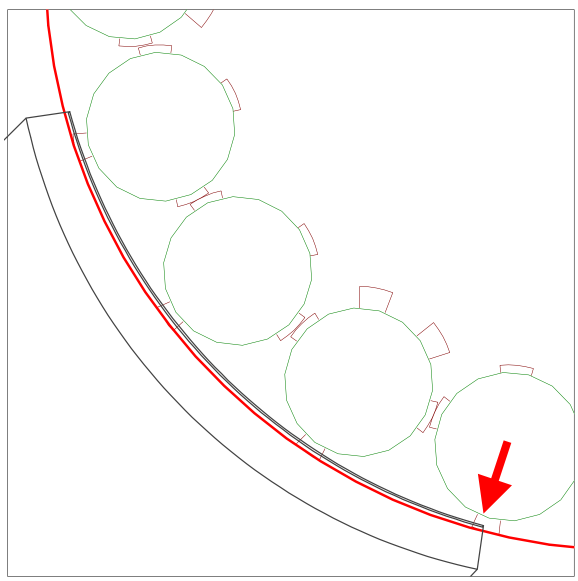
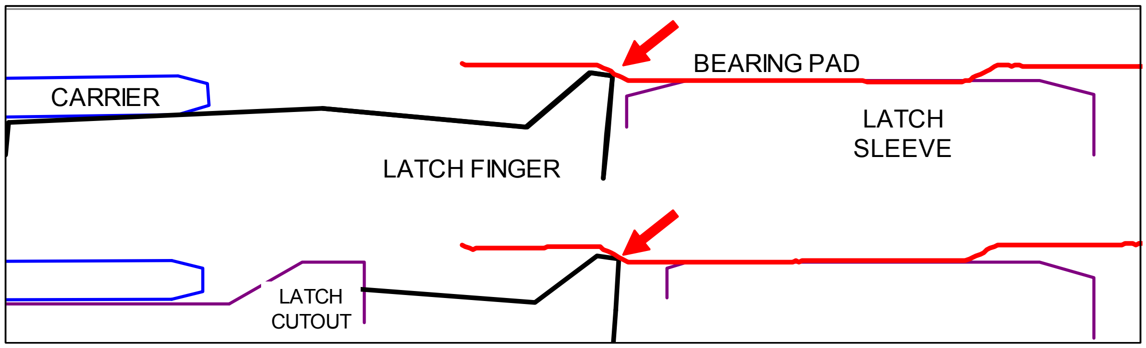


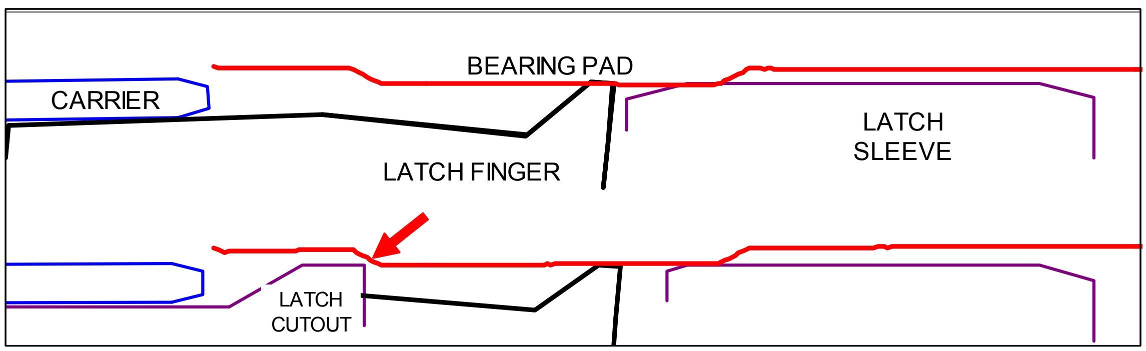
FIGURE 2: AXIAL VIEW OF BOTTOM LATCH FINGER PARTIALLY OPEN SHOWING POTENTIAL INTERFERENCE WITH BEARING PADS

FIGURE 3: SIDE VIEW OF BOTTOM ELEMENTS SHOWING POTENTIAL BEARING PAD INTERFERENCE (RED ARROWS) WITH:

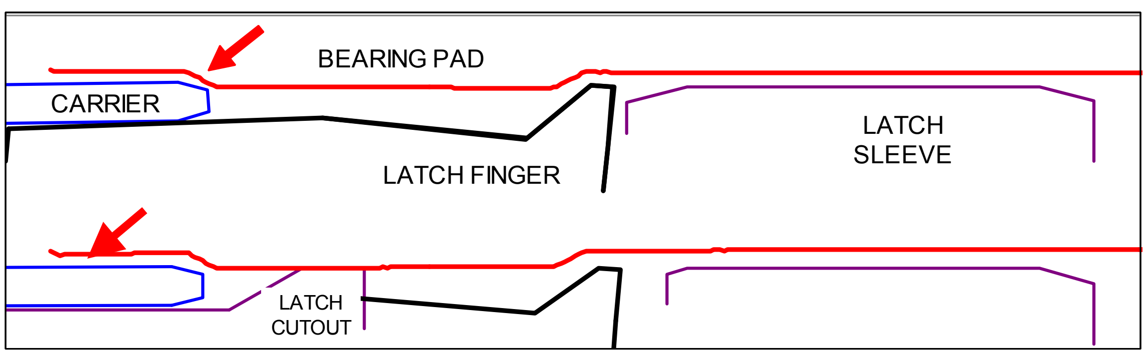
a) bottom latch finger



b) latch cut out



c) fuel carrier nosepiece



As part of any investigation, the root cause needed to be identified before solutions could be found and implemented. Testing was required to demonstrate the mechanism and test solutions. The flow visualization test rig at AECL Sheridan Park in Mississauga Ontario offered the best option to investigate the proposed mechanisms within the shortest time period.

4 AECL FLOW VISUALIZATION TEST PROGRAM

For more than 25 years, the flow visualization test rig at AECL's Sheridan Park facility has been a developmental tool for investigating problems and solutions for CANDU fuel and fuel channel components. The test rig is an instrumented low pressure, low temperature water loop with a mock-up fuel channel. Although the in-reactor temperatures, pressures, and fuel channel and coolant material properties are not representative, the test geometry and flow rates are representative. The flow visualization test rig is versatile and provides a means to quickly investigate and understand the various damage mechanisms. Figure 4 shows the test concept for which the current test program is based.

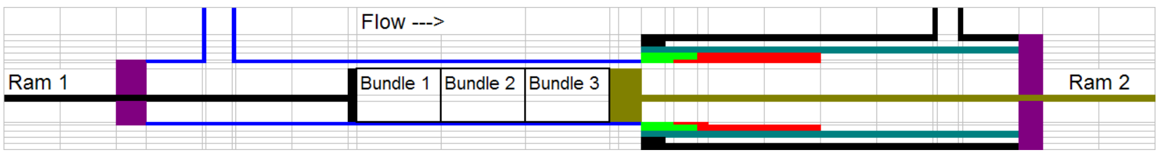


FIGURE 4: AECL FLOW VISUALIZATION TEST RIG SET UP SHOWING A THREE BUNDLE FUEL STRING WITH SUPPORTING RAMS AND FUEL CARRIER INSIDE ENDFITTING LINER

For these tests, the internal geometry of the mocked-up fuel channel consisted of an acrylic end fitting assembly connected to a short length of acrylic pressure tube, long enough to accommodate three Bruce fuel bundles under representative fuelling operations. The channel components had the same internal geometry as that of a Bruce B fuel channel. The end fitting and pressure tube were fabricated from clear plastic sections so that the movement and interaction of fuel bundles with fuel channel and fuel handling hardware could be observed during simulated on-reactor fuelling operations. An authentic unirradiated Bruce B fuel latch assembly, FWF carrier, and Bruce B liner were installed inside the endfitting. To simulate bundle movements, a variable speed/load ram system was designed and installed at both ends of the test section as schematically shown in Figure 4. The upstream ram head simulated the axial loading between endplates of two bundles and the downstream ram and charge tube assembly were built to the same dimensions as the Bruce B ram head and charge tube assembly.

The test loop delivered coolant channel flows up to 30 kg/s light water, fuel string coolant drag up to 1500 lbs, and fuel bundle movement through the latch and carrier assembly at representative Bruce B fuelling machine ram speeds. The ram system applied mechanical loads to supplement the coolant drag forces generated over the three fuel bundles. In addition to the channel flow, a secondary flow circuit was attached to the downstream endfitting to simulate fuelling machine flow injection rates up to 1.5 kg/s.

The test rig was designed and constructed in 2004 and testing started in December 2004. The rig along with its ram system could simulate fuel bundle and fuel carrier movements associated with discharging two bundles through the fuel latch and into the carrier.

4.1 Test Results

By early 2005, approximately 100 tests had been performed. The results indicated that the bearing pads were nicked to the same extent as in-reactor whenever the bearing pads of a bundle were orientated about 13 to 15 degrees from the bottom of the latch cage. It became apparent that the bearing pads were being damaged by the latch cut out. The tests also showed the first two theories for the damage mechanism could be discarded since the extent of bearing pad damage was independent of:

- latch finger penetration into the latch cage,
- latch finger spring constant,
- worn latch fingers,
- missing latch finger,
- carrier axial location,
- flow rate, and
- axial loading of the fuel string.

The next series of tests were designed to focus on why bearing pads were damaged by the latch cut out. To generate evidence that showed the interaction between the bearing pads and latch cut out, one of the bottom latch fingers was removed so that a video camera could record bearing pad movements as the bundles traversed the latch cut out and into the carrier nosepiece. The nosepiece of the carrier is designed to have a “lip” or 0.200 inch step on one side of the inside surface of the carrier to ensure bundles do no wash out during carrier retraction to the fuelling machine.

For FWF operations at Bruce B, the carrier is aligned so that the lip is located at the bottom in the six o’clock position while parked inside the latch cage. The video recordings showed that when a bottom fuel element was aligned at the worst angle for damage, the bundle would deflect downward and the bearing pads of the bottom element would drop into the latch cut out before sliding upward and over the edge of the latch cut out. The pad scraping along the edge of the cut out resulted in corner dig damage. Further testing showed that the fuel element deflection did not occur when the fuel carrier was rotated 180 ^{o} with the lip positioned at the top of the endfitting liner. The video recordings provided the first major clue as to the cause of bearing pad damage.

4.2 Damage Mechanism

The manufacturing drawings of the Bruce carriers showed that the inside opening of the fuel carrier nosepiece is defined by two circles of equal diameter, but with an offset of 0.038 inches (0.97 mm). When the carrier lip is down and the nosepiece parked inside the latch cage, the bottom inside surface of the nosepiece is 0.038 inches below the latch cage bore surface. When the lip is up, both surfaces are aligned. This small difference in elevations has a significant impact on whether or not a 0.048 inch high bearing pad drops into the latch cut out as the bundle slides through the latch.

When the fuel column is supported by the fuelling machine ram, the downstream bundle is subjected to about a 1500 lb loading against the ram face due to the coolant hydraulic drag on the fuel column. With this high axial loading, there is no slippage between the ram head and fuel bundle endplate and the bundle end will move up or down with the ram head as it slides over discontinuities inside the latch cage and carrier.

The ram head is supported inside the channel by four rollers equally spaced around the circumference of the ram head. The bottom roller supports the ram at the six o'clock orientation. As the ram retracts, it drops 0.038 inches as the bottom roller moves from the latch bore to the carrier nosepiece when the lip is down. The ram head drops again as its bottom roller falls off the carrier lip. Each time the ram head drops, the bundle endplate drops as well and the entire bundle drops downward. When this happens, the bottom fuel elements deflect inward and the bearing pads that align at the critical angles of 13 to15 degrees from the bottom simply drop into the latch cut out. These bearing pads slide up over the edge of the cut out as the ram continues to retract. When this happens, bundle (and ram) do not lift back up. Instead, the bottom fuel element is significantly deflected inward as its bearing pad comes out of the cut out, giving rise to high bearing pad loading as the pad scrapes over the edge of the cut out.

The video tapes confirmed that the elevation of the fuel bundle under high axial loading is controlled by roller wheel at the six o'clock orientation on the downstream ram head.

Subsequent testing in the high pressure loop at General Electric Canada in Peterborough, Ontario confirmed that the bearing pad damage was similar to that observed in-reactor and in the AECL flow visualization rig.

5 SOLUTION

The most obvious solution to the damage mechanism was to change the carrier orientation so that the lip was up while carriers receive irradiated fuel during FWF operations. This eliminates all changes in elevation that the ram head rollers must pass over while bundles are moved into the carrier. This change had been anticipated as a possible solution and engineering support to implement this change was well underway in 2004. The fuelling sequences were modified in early 2005. By June 2005, 33 bundles discharged with the carrier lip up orientation have been inspected and the results show a significant reduction in bearing pad damage. Ongoing technical surveillance and fuel inspection efforts are encouraging and continue to provide confidence that the fuel damage problem is solved. However, work is continuing on identifying the fuel carrier galling mechanism and the source of debris generation.

6 CONCLUSIONS

The cause of the bearing pad damage among the Bruce B bundles that have been removed during FWF operations is attributed to the latch cut out and carrier orientation based on out-reactor testing in the cold and hot loops of AECL and General Electric Canada, respectively. Changing the carrier orientation appears to offer an acceptable solution, based on ongoing fuel surveillance results.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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