Fuel Testing to Simulate a Darlington Channel and Fuel Damage

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Summary

The fuel damage in some channels of Darlington Unit-2 resulted in the breakage of end plates, spacer wear on the inner elements , and wear of the end plates between bundles. The detailed examination of the fuel indicates that the damage to the end plates was a result of fatigue.

This summary focuses on the experiments which were key in developing the understanding of the behaviour in the channel. The paper provides the evidence of the significant damage mechanisms to the fuel in Darlington Unit 2.

The main conclusions of the loop tests are:

- pressure pulsations can cause the end plate of the latched bundle to deflect (dome) to the extent that fatigue failures could be expected. The deflection can occur at the same frequencies as the pressure pulses and at frequencies up to 300 Hz.

- endurance testing cold demonstrated that fatigue failure of the end plates could occur at around 150 Hz.

- an additional test at 136 Hz demonstrated all the significant damage features which are evident in the Darlington Unit 2 fuel channels:

1) fatigue failure of the end plates,

2) excessive spacer pad wear between the intermediate and inner ring elements

3) end plate to end plate wear

4) excessive wear on the bearing pads of bundle 13 and other bundles along the channel

All the damage factors appear to be evident in the tests where pressure pulses are at around 150 Hz, the main pump impeller frequency. It appears unlikely that all the evidence could be supported by other excitation frequencies. Lower excitation frequencies can certainly cause a large amount of damage to the fuel as well. However, pulsation frequencies around the 20 to 100 Hz cause different modes of vibration which is supported by bearing pad wear maps along the channel.

There is not perfect agreement with the fuel examinations, nor would perfect agreement be expected. Concerning the main damage observations:

- We conclude that creep of the end plates plays a significant role. The end plates are stressed to a high level. Hence the time available during operation, temperature, and neutron flux of up-stream bundles, can transfer the loads gradually to the downstream end plates. Thus the fracture features and the exact location of the cracks on the end plates are expected to be different between the loop tests and in-reactor. Also the exact morphology of the fatigue surface may be modified by the higher sustained stress on the fatigue cracks in reactor. The location of the end plate cracks is not critical. The fact that they occur is.

- End plate to end plate fretting was observed in both the in and out reactor fuel. The extent of fretting was less probably due to the reduction of time in the out reactor tests.

- The spacer pad wear on bundle 1 appears very similar to that from the damaged Darlington Unit-2 fuel. The fact that they are so similar suggests that the main mode of vibration was similar. The examination of the wear surface shows that the main scratches are axial and about 50 µm in length.

- The bearing pad wear is much more in-reactor than in these tests mainly because the tests were of much shorter duration. The amount of wear in the tests was a maximum at bundles positions 5 and 10.

In conclusion, the authors believe that the evidence is convincing that pressure pulsing at 150 Hz caused the fuel damage in Darlington Unit-2. It is not completely known why similar fuel damage is not found in Unit 1.

1. INTRODUCTION

The experimental program was planned to address vibration and wear characteristics of fuel in a full scale channel in an attempt to understand the failure mechanisms. In particular, attempts were made to induce the type of fuel vibrations which could cause fatigue cracking of end plates and end plate / end plate fretting with pressure pulsations and frequencies known to occur in the reactor.

Subsequent tests on Darlington Unit-2 found that there were significant pressure pulses in the inlet header at 150 Hz. The fuel / loop investigations were started to rapidly determined whether pressure pulsations could explain the observed damage. This report elaborates on the STERN test data which initially demonstrated that end plate deflections could occur with pressure pulses at 150 Hz.

1.1 STERN LABORATORIES Loop Configuration

A Darlington fuel channel was assembled and installed in an existing high pressure loop at Stern Laboratories. The feeder geometry was arranged to simulate the inlet feeder on channel K12 and some features of the outlet feeder. The loop was equipped with a variable frequency pulse generator and the channel was fuelled with GEC fuel. The fuel channel and feeders were fitted with dynamic instrumentation to measure pressure, acceleration and fuel vibration and strain.

A schematic of the test apparatus is shown in Figure 1. The loop piping is designed to operate at 13 MPa and 310° C and the main circulating pump can provide a flow of 60 $kg.s^{-1}$ at 360 m head when operating at 50° C. The loop operates on a "feed-and-bleed" principle for pressure and temperature control. A boiler feed pump and pressurizer are used to control pressure while excess pump heat is rejected from the pressurizer to a condenser to maintain constant coolant temperature. Tests carried out here were operated with the pressurizer full of water (no vapour). A variable frequency pressure pulse generator was installed upstream of the inlet feeder, the preheater and the flow measuring spool.

The following parameters were monitored for each test in selected combinations:

- Dynamic Pressure in Feeders and Channel
- Acceleration of Feeders and End Fittings
- Fuel Bundle Element Radial Velocity
- Strain of Downstream End Plate Bundle 1
- Axial motion of bundles 1 and 13.

1.1.1 Pressure Pulsation Facility

The variable frequency pressure pulse generator is located upstream of the flow measuring orifice, as shown in Figure 2. It consists of a centrifugal pump with modified internals and a variable speed drive DC motor capable of generating single frequencies from 2 to 260 Hz. A photograph of the modified internals is shown in Figure 3. A by-pass valve was installed around the pump to control the amount of flow through the pump and hence the pulsation amplitude. The by-pass valve can also be used to provide flow oscillations at fractional Hz frequencies. A combination of a very low base oscillation with a superimposed higher frequency from the pulse generator can be obtained by the combination of the two devices.

1.1.2 Feeders

Figure 2, the inlet feeder is designed to duplicate channel K12E at DNGS hydraulically and in most mechanical respects. The pipe diameters are the same and by using equivalent lengths of straight pipe as substitutes for some of the elbows, the total feeder resistance loss (L/D ratio) has been matched. Some of the elbows have been rotated due to space limitations. A pipe hanger supports the inlet feeder at the same position as in the reactor.

The outlet feeder design matches the reactor's 2.5" diameter section in size and equivalent pipe resistance loss (L/D); the 3" remainder, however, does not quite correspond to that of the reactor, due to the physical layout.

1.1.3 Fuel Channel Assembly

The fuel channel assembly completes the high pressure test loop and it consists of a full scale Darlington fuel channel mounted on a large steel I-beam. Due to the physical layout of the laboratory, the fuel channel is located on a structural steel mezzanine above the pumps. The I-beam was mounted on vibration isolators to minimize vibration transmission from the floor. Photographs of the channel assembly mounting arrangement are shown in Figure 4.

Fuel String

New fuel bundles were used for all the tests described here. The bundles were manually loaded in the fuel channel and set to have a 12° misalignment between elements on the outer ring of alternate bundles in the string. The loading process employs a continuous stainless steel shim, used to minimize pressure tube damage. Selected outer elements of some bundles are equipped with internal magnets to allow monitoring of their radial velocity. The initial Bundle #1 had a strain gauge attached to its downstream end plate.

Bundle Motion with Ultrasonic Transducers

Ultrasonic transducers supplied by Hydro Research were installed in the faces of the inlet and outlet shield plugs to measure the relative displacement of the end plate circumferential rings on the upstream end of bundle 13 and the downstream end of bundle 1. A schematic of the relative locations of the shield plug ultrasonic probes is shown in Figure 5. The ultrasonic transducers were connected to Novascope signal conditioning equipment to provide signal conditioning and displacement histories.

1.1.4 Data Acquisition

The instrumentation sensors were installed as required on the test loop and connected with appropriate cabling to the signal conditioning amplifiers located near the test section. The output from there is then routed to the data acquisition and analysis work station. This is a Zonic 7000 Workstation with a 16 channel input section (upgraded to 48 channels in January 1992) and Zeta software for data acquisition and conversion to the spectral domain. All input channels are sampled simultaneously and the time history data are stored on the system "thru-put disc" for processing in different and relative ways after testing. The digital data can be transferred to magnetic or optical storage media for long term storage and retrieval for further processing. A typical power spectral density (psd) output is shown in Figure 6.

2. FUEL RESPONSE TO PRESSURE PULSE FREQUENCIES

A knowledge of how fuel responds to pressure pulsations was critical to developing an understanding of the detailed damage at DNGS. The first question that needed to be answered, in July 1991, was whether the fuel end plate resting on the latches could move with deflections that might fatigue the fuel.

The initial series of tests was completed by mid July 1991. The results indicated that the fuel on the latch could respond to the pressure pulsations introduced into the loop. Those first tests were conducted with a strain gauge attached to the end plate. The results were used to specify the conditions for the endurance tests. Most of these initial observations have been superseded by better measurements with ultrasonic transducer at the inlet and outlet end of the channel.

The first tests were conducted with a strain gauge attached to the end plate. The fatigue limit of the end plate was estimated to be about 0.1 mm deflection, peak-to-peak, based on tests on fatigue testing results on a fuel bundle completed at AECL-CANDU[1]. Transfer functions of the end plate strain response versus input pressure pulses, at the feeder reducer, were generated. The results are shown in Figure 7. From these results the pressure pulse required to cause a fatigue strain level of 0.1 mm can be generated as a function of frequency. Pressure pulses to cause fatigue failures are estimated, cold to be about 45 kPa at 118 Hz, and 140 Hz, and 100 kPa at 150 Hz. At 295 C, equivalent to the 265 C operating temperature in heavy water, the failure threshold is similar. However, these data only considered the strain relative to the inlet shield plug ring pressure. We now know that the acoustics of the system can significantly alter the magnitude of pressure measured depending upon the position of the pressure wave. Hence the actual transfer function is likely to be less sensitive to frequency than the figures indicate.

These results were significant as the first indication that pressure pulses were able to cause fuel string movements. Subsequent tests, discussed later, then examined the way the fuel string moved in the channel. The inlet and outlet bundle movements were measured with ultrasonic probes supplied by OH-Research.

3. ENDURANCE TESTS AT ABOUT 150 HZ

3.1 Test 1 at 134 - 166 Hz

After the initial fuel response tests were completed, a new estimate of the dynamic strain and pressure required to cause fuel damage was available. A test was completed to test the fuel bundle endurance criteria.

The first endurance test was carried out at the following nominal conditions for a period of 59 hours:

Coolant Flow Rate:	32 $kg.s^{-1}$
Coolant Temperature:	60° C
Channel Outlet Temperature:	9.5 MPa
Bundle Misalignment:	12 °
Pressure Pulse Range:	134 to 167 Hz
Pressure Pulse Amplitude:	to cause 100 µstrain on the end plate

It commenced on 91/07/23 and was completed on 91/08/26. Bundle # 9652 C was removed from the string for a 14 hour period to accommodate a low frequency flow test. The channel was opened up after 23, 43 and 59 hours to inspect bundles #1, #2 and #13 and to check and record damage. A synopsis of the findings follows.

3.1.1 Damage Characteristics

The damage to the fuel bundles consisted of partial- and full depth cracks, and fretting wear marks on the end plate surfaces of the bundles in position #1 and #2.

The damage to the fuel bundles can be described as follows:

Bundle # GE 9652 C, (position #1) downstream end plate: see Figure 8

After 23 hours:(12.4 x 10^6 cycles) full cracks in the intermediate ring at elements #22 and #26, partial crack at element #26, strain gauge lead missing. A piece of web between elements #26, #27 and #34 was removed for analysis.
After 43 hours: no new cracks were found.
After 59 hours (27.2 x 10^6 cycles): full cracks in the cross web at elements #36 and #37.

Bundle # GE 9652 C, (position #1) upstream end plate: see Figure 9

After 23 hours: full cracks in the intermediate ring at elements #22 and #30.
After 43 hours: no new cracks were found.
After 59 hours: full crack in the intermediate ring at element #26, full crack in the inner ring at element #36. End plate fretting marks between the bundles is shown in the photograph, Figure 10
Photographs of these four cracks of the upstream end plate are shown in Figures 11 to 14

Bundle # GE 9651 C, (position #2) downstream end plate: see Figure 15

After 23 hours: full crack in the intermediate ring at element #26
After 43 hours: no new cracks were found.
After 59 hours: full cracks in the intermediate ring at elements #22 and #26. Fretting marks on long cross web between elements #30 and #36, #23 and #33, #21 and #22.

Bundle # GE 9651 C, (position #2) upstream end plate: see Figure 16

After 43 hours: no cracks.
After 59 hours: partial crack in the intermediate ring at element #22. Fretting marks on inner ring and web between elements #31 and #36, #31 and #32, 34 and #37, see photograph, Figure 17

Bundles 1, 2, and 13 were dimensionally examined at AECL-SPEL for inter-element spacer and bearing pad wear, and end-plate profiles. The spacer wear is heavy on bundle #1 and consistent with the pattern of wear seen on the bundles from Darlington Unit-2. The maximum wear was .324 mm between two spacer pairs, Figure 18. The wear was concentrated between the intermediate ring and the inner rings of elements. The locations of the cracks in the end plate are also consistent with the observations from Darlington Unit-2. However, the cracks did occur on the intermediate ring web in the test whereas the cracks in-reactor occur both in the radial spoke and the rings. The end plates of bundle 1 and 2 contained early signs of end plate fretting and an impression or "witness" mark of the adjacent bundle serial number.

The shape and location of the end plate cracks was similar to those found on the damaged fuel in Darlington Unit 2.

During testing, the frequency was varied in order to obtain a strain gauge response equivalent to 0.25 mm on the end plate. (The amplitude of the pressure pulse was at a maximum with the bypass valve closed, so the variation of frequency provided an alternate mechanism of control.) After the first examination at 14 million cycles, the strain gauge failed and the test was continued with only a 150 Hz pressure pulse, for a further 10 million cycles. This failed to propagate the cracks. Thus we conclude that the pressure pulse amplitude during the 150 Hz period was below the fatigue limit. After a review of these test data, the bundle end plate response as measured by the strain gauge was found to be highest between 134 and 140 Hz. The test was therefore continued at 136 Hz and ran a further 4.9 million cycles with additional cracks developing in bundles 1 and 2.

3.2 Tests at 137 Hz

The previous endurance tests had shown that with pressure pulses in the 135 to 165 Hz range and levels of 125 kPa in the inlet feeder, the end plates in bundle position one will crack after 10 x 10^6 cycles. The objectives of this test were to demonstrate that the end plate cracking found in the previous endurance test could be repeated under the same conditions and that the cracking could be propagated further upstream with increased cycles. The test was carried out under the following conditions for 47 hours.

Flow rate	32 kg.s^{-1}
Channel outlet pressure	9.5 MPa
Coolant temperature	60° C
Fuel bundle misalignment	12°
Pulse pump frequency	137 Hz
Pressure pulse at feeder reducer	100-125 kPa 0 to pk (time)
Total time	47 hrs (23.2 x 10^6 cycles)
Examinations after	10 hours
	25 hours
	47 hours

A summary of the zero to peak values of the pressure pulses, and end fitting and bundle displacements (at 137 Hz) is given in Table 1. End fitting axial displacements vary between .2 and 4.9 µm on the outlet end fitting (yoke end). Bundle thirteen vibration levels are low (average about 6 µm).

3.2.1 Damage Characteristics of Fuel

The results of visual bundle examinations during and after the test on the end plates of bundle 1 are given in Figures 19 and 20. In summary after 23.2 x 10^6 cycles the following results were found:

Position #1	Fourteen cracks in end plate - 1 loose element
Position #2	Eight cracks in end plate- 4 loose elements (3 at only one end)
Position #3	Two cracks

Evidence of end plate fretting was found as far upstream as bundle five with the degree decreasing as we move upstream. No cracks or signs of end plate fretting were found in bundles 6 through 13. Bundle 13 showed signs of fretting wear on the bottom bearing pads.

3.3 Fatigue on End Plates

Westinghouse assessed the failures as follows. The fracture surface shown in Figure 21 displays fatigue beach marks and radial marks emanating from a single origin at the inside surface of the end plate / element cap interface. The fracture began at the notch associated with the non-bonded lap area of the weld. Some of the contours suggest fatigue striations but they were scattered over small areas on the fracture surface. The fracture showed transgranular features characteristic of high cycle fatigue.

The test was completed at 60° C and therefore the detailed fracture surface might be expected to be different from the reactor for two reasons:

1) the in-reactor loading conditions were different. Section 1.2 describes the loading conditions on the latched bundle. The loads are affected strongly by load shedding and creep effects. These factors depend on the operating time at temperature and the loads applied (in these tests only a short time is available to condition the fuel). The loads are also altered if the fuel is on-power.
2) the test temperature was different from that in-reactor.

These factors may result in some of the detailed features in the tests being different from the reactor damaged fuel. The main objective was to duplicate the general phenomena.

4.0 ACOUSTIC CHARACTERISTICS OF LOOP

4.1 General Acoustic Behaviour and Possible Reflection Points

Introduction

Calculations were completed on the acoustics of the Stern Laboratories loop as a means of understanding the test results. The mechanical vibration of the fuel is ignored.

1) The feeder and channel contain a number of reflectors, such as reducers and other sudden changes in flow area, which appear significant in setting up acoustic resonance.

2) The pulsing might have been more effective in causing end plate strain at 150 Hz with a different pipe length between the pulse

generator and the feeder.

3) The calculations suggest that the positioning of the partial reflectors in channel K-12 is unfortunate for operation at 265°C.

4) Table 2 suggests why conditions were unstable in the cold endurance testing at around 137 Hz.

5) At 210 Hz calculations suggest better performance, but possible problems at operating temperatures with channels that have shorter or longer feeders than K-12.

6) Generally, the calculations suggest that since there are many different feeder lengths and reducer positions, resonance in some feeders or channels is likely if there are high frequency pulsations.

4.2 Measurement of Standing and Travelling Waves

Measurements to determine whether standing waves exists in the loop require a lot of detailed instrumentation. Because the acoustic wave interaction at reflection points is specific to the wave length within the pipe the measurements have to be taken over the narrow frequency band where the acoustic reflections exist The possibility of the combination of standing and travelling waves further tends to obscure the information.

To obtain a better picture of what was occurring in the inlet feeder, additional dynamic pressure transducers were added. Recently, the loop was modified to reduce the length of the pipe between the K-12 feeder connection and the pulse generator. At the same time, the analysis technique was improved by filtering the examination frequency (usually the pulse frequency) and displaying the magnitude as a function of the distance along the feeder and channel.

Figure 22 shows the magnitude of the pressure distribution in the feeder and the un-fuelled channel at temperatures from 205 to 295° C. For a channel with 13 bundles, Figures 23 and -24 show the measured magnitude times phase angle for each transducer (relative to the pulse generator outlet transducer) at instants in time at 150 Hz and 85 and 295° C respectively. Each curve in the plot is, in effect, a snapshot of the dynamic pressure distribution along the pipework. The different phase angles are equivalent to steps in time; 60° is equivalent to 1.1 ms at 150 Hz. It appears that at 85° C the feeder contains a dominant standing wave. However at 295° C, the waves appear mainly travelling in the feeder and standing in the fuel channel. The results show that the node points move with temperature. The pulse generator acts as a pressure node at 295° C but is nearly an anti-node at 60° C.

Figure 25 shows the wave pattern present in the loop at 90 Hz and 60°C. Her we see a magnification and standing wave in the inlet feeder and a travelling wave in the channel and part of the outlet feeder.

5 CONCLUSIONS

This investigation has resulted in a better understanding of the causes of the damage that can occur in a fuel channel due to pressure pulses. The tests have shown that the cyclic elastic deformation of the end plate is sufficient to cause fatigue failure of the end plates in both hot and cold conditions over a wide range of frequencies including 150 Hz and above. This was confirmed by cold endurance tests, which resulted in many of the characteristic features observed in the damaged fuel from Darlington Unit 2. These features were:

- End plates cracked by fatigue, in several bundles starting at the latch.
- End plate to end plate fretting damage.
- Very large amounts of spacer wear on bundle 1.
- Bearing pad wear along the channel.

The damaged fuel exhibits some minor features not found in the fuel damaged in the reactor. The main objective of the program was to duplicate the general phenomena. This was successful. The difference in the details can be explained by the known differences in conditions that cannot be duplicated out- reactor.

The fuel movement tests indicate that the fuel can move in many vibration modes. Some of the vibration characteristics observed in the loop tests are likely due to the acoustic properties of the loops. Both standing waves and travelling waves are observed. The measurement of the pressure pulse amplitude is sensitive to location if a significant part of the pressure pulse is in the form of a standing wave.

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REFERENCES:

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Table 1

AVERAGE ENDURANCE DYNAMIC CONDITIONS.

SECOND ENDURANCE TEST

TEST #82 to #136
Base Frequency: 136 Hz
Modulation Frequency: 0.0 Hz

LOCATION	UNITS	AVERAGE:	MINIMUM:	MAXIMUM:
125 IN. UPSTR. ORIFICE	(kPa)	152.4710	44.0513	225.3968
INLET FDR. REDUCER	(kPa)	123.5158	72.0482	146.3852
INLET SHLD. PLUG RING	(kPa)	73.3230	46.7948	92.2904
P/T BUNDLE #12	(kPa)	108.5307	61.3626	134.1428
P/T BUNDLE #4	(kPa)	110.9985	65.4893	133.5222
P/T BUNDLE #2	(kPa)	52.1662	29.1760	67.2562
OUTL. LATCH DOWNSTR.	(kPa)	29.5343	20.5580	40.3221
DISPL. Z INL. E/F	(mm)	0.0022	0.0004	0.0050
DISPL. Z OUTL. E/F	(mm)	0.0017	0.0002	0.0049
DISPL. EL. 7 MID	(mm)	0.0038	0.0004	0.0069
DISPL. EL. 14 MID	(mm)	0.0059	0.0028	0.0103
DISPL. EL. 14 DWN	(mm)	0.0057	0.0008	0.0099
DISPL. EL. 7 DWN	(mm)	0.0135	0.0071	0.0212
DISPL. EL. 1 MID	(mm)	0.0056	0.0024	0.0081
AVG. BNDL. VELOCITY	(mm/s)	5.9438	3.4429	7.3715
AVG. BNDL. DISPL.	(mm)	0.0069	0.0040	0.0085

ALL UNITS 0 to PEAK

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Table 2

DISTANCES OF λ ACOUSTIC REFLECTORS FROM THE PULSER FOR FREQUENCIES CLOSE TO THE ENDURANCE TEST FREQUENCY.

CONDITIONS: H_2O, 60°C, 150 and ~ 137 Hz, STERN LOOP

	DISTANCE	NUMBER OF λ/4 s				
	(m)	150(Hz) λ/4=2.333m	136	137.5	138	139(Hz)
PULSER	0	0	0	0	0	0
INLET FEEDER HEADER FLANGE	16.10	6.9	6.25	6.32	6.35	6.39
INLET FEEDER REDUCER	21.013	9.0	8.16	8.25	8.28	8.34
CHANNEL INLET GRAYLOC	25.688	11.0	9.97	10.08	10.12	10.19
INLET SHIELD PLUG RING	27.93	11.97	10.85	10.97	11.01	11.09
LATCH	37.68*	16.1	14.59	14.75	14.81	14.92
CHANNEL OUTLET GRAYLOC	39.93*	17.1	15.50	15.67	15.73	15.84
OUTLET FEEDER REDUCER	44.56*	19.09	17.31	17.49	17.56	17.69
REDUCER NEAR SEPARATOR	51.54*	22.08	20.02	20.24	20.31	20.46
SEPARATOR	53.18*	22.79	20.66	20.89	20.96	21.12

* This length includes an extra length of 3.243 m to allow for the slower speed of sound in the pressure tube. In this case it is 934.3 m/s instead of 1400 m/s in steel.