Results of Qualification Program Performed to Prepare 37M Fuel for Use in Darlington Nuclear Power Stations

R. Van Lochem[1], G.I. Hadaller[1], Todd Daniels[2]

[1]**Stern laboratories Inc.**
Hamilton, Ontario, Canada L8H 3L3, 905-548-5320
rvanlochem@sternlab.com , ghadaller@sternlab.com

[2]**Ontario Power Generation**
Pickering, Ontario, L1W 3J2, 905-839-6746 X4311
Todd.daniels@opg.com

ABSTRACT- An out-reactor qualification program was performed in the full scale CANDU fuel channel facility located at Stern Laboratories to measure the response of Modified 37-element (37M) fuel and compare this to reference 37-element (37R) fuel under flow and acoustic pulsation excitation over the full range of reactor operating conditions. Tests were also performed to ensure the rates of fretting in the 37M fuel and pressure tube were within acceptable limits.

The qualification program included a series of acoustic/vibration tests using 3 different fuel strings: 37M, 37R and a mixed string. Also performed were two endurance tests (Test 1 with the modified fuel design string and Test 2 with the reference fuel design string) and a crossflow test to confirm acceptable rates of fretting.

The acoustic tests were performed with each fuel string subjected to dynamic pressure pulsations at 210 Hz over a full range of operating temperatures. The fuel strings were also subjected to dynamic pressure pulsations at variable frequency conditions at specific temperatures. The pressure drop was also measured and compared.

The endurance tests were conducted at 265 deg C with a flow rate of 28 kg/s and pressure pulsations of 210 Hertz for an elapsed time of 168 hours.

The acoustic test results indicated that the pressure patterns and vibration responses of the modified and reference fuel strings were not demonstrably different and no unacceptable bundle wear or deformation was observed in the post-test inspections. Similarly, the Endurance tests indicated no demonstrable differences in the rates of fuel bundle fretting, vibration levels or pressure tube fretting.

Introduction

Ontario Power Generation is endeavoring to qualify Modified 37-Element (37M) fuel bundles for use in Darlington Reactors and several out-of–reactor qualification tests have been conducted at Stern Labs to support this program. This paper summarizes the qualification tests performed, provides an overview of the results and a review of the acceptance of the use of the fuel.

As an overview, three qualification test series were performed to analyze and compare the use of 37M fuel performance with various aspects of the reactor fuel channel operating conditions. These test series include an Acoustic Testing Program which includes temperature and frequency sweep, steady state and pressure drop tests and an Endurance Program.

1. Test Apparatus

1.1 Test Loop and Fuel Channel

The test programs were all performed using the Darlington Fuel Channel and loop located at Stern Laboratories. The loop consists of a circulating pump, flow control valves, flow measurement assemblies (orifice and venturi), variable frequency pulse generator, Darlington K12 equivalent inlet feeder, fuel channel complete with Darlington end fittings and an un-crept pressure tube, outlet feeder, pressurizer/separator and interconnecting piping. See Figure 1 for the test loop schematic.

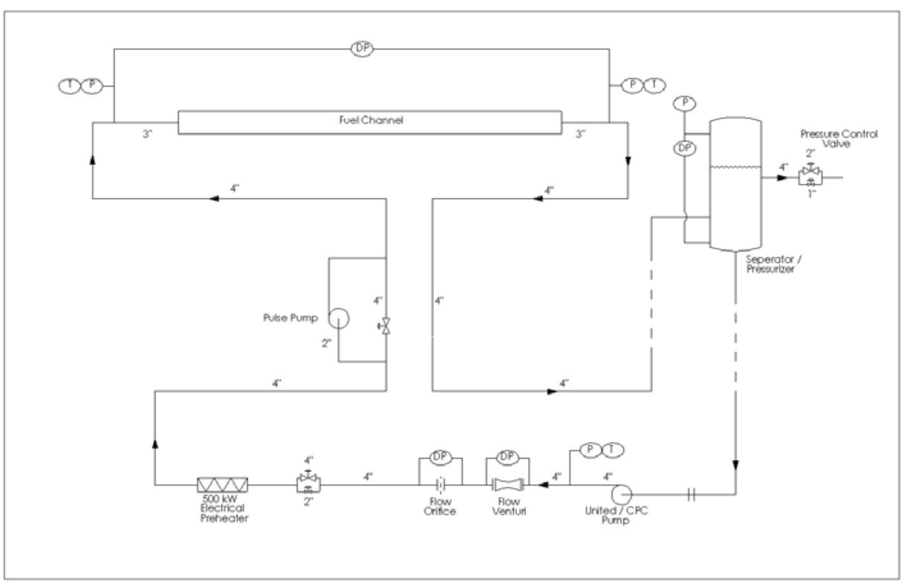

Figure 1 - Test Loop Schematic

The Darlington fuel channel, which has been used for several qualification test programs in the past, consists of Darlington end fittings, uncrept pressure tube, annulus spacer mounted in simulated calandria tube supports, liner tubes, Darlington Type Mark III-A inlet and Mark III outlet shield plugs and the required instrumentation. See Figures 2 and 3 for fuel channel and fuel channel instrumentation schematic.

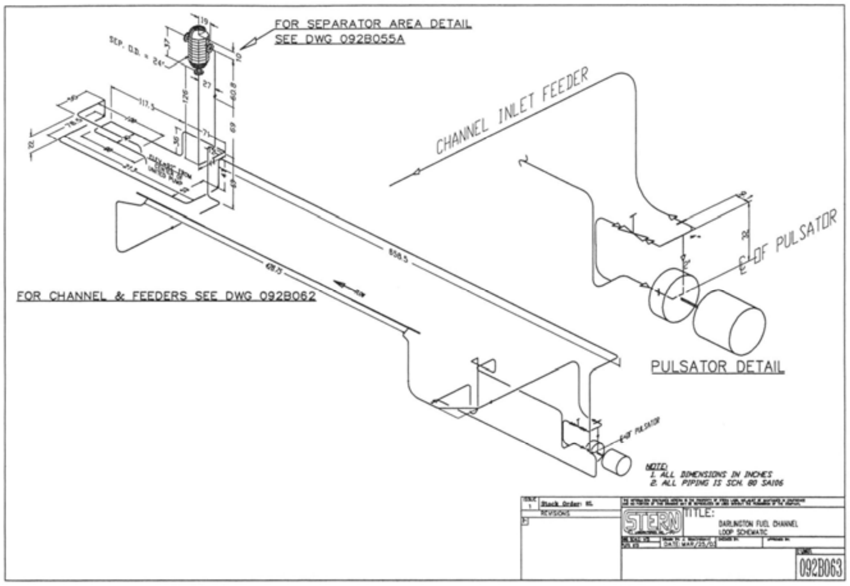

Figure 2 - Fuel Channel Schematic

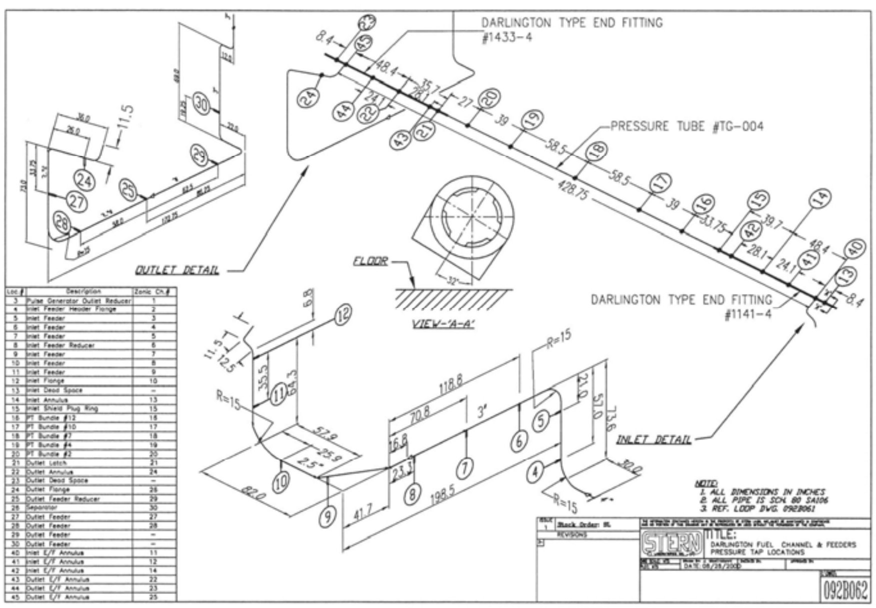

Figure 3 Fuel Channel Schematic - Instrumentation

1.2 Instrumentation

The test loop and fuel channel were instrumented with static and dynamic pressure transducers, thermocouples, magnetic velocity transducers, flow metering assemblies with an orifice and venturi and a displacement transducer to measure pulsation control valve position.

For all test programs the instrumentation was in current calibration traceable to national standards and where in-house calibrations were required, pertinent instruments were calibrated according the relevant procedures. Instrument calibration certificates were created and kept on file.

For these particular tests, there were two types of data acquisition required; low speed or steady state and high speed or dynamic. The low speed instruments generally consist of loop instrumentation (temperature, pressure and flow) and were scanned at 10 Hz, recording 30 second averages. The high speed instruments such as velocity and pressure transducers were scanned at 1250 Hz and were recorded in 50 ensemble averages. Typical high speed / dynamic instruments are used to measure fuel bundle / element radial vibrations, fuel bundle displacements and pressure pulsations.

For the bundle vibration measurements, several bundles were uniquely manufactured with duel pellet magnetic cores. These bundles typically contained up to four specially made pellets in four specific outer elements. Once the fuel bundles were loaded into the fuel channel, a few of these magnets were located in specific fuel string locations and used in conjunction with velocity transducers to determine bundle radial vibration. For typical tests, the first two or three inlet bundles and two outlet bundles are monitored.

2 Acoustic Program

2.1 Outline

For the Acoustic Program, temperature and frequency tests were performed to extensively compare the vibratory response of the 37M fuel to that of 37R fuel. Pressure drop tests were also performed to measure the pressure drop across the 37M string compared to the 37R string. The tests were conducted on three separate fuel strings, as outlined in Table 1.

2.2 Fuel Strings

For the acoustic qualification tests, three individual fuel strings were tested to compare the effects of using 37M fuel to 37R fuel. The first string tested, considered the reference string, consisted of eleven 37R and two 37R long bundles, the second consisted of eleven 37M and two 37M long fuel bundles and the third was considered a mixed string of four 37R, one 37R long, seven 37M and one 37M long fuel bundles. The long fuel bundles were used to align the outboard bearing pad of the first bundle onto the bearing sleeve and a mixed string was used to simulate the transition period of loading 37M fuel into the fuel channels. During the fuel string installation every other fuel bundle was offset by 12 degrees to produce maximum pressure drag along the fuel string.

Type of Test	Temperature (ºC)	Frequency (Hz)	Flow* (kg/s)	Pulse Amplitude (kPa)
Temperature Sweep	Increase (3° increments); 60°C to 305° Decrease (6° increments); 305° to 120° (Q2, Q3) & 305° to 227° (Q1)	210	28	30
Frequency Sweep	70, 150, 205, 265 and 295	70 - 250	28	20
Steady State	265 and 295	210	18, 24 and 28	20
Pressure Drop	70, 265 and 305	0 and 210	18, 24 and 28	0

*Or maximum achievable flow.

Table 1 – Test Conditions

2.3 Data reduction and Analysis

The results of the temperature sweep tests were compared using the maximum pressure pulsations at the inlet feeder, fuel channel and outlet feeder as a function of temperature for both the temperature increasing and temperature decreasing trends. These results indicated that the relative maxima at 60, 250 and 305ºC for each test series were nearly identical for each fuel string. Figures 4 & 5 provide maximum pressure pulsation comparisons for the temperature increasing sweeps of the inlet feed and the fuel channel.

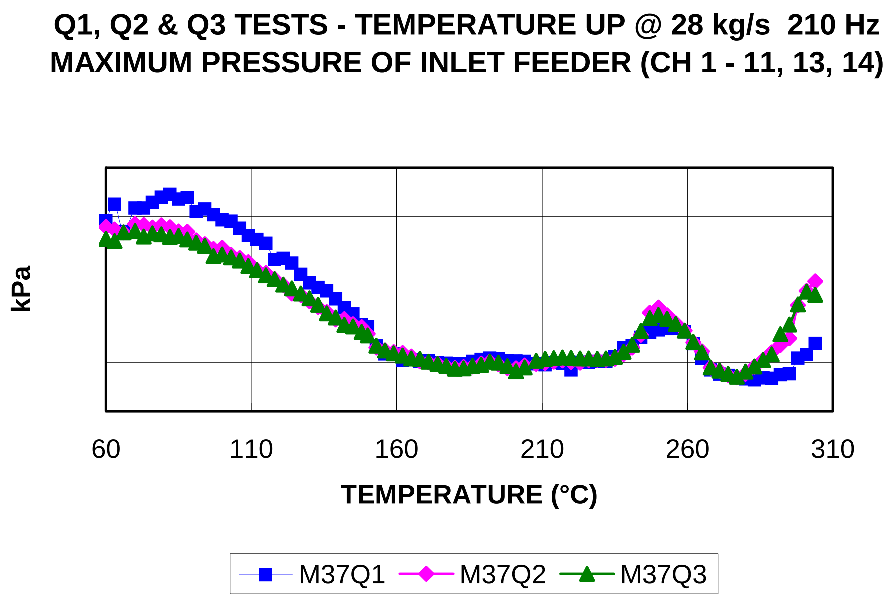

Figure 4 – Maximum Pressure Pulsation in the Inlet Feeder

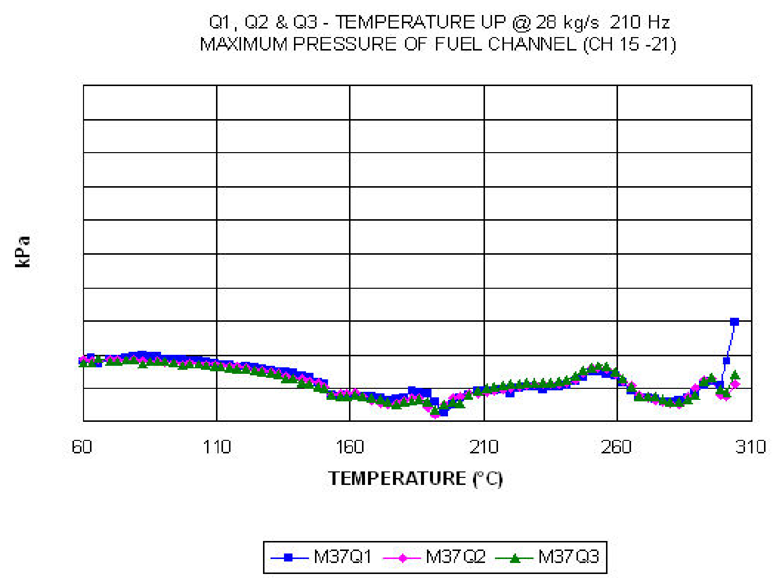

Figure 5 – Maximum Pressure Pulsation in the Fuel Channel

In addition to the maximum pressure measurements analysis, the temperature sweeps were also used to analyze the radial velocities of the fuel bundles as a function of temperature. The radial velocity measurements are used to determine the bundle rocking (5 to 20 Hz), the element fundamental (20 to 55 Hz) and the overall bundle displacements. The results of these comparisons indicated that the fuel strings are in very close agreement through-out the temperature sweep. The higher levels noted in test series 1 are mainly due to the results of a single measurement channel, bundle 12 in the mid plane of element 12. Refer to Figures 6 thru 8 for plots of the average RMS bundle displacements during portions of the temperature sweep tests.

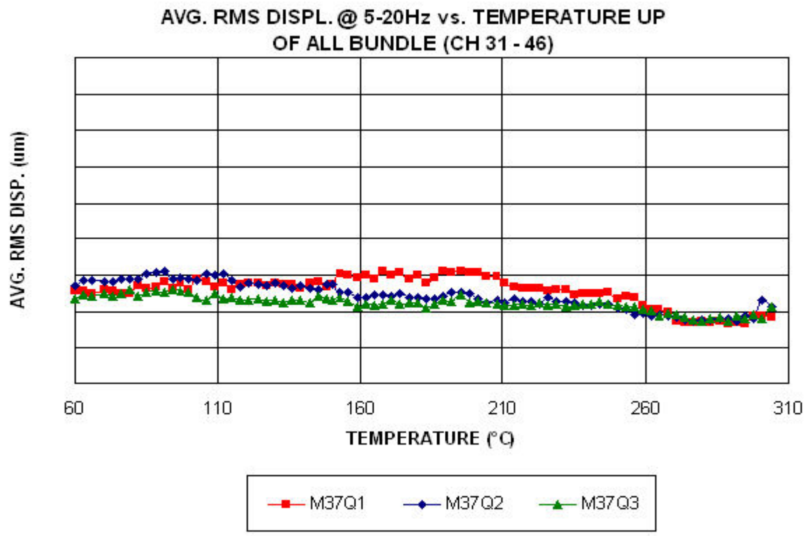

Figure 6 – Bundle Vibration (0 to 20 Hz)

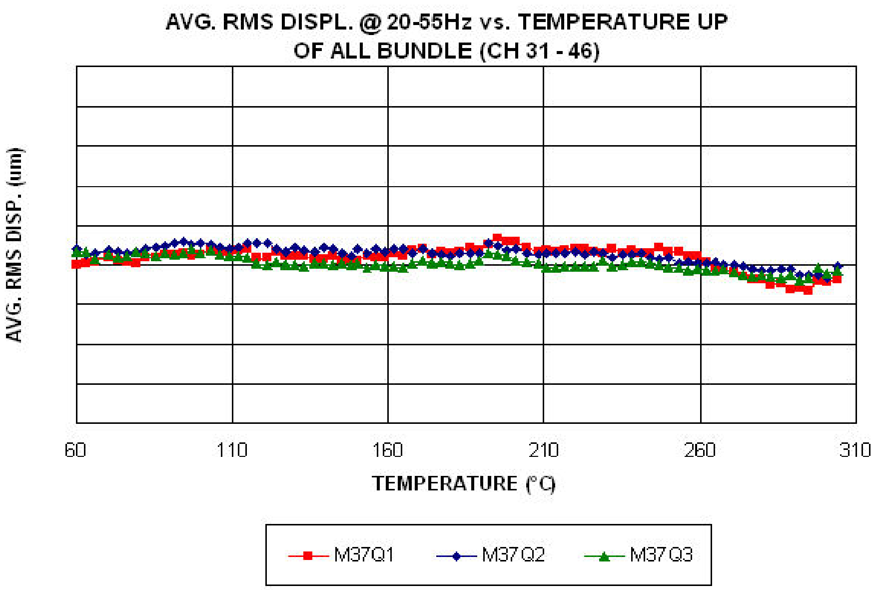

Figure 7 – Bundle Vibration (20 to 55 Hz)

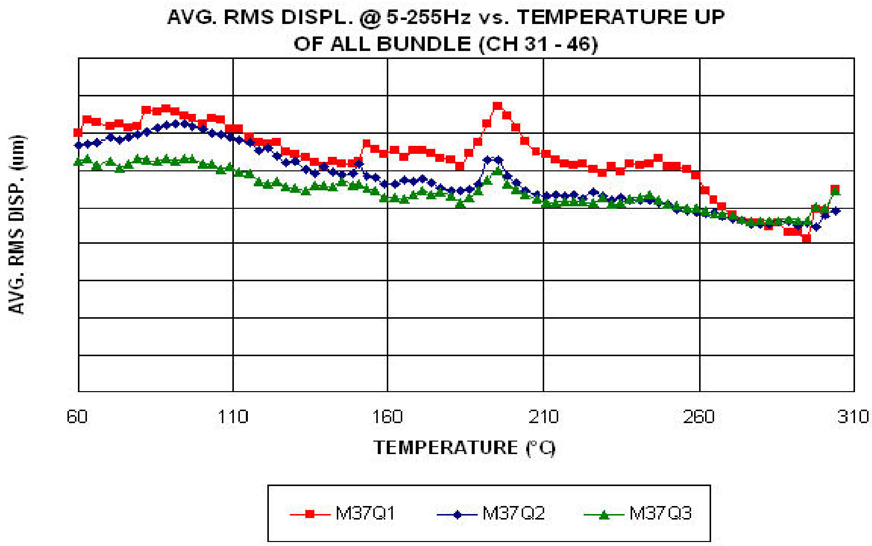

Figure 8 – Bundle Vibration (5 to 255 Hz)

As a further evaluation of the vibration data, a statistical analysis was performed using the Student T method, in which the second and third tests are compared to the reference string. The Student T results indicated all the Student T values were less than 1 and far lower than the 95% confidence level of 2.04. This value demonstrated that all the tests performed could be from the same data population and thus determined the average RMS displacement for the modified fuel is not statistically different than the regular fuel, with a 95% confidence level.

The frequency sweep test results were used to compare the measurements of the dynamic instruments as well as the maxima pressure in the inlet feeder, fuel channel and outlet feeder as shown in Figure 9. These results were also statically compared in reference to the 37R fuel string and produced Student T levels that are lower than 1 for the 95% confidence interval. Similar to the bundle vibration levels, the frequency sweep data determined all the results could be from the same population.

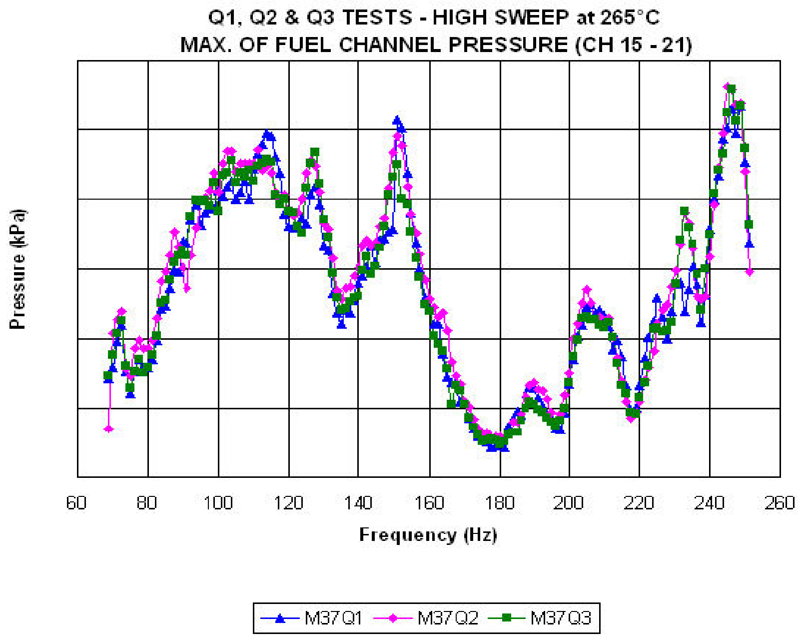

Figure 9 – Fuel Channel Frequency Sweep

Further to the Temperature and Frequency sweep tests, steady state and pressure drop tests were also conducted. As part of the fuel string installation prior to testing, the bundle orientations were measured and recorded to ensure the alignment for all the fuel strings were identical. During the steady state tests, both fuel string pressure drop and bundle vibration measurements were recorded for all three fuel strings.

The pressure drop measurements, in general, were the lowest for the Acoustic 2 test (37M), followed by the Acoustic 3 test (mixed string) and the Acoustic 1 test (37R). These are the results expected due to the ~0.9% increase in flow area of 37M fuel bundles relative to 37R fuel bundles, which would result in ~1.8% decrease in pressure drop in bare elements and ~1.0% overall. Following a similar trend, the pressure drop in the mixed string is expected to decrease by ~0.7% in relation to the 37R fuel string. The pressure drop measurements are in close agreement with the expected results as shown in Figure 10.

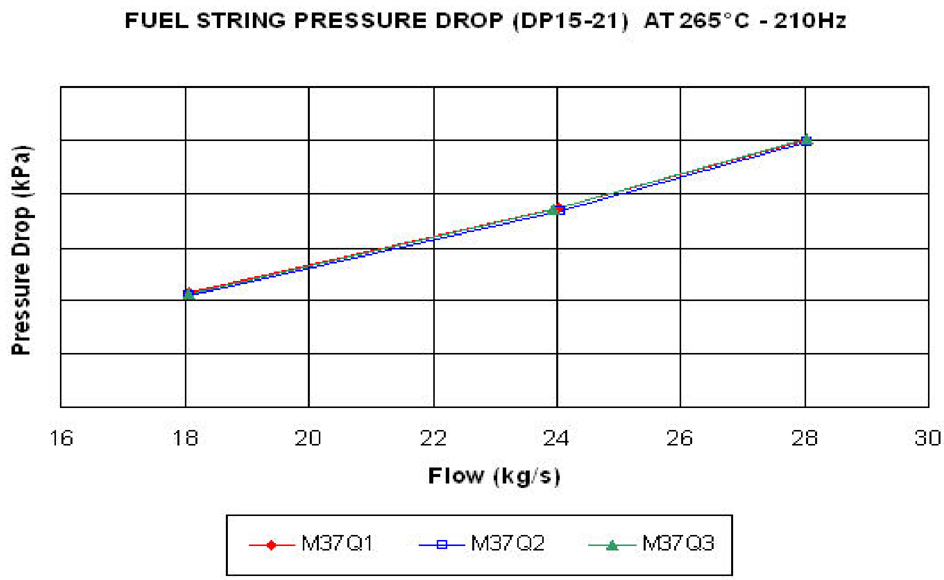

Figure 10 – Fuel String Pressure Drop

Fuel vibration tests were also performed in conjunction with the steady state tests over a range of flows at temperatures of 70, 265 and 310°C with a minimal dynamic pressure pulse at 210 Hz. As a result of the increasing flow, the fuel bundle element displacements over the 5 to 255 Hz frequency range increased, consistent with historical fuel performance test programs. Figure 11 confirms the consistency of this characteristic behavior between the three fuel stings. Further vibration tests with the addition of pressure pulsations provided an approximate 20% increase in the average fuel vibration. The dynamic pressure patterns were similar for all three fuels strings. See Figure 12 for of the dynamic pressure pattern as recorded during the Q3 tests.

The post test fuel bundle inspections (FEMER, destructive etc…) indicated there were no significant changes in bundle geometry, no weld failures or excessive wear and no endplate cracks.

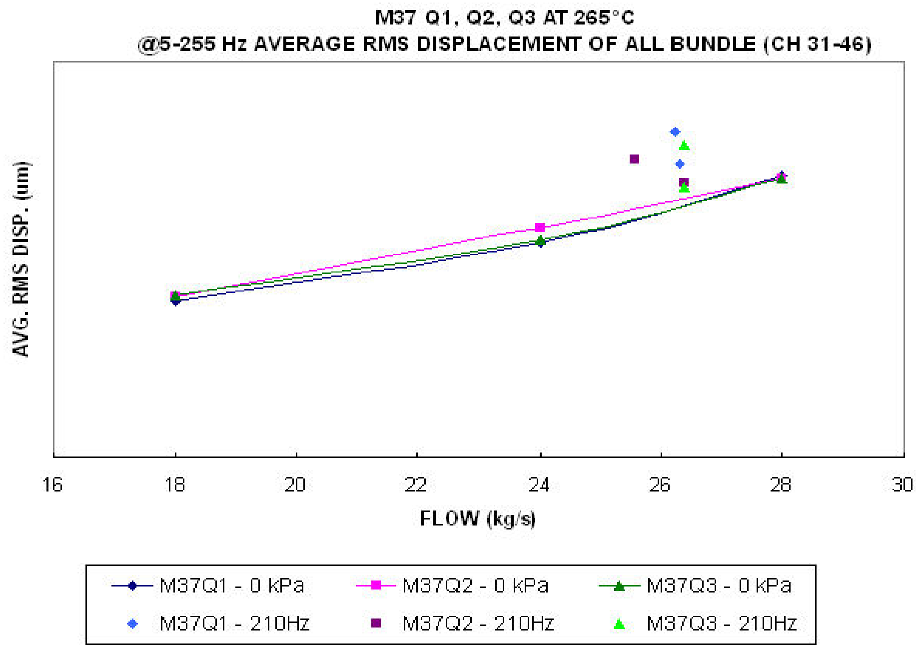

Figure 11 – Average Fuel Bundle Vibration

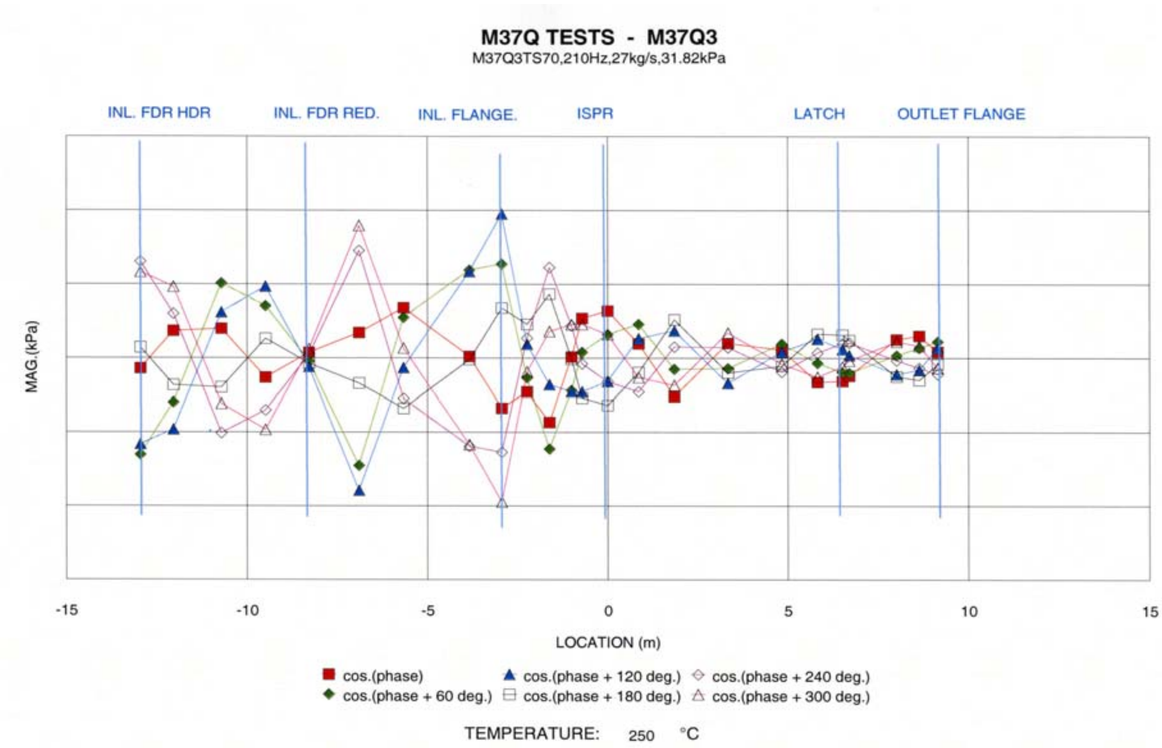

Figure 12 – Dynamic Pressure Pattern

3 Endurance Program

3.1 Outline

The Endurance Program was used as a method to compare the rates of fretting of fuel, the rates of mechanical damage to the fuel, the fuel vibrations and the rates of fretting in the pressure tube when using 37M fuel compared to 37R fuel. These tests were performed over an elapsed time of 168 hours to provide an adequate length of time to allow fretting and wear to occur. The tests were conducted on two separate fuel strings, as outlined below.

The tests were performed with a loop temperature of 265ºC, 10.7 MPa, a coolant flow of 28 kg/s and a pulse frequency of 210 Hz to establish a 20 kPa pressure pulsation at the inlet shield plug ring. These conditions were maintained for the duration of the test. Data were recorded on both the high speed DAS and the steady state DAS at a minimum of 1, 2, 5, 10, 25, 50, 75, 100, 125, 150 and 168 hours of elapsed time.

3.2 Fuel Strings

For the Endurance Tests, the two fuel strings consisted of 13 fuel bundles, 11 regular length and two long fuel bundles, using 37M fuel for the first string and 37R for the second string. For both tests, the bundle in position 1 was located in the outlet of the channel, resting on the latch.

3.3 Data Reduction and Analysis

The loop conditions were maintained for the 168 hour duration as required by the Endurance test procedure. The dynamic radial velocity of the elements were consistent with the majority of the measured channels, with the exception of one failed instrument.

The time histories for both the 37M and 37R fuel strings indicated that the maximum radial velocities of the instrumented bundles appeared on element 12 in position 12 for each fuel string, with the 37M maximum radial velocities ~5% higher. In addition, the second highest radial velocities were located on element 12 in position 13 for each fuel string, with almost identical radial velocities.

The bundle rocking motion, as recorded by the displacement measurements in the 5 to 20 Hz frequency range, was at a maximum for both fuel strings on element 16 in position 13. The magnitude of this rocking was 38.5% higher on the regular fuel bundle in comparison to the modified fuel bundle. Conversely, the largest overall element radial displacement was located in the same bundle position, but on element 3. These values demonstrated the modified fuel had an increase of 20% in comparison to the reference fuel.

The grand average and standard deviations recorded for both tests are summarized in Table 2 below. These values indicate that the average bundle rocking (5 to 20 Hz) and element vibration (20 to 55 Hz) are very similar for both the 37M and 37R fuel strings.

ENDURANCE TESTS

"GRAND" AVERAGE & STD DEV. RMS DISPLACEMENT

(All channels: 31 - 46)

	5-20Hz		20-55Hz		5-255Hz	
	AVG.	STD DEV.	AVG.	STD DEV.	AVG.	STD DEV.
ENDURANCE 1 (n = 328)	4.46	2.86	8.94	6.69	11.37	6.31
ENDURANCE 2 (n = 336)	5.17	4.09	8.67	7.37	11.65	7.19

*Endurance 1: 37M fuel String & Endurance 2: 37R Fuel String

Table 2 – Fuel Bundle Vibration

Similar to the Acoustic tests, the fuel string pressure drop was also measured and recorded. The results were consistent, and as anticipated, showed the modified fuel string had a 0.8% lower pressure drop in comparison to the regular fuel string. These tests were performed in a maximum misaligned position, with every other fuel bundle in the string offset by 12 degrees.

In addition to the bundle vibration characteristics, pressure drop and statistical analysis, fuel bundle visual and dimensional inspections were performed. These inspections included the kink tube inspection, a Fuel Element Measuring Rig (FEMER – automated measuring system, see Figure 13) scan for element and endplate dimensional characteristics and a destructive inspection to visually inspect the spacer pad wear.

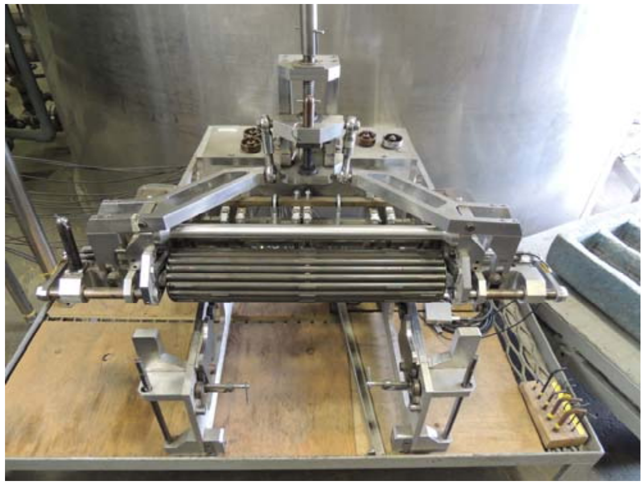

Figure 13 – FEMER

As a result of the visual inspection of the pressure tube and fuel bundles, the only noticeable wear noted was on the spacer ring. It has been determined that a bearing pad from the 37M fuel bundle in position 13 was in contact with the ring and over time started fretting, as shown in Figure 14.

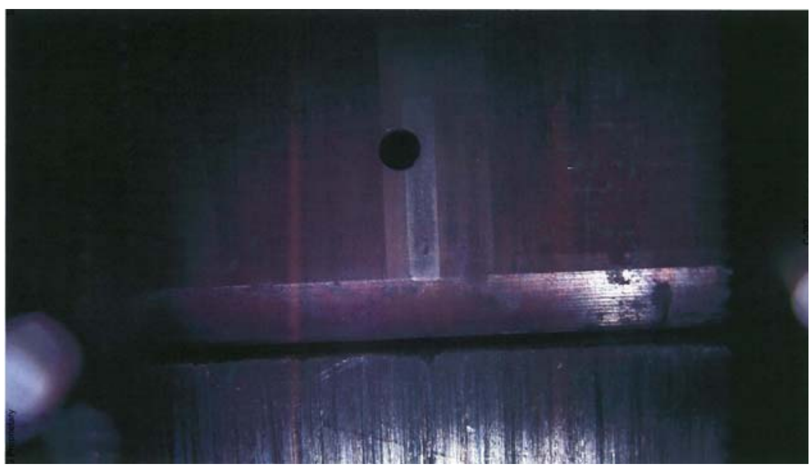

Figure 14 – Bearing Pad Wear – Endurance Test 1, Bundle Position 13

As part of the post-test inspections, the fuel bundles in positions 1 (flow outlet), 12 and 13 (flow inlet) were disassembled by dissecting the end plates. A spacer pad wear characterization table (see Figure 15) was used to assign the specific wear values. The resulting visual inspections indicated a maximum spacer pad wear of Type 4 for both fuel strings. Wear tables were created to summarize the overall spacer pad wear of each dismantled fuel bundle, which indicated the overall wear type was 8%, 18% and 3% higher on the reference fuel compared to the modified fuel for bundles in positions 1, 12 and 13 respectively. See Figure 16 and Table 4 and 5 for spacer pad wear summaries. However, due to the low magnitude of wear rates and a test acceptance criteria of less than Type 6, these spacer pad wear rates were considered inconsequential and acceptable.

WEAR TYPE	VISUAL APPEARANCE	DESCRIPTION
1		No visible wear.
2		Small wear area at either or both ends. Estimated depth of wear up to 0.05 mm (i.e., 2/1000th inch).
3		Larger wear area at either or both ends. Estimated depth of wear up to 0.10 mm (i.e., 4/1000th inch).
4		Area of wear at both ends connected in a figure eight pattern. Estimated depth of wear up to 0.10 mm at ends, 0.05 mm in connecting area (i.e., 2/1000th inch).
5		Similar to 'Type 4' but wear covers a larger area. Connecting area wider and deeper than 'Type 4'. Estimated depth of wear overall up to 0.10 mm (i.e., 4/1000th inch).
6		Axis of wear area at a less acute angle to axis of pad. Wear more even in effected area. Estimated depth of wear up to 0.20 mm (i.e., 8/1000th inch).
7		Similar to 'Type 6' but more severe. Estimated depth of wear greater then 1/4 of the initial pad thickness (minimum pad height is 0.70 mm or 28/1000th inch).
8		Wear similar to 'Type 6' and 'Type 7' but more severe. Depth of wear is sufficient to allow mating spacer pad to contact sheath of adjacent fuel element as indicated by dotted line. Up to 50% of sheath thickness has worn.
9		Wear similar to 'Type 8' but more severe. Most of sheath thickness has worn but not yet through sheath. Fuel is not exposed.
10		Wear similar to 'Type 8' and 'Type 9' but depth of sheath wear is greater than sheath thickness. Fuel is exposed.

Figure 15 – Spacer Pad Wear Classification

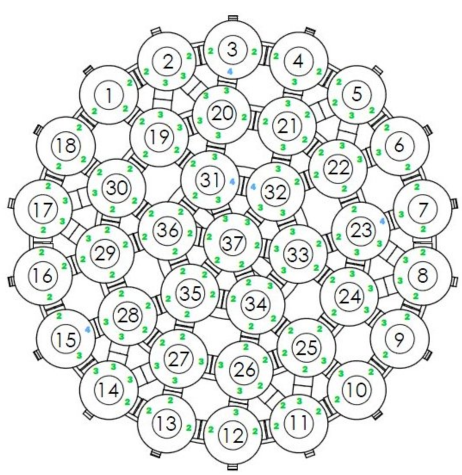

Figure 16 – Sample Spacer Pad Wear Diagram

Post Endurance Test No. 1																		
Fuel Bundle	Position 1						Position 12						Position 13					
Test Series	1						1						1					
Bearing Pad / Element #	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	1	1	2				1	1	2				1	4	2			
2	2	1	2	2			3	1	2	3			2	1	2	2		
3	2	2	3				2	1	3				2	1	2			
4	2	2	1				3	2	1				1	1	1			
5	2	2	2	2			1	2	1	1			1	1	1	1		
6	2	2	4				2	2	1				1	1	2			
7	4	2	4				1	3	1				2	2	4			
8	3	2	2	1			1	1	1	1			4	2	2	1		
9	2	2	3				1	1	1				1	2	1			
10	2	2	2				1	3	2				1	2	3			
11	2	2	2	2			2	2	1	1			3	2	2	4		
12	2	2	1				2	4	1				4	2	2			
13	1	2	1				1	2	1				1	2	1			
14	2	1	2	2			1	2	1	1			1	2	4	1		
15	1	1	1				1	3	1				1	2	1			
16	1	2	1				1	3	2				1	1	2			
17	2	4	2	1			1	1	2	1			2	2	1	1		
18	1	2	2				1	1	1				1	2	1			
19	2	2	2	1	1		2	1	1	2	2		2	2	1	1	3	
20	2	2	2	2	2		1	2	2	1	1		1	2	2	2	2	
21	1	1	2	2	2		2	1	2	2	1		2	3	2	1	1	
22	2	2	1	1	2		2	1	1	1	1		2	2	1	1	2	
23	2	2	1	1	1		2	2	1	1	2		2	3	3	2	2	
24	1	2	2	2	1		1	2	1	1	1		2	4	1	2	1	
25	1	2	1	2	2		2	2	1	1	3		1	3	2	1	2	
26	1	2	2	2	1		2	3	2	4	2		2	3	1	1	1	
27	2	2	2	2	2		2	2	2	2	2		2	2	2	2	1	
28	2	2	1	1	2		2	2	3	1	2		2	2	3	1	2	
29	2	2	2	3	2		2	3	1	2	2		2	2	2	2	1	
30	1	1	2	1	1		2	1	1	1	1		1	1	1	1	2	
31	1	2	2	1	2		1	1	2	1	1		2	1	1	2	2	
32	1	2	2	2	1		2	2	1	2	1		2	1	2	3	3	
33	2	2	2	2	2		1	3	2	2	2		2	2	1	4	3	
34	1	2	1	2	2		1	2	2	3	2		1	2	3	2	2	
35	1	2	2	2	2		1	2	2	2	3		3	2	2	2	2	
36	2	2	1	1	2		2	2	1	1	2		2	1	2	1	2	
37	1	2	2	2	2	3	2	3	3	2	2	2	2	2	2	2	2	2
Average Wear Type:	1.782						1.673						1.833					

Colour	Wear Type
	1 to 2
	3 to 4
	5 to 8

Table 4 – 37M Spacer Pad Wear Summary

Post Endurance Test No. 2																		
Fuel Bundle	Position 1						Position 12						Position 13					
Test Series	2						2						2					
Bearing Pad / Element #	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	1	2	2				1	2	2				2	2	2			
2	2	2	2	3			2	2	2	3			2	1	3	2		
3	3	2	2				2	2	2				1	2	1			
4	2	2	2				2	2	2				1	2	1			
5	2	1	2	1			2	2	2	2			1	2	2	1		
6	1	2	1				2	2	3				1	2	2			
7	1	2	1				3	2	2				2	3	2			
8	1	3	2	2			2	3	4	2			2	2	2	1		
9	1	2	1				1	2	1				1	2	1			
10	1	2	1				1	2	1				1	2	2			
11	2	2	1	2			1	2	2	1			2	2	2	1		
12	1	2	2				1	1	2				1	2	1			
13	2	2	2				2	2	1				1	2	2			
14	2	2	2	2			1	2	2	1			2	2	3	1		
15	2	2	2				1	2	2				2	2	1			
16	1	2	2				2	2	2				1	2	2			
17	2	4	4	1			2	2	4	1			2	2	2	2		
18	1	2	1				1	2	2				2	2	2			
19	2	2	1	1	2		2	2	2	1	2		1	1	2	1	2	
20	1	3	2	2	2		2	2	2	2	2		2	2	2	2	3	
21	2	2	2	1	2		2	2	1	2	3		2	2	2	1	2	
22	2	1	2	2	2		2	2	2	2	2		1	2	1	2	2	
23	1	2	1	3	2		2	2	3	2	2		2	2	2	2	3	
24	1	2	2	2	2		2	3	2	2	2		2	2	2	2	2	
25	2	2	2	3	2		2	2	2	2	2		2	2	2	2	2	
26	2	1	2	2	2		2	2	1	1	2		2	2	2	2	2	
27	2	2	2	2	2		2	2	2	2	2		2	2	2	2	2	
28	2	2	2	2	2		2	2	2	3	2		2	2	3	2	2	
29	2	2	3	2	2		2	2	2	2	2		2	2	2	2	3	
30	2	2	2	2	4		1	2	2	2	4		1	2	2	1	2	
31	2	2	2	2	2		2	2	2	2	2		1	2	2	3	2	
32	3	1	2	3	2		2	2	1	2	3		2	2	2	2	2	
33	2	2	2	1	2		2	2	3	2	2		1	2	2	1	2	
34	2	2	2	2	2		3	2	2	2	2		1	2	2	2	1	
35	2	2	2	3	3		1	2	2	3	2		2	2	2	3	4	
36	2	2	2	2	2		3	2	2	1	2		3	2	2	2	2	
37	2	3	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	4
Average Wear Type:	1.923						1.974						1.885					

Colour	Wear Type
	1 to 2
	3 to 4
	5 to 8

Table 5 – 37R Spacer Pad Wear Summary

The remainder of the physical inspections indicated the following:

- No sheath deformation occurred
- No sheath collapse on the centre element of any disassembled bundles
- Both the reference and the modified fuel bundles passed the post-test kink tube inspection
- No mechanical damage such as endplate cracking or element weld failure occurred

4 Conclusions

Various qualification tests for the use of 37M fuel bundles in the Darlington Reactors were performed at Stern Laboratories, and the results were presented in this paper. Several series of Acoustic and Endurance tests were conducted. After the completion of each testing program various inspections and data analysis were performed to evaluate the performance of 37M fuel bundles in relation to 37R fuel bundles. The results of these tests indicated that the 37M fuel bundles performed in very similar manner to the 37R fuel bundles and the customer's acceptance criterion were met. In summary, the 37M fuel bundles are suitable for use in the Darlington Reactors.

5 References

1. S. Titizian, G.I. Hadaller, "Out-reactor Acoustic and Pressure Drop Qualification Tests of Modified 37-Element (37M) fuel bundles for use in Darlington Reactors", Stern Lab Report SL-208, 2010, March.
2. R.C. Hamilton, G.I. Hadaller, "Out-reactor Endurance Qualification Tests of Modified 37-Element (37M) fuel bundles for use in Darlington Reactors", Stern Lab Report SL-209, 2010, March.
3. S. Titizian, G.I. Hadaller, "Out-reactor Crossflow Qualification Tests of Modified 37-Element (37M) fuel bundles for use in Darlington Reactors", Stern Lab Report SL-210, 2010, March.