CANDU FUEL QUALIFICATION TESTING IN COOLANT PRESSURE PULSE CONDITIONS

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ABSTRACT

In Nov. 1990, fuel damage occurred during refueling in Ontario Hydro's Darlington Unit 2 Generating Station. The fatigue damage to the end plates was determined to be a result of acoustic pressure pulsations caused by the main coolant pumps. The pumps generated a pressure pulse in the coolant at 150 Hz, due to the 30 Hz pump rotation frequency multiplied by the five pump impeller vanes. Furthermore, the acoustic response of the piping amplified the pressure pulses in the headers and feeders. Thus pulsation amplitudes greater than 40 kPa (0-to-peak) reached the fuel. This system response had not been anticipated in the primary heat transport system design, nor was the fuel designed for such pressure pulse conditions. Thus, a small number of fuel channels was subject to unexpectedly high levels of pressure pulsations.

The realization that all fuel channels have some potential for pressure pulsations, required that these conditions be incorporated into the tests qualifying new fuel or new channel hardware designs. As a result, methods were developed to test fuel in conditions similar to those experienced in reactor, and to develop techniques to determine acceptable fuel behavior.

INTRODUCTION AND BACKGROUND

The past practice for CANDU reactors to qualify the fuel was to assess the vibration characteristics due to the flow conditions and to qualify the fuel / channel system through long term out-reactor endurance tests. In order to optimize the geometry for higher flows, the subsequent emphasis was at the fuel channel inlet where significant turbulence remains from the coolant entrance effects to the channel through the end fitting / liner tube / shield plug / pressure tube. A.D. Lane, I.E. Oldaker et al [1] led many of these studies to examine the effects of mass flows, shield plug designs, spatial gaps between the shield plug and the fuel, feeder pipe configuration and fuel designs. From this information, the endurance test conditions could be selected carefully to establish the geometry which would lead to the most turbulence and vibration. The selected flow would be 10 - 20 % greater than the highest nominal mass flow for the reactor.

The fuel in Ontario Hydro's Darlington Generating station was found to have been damaged by acoustic pressure pulsations caused by the main coolant pumps [2,3,4] after the fuel caused a fuel handling event on November 30, 1990. The damage to the fuel was end plate cracks caused by fatigue which had been induced by the pressure pulsations causing the relative axial movement between the inner and outer rings of fuel, particularly fuel on the latch at the end of the channel.

Changing the number of impeller vanes from 5 to 7, and hence the coolant pulsation frequency from 150 Hz to 210 Hz, greatly reduced acoustic pressures reaching the fuel. Thus, the causes of this incident have been identified, isolated and corrected in Darlington.

The vibration of the fuel string caused by the pressure pulsations has also been related to an increased level of fretting of the pressure tube.

As a result of the findings that pressure pulsations were not negligible in-reactor, and that the fuel was sensitive to them, it was determined that future testing of fuel for Ontario Hydro's reactors should also incorporate tests at realistic reactor pulsation conditions. Therefore, new test methods have been developed to assess the effects of fuel design changes and potential solutions to further mitigate the fretting of pressure tubes. Stern Laboratories has recently tested the following components.

1) The "long" fuel bundle [5], which is simply longer than the standard bundle by 0.5 inches (12.7 mm). This design change allows the fuel string to be loaded into fuel channels such that the bundle at the coolant inlet end of the channel always rests on the spacer sleeve. This prevents the inboard bearing pad from causing fretting of the "burnish" mark of the pressure tube, a critical area of the channel. The maintenance of a relatively small axial gap between the fuel string and the inlet shield plug also prevents significant movement of the string in the event of a large break LOCA, reducing the reactivity insertion that such a fuel string movement might cause.

2) The flow straightening inlet shield plug design [6], which has a 42 mm thick plate with 6.3 mm flow holes installed in a plate in the shield plug skirt, just before the start of the fuel string. This was one of the design solutions to the Darlington fretting problems at the rolled joint area of the channel. The vibration of the bundle at the inlet end was significantly reduced.

3) The F3SP shield plug design [7], which supports the downstream end plate during operation, rather than the latch support which supports the fuel string only on the shoulders of about 12 outer elements of the downstream bundle. This shield plug is necessary in the Bruce A reactors for the "fueling with flow" (FWF) mode of operation. Without F3SP's, FWF operation potentially could cause delayed hydride cracking failures of end plates, given the high stresses on the end plate, sufficient hydride buildup in the end plate and sufficient hydrogen supersaturation caused by operation at reduced temperature.

4) The acoustic shield plug design [8], which virtually eliminates the coolant pressure pulsation which could enter the channel. This design of inlet shield plug is useful in order to prevent both end plate cracking and severe pressure tube fretting.

Fuel test methods, particularly for qualification tests, should provide data which are clear and unambiguous about the effects of design changes or the operating conditions. However, the examination of data from Ontario Hydro's reactors demonstrated that there was a very high degree of variability between channels, and a problem identifying which fuel bundles had caused the fretting damage in a particular channel. Some fuel geometric factors related to mid plane fretting are necessary to cause fretting of the pressure tube [9]. Thus, it has become apparent that not only do the flow and geometric conditions have to be bounded in the tests, the high degree of variability must also be considered.

The approach developed to quantify the variability was one of optimization. Ideally, a large number of endurance tests at the conditions imposed by the reactor, would provide confidence that the design meets all requirements. However, this was not possible because it would impose unreasonable demands on schedule and finances. The general approach taken is as follows.

1) Tests were developed which would span the reactor conditions and search for differences in the response between the standard fuel or conditions, and the test fuel or conditions. This makes an implicit assumption that the standard bundles perform in an acceptable way.

2) If it was felt to be necessary, a short endurance test would then be completed. The short duration of the test would provide sufficient information to ensure that a severe fuel or pressure tube problem did not exist, and that the design could be put into service with some confidence in a minimal amount of time.

3) Final "proof" tests would be completed in-reactor on a small scale, before full implementation of the design change. It is to be recognized that the reactor imposes unique pressure pulsation and flow conditions on each channel in the core. Therefore, a selection of channels is required. The fuel bundles are then put through a standard irradiation, after which they are examined in the fuel bays for wear or any other indications of damage. If this process is successful, the design can then be accepted for full implementation.

In this paper we discuss the methods which were developed to investigate the fuel vibration response under pressure pulsation conditions.

EXPERIMENTAL

MATERIALS AND TEST METHODS

Loop Configuration At Stern Laboratories

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 fueled. 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 11 MPa and 310 °C and the main circulating pump can provide a flow of 60 $kg.s^{-1}$ at 360 m head. 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 vapor).

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 or displacement of downstream end plate bundle 1
- Axial motion of bundles 1 and 13.

Pressure Pulsation Facility.

The variable frequency pressure pulse generator is located downstream of the flow measuring orifice, as shown in Figure 1. 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 bypass valve was installed around the pump to control the amount of flow through the pump and hence the pulsation amplitude. The bypass 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.

Feeders.

The inlet feeder is designed to duplicate channel K12E at DNGS hydraulically and in most mechanical respects. The pipe diameters and lengths are the same although 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 of the other loop components.

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.

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. Selected outer elements of some bundles were 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. In some tests, Bundle #1 had the end plate deflection and dynamic motion monitored with ultrasonic position transducers, or eddy current proximity probes.

Bundle Motion with Ultrasonic Transducers

Ultrasonic transducers supplied by Ontario 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. The ultrasonic transducers were connected to Novascope signal conditioning equipment to displacement histories. The position and motion of the elements relative to the pressure tube could also be monitored with the ultrasonic transducers located on the outside of the pressure tube. In this way it could be determined whether the fuel elements were clear of the pressure tube and hence free to vibrate as seen in Figure 2. In addition, this technique allowed the measurement of the vibration at any location along an element.

Data Acquisition

The instrumentation sensors were installed as required on the test loop and the output from the signal conditioning amplifiers routed to the data acquisition and analysis work station. A Zonic 7000 Workstation with a 48 channel input section used Zeta software for data acquisition storage and conversion to various functions in the time or spectral domain. All input channels were sampled simultaneously and the time history data are stored on the system "thru-put disc" for processing after testing. The digital data can be transferred to magnetic or optical storage media for long term archival or retrieval for further processing. The equipment allows all data to be processed on a time signal basis and the relation between signals assessed from the stored data. Thus analysis of the data could be done off-line after the test equipment was shut down. A typical power spectral density (psd) function is shown in Figure 3.

SELECTED TEST RESULTS

Data related to the acoustic pressure pulse conditions are required for the assessment of the driving forces placed on the fuel. The acoustic response of the loop and fuel / channel is measured during the tests in order to identify whether the new design has caused a change. The pressure waves can consist of traveling, or standing waves, or a combination. Figure 4 shows the dynamic pressure pattern in the inlet feeder and channel at 150 Hz excitation frequency and 265 °C. This has been developed using the measured response of 25 dynamic pressure transducers located along the feeder-channel assembly. Each phase angle provides a snapshot of the pressure pattern along the assembly at that instant in time. Following through a complete cycle (360°) provides the complete wave pattern at one frequency. The analysis software allows the easy gathering and analysis at the frequency of interest, and ignoring other components not of interest.

Figure 4 shows a plot of the wave form in the loop at the pump pressure pulse frequency of 150 Hz, and the operating condition of 265 °C. Marked on the figure are the positions of components of the fuel channel. It can be seen that the dynamic pressures within the feeder are highest, and that there is a significant component of standing wave. Within the channel, the pattern indicates that a traveling wave exists. Figure 5 shows a similar plot at the 310 °C temperature where the standing wave pattern appears within the channel as well. These acoustic wave patterns determine the forcing function available to excite the fuel. It should be noted that single point pressure measurements cannot be used to define this forcing function.

Displacement measurements of fuel elements are made with magnetic velocity transducers that require a target magnet but can cover the full temperature range to 310 °C, or with ultrasonic transducers that can be positioned anywhere along an element but are limited in operation to temperatures below 100 °C. In general the two methods give very similar results with agreement within ±5 %.

Fretting Potential

The vibration of the fuel elements is the main cause of fretting between the elements and the pressure tube. The measured parameters in these tests cannot directly determine whether a particular element has the ability to fret, because the vibration of the elements in contact with the pressure tube, is small. That is, the elements with bearing pads that are in close proximity to the pressure tube, have a small amplitude of vibration but it may be sufficient to cause fretting. However, the elements which are away from the pressure tube and are free to vibrate can vibrate with higher amplitudes. Thus, for the fretting elements there is an inverse relation between the vibration amplitude and fretting. However, the fretting potential can be inferred from the amplitude of vibration response for the non fretting elements and statistical methods (Student's t) were used for the comparison of designs.

The results for the long bundle design showed a high degree of variability. The mode shapes of the element vibration response from measurements made with ultrasonic transducers are shown in Figure 6.

Figures 7 to 9 show how the characteristic vibration of the bundles is assessed. Figure 7 shows the magnitude, phase and coherence of two elements measured at the end of the bundle location, on opposite sides of the bundle (position 13, channel coolant inlet end). The fact that the elements are coherent showing the same amplitude and 180° out of phase means that the bundle is moving in a side to side motion at that location in the 5 to 20 Hz range. Similarly in Figure 8, near the mid plane, there is poor coherence at the maximum element vibration of 30 to 35 Hz, indicating the fundamental element vibration is independent of the other elements. In Figure 9 the same two signals have high coherence only at the 150 Hz excitation frequency.

Figure 10 shows the dynamic pressure amplitude at 150 Hz along the fuel channel and the element vibration amplitudes at the stimulated frequency for a fuel string. The tests were conducted in a "temperature sweep mode" where the temperature of the loop was changed and the characteristic acoustic response would cause dynamic pressure increases within the channel. Clearly there is a high degree of variation of the element vibration along the channel. It was also noted that changing the test conditions could significantly change the amplitude of one of the high amplitude elements. However, the element vibrations followed the stimulated pressure pulse within the channel. Frequency sweep tests are also used at fixed temperatures to look for resonances in the fuel or acoustics.

Investigation of the response of the fuel to temperature changes, allowed a comparison of the response to changes in design. Vibration of the fuel is very dependent on the fuel geometry, the specific support and contact conditions for a particular fuel element. The clearances between the fuel bearing pads and the pressure tube determine whether a particular element might cause fretting [4].

SUMMARY

1. Acoustic pressure pulsations in reactor loops can potentially induce vibrations in fuel which can cause damage to the fuel and channel. Therefore qualification tests should include representative acoustic test conditions to ensure acceptable performance.

2. Techniques have been developed to provide "temperature" and " frequency" sweeps that cover the full range of conditions that could occur in reactor. These tests provide assurance that new fuel bundle designs will function satisfactorily under reactor conditions.

3. Test loop acoustics must be carefully assessed to ensure they produce forcing function that are representative of those the fuel experiences in reactor and thus result in realistic vibration response.

4. Vibration amplitudes in CANDU fuel can be highly variable and therefore vibration measurements must be made at many locations to provide a reliable estimate of fuel response in assessing the effect of a design change.

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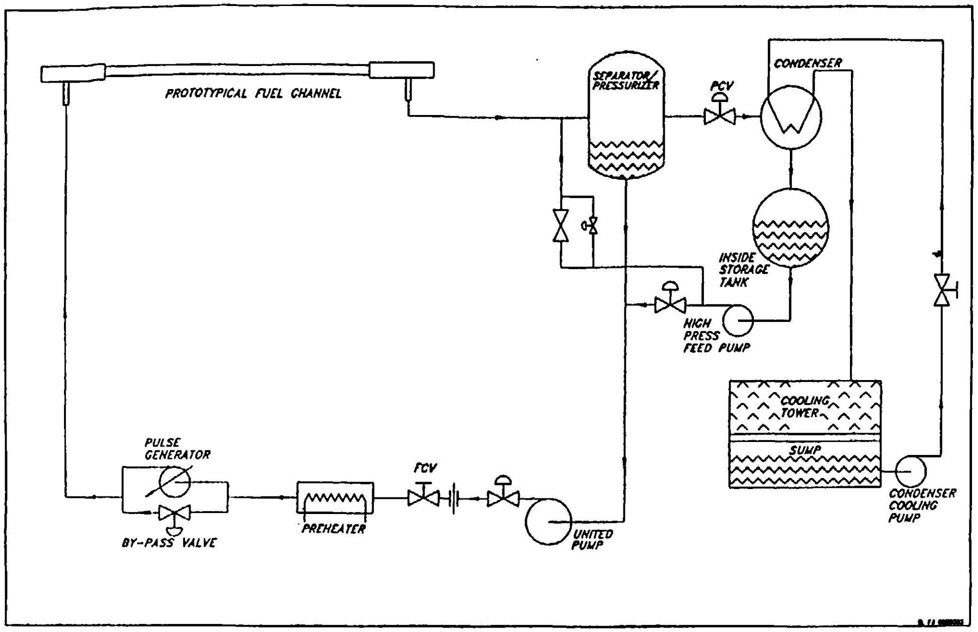

Figure 1: SCHEMATIC OF THE TEST APPARATUS

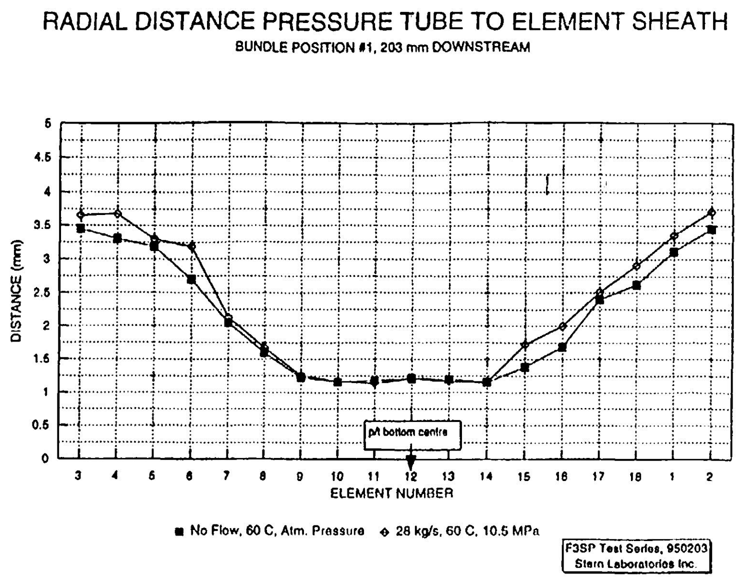

Figure 2: STATIC POSITION OF BUNDLE ONE ELEMENTS

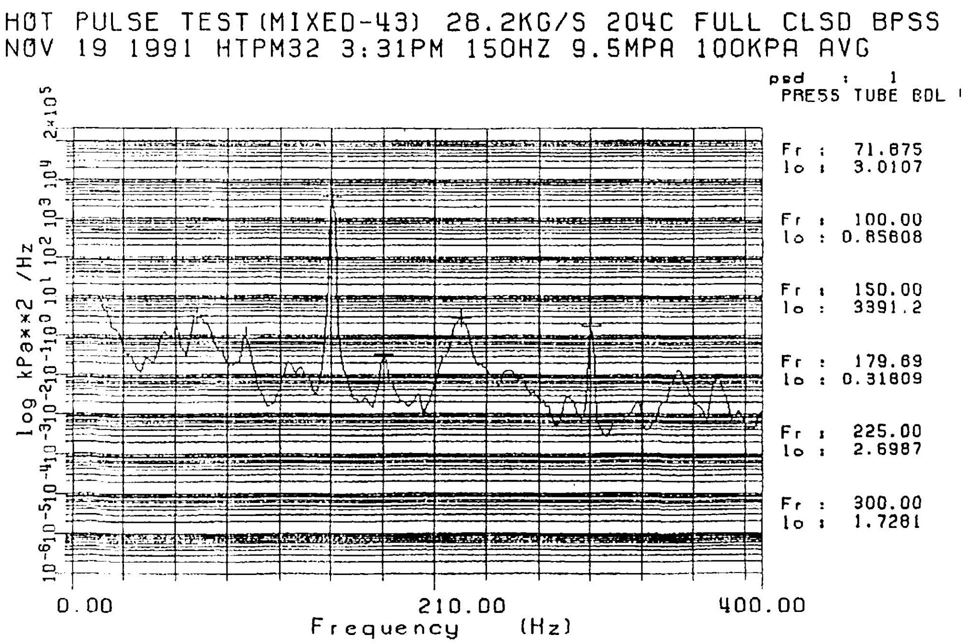

Figure 3: TYPICAL POWER SPECTRAL DENSITY FUNCTION

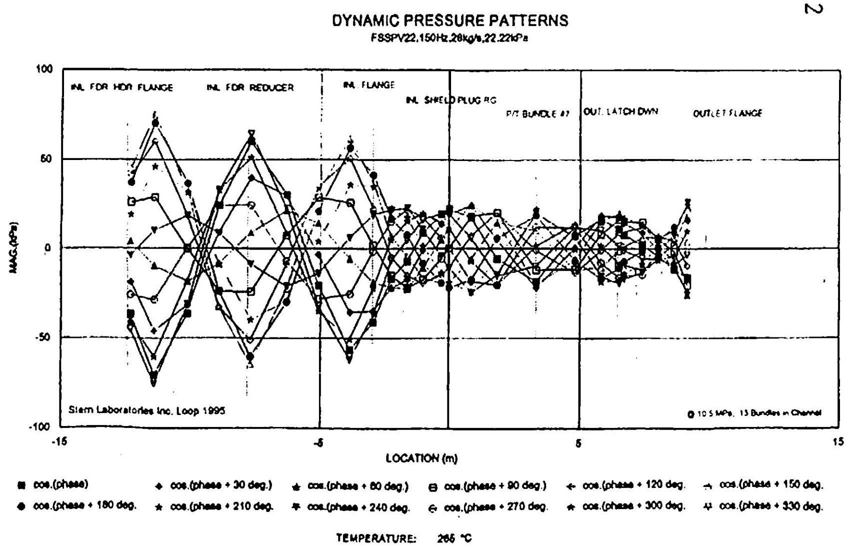

Figure 4: DYNAMIC PRESSURE PATTERN ALONG THE LOOP AT 265°C

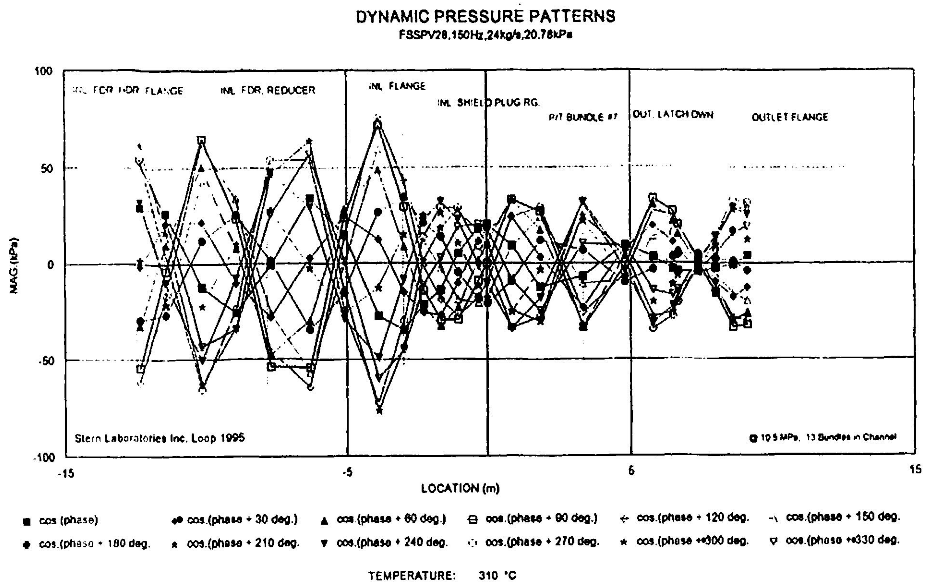

Figure 5: DYNAMIC PRESSURE PATTERN ALONG THE LOOP AT 310°C

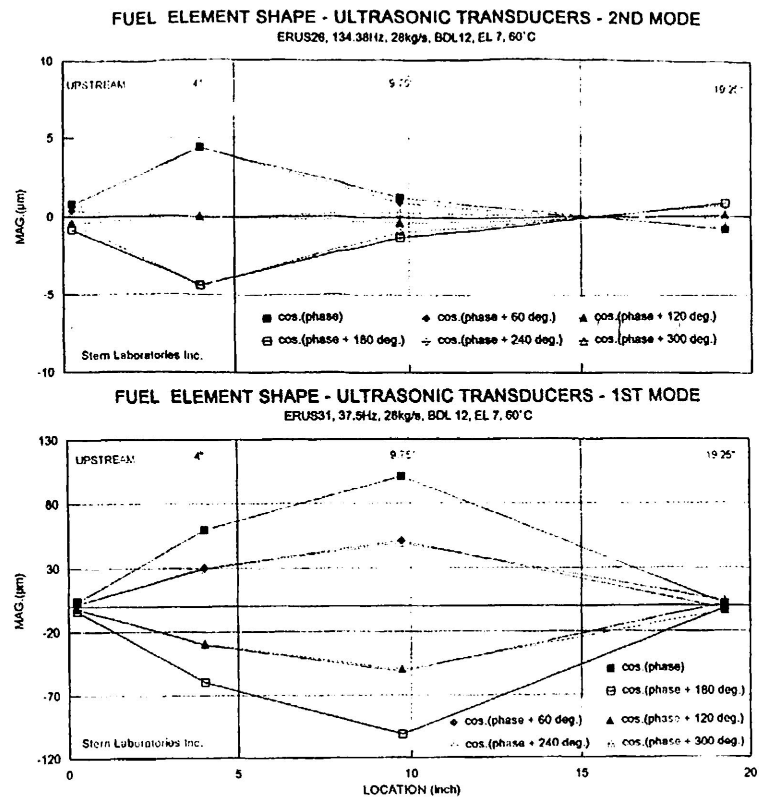

Figure 6: ELEMENT MODE SHAPES

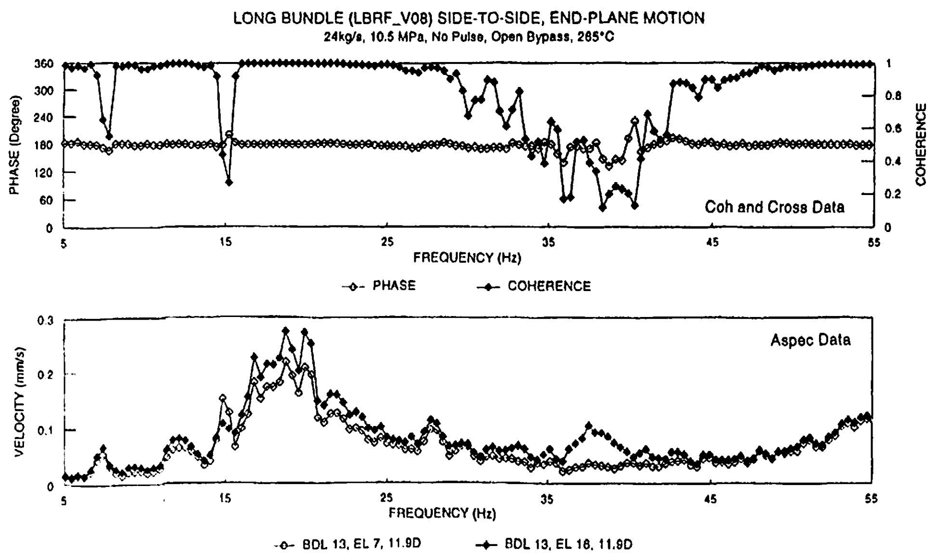

Figure 7: PHASE, COHERENCE AND MAGNITUDE OF TWO ELEMENTS ATEND-PLANE (5-55Hz)

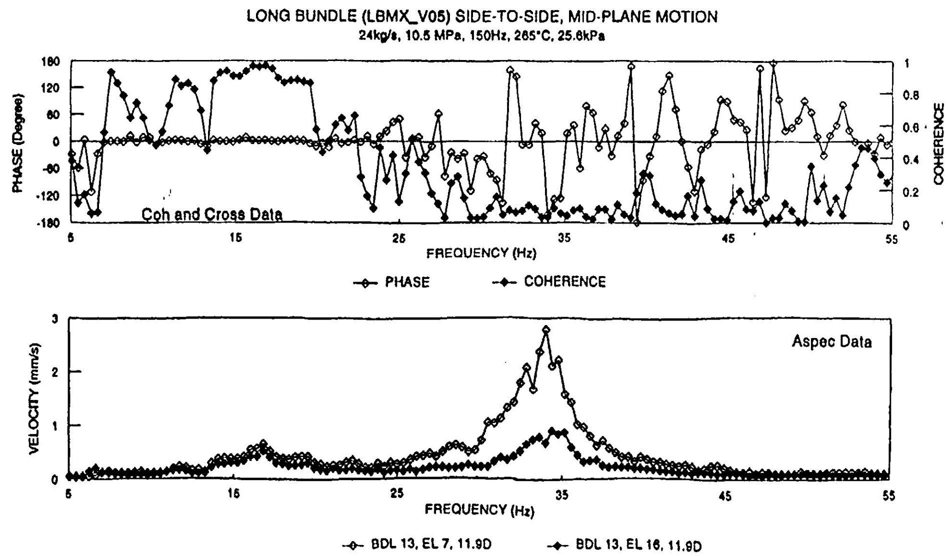

Figure 8: PHASE, COHERENCE AND MAGNITUDE OF TWO ELEMENTS AT MID-PLANE (5-55Hz)

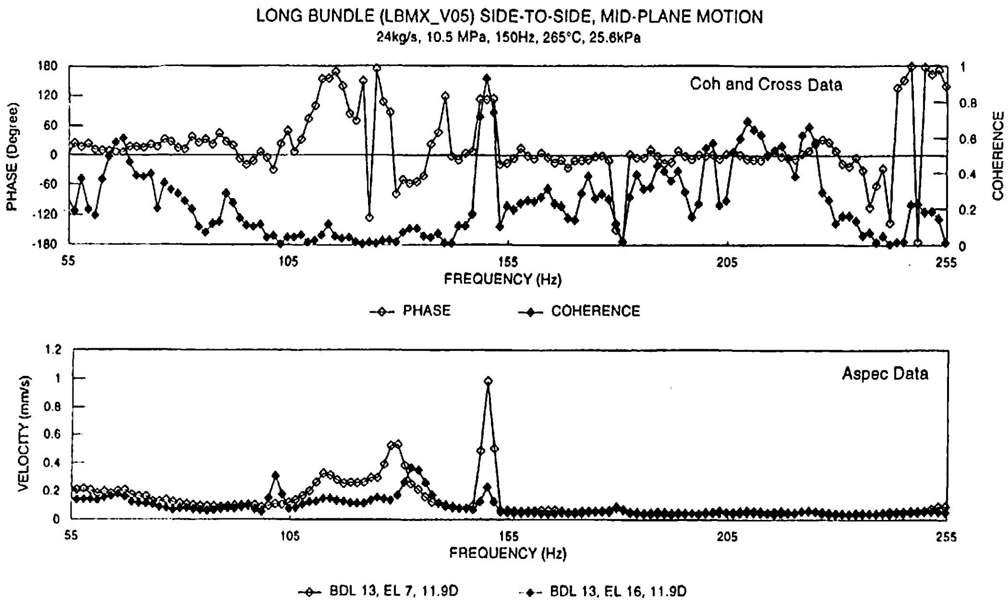

Figure 9: PHASE, COHERENCE AND MAGNITUDE OF TWO ELEMENTS AT MID-PLANE (55-255Hz)

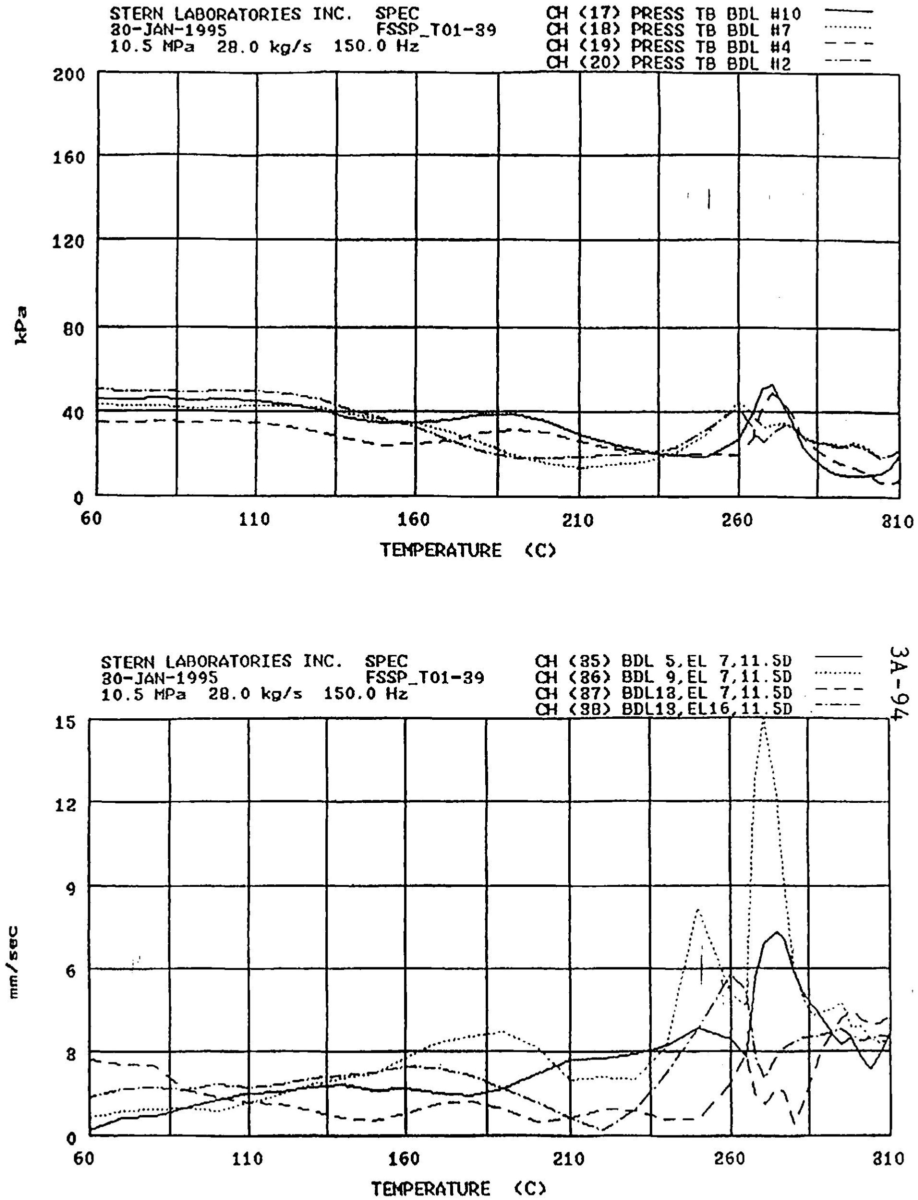

Figure 10: DYNAMIC PRESSURE AND ELEMENT VIBRATION AMPLITUDE ALONG THE CHANNEL