Flow-Induced Vibration And Acoustic Behaviour Of CANFLEX-LVRF Bundles In A Bruce B NGS Fuel Channel

M. Shams*, P. Alavi*, S.J. Palleck*, P.F. Sandig** And G.I. Hadaller**

*Atomic Energy of Canada Limited (AECL)
Fuel Design Branch
2251 Speakman Drive
Mississauga, Ontario
Canada L5K 1B2

and

**Stern Laboratories Inc.
1590 Burlington Street East
Hamilton, Ontario
Canada L8H 3L3

1. ABSTRACT

Frequency/temperature sweep tests were performed in a high-temperature/high-pressure test channel to determine the acoustic and flow-induced vibration characteristics of the CANFLEX-LVRF bundle. The vibratory response of CANFLEX-LVRF bundles was compared with that of 37-element fuel bundles under Bruce B NGS fuel channel normal operating conditions. The tests were performed with a 12-bundle string of CANFLEX-LVRF bundles as well as a mixed string for the transition core.

The tests showed that the LVRF bundles performed as required without failure or gross geometry changes. The mixed fuel strings behaved in a manner similar to that of a string of CANFLEX-LVRF bundles.

2. INTRODUCTION

The current fuel design for the Bruce B Nuclear Generating Station (NGS) is the 37-element natural uranium (NU) fuel bundle. Bruce Power is considering implementing a new fuel type with reduced coolant void reactivity. The 43-element CANFLEX® Mk-4

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fuel bundle design forms the basis for the LVRF bundle design for the Bruce B NGS reactor. The CANFLEX Mk-4 bundle design has been qualified for use in CANDU® 6 (C-6) reactors and has undergone a successful demonstration irradiation (DI) at the Point Lepreau Generating Station.

In addition to the use of a different fuel material, the LVRF bundle geometry has been modified slightly from the C-6 CANFLEX Mk-4 NU fuel bundle design to ensure interfacing compatibility with the Bruce B NGS fuel channel. The key geometric modifications are as follows:

a) The LVRF bundle end-bearing pads are staggered in an arrangement that provides bridging support that is similar to the current Bruce 37-element fuel bundle.
b) The bearing pad height on an LVRF bundle is higher than that on the CANFLEX Mk-4 NU bundle.
c) The end caps of all fuel elements have a square profile, which is similar to those in the current Bruce 37-element fuel bundle.
d) The endplate outer diameter and the inter-element spacer heights are reduced and the central web thickness is increased, compared to the CANFLEX Mk-4 bundle design.

The vibration behaviour of a string of bundles is a complex phenomenon. The above bundle modifications together with the operating conditions of the Bruce B NGS reactor may affect the LVRF bundles vibration behaviour. Hence, vibration tests were required to qualify the LVRF bundles for use in Bruce B NGS. The overall fuel verification program for Bruce CANFLEX-LVRF fuel is described in Reference 1.

3. BACKGROUND

Fuel bundle design, axial position and angular alignment of bundle are important factors in fuel element vibration and fretting-wear. Past experience shows that the effect of axial bundle location on displacement levels is greater than the effect of individual bundle characteristics; that is, the bundles at the inlet location generally vibrate more than those farther downstream. Displacement in the mid-bundle region is generally greater than the end-bundle displacement (i.e., individual fuel elements are most effectively excited close to their midpoint). In addition, tests with different bearing pad arrangements show that vibration response of typical CANDU bundles is sensitive to the positioning of the end bearing pads.

In prototype tests where the fuel channel geometry, the fuel bundle geometry and the flow conditions (temperature, pressure, velocity) are consistent with reactor conditions, it is possible to reproduce the in-reactor near-field conditions. The large-scale turbulence generated by the fuel channel inlet hardware can have a large effect

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on the overall fuel string motion especially near the inlet. Fuel element vibration is generally excited most by turbulence generated within the bundles. However, the far-field effects due to the presence of pumps, control valves, feeders and other components cannot be simulated easily. The disturbances generated in the far field are usually transmitted as acoustic plane waves and are not easily attenuated.

In the absence of acoustic excitation, pressure tube fretting damage is attributed to the fuel element vibration and to gross motion of inlet fuel bundles. It is known that acoustic pulsations can produce deep pressure tube fretting wear marks. Therefore, any test to qualify a new bundle should be performed with a typical pulse in a fuel channel.

In order to investigate vibration characteristics of the CANFLEX-LVRF bundle and to confirm its selected bearing pad configuration, flow-visualization tests were first performed in room temperature water.

The frequency/temperature sweep tests were then performed to demonstrate that there are no unacceptable effects on LVRF fuel bundles due to acoustic and flow-induced vibrations under normal operating conditions of temperature, pressure, flow, and pulsations expected in Bruce B NGS channels.

The scope of this program was to compare the vibratory response of LVRF bundles to that of 37-element fuel bundles under Bruce B NGS fuel channel normal operating conditions. The test was performed for the LVRF bundle with a fuel-string-supporting outlet shield plug (F3SP) and a Mark IIIA inlet shield plug. The fuel bundle string arrangement was specified to match that used in test series 2 of the 37-element reference tests conducted for the Bruce-B Core Conversion (BBCC) Program. Two transition channels with mixed LVRF and 37-element fuel bundles were also studied.

4. FLOW VISUALIZATION TESTS FOR LVRF BUNDLE

A series of flow-visualization tests was performed to investigate vibration characteristic of the LVRF bundle with the selected bearing pad configuration.

The flow visualization test simulated the inlet section of a Bruce B NGS fuel channel that is fuelled with the flow and contains a twelve-bundle fuel string. The test rig had the capability of changing the axial gap between the inlet shield plug and the bundle at the inlet to test the bundles at different axial gaps.

Tests were performed in a flow range of 25 to 42 kg/s at increments of 5 kg/s. All the tests were conducted at room temperature.

An acrylic tube was used with inside dimensions that simulate the worst combination of pressure tube radial creep and sag of a typical CANDU 6 fuel channel at the inlet region, within the normal tolerance range of a pressure tube inside diameter. These dimensions were more conservative than those predicted for Bruce B NGS pressure tubes. The Mark IIIA shield plug (without flow straighteners) was used for these tests to simulate worst-case high flow at the inlet location.

The root-mean-square (RMS) displacements at several selected points were measured over frequency ranges that include the following:

a) The lowest natural frequencies of the fuel string (bundle rocking modes), and

b) Element vibration fundamental frequencies.

This investigative test showed that vibration measurements of an LVRF bundle in a crept pressure tube of Bruce B NGS fuel channels were not significantly different from those of the CANFLEX bundles in CANDU 6 reactors. The measurements were also comparable with those of a 37-element bundle in both the CANDU 6 and Bruce NGS B fuel channels.

The frequency/temperature sweep qualification tests were then performed under the test conditions described in the next section.

5. FREQUENCY/TEMPERATURE SWEEP TEST CONDITIONS

Three test series were conducted, each with multiple pressure pulsation levels, pulsation frequencies, coolant temperature and several flow rates.

Test conditions were as follows:

- Frequency sweep from 15 to 250 Hz,
- Temperature sweep from 60 to 310°C at a frequency of 150 Hz,
- Pulse amplitude from 22 to 50 kPa,
- Flow rate from 18 to 29 kg/s, and
- Channel pressure at 10.5 MPa and coolant pH between 7.5 and 8.5.

Test series 1, with a string of twelve LVRF bundles, is the qualification test whose test results were compared with the reference 37-element test results. Test series 2 and 3 were conducted to simulate a transition channel. These transition test results were compared with those of LVRF test series 1.

Test series 2 had a mixed string of four LVRF bundles at the inlet end of the channel and eight 37-element bundles toward the outlet end of the channel and test series 3 had a mixed string of eight LVRF bundles at the inlet end of the channel and four 37-element bundles toward the outlet end of the channel.

6. FULL-SCALE TEST SET-UP

The tests were conducted in the Darlington fuel channel and loop located at Stern Laboratories Inc. A string of twelve 12 fuel bundles in several combinations of the 43-element LVRF bundles, and standard/long length 37-element fuel bundles were used. FIGURE 1 shows the flow loop used for the tests. The loop consists of a main circulating pump, flow control valves, flow orifices, variable frequency pulse generator, an inlet feeder equivalent to Darlington K12, a fuel channel with Darlington-type end fittings, an outlet feeder, pressurizer/separator and interconnecting piping. The following is a brief description of the test set-up.

The channel and loop were instrumented with static and dynamic pressure transducers, thermocouples, magnetic velocity transducers and accelerometers. A Darlington Mark III-A inlet shield plug and a Bruce fuel-supporting outlet shield plug (F3SP) were used in this test program.

Three twelve-bundle LVRF fuel strings were specified with several bundle combinations. Several bundles had embedded magnets to enable radial element velocity measurements. The output signals of the magnetic transducers used in test series 1, 2 and 3 were reduced to RMS displacements over certain frequency ranges. First, a power spectral density plot of the velocity was generated, and then integrated over three frequency ranges: 5 to 20 Hz, 20 to 55 Hz and 5 to 255 Hz. To compare the vibratory response of 43-element LVRF fuel bundles to that of 37-element fuel bundles, the arrangement of the magnets in the instrumented LVRF bundles was closely matched to that of the 37-element reference string.

7. TEST RESULTS

7.1 Temperature Sweep Data

Temperature sweep tests were performed from 60 to 310°C with a 150 Hz frequency pulse. FIGURE 2 shows the maximum radial velocity of the fuel bundles. The overall maximum radial velocity of elements in test series 1 was lower than that in the reference test.

7.2 Frequency Sweep Data

The frequency sweep tests were conducted at coolant temperatures of 60, 265 and 295°C in two frequency ranges: low frequency (15 to 80 Hz) and high frequency (70 to 250 Hz).

FIGURE 3 and FIGURE 4 show the maximum velocity responses of fuel elements during the low and high frequency sweeps, respectively. The results show that the maximum radial bundle velocities in test series 1 were generally the same as those of the reference tests.

7.3 Acoustic Mode Shapes

FIGURE 5 shows a comparison of dynamic pressure patterns of test series 1 with that of the reference test for coolant temperature of 310°C. The plot is based on variations of magnitude and phase, in different locations along the fuel channel at instants in time. This curve is, in effect, a snapshot of the dynamic pressure distribution along the channel, with the phase angles being equivalent to steps in time. The results show that the dynamic pressure magnitudes of test series 1 and that of the reference test were similar.

7.4 Bundle Vibration

Bundle vibration measurements were made in each test series at several flow and pressure pulse conditions and at three temperatures of 60, 265 and 310°C. FIGURE 6 shows the average RMS displacement of all bundles plotted versus flow and versus coolant velocity for test series 1 and the reference test, for temperatures of 60, 265 and 310°C. The results show that the average RMS displacements of bundles in test series 1, 2 and 3 were lower than those of the reference tests.

8. CONCLUSIONS

Measurements of vibration amplitudes during temperature and frequency sweeps (with and without pulsations) revealed that the mechanical response of CANFLEX-LVRF fuel is similar to or lower than that of the existing 37-element fuel. The tests show that the LVRF bundles performed as required without failure or gross geometry changes. Mixed fuel strings composed of LVRF bundles and 37-element bundles were also tested and the results show that the mixed fuel strings behave in a manner similar to a string of twelve LVRF fuel bundles.

It is concluded that LVRF bundles meet the performance requirements while subjected to acoustic and flow-induced vibrations in a Bruce NGS B fuel channel under normal operating conditions.

9. REFERENCES

[1] PALLECK, S.J., K-S. SIM, M.R. FLOYD, J.H. LAU and F.J. DORIA, "Bruce CANFLEX-LVRF Fuel Qualification", in proceedings of this conference.

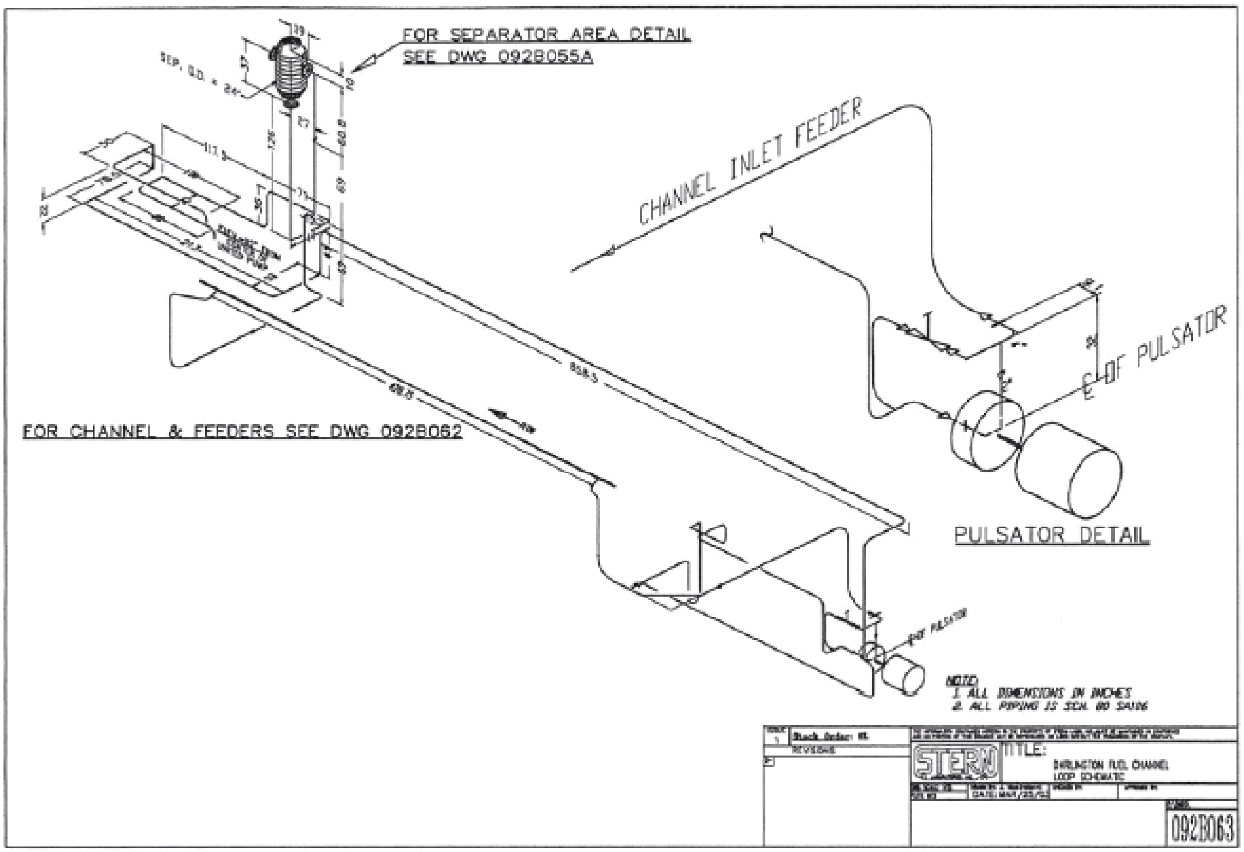


FIGURE 1 SCHEMATIC OF A TYPICAL DARLINGTON FUEL CHANNEL WITH PRESSURE PULSATION PUMP

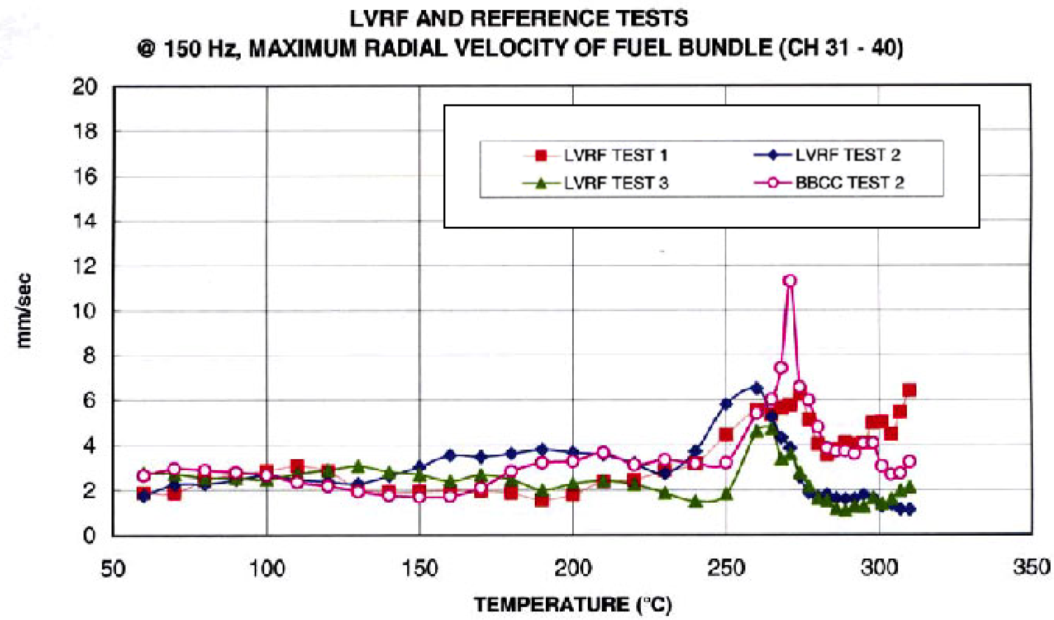
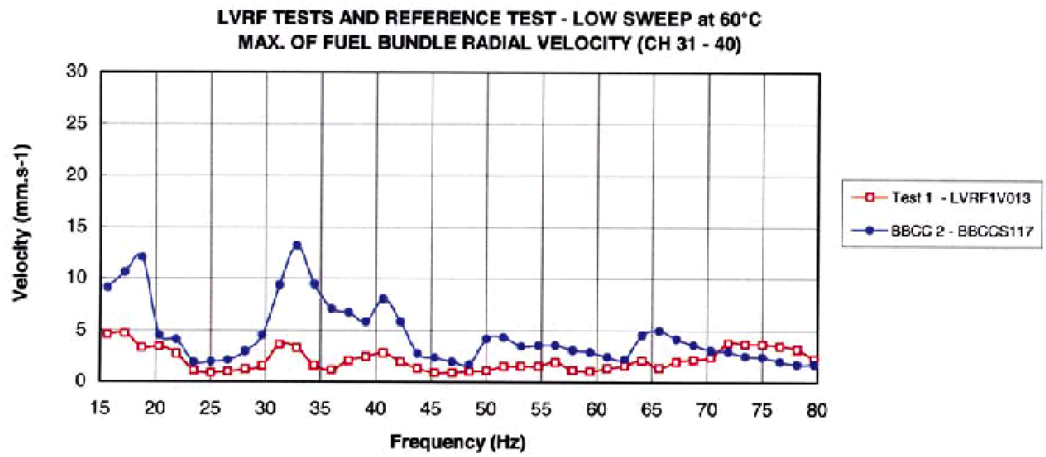
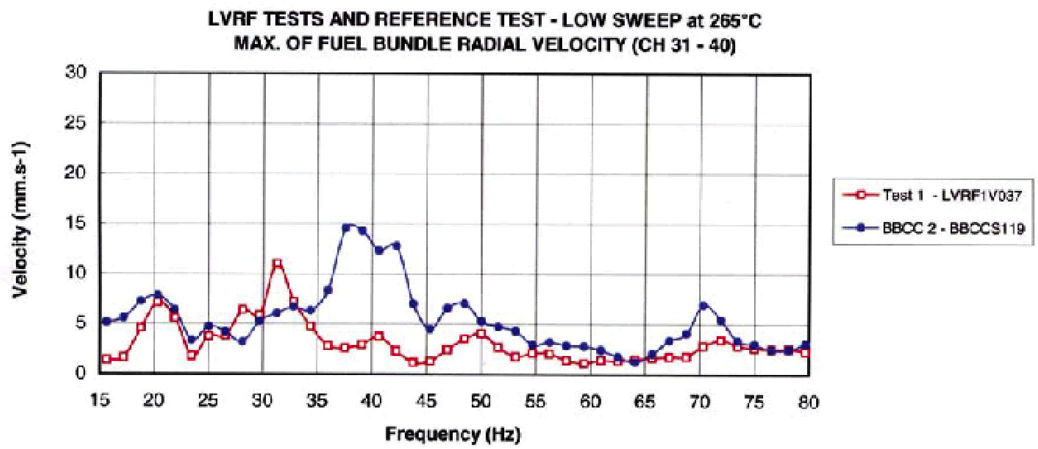


FIGURE 2 MAXIMUM RADIAL VELOCITY OF FUEL BUNDLE VERSUS TEMPERATURE FOR LVRF TEST SERIES 1-3 AND BBCC TEST SERIES 2





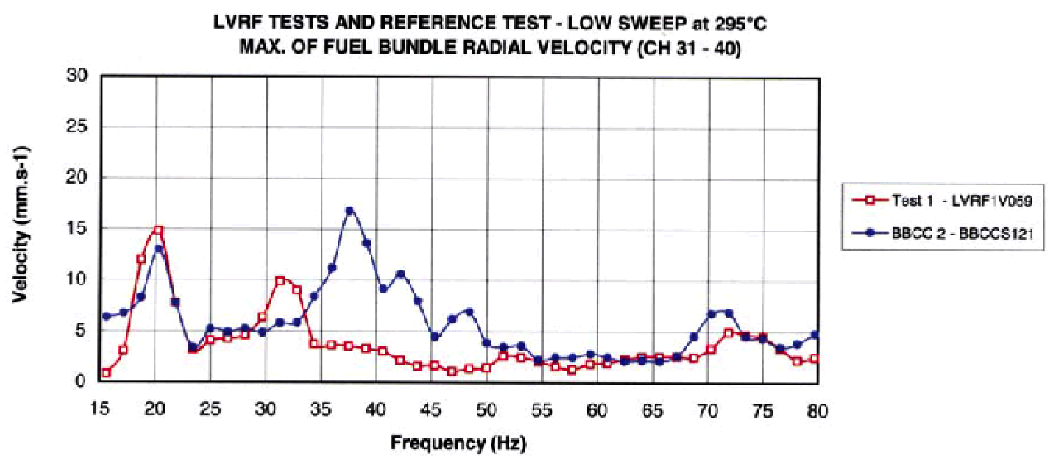
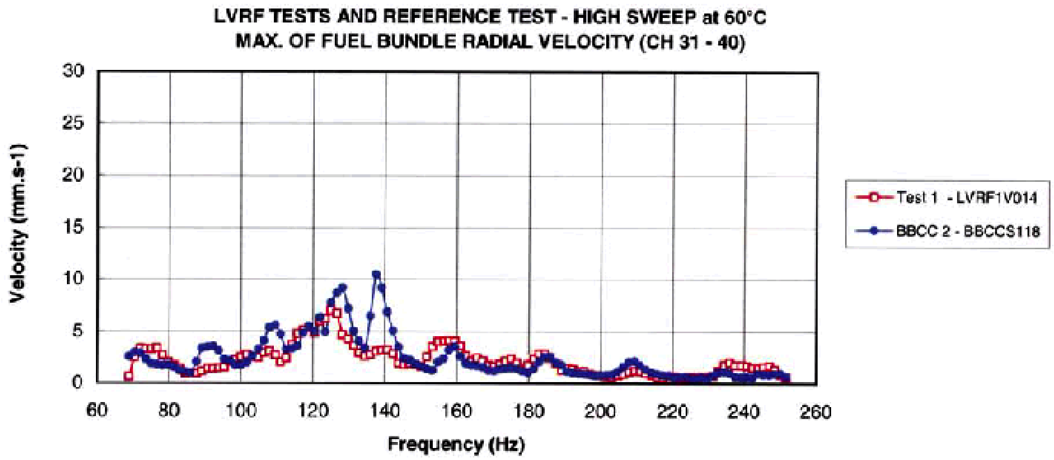
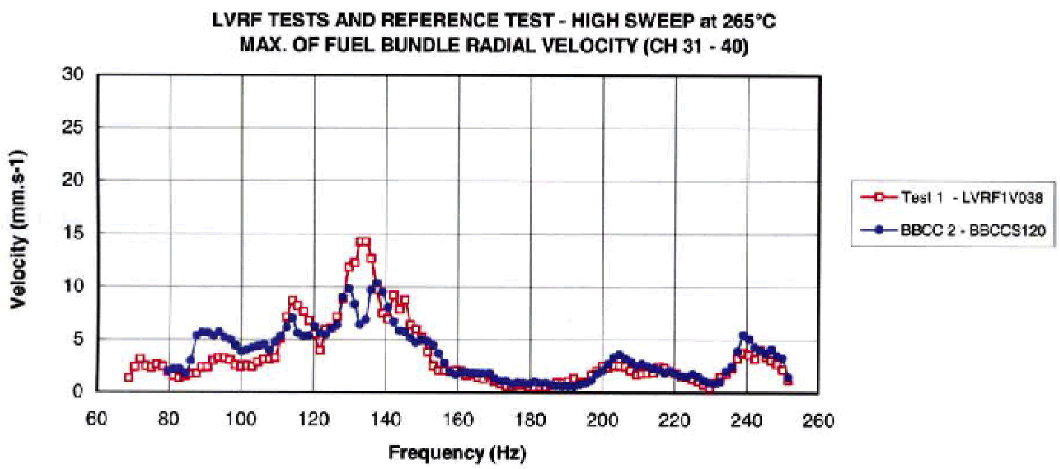


FIGURE 3 MAXIMUM FUEL BUNDLE RADIAL VELOCITY VERSUS FREQUENCY, LOW FREQUENCY SWEEP AT 60, 265, AND 295°C, LVRF TEST SERIES 1 AND BBCC TEST SERIES 2





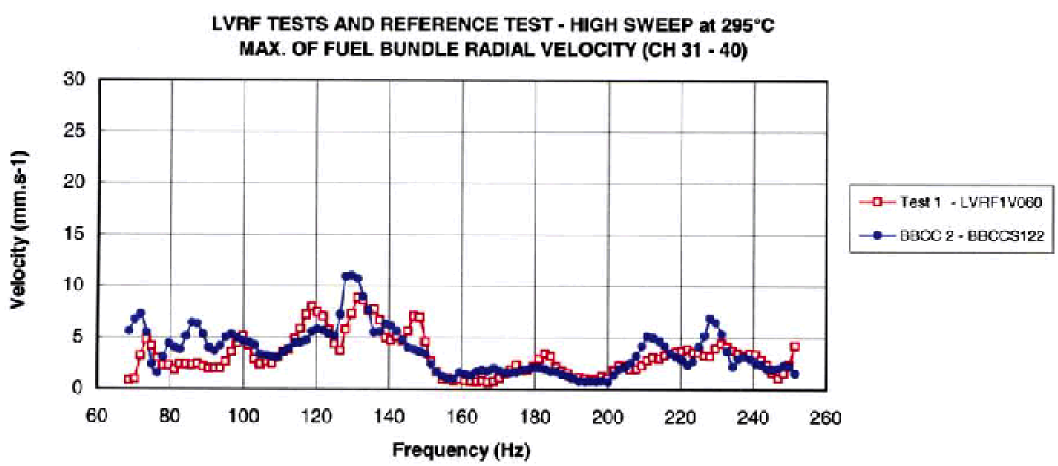
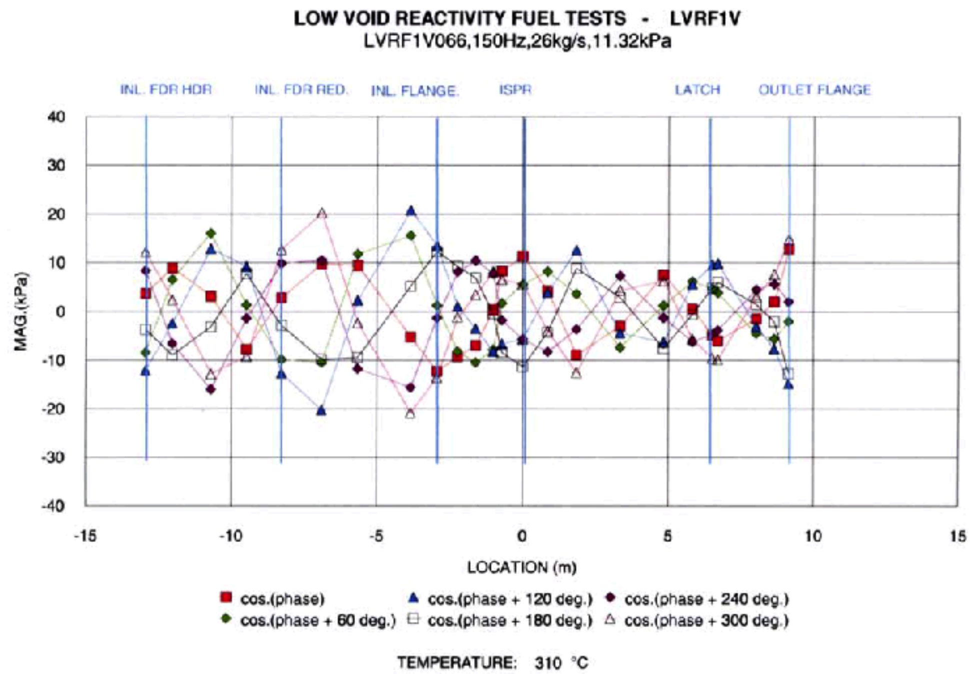


FIGURE 4 MAXIMUM FUEL BUNDLE RADIAL VELOCITY VERSUS FREQUENCY, HIGH FREQUENCY SWEEP AT 60, 265, AND 295°C, LVRF TEST SERIES 1 AND BBCC TEST SERIES 2



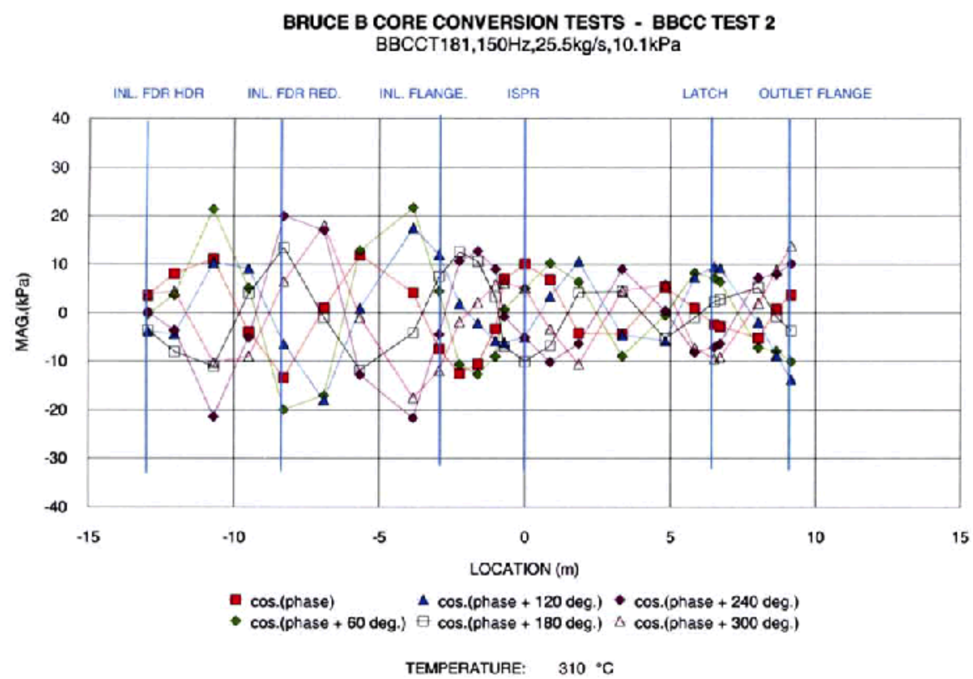
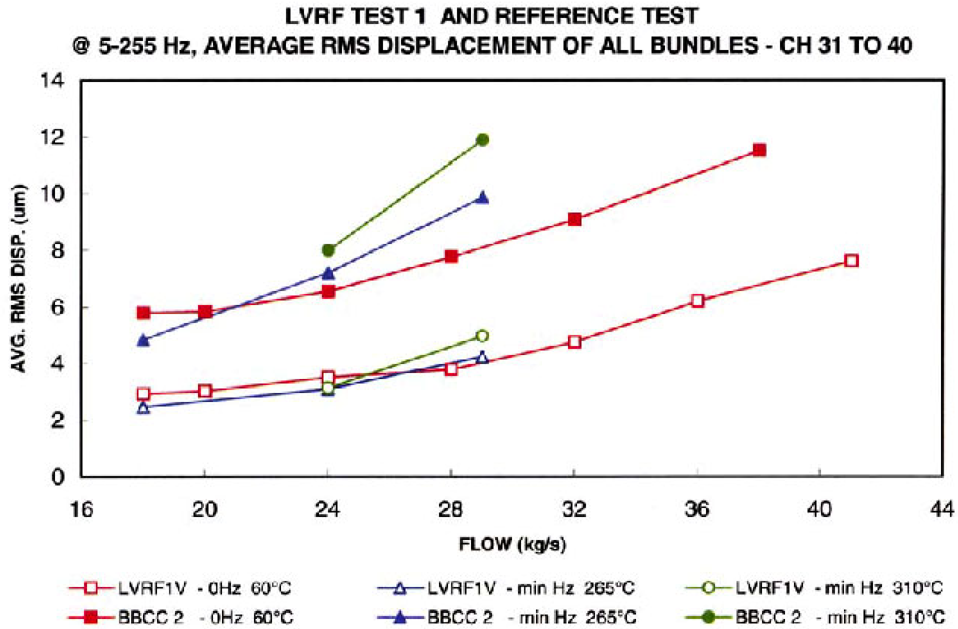


FIGURE 5 COMPARISON BETWEEN DYNAMIC PRESSURE PATTERNS OF TEST SERIES 1 AND BBCC TEST SERIES 2 (REFERENCE TEST) AT 310°C



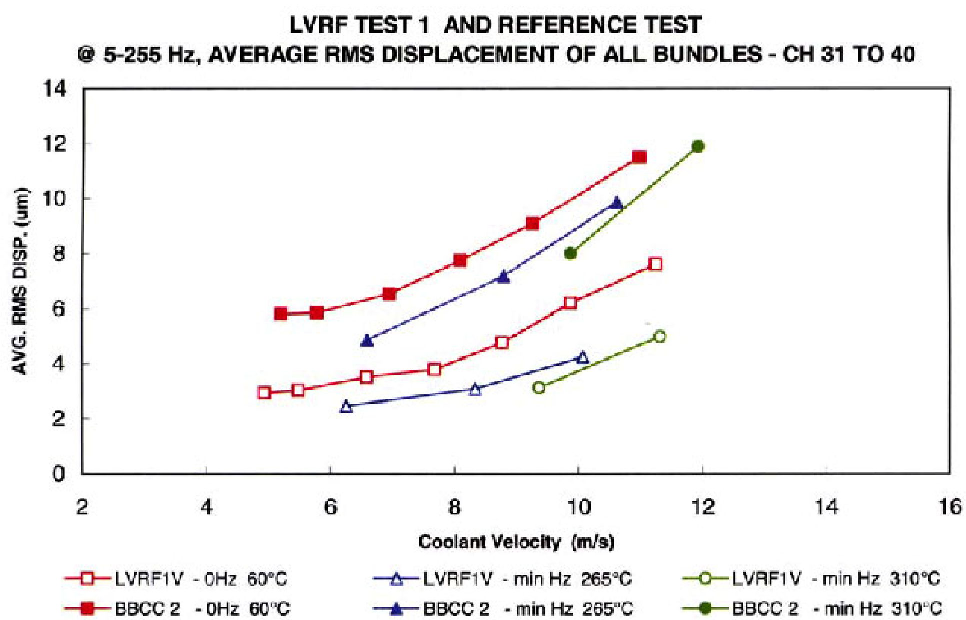


FIGURE 6 AVERAGE RMS DISPLACEMENT VERSUS FLOW AND VERSUS CHANNEL COOLANT VELOCITY FOR LVRF TEST SERIES 1 AND BBCC TEST SERIES