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HYDRAULIC NOISE IN REACTOR CIRCUITS AND LOOPS, AND ITS EFFECT ON NUCLEAR FUEL VIBRATION

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Abstract

Vibration of nuclear fuels and pressure tubes which may lead to fretting can be caused by inherent flow turbulence, structurally-transmitted excitation, velocity fluctuations and hydraulic noise in the circuit. The latter type of excitation, system hydraulic noise, which refers to the absolute pressure fluctuations in the coolant circuit, is the subject of the present study.

This paper reports the results of an investigation at WNRE to monitor noise levels in reactor circuits and loops, so as to characterize the systems and establish the importance of this noise on fuel and pressure tube vibration. Some of the techniques necessary for in-reactor installations of pressure transducers have been developed and measurements have been obtained in the vertical fuel channels of a very noisy out-reactor loop as well as in the WR-1 reactor circuits.

A very quiet out-reactor loop has been constructed to study the vibration behaviour of 37-element fuel bundles in the horizontal CANDU pressurized-heavy-water reactor systems. In this facility various types and levels of hydraulic noise are being generated to study their effect on the fuel bundles and flow tube at flow velocities up to approximately 13 m/s. (Author)

INTRODUCTION

Vibration of nuclear fuel assemblies and pressure tubes may cause fretting damage under certain conditions of contact, and in certain environments[1,2,3]. Most previous studies[4]* have concentrated on the inherent turbulence in the flow as the excitation source. However vibration levels produced by inherent turbulence alone are below those required to produce the fretting observed on occasion in reactors[3] and in out-reactor endurance type tests. The effects of another excitation cause, structurally-transmitted excitation, diminish considerably as the flow velocity is increased in vertical systems, although it is not known yet if this is true for horizontal systems. A major cause of vibration, velocity fluctuations caused by radial flows which are associated with distorted velocity profiles, is discussed, but the main cause of vibration discussed in this paper is the effect of hydraulic noise which refers to the absolute pressure fluctuations travelling through the system.

In many previous fundamental fuel vibration experiments the effects of the system hydraulic noise were often overlooked because they were thought unimportant or because the experiments were done in loops with low hydraulic noise levels. However, the hydraulic noise in reactors is not necessarily low, and its effect can be important. Also, since endurance tests on new fuel designs are done in out-reactor loops it is important to know whether the environment in that loop is representative of that in an operating reactor. Therefore there is a need to characterize the environments and to establish the effect of the hydraulic noise.

In many studies where the effect of the flow turbulence is investigated, differential-pressure measurements are made in the boundary-layer around the fuel to characterize the forcing field. These data are then used in semi-empirical expressions to predict the fuel vibration. We use out-reactor endurance tests to prove our fuels and we know that these are usually more severe on the fuels than the reactors themselves[illegible]. Hence, to obtain realistic data for in-reactor vibration predictions, measurements are being made at the inlet and outlet of the fuel channels and these data related to those obtained near the fuel.

We have concentrated on absolute-pressure fluctuations since it is feasible to measure these at the inlet and outlet of fuel channels in power reactors. There are many difficulties involved in installing pressure transducers in power reactors, especially for high-frequency measurements: but some of the techniques have been developed, and measurements of pressure fluctuations up to 200 Hz have been made in the WR-1 reactor.

Possa et al.[5] have also measured absolute-pressure fluctuations in a reactor for the purpose of early detection of component failures. Their measurements were for the 0-30 Hz range.

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* Reference 4 contains the most recent comprehensive review of fuel vibration studies.

To study the effect of hydraulic noise on fuel vibration a very quiet loop has been built in which various types and levels of noise can be added, and in which the fuel vibrations can be monitored optically through an acrylic flow tube. The effects of high flow velocities on the fuel vibration can also be studied in an attempt to determine if the current upper velocity limit on CANDU pressurized-heavy-water (PHW) power reactors can be extended.

Figure 1 shows a simplified sketch of the types of fuel channel system to be discussed in this paper. The vertical channel with the top support is used in the WR-1 organic-cooled reactor and in the ILI organic loop at WNRE. The fuel bundles are fastened together to form a fuel string which is held at the top of the channel; most of the vibration is associated with this fuel string rather than with the individual fuel elements.[6] The horizontal channel is the type currently used in the PHW power reactors. The fuel bundles are not fastened together in a string but are held against a downstream fuel stop by the thrust of the coolant flow. Less pressure-tube fretting has been observed in these horizontal systems because there are no large-amplitude string vibrations, and because the bundles are held against the pressure tube by gravity.

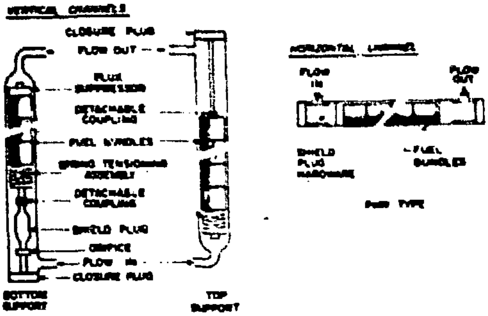

Figure 1. Fuel-Channel Types in CANDU Reactors

EQUIPMENT AND INSTRUMENTATION

The pressure transducers chosen to withstand the high organic-coolant temperatures of 400°C were the CEC model 4-317-0001 which have a resonant frequency of 8000 Hz. They therefore have good frequency response in the range of interest which is 0-200 Hz for fuel vibration studies.

The recording and analyzing equipment used for the noise measurements is shown in Figure 2. After amplification the signals were fed to an ultra-violet stripchart recorder, an oscilloscope and tape recorder. The recorded signals were fed back into the oscilloscope to compare with the on-line signals to ensure that good recordings were being obtained. At the recording speed of 190 mm/s used in these tests, the signal to noise ratio is 56 dB and the total harmonic distortion is 1.2% for the frequency range of 0 to 2.5 kHz. A spectrum analyser was used on-line in some cases, and later to give frequency spectra from the recorded tape for all the tests. The tape was also played back through the low-pass filter to an rms meter to give signal amplitudes for the 0-200 Hz frequency range.

Since the energy which is available to cause fretting is thought to be dependent on the velocity of the vibration, magnetic velocity transducers are used to monitor the motions of fuel elements which were instrumented with magnets. Vibration displacements can be calculated from the velocity signal if it is concentrated at a particular frequency. To measure the displacements directly, an optical sensor was used in later tests which would focus on the fuel elements through the acrylic flow tube. Basically the same recording and analyzing equipment, shown in Figure 2, was used for the vibration sensors.

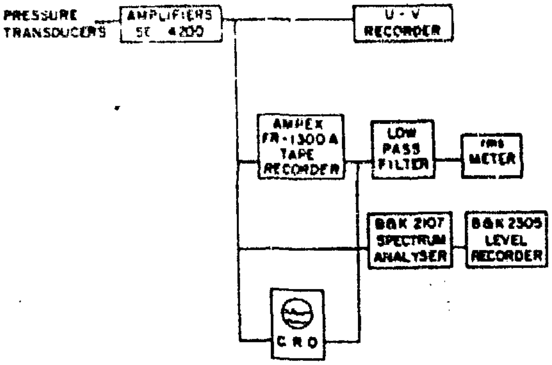

Figure 2. Signal Conditioning and Analysis Equipment

HYDRAULIC NOISE AND ITS EFFECT IN A VERTICAL LOOP

The rms amplitudes of the hydraulic noise in the ILI vertical out-reactor organic loop* are plotted in Figure 3. The predominant frequency was 180 Hz which corresponds to the vane frequency of the pump.** Acoustic pressure fluctuations are normally at a discrete frequency as they are in this case, whereas turbulent pressure fluctuations are much more broad-banded. The large amplitudes at coolant temperatures of 180°C and 280°C were due to fuel channel resonances which occur when the 180 Hz pressure waves correspond to one of the resonant frequencies of the organic-filled pipe from the top of the fuel channel to the inlet header at those temperatures. This is explained more fully in the appendix. Such resonances may occur in reactor channels unless they are considered in the initial design.

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* The vertical fuel channel for this loop is shown in Figure 1

** The pump rotating speed is 60 Hz and there are 3 vanes.

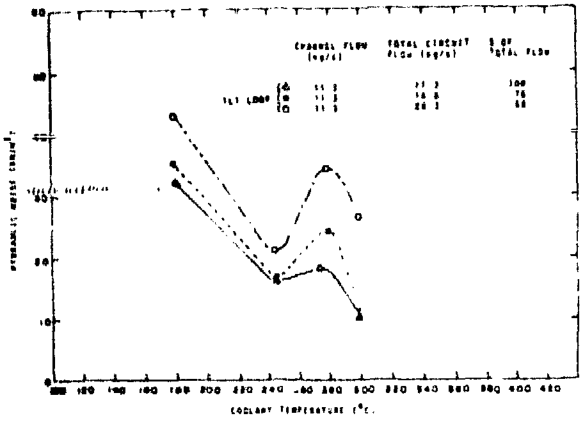

Figure 3. Hydraulic Noise at 1L1 Fuel Channel Inlet

In other tests in the above facility, the vibrations of two fuel elements containing magnetic pellets in a string of four bundles were measured using magnetic velocity transducers. It was found that when the hydraulic noise levels increased at the resonant conditions, the vibration levels also increased from those at non-resonant conditions. Appelt et al.[7] also found that fuel vibration in a vertical system was dependent on the system hydraulic noise.

There are three parallel fuel channels in this loop. With all of the flow passing through only one of these channels the hydraulic noise increased at the inlet and outlet as the flow rate was increased. The relative flow distribution between two fuel channels was varied to observe the effect on the hydraulic noise in one of the channels. The resonances still existed at 180°C and 280°C. The noise at the channel inlet varied directly as the total loop flow when the flow in that channel was kept constant, as shown in Fig. 3. This is because the larger opening in the loop flow-control valve resulted in less attenuation of the pressure fluctuations travelling through the circuit from the pump. "Control valve noise" would increase as the opening was reduced but its effect was less than that of the pump noise in this case. However this trend was not evident in the noise at the channel outlet where there was a more complex effect of parallel-channel flow.

HYDRAULIC NOISE AND ITS EFFECT IN A HORIZONTAL LOOP

Most Canadian power reactors are of the horizontal type. To study the effect of hydraulic noise on fuel vibration in this type of system, a horizontal pipe with an acrylic test-section was connected via rubber hose sections to the RD6 water loop. This resulted in a very quiet system with absolute-pressure fluctuations generally below 3 kN/m^2 for all of the tests. Differential pressure fluctuations were not measured since it was the absolute pressure fluctuations that were of interest in this study, as outlined in the introduction. Flow velocities up to 13 m/s, which is 140% of the current PHW design flow, were used.

The hydraulic noise was measured with pressure transducers at the inlet and outlet of the acrylic section. Vibration measurements of elements at the side, top and bottom of the fuel bundle at the center and upstream end were made with magnetic velocity transducers fastened to the flow tube. A number of 37-element fuel bundles, of the type developed for the Bruce Generating Station, were instrumented with magnets and used for the tests.

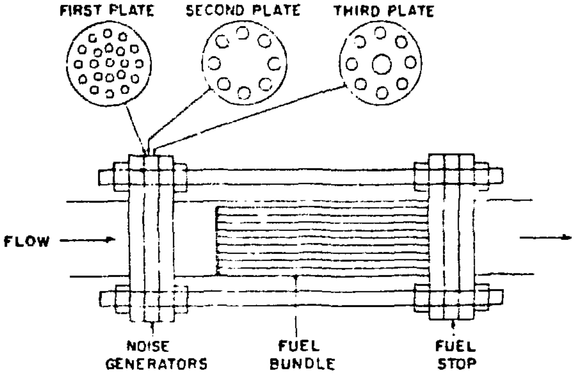

Figure 4. Single bundle tests in RD6 Horizontal Loop

In the single bundle tests, the angle of the stop which held the bundle against the flow (See Fig. 4) had an appreciable effect on the vibration of its upstream end, particularly its vibration in the vertical direction. If the bundle was tilted upwards the upstream end of the bundle would "lift-off" the flow tube at high flow causing the fuel vibration to increase by as much as 5 times.

Noise Generators

In order to impose the types of noise which would be produced by the inlet hardware of power reactor channels, three noise generators in the form of plates with various hole patterns were installed 100 mm (4 in.) in front of the bundle as shown in Fig. 4. These were used to study some of the effects which result at high flow rates from various shield plug designs used at the inlet of horizontal fuel channels.

Basically the same level of hydraulic noise was produced by all three plates, however, the resulting flow velocity distribution was quite different. The noise level did not go above 3 kN/m^2 in these tests, which is well below the 1L1 loop and WR-1 reactor noise.

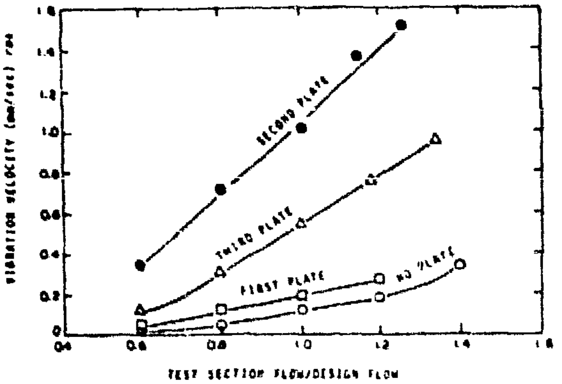

Figure 5. Vibration of Side Element at Center of Bundle in RD6 Horizontal Loop.

Noise generator number 1, which had a uniform distribution of 8 mm (5/16 in.) diameter holes causing a 72% reduction in flow area, increased the fuel vibration slightly as shown in Figs. 5 and 6. Noise generator number 2, which had 19 mm (3/4 in.) diameter holes around the outside causing a 59% flow area reduction, forced the flow to the outside of the flow tube as well as creating noise. It produced a considerable increase in fuel vibration especially at the upstream end of the bundle where bundle motions of 20-40 Hz were evident. Noise generator number 3 was identical with number 2 but also had a 32 mm (1 1/4 in.) diameter hole in the center as shown in Fig. 4. This plate, which caused a 50% flow area reduction, forced some of the flow to the outside and some to the center of the flow tube. The resulting vibration levels were between those of the first two plates. These differences in vibration levels were produced primarily by the differences in flow velocity profiles rather than by the hydraulic noise.

In later two bundle tests, noise generator number 3 was placed 470 mm (18 1/2 in.) in front of the upstream bundle. The fuel vibration was approximately 50% less than when this plate had been placed 100 mm in front of the bundle because the disruption in local flow velocities decreased with increasing distance away from the plate.

Pump Noise

To determine the effect of hydraulic noise from the pump, the flow rate through the by-pass circuit was varied so as to vary the pump flow and hence the pump noise, while maintaining a constant test-section flow rate. The vibration of a side element between the upstream end and the middle of the upstream bundle was monitored using the optical displacement sensor mounted independently of the flow tube. With 80% PHW design flow rate in the test-section, the rms values of hydraulic noise and fuel vibration displacement shown in Table 1 were recorded.

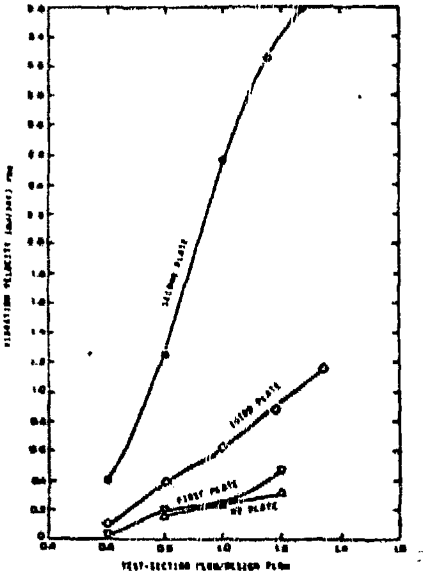

Figure 6. Vibration of Side Element at Upstream End of Bundle in RD6 Horizontal Loop.

Table 1. Vibration Displacement versus Hydraulic Noise.

Hydraulic Noise kN/m^2	Vibration Displacement mm
1.66	0.008
2.15	0.013
2.59	0.016

Since the test-section flow rate was constant, the mean flow velocity in the fuel bundle was constant and therefore not a factor. The increase in the hydraulic noise resulted primarily from the pump and it was this noise which accounted for the increased vibration.

As the hydraulic noise increased the flow-tube vibration also increased. Hence, much of the fuel bundle vibration was due to the flow tube movement, since the bundles rest on the flow tube. The pressure pulses from the pump were predominantly at 30 Hz which corresponds to the pump-shaft rotating speed. The test-section natural frequency was approximately 14 Hz which is nearly one-half of the excitation frequency leading to a primary parametric instability condition.[8] When the flow tube vibration was reduced by the use of additional constraints, the fuel bundle vibrations also decreased.

In power reactors some pressure-tube vibration will occur, however it is not known if the amplitude is large enough to cause fretting.

More tests are continuing in this facility to study the effect of test-section vibrations, hydraulic noise produced by valves, specific shield plug designs and fuel bundle misalignment.

IN-REACTOR PRESSURE TRANSDUCER INSTALLATIONS

To obtain hydraulic noise data in a power reactor the following problems must be overcome. Firstly there is the problem of installing the connecting tubing and wiring in amongst the shielding and other reactor hardware in such a way that it does not interfere with this equipment and yet provides good signals to the transducers. Since the transducers form part of the reactor containment, safety aspects of the installation must be investigated. Also the installation must be such that it can easily be connected and disconnected.

To develop and evaluate installation techniques to meet the above requirements a program was undertaken to measure hydraulic noise levels in the WR-1 organic-cooled reactor. Prior to doing this, a channel in an out-reactor loop was used to compare various installation designs. In the upper portion of the channel one transducer was flush-mounted and one was connected with various lengths of 9.5 mm (3/8 in.) tubing. Others were connected through the top of the channel with tubing and a back-filling arrangement.

With the top connections the readings were distorted at high temperatures. For instance, at coolant temperatures above 260°C larger random noise signals appeared between 130 Hz and 165 Hz. These stray signals were not present in the readings taken at the bottom of the channel and could be eliminated for only short time periods by back-filling. It was concluded that these distortions were due to vapour bubbles from the multi-component organic coolant collecting in the line, and that this type of connection is unsatisfactory for high temperatures.

With the connections at the side, a long length of tubing would produce resonance in the line and magnify the pressure signals considerably. However, if the length of line was kept below about 1/8 wavelength of the highest frequency pressure waves measured, then no appreciable distortion occurred in the readings. This was determined by comparing the readings using various line lengths with the readings from the flush-mounted transducers.

For the WR-1 reactor installations, short lengths of 9.5 mm tubing were welded to the inlet elbow at the bottom of one of the fuel channels and through the wall of the upper part of the channel. These lines were inclined downwards slightly so as to prevent vapour bubbles entering the line. Since the transducers formed part of the reactor containment they were fastened into enclosures designed for the temperature and pressure to protect against the possibilities of a diaphragm rupture.

IN-REACTOR HYDRAULIC NOISE

Recordings were first taken during reactor shutdown at 110°C with only the pressurizing pump running and neglible flow through the channel. With the circulating pump running and a, near normal, 15 kg/s flow rate in the channel, readings were taken from 260°C to 403°C at various reactor powers. The amplitudes of the pressure fluctuations were larger with the larger pump operating and with the higher flow rate, as would be expected. The rms amplitudes for the frequency range of 0-200 Hz are plotted in Figure 7. The major frequency component in the signals was 6-8 Hz, however the spectra were quite broad-banded up to 200 Hz. Typical frequency spectra are shown in Figure 8.

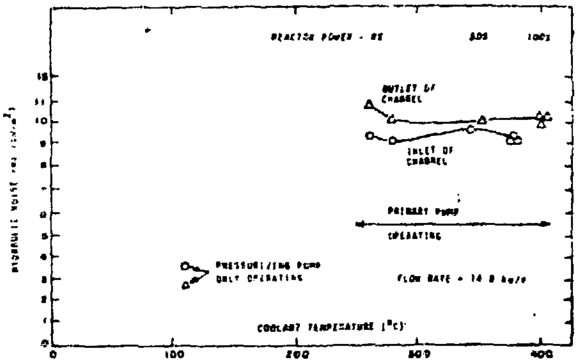

Figure 7. Hydraulic Noise in the WR-1 Reactor

As shown in Figure 1 the WR-1 fuel-channel inlets are streamlined compared with typical power-reactor channel inlets, and do not offer any obstructions to the flow before it enters the first fuel bundle. In power-reactor channels the flow must pass through a "T connection" and shield plug before entering the first fuel bundle. Therefore the hydraulic noise at the fuel bundles is likely higher than in the WR-1 reactor, due to noise generated at these locations.

Comparing these results with those in Figure 3, it is evident that the hydraulic noise in this reactor circuit is much lower than in the U-1 loop even though the channel flow rate is higher. The lower noise level is due to the damping effect of the much larger multi-channel circuit, differences in the pumps, and temperature gradients in the core which tend to eliminate resonances in the fuel channels.

CONCLUSIONS

From the above investigations it is clear that various reactor circuits and loops can have quite different hydraulic noise characteristics and that this noise can have a significant effect on fuel

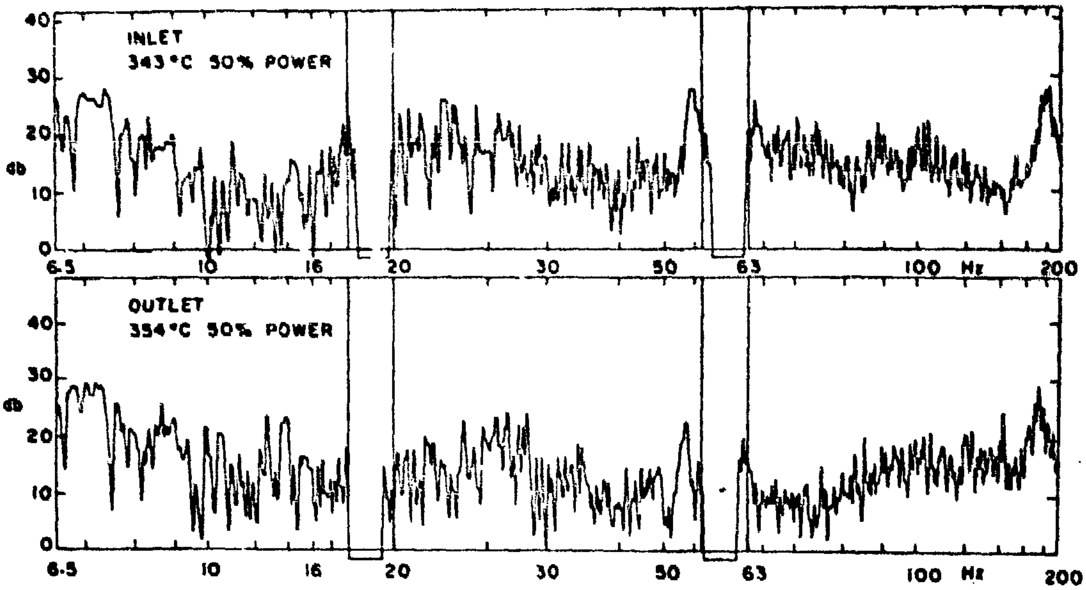

Figure 8. Frequency Spectra for the WR-1 Reactor

and channel vibrations. It is therefore important to characterize both power reactor circuits and various out-reactor facilities so that testing can be carried out in representative environments.

Some of the techniques required for measuring hydraulic noise in power reactors have been developed and used successfully to obtain data from the WR-1 reactor.

It was found from the ILI loop tests that fuel channel resonances are possible under certain conditions. These can have a significant effect on fuel vibration and must be avoided by fuel-channel designers.

Noise levels in reactor systems are generally lower than in hydraulics test loops because the larger coolant volumes in the reactors provide more damping of the pressure pulsations from the pumps. Hence out-reactor endurance tests are generally more severe on the fuel than is the corresponding reactor. However the noise in reactor fuel channels is larger than in loops such as RD6 in which rubber hose connections, or filters, are used to absorb pressure fluctuations. In PHW reactor channels fuel vibration and fretting is thought to be less than in the WR-1 reactor even though the noise levels may be higher, because there are probably no fuel string-like vibrations, and because the fuel bundles are held against the fuel channel by gravity.

Tests in the RD6 horizontal loop have confirmed that hydraulic noise will excite fuel assemblies and flow tubes, and also show that if the upstream fuel bundle is allowed to tilt upward the vibration will increase considerably at its upstream end. The noise generator tests have shown the importance of the flow velocity profile developed in front of the fuel bundles by shield plugs and channel inlet configurations.

ACKNOWLEDGEMENTS

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APPENDIX, ILI LOOP RESONANCES

The resonances which were detected in the ILI out-reactor test facility at temperatures of 180°C and 280°C can be explained using the following formula for the resonant frequencies of the organic-filled tube:

$$f_n = \frac{na}{2L}$$

where $n = 1,2,3 \ldots\ldots\infty$
a = sound speed in fluid
L = length of tube

In the case of the ILI loop, the critical length of tube is from the top of the fuel channel to the inlet feeder, which is 11.8 m. The calculated frequencies for the ILI test conditions are listed in Table 2.

Table 2. Resonant Frequencies of the ILI Loop's Fuel Channel.

Temperature °C	Coolant acoustic velocity m/s	n	f_n
180	1041.6	1	44.1
		2	88.2
		3	132.2
		4	176.3
		5	220.4
245	901.0	1	38.2
		2	76.3
		3	114.5
		4	152.6
		5	190.8
280	819.6	1	35.6
		2	71.2
		3	106.8
		4	142.5
		5	178.0
298	799.8	1	33.9
		2	67.8
		3	101.6
		4	135.4
		5	169.3
		6	203.2

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