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ABSTRACT

This report describes the use of noise analysis to investigate in-core instrument tube vibrations in BWR-4 reactors. Neutron noise signals from in-core fission chambers and acoustic noise signals from externally mounted accelerometers were used in these studies. The results show that neutron noise can be used to detect vibration and, more importantly, impacting of instrument tubes against adjacent fuel channel boxes. Externally mounted accelerometers detect impacting but not rubbing of instrument tubes against fuel channel boxes. Accelerometers can monitor impacting only on the particular instrument tube where the accelerometer is mounted.

Surveillance for instrument tube impacts can be accomplished using standard BWR-4 in-core power range neutron flux detectors at all instrument tube locations containing these detectors. Ex-vessel accelerometers can then be used to monitor instrument tubes that lack power range neutron flux detectors. However, noise on axial flux profiles obtained with movable in-core detectors is not a reliable indicator of impacting, because the recorder used to plot the flux profiles does not respond adequately to the noise frequency generated by impacting.

CONTENTS

1. INTRODUCTION

This report summarizes the results of our investigation of in-core instrument tube vibrations in BWR-4s. The objectives of this investigation were to: (1) determine if acoustic noise from accelerometers mounted outside the reactor vessel can be used to detect and quantify impacting of instrument tubes against fuel channel boxes, (2) determine if neutron noise from fixed in-core detectors can be used to detect impacting of instrument tubes against fuel channel boxes, (3) determine if neutron noise from in-core detectors can be used to assess the degree of wear of fuel channel boxes caused by instrument tube impacts, and (4) determine the degree to which instrument tube vibrations are reduced by plugging the bypass cooling holes in the core support plate.

BWR-4s have in-core instrument tubes (thin walled and unconstrained through the core region) that house neutron detectors or neutron sources. To improve cooling in the vicinity of an instrument tube, from 0 to 4 holes (as needed) have been drilled through the lower core support plate near each instrument tube penetration. While improving the cooling, these coolant bypass holes apparently also create a cross flow that induces vibrations in the instrument tubes of sufficient amplitude that some of the instrument tubes contact the corners of adjacent fuel channel boxes with sufficient force and rapidity to cause excessive wear of the boxes.

To accomplish the preceding objectives, we measured the acoustic noise with out-of-vessel accelerometers and the neutron noise with fixed, in-core detectors at several BWR-4s. The specific BWR-4 plants are not identified in this report because they are nominally of the same design, and we assume that the differences such as core size and instrument tube diameter (some plants have 0.70-in.-diam tubes and others 0.75-in.) do not significantly affect the noise signatures obtained. Evidence to support this assumption is presented in Sect. 3, where signatures from three plants are compared.

During a refueling shutdown at a BWR-4, we performed a test to determine the sensitivity of ex-vessel accelerometers to rapping on an in-core instrument tube. This experiment and its results are described in Sect. 2.

Ex-vessel accelerometer signals and in-core neutron noise from an operating BWR-4 were compared to determine if neutron noise can be used to detect impacting in lieu of mounting accelerometers on all instrument tubes (Sect. 3).

We analyzed neutron noise signatures from the BWRs to compare the shape and magnitude of noise spectra as a function of flow rate and to assess the change in the noise signatures after the bypass cooling holes in the core support plate were plugged. These results are described in Sect. 5.

The utilities and the General Electric Company (GE) visually inspected the fuel channel boxes at several BWRs. During these inspections, the channel box wear was measured optically, and the boxes were rejected or reused based on criteria established by GE. We compared these measurements with neutron noise signatures obtained prior to shutdown (see Sect. 6) to determine to what degree neutron noise correlates with wear of channel boxes.

2. IN-CORE IMPACT TESTS

Realizing that we lacked a quantitative understanding of the relationships between mechanical contacts among instrument tubes and fuel channel boxes within the core and acoustic energy sensed at ex-core locations, we proposed special tests wherein ex-core accelerometer responses to in-core impacts of known magnitude would be recorded, thereby establishing a space- and (perhaps) amplitude-dependent transfer function. Access to the core internals naturally presented a problem, but fortuitously a BWR-4 in a defueled state for other reasons was made available for these special tests, which were carried out jointly by the utility, GE, and ORNL personnel.

The primary objective of these tests was to define the detection sensitivity of ex-core accelerometers to simulated metal-on-metal impacting or rubbing at selected axial positions along the surface of the instrument tubes. The secondary objective was to compare the detection sensitivities of accelerometers already in use at two ex-core locations at affected BWR plants (labeled "Flange Accelerometer" and "TIP accelerometer and Cable Clamp" in Fig. 1, which are ∿23 ft and ∿110 ft from the fuel centerline, respectively). Specifically, we sought answers to the following questions:

1. How light an impact can be detected reliably in the presence of normal plant background noises?
2. Is detection sensitivity dependent upon axial location of metal-on-metal impacting or rubbing?

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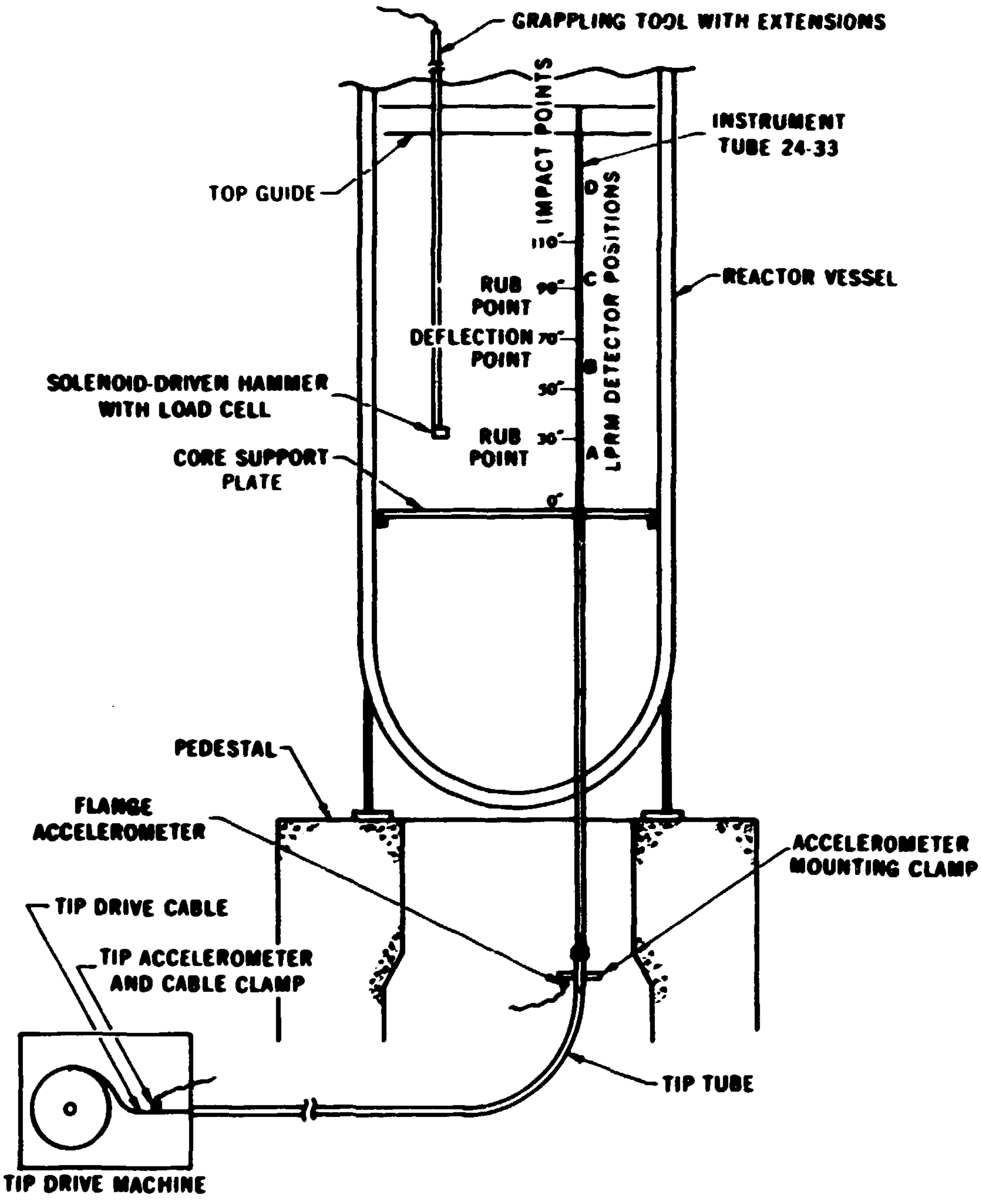

Fig. 1. In-core impact test instrumentation and axial test positions. (A, B, C, and D indicate the locations of Local Power Range Monitor detectors.)

3. Is the character of the detected noise due to rubbing different from that due to impacting?

4. Is crosstalk within the reactor internals structure appreciable, i.e., can impacts on a given instrument tube be detected with an accelerometer attached to an adjacent tube? Is control blade rattling a significant source of competing noise?

5. Can characteristics of the detected noise pulses (amplitude, oscillation count, etc.) be simply related to the impact force (or energy) so that the flange-mounted accelerometer system might be calibrated in terms of the input?

6. Is there a decided advantage in either the flange or the TIP machine mounting position for accelerometers?

Figure 1 is an elevation view of the reactor vessel and its supporting pedestal, an in-core instrument tube with its TIP tube leading to the TIP drive machine outside the primary containment, the two accelerometer mounting positions, and the grappling tool that was manipulated by personnel to simulate impacting and rubbing of the instrument tube and other in-core structures. Figure 2 is a plan view of the relative radial locations of the instrumented tube position (24-33) that was directly impacted or rubbed, and the control blade (position 26-31) and adjacent tube (position 32-33) that were also impacted to assess the degree to which acoustic energy thus generated is transmitted to the instrumented tube. Figures 1 and 2 are not intended to show the actual state of core disassembly; in fact, all fuel channel boxes were removed at the time of the tests, but

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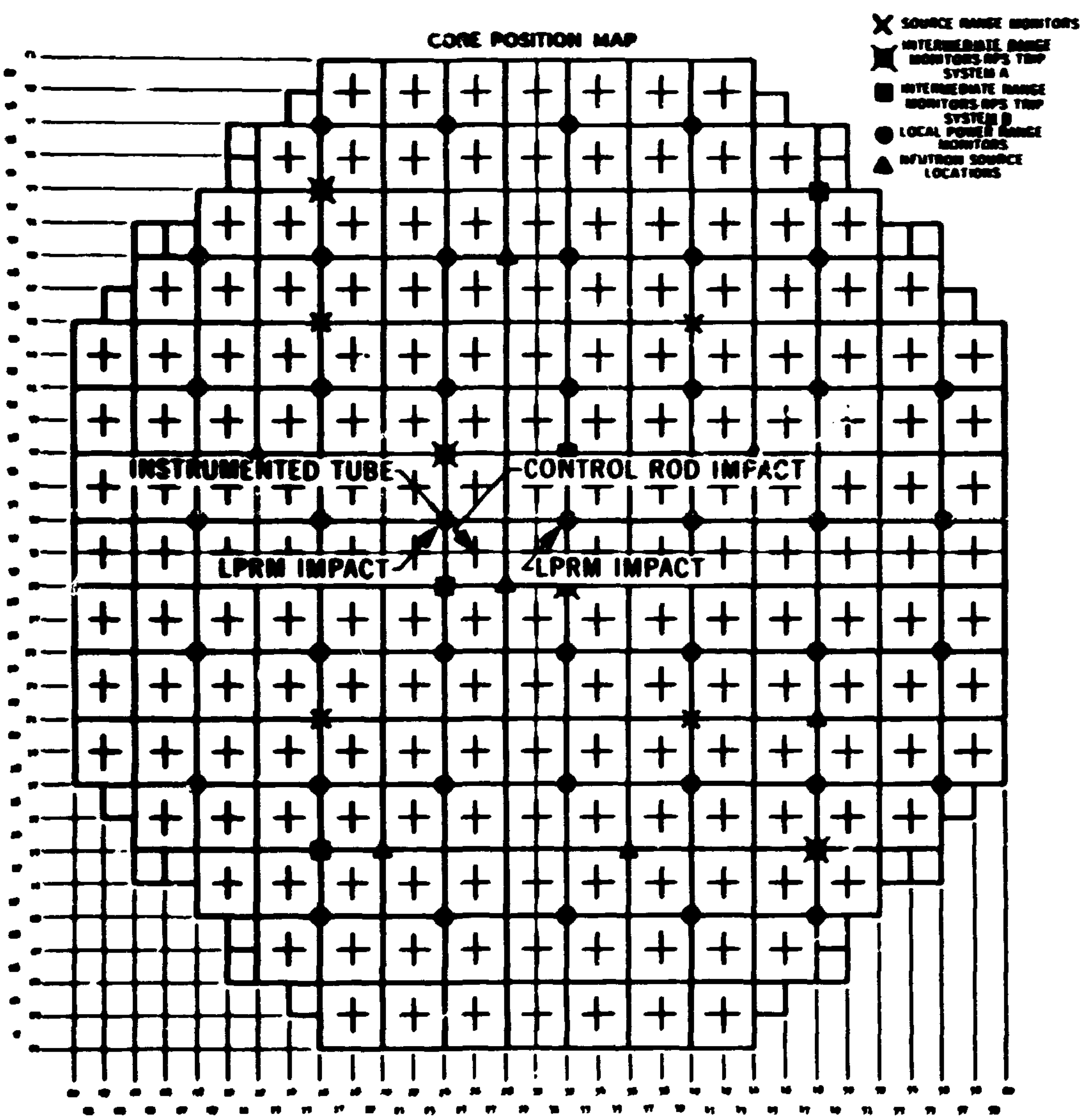

Fig. 2. Radial test positions for in-core impact tests.

most instrument tubes (indicated in Fig. 2 by X's, filled squares, filled circles, and X-ed squares) and some control blades (indicated by crosses) were installed.

Figure 1 also shows the axial positions where instrument tube 24-33 was impacted and rubbed and the relation of these positions to the locations of the LPRM detectors A, B, C, and D. In the original test plan, the impacting device (a solenoid-driven hammer with a load cell, Fig. 1) was to have given both reproducible and calibrated results (in terms of momentum transferred to the impacted object). However, the load cell which operated as expected in air prior to insertion in the reactor pool failed to do so when immersed in water in the reactor. Therefore, the impacting hammer was used, but the load cell was not used for the tests.

Typical accelerometer responses to impacts at various axial positions are shown in Fig. 3. The ordinates are g values sensed at the accelerometer positions ($g = 32.2\ ft/sec^2$, or $9.81\ m/sec^2$), but it must be stressed that these values are not directly translatable to accelerations imparted to the instrument tube at the impacted point. All plots cover a time span of 12.5 msec, but the abscissa origins, $t = 0$, are displaced arbitrarily relative to the initiating impact; so the initial sound arrival times are not to be compared among the three plot pairs. Conclusions drawn from Fig. 3 are that (1) instrument tube impacts by the solenoid-driven hammer are readily detectable above the background noise, with an S/N ratio >10 at the flange mounting position; (2) the S/N ratio and the general character of the flange accelerometer signal are essentially independent of the axial position of the impact; and (3) these same impacts are not detected above background by identical accelerometers mounted at the TIP drive machine.

Before suggesting universal applicability of these conclusions, we must assess the realism of the test conditions, i.e., the S/N ratio (which affects the probability that an event will be detected) obviously depends both on the level of background noise and on the force of the impact imparted to the instrument tube. Owing to the lack of meaningful results from the load cell, we have no quantitative measurement of the latter. However, other information suggests that the conditions were realistic: the actual flow-induced instrument tube vibrations at an operating BWR-4 produced accelerations at the flange mounting position of 0.5–12 g peak-to-peak (Fig. 3 shows typically 1.5–3 g p-p), while the operating plant background was $\leq$0.1 g p-p (Fig. 3 shows $\sim$0.2 g p-p).* Hence, the S/N ratio for our tests was roughly the same or slightly poorer than had been observed during actual dreactor operation; this implies that conclusions regarding detectability drawn from the in-core impact tests will probably not be overly optimistic in practice.

A typical flange-mounted accelerometer response to five rubbing contacts, each $\sim$0.6 sec duration, of instrument tube 24-33 with the grappling tool over a 20-sec interval is shown in Fig. 4. The upper, square-pulse trace is a marker signal that indicates the intervals during which rubbing took place (output level = 0 V) versus the quiescent intervals (output level = 1 V). Since there are no discernible differences in the accelerometer signal characteristics during the two intervals, we conclude that rubbing sounds of the (unknown) magnitude that we were able to

*We have no explanation for this last discrepancy except that extensive, noise-producing maintenance work was being carried out in the test area at the shutdown plant.

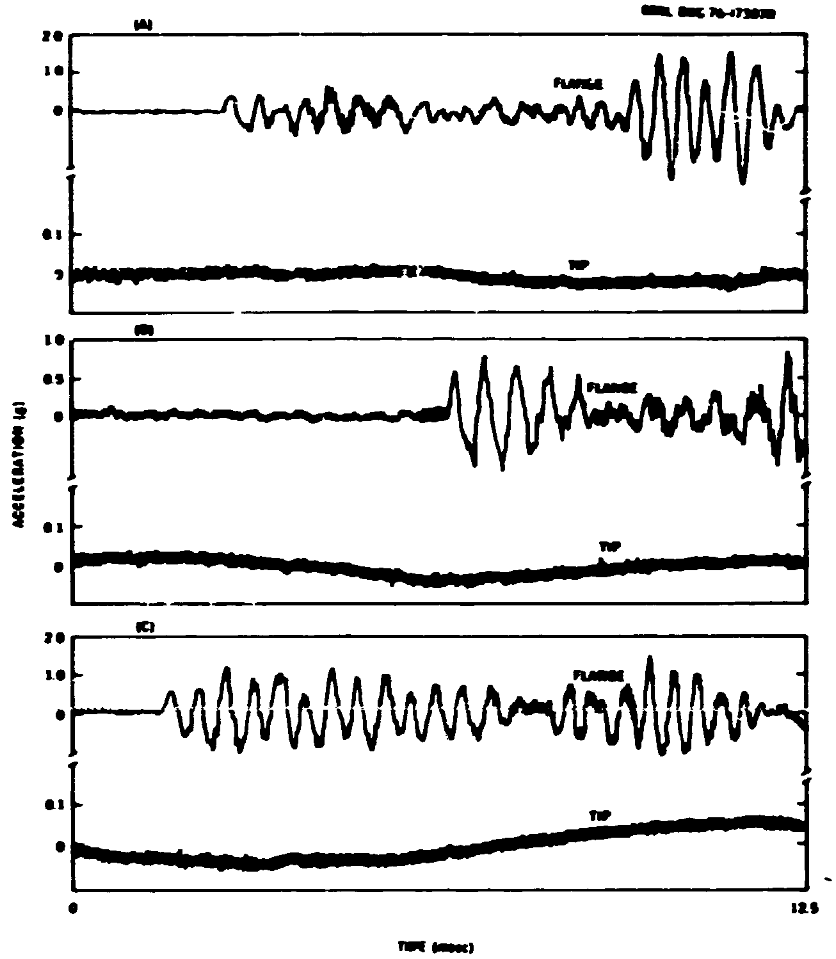

Fig. 3. Response of flange and TIP machine accelerometers to impacts at (A) 70 in., (B) 90 in., and (C) 110 in. from the core support plate.

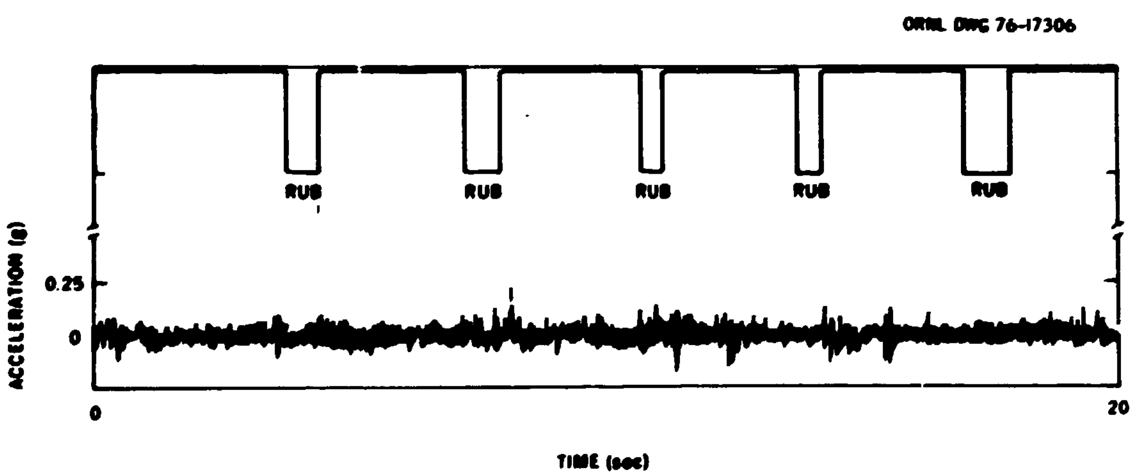

Fig. 4. Response of flange accelerometer to rubbing at 90 in. from core support plate.

produce with a grappling tool would be undetectable in the presence of normal reactor background noise by accelerometers mounted outside the reactor pressure vessel.

Other tests were performed in an attempt to answer the questions posed previously. Since the signal waveforms obtained did not differ substantially from the figures already shown, we merely summarize our over-all conclusions below without presentation of additional data:

1. Instrument tube impacts of sufficient force to produce accelerations of a few g at the flange mounting position were readily detectable (S/N ≈ 10), but these impacts were not detected at the TIP drive machine location. By comparing acceleration levels at the flange location in an operating reactor where impacting was occurring with the signals from our in-core tests, we conclude that impacts of the level we introduced could be detected at the flange location in the presence of operating reactor background noise.

2. Owing to the lack of meaningful results from the load cell on the impacting hammer, no absolute calibration of the impacting force required to produce a 1 g acceleration at the flange position was obtained. However, from tests performed both in air and in water at GE, using a similar impacting hammer and load cell, the maximum impact force was estimated to be 6-15 lb.

3. Impact detection sensitivity at the flange mounting position was found to be essentially independent of the impact position along the instrument tube.

4. Rubbing of the instrument tube could not be detected reliably above background noise at either sensor location.

5. Crosstalk within the reactor internals structure was determined to be immeasurably small, i.e., flange mounted accelerometers responded only to impacts delivered directly to the instrument tube on which they were attached, but they were completely insensitive to impacts on adjacent instrument tubes or control rods.

6. Characteristics of the detected sound pulses from the accelerometers were not found to be simply related to the impact force or energy, i.e., no "transfer function" for acoustic energy propagation was developed.

3. IN-CORE NEUTRON NOISE vs EX-VESSEL ACCELEROMETER SIGNALS

As stated previously, BWR-4s have a large number of in-core fission chambers that are used to monitor local neutron flux. Measurements were made in an operating BWR-4 to compare signals from in-core detectors with signals from ex-vessel accelerometers to determine if in-core neutron noise could be used to detect impacting of the guide tubes against fuel channel boxes. We concluded from previous studies in another BWR-4 (Sect. 2) that accelerometers mounted on the guide tube flange just below the reactor vessel detect impacting (but not rubbing) reliably.

Neutron noise analysis of signals from in-core fission detectors has been demonstrated to detect vibration of instrument tubes.[1] The normalized power spectral density (NPSD) has a clearly defined resonance at 2.5 Hz (presumably the tube's fundamental frequency). However, attempts to correlate the magnitude of this resonance with channel box wear were unsuccessful, and we concluded that the magnitude of this vibrational mode is not necessarily related to impacting. This is plausible because the tube may have a much larger (but noncontacting) displacement in a direction parallel to the channel box wall than in the perpendicular direction. Therefore, another method of detecting impacting is required.

We postulated that the magnitude of the normalized* cross-power spectral density (NCPSD) of the upper two LPRM detectors (C and D) in the instrument tube (see Figs. 1 and 2 for axial and radial detector locations) at a frequency between ~4 and 6 Hz (the exact frequency is indicated by a maximum in the coherence) might be an indicator of impacting. This appears physically reasonable for two reasons: (1) impacting, a nonlinear phenomenon, causes an upward shift in resonant frequency, and hence a resonance in the 4-6 Hz range rather than at the tube's fundamental frequency; and (2) the calculated natural frequency of the fuel channel box is ~5 Hz. Therefore, whenever impacting occurs, the channel box also vibrates. Its motion is similar to a cantilevered beam attached to the lower core support plate, with the largest amplitude in the upper region of the core. This motion should cause perturbations in the neutron flux that are coherent along the tube axis.

The above postulate was verified by comparing the NCPSD in the nominal 4-6 Hz range with results from accelerometers mounted on the instrument tube flange immediately below the pressure vessel (see Fig. 1). The

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*The magnitude of CPSD was normalized by dividing by the product of the steady-state signal levels (see ref. 2 for a more complete explanation of neutron noise signal analysis).

ability of the accelerometers to detect impacting was established as described in Sect. 2. Spectra were obtained for a number of core flow rates ranging from 50 to 90% of full-rated flow. Figure 5 shows the flow dependence of NCPSD. Note that the resonance in the 1-3 Hz frequency range does not disappear at 50% flow. However, the broader resonance in the vicinity of 5 Hz diminishes as the flow is reduced. We believe that this peak is caused by impacting of the instrument tube against fuel boxes; therefore, we compared its amplitude with accelerometer signals.

Figure 6 presents the magnitude of the NCPSD at the frequency of maximum coherence (in the 4-6 Hz range) as a function of flow; also displayed is the threshold flow above which impacting, as determined by the accelerometers, was in evidence. The values of NCPSD at the onset of impacting lie in a range from $(1.5 \text{ to } 3.0) \times 10^{-6}\ \mathrm{Hz}^{-1}$. For the two tubes where impacting was never detected by accelerometers, the NCPSD remained below $10^{-6}\ \mathrm{Hz}^{-1}$ for all flows (see Fig. 6).

We therefore conclude that impacting of instrument tubes against fuel boxes in BWR-4s can be detected by noise analysis of the signals from the in-core fission detectors presently installed. When the magnitude of the NCPSD between the upper two detectors exceeds $\sim 2 \times 10^{-6}\ \mathrm{Hz}^{-1}$ in the vicinity of 5 Hz, impacting is probably occurring. If impacting is detected by neutron noise, additional diagnostic information (such as accelerometer measurements) could be used to confirm the diagnosis.

A prerequisite for universal application of the criterion for impacting stated in the preceding paragraph is that normal background neutron noise must be similar in all BWR-4 plants. Therefore, we performed

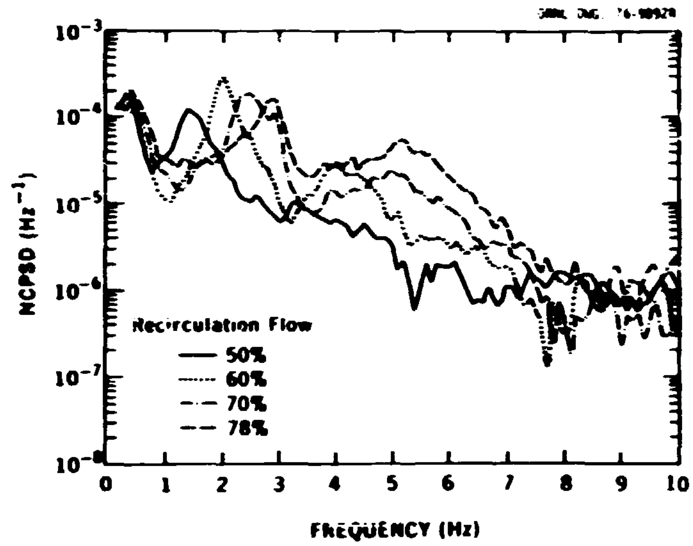

Fig. 5. Flow dependence of NCPSD between C and D detectors.

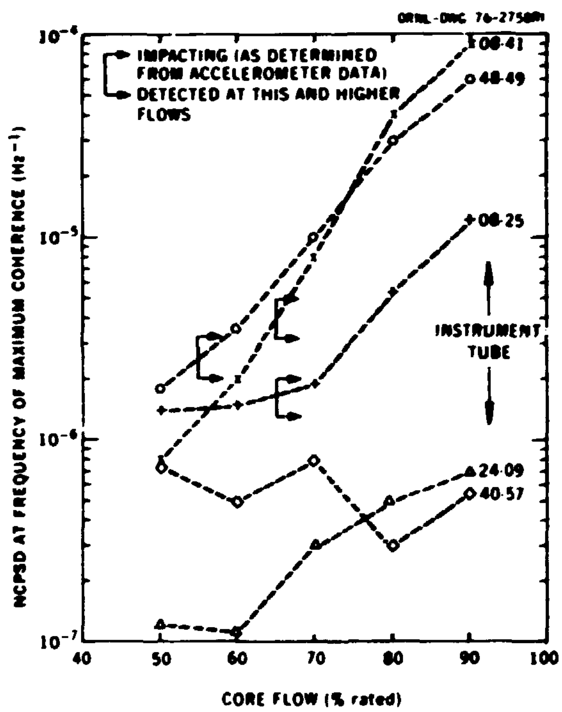

Fig. 6. Comparison of 4-6 Hz NCPSD between C and D detectors with ex-vessel accelerometer results.

measurements in three BWR-4s to establish that the shape and absolute level of normal background noise are common properties among plants. In this comparison, care was taken to select instrument tubes that showed no evidence of vibration or impacting; even so, some of the spectra indicate some slight evidence of vibration (2-3 Hz) at higher flows (see Fig. 7). Nevertheless, the results in Fig. 7 show that neutron noise signatures from different BWR-4s are quite similar. We therefore conclude that the criterion described in the preceding paragraph for the neutron noise level that indicates impacting can be applied to all BWR-4s.

4. USE OF TIP TRACES FOR IMPACT MONITORING

In addition to the fixed-position LPRM detectors, BWR-4s also have traversing in-core probes (TIP) that can travel continuously along the channel in a guide tube contained within the same instrument tube that houses the LPRM detectors. It has been suggested by Cheng[3,4] that the amplitude of noise superimposed on a TIP axial flux plot (commonly called a TIP trace, Fig. 8) has, in some cases, a significant correlation with channel box corner wear.

However, we believe that because the x - y recorders used to plot TIP traces have a poor frequency response (-3 dB at <2 Hz) that varies greatly from plant to plant, TIP traces cannot be used as a reliable surveillance tool for instrument tube impacting, because the latter generates 4-6 Hz neutron noise. In addition, TIP traces are often contaminated by low-frequency noise (unrelated to instrument tube vibration) that is introduced by void transport and normal flow and pressure fluctuations. By contrast, spectral analysis of the signals from LPRM or TIP

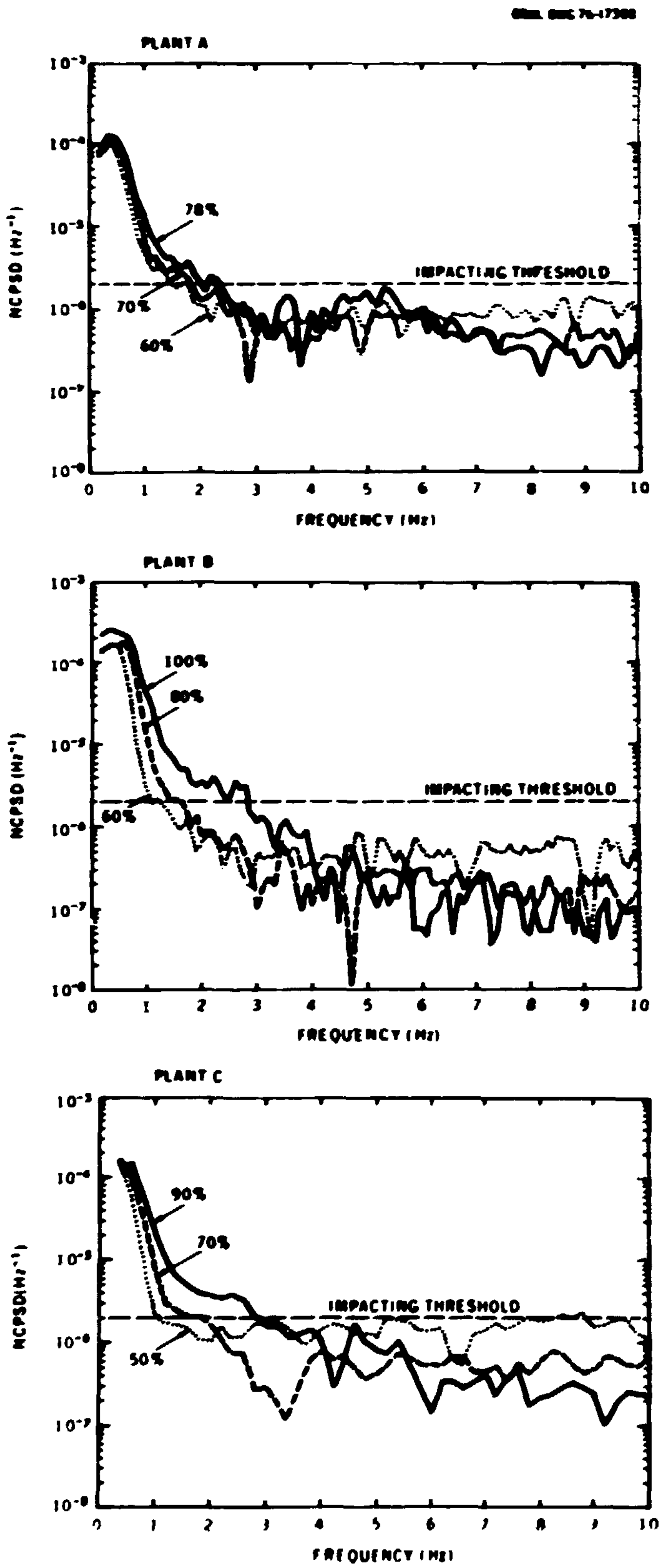

Fig. 7. Typical NCPSD between C and D detectors vs flow for three BWR-4s.

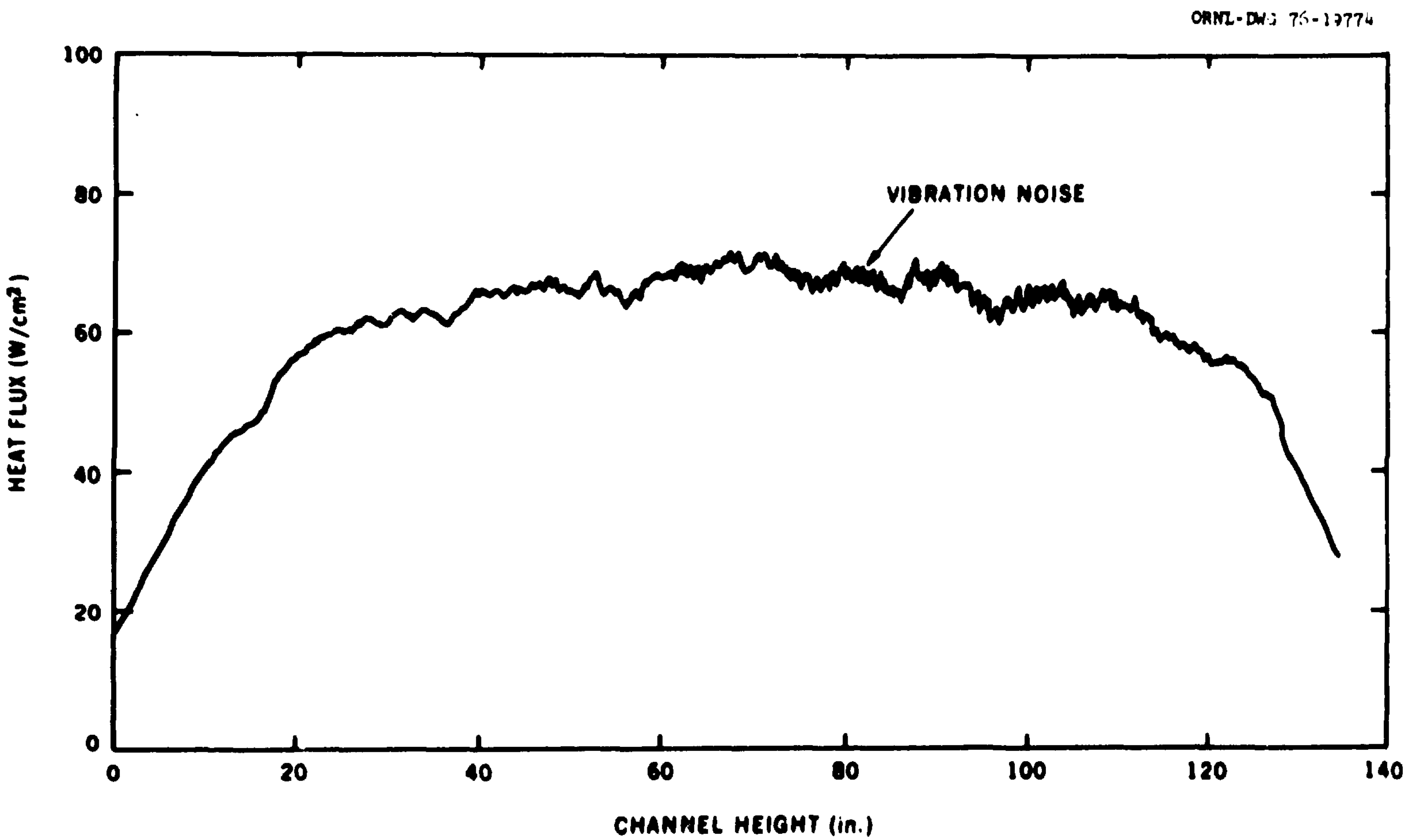

Fig. 8. Typical axial flux plot (TIP trace).

detectors allows isolation of the noise directly related to instrument tube vibration or impacting.

5. EFFECT OF BYPASS HOLE PLUGGING ON VIBRATIONS

Neutron noise analysis (NCPSD) was used to determine the degree to which plugging of the bypass cooling holes in the core support plate eliminated instrument tube vibrations and impacts. Neutron noise measurements were made at a BWR-4 plant before and after the coolant holes were plugged. The NPSD of the LPRM C and D detectors and the NCPSD between these detectors in each of 31 in-core detector strings were computed utilizing an on-line, minicomputer-based noise analysis system.

Figure 9 shows spectra obtained at ~80% flow before and after plugging. Note that the amplitude of the NCPSD in the 4- to 6-Hz range is below 2×10^{-6} Hz^{-1} after plugging. Furthermore, the coherence between C and D detectors is negligible in the 4- to 6-Hz range after plugging (Fig. 10). These coherence measurements support the conjecture presented in Sect. 3 that channel box motion caused by impacting causes perturbations in the neutron flux which are coherent along the tube axis.

The neutron noise signatures at 80% flow from all 31 LPRM strings after plugging are shown with a typical signature obtained before plugging in Fig. 11. Based on the criterion stated in Sect. 3 (NCPSD < 2×10^{-6} Hz^{-1}), we conclude that plugging the bypass coolant holes greatly reduces (and most probably eliminates) impacting of instrument tubes against channel boxes. However, it should be reemphasized that these signatures were obtained at ~80% of full rated flow (due to temporary plant power restrictions at the time the measurements were made).

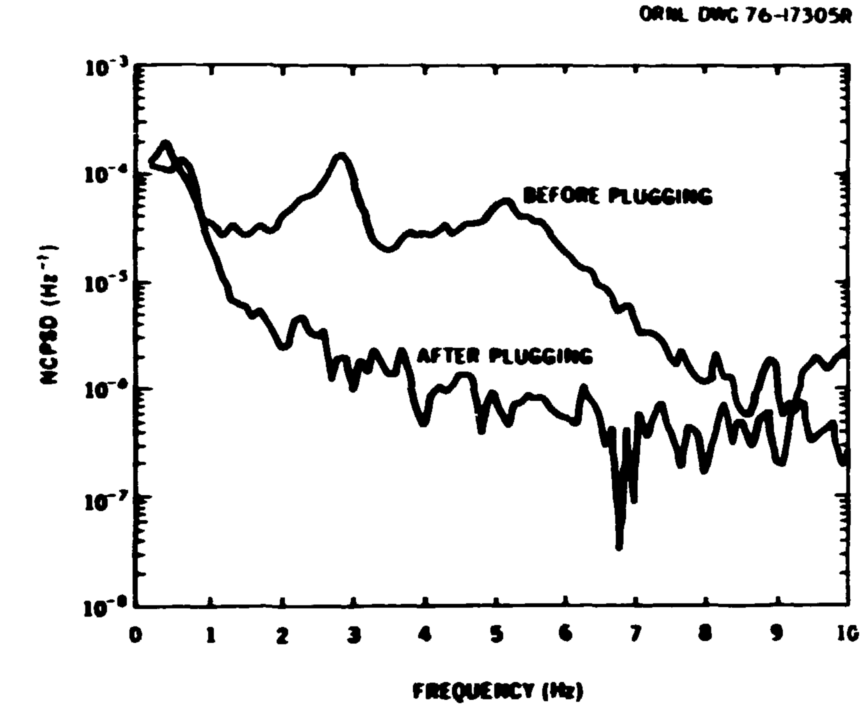

Fig. 9. NCPSD between C and D detectors at 80% flow before and after plugging.

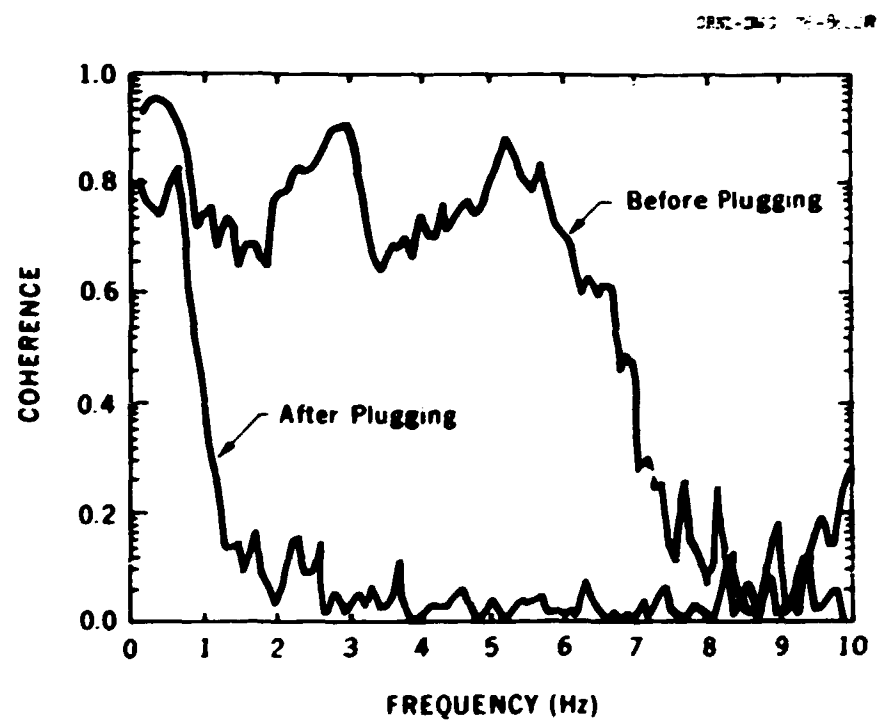

Fig. 10. Coherence between C and D detectors at 80% flow before and after plugging.

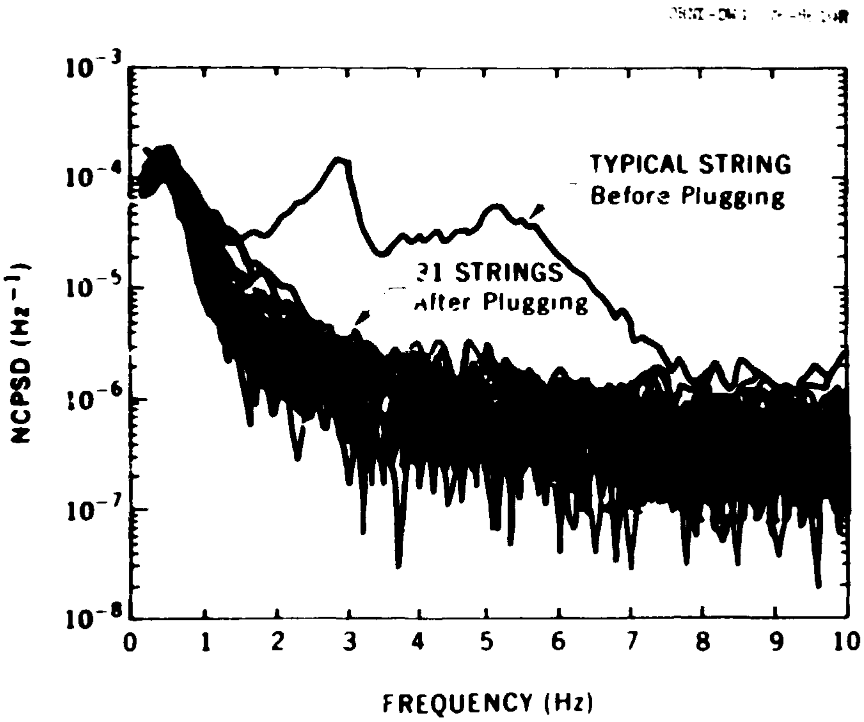

Fig. 11. Comparison of a typical impacting signature (C and D NCPSD) before plugging with signatures from 31 strings after bypass cooling holes were plugged.

6. COMPARISON OF NOISE SIGNATURES WITH VISUAL INSPECTION OF FUEL BOXES

Neutron noise signatures were compared with the results of visual inspection of fuel channel boxes in three BWR-4s.* In making this comparison, we postulated that if the NCPSD between C and D detectors in the frequency range from 4 to 6 Hz is $>2 \times 10^{-6}\ Hz^{-1}$ the fuel boxes should show wear. We believe that damage of channel boxes is related to the cumulative impacting and rubbing experienced by the boxes, whereas the noise signatures indicate only the conditions at the time of the measurement. Nevertheless, we attempted to compare the noise level in the 4- to 6-Hz frequency range with the number of fuel boxes rejected based on visual inspection. The results are tabulated in Table 1.

The comparison of Table 1 has several limitations: (1) the plant operating procedure at the time of noise measurements limited the core flow to less than 100% of full rated flow in some cases (in Sect. 3 we showed that impacting diminishes as flow is reduced); (2) the NCPSD of all LPRM strings could not be obtained because some C or D detectors were out of service; (3) noise measurements were not made immediately prior to shutdown for fuel box inspection (the time between measurements and inspection was as great as 6 months in the case of one plant).

Although the results are encouraging in that damaged boxes were found at locations where the NCPSD was $>2 \times 10^{-6}$, there were also damaged boxes at locations where neutron noise analysis indicated no impacting at the time of measurement. One possible explanation is that the damage

*GE and plant personnel inspected the fuel boxes.

Table 1. Visual inspection of fuel boxes vs neutron noise level

Plant	No. of LPRM Strings	No. of LPRM Strings[a]	Time Lapse[b] (months)	Core Flow[c] (% of full rated)	Number of LPRM Strings Surrounded By At Least One Rejected Channel Box for NCPSD (Hz^{-1})[d]		Number of LPRM Strings Surrounded By No Rejected Channel Boxes for NCPSD (Hz^{-1})	
					$<2 \times 10^{-6}$	$>2 \times 10^{-6}$	$<2 \times 10^{-6}$	$>2 \times 10^{-6}$
A	31	31	0.5	80	2	23	3	3
B	43	33	5	90	6	21	5	1
C	43	39	6	80	7	16	12	4
C	43	33	6	100	1	21	6	5

[a]Number of LPRM strings examined by neutron noise.

[b]Time lapse between noise measurements and inspection.

[c]Core flow at time of noise measurement.

[d]Boxes are (in general) rejected if any portion of the box wall is worn more than ~30 mils.

might have occurred prior to the noise measurements, but, owing to channel box wear, the vibrating instrument tube no longer contacted the fuel box at the time the neutron noise measurements were made. Damage may also have occurred between the time of noise measurement and shutdown for inspection. It is surmised that periodic noise monitoring from plant start-up to shutdown might have detected impacting during some interval. As expected, the results indicate in the case of Plant C that noise measurements at full flow are a more reliable indicator of wear than measurements at 80% of full flow.

Table 1 also shows the converse situation, i.e., some LPRM strings had no rejects around them, but there was a definite indication of impacting based on the NCPSD. However, "no rejects" does not imply zero box wear, because the inspection criteria for re-use allows a slight amount of wear.

Although these results are, in general, encouraging, we believe it is premature to conclude positively that neutron noise analysis can be used to predict wear of channel boxes.

7. CONCLUSIONS AND RECOMMENDATIONS

We conclude that: (1) accelerometers mounted on the instrument guide tube extension outside the reactor vessel can be used to detect impacting, but not rubbing, of that (and only that) instrument tube against surrounding fuel channel boxes; (2) 4- to 6-Hz neutron noise from the C and D LPRM detectors can likewise be used to detect impacting at any core location having a string of LPRM detectors; (3) plugging of the bypass cooling holes greatly reduces instrument tube vibration and eliminates impacting for core flow rates of 0-80% of full rated flow (measurements could not be obtained at higher flow rates); (4) neutron noise signatures obtained at a single time prior to shutdown are not a reliable replacement for visual determination of cumulative channel box damage caused by impacting by instrument tubes; and (5) the noise on TIP traces obtained with standard plant instrumentation is not a reliable indicator of impacting.

We recommend that: (1) a combination of accelerometers and LPRM signals would provide the best method for in-service monitoring for impacts (accelerometers would be used to monitor those instrument tubes containing intermediate-range monitors, source-range monitors, and sources); (2) if some impacting still occurs after BWR-4 cooling hole modifications, then additional studies should be conducted to determine if neutron or accelerometer noise monitoring performed periodically during a fuel cycle can be used to predict the degree of channel box damage; (3) a calculational methodology should be developed for calculating the response of in-core neutron detectors to flux perturbations caused by such movements as instrument tube vibrations, channel flow perturbations, and control rod perturbations; and (4) mechanical calculations should be made to determine if rubbing excites the 4- to 6-Hz channel box resonance, and, if it does, the relative amplitude of neutron noise seen by in-core detectors should be determined.

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