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MASTER

ACOUSTIC-EMISSION MONITORING OF
LOFT FUEL-CLADDING-BURST TESTS

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U.S. Department of Energy

Idaho Operations Office • Idaho National Engineering Laboratory

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ABSTRACT

Experiments at the Loss-of-Fluid Test Facility (LOFT), beginning with experiment L6-8 (Anticipated Transient Experiment), will use a core equipped with several pressurized fuel rods. Because some of the tests may produce temperature and pressure conditions which could conceivably burst a number of rods, a nondestructive method for burst detection is needed. Acoustic emission monitoring of a number of tests of small zircaloy tubing samples, each with internal gas volume similar to that of an actual fuel rod, showed this technique to be feasible and warranting further investigation. Burst signal amplitudes at room temperature and even at temperatures in excess of 1144 K (1600°F) (in tests run as part of another program) were 30 to 40 dB above background noise levels. The success of the experiment will depend on the acoustic transmission of fuel rod burst signals through high pressure, high temperature steam to a waveguide which will transmit the acoustic signals from the reactor core to an area outside the reactor-vessel head. If reactor background noise levels are low, in the frequency range used for acoustic emission monitoring, compared with the typical acoustic emission signal levels at high temperature, acoustic emission monitoring should be a suitable technique for remote monitoring of the reactor core region during testing.

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ACOUSTIC EMISSION MONITORING OF LOFT FUEL CLADDING BURST TESTS

1. INTRODUCTION

Beginning with the Loss-of-Fluid Test (LOFT) experiment L6-8 (Anticipated Transient Experiment) a combination of high temperatures and internal gas pressures in some of the fuel rods may cause cladding failure by bursting, during blowdown. Pressures can be monitored in only a few rods; a method is needed to detect bursting of uninstrumented rods.

Acoustic emission (AE) monitoring was thought to be a possible approach, but its use to monitor fuel rod failure events in an operating reactor has several complications:

- a. Application of the technique depends on the burst signal amplitudes exceeding reactor background noise levels by a sufficient amount to permit adequate detection.
- b. Placement of specialized sensors in the reactor core, close to the points of interest, is not feasible; no provision was made in the design for mounting even a small AE sensor in the core assembly.
- c. No direct mechanical sound transmission path exists from the fuel rods to the reactor exterior.
- d. High-frequency sound transmission through 13.8 MPa (2000 psi) steam at 616 K (650°F) is at present an unknown quantity.

Determining the feasibility of the approach requires conducting several burst tests of cladding material to obtain signal amplitudes as a function of temperature, and comparing the resulting data with the power spectrum of the background noise from the LOFT reactor system during operation and blowdown.

During FY-81, only room temperature burst tests were performed in this AE study. Additional information was provided by some high temperature burst tests performed as part of another program dealing with the burst characteristics of LOFT fuel cladding. This report presents the results of the 12 room-temperature burst tests performed; provides details of specimen design, test instrumentation used, and the test system employed; and discusses the test results. Recommendations for future work are given.

2. EXPERIMENTAL PROGRAM

The first six test specimens were fabricated with a machined notch; the specimen design is shown in Figure 1. These specimens were used for initial testing, development of the optimum test techniques, and for preliminary evaluation of acoustic emission for monitoring burst tests.

Figure 1. Machined-notch burst test specimen.

The monitoring equipment consisted of an Acoustic Emission Technology Corporation (AET) Model 201/202A acoustic emission system with an AET Model 160 (60 dB) preamplifier and a Dunegan/Endevco S140B (140 kHz) acoustic emission sensor. The RMS output of the AET equipment was useful for monitoring both gas noise and burst characteristics in these particular tests.

For the last two tests of notched specimens, an Ampex model FM 1300 instrumentation tape recorder with a frequency response to over 200 kHz in the direct record mode at 1.5 m/s (60 in./s) tape speed was connected into the AE system after the 60 dB preamplifier, to directly record the RF signals. A DC amplifier was used to match AE signal levels to the tape recorder FM channel input requirements. In addition, a modified Sony AV-3650 video tape recorder with response to 4 MHz was used in the system to see if burst signals could be captured in a form suitable for frequency content analysis.

The specimens for these tests were sized to duplicate the approximate gas volume of actual LOFT fuel rods. Specimens were pressurized from a high pressure argon gas bottle (up to 22 MPa/3200 psi available) equipped with appropriate regulators and valves. Both the autoclave and specimen gas lines were equipped with pressure transducers.

Specimens were burst tested in several different ways:

- A. Pressurize specimen in autoclave filled with air at 0.1 MPa (1 atm).
- B. Pressurize specimen and autoclave simultaneously to 20.7 MPa (3000 psi). Slowly release pressure in autoclave until differential pressure causes sample to burst.
- C. Fill autoclave with water. Pressurize autoclave and specimen simultaneously to 20.7 MPa (3000 psi). Valve off specimen and release pressure in autoclave until specimen bursts. (This technique reduces system gas flow noises to very low levels.)
- D. Pressurize specimen with argon, in autoclave filled almost to the top with water, until specimen bursts. This method keeps the specimen from flying around in the autoclave upon bursting.

Method A, filling and pressurizing the specimen with argon until burst, with the specimen in an air-filled autoclave at room temperature and

pressure, worked well, but gas noise during specimen filling and immediately after bursting was readily detectable (although not overpowering). Method B is most similar to an actual fuel cladding burst situation, except that the cladding, which is pressurized to about 2.1 MPa (300 psi) at room temperature, may be at a temperature of 1200 K (1700°F) or higher when bursting occurs.

A different test specimen design, shown in Figures 2 and 3, was used in the second phase of the room temperature tests. Although difficult to machine (Figure 4 shows a sample damaged during machining), this reduced-section design does allow more accurate control of the tubing wall thickness during machining than did the machined notch design previously used. After careful machining (an internal mandrel was used to support the tube) the tube wall thickness was measured ultrasonically to determine the minimum thickness in the reduced section. Measured thicknesses ranged from 0.07 to 0.14 mm (0.0026 to 0.0057 in.). Because of a lack of proper tooling, sample thicknesses could not be measured continuously but were taken at five points from top to bottom of the reduced section at 0°, 90°, 180°, and 270° orientations, using a high resolution 25-MHz immersion transducer and appropriate high frequency electronics. Measurement accuracy was estimated to be $\pm 10\%$, sufficient for our purposes; Table 1 gives the measured values for each of the six samples.

For the second series of six tests, the AET acoustic emission system was replaced with a Dunegan/Endevco 3000 series AE instrumentation system including an X, Y, Z oscilloscope and a Dunegan Model 115 X-Y plotter. The 3000 series instrumentation consisted of a Model 220 bin, a Model 920 distribution analyzer, and a Model 921 amplitude detector used in conjunction with a Model 1801 (40 dB) preamplifier and the S140B AE sensor (transducer) used previously with the AET equipment. The revised instrumentation permitted amplitude distribution measurements on each burst test, allowing better characterization of the burst events and minimizing the amount of information obscured by gas flow noise.

Samples were mounted in an autoclave filled with air at room temperature and pressure, and then were pressurized with argon gas. The

Figure 2. Reduced-section burst test specimen.

TABLE 1. REDUCED-SECTION THICKNESS MEASUREMENTS

Sample	Minimum		Maximum	
	(mm)	(in.)	(mm)	(in.)
1	0.097	0.0038	0.145	0.0057
2	0.066	0.0026	0.117	0.0046
3	0.102	0.0040	0.119	0.0047
4	0.099	0.0039	0.119	0.0047
5	0.117	0.0046	0.140	0.0055
6	0.094	0.0037	0.124	0.0049

Figure 3. Photograph of reduced-section specimen.

Figure 4. Damaged reduced-section specimen.

pressurization rate was carefully controlled to avoid obscuring test data with gas flow noise.

Figure 5 is a block diagram of the instrumentation and gas pressurization system used for all of the burst tests.

Figure 5. Burst test system block diagram.

3. RESULTS AND DISCUSSION

Six machined-notch tubing specimens were tested using the methods and the equipment described in Section 2. Burst pressures ranged from approximately 1.4 to as high as 17.1 MPa (200 to 2480 psi). Figure 6 shows three of the notched specimens. The center one, not tested, includes the small diameter tubing and fittings used for specimen pressurization. Figures 7 and 8 show closeup views of the two failed specimens in Figure 6 after the burst test. Figure 9 shows the three remaining machined-notched specimens after testing; the one on the left was burst in a water-filled autoclave, while the others were burst in air. Note the degree of crack propagation.

The AE signal output vs. pressure for Specimen 1 is shown in Figure 10; this was typical of the results for the machine-notch specimens. At burst, the RMS voltage went to about 4.0 volts as the pressure dropped. The voltage output shows that the burst energy is quite high and, since the burst event duration is very short, the RMS reading indicates a high signal amplitude (probably saturating the preamplifier). After the burst, gas rushing through the lines and out of the broken tube keeps the RMS voltage level high. Data from this test are of limited value because all that can be seen is that the specimen did burst; signal amplitudes from the burst cannot be measured or even deduced.

Because of the need to determine burst signal amplitude, an Ampex model FM 1300 instrumentation tape recorder was set up for Specimens 5 and 6, in conjunction with appropriate DC signal amplifiers for pressure transducer recording, to record both the high frequency signals from the acoustic emission equipment on the direct record channels and the low frequency (essentially DC) signals from the pressure transducers on the FM channels. The system was checked out using simulated AE signals, since precise setting of gain levels was critical in obtaining undistorted RF signals on playback because of the limited dynamic range and relatively poor signal-to-noise ratio of the tape recorder.

Figure 6. Three notched test specimens, one untested.

Figure 7. Closeup view of failed notched burst test specimen in Figure 6.

Figure 8. Closeup view of second failed burst test specimen in Figure 6.

Figure 9. Remaining three notched burst test specimens after failure.

Figure 10. Acoustic emission RMS voltage versus specimen internal pressure.

Due to unfortunate circumstances, burst tests were not recorded by the tape machine. Test data from the fifth notched test specimen were being taped during pressurization when the pressure limit of the gas bottle was reached at approximately 17.23 MPa/2500 psi. After holding for about three minutes, a decision was made to release the specimen pressure and refill the gas bottle to approximately 20.67 MPa (3000 psi). The tape recorder was shut off just as the pressure was released and simultaneously the specimen burst. Since test 5 was missed, test 6 was to be recorded; normal routine included raising the system pressure to about 1.38 MPa (200 psi) (the noisiest part of the test for the AE monitoring) before turning on the X-Y recorders and tape recorders. This specimen burst on the initial loading cycle at about 1.38 MPa (200 psi) before the recorders were turned on. The thickness of the specimen in the notched region could not be measured accurately, but appeared to be less than 0.025 mm (0.001 in.).

These initial tests were intended to be used to guide development of optimum AE instrumentation and to determine whether the sample configuration was suitable for simulating burst behavior in actual fuel cladding. The results showed that changes in both sample design and instrumentation were needed.

With existing techniques, notched samples could not be accurately machined to a controlled and consistent tubing wall thickness at the bottom of the notch (in order to obtain consistent burst test failure pressures). Test monitoring using an RMS display did not provide sufficient detail to allow meaningful characterization of the burst response. In addition, the use of a tape recorder, which should give much improved resolution of burst signals and playback for later analysis, was difficult unless two people were monitoring the tests. Because of these problems, careful thought was given to improving both the specimen design and the method of obtaining and recording the acoustic emission information.

The specimen design shown in Figures 2 and 3 provided a more controllable and nondestructively measurable wall thickness with a target value of 0.076 mm (0.003 in.). During subsequent burst testing, this reduced-section design proved much superior to the notched specimens, with more consistent burst pressures obtained. The main disadvantage of this design (other than machining difficulty) is the possibility of high stress concentrations at the sharp step between thick and thin sections of the tube wall, but the problem could be minimized by a suitable machined radius at the transition.

Discussions were held with Dunegan/Endevco (D/E) applications people concerning ways to obtain more useful AE information from the reduced-section specimen tests. It was decided that, short of buying a new computerized AE system, a D/E Model 921 amplitude detector module used to drive a D/E Model 920 distribution analyzer would provide a distribution of peak event amplitudes derived from the burst emission signals. This distribution covers a usable range of signal amplitudes over the approximately 74 dB dynamic range of the preamplifier used. The Model 920

distribution analyzer plots a distribution of events over a 100-channel (100-dB) range and displays the number of events in a given amplitude window. With this approach, useful data on burst characteristics were obtained. Burst signal amplitudes could be discriminated from gas flow noises for the first time.

One problem with this system was revealed during initial testing. It was found that gas flow noise was effectively "locking up" the Model 920 distribution analyzer due to both large amounts of data and too long a reset period. The reset is designed to be delayed for an adjustable period of time after an acoustic emission event goes through. If large numbers of events of varying amplitudes are being received, it is possible for the system to be locked onto a low amplitude signal (above the threshold) and thereby miss a much higher amplitude signal.

Test results for reduced-section Specimen 1 are shown in Figures 11 and 12. The first pressurization run on this sample was stopped at 10.34 MPa (1500 psi) when a rupture disk in the autoclave failed. It was noticed during this test run that the Model 920 distribution analyzer reset rate was too slow; for the second run, shown in Figure 12, the reset rate was set for the shortest possible interval. In addition, the amplitude detector module threshold for this test was set so that only signals of amplitude 80 dB (it was set at 35 dB for the other five tests) and over would be processed. Signal amplitude at burst was 100 dB, as it was for the remaining five reduced-section specimens tested at room temperature.

Figures 13 through 16 show test results for reduced-section Specimens 2 through 6. In Figure 13, data for specimen 2 show the effect of using a switchable 20 dB attenuator placed between the transducer and preamplifier. With the D/E equipment it was not practical to lower the gain below the fixed level of 100 dB, (40 dB preamplifier, 60 dB in amplitude detector) by a known amount because even a 1 or 2 dB setting on the attenuator reduced system gain much more than 1 or 2 dB. No test results are shown for specimen 4 (burst at 17.85 MPa/2590 psi) because of an operator error which resulted in erasure of the memory contents of the

Figure 11. Burst test record, specimen 1, first run (test aborted).

Figure 12. Burst test record, specimen 1, second run.

Figure 13. Burst test record, specimen 2.

Figure 14. Burst test record, specimen 3.

Figure 15. Burst test record, specimen 5.

Figure 16. Burst test record, specimen 6.

Model 920 distribution analyzer before the data were plotted on the X-Y recorder. The amplitude distribution display did, however, show a peak at 100 dB. Note the presence of multiple peaks in the amplitude distributions shown in Figures 14 to 16 (ignore the gas noise peaks). It is theorized that as the specimen began to fail, the resulting high pressure gas jet drove the specimen sideways, bending the small attaching capillary tube. When the sample hit the side of the autoclave, it broke into at least three pieces. These impact and specimen failure noises probably gave rise to the multiple peaks seen below 100 dB. (The amount of stored energy in the specimen and the supply tubing is relatively large, and would tend to drive the burst specimen into the autoclave wall at very high velocity.) It is also possible that some of the peaks were due to deformation and tearing of the reduced section wall, although these events should result in fairly low amplitude signals which might be somewhat obscured by the noise of gas escaping from the failed specimen. Figure 17 is a photograph of specimens

Figure 17. Reduced-section specimens 1-6 (left to right) after burst testing.

1-6 (left to right in the picture.) Note how the reduced center section failed in each case. Because every test produced a peak AE signal amplitude of 100 dB, it was obvious that the overall AE system gain was too high to accurately record the high amplitude signals received; these signals were driving the amplifier system into saturation. However, these results do indicate that room temperature burst testing produces very high amplitude signals, especially when attenuation between source and AE sensor is considered. Since waveguides smaller than 3.2 mm (1/8 in.) in diameter have been found to cause severe attenuation at the frequencies used in these tests, the combination of the 1.6-mm (1/16 in.) diameter pressurizing capillary and its valves and fittings may well have caused losses up to 20 dB, although these losses were not measured.

To evaluate the amplitudes of burst signals occurring under conditions more closely duplicating those in the LOFT reactor core, higher temperature test data are needed. Methods developed for this study were used to monitor a series of high temperature burst tests on another LOFT materials program. The results were quite encouraging, with burst pressures of approximately 7.58 MPa (1100 psi) at 1089 K (1500°F) yielding burst amplitudes over 90 dB. At temperatures over 1144 K (1600°F), burst amplitudes were down to around 60 dB at 3.79 MPa (550 psi). Details on these high temperature tests, including test data, are given in Appendix A.

Knowing the sensitivity of the AE sensor used, in dB relative to 1V/microbar, it is possible to calculate sensor voltages corresponding to peak signal amplitudes (sound pressure levels) at the AE sensor for each burst test. Determining burst sound pressures at the sample involves some additional corrections; these pressures have not been calculated because the specific signal amplitudes at burst are not presently required for feasibility evaluation. Many questions remain to be answered before the feasibility of AE monitoring for detection of bursting fuel rods during an actual LOFT experiment can be established.

4. FUTURE WORK

Further experimental work on pressurized cladding material specimens is needed to provide an adequate basis for assessing the feasibility of AE monitoring of LOFT fuel rod bursts. The following investigations are recommended:

- (a) Room temperature tests should be run with the AE sensor mounted on a waveguide which is not in acoustic contact with the test sample -- separated by 50 to 75 mm (2 to 3 in.) of air, for example. These tests will help determine whether the burst is of sufficient energy to propagate a reasonable distance in a gas and be detected, and will simulate more closely the constraints of operation in the reactor core. A direct acoustic (mechanical) path will probably not exist between bursting fuel rods and the waveguide used to bring sound from the core to the outside of the reactor vessel.
- (b) If room temperature results provide usable signal strength levels, the tests should be repeated in a saturated steam atmosphere at temperatures of 586 to 644 K (600 to 700°F) to simulate, even more closely, in-reactor conditions.
- (c) Several isothermal tests should be run at high temperatures to establish how AE signal amplitude or amplitude distribution from a burst correlates with burst pressure at a given temperature and to determine the repeatability of the test results.
- (d) If the above tests show adequate signal strength levels and signal-to-noise ratios for AE monitoring, the next step is to perform noise spectrum measurements on the LOFT reactor during operation. Such measurements would show levels of background noise as a function of frequency. By using appropriate frequency range AE sensors, it may be possible to eliminate most of the noise pickup problems in the system.

A determination should be made, after these measurement results are known, of the feasibility of detecting fuel cladding bursts. Burst signal amplitudes at a given frequency should exceed the background noise (at the same frequency) by several dB in order to maintain adequate signal-to-noise ratios and not require the use of sophisticated signal processing techniques to extract the desired signals from noise.

If burst signal detection in the operating reactor appears feasible, the next step is to install AE sensors on a reactor instrument tube (TIPS tube) penetration (on the outside of the reactor head) in preparation for monitoring fuel cladding behavior during experiment L6-8 and future experiments. (The TIPS tube runs down into the reactor core region.) The actual monitoring would require more sophisticated instrumentation than was used in the initial feasibility testing because burst amplitudes must be monitored versus time in order to detect more than one burst in a short time interval. A computerized system offers the best method of recording and analyzing data because the signals can be stored in digital form for various methods of data analysis. Signals could be better characterized and specific times and time intervals between AE events during the test could be utilized for their analysis. Signal enhancement or other processing could also be done on a larger computer if required.

5. OBSERVATIONS AND CONCLUSION

Of the different AE approaches used, signal amplitude monitoring was the most useful.

Burst tests produced very high amplitude signals, exceeding the dynamic range of the available monitoring instrumentation.

Burst test samples of LOFT fuel cladding monitored for a different program showed that tests performed at over 1144 K (1600°F) produced signal amplitudes 30 to 40 dB higher than test system noise.

Additional work, including reactor noise spectrum measurements, is needed to determine whether the burst signals can be detected in the reactor environment.

APPENDIX A

ELEVATED-TEMPERATURE BURST TEST RESULTS

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APPENDIX A

ELEVATED TEMPERATURE BURST TEST RESULTS

Eighteen elevated-temperature burst tests of zircaloy fuel cladding (tubing) were performed as part of a subsequent investigation of LOFT cladding material behavior. Data from these tests are given in Table A-1. Test 1 was essentially a stress rupture test (held at temperature and pressure for approximately five minutes) and, as such, was not representative of the other tests. Tests 2-10 were all isothermal i.e., specimens were brought to temperature, then filled with gas (normally in less than two minutes) and pressurized until burst. Tests 11-18 were thermal ramp tests; i.e., specimens were initially pressurized and valved off, then inserted into a high-temperature tube furnace and heated at a high rate. The Model 920 distribution analyzer plots for tests 11-18 are not shown in this appendix because all of the thermal ramp specimens failed at an end fitting weld rather than in the mid-section of the tube.

A Dunegan/Endevco 3000 series AE system was used to amplify and process the AE signals. The test setup was the same as used previously for the reduced-section room temperature tests described in the body of this report, with a vertical tube furnace replacing the autoclave. The specimens were similar to those tested at room temperature except for a constant wall thickness (no reduced section) and a 3.2-mm (1/8-in.) diameter gas supply tube. The larger tubing was used to provide a less attenuating sound transmission path than the 1.6-mm (1/16-in.) diameter tube used previously. (As a side benefit, the larger tubing also had appreciably greater stiffness.) The elevated-temperature specimens were partially filled with a ceramic rod designed to simulate the effects of fuel pellets in an actual fuel rod.

The results for specimens 2-10 are shown as plots of AE signal amplitude distribution in Figures A-1 through A-9. The plots are similar to those obtained previously at room temperature, showing gas noise over the range 30-50 dB. The burst amplitudes show clearly, without additional

TABLE A-1. ELEVATED TEMPERATURE BURST TEST DATA

<u>Test</u>	<u>Temperature</u>		<u>Burst Pressure</u>		<u>Signal Amplitude</u>	<u>Type of Test</u>
	<u>(K)</u>	<u>(°F)</u>	<u>(MPa)</u>	<u>(psia)</u>	<u>(dB)</u>	
1	950	1251	10.34	1500	96	stress rupture
2	983	1311	9.72	1411	100	isothermal
3	1005	1350	9.68	1405	100	isothermal
4	1008	1355	9.64	1399	100	isothermal
5	1083	1490	7.99	1159	90	isothermal
6	1080	1484	8.20	1190	99	isothermal
7	1080	1484	7.14	1036	99	isothermal
8	1156	1622	5.06	735	76	isothermal
9	1161	1631	3.82	554	61	isothermal
10	1159	1628	3.86	560	59	isothermal
11	1007	1353	9.24	1341	72	thermal ramp
12	912	1183	9.94	1442	62	thermal ramp
13	1020	1376	9.11	1322	93	thermal ramp
14	1022	1380	8.05	1168	60	thermal ramp
15	1043	1418	7.80	1132	100	thermal ramp
16	1090	1502	7.39	1073	82	thermal ramp
17	1160	1629	3.73	542	76	thermal ramp
18	1140	1592	4.81	698	64	thermal ramp

Figure A-1. Isothermal acoustic emission signal distribution, burst test 2.

Figure A-2. Isothermal elevated temperature burst test 3.

Figure A-3. Isothermal elevated temperature burst test 4.

Figure A-4. Isothermal elevated temperature burst test 5.

Figure A-5. Isothermal elevated temperature burst test 6.

Figure A-6. Isothermal elevated temperature burst test 7.

Figure A-7. Isothermal elevated temperature burst test 8.

Figure A-8. Isothermal elevated temperature burst test 9.

Figure A-9. Isothermal elevated temperature burst test 10.

Figure A-10. Linear regression fit of specimen burst signal amplitude as a function of burst pressure.

signals being detected between the gas noise and actual burst signals. (The lack of other signals is probably due to the stiffness of the 3.2-mm (0.125-in.) capillary tubing and the fairly small diameter inner furnace tube which restrained the sample from much movement at burst; there would be little chance of the sample being thrown violently against the tube wall).

Figure A-10 shows data from tests 2-10 plotted with AE signal amplitude as a function of burst pressure. Results from tests 5-10 were used to calculate a best straight-line fit of the available data, using a linear regression analysis. Tests 2-4 were not used because burst AE signal amplitudes from these three were recorded at 100 dB levels and were thought to have saturated the system. Confirming this appraisal, if the burst pressures for tests 2-4 were plotted on an extension of the linear regression calculated line, the signal amplitudes for these three tests should actually have been approximately 110 dB.

The data obtained from this series of elevated temperature tests show that the amplitude of AE burst signals is probably sufficiently high to be detected in a somewhat noisy reactor environment. Further test work is indicated in order to estimate what the probable signal-to-noise ratios might be in an operating reactor with fuel rod burst events in the reactor core.