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NUREG 0250-1
BNWL-2232-1
NRC-5

Program to Develop Acoustic Emission—Flaw Relationship for Inservice Monitoring of Nuclear Pressure Vessels

Progress Report No. 1

July 1, 1976 to February 1, 1977

P. H. Hutton
E. B. Schwenk

March 1977

Prepared for the
Nuclear Regulatory Commission
Reactor Safety Research Division
Under Contract No. EY-76-C-06-1830
Fin. No. B2088-7, TDO No. 872

Battelle
Pacific Northwest Laboratories

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PROGRAM TO DEVELOP ACOUSTIC EMISSION-FLAW RELATIONSHIP FOR INSERVICE MONITORING OF NUCLEAR PRESSURE VESSELS

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Richland, Washington 99352

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ABSTRACT

This is a laboratory research program to characterize acoustic emission (AE) from flaw growth and noise from innocuous sources in A533B Class 1 pressure vessel steel. The objectives are

- Characterize AE from a limited range of defects and material property conditions of concern to reactor pressure vessel integrity.
- Characterize AE from innocuous sources (including defects).
- Develop criteria for distinguishing significant flaws from innocuous sources.
- Develop an AE flaw damage model to serve as a basis for relating in-service AE to pressure vessel integrity.

The purpose of the program is to build an experimental evaluation of the feasibility of detecting and analyzing flaw growth in reactor pressure boundaries by continuously monitoring for AE.

A detailed program plan in the form of an analysis-before-test document has been prepared and approved.

An AE monitoring system incorporating a new concept with data recording in solid-state digital memories and signal source isolation has been adapted for use on this program.

A Biomation Model 8100 transient wave analyzer has been purchased and interfaced with the AE monitor system for signal wave form and frequency spectrum analysis.

Two PNL AE sensors have been calibrated in absolute terms (re 1 volt/μbar) by an independent calibration laboratory for reference sensors.

The hydraulic system on an MTS test frame has been modified to reduce noise.

The range of AE monitoring frequency to be used in laboratory test work has been evaluated in relation to the range limitations to be expected on an inservice reactor.

Initial calibration tests of the integrated AE monitor-mechanical test system have been performed using an A533B Class 2 steel specimen. Purchase of an existing 8 1/4 in. (210 mm) thick plate of A533B Class 1 steel is in progress in collaboration with the Naval Research Laboratory. To facilitate an early start of testing, a well characterized weldment specimen will be used.

High temperature (600° F) commercial AE sensors have been purchased for test and evaluation for long term inservice reactor monitoring.

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ACOUSTIC EMISSION - FLAW RELATIONSHIP FOR
INSERVICE MONITORING OF NUCLEAR PRESSURE VESSELS

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INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has authorized Battelle, Pacific Northwest Laboratories (PNL) to perform a laboratory research program to characterize acoustic emission (AE) from flaw growth and noise from innocuous sources in A533B Class 1 pressure vessel steel. The primary objectives of this program are:

- Characterize AE from a limited range of defects and material property conditions recognized as being of primary concern to reactor pressure vessel integrity.
- Characterize AE from innocuous sources (including defects) which can be reasonably expected to exist in a pressure vessel.
- Develop criteria for distinguishing significant flaws from innocuous sources.
- Develop an AE flaw damage model to serve as a basis for relating in-service AE to pressure vessel integrity.

The purpose of the program is to build an experimental evaluation of the feasibility of detecting and analyzing flaw growth in reactor pressure boundaries by continuously monitoring for AE. This report is the first published progress review of the program. The period covered is July 1, 1976 to February 1, 1977.

SUMMARY

The program is reviewed by specific topics which collectively encompass the total effort.

PROGRAM PLAN

The detailed program plan in the form of an analysis-before-test document has been prepared and approved by NRC. It is included as Appendix A of this report.

NRC and PNL staff members visited the Battelle-Frankfurt, Germany Laboratory in September 1976 to review their AE research work. The purpose of the visit was to promote a complementary relationship between their program and the NRC-PNL program and to discuss analytical techniques and results. A trip report on this visit is included as Appendix B of this report.

PREPARATION FOR TESTING

An AE monitoring system incorporating a new concept with data recording in solid-state digital memories and signal source isolation has been adapted for use on this program. The system is capable of simultaneously analyzing and storing five AE parameters and up to two mechanical test parameters. All parameters are related on a common time base.

A Biomation Model 8100 transient wave analyzer has been purchased and interfaced with the AE monitor system. This will serve the function of signal wave form and frequency spectrum analysis.

Two PNL AE sensors have been calibrated in absolute terms (re 1 volt/μbar) by an independent calibration laboratory. These will serve as reference sensors for routine calibration of test sensors.

The hydraulic system on an MTS test frame to be used in specimen testing has been modified to reduce noise which might contaminate AE data.

The range of AE monitoring frequency to be used in laboratory test work has been evaluated in relation to the range limitations to be expected on an inservice reactor. Reactor flow noise was simulated on a hydraulic test loop and AE detection vs monitoring frequency was evaluated in the presence of this noise. Inservice monitoring appears to be limited to frequencies >300 - 400 kHz. Primary monitoring frequency planned for laboratory testing is 200 kHz to 1 MHz.

Initial calibration tests of the integrated AE monitor-mechanical test system have been performed using an A533B Class 2 steel specimen on hand. Items checked included performance of the AE monitor system, tuned vs untuned sensors, response of the AE system to various types of induced noise signals, and mechanical test system noise level. Some adjustments to the AE monitor system were indicated but in general the total test system operated as expected.

SPECIMEN MATERIAL

Procurement of suitable material for fabrication of test specimens has been a problem. Purchase of an existing 8 1/4 in. (210 mm) thick plate of A533B Class 1 steel is currently planned in collaboration with the Naval Research Laboratory, however, the material will probably not be available until about April 1977. To facilitate an earlier start of testing, a well characterized weldment specimen has been obtained from a discontinued NRC program. The weldment will provide sufficient specimens to initiate two of the planned tests.

HIGH TEMPERATURE SENSORS

Two high temperature (600° F) commercial AE sensors have been purchased from each of two companies for test and evaluation for long term inservice reactor monitoring. Sensors from a third commercial source are available as NRC property.

HSST TEST AE DATA

PNL has met with Westinghouse HEDL Staff to coordinate plans to obtain AE data from forthcoming irradiated fracture specimen testing to be conducted for HSST by HEDL.

PNL participated in AE monitoring an HSST thermal shock test at Oak Ridge, TN on January 19, 1977. Using tuned sensors overcame a hydraulic noise problem associated with the test and observed AE appeared to correlate with expected crack growth. Fully analyzed and recorded AE data was not obtained due to low sensitivity on one sensor. This resulted from the necessity to relocate sensors immediately prior to the test.

AE LIBRARY

Reported work in Germany and Japan, as well as the United States, relevant to this program are being reviewed for information beneficial to the NRC program. Summaries are being included with the monthly reports.

DISCUSSION

Discussion is presented under the same topics as used in the summary.

PROGRAM PLAN

A detailed program plan to achieve the program objectives and the rationale used in arriving at this plan are contained in the Analysis-Before-Test document. The document is included as Appendix A of this report. Briefly the program consists of:

- Thirteen different types of laboratory specimen tests (56 specimens) using ASTM A533 Grade B, Class 1 steel.
- Flaw growth by fatigue and fracture at room temperature and 550° F in both weld metal and base metal.
- Innocuous noise sources of slag inclusion and surface oxide.
- Investigate circumstances for possible flaw growth without detectable AE generated.
- Make available a 600° F AE sensor system suitable for inservice reactor monitoring.
- Coordinate and participate in collection and evaluation of AE data from HSST tests.
- Establish a library of and review reports on relevant AE R&D in foreign countries as well as in the United States.

The Battelle-Frankfurt (BF) Laboratory in Frankfurt, Germany has performed a significant amount of AE R&D related to application to reactor systems over the past several years. Most of this work has been sponsored by the West German government (FRG). NRC and PNL staff members visited BF in September, 1976 to discuss their results and review our tenative program with them. The objective was to promote a complementary relationship between the two programs and to discuss analytical techniques. A copy of the trip report for the visit is included as Appendix B of this report. In summary, the BF-FRG work has the following features:

- General emphasis is on application of AE to detect flaws during hydrostatic testing of pressure vessels, to detect loose parts in steam generators, and to detect leaks in pressure system during operation.
- Strong emphasis on basic research - study of AE source mechanisms. Seismic theory being used to guide initial investigation.
- Concentration on study of natural defects with fatigue as initial consideration.

- Ultimate testing of heavy sections up to 27 1/2 in. (70 cm) thick being considered.
- Have performed reactor noise studies. Results not clear in our discussions. Implied a lower significant frequency range than shown by U. S. studies.
- Related work being performed at Saarbrucken, Bremer Inst., and Berlin Inst. in pipe testing, welding, and delayed cracking.

PREPARATION FOR TESTING

An AE monitoring system with unique features developed at PNL has been adapted for use on this program. Figure 1 shows the instrument and its main features. The system expands on a new concept previously demonstrated on programs for the Federal Highway Administration and the Electric Power Research Institute. Key elements are use of solid state digital memories for data recording and source isolation to exclude test system noise. Data parameters recorded are:

- AE event count (total)
- AE event count (valid[a])
- AE energy (valid)
- AE signal rise time (valid)
- AE signal amplitude (valid)
- Mechanical test parameters - either level of a ramp load or total load cycles and the load cycles producing valid AE signals.

All data is recorded in digital memories on a common time base. Thus, all parameters are directly correlateable. Memories are readout directly to a printer to provide a numeric tabulation of data. This greatly reduces

(a) "Valid" designates those signals which the source isolation system has validated as originating from the area of interest.

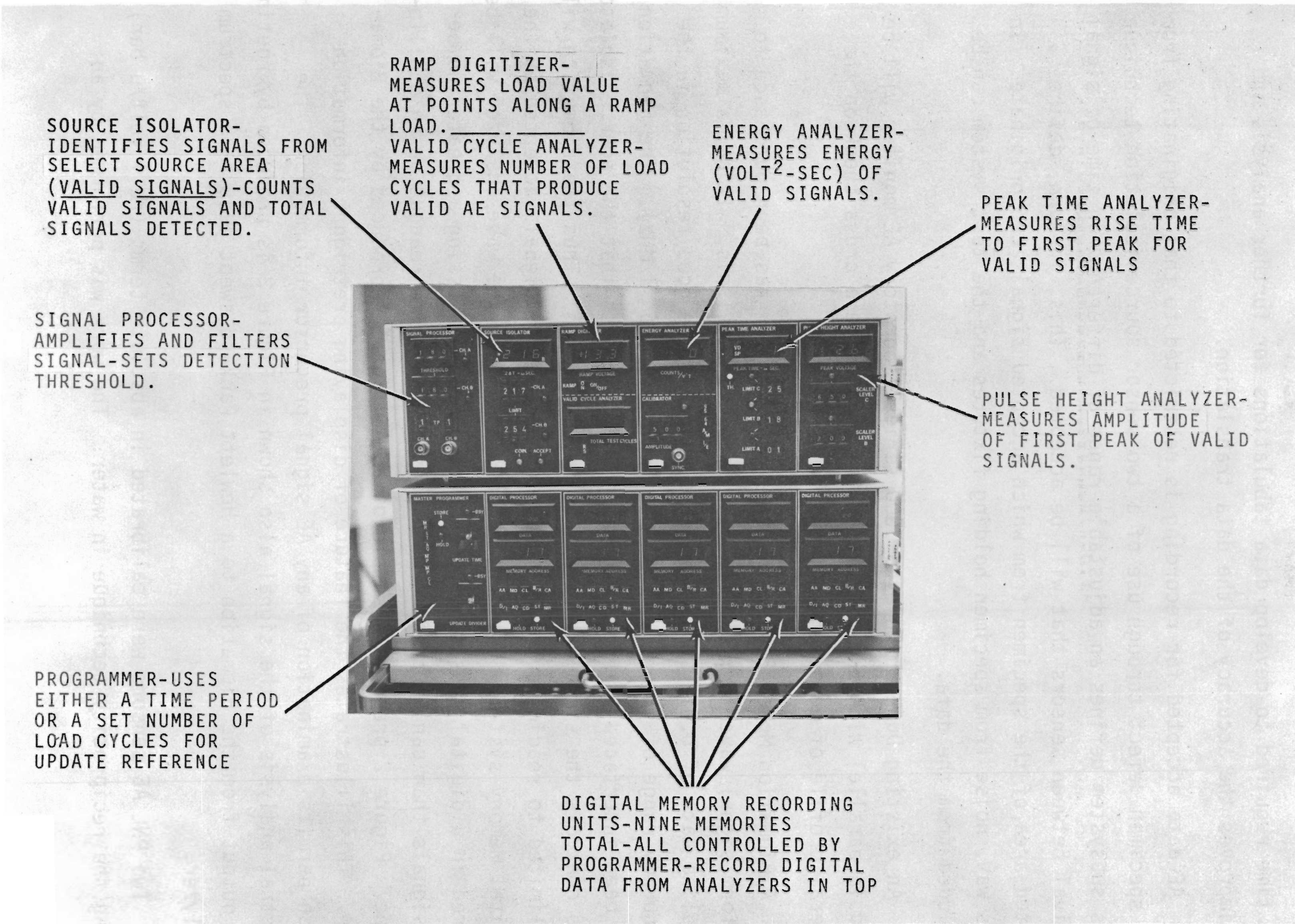


FIGURE 1. Digital Memory AE Monitor System with Source Isolation

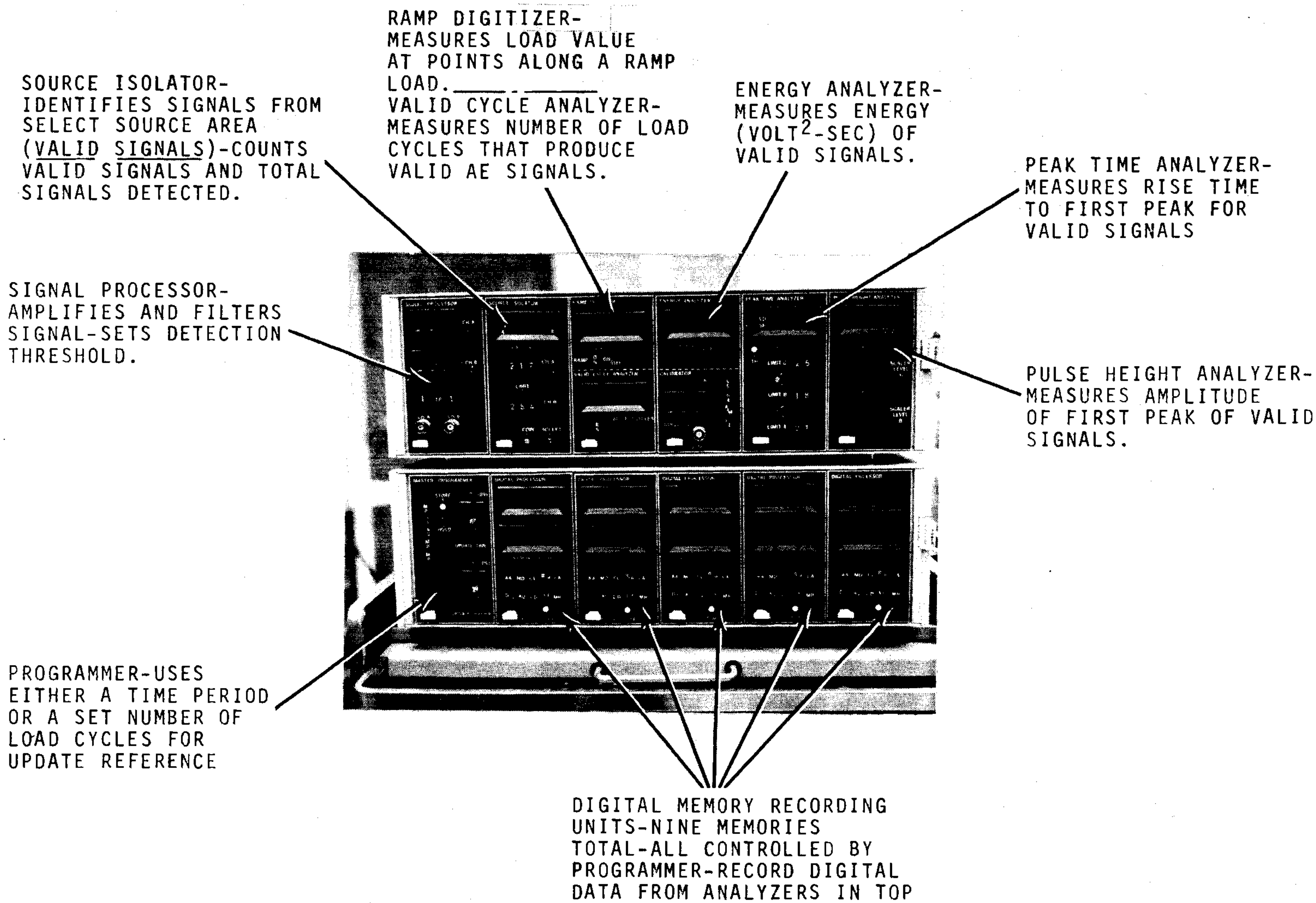


FIGURE 1. Digital Memory AE Monitor System with Source Isolation

the time required to develop data tabulations for further analysis and it improves the accuracy of the data translation.

AE data accepted for recording is restricted to that originating from the specimen defect through use of a two sensor source isolation technique. This subsystem defines an adjustable range of difference in time of signal arrival between sensors that will be accepted. This, in turn, defines a limted area of the specimen from which accepted signals can originate. In this way, noise from specimen holding fixtures and the test system can be excluded from the data.

An existing Dunegan/Endevco 3000 series laboratory AE monitor will be used in parallel with the digital system to provide a cross check on the general profile of measured AE.

A Biomation Model 8100 transient wave analyzer has been purchased to perform signal wave form and frequency spectrum analysis. It has a maximum sampling rate of 0.01μ seconds which should provide good resolution in the frequency range of interest in AE monitoring (up to ∿1 MHz). The Biomation has been interfaced with the digital AE monitor such that the source isolator also controls the signals retained by the Biomation. Thus the Biomation will be limited to reading out information on only those signals accepted by the digital memory system. Ultimately the output from the wave analyzer will be stored in a digital cassette recorder to permit processing a greater number of signals than can be handled with present real time readout on an oscilloscope. Figure 2 presents a sample of an AE signal reproduced by the Biomation. This illustrates the feature of displaying pretrigger information which permits examination of any AE signal precursor information. The spectral analysis of the signal also shown in Figure 2 is produced by routing the output from the Biomation to a Hewlett Packard swept pass band spectrum analyzer.

Two PNL AE sensors were calibrated in absolute terms (re 1 volt/μ bar) using the reciprocity technique in water. The work was performed by an

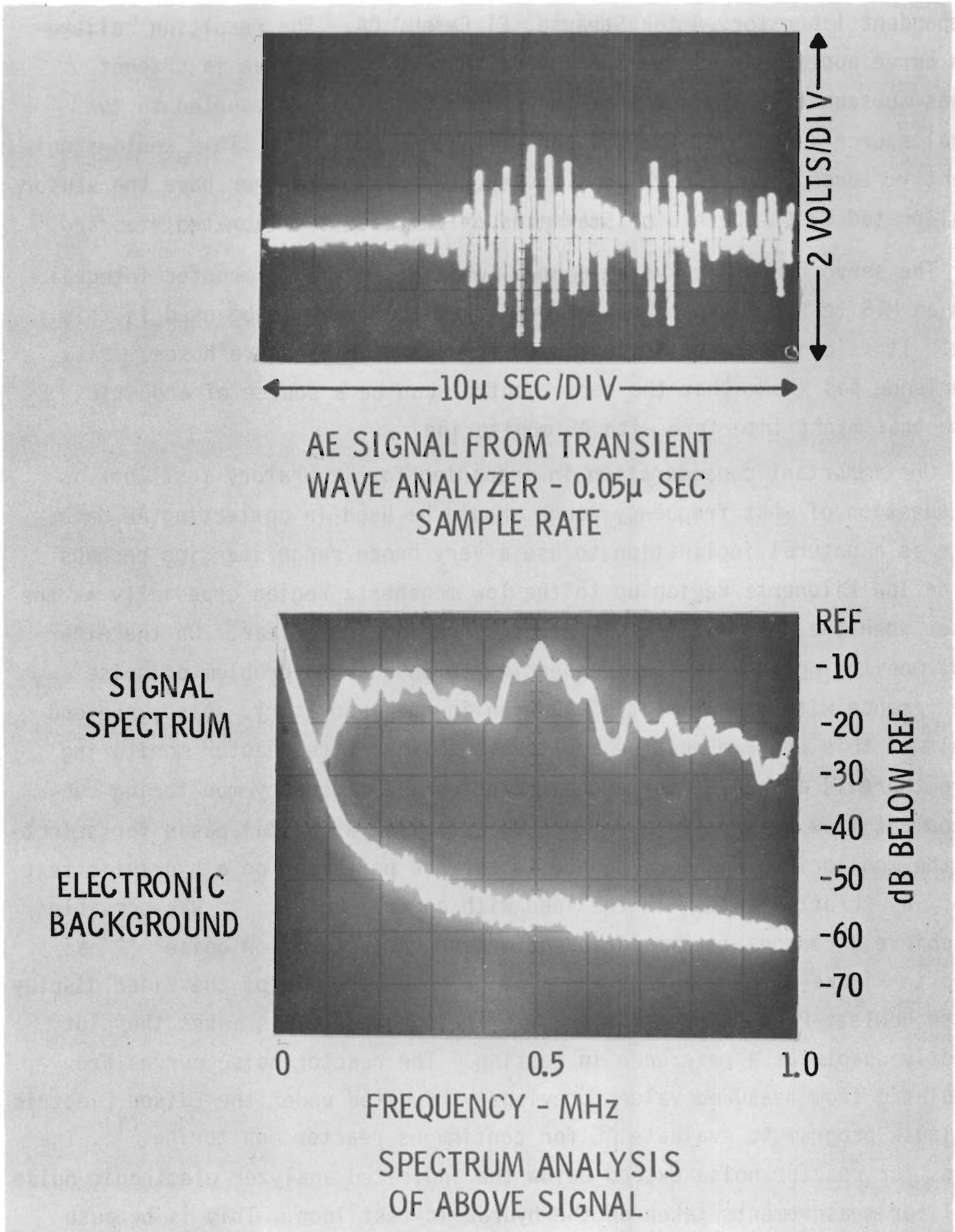


FIGURE 2. Transient Wave Analyzer Reproduction of AE Signal

independent laboratory-Amtek Strausa, El Cajon, CA. The resulting calibration curve appears in Figure 3. The validity of this curve is suspect. It was subsequently learned that the sensor was pressure coupled to the signal source as opposed to using an ultrasonic couplant. This would significantly reduce the apparent sensitivity. We plan to either have the sensor recalibrated by the Bureau of Standards or purchase a calibrated standard.

The servo hydraulic system control which is normally mounted integral with an MTS test frame has been removed from the frame to be used in this work. It is connected to the cylinder through high pressure hoses. Past experience has shown that the servo control can be a source of acoustic noise that might interfere with AE monitoring.

One important consideration in preparing for laboratory test work is the question of what frequency range should be used in collecting AE data. There is a natural inclination to use a very broad range starting perhaps in the low kilohertz region up to the low megahertz region especially at the outset when the most meaningful frequency region is unclear. On the other hand, monitoring at very low frequencies compounds the problem of noise interference with measurement of AE even in the laboratory. Also, the end result of this program must be applicable to inservice reactor monitoring where there is a very definite constraint on low frequency monitoring due to coolant flow noise. In an effort to establish a logical basis for selecting the monitoring frequency range, tests were performed on a hydraulic test loop. By throttling flow in the loop with control valves, it was possible to achieve a reasonable simulation of measured reactor flow noise(1,2) as shown in Figure 4. The curves are plotted on a facsmile of the video display on the Hewlett-Packard spectrum analyzer being used. This makes the plot directly usable as a reference in testing. The reactor noise curves are calculated from measured values previously reported under the Edison Electric Institute program to evaluate AE for continuous reactor monitoring.(1) The curves for reactor noise extend below the indicated analyzer electronic noise level for measurements taken on the hydraulic test loop. This is because the reactor measurements were made at a higher monitor gain, hence there are identifiable data points which fall below the analyzer noise level when reduced to the equivalent conditions for the current hydraulic loop measurements.

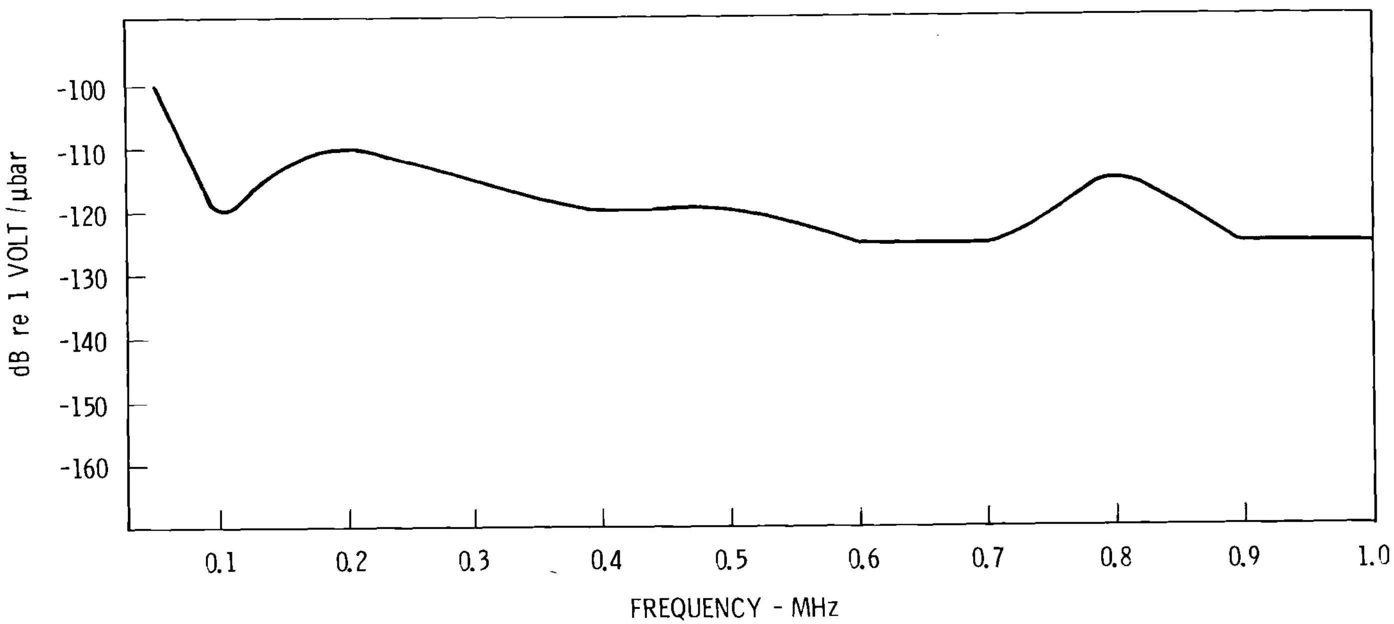


FIGURE 3. PNL AE Sensor Calibration

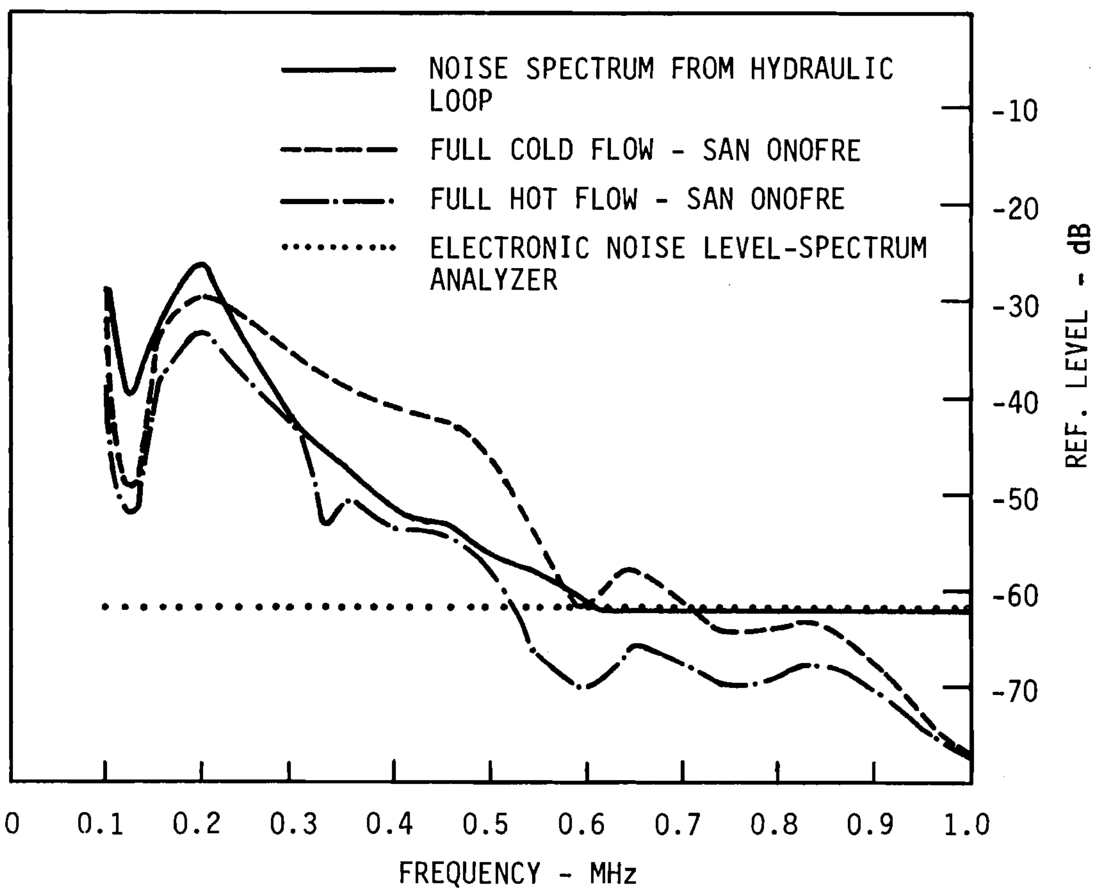


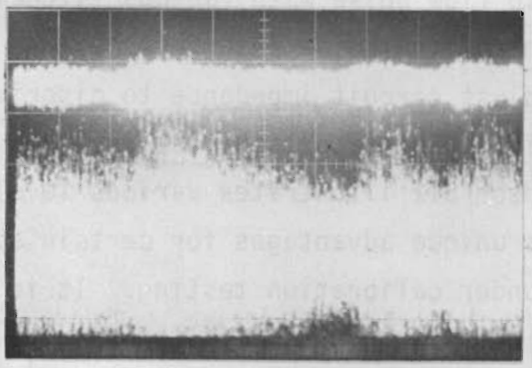
FIGURE 4. Flow Loop Noise Spectrum Compared to Reactor Flow Noise Spectrum

Figure 5 shows AE sensor response to flow noise with various filtering conditions. Two basic approaches to controlling noise interference are illustrated. Sensor 532 was tuned to adjust circuit impedance to discriminate against frequencies below the tuning point. This approach also enhances sensitivity at the tuned frequency. Sensor 512 illustrates various levels of electronic filtering. Each approach has unique advantages for certain applications. This will be discussed further under calibration testing. It is evident from Figure 5 that with 100 and 200 KHz high pass filtering, the hydraulic noise is being detected quite strongly making identification of AE signals doubtful. At 400 KHz high pass, the hydraulic noise is effectively suppressed.

The effect of 100 kHz and 400 kHz high pass filtering on AE signal detection in the presence of hydraulic noise is illustrated in Figure 6. The bottom trace in the top photograph shows sensor 512 response over a frequency bandwidth of 100 kHz to 3 MHz. The enhanced sensitivity of the tuned sensor (532) is evident in the bottom photograph by comparing its response to sensor 512 with electronic filtering. On the basis of these test results plus past experience, it was concluded that a monitoring frequency range of 200 kHz to 1 MHz for laboratory testing was a reasonable compromise for the various considerations discussed earlier.

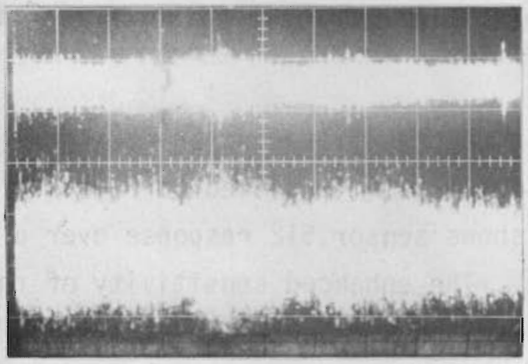
Initial test system calibration tests have been conducted using a single edge notch fatigue specimen of A533 Grade B Class 2 steel which was on hand. The purpose of this test was to evaluate the interfacing of the mechanical and electronic systems, interfacing of the major components in the AE detection analysis system, and performance of the AE system. Several important pieces of information were established from this test.

The source isolation function performed well. Figure 7 shows a sample of the acoustic data and load waveform input. At this point in the test, relatively large noise signals from the pin-specimen interface were included in the acoustic data along with AE signals from the growing crack. The conclusion that the source isolator is rejecting pin noise and accepting signals from the crack is by inference. The groups of pin noise signals were very regular occurring every load cycle. AE signals were intermittent.



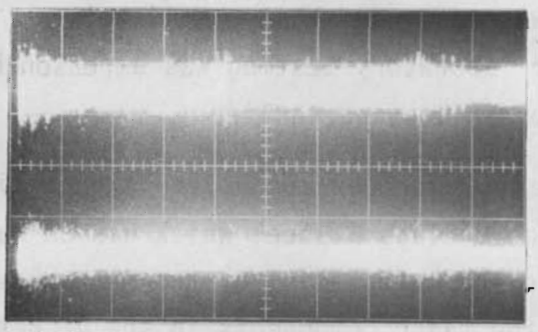
SENSOR 532 - TUNED TO 400 KHz HI-PASS
PREAMP B.W. - 0.4 TO 1.5 MHz
GAIN - 62.2 dB

SENSOR 512 - UNTUNED
PREAMP B.W. - 0.1 TO 3 MHz
GAIN - 61.7 dB



SENSOR 532
SAME AS ABOVE

SENSOR 512
SAME AS ABOVE EXCEPT
200 KHz HI-PASS FILTER
ADDED



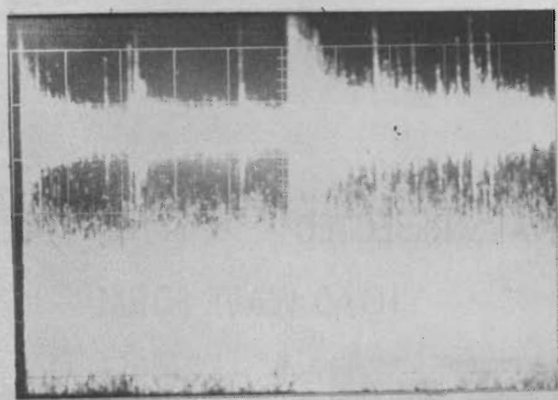
SENSOR 532
SAME AS ABOVE

SENSOR 512
SAME AS ABOVE EXCEPT
400 KHz HI-PASS FILTER
ADDED

CONDITIONS:

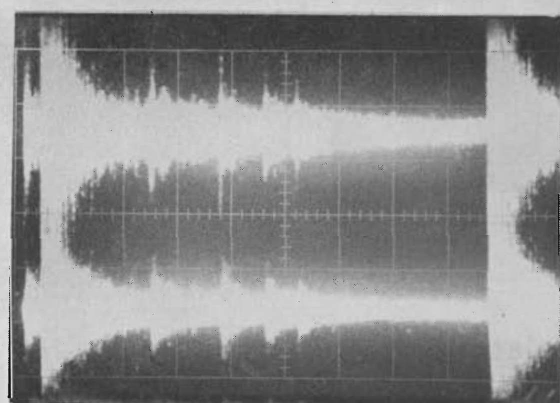
- BOTH SENSORS MOUNTED SIDE BY SIDE ON PIPE SURFACE WITH AIR CURING EPOXY
- OSCILLOSCOPE SETTINGS - 2 VOLTS/DIV VERTICAL AND 5 MILLISECONDS/DIV HORIZONTAL - SAME FOR ALL PHOTOGRAPHS
- REACTOR FLOW NOISE SIMULATED BY THROTTLING FLOW LOOP CONTROL VALVES

FIGURE 5. Oscilloscope Photographs of AE Sensor Response to Hydraulic Flow Noise



SENSOR 532 - TUNED TO 400 KHz HI-PASS
PREAMP B.W. - 0.4 TO 1.5 MHz
GAIN - 62.2 dB

SENSOR 512 - UNTUNED
PREAMP B.W. - 0.1 TO 3 MHz
GAIN - 61.7 dB



SENSOR 532
SAME AS ABOVE

SENSOR 512
SAME AS ABOVE EXCEPT
400 KHz HI-PASS FILTER
ADDED

CONDITIONS:

- BOTH SENSORS MOUNTED SIDE BY SIDE ON PIPE SURFACE WITH AIR CURING EPOXY
- AE SIGNALS GENERATED BY BENDING DRILL RODS WELDED TO PIPE SURFACE
- REACTOR FLOW NOISE SIMULATED BY THROTTLING FLOW LOOP CONTROL VALVES
- OSCILLOSCOPE SETTINGS - 2 VOLTS/DIV VERTICAL AND 5 MILLISECONDS/DIV HORIZONTAL

FIGURE 6. Detection of AE Signals in Presence of Hydraulic Flow Noise

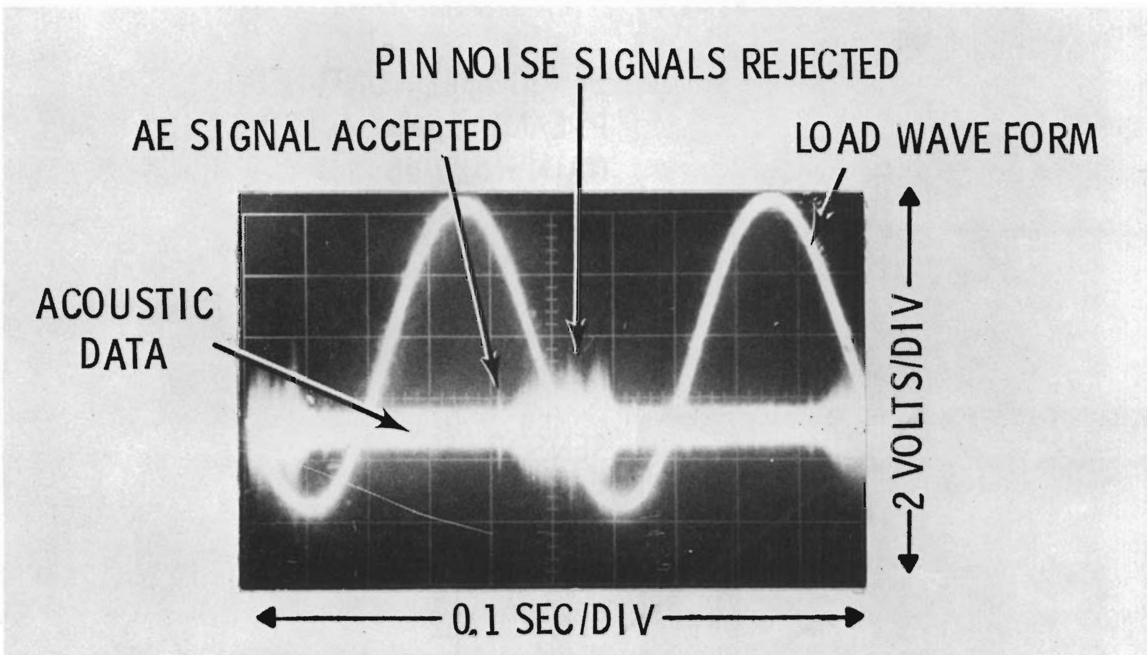


FIGURE 7. Examples of Source Isolator Signal Discrimination

The valid count data was also intermittent. Oscilloscope photos taken when the monitor was counting consistently showed the presence of signals such as the one labeled AE signal in Figure 7. Photos taken when the monitor was not counting showed only the pin noise signals. This basic type of source isolation system has been used in several tests in the past with similar results.

It appears that tuned sensors will not be suitable for laboratory tests at least at the outset. Figure 8 illustrates the basis for this statement. Tuning the sensors is a very effective method for eliminating frequency components below the tuning point from data. It also enhances sensitivity near the tuning point by perhaps 15 to 20 dB. The result of this latter effect is to make the tuning frequency predominant in the measured response as shown in Figure 8. The top set of photographs show an untuned sensor response to an AE signal. The spectral content is quite broad with a peak about 500 KHz. The bottom set of photographs show the response of the same sensor to an AE signal only now the sensor has been tuned to 350 KHz high pass. The spectral content is now strongly biased to the near vicinity of the tuning frequency. These are two different AE signals, however, the apparent influence of the tuning on indicated frequency content was observed repeatedly. Until more is known about what elements of the measured response to an AE wave are important to program objectives, it would be unwise to bias the frequency content by tuning. This is not intended to say that sensor tuning is always undesirable. In field tests, for example, where low frequency noise is strong and AE detection and location are the primary concerns, use of tuned sensors may be the only reasonable method for obtaining any data.

Untuned sensor response to a noise signal (screw driver impact) is shown in Figure 9. This can be compared to the AE signal response at the top of Figure 8.

The calibration test was not intended to produce data for detailed analysis, however, a limited amount of data is plotted in Figure 10 to illustrate a point. This shows valid AE signal count (those accepted by the source isolator) and measured crack growth. The crack was intentionally

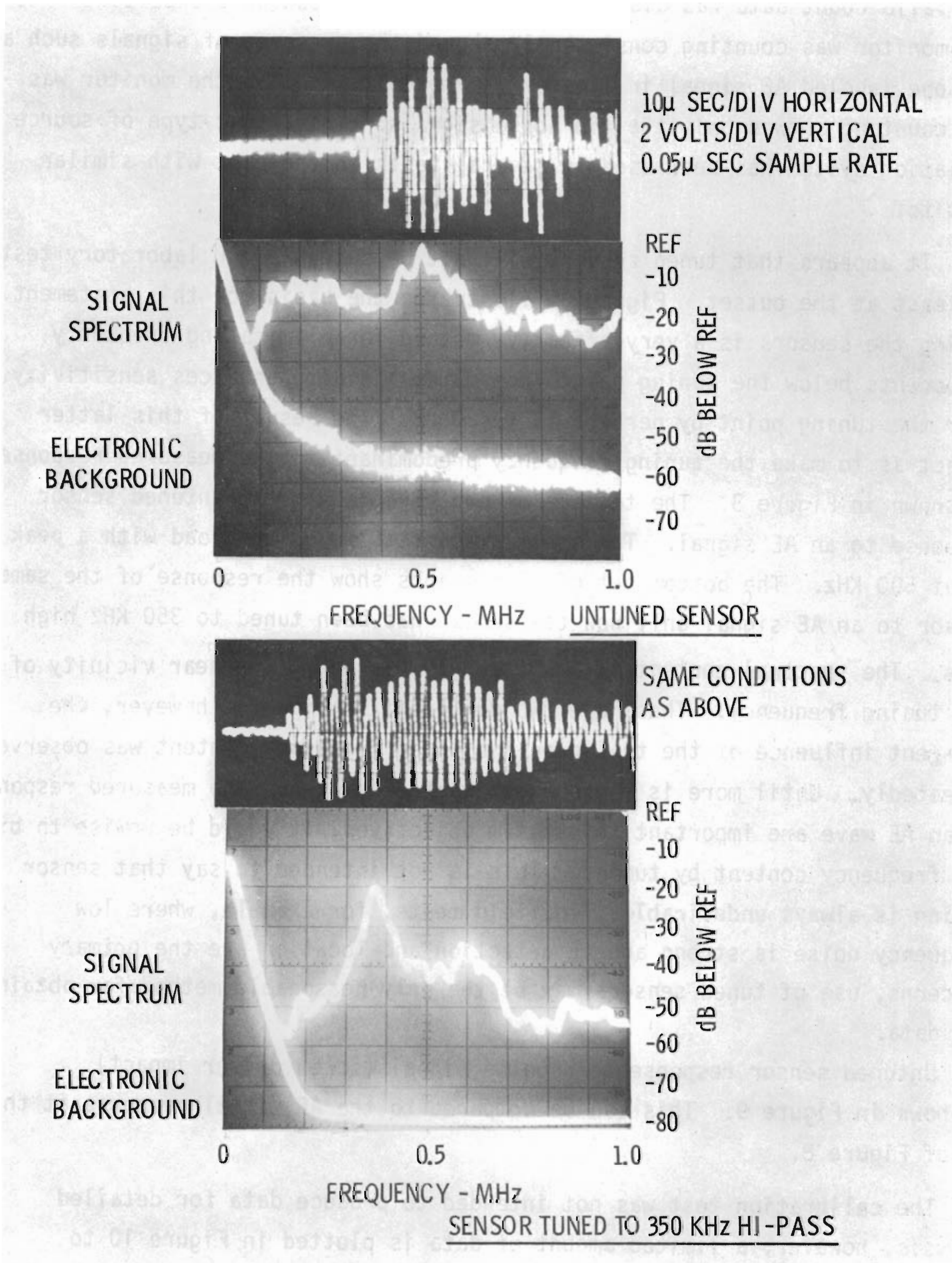


FIGURE 8. Effect of Sensor Tuning on Frequency Response

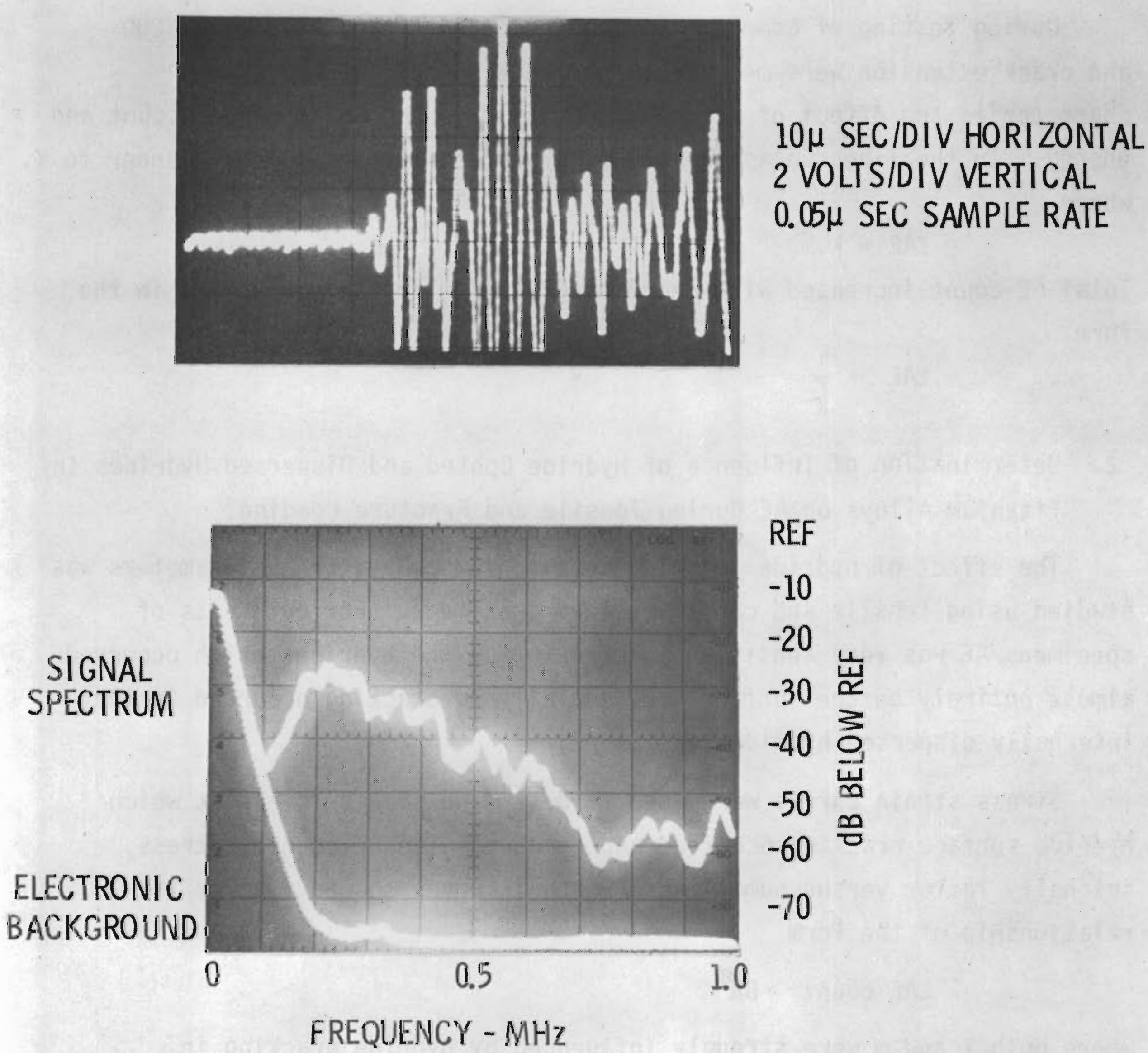


FIGURE 9. Untuned Sensor Response to a Noise Signal (Screw Driver Impact)

During testing of compact tension specimens, load, load rate, COD and crack extension were mechanical parameters that were used to characterize the effect of stress intensity rate ($\dot{K}$) on ΣAE event count and energy. In the linear elastic range, AE was related in a linear manner to K, where

$$\Sigma AE \propto K.$$

Total AE count increased with decreasing stress intensity rate ($\dot{K}$) in the form

$$\Sigma AE \propto \frac{1}{\dot{K}}$$

2. Determination of Influence of Hydride Coated and Dispersed Hydrides in Titanium Alloys on AE during Tensile and Fracture Loading.

The effect of hydride location in titanium alloys on AE parameters was studied using tensile and center-notched specimens. For both sets of specimens, AE was very sensitive to cracking of the hydrides which occurred almost entirely on the surface. Essentially no cracking occurred in the internally dispersed hydrides.

Stress strain curves were used to determine stress levels at which hydride surface cracking occurred and compared with AE count. Stress intensity factor versus summations AE count curves showed a power law relationship of the form

$$\Sigma AE \text{ count} \propto BK^{m}$$

where both B and m were strongly influenced by hydride cracking in comparison to base metal deformationand crack extension.

3. Determination of the Relation of AE to Fatigue Crack Initiation and Growth.

Fatigue data (load level, load cycle rate, crack length) was characterized by Paris-Erdogan crack growth law

$$\frac{da}{dN} = B(\Delta K)^{m}\text{, where B and m are constants} \qquad \text{Eq. (1)}$$

grown at a high rate. The first measured point of crack growth was 31 1/2 mils. The point to be made here is the discontinuous slope of the AE signal count curve indicates a potential for distinguishing plastic zone growth from actual crack area increments.

SPECIMEN MATERIAL

Procurement of suitable material for fabrication of test specimens has been a problem. A number of possible sources were contacted starting early in the program. The sources contacted were,

1) Lukens Steel, Coatesville, PA
2) Combustion Engineering, Chattanooga, TN
3) HSST, Oak Ridge, TN
4) Chicago Bridge and Iron, Chicago, IL
5) Marrel Freres, France
6) EPRI, San Jose, CA
7) Babcock and Wilcox, Lynchberg, VA/Barberton, OH and
8) Rockwell International, Los Angeles, CA

Material was available from sources (3), (5), (7) and (8), but was either limited in amount, or thickness, untypical of steel used in most U.S. reactor pressure vessels, or excessive in cost.

Presently BNW is collaborating with the Naval Research Laboratory (NRL) for purchase of an 8 1/4 in. (210 mm) thick plate of A533 B Class 1 steel from Lukens Steel. This material, however, will not be available until about April, 1977. It could even take longer because of restrictions on natural gas use in the Eastern U.S. Because of this restriction, heat treatment of the plate could be delayed thus further extending the date at which the material would be available for fabrication into specimens.

To begin testing earlier, a piece of HSST welded A533B Class 1 plate was obtained from a discontined NRC program. The material is approximately 6 x 20 x 23 inches with the weldment running the 23 inch dimension at the midpoint of the 20 inch dimension. The piece was designated by HSST as, "weldment no. 57G, D, 96151-001, code-SD-401 U C Cont 3269, HT-C6200-4, A533-67A, LUK." Welding parameter information is

A. Inspection

1. Magnetic Particle

2. Radiography

B. Welding Process

Submerged Arc

C. Weld Data

	ROOT	REMAINDER
Electrode Size & Type	1/4 in., E-8018, C-3	3/16 in., B-4 MOD.
Flux Type & Size		LINDE 1092, 65-200
Current & Polarity	325 to 375 DC-SP	650 AC
Arc Voltage	25	31
Travel Speed in./min		13

Welding Position:	Flat
Preheat:	250° F, Held until PWHT
Interpass Temperature:	500° F max
Intermediate Post Weld Heat Treatment:	1100° ± 25° F, Held 1 hr
Post Weld Heat Treatment:	1150° ± 25° F, Held 1 hr/in.

HIGH TEMPERATURE SENSORS

In preparation for evaluating available high temperature (600° F) AE sensor systems, two each of Westinghouse and Trodyne sensors have been purchased. Dunegan/Endevco high temperature sensors are available as NRC property from a discontinued program. Sensor system as used here includes the sensor, a mounting technique and on acoustic coupling technique suitable for reactor application.

The objective of this phase of the program is to first evaluate commercially available sensor systems for their adequacy for long term reactor monitoring in the context of this program. Questions of primary importance include

- Is the basic sensor sensitivity adequate and is it consistent with time and temperature exposure?
- Is the coupling efficiency adequate and does it change with temperature?
- Have radiation effects been adequately investigated?
- Is the mounting technique suitable for existing plants as well as new plants.

The sensor systems will be evaluated at room temperature and then at 600° F for about two months. For any combinations that appear promising, the high temperature testing will be continued for several months with temperature cycling added. From the results of this testing, it should be possible to establish whether further sensor system development is needed and if so, what aspects need to be emphasized, i.e., the basic sensor, coupling technique, etc.

HSST TEST AE DATA

A meeting was held January 26, 1977 with HEDL staff members to review plans for performing HSST irradiated fracture specimen tests. The test plan is still under discussion with NRC, however it appears that the testing will be several months away. From examination of the furnace assembly to be used for heating the specimens, it appears that there is adequate clearance for mounting AE sensors.

The first HSST test since the start of this program was a thermal shock test performed at Oak Ridge, TN on January 19, 1977. PNL participated in this test using the digital memory AE monitor system. AE data was detected and observed during the test, however a record of analyzed data was not obtained due to one faulty sensing point. This was an outgrowth of the necessity to relocate sensors immediately prior to the test. There were several positive results from this test even though recorded AE data was not obtained.

- Observed AE appears to agree well with predicted crack growth sequence.
- Adjusting the sensing system impedance proved to be effective in overcoming the hydraulic noise interference problem.
- The wave guide configuration used is basically an effective method for sensing AE from a high temperature surface.
- The digital memory system recorded information from the COD gauge as expected.

AE LIBRARY

AE research reported from Europe and Japan as well as the United States which is relevant to the objectives of this program are being reviewed. Work at Battelle-Frankfurt is discussed in a trip report attached as Appendix B of this report. A survey report from Denmark[3] yielded the following observations relevant to the NRC-PNL program:

A. P. Bently, et al. reported results from an experimental vessel test where AE was not detected from an artificial defect which ultimately caused failure by leakage. This was reported at the 3rd Conference on Periodic Inspection of Pressurized Components, London, England, September 1976. A copy of the proceedings from this conference is being sought to gain further information on this.

B. There is need for a stable versatile AE signal source for use in calibrating signal transfer from a structure to the AE monitoring system.

C. In the area of AE signal analysis, signal amplitude variation is cited as a specific parameter which has shown confirmed relation to cracking vs. plastic deformation. This arises from work by H. A. Crostack, et al. in Germany. Signal amplitude is one of the parameters included in the NRC-PNL program.

D. The report includes an extensive list of references, many from Europe, which may be useful to this program.

Another report concerned AE testing on small pressure vessels in Japan.[4] This provided the following information:

A. Relatively small amplitude AE signals were generated by plastic deformation and relatively large amplitude signals were generated by cracking. The high amplitude cracking signals were usually preceded and followed by low amplitude signals.

B. Pronounced changes in emission rate occurred when the fatigue cracks initiated and began to propagate and when the cracks approached penetration of the wall. These changes were most evident in change of slope of the cumulative AE count curve.

C. AE during the initial period of fatigue testing which was attributed to plastic deformation occurred at maximum load. However, during the "process of fatigue damage" (crack growth?) AE occurred more at descending loads or at minimum load.

   Note: This sounds as though they may have been detecting crack interface noise during crack growth.

D. Source location efforts were generally effective.

E. Noise interference was experienced using the 100 kHz resonant sensors.

F. Conclude that in-service monitoring would likely be done in the mode of monitoring known areas of concern (e.g., known cracks) rather than total volumetric monitoring.

This type of review is planned on a continuing basis during this program.

REFERENCES

1. P. H. Hutton, Summary Report on Investigation of Background Noise at the San Onofre Nuclear Power Reactor as Related to Structural Flaw Detection by Acoustic Emission, Battelle-Northwest, July 1971. Contained in In-Service Inspection Program for Nuclear Reactor Vessels, Southwest Research Institute Project 17-2440, Biannual Progress Report No. 6, Vol. I, Projects I through IV, January 7, 1972.

2. S. P. Ying, Southwest Research Institute, J. E. Knight and C. C. Scott, Atomic Power Development Associated, Inc., Background Noise for Acoustic Emission in a Boiling Water and a Pressurized Water Nuclear-Power Reactor, The Journal of the Acoustical Society of America, Volume 53, Number 6, 1973.

3. Acoustic Emission Surveillance Methods, Arved Nielsen, Research Establishment RISO, Denmark, RISO-M-1896, October 1976.

4. Acoustic Emission Method for Tracing Crack Propagation in Pressure Vessels, Group Research, Japan JAERI-Memo 5753, Translation underNTIS, No. NR-tr-002, NRC-1, June 1974.

APPENDIX A

ANALYSIS-BEFORE-TEST PROGRAM PLAN

ANALYSIS BEFORE TEST

PROGRAM TO DEVELOP ACOUSTIC EMISSION CHARACTERIZATION OF FLAW GROWTH IN A533B PRESSURE VESSEL STEEL

to
Metallurgy and Materials Branch
Reactor Safety Research Division
Nuclear Regulatory Commission

by
P. H. Hutton, Project Manager
E. B. Schwenk, Project Engineer

December 3, 1976

Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

ANALYSIS BEFORE TEST

PROGRAM TO DEVELOP ACOUSTIC EMISSION CHARACTERIZATION OF FLAW GROWTH IN A533B PRESSURE VESSEL STEEL

P.H. Hutton
E.B. Schwenk

Battelle
Pacific Northwest Laboratories

December 3, 1976

EXECUTIVE SUMMARY

INTRODUCTION

The purpose of this work is to build toward an experimental evaluation (laboratory and ultimately on-reactor) of the feasibility of continuously assessing reactor pressure boundary integrity by acoustic emission (AE) techniques. The current program is the first of a sequencial three step approach to laboratory evaluation. The three steps are:

1. Demonstrate that meaningful AE-flaw growth relationships can be developed considering a limited range of variables. This includes distinguishing AE signals from various insignificant acoustic noise signals.
2. Demonstrate that the relationships can be identified under the conditions of the full range of variables expected in a nuclear pressure vessel.
3. Develop the transfer function(s) to translate laboratory specimen relationships to describe failure processes in a full size pressure vessel structure. Included here also is development of an algorithm(s) whereby a reactor operator can evaluate the significance of AE data obtained from a pressure vessel.

OBJECTIVES

The primary objectives of this program are:

- Characterize AE from a limited range of defects and material property conditions recognized as being of primary concern to reactor pressure vessel integrity.
- Characterize AE from innocuous sources (including defects) which can be reasonably expected to exist in a pressure vessel.
- Develop criteria for distinguishing significant flaws from innocuous sources.
- Develop an AE flaw damage model to serve as a basis for relating in-service AE to pressure vessel integrity.

TEST APPROACH

Two primary considerations underly development of the test approach. They are:

- The test plan by intent includes a restricted number of variables in flaw type, flaw growth mechanisms, innocuous noise sources, material properties, and environmental conditions.
- The program is designed to develop macro-scale AE-flaw growth relationships. It will not directly investigate basic AE source mechanisms.

The test approach is described under the two categories of Material - Fracture Mechanics and Acoustic Emission.

MATERIAL - FRACTURE MECHANICS

Test work will be performed using specimens of Type A533 Grade B, Class 1 pressure vessel steel. Emphasis will be on simulating pressure vessel weld and plate skin (outer 2 to 3 in.) material.

Conditions listed below will be investigated approximately in the order listed:

Test No.*	Condition	Specimen Type	Number of Specimens
1-1	Uniaxial elastic/plastic deformation base metal and weld material at room temp. and 550° F	Tensile	20
3-4	Fatigue crack growth through pre-existent plastic zone	Plate tension Surface notch	2
1-1A	Biaxial elastic/plastic deformation	Biaxial restraint -two notch ratios	4
2-1	Fracture in base metal at room temp. and 550° F	Single edge notch Surface notch	4 2
2-4	Fracture in weld metal at room temp. and 550° F	Single edge notch	4
1-11	Slag inclusion - no crack growth - cyclic elastic loading	Plate tension	3
2-12	Fatigue crack growth in base metal at room temp. and 550° F	Single edge notch	3
2-12A	Fatigue crack growth in weld metal at room temp. and 550° F	Single edge notch	3
2-19	Surface notch growth by fatigue	Surface notch	2
2-14	Water in a fatigue crack with and without crack growth	Double cantilever beam	2
2-9	Oxide on crack surfaces during unload and cyclic load - air and 200° F water	Double cantilever beam	4
2-17	Fatigue crack growth at constant K level through base metal, heat affected zone, and weld metal at room temp. and 550° F	Tapered double cantilever beam	2
3-6	Simulate pressure vessel service loading sequence with subsequent fatigue crack growth	Plate tension	1

* Test No. relates to a master table in Appendix B of 189 proposal

These tests are categorized under the following topics:

- Metal deformation and crack growth under monotonic loading, 1-1, 1-1a, 2-1, 2-4,
- Metal deformation and crack growth under fatigue loading, 2-12, 2-12A, 2-14, 2-17, 2-19, 3-4 and 3-6.
- Oxides and weld inclusions, 1-11, 2-9.

- Weldments, 1-1, 1-11, 2-4, 2-12A, 2-17
- Simulated reactor operation conditions (temperature, coolant, defect and stress state) 2-1, 2-4, 2-9, 2-12, 2-12A, 2-14, 2-17, 3-6
- Kaiser effect 3-4 and 3-6.

ACOUSTIC EMISSION

AE data must provide two basic capabilities: 1) the ability to distinguish between significant and insignificant AE sources, and 2) the ability to evaluate flaw significance.

The primary monitor system will be a digital memory AE monitor system with source isolation developed at Battelle. It utilizes two sensors to limit accepted data to that originating from an area of interest. Commercial AE equipment on hand will be used as a backup to and cross check on the digital system.

Parameters that will be measured with the digital memory system are:

Parameter	Purpose
AE event count	Relate to flaw growth parameters.
AE energy	Same
AE signal amplitude - four ranges	Distinguish between AE sources - cracking versus plastic deformation, and innocuous sources
AE signal rise time - four ranges	Distinguish between AE signals and innocuous noise sources
Mechanical - either Load cycles producing AE	Develop power law relations between AE and flaw growth parameters
and	
Total load cycles	Basic test correlation
or	
Ramp load level versus time	Relate AE data to increasing load levels

In addition to the digital memory system, a commercial transient wave analyzer will be used to study details of the AE signal wave form. Also, a commercial multichannel analyzer will be used to measure distribution of AE signal amplitudes and rise time.

AE sensors calibrated to recognized standards by an independent commercial laboratory will be used as a standard reference for all test sensors. Also, the monitor system performance will be checked prior to each test using a series of AE signals recorded on magnetic tape.

DATA ANALYSIS

There are two primary analysis areas to be considered. One is distinction between meaningful AE signals and other acoustic information. The other is development of AE-flaw growth interpretation models. Our initial approach to analysis is described below. It must be recognized, however, that the approach may change as the program progresses and results are examined.

SIGNAL DISTINCTION

AE signal amplitude, signal rise time, and signal frequency will be analyzed for characteristics to distinguish AE signal sources. Previous work with A533B steel has shown evidence that there is a difference in amplitude of AE signals from deformation vs crack growth with crack growth producing the higher amplitude. Through a combination of signal amplitude distribution and scaler sorting of the amplitudes into different ranges, we should be able to correlate data with generating processes accurately.

Signal rise time will be examined as a means of distinguishing AE signals from acoustic signals generated by innocuous slag inclusions. Acoustic energy released by perhaps interface movement between slag and metal should occur over a longer time period and contain relatively stronger low frequency components than that for an AE signal. The AE signal should thus show a faster rise time than the signal from the slag inclusion. If the slag were cracking, we would expect the same effect due to inefficient coupling across the interface between slag and metal.

Signal frequency will be examined also as a possible means of discriminating between AE of interest and unwanted acoustic signals.

As we develop evidence of the validity of the above methods, we plan to incorporate circuitry in our monitor system that will impose limits of acceptance for these parameters either individually or in combination. This will then allow us to confirm that they do perform the desired discrimination function in real time.

AE INTERPRETATION MODELS

Since AE data frequently display scatter, statistical analyses utilizing least squares regression analyses and the correlation coefficient "r" can be used as an index of the correlation between least square lines and the data points through which they are drawn. This approach has proven effective in showing the capability of a selected AE-fatigue parameter model to fit measured data.

For AE developed during crack initiation, no consistent and encompasing theory is presently available for comparison. Limited BNW data suggest that nearly all AE produced during fatigue in A533B is related to growth of the crack as opposed to initiation of crack growth both at the beginning of the test as well as when a fatigue crack is propagating. Once a readily measurable crack is formed, many crack propagation laws exist as a basis for comparison with AE parameters.

SUMMARY

In summary, we feel that the most demanding question at this time is, "Can a meaningful relationship be identified even with the advantages of a limited number of variables?" We believe that this can be accomplished based on recent results from some of our privately sponsored research and the results achieved by others. We are aware that details of AE-defect evaluation relationships developed could be ultimately affected by field application conditions such as variation in effective sensing threshold due to signal attenuation in the material. This type of problem is not considered unsolvable, however. In this instance, a combination of total volumetric monitoring for flaw detection and location plus local area monitoring for known defect evaluation may provide a solution. We feel that the immediate program is the critical test of the validity of the total concept of continuous monitoring of reactor pressure boundaries using AE. With laboratory development of an AE data interpretation method accomplished, we have total confidence that it can then be projected to effective application.

TABLE OF CONTENTS

ANALYSIS BEFORE TEST

PROGRAM TO DEVELOP ACOUSTIC EMISSION

CHARACTERIZATION OF FLAW* GROWTH IN A533B PRESSURE VESSEL STEEL

1.0 INTRODUCTION

The U. S. Nuclear Regulatory Commission has authorized Battelle Northwest to perform a laboratory research program to characterize acoustic emission (AE) from flaw growth and noise from innocuous sources in A533B pressure vessel steel. The purpose of this work is to build toward a thorough experimental evaluation (laboratory and ultimately on-reactor) of the feasibility of assessing reactor pressure boundary integrity by acoustic emission on a continuous basis. This document presents the specific technical approach planned for this program which is concerned with laboratory development of necessary analytical AE-flaw growth relationships.

2.0 OBJECTIVES

The primary objectives of this program are:

1. Characterize AE from a limited range of defects and material property conditions recognized as being of primary concern to reactor pressure vessel integrity.
2. Characterize AE from innocuous sources (including defects*) which can be reasonably expected to exist in a pressure vessel.
3. Develop criteria for distinguishing significant flaws from innocuous sources.
4. Develop an AE flaw damage model to serve as a basis for relating in-service AE to pressure vessel integrity.

*By definition in this discussion, a defect includes any material imperfection and a flaw is a defect (primarily a crack) of engineering significance.

3.0 APPROACH PHILOSOPHY

We are conscious of the fact that this laboratory research program is to provide a basis for ultimate effective application of AE techniques for continuous integrity monitoring of nuclear reactor pressure boundaries. Realistically, we feel that the laboratory research must be approached in a progressive fashion which we view as falling into the following areas of development:

- Demonstrate in the laboratory that a meaningful AE-flaw growth* relationship can be achieved considering a very limited range of variables (flaw type, flaw growth mechanism, material condition, environment, noise interference, etc.).
- Demonstrate in the laboratory that the relationship can be extended to the full realistic range of variables expected in a nuclear pressure vessel.
- Develop the transfer function(s) to translate the laboratory specimen relationships to a real structure in a form useful to a reactor operator. By this we mean determination of the validity of the laboratory relationship to describe failure processes in the real structure and converting the relationships to a format directly usable by a reactor operator for flaw evaluation.

The immediate program is concerned with the first developmental area. The most demanding question at this time is, "Can a meaningful relationship be identified even with the advantages of a limited number of variables?" We believe that this can be accomplished based on recent results from some of our privately sponsored research and the results achieved by others such as D. W. Prine's work[1] on AE analysis of weld quality. We are aware, that details of AE-defect evaluation relationships developed could be ultimately affected by field application conditions such as variation in effective

*The word growth is used in the widest sense ranging from plastic zone growth, to slow crack growth in fatigue to growth rates short of rapid fracture.

sensing threshold due to signal attenuation in the material. This type of problem is not considered unsolvable, however. In this instance, a combination of total volumetric monitoring for flaw detection and location plus local area monitoring for known defect evaluation may provide a solution. We feel that the immediate program is the critical test of the validity of the total concept of continuous monitoring of reactor pressure boundaries using AE. With laboratory development of an AE data interpretation method accomplished, we have total confidence that it can then be projected to effective application.

4.0 SPECIFIC TEST APPROACH

The purpose of this section is to present the specific test program planned in support of the objectives of this program. The justification and criteria applied are discussed in Section 5.0. There are two primary considerations to be kept in mind in reviewing this test plan.

1. The test plan by intent includes a restricted number of variables in flaw type, flaw growth mechanisms, innocuous noise sources, material properties, and environmental conditions. We recognize that a wider range of variables must be considered ultimately; however, we feel that the program outlined is appropriate for the initial investigation.
2. The program is designed to develop macro-scale AE-flaw growth relationships. It will not directly investigate basic AE source mechanisms. This latter area could be important to our objectives, however. Review of AE investigations both at Battelle Frankfurt, Germany, and in Japan show that a signficant effort is being directed to study of basic AE mechanisms in both countries. For expediency, we plan to supply our near future needs for basic mechanism information through an information exchange arrangement particularly with Battelle Frankfurt. We will, of course, also utilize any information in this area which is available to us from

work done by others in the United States. In addition, BNW has in-house capability for doing basic mechanism investigation where required.

A more extensive discussion of background considerations involved in designing this program is included in attachment 1 of our 189 Proposal to NRC dated March 1976. In the interest of conciseness, this is not repeated here.

4.1 MATERIAL STUDIES AND FRACTURE MECHANICS

The tests described are designed for initial evaluation of AE generated by flaws and innocuous sources of noise. These tests are centered on the general propositions of detecting and assessing AE associated with:

- a growing crack,
- a growing plastic zone and,
- a growing elastic/plastic strain field.

Within this general framework, the conditions expected to exist in a nuclear reactor pressure vessel which are addressed together with the associated test numbers include:

1) Metal deformation and crack growth under monotonic loading, 1-1, 1-1a, 2-1, and 2-4.
2) Metal deformation and crack growth under fatigue loading, 2-12, 2-12A 2-14, 2-17, 2-19, 3-4 and 3-6.
3) Oxides and weld inclusions, 1-11, 2-9.
4) Weldments, 1-1, 1-11, 2-4, 2-17, 2-12A
5) Simulated reactor operation conditions (temperature, coolant, defect, and stress state) 2-1, 2-4, 2-9, 2-12, 2-12A, 2-14, 2-17, 3-6.
6) Kaiser Effect, 3-4 and 3-6.

A description of each test is given in Table 1, Experimental Program. Test specimen configurations currently planned are shown in Figures 1a and 1b.* An estimate of material requirements for specimen layout is shown in Figure 2. This might change depending on the plate thickness, etc., selected. The quantity of material shown in Figure 2 includes a piece of four inch thick material for presently undefined test specimens.

During the program we anticipate testing:

- 15 to 20 tensile specimens,
- up to 4 biaxial restraint specimens,
- up to 4 plate tension specimens, two containing slag inclusions,
- 14 single edge notch specimens,
- 6 double cantilever beam specimens
- 2 tapered double cantilever beam specimens,
- 6 surface notch specimens

4.2 ACOUSTIC EMISSION

AE data must provide two basic capabilities: 1) the ability to distinguish between significant and insignificant AE sources, and 2) the ability to evaluate flaw significance. Furthermore, these capabilities must be developed in a form that can be incorporated into a practical operational monitoring system. In our work to develop these capabilities, we plan to use the approach described in this section to obtain AE data.

General

The primary monitor system will be a digital memory AE monitor system with source isolation (Figure 3). This utilizes two sensors to limit accepted data to that originating from the area of interest. Commercial AE

*Long specimens such as the plate tension specimen for single-edge notch and surface notch flaw geometries and double cantilever bend and tapered double cantilever bend specimens are used because of their overall ability to satisfy test program needs and the ability to maintain AE sensors in nearly ambient temperature areas.

TABLE 1. TEST PROGRAM

Test No.	Test Objective	Specimen Type	Material Failure - Structural Conditions				Noise Source	Comments
			Loading	Geometry	Environment	Matl Properties		
1-1	Determine uniaxial elastic/plastic deformation AE parameters and for periodic final equipment checks.	Uniaxial tensile (UT) 1/4" dia.	Monotonic.	Smooth gage section.	Air, RT some at 550°F.	As heat treated, with weld stress relief; base metal and weldment.	None.	Load several specimens without reduced section to help assess noise from threaded ends.
3-4	Effect of prior uniform plastic strain on AE during fatigue crack growth.	PT-1/2" thick.	Monotonic plastic load. GETT cyclic load.	Part-thru wall.	RT-Air.	As heat treated.	None.	
1-1a	Determine biaxial elastic/plastic deformation AE parameters.	Biaxial restraint. Thickness to be determined.	Monotonic, uniaxial	Smooth gage section. Two L/W ratios.	Air, RT.	Same as 1-1.	None	
2-1	Determine effect of temp on AE-flaw parameters during monotonic loading of base metal fracture mechanics specimens.	Single edge notch (SEN) 1" thick and surface notch 1" thick.	Uniaxial, monotonic.	Notched, and fatigue precracked.	Air, RT and 550 F.	As heat treated with weld stress relief; crack propagation direction perpendicular to rolling direction	None	

TABLE 1. TEST PROGRAM (CONTINUED)

Test No.	Test Objective	Specimen Type	Material Failure - Structural Conditions: Loading	Geometry	Environment	Matl Properties	Innocuous Noise Source	Comments
2-4	Determine effect of temperature on AE-flaw parameters during monotonic loading of fracture mechanics weldment specimens.	Sen 1" thick.	Monotonic, uniaxial	Thru-wall notched	Air, RT, 550°F	Same as 2-1 except with weldment.		
1-11	Determine effect of slag inclusions on elastic cyclic load AE parameters.	Plate tension (PT) 1" thick.	Uniaxial, sinusoidal waveform, gross elastic tension-tension to 1/3 UTS.	Smooth gage section. Inclusions internal.	Air, RT.	Same as 1-1 with weldment.	Slag inclusions [radiograph to determine approx. inclusion size and distribution].	Cycle at fixed min, max stress to given no. of cycles fracture. Look for any fatigue cracks to determine if all AE due to slag inclusion rubbing/cracking.
2-12	Determine the effect of temperature on AE-fatigue crack growth properties at RT and 550°F.	Sen, 1" thick.	GETT sinusoidal cyclic load; gross plastic T-T sinusoidal cyclic load for a long crack.	Thru-wall notched	Air, RT, 550°F	Same as 2-1	None	Evaluate one specimen without notch at 550°F and RT. As crack becomes long, net section will plastically cycle.

TABLE 1. TEST PROGRAM (CONTINUED)

Test No.	Test Objective	Specimen Type	Material Failure - Structural Conditions: Loading	Geometry	Environment	Matl Properties	Innocuous Noise Source	Comments
2-12A	Same as 2-12 except weldment	Same as 2-12	Same as 2-12	Same as 2-12	Same as 2-12	Weldment		
2-19	Determine effect of a semi-embedded flaw on AE properties during fatigue crack growth	PT 1" thick.	GETT sinusoidal cyclic load.	Part-thru wall notched.	Air, RT.	Same as 2-1 except crack growth in thickness direction and perpendicular to rolling direction.	None	Compare with thru-wall crack growth AE properties.
2-14	Evaluate effect of water on fatigue crack surfaces during fatigue loading. Evaluate crack closure noise.	DCB 1 1/2 in. thick.	Sinusoidal for pre-fatigue GETT cyclic load. Sinusoidal GETT in H_2O. Peak overload, then sinusoidal GETT load same as prior fatigue load.	Thru-wall notched.	Air, then H_2O: RT, 200°F. Peak overload and repeat in H_2O.	Same as 2-1	Water, complete immersion.	Conduct H_2O evaluation when crack growing and not growing (after peak overload).

TABLE 1. TEST PROGRAM (CONTINUED)

TEST NO.	TEST OBJECTIVE	SPECIMEN TYPE	MATERIAL FAILURE - STRUCTURAL CONDITIONS: LOADING	GEOMETRY	ENVIRONMENT	MATL PROPERTIES	INNOCUOUS NOISE SOURCE	COMMENTS
2-9	EVALUATE EFFECT OF OXIDE LAYERS ON CRACK SURFACES DURING UNLOAD AND FATIGUE CYCLING AT RT AND 200°F H_2O.	DOUBLE CANTILEVER BEAM (DCB) SPECIMEN 1 1/2 IN. THICK.	SINUSOIDAL FOR FATIGUE PRE-CRACK. CONSTANT COD DURING EXPOSURE; GROSS ELASTIC CYCLIC LOAD (<COD MAX. LOAD).	THRU-WALL NOTCHED AND PRE-FATIGUE CRACKED. TWO CRACK LENGTHS.	RT AIR FOR PRE-FATIGUE; 550°F AIR AND RT H_2O EXPOSURE. RT AIR FOR UNLOAD AND CYCLIC LOAD. CYCLIC LOAD AT 200°F IN H_2O.	SAME AS 2-1.	OXIDE LAYER ON CRACK; MACHINE OFF OXIDE ON OUTSIDE SURFACES. FATIGUE CRACK GROWTH UNLIKELY DUE TO FATIGUE LOAD <COD LOAD.	
2-17	DETERMINE EFFECT OF BASE METAL, HAZ AND WELD METAL DURING FATIGUE CRACK GROWTH AT A CONSTANT K-LEVEL.	TAPERED DOUBLE CANTILEVER BEAM (TDCB) 1" THICK.	CONSTANT LOAD RANGE.	THRU-WALL NOTCHED.	AIR; RT AND 550°F.	SAME AS 2-1 EXCEPT WITH WELDMENT.	NONE.	GROW CRACK AT ACUTE ANGLE TO WELD SO THAT CRACK PROPAGATES BM-HAZ-WM-HAZ-BM.
3-6	DETERMINE THE EFFECT OF PRIOR PRESSURE VESSEL SERVICE LOADING AND TEMPERATURE CONDITIONS ON SUBSEQUENT AE FATIGUE CRACK GROWTH.	PT 1/2" THICK.	SEE FIGURE 1.	SEE FIGURE 1.	SEE FIGURE 1.	SAME AS 2-1.	NONE	

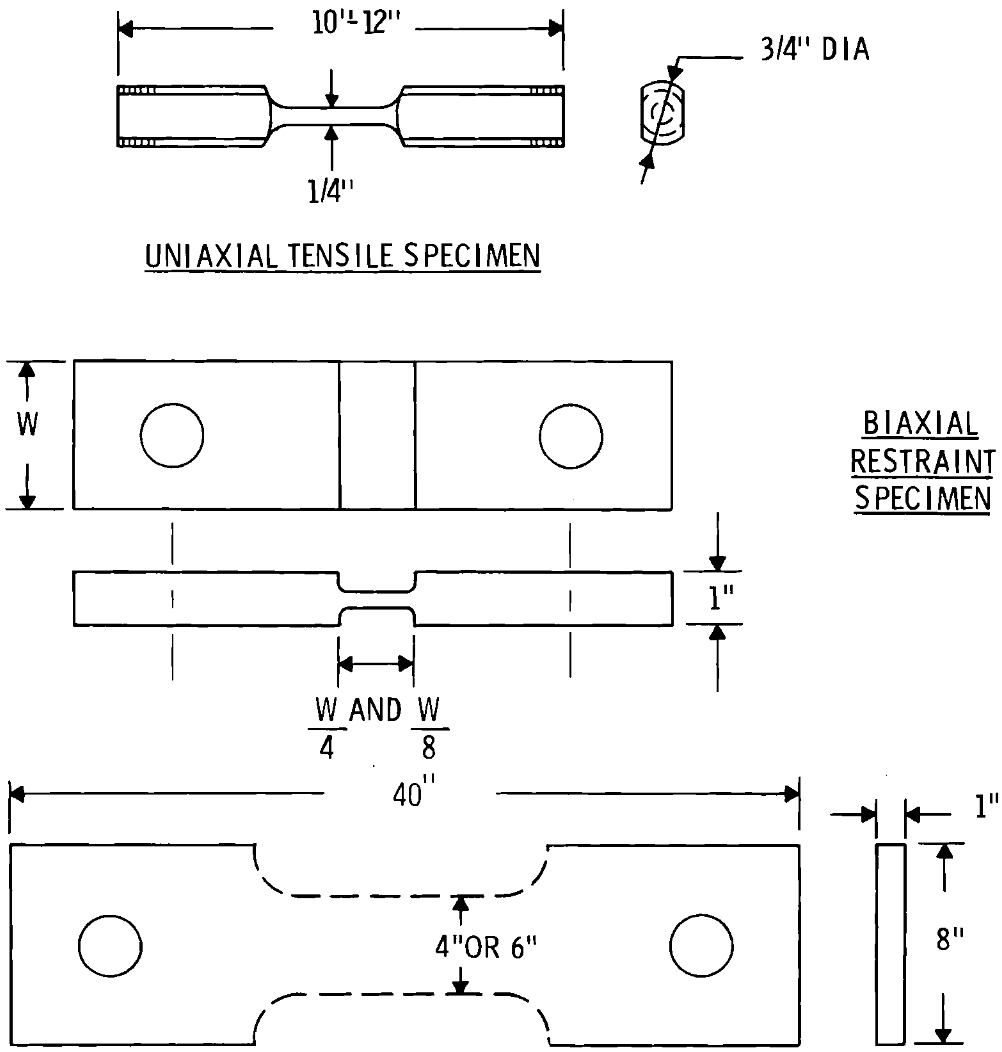


PLATE TENSION SPECIMEN:

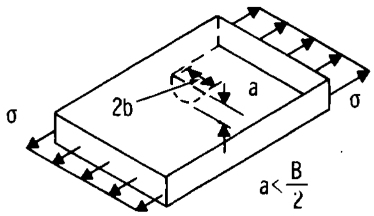
UN-NOTCHED (AS IS)

SURFACE NOTCHED (4 in. WIDE TEST SECTION)

SINGLE EDGE NOTCH (AS IS)

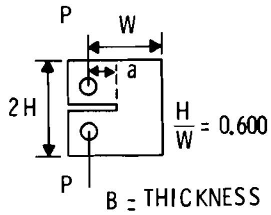
KAISER EFFECT (1/2 x 6 IN. WIDE TEST SECTION)

FIGURE 1A. Specimen Geometries



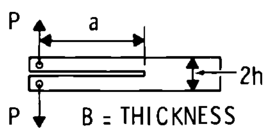
SC
SURFACE-CRACKED

$$K = \frac{\sigma\sqrt{\pi a}}{\int_0^{\pi/2}\left[1-\left(\frac{b^2-a^2}{b^2}\right)\sin^2\theta\right]^{1/2} d\theta}$$



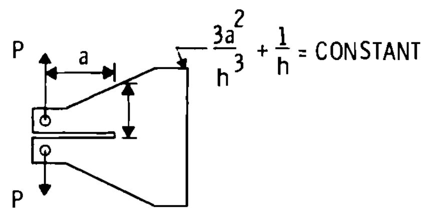
CT
A.S.T.M. COMPACT TENSION

$$K = \frac{P}{B\sqrt{W}}\left[29.6\left(\frac{a}{W}\right)^{0.5} - 185.5\left(\frac{a}{W}\right)^{1.5} + 655.7\left(\frac{a}{W}\right)^{2.5} - 1017.0\left(\frac{a}{W}\right)^{1.5} + 638.9\left(\frac{a}{W}\right)^{4.5}\right]$$



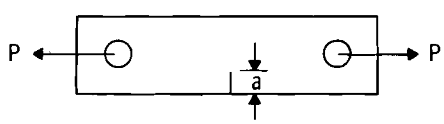
DCB
DOUBLE-CANTILEVER BEAM

$$K = \frac{P}{B}\sqrt{4\left[\frac{3a^2}{h^3} + \frac{1}{h}\right]}$$



TDCB
TAPERED DOUBLE-CANTILEVER BEAM

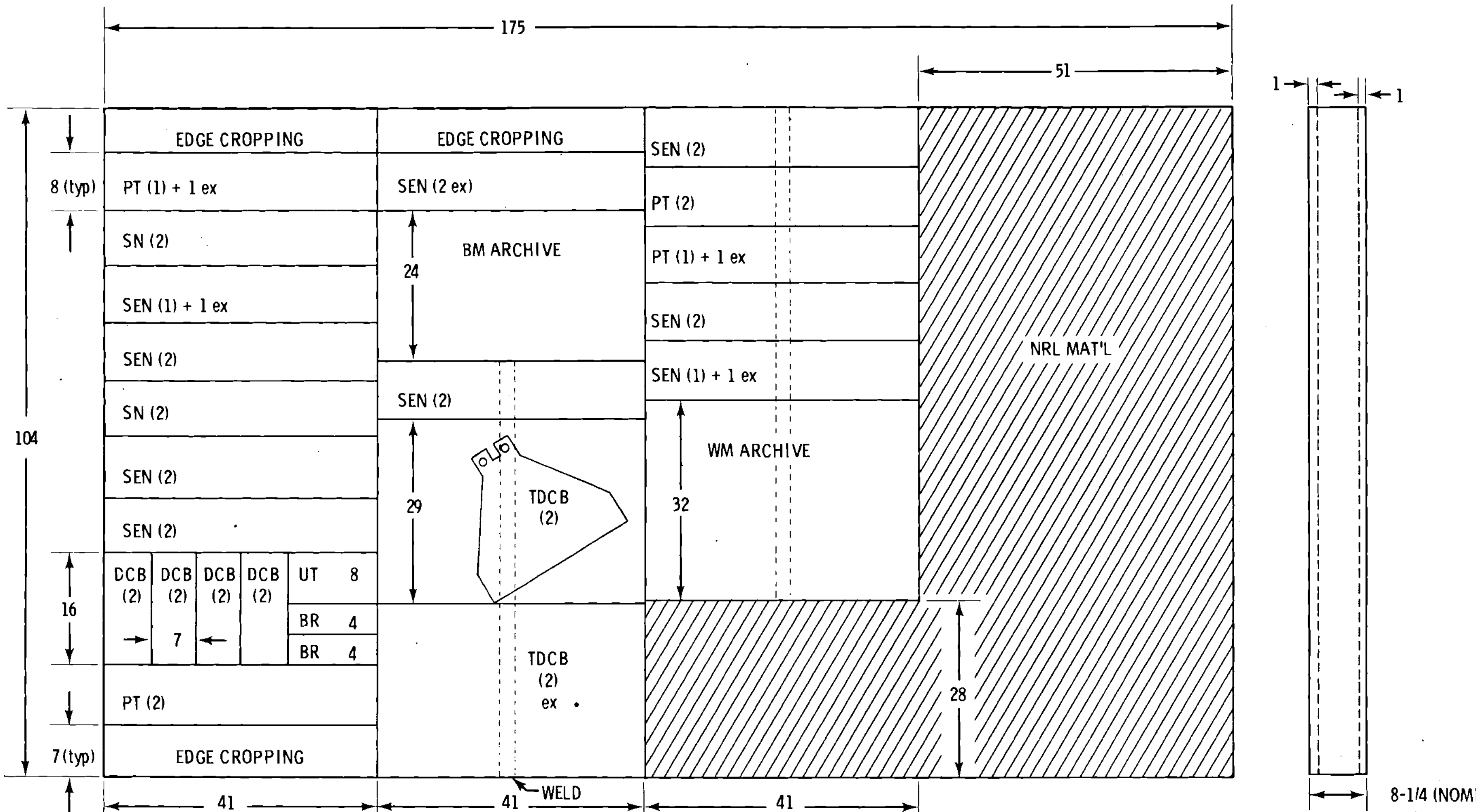
$$K = \frac{P}{B}\sqrt{4\left[\frac{3a^2}{h^3} + \frac{1}{h}\right]}$$



SEN
SINGLE EDGE NOTCH

$$K = \frac{P\sqrt{a}}{BW}\left[1.99 - 0.41\left(\frac{a}{W}\right) + 18.70\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4\right]$$

FIGURE 1B. Specimen Geometries



ALL DIMENSIONS IN INCHES

DESIGNATION	DEFINITION
UT	UNIAXIAL TENSION
DCB	DOUBLE CANTILEVER BEAM
SEN	SINGLE EDGE NOTCH
SN	SURFACE NOTCH
PT	PLATE TENSION
TDCB	TAPERED DOUBLE CANTI-LEVER BEAM (MOSTOVOY)
BR	BIAXIAL RESTRAINT

FIGURE 2. Test Specimen Layout

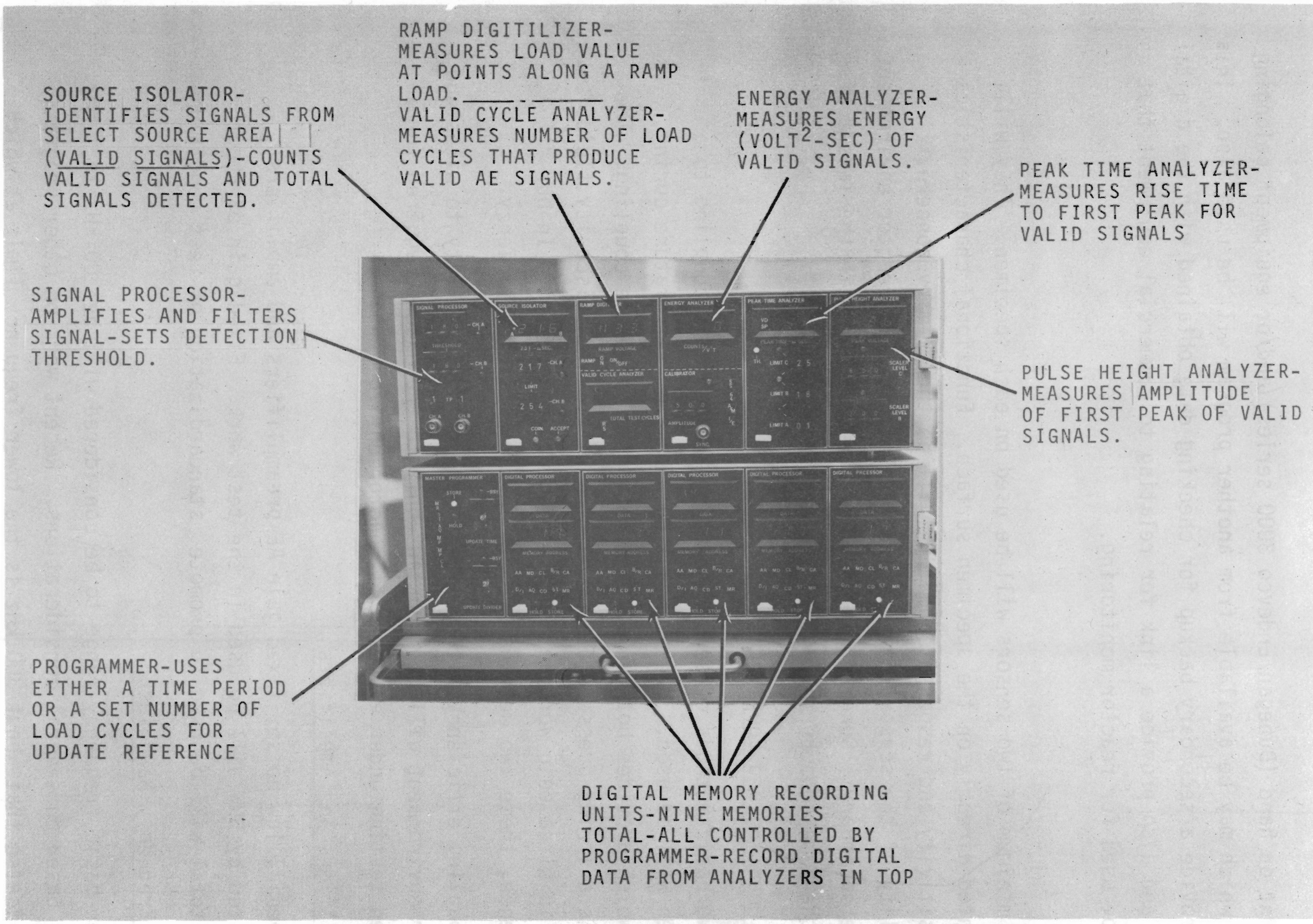


FIGURE 3. Digital Memory AE Test System

equipment on hand (Dunegan/Endevco 3000 series) and/or equipment belonging to NRC which may be available from another program will be used also. This will provide a secondary backup for checking data obtained with the digital system and also provide a link for relating to commercial equipment that might be used for reactor monitoring.

Sensor

A minimum of two sensors will be used on each specimen. They will be mounted directly on the specimen surface. Functional characteristics of sensitivity and response bandwidth will be the primary concern. Capability of the sensor to withstand long exposure to reactor environment will be secondary. Sensors will be fabricated by BNW with the intent of using the same sensors throughout the testing.

Sensor Mounting and Coupling

Two basic methods of sensor mounting and acoustic coupling to a specimen will be used. One is mounting with room temperature curing epoxy which provides both physical mounting and acoustic coupling. The other is a spring pressure clamp mounting with a high viscosity fluid common in ultrasonic work acting as an acoustic couplant. In our experience, these two methods are similar in sensing efficiency.

Coupling efficiency will be the first concern. Ability to withstand reactor environment will be important only to the extent required for specimen testing under elements of reactor environment.

Preamplifiers and Amplifiers

Special low noise, fixed gain AE preamplifiers and amplifiers fabricated by BNW will be used in the test work. Fixed gain of about 90dB total will be used to promote standardization of test conditions.

System Frequency Bandwidth

The basic frequency range to be considered will be 200 kHz to 1 MHz. This is based on several considerations. Recent work on other programs has indicated that about 300 kHz is the lower frequency limit at which

AE could be effectively monitored in the presence of reactor flow noise. It is necessary to filter at the sensor using an inductance tuning coil to reach this lower frequency level. We feel that to monitor tests at a frequency below 200 kHz would be adding significantly to noise interference problems without gaining any added information that could be used in the ultimate application on a reactor. The upper limit of 1 mHz is generally accepted as the upper frequency range limit at which AE can be monitored practically due to the increasing signal attenuation in steel at higher frequencies.

As AE-flaw growth relationships are developed, it would ultimately be desirable to investigate detection of these same relationships using AE data over a frequency range limited to 500 kHz to 1.0 MHz. If the relationships can be verified at this higher frequency range, it will confirm the validity of minotoring on reactor in a range that will minimize noise interference. This work would be done under a later phase where a wide range of all variables would be considered.

Analyzer and Recorder

The AE analyzer-recorder system being extended for use on this program expands on a new concept previously demonstrated on programs for the Federal Highway Administration and the Electric Power Research Institute. Key elements are use of solid state digital memories for data recording and source isolation to exclude test system noise. All data parameters will be recorded in digital memories on a common time base. Thus, all parameters are directly correlateable. Memories are readout directly to a printer to provide a numeric tabulation of data. This greatly reduces the time required to develop data tabulations for further analysis and it improves the accuracy of the data translation.

AE data accepted for recording will be restricted to that originating from the specimen defect through use of a source isolation technique. This subsystem defines an adjustable range of difference in time of signal arrival between sensors that will be accepted. This, in turn, defines a limited area of the specimen from which accepted signals can originate. In this way, noise from specimen holding fixtures and the test system can be excluded from the data.

In addition to the digital memory system described above, a commercial transient wave analyzer will be used to study details of the AE signal wave form. Also, a commercial multichannel analyzer will be used to measure distribution of AE signal amplitudes and rise time.

Parameters

Parameters that will be measured with the digital memory system are:

Parameter	Purpose
AE event count	Relate to flaw growth parameters.
AE energy	Same
AE signal amplitude - four ranges.	Distinguish between AE sources - cracking versus plastic deformation, and innocuous sources.
AE signal rise time - four ranges.	Distinguish between AE signals and innocuous noise sources.
Mechanical - either Load cycles producing AE.	Develop power law relations between AE and flaw growth parameters.
and	
Total load cycles.	Basic test correlation.
or	
Ramp load level versus time.	Relate AE data to increasing load levels.

An identified parameter which may be added or substituted for one of the above is signal duration. This may be useful in discriminating against electrical transients as well as possibly providing signal identification information. Other parameters can be added to or substituted for those listed as the work progresses if justified.

The multichannel analyzer will be used in parallel with the digital system to measure distribution of signal amplitude and rise time values. This will guide definition of the four ranges of these parameters to be monitored on a scaler basis.

A transient wave analyzer will be used to study AE signal wave form. This will provide insight to changes in information contained in the different wave propagation modes, and to signal frequency content.

Calibration

System calibration is critical to the success of this program. Constant measurement conditions should be maintained to establish methods of identifying different signal sources and significant data parameter changes. Subsequent investigation of the effect of changes in measurement conditions such as threshold changes must be done in a carefully controlled manner that can be related back to the base measurement conditions. The following calibration procedure will be used:

1. All sensors will be calibrated on a 4 in. x 12 in. x 12 1/2 in. Type A212B carbon steel block using a 50 micron alumina grit blast from a 0.070 in. inside diameter nozzle under 80 psig air pressure to generate broadband input energy. The grit blast nozzle is held 3/8 in. from the block and directed at a point 1 1/2 in. from the sensor. We have found from testing and experience that this provides a repeatable input energy from 100 kHz up to about 2 MHz. A permanent reference sensor independently calibrated to a traceable standard will be used to check consistancy of calibration input in terms of absolute reference to 1 volt/μ bar.
2. While mounted on the steel block, sensor response to an electronic field pulser will also be measured.

The above steps are considered to be a basic calibration. In addition to this:

3. After the sensors are mounted on each specimen ready for testing a calibration measurement will be made using the BNW grit blast directly on the specimen.
4. Response of the full AE monitor system to a field pulser will be measured with the sensor in place on the specimen ready for test.

Steps 3 and 4 will be performed for each test specimen both at the beginning and at the end of the test. These last two steps serve several purposes. It guards against unexpected changes in mounted sensor characteristics and monitor system performance. It also provides a basis for comparing effective monitor system gains and sensitivity in each test and between tests.

In addition to the calibration procedure described in 1 and 2 above, we plan to obtain a description of the reciprocity calibration method used by Battelle Frankfurt and apply it in parallel with the grit blast. This will provide a second basic calibration for cross checking and it will also provide a reference point in our data for use by Battelle Frankfurt in information exchange.

Records

Permanent records will be maintained for each test. In addition to basic data tabulations, this will include sensor identification and calibration, instrument system hook up diagram, instrument control settings, and any observations made during the test. Such a record is particularly valuable in this type work as reference in data analysis.

4.3 DATA ANALYSIS

Our planned analytical approach for initial testing is discussed in this section. We stress initial because it is essential that we retain the flexibility to change analytical methods. Typical of R&D, results as the work progresses may significantly alter what is the optimum analysis method. There are two primary analysis areas involved. One is distinction between meaningful AE signals and other acoustic information. The other is development of AE interpretation models.

4.3.1 Signal Distinction

AE signal amplitude, signal rise time, and signal frequency will be analyzed for characteristics to distinguish AE signals sources. Previous work at BNW[2] with A533B steel has shown evidence that there is a difference in amplitude of AE signals from deformation vs crack growth with crack growth producing the higher amplitude. This relation has also been observed by other investigators[3] including Battelle Frankfurt.[4] Through a combination of signal amplitude distribution and scaler sorting of the amplitudes into different ranges, we should be able to correlate data with generating processes accurately.

Signal rise time will be examined as a means of distinguishing AE signals from acoustic signals generated by innocuous slag inclusions. Acoustic energy released by perhaps interface movement between slag and metal should occur over a longer time period and contain relatively stronger low frequency components than that for an AE signal. The AE signal should thus show a faster rise time than the signal from the slag inclusion. If the slag were cracking, we would expect the same effect due to inefficient coupling across the interface between slag and metal. This would be analogous to observations of slag cracking vs metal cracking signals in monitoring submerged arc welding. After being transmitted across the interface between slag and metal, the slag cracking signals have lost much of their high frequency content resulting in a detected signal with slow rise time and a predominance of low frequency. Metal cracking signals do not traverse that interface and hence retain the higher frequency with faster rise time.

Signal frequency will be examined also as a possible means of discriminating between AE of interest and unwanted acoustic signals. The basis for this is included in the discussion above.

As we develop evidence of the validity of the above methods, we plan to incorporate circuitry in our monitor system that will impose limits of acceptance for these parameters either individually or in combination. This will then allow us to confirm that they do perform the desired discrimination function in real time. Some of the relationships described are already being used successfully by D. W. Prine in his weld monitoring program for NRC.[1]

4.3.2 AE Interpretation Models

In previous work, AE has been interpreted with respect to specific mechanical parameters and material conditions. The mechanical parameters were associated with experiments involving "uniform" strain in unnotched specimens and flaw growth in notched specimens.

Several examples based on previous work are shown below:

1. Determination of the Effect of a Monotonically Increasing Stress Intensity Rate ($\dot{K}$) on AE Parameters.

During testing of compact tension specimens, load, load rate, COD and crack extension were mechanical parameters that were used to characterize the effect of stress intensity rate ($\dot{K}$) on ΣAE event count and energy. In the linear elastic range, AE was related in a linear manner to K, where

$$\Sigma AE \propto K.$$

Total AE count increased with decreasing stress intensity rate ($\dot{K}$) in the form

$$\Sigma AE \propto \frac{1}{\dot{K}}$$

2. Determination of Influence of Hydride Coated and Dispersed Hydrides in Titanium Alloys on AE during Tensile and Fracture Loading.

The effect of hydride location in titanium alloys on AE parameters was studied using tensile and center-notched specimens. For both sets of specimens, AE was very sensitive to cracking of the hydrides which occurred almost entirely on the surface. Essentially no cracking occurred in the internally dispersed hydrides.

Stress strain curves were used to determine stress levels at which hydride surface cracking occurred and compared with AE count. Stress intensity factor versus summations AE count curves showed a power law relationship of the form

$$\Sigma AE \text{ count } \propto BK^m$$

where both B and m were strongly influenced by hydride cracking in comparison to base metal deformationand crack extension.

3. Determination of the Relation of AE to Fatigue Crack Initiation and Growth.

Fatigue data (load level, load cycle rate, crack length) was characterized by Paris-Erdogan crack growth law

$$\frac{da}{dN} = B(\Delta K)^m, \text{ where B and m are constants} \qquad \text{Eq. (1)}$$

AE data were obtained in a manner analogous to fatigue crack growth data as shown in Figure 4.

Differential fatigue parameter $\frac{da}{dN}$ and the crack driving force ΔK can be compared with equivalent differentially-obtained AE parameters. For example:

$\frac{\Delta E}{\Delta N}$, energy per load cycle

$\frac{\Delta E}{\Delta a}$, energy per mm of fatigue crack extension

$\frac{\Delta C}{\Delta N}$, counts per load cycle

$\frac{\Delta C}{\Delta a}$, counts per mm of fatigue crack extension

Comparisons can be made assuming various curve fitting schemes. One method that has been used with success is to compare AE parameters with fatigue parameters on a power law basis of the same form used to characterize fatigue crack growth rate data (see Equation 1). Example:

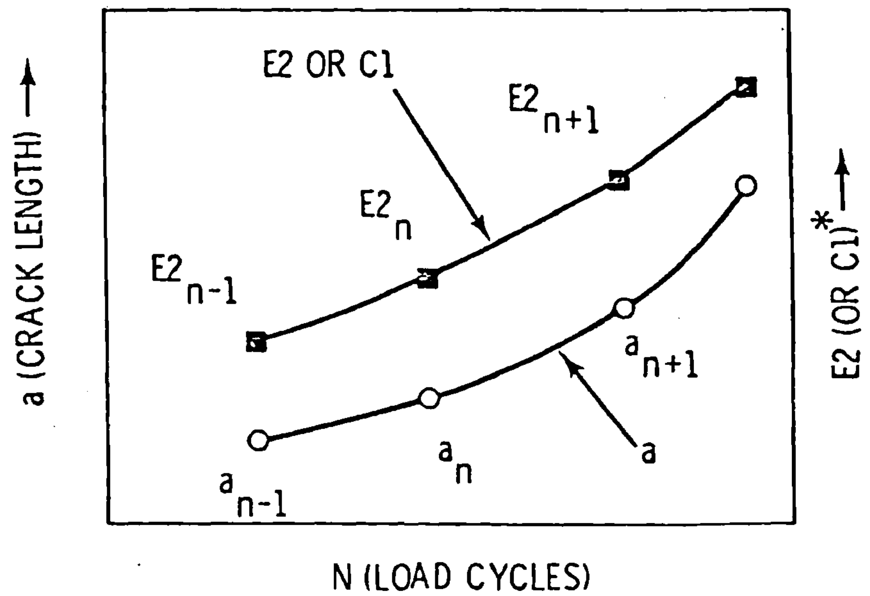
$$\frac{dE}{dN} = D \left(\frac{da}{dn}\right)^{+p} \text{ with noise} \quad (2)$$

$$\frac{dE}{dN} = G \left(\frac{da}{dn}\right)^{-q} \text{ without noise} \quad (3)$$

$$\frac{dc}{da} = H \left(\frac{da}{dn}\right)^{+r} \text{ with noise} \quad (4)$$

$$\frac{dc}{da} = J \left(\frac{da}{dn}\right)^{-s} \text{ without noise} \quad (5)$$

where D, G, H, J. $\bar{p}$, q, r and s are all constants



*E2 = D/E AE ENERGY

C1 = BNW AE COUNT

DERIVED DIFFERENTIAL AE - FATIGUE DATA

a, mm	N, cycles	E2 (OR C1)	Δa, mm	ΔN, cycles	ΔE2 (OR ΔC1)
a_{n-1}	N_{n-1}	$E2_{n-1}$			
a_n	N_n	$E2_n$	$a_n - a_{n-1}$	$N_n - N_{n-1}$	$E2_n - E2_{n-1}$
a_{n+1}	N_{n+1}	$E2_{n+1}$	$a_{n+1} - a_n$	$N_{n+1} - N_n$	$E2_{n+1} - E2$

FIGURE 4. Schematic Plot of Crack Length and D/E AE Energy (or BNW AE Count) Versus Load Cycles

Because AE data frequently display scatter, statistical analyses utilizing least squares regression analyses and the correlation coefficient "r" can be used as an index of the goodness of fit between least square lines and the data points through which they were drawn. The latter approach has proved helpful for showing the capability of a selected AE-fatigue parameter model to fit the data and how pin noise can so significantly bias AE data where AE from the full load waveform, as opposed to a gated portion of the waveform, is used.

The above represent a few of the many possible ways that AE and deformation-crack extension data can be compared for the purpose of obtaining an AE-flaw growth relationship.

For AE developed during crack initiation, no consistent and encompasing theory is presently available for comparison. Limited BNW data suggest that nearly all AE produced during fatigue in A533B is related to growth of the crack as opposed to initiation of the crack both at the beginning of the test as well as when a fatigue crack is propagating. This claim, however, must be investigated further. Once a readily measurable crack is formed many crack propagation laws exist as a basis for comparison with AE parameters. They include fatigue crack propagation laws of Head[5], Frost and Dugdale,[6] Liu,[7] Foreman,[8] and Paris and Erdogan.[9] Stress corrosion crack propagation behavior has been investigated by Johnson and Paris,[10] Brown[11], Hyatt and Quist[12], Novak and Rolfe[13], Smith, Piper and Downey[14], Johnson and Willmer[15]; hydrogen embrittlement crack propagation by Dunegan and Tetleman[16]; elevated temperature crack propagation by Popp and Coles[17], James[18] and James and Schwenk.[19] Where applicable, investigation and comparison of AE data with such laws would be attempted.

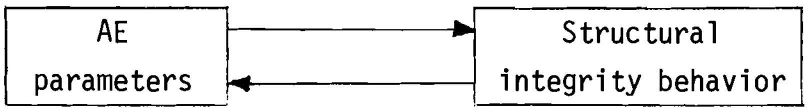
4.3.3 Defect Evaluation Model Development

Two parts of a three part analysis are considered in the current program:

1. AE analysis for unique characteristics relative to defect growth and innocuous sources.

2. Relating AE data to metal deformation and flaw growth parameters.

A third future analysis is expected to involve the broad relationship of

3. 

We envision this future analysis to involve experimental and analytical stress analysis methods with the goal of partitioning measured AE into a range of possible flaw types and failure condition sources which can be examined with a computer program. Detailed discussion of this third type of analysis concerned with direct application of AE in the field for defect evaluation is beyond the scope of this program. The ultimate need for such a phase of analysis must, however, be recognized at this time.

5.0 DISCUSSION OF TEST PLAN DEVELOPMENT

Having presented the specific test approach planned in Section 4.0, it is now necessary to consider how the test approach was developed.

5.1 FACTORS CONSIDERED IN SELECTING TEST CRITERIA

The general factors included in the framework for identifying criteria to be used in developing the test approach are:

1) AE limitations,

2) Sources of noise,

3) The basic nature of AE source mechanisms,

4) The path dependance of received AE signals,

5) The relationship of AE source mechanisms to failure driving forces, and

6) The relationship of specimen to structural behavior.

5.1.1 AE Technology Limitations

AE technology at the present generally does not include a demonstrated method to unambiguously separate the different sources of AE from each other including sources of noise.

5.1.2 Sources of Noise

Sources of noise include those developed within the material, those developed by the method of load transfer from test machine to the specimen and those produced by the test machine. (Other sources of noise expected in a reactor are discussed on pages 4 and 5 of attachment 1 to the 189 program proposal).

Test and material-related sources of noise include oxide, slag inclusions, possibly crack closure noise, contact-induced fretting corrosion in pinned joints and abrasion slippage in certain friction grips, and mechanical hydraulic noises associated with testing machines. Some can be eliminated or reduced but all must be considered in laboratory tests to avoid biasing AE data.

5.1.3 Basic Nature of Source Mechanisms

Knowledge of the basic character of AE source mechanisms is desirable but not necessary to satisfy program objectives. During this work macroscopic mechanically-based quantities such as stress, strain, load, COD, specimen bending displacement, stress intensity factor, J-integral...and crack dimensions are planned to be measured and/or calculated.

Dislocation-obstacle interactions and general atomic or microstructural defects within and around gross or localized strain fields are presently beyond the scope of this program. Only geometric discontinuities* on an engineering scale will be considered.

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*The term geometric discontinuities used herein denotes engineering scale discontinuities such as dents and scratches, section size changes and penetrations and defects such as slag inclusions, lack of penetration, and cracks...

5.1.4 Path Dependence of Received AE Signals

Consideration of path dependence of AE signals falls into two general areas:

1. Modifications to the fundamental energy pulse released at the source as it travels to the sensing point.
2. Macro scale effects such as interface attenuation and frequency filtering.

The first area is a very complex basic question beyond the scope of this program. Work is currently being done in this area at the National Bureau of Standards under joint sponsorship of the Electric Power Research Institute and NBS. The results may be an expanded understanding of AE fundamentals and improved capability to analytically predict AE data. This information is not considered a prerequisite for developing the experimental macro scale relationships being sought in this program.

The second area is directly related to this program. It can be important to characterizing innocuous noise sources such as slag inclusions due to the unique path of these signals to a sensor and the attendant influence on signal wave form.

5.1.5 The Relationship of AE Source Mechanisms to Failure Driving Forces

The relationship of AE source mechanisms to failure driving forces associated with crack initiation and propogation is one of the least well defined areas. Consider first that AE source mechanisms in specimens or structures are generally attributed to discontinuous or discrete movements associated with plastic deformation and crack extension in the neighborhood of flaws or geometric discontinuities. Plastic deformation precedes but also accompanies crack extension; thus both possible sources of AE could be operating simultaneously during the growth of a crack even though different failure or flaw propagation mechanisms** could be occurring.

**Metallurgical failure mechanisms resulting in crack initiation and propagation include, but are not limited to, ductile rupture, fatigue, stress-corrosion, hydrogen embrittlement and creep.

The failure driving forces, which govern material crack initiation and propagation mechanisms and attendant AE are also intimately related to structural design concepts and vessel operation. Thus, this factor is important to our program. We lump the failure driving forces and design/operation factors into a single term 'material failure-structural factors'. They include, but are not limited to:

1. Loading or Stress State. Load, pressure or stress level (gross elastic to gross plastic), load waveform, frequency and number (low-cycle to high cycle fatigue) thermal loadings, residual stresses, multiaxial stresses....

2. Geometry. Stress concentrations ranging from surface roughness, section size changes and penetrations through sharp defects including built-in base and weld metal defects..., through-wall, semi-embedded and fully-embedded flaws.

3. Environment. Aggressive liquids and gases to inert gas, vacuum, temperature, irradiation...,

4. Material Properties. Alloy type, strength level, ductility, microstructure, including the effect of welding techniques, prior history, fracture toughness...

Selected sets of the above factors are considered in the framework of the test program.

Substantive failure analysis information will also be factored into the program. It will be used as a basis for concentrating program tests on those pressure boundary failures that are most dominant and considering those failures that are most likely to produce the least emission during crack propagation.

5.1.6 The Relationship of Specimen to Structural Behavior

The relating of specimen behavior to structural flaw growth behavior is another important area including the effect of full thickness plates and flaw location. In a laboratory program, we need to use analytically tractable specimens undergoing constant amplitude loading in a controlled environment for the most rational analytic means for comparison of AE data with appropriate failure modes.

In contrast, real flaws in a vessel will experience variable amplitude loading and variable environmental conditions. Thus it will ultimately be necessary to consider how such conditions influence laboratory AE-flaw growth relationships. This latter consideration, as discussed earlier, constitutes a later phase and is not considered in this program.

Two inter-related material and flaw factors need to be considered. One factor concerns the variation in material properties and hence, possibly AE properties between the outer surface or case material (say 2 to 3 in. deep) and the inner core of thick (12 in.) pressure vessel plate. The other factor concerns the most likely location of built-in and operation-induced flaws and their direction of propagation.

Consider built-in flaws and their location first. Most built-in flaws will be located in or around welds with a lesser number in the base metal plate. Propagation due to gross or localized loadings would thus be dominantly in weld metal and/or heat affected zone, with possible ultimate propagation into the base metal.

Service-generated flaws are not so well-defined by location. Localized stresses due to fit-up, welding, heat treatment, nozzle supports and thermal variations could all contribute to flaw initiation and propagation. In the case of service-generated flaws, initiation could be expected to occur at or near the surface with propagation first through case metal or weld metal/HAZ towards core material. It thus appears that the AE-material studies should be centered primarily on case (outer 2-3 in.) metal and weld metal/HAZ with perhaps some limited testing and evaluation of AE characteristics of core material.

In this section, we have discussed a range of general factors which must be considered in the development of adequate test criteria.

5.2 TEST CRITERIA

Section 5.1 outlined general factors that could affect and possibly bias rigorous laboratory investigations of AE generated by defects and innocuous sources of noise. Based on that, we have selected specific test criteria which will consider those influencing factors in our test approach. The criteria selected are discussed in the same context and order as the general factors presented in Section 5.1.

5.2.1 AE Technology Limitations

Criterion 1

Use AE systems which are: a) capable of excluding from test data acoustic information or noise that is unique to the laboratory test system such as grip or load pin noise, and b) capable of measuring parameters expected to be useful in distinguishing flaw growth AE from other acoustic or noise sources expected in a pressure vessel.

5.2.2 Sources of Noise

Sources of noise to be considered are broken down into those occurring

a) within the material,

b) at the specimen-grip load transfer interface,

c) from the test machine.

Noises within the material

Criterion 2. Evalute the effect of oxide layers on crack surfaces (Test 2-9).

During operation of a pressure vessel pre-existent flaws and eventually service-induced cracks open to coolant exposure, may form oxides on their surfaces. During shutdown or a significant decrease in operation pressure, the oxides (whose molar volume is greater than the metal they formed from) could experience a crushing or mutual rubbing effect. Acoustic signals associated with this phenomenon could provide information as to the presence of flaws even though that flaw may not have grown during service. This phenomenon has been reported[20,21 Specimens containing fatigue cracks were heat treated at 300-650°C resulting in oxide formation within the crack. High AE count subsequently occurred at low fatigue loads suggesting oxide film cracking.

Criterion 3. Evaluate the existence of crack closure noise during fatigue (Test 2-14).

During unloading of a cracked specimen, it is believed that the crack surfaces rub against each other prior to reaching zero applied load.[22]

If so, acoustic signals associated with this phenomenon could also provide information on the existence of a growing crack.(23) However, apparent crack closure could be a manifestation of machine/speciment load transfer-induced noise.(24) Thus, tests should be conducted to determine if crack closure noise is real and if it displays acoustic properties different from plastic deformation and/or flaw growth.

Criterion 4. Evaluate the effect of interaction between slag inclusions and weld metal during fatigue (Test 1-11)

Slag inclusions within weld metal could produce acoustic signals during fatigue loading. Interfacial forces including differential motion (rubbing) between the metal and the slag inclusion and inclusion fracture could produce acoustic signals. It is important that the nature and characteristics of slag-induced signals be determined for possible separation from crack growth-related AE.

Criterion 5. Evaluate the effect of water on crack surfaces during fatigue loading (Test 2-14)

Water within a crack may or may not have any influence on indicated AE signals. Eisenblatter found that both oil(23) and water,(25) when placed in a crack, reduced indicated AE signals. Schwenk and Hutton(26) have found no significant effect of water on AE during fatigue crack growth in A533B steel. Neither investigation, however, included testing with the crack completely immersed in the fluids. Thus, this aspect should be examined to determine if water in the crack does generate acoustic signals. In addition to growing a fatigue crack during water immersion, an overload should be applied to the specimen to produce a crack arrest affect. Fatigue-cycling at the same prior fatigue load would then allow determination of the influence of water alone.

Noises due to specimen-grip load transfer

Criterion 6. Evaluate the effect of specimen-machine load transfer on the generation of acoustic signals during fatigue (Test 2-12).

We have experienced a significant affect of acoustic noise generated by contact-induced fretting corrosion between pin, specimen and loading clevis.

We have found that such sources arise usually during decreasing load in bending type specimens (compact tension) but during both increasing and decreasing load for axially loaded specimens (center notch). Moreover, the nature and magnitude of the acoustic signals are highly dependent upon the amount of fretting corrosion varying from low amounts for mirror-polished load transfer surfaces to high amount for highly corroded surfaces. Because such signals occur in the same load region as the so-called crack closure noise, tests should be conducted to evaluate this possible joint effect.

Test Machine Related Noise

Test machine related noises are planned to be studied only for their presence and to devise ways and means to either eliminate or reduce them to an acceptable level during a given test.

In the past, before development of the two sensor isolation system, considerable time and expense along with restricted test operating conditions (lower load levels and lower load frequencies) and noise suppression methods were necessary to avoid noise contamination of AE data. A combination of noise reduction methods with AE source isolation should assure relatively noise-free AE data.

5.2.3 Acoustic Emission Source Mechanism

Criterion 7. Evaluate AE from uniaxially loaded tensile specimens (Test 1-1).

The purpose of this section is to:

- Assess the engineering significance of uniaxial loading AE behavior relative to flaw growth AE behavior.
- Obtain basic mechanical properties of the material to be used in this program.
- Use tensile tests for periodic checking of AE equipment.

The engineering significance of uniaxial loading AE behavior is important as each crack growing in a metal structure or specimen has a zone of plastic deformation at its tip. Plastic deformation and crack extension are in the broadest sense two possible sources of AE that can operate concurrently during the growth of a crack. We believe it is important to obtain uniaxial load AE data for comparison with flaw growth AE to determine if flaw growth AE is in any way a manifestation of plastic deformation AE.

One investigator[27] claims that AE in a flawed specimen arises principally from growth of the crack tip plastic zone. Investigation by Eisenblatter, et al[23] however, indicate that uniaxial deformation AE (burst or continuous) does not occur at room temperature for fully annealed or for heat treated ASTM A508 Class II material. Increasing the test temperature to 100° to 300°C did cause the material to produce continuous AE around yield stress, but apparently no burst AE occurred. Holt and Palmer[28] on the other hand refer to "bursts of continuous emission" during crack tip yielding in a pressure vessel steel in the 100° to 200°C range. They explain the effect being due to dynamic strain ageing and a serrated stress strain curve observed in a tensile specimen tested at the same temperature. Reference to burst, bursts of continuous and continuous emission suggest that AE in pressure vessel steel, such as A533B must be carefully scrutinized for all such forms of emission and how that emission could be altered when a flaw is present.

Tensile tests will be used for periodic checking of AE equipment by using heat treatments if necessary to produce luder deformation AE.

Criterion 8. Evaluate AE from a uniaxially loaded biaxially restrained tensile specimen. (Test 1-1A)

Plastic deformation can occur in a vessel under conditions of multiaxial strain, both gross and localized. Yield stress level is increased due to biaxial stress and could affect the nature and amount of AE produced.

Biaxial restraint is produced in a specimen of the type shown in Figure 1a. Uniaxial loads are applied along one axis. Transverse restraint is introduced by yielding of the thinner section. The biaxial stress field produced will not be the same as biaxially loaded test specimens but it will allow an initial assessment of biaxial stress field effects on AE.

5.2.4 <u>The Relationship of AE Source Mechanisms to Failure Driving Forces</u>

Because of the present lack of definition of the interrelationship between AE source mechanisms and failure driving forces, these two areas are considered simultaneously in this section. They are broadly separated into:

- Deformation AE without crack growth AE (see above section for discussion on on topic)
- Deformation AE with crack growth AE
- Crack growth AE without deformation AE

and, material failure-structural factors:

- loading or stress state
- geometry
- environment
- material properties.

<u>Criterion 9</u>. Determine effect of temperature on AE-flaw parameters during monotonic loading of fracture mechanics specimens (2-1).

During ramp loading of a pre-existant flaw, a plastic zone grows at the flaw tip. After a particular load (or K-level) is reached a major crack forms and grows within the plastic zone. With further loading both plastic zone growth and crack growth occur concurrently. For a relatively ductile material like A533B in thin section (1-2 inch), the plastic zone grows to cover the entire ligament (uncracked section) and the specimen slowly fails by plastic instabiliy.

During hydrotesting and ramp loading during vessel service, flaws could be loaded high enough to induce AE and thus provide a measure of flaw severity. The intent of this portion of the investigation is to determine the properties of AE during plastic zone growth in the absence of crack front movement and plastic zone growth accompanying crack front movement. This investigation should also clarify Palmer, Brindley and Harrison's[27] claim that AE arises principally from expansion of the crack tip plastic zone and that the total AE count is directly proportional to plastic zone size. Their results indicate that plastic zone growth with or without crack extension is the dominant source of AE. In the absence of material conditions that could produce discontinuous straining or discontinuous crack growth increments, it is important to determine if there is any change in AE properties when visible crack extesnion accompanies plastic zone growth.

Criterion 10. Determine the effect of temperature on AE-flaw parameters during monotonic loading of fracture mechanics specimens. (2-4).

The majority of built-in flaws are expected to be in or around welds. Investigation of the properties of AE during plastic zone growth and crack extension in and around weld metal will indicate the relative AE character of weld metal in comparison to base metal.

Criterion 11. Determine effect of temperature on fatigue crack growth AE parameters at RT and 550^{o} F. (Test 2-12 and 2-12A)

During cyclic loading of built-in or prior service-generated pressure vessel flaws, AE will accompany flaw growth. The intent of this investigation is to determine the properties of AE that accompany fatigue crack growth at RT and 550°F. In addition the cracks will be grown until failure (separation) occurs allowing determination of the effect of gross plastic load cycling on AE during fatigue.

Criterion 12. Determine the relative AE behavior of base metal, HAZ, and weld metal during fatigue crack growth at a constant K level at R.T. and 550°F (Test 2-17).

During the growth of pressure vessel fatigue cracks, such cracks could begin their growth in one area such as weld metal, then progress into HAZ metal and possibly into base metal or some other combination of the three conditions. The intent of this work is to determine the relative effect of different material states on AE as a crack uniformly progresses across a weld. The tests will be conducted using a constant "K" specimen which, for a "constant" material condition, will produce a constant da/dN within experimental scatter. Stress relieving will be done to minimize possible effects of residual stresses which can exist around welds.

Criterion 13. Determine the effect of a semi-embedded flaw on AE properties during fatigue crack growth. (Test 2-19).

Flaws of concern in a vessel will most likely be semi-embedded or fully embedded. The intent of this section is to determine the properties of fatigue crack growth AE from a semi-embedded (thumbnail) notch and to determine if there are relationships between through-wall and part through-wall flaws.

Criterion 14. Determine the effect of prior uniform plastic strain on AE properties during fatigue crack growth. (Test 3-4)

In the life of a vessel, conditions can lead to plastic strain in the neighborhood of gross stress concentrations such as nozzles. During subsequent vessel operation a crack could initiate and grow within such an area of prior plastic strain. The intent of this section is to determine if prior plastic strain in the absence of subsequent thermal exposure can produce a material condition where a fatigue crack could grow without producing detectable AE.

Criterion 15. Determine the effect of prior pressure vessel service loading and temperature conditions on subsequent fracture and fatigue crack growth AE. (Test 3-6)

The influence of a "Kaiser Effect"* due to prior pressure vessel service loading and temperature conditions is unknown at this time. Because of this, and the inherently wide range of vessel operation conditions that can exist (including material history), a specific prototypic test is planned. The intent is to apply prototypic loading and temperature conditions from original hydrotest through simulated operation cycles and determine if and how subsequent fatigue crack growth-AE properties are altered.

The Kaiser Effect noted at room temperature does not necessarily hold when environmental effects are brought into play. For example, Schwenk and Hutton[29] have found for a nonsteel alloy that rapid reversibility can occur. This phenomenon occurred during high level proof loading of a notched specimen at 550^{o}F (without failure), unloading at 550^{o}F, followed by loading to fracture at room

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*Kaiser was the first investigator to use electronic instrumentation to detect audible sounds produced by metals during deformation. He observed that AE activity was irreversible and that further AE was not generated during the reloading of a material until the stress level exceeded its previous level. This irreversible phenomenon has become known as the Kaiser Effect.

temperature, several hours later. AE occurred during loading at both temperature levels. Prior loading at 550° F may have affected AE during subsequent loading to failure at RT. However, AE at RT began at a load (or K) level about 10% of the prior 550°F proof load. In addition AE count behaved in a power law manner ($N \alpha K^M$) for both loadings. A533B may or may not behave in the same manner.

The plan is to simulate shakedown-type plastic deformation associated with an initial hydrotest (about RT),* a hot functional hydrotest (> RT) and a short period of operation (550° F) in an unnotched state. While the specimen is still warm (say 250-300°F) following the operation cycle, a notch will be cut in the specimen and fatigue cycling conducted at 550° F. (See Figure 5 for one possible sequence of loading and temperature conditions). AE would be monitored throughout the entire test. Production of AE throughout this test does not assure that AE will occur under more varied conditions expected under actual operation. It does, however, provide initial assessment of AE characteristics of a growing flaw under a simulated operation condition.

Four other areas identified for future investigation of possible flaw growth without AE are:

1. Determination of the temperature dependance of the Kaiser Effect in unflawed specimens. Proof loading and unloading of specimens at one temperature level (RT, 400° and 600° F) followed by proof loading at another temperature level (600° F to RT).
2. Determine the temperature dependance of the Kaiser Effect in flawed specimens. Proof loading and unloading at one temperature (RT, 400°, and 600° F) followed by proof loading at another temperature (600° F to RT) to simulate hydrotest and service induced ramp loading.
3. Determination of the time-dependance or "aging while unloaded effect" (strain aging) on AE in Items 1 and 2 above. Aging temperature would be RT, 400° and 600° F. Aging times 1, to 1,000 hours.

*RT is selected because it is estimated that there will be little difference between RT and NDT + 60°F.

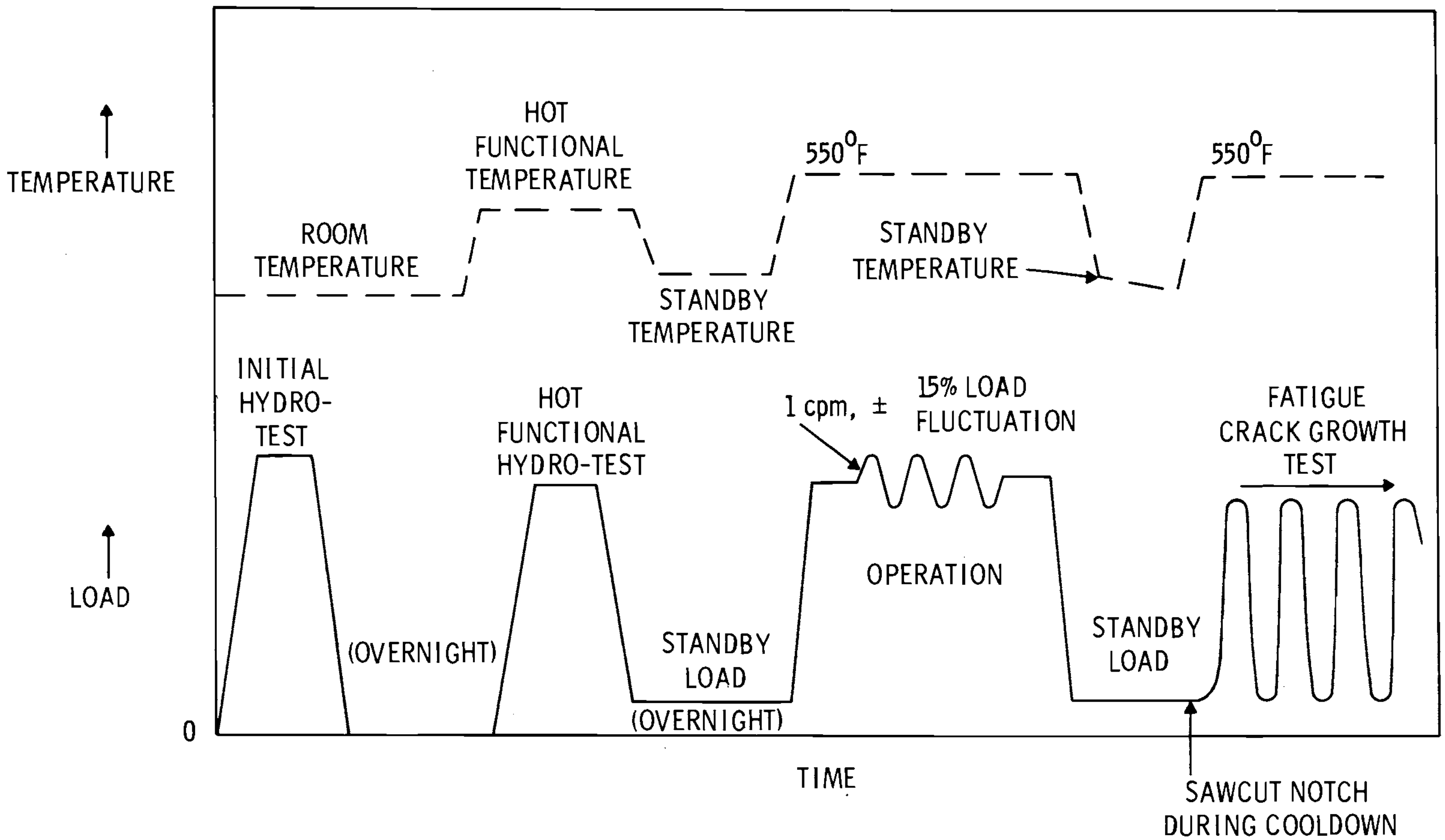

FIGURE 5. Simulated Pressure Vessel Loading and Temperature Sequence with Fatigue Crack Growth

4. Determination of the fracture and fatigue crack growth AE properties of prior loaded and exposed, unnotched metal.

5.2.5 Relationship of Specimen to Structural Behavior

The relationship of specimen AE to structural AE behavior is beyond the present scope of this work. Experiments involving complex loadings or stresses associated with subsize pressure vessels and simulated environment conditions are necessary for developing this area of technology. (See also Appendix A, Technology Requirements for Monitoring Integrity by AE, Schedule 189). This work is considered in a potential future phase of the overall effort.

6.0 SCOPE EXPANSION ITEMS

This section is devoted to discussion of three work items which have been added to the original program scope. These items are pheripheral to the main program but very directly related. It thus appears that they should be included in this analysis but separate from the main program.

6.1 HIGH TEMPERATURE AE SENSOR

This work is concerned with establishing the availability of a high temperature (600°F) AE sensor with a mounting and acoustic coupling method for long term reactor service. To date, the major monitor system problem for continuous monitoring has been lack of a proven sensor with couplant and mounting techniques for long term exposure to a reactor environment.

Several commercial suppliers of AE equipment market high temperature sensors claimed to be suitable for reactor service. These include Dunegan/Endevco, Westinghouse Nuclear, Trodyne Corp., and Exxon Nuclear. These represent a sizeable investment of R&D dollars. We feel it is logical to evaluate the currently available sensors first. Results of this evaluation will determine the need for further R&D effort on high temperature sensors under this program and aspects requiring particular attention. Thus, we can define only the initial phase of this work now.

We plan to obtain two of each type of commercial high temperature sensor. Using both grit blast calibration input and pulser input, they will be evaluated for base sensitivity and response bandwidth at room temperature. These tests will then be repeated at intervals with the sensor continuously in a 600°F furnace for a period of about two months. The high temperature tests will measure sensitivity changes at temperature and the ability of the sensor to withstand continuous exposure to 600°F temperature.

Where available, sensor mounting and acoustic coupling methods recommended by the sensor manufacturer will be incorporated in the above tests. Two identified couplants that will be tested specifically are one developed at Battelle Frankfurt and one used by Exxon Nuclear. General availability of both of these has been stated by the concerns involved.

At the conclusion of the above testing, a decision will be made in collaboration with NRC as to subsequent action. This might take the form of further testing of a particular commercial sensor-couplant combination(s) on a nuclear reactor or initiation of a high temperature sensor development effort.

6.2 LIBRARY OF FOREIGN RESEARCH IN AE APPLICATION

In the overall scope of work to develop continuous AE monitoring capability for reactor use, it is necessary to be informed on related work being done in foreign countries. Results of some of that work could serve two major purposes:

1. accelerate our progress toward the ultimate objective at little cost, and
2. help us avoid unforeseen problems.

In general, information on these foreign programs should be available to us through government technical information exchange agreements. Two countries already identified as having extensive AE application development programs are Germany and Japan.

We plan to approach this information need initially through contacts in these two countries to obtain identification of pertinent programs and obtain published reports on the programs. Technical symposium proceedings are another source of information. We are also attempting to identify programs of interest in other parts of Europe and England through a European Common Market representative (Arved Nielsen) who recently visited BNW. We also plan to use the normal U.S. technical information centers but we feel that the above approach should yield more current information.

6.3 COORDINATE AE DATA FROM HSST SPECIMENS

A major consideration in this work is to be able to relate the AE data obtained from HSST specimens to laboratory results obtained in the AE characterization work. We feel at least at the outset, this can be most effectively accomplished by BNW performing the AE measurements on HSST tests using generally the same instrumentation that will be used in the laboratory work. The sensing technique used is especially critical in this work. At the same time we would expect to also start developing a specific AE measurement criteria which could be used eventually by others to perform AE measurements on the HSST specimens.

One set of fracture specimens are currently undergoing irradiation. The approximate schedule for testing these at HEDL is late February. We plan to perform the AE monitoring on these specimens. Details of the test procedure remain to be determined.

Collection and analysis of AE data from HSST specimen tests is potentially a very important part of developing AE-material fracture relationships. It should provide insight to the influence of material irradiation on AE characteristics

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APPENDIX B

TRIP REPORT
TRAVEL TO BATTELLE FRANKFURT LABORATORY
FRANKFURT, GERMANY

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September 30, 1976

Dr. J. Muscara
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Mail Stop 1130-55
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Dear Joe:

Trip Report - Visit to Battelle Frankfurt
Laboratory, Frankfurt, Germany - 9/2, 3, 4/76

The subject travel related to a recently established research program at Battelle Northwest (BNW) under Nuclear Regulatory Commission (NRC) sponsorship to characterize acoustic emission (AE) from A533B pressure vessel steel in support of continuous pressure vessel integrity monitoring by AE methods. The purpose of the trip was to discuss results of related work performed at Battelle Frankfurt (BF) under sponsorship of the Federal Republic of Germany (FRG) with the objective of optimizing the format of the BNW-NRC program to provide maximum new information. Results obtained from the trip are summarized below.

Principle Persons Involved in Discussions

Dr. J. Muscara - NRC

E. B. Schwenk, P. H. Hutton - BNW

Dr.'s. J. Eisenblatter, P. Jax, R. Von Klot - BF

Mr. Harbecke - FRG

Locations Visited

BF Laboratories

Saarbrucken Nondestructive Testing Institute

Summary of BF-FRG Work

- General emphasis is on application of AE to detect flaws during hydrostatic testing of pressure vessels, to detect loose parts in steam generators, and to detect leaks in pressure system during operation.

- Strong emphasis on basic research - study of AE source mechanisms. Seismic theory being used to guide initial investigation.

Battelle

- Concentration on study of natural defects with fatigue as initial consideration.
- Ultimate testing of heavy sections up to 27½ inches (70 cm) thick being considered.
- Have performed reactor noise studies. Results not clear in our discussions. Implied a lower significant frequency range than shown by U. S. studies.
- Related work being performed at Saarbrucken, Bremer Inst., and Berlin Inst. in pipe testing, welding, and delayed cracking.

Technical Points

- BF has developed a promising adhesive for mounting and acoustically coupling AE sensors for long term at 550 to 600°F.
- BF indicated that AE-tensile data in the literature could be biased by the method of gripping. BF uses a unique friction grip loading system including impedance mismatching to minimize test system noise.
- In the absence of serrated yielding or luders strains, BF does not detect AE during tensile straining of A508 class 2 steel (annealed or heat treated) or AISI 304 SS. Other investigators using non-friction grip loading report low strain (up to 1-2%) AE. This indicates importance of minimizing or electronically isolating sources of noise.
- BF believes that AE in nuclear pressure vessels occurs due to plastic zone growth accompanying crack extension.
- One test showed that Kaiser effect was eliminated by an operating period of several weeks in a petrochemical vessel at 350°C.
- Do not feel that "continuous" AE is of practical value in range of strain rates expected for pressure vessels.
- No temperature effect observed in short term tensile tests to 300°C.
- Observations indicate that in heavy section material (>than 3 times wave length of surface wave) that longitudinal and shear wave convert to surface wave within three thicknesses from source. This is contrary to theory as pointed out by BF. We have not observed this yet.
- Maintain that crack closure noise in fatigue is real. We have not yet seen crack closure noise.
- Have observed AE from cracks during depressurization of a pressure vessel (perhaps oxide crushing). Could be useful in authenticating a crack vs. innocuous source.

Battelle

- Indicate nothing unique in high temperature sensors. Claim that they depend on commercial sensors such as Dunegan/Endevco.
- BF experience with spectral frequency analysis of AE signals is similar to ours - ie, inconsistant results.
- Have been successful in detecting under clad cracking by AE.
- BF people are skeptical of Packman's technique for deconvolution of an AE signal to describe its original form.
- Much of BF study of AE appears to concentrate on lower frequency data - below 300 KHz.

General

- There appears to be 20-30 reports on AE work that are not generally available. Some of these are up to 3 years old.
- BF exhibits a definite interest in more thorough information exchange.
- Methods considered to improve information exchange include

  1. exchange of technical people for about a three month period.
  2. place a small program effort with BF.
  3. more frequent person to person meetings.

  Note: Item (1) is excellent in principle but it would be difficult for BNW to comply without crippling our effort.

- With BF's emphasis on basic mechanism study, their program does not appear to be in conflict with BNW-NRC program.
- Saarbrucken NDT research facility is worthy of note. It is designed to do both laboratory development of NDT methods and proof on full scale components before taking new methods to the field. They are starting on a DM 50 million ($20 million) program to develop improved methods of defect detection starting with plates as they are fabricated at the steel mill.

Items BF Agreed To Supply To Us

- Information on the composition of their high temperature adhesive for mounting sensors.
- Details on their reciprocity method for sensor calibration.

Battelle

- A complete list of BF publications and reports on AE work.

Items We Agreed To Supply To BF

- Details on our grit blast sensor calibration method
- Information on ultrasonic pulse propagation in thick section steel
- A copy of Dr. P. Packman's paper describing his theory and method for deconvolution of AE signals to obtain a description of the initial AE energy pulse.

Mutual Exchange Effort

- BF was receptive to the suggestion to exchange AE sensors and calibration information. The benefit of this would be that BF and BNW would have a specific and direct comparison of their respective AE sensor response characteristics to two different calibration methods. This will not only provide a measure of the relative effectiveness of the two calibration techniques, but more important, it will allow evaluation of the comparative sensitivity of the two types of AE sensors. I consider this to be very important to the BNW-NRC program. The AE sensor is the most critical element of the entire measurement system. This exercise will provide tangible assurance that we will be using AE sensors in our program that are at least equivalent to those used by another reputable investigator (BF).

Items Specific To BNW-NRC Program

- Lack of weld fusion should be included as a defect type.
- Consider studying data in two frequency ranges - <400 KHz and >400 KHz.
- Measure AE signal amplitude distribution in parallel with scaler time distribution of selected amplitudes.
- Record data samples on video tape to provide for at least limited frequency spectrum analysis.
- Make special observation for evidence pro or con concerning propagation mode conversion to surface waves as indicated by BF.
- Emphasize determination of plastic zone AE vs. crack growth AE.
- Incorporation of a transient wave analyzer to obtain specific information on AE signal make-up appears to be justified. BF is using this analytical tool beneficially.

Battelle

- The recognized requirement that relationships developed from thin (< 2") lab. specimens must be confirmed on thicker material was reinforced by the BF discussions.

Summary

In an overall view, discussions with BF and subsequent unrelated meetings in Japan showed that there is considerably more basic AE study being performed in both countries compared to the U.S. "Basic" is here defined as study of basic AE generating mechanisms and changes relative to material and environment. Japan is also doing a significant amount of large specimen (vessels including even full size reactor vessels) testing.

It thus appears to us that the BNW-NRC program which focuses initially on macro scale laboratory experiments meshes well with work being done in other countries. A free exchange of current information developed from the BF-FRG program and the BNW-NRC program should be of substantial mutual benefit. A similar exchange with the Japanese program which focuses on vessel testing should also be considered. This is a joint research program by the Japan Atomic Energy Research Institute, Central Research Institute of Electric Power Industry, and Tokyo University Institute of Industrial Science. It is concerned with tracing crack propagation in pressure vessels using AE methods. The program started in 1967 and is currently ongoing.

We feel that the subject discussions with BF were beneficial and hopefully a free exchange of program information and results will develop.

Very truly yours,

P. H. Hutton

P. H. Hutton
Nondestructive Testing

E. B. Schwenk

E. B. Schwenk
Metallurgy

PHH:dc