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

**Annual Report
July 1, 1976 - October 1, 1977**

**P. H. Hutton R. J. Kurtz
E. B. Schwenk C. Pavloff**

Battelle-Pacific Northwest Laboratories

**Prepared for
U. S. Nuclear Regulatory Commission**

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Division of Reactor Safety Research
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PROGRAM TO DEVELOP ACOUSTIC EMISSION-FLAW RELATIONSHIP FOR INSERVICE MONITORING OF NUCLEAR PRESSURE VESSELS

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

ANNUAL REPORT NO. 1

P. H. Hutton
E. B. Schwenk
R. J. Kurtz
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Battelle
Pacific Northwest Laboratories

January, 1978

ABSTRACT

Laboratory mechanical tests were conducted to evaluate AE during uniaxial tensile, fracture and fatigue crack growth in A533B pressure vessel steel. The A533B steel included two heats of Class 1, one heat of Class 2 and a weldment made for the Heavy Section Steel Technology (HSST) Program. Specimen types included uniaxial tensile specimens, size 2 compact tension specimens for fatigue crack growth and fracture tests, and a single-edge notch specimen also for fatigue crack growth through material that was uniformly strained 3% prior to fatigue testing. In addition, AE monitoring was conducted on the HSST V-7B 6-inch thick pressure vessel test.

AE data were partitioned into four ranges of signal amplitude and rise time. All the AE data were analyzed, with respect to mechanical behavior of A533B steel. Linear elastic fracture mechanics analysis methods were used to relate AE parameters to fracture and fatigue crack growth parameters. AE data from the V-7B vessel test were correlated with stress intensity factor and crack opening displacement. AE data from the fatigue crack growth tests were investigated using models based on fatigue crack growth rate, fatigue crack area and theoretical crack tip plastic zone size.

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PROGRAM TO DEVELOP
ACOUSTIC EMISSION-FLAW RELATIONSHIPS FOR
INSERVICES MONITORING OF NUCLEAR PRESSURE VESSELS

Annual Report No. 1

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Pacific Northwest Laboratories

1.0 INTRODUCTION

The integrity of a pressure boundary is dependent on several factors such as adequate design, satisfactory material, proper manufacturing and fabrication, good nondestructive inspection methods and knowledge of the possible failure modes that can occur during manufacturing, fabrication and operation. Although fracture of a pressure vessel built in accordance with the ASME Boiler and Pressure Vessel Code, Section III, is a rare event,⁽¹⁹⁾ it follows that the probability of fracture depends strongly on the care taken to minimize the development and growth of defects and the adequacy of inspection procedures.

Results of two surveys^(20,21,22) of defects in pressure vessels indicated that defects that occurred in manufacturing and fabrication, coupled with operation-induced fatigue crack growth from those defects, was the dominant cause of failure. AE is generated during the growth of fatigue cracks. Thus the use of a continuous monitoring technique such as acoustic emission presents a possible method for detecting, locating and monitoring fatigue crack growth during reactor operation.

For AE monitoring to be successful as a crack sensing technique requires that AE from crack growth must be reliably detectable on reactor. Furthermore, detection of the crack must be achieved before the defect is either too large or is growing at a rate that could affect structural integrity.

To accomplish this, there must be analytical relationships between AE and the severity of the flaw or cracks so a vessel operator could make a technical decision on the level of flaw severity and hence the margin of vessel safety.

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 purpose of the program is to develop an experimental evaluation of the feasibility of detecting and analyzing flaw growth in reactor pressure boundaries on a continuous basis using AE. The primary objectives of this program are:

- Develop criteria to distinguish flaw growth AE from other non-significant acoustic signals including those from innocuous defects.
- Develop an AE-flaw growth model as a basis for relating inservice AE to flaw significance.

The program was initiated July 1, 1976 and is presently continuing through FY-78.

This report is designed to provide: (1) a summary of results on the program through FY-77, and (2) a topical discussion of the feasibility of AE inservice monitoring of reactors as indicated by program results to date.

The total program design and discussion of the justification for various types of tests scheduled is contained in an analysis-before-test document. This document was published as part of the first progress report.⁽¹⁾

2.0 SUMMARY

The summary will review first the results of the FY-77 program, and then the topic of feasibility of flaw evaluation by inservice AE monitoring of reactors.

2.1 EXPERIMENTAL RESULTS

A multiparameter AE detection and analysis system with source isolation is being used on this program. It measures seven parameters (five AE parameters and two mechanical test parameters) simultaneously and records these on solid state digital memories. The source isolation feature limits accepted AE data to that originating in the predetermined area of interest. The source isolation also controls a transient wave analyzer so that displayed signals for waveform and frequency spectrum analysis are limited to those originating in the area of interest. A method for rating the sensitivity of the entire AE monitor system has been devised to make the results of this program relatable to other AE monitor systems and tests.

Smooth tensile specimens of both base metal and weld metal tested at room temperature and at 550⁰ F produced essentially no detected AE. This suggests that elastic/plastic deformation in a vessel in the absence of serrated yielding and stress concentrations (K_t) may produce little or no detectable AE.

One notched round tensile and three fracture toughness specimens all produced readily detectable AE, but at different degrees of plasticity. The single notched round specimen produced a large amount of AE until net section yielding and plastic flaw growth occurred. In contrast the fracture specimens produced the majority of their AE after net section yielding and plastic flaw growth were occurring. This effect will be studied further to see if there is a specimen geometry effect which leads to different AE behavior. The fracture toughness specimens, however, indicated that AE is detectable for both gross elastic loading and both continuous and discontinuous propagation of the crack through grossly plastic material.

The HSST V-7B vessel test produced AE data which were indicative of flaw development and correlated well with stress intensity factor (K) and crack opening displacement (COD). This indicates that AE data can be correlated with flaw severity in a test vessel.

The primary emphasis has been to identify AE-fracture mechanics relationships which hold a potential for defining flaw significance from AE data. To this point, such analysis has been focused on fatigue crack growth. The overall concept being applied in analysis considers that a flaw growing in a pressure vessel will produce AE and that advanced instrument systems are available for developmental detection and analysis of AE signals. Effort concentrated on determining which AE parameter(s) most effectively correlates with flaw growth to provide a basis for flaw evaluation relationships.

A statistical approach has been used to screen the various parameter combinations for the most promising relationships in the following manner. Rate data are developed from the basic crack length and AE event count and energy data versus load cycles by determining the slope of the various curves (e.g., da/dN , dC_3/dN and dE/dN) between selected load cycle values. Fatigue crack growth rate (da/dN) is characterized by using the stress intensity factor range (ΔK). AE rate data is compared with da/dN to derive a power-law relationship and a correlation factor.

Preliminary AE- da/dN correlations show that event count of low amplitude AE signals with fast rise time provide the best measure of da/dN and that plastic zone volume appears to play a dominant role in the production of the low amplitude-fast rise time signals. These data are preliminary, but the results are encouraging for using rate of change of AE signals over a period of time as measure of flaw growth rate in a pressure vessel.

Limited work on AE signal characterization produced the following tentative indications of methods to effectively separate AE signals from other acoustic signals:

- A combination of peak time and amplitude discrimination,

- Polarity of the first half cycle of the signal,
- Signal frequency content.

Comparing AE signal waveforms from the HSST V-7B vessel test (6 in. wall thickness) and those from laboratory test specimens (1 in. thick) showed them to be similar. This is encouraging to the potential usefulness of AE-flaw relationships developed from laboratory specimens.

Investigation of high temperature AE sensors for reactor application has shown:

- Commercially available high temperature sensors have relatively low sensitivity compared to the normal room temperature sensor,
- Two sensors tested show characteristics at room temperature which should be adequate for AE detection,
- Barring new developments in epoxies or other acoustic coupling materials, it appears that sensors on a reactor will need to be pressure-coupled.
- Use of metal waveguides is one proven method for detecting AE signals for a high temperature surface.

High temperature sensor investigation is continuing.

2.2 PRELIMINARY FEASIBILITY OF AE INSERVICE MONITORING OF REACTORS

This is our first feasibility report on how AE information alone is expected to provide a basis for determining flaw severity in an operating nuclear reactor pressure vessel. In this work, flaw severity centers on the magnitude of the stress intensity factor K , and its relationship to flaw growth rate, da/dN . This feasibility report is based on program activities through fiscal year 1977.

To illustrate our approach, we have assumed an application where fatigue is propagating a crack in a vessel. Our analytical method employs rate of change of AE and fatigue parameters. We will show, using laboratory-developed data, that both da/dN and the fatigue crack driving force, ΔK , can be obtained from the acoustic emission rate, dC_3/dN . These two factors, da/dN and ΔK , permit an evaluation of flaw severity.

The composite curve of an AE (dC_3/dN) and a fatigue parameter (da/dN), Figure 1, was obtained from fatigue crack growth tests using two different heats of A533B Class 1 steel, one weldment, two different thicknesses (0.48 vs 1.75 in. thick), and two different geometry specimens (single-edge notch and size two compact tension). Furthermore, one specimen was uniformly pre-strained 3% prior to fatigue testing to simulate localized straining that might occur in a pressure vessel during a hydro-test. These data (Figure 1) were characterized using a least squares regression technique assuming a power-law behavior between dC_3/dN and da/dN where,

$$\frac{dC_3}{dN} = 2.529 \times 10^5 \left(\frac{da}{dN} \right)^{1.182} \quad (1)$$

For purposes of analysis, it was assumed that there were no statistically significant differences in the AE-fatigue data for the different specimen types. Statistical verification tests will be conducted on the data to clarify their behavior.

The determination of flaw severity by AE alone is shown in the following example. Suppose that an average of one AE event count/cycle is occurring during reactor operation. Based on the confidence limits on Figure 1 for an average of one AE event count per cycle, there is a 90% confidence that a crack within the vessel is growing at a rate (da/dN) somewhere between 8 and 90 micro-inches cycle. From the same three specimens, a Paris-Erdogan fatigue crack growth rate equation was derived,

$$da/dN = 3.657 \times 10^{-9} (\Delta K)^{2.242} \quad (2)$$

This is shown in Figure 2. Substituting the above range of da/dN values, derived from AE data, into Equation 2 yields a 'crack driving force' ΔK , ranging from about 31 to 91 Ksi $\sqrt{\text{in.}}$ (or correspondingly a K_{max} level of about 34 to 101 Ksi $\sqrt{\text{in.}}$ based on an $R=P_{\text{min}}/P_{\text{max}}$ of 0.1). Thus, knowledge of ΔK (or K_{max}) based on dC_3/dN (AE rate) alone could permit a reactor operator to estimate severity of the AE source with respect to a limiting value of K_{max} .

This conclusion appears to be viable because the data generated thus far indicates that, within some reasonable bounds, knowledge of crack size is not necessary. Based on Equation 1, rate of change of flaw size dominates the production of AE.

Figure 1. Composite Plot of AE Count per Cycle ($\frac{dC_3}{dN}$) vs Fatigue Crack Growth Rate ($\frac{da}{dN}$) for Three Fatigue Tests, $R=0.1$, 3 Hz.

Figure 2. Fatigue Crack Growth Rate ($\frac{da}{dN}$) vs Stress Intensity Factor Range (ΔK) for Three Fatigue Specimens, $R=0.1$, 3 Hz.

Even if crack size should be determined to influence AE in addition to crack growth rate, the basic method described still remains a viable means for evaluating flaw severity. The AE monitoring method should be able to detect and locate growing cracks as being within a definable volume. Finite element stress analysis techniques coupled with known vessel design load ranges in the crack vicinity and an AE estimate of K from Equations (1) and (2) can allow estimation of crack size through the generalized stress intensity factor equation,

$$g(a) = \frac{K_I}{h(\sigma, \phi)} \quad (3)$$

where, $g(a)$ = flaw size parameter

K_I = opening mode stress intensity factor derived from AE, and

$h(\sigma, \phi)$ = governing stress field parameter (σ) and shape factor (ϕ) which are estimable values.

Thus we feel that the above discussion demonstrates that it is possible to make a useful estimate of flaw severity using only the AE generated by that flaw. We realize that there are elements in the model that must obviously be further defined. These include:

- Confirmation of the influence of crack size and shape on AE-flaw relationships. Different flaw geometries will be investigated. (The data used herein was derived from a through-wall crack. Some of our past work has suggested that flaw geometry is not significant. This, however, needs to be confirmed.)
- The effect of load-cycle rate on AE generated during fatigue crack growth. This is needed to translate from a load cycle (da/dN) basis to a time (da/dt) basis for reactor application. Definition of load cycles in the sense used here for rate determination would be difficult to establish on a reactor.
- The effect of R ratio on AE. Data used in this discussion was based on an R ratio of 0.1. On a reactor, outside of startup and shutdown, R ratios may be more in the order of 0.5 to 0.7.

- The data scatter needs to be reduced. There is encouragement that this may be improved by more specialized data acquisition methods such as rise time and amplitude discrimination.
- The effect of material thickness on detected AE. The data used was measured for specimens 1/2 to 1-3/4 in. thick.

All of the above items are being addressed to at least a limited degree in ongoing work planned.

One final aspect of this feasibility evaluation which must be considered is AE data acquisition from a reactor on a long-term basis. It can be safely stated that instrumentation and electronic technology is available now to perform any necessary data processing once the AE signal analog is acquired out of a sensor. The sensor subsystem (sensor, sensor mounting device and sensor-to-vessel wall acoustic coupling method) is the critical part of an on-reactor AE data acquisition system. Development of a sensor subsystem suitable for long-term application on a reactor has been a continuing problem. Progress has been achieved, however:

- Metal waveguides - either pressure coupled or metallurgically bonded to the vessel surface - offer one possible answer to the problem. This technique has been demonstrated in the laboratory and in the Edison Electric Institute AE experimental program on the EBOR reactor vessel to be capable of detecting AE under thermal conditions equal to and in excess of light water reactor conditions. Waveguides have the disadvantages of signal distortion and they would be a bothersome protrusion from the wall of a vessel.
- One manufacturer of a commercial sensor which is surface mounted, pressure coupled, claims about five years of on-reactor exposure with no functional degradation of the sensor. Unfortunately, the supporting data is not publicly available. Until it is, this cannot be considered a solution to the problem.

- One part of this program is concerned with making available a sensor subsystem suitable for reactor monitoring. This includes developing a new sensor, if necessary.

Thus, the sensor subsystem is the critical part of an on-reactor data acquisition system. One method of performing the function (metal waveguides) is available and there is encouragement that a surface mounted sensor without the disadvantages of waveguides can be made available in the next one to two years.

In summary, the successful development of analytical relationships between fatigue and AE parameters indicate that it should be feasible to assess the significance of a detected flaw in an operating reactor vessel by AE alone.

3.0 DISCUSSION

This section covers a description of the test material and specimens, instrumentation, test results and analysis of the AE-fracture mechanics data. All topics in the FY-77 program brief are included.

3.1 MATERIAL AND TEST SPECIMENS

A533B Class 1 material for this program came from two sources: the Heavy section Steel Technology (HSST) program of Oak Ridge National Laboratory and Lukens Steel Company of Coatesville, Pennsylvania. A small amount of 1-1/2 inch thick Class 2 A533B material was available at PNL. The Class 2 A533B material was originally purchased from Lukens Steel.

The HSST material was 6x20x23 inches with a weldment through the thickness running parallel to the 23-inch dimension at the midpoint of the 20-inch dimension (see Figure 3). Details on the material and welding conditions may be found in Reference 1. Primary program material (8-1/4 inches thick) was received from Lukens Steel and Tooling Specialists, Inc. machine shop beginning August, 1977. Chemical analysis, physical properties, Charpy impact, drop weight transition curve data and heat treatment information are found in Reference 2.

To obtain HSST material tensile specimens, a piece 6 inches wide by 6 inches thick by 20 inches long was band-saw cut from the original block (Figure 3). Next, approximately one inch thick slabs, designated A-1 and A-2, were removed from the top and bottom "skin" surfaces. Hardness measurements were taken in the base and weld metal region of each slab across their 6 inch width. Slab A-2 base metal and weld metal hardness averaged Rockwell "B" 93 and 90, respectively. Slab A-1, from the surface opposite Slab A-2, had base and weld metal hardnesses that both averaged R_B-91. Fifteen measurements were made for each base and weld metal configuration. The respective levels of hardness indicates relatively little difference in tensile strength between base and weld metal for both slabs.

Figure 3. Cutting Diagram for Tensile Specimen Blanks - HSST Material.

The tensile specimen blanks were cut from the slabs as shown in Figure 3. The axis of all the HSST tensile specimens were perpendicular to the weld axis. Weldment tensile specimens were centered on the 1.4 inch minimum width weld so the entire 1/4 inch diameter by 1-1/4 inch long reduced section (Figure 4) contained weld metal. The base metal specimens were parallel to the weld metal specimen but offset from the weld so the reduced section contained base metal only; the weld metal section was thus displaced into one of the thick shank sections of the specimen.

AE sensors were mounted on the flats of the tensile specimen shanks (Figure 5). With this arrangement, the system could limit accepted data to only that from the test section.

Four 1-3/4 inch thick size 2 compact tension specimens (2T-CT) were also removed from the HSST material. First another piece of 5-3/4 inch wide by 20 inches long was bandsaw cut from the original 6x20-23 piece (Figure 3). The 6x5-3/4x20 slab was bandsaw cut (with the weld parallel to the 5-3/4 inch dimension at the midpoint of the 20" dimension) into three slabs each about 1-3/4 inch thick by 5-3/4x20 (Figure 6). Two specimens each were removed from the outer or "skin" slabs. The central or "core" slab was stored for future use.

All the 2T-CT specimens were oriented such that the notch was parallel to the weld. For specimens B2-1A and B2-3A, the notch was centered within the approximately 1.4 inch (minimum) width weld. For specimens B2-1B and B-23B, the notches were entirely removed from the weld (see Figure 6).

AE sensors were located at those specimen corners most remote from the loading holes (Figure 7). The AE system was adjusted to accept signals only from a narrow strip (approximately 1/2 inch wide) parallel to and including the notch region.

A single notch (SEN) specimen (Figure 8) 1-1A-2A, 9x41 inches with a 1/2 inch thick test section was removed from the 8-1/4 inch thick Lukens A533B Class 1 plate. The specimen was machined from the outer or "skin" region as shown on Page A-9 of Reference 2 with its longitudinal axis parallel to the plate rolling direction. The specimen was stress relief

Figure 4. Acoustic Emission Tensile Specimen.

Figure 5. Acoustic Emission-Tensile Specimen Setup.

Figure 6. Cutting Diagram - Size 2 Compact Tension Specimens - HSST Material.

Figure 7. Acoustic Emission - Compact Tension Specimen Test Setup.

Figure 8. Single Edge Notch (SEN) Plate Specimen, 3% Pre-Strain.

annealed at $1150^{\circ}\text{F} \pm 25^{\circ}\text{F}$ for 40 hours and lightly grit-blasted to remove any oxide layers which might act as spurious sources of AE. Prior to notching, the $1/2 \times 5 \times 18$ inch reduced section was pre-strained 3% (see Figure 9) to simulate shakedown strain that might occur in a pressure vessel during hydrotesting. In Figure 9, the sensors are located remote from the central region of the specimen where the notch was subsequently located for fatigue crack growth testing.

Details concerning mechanical test procedures are presented in Appendix A.

3.2 INSTRUMENTATION AND TEST SYSTEMS

The primary AE measurement system is shown in Figure 10. It is made up of a Battelle built digital memory, multiparameter AE monitor with source isolation, a Biomation 8100 transient wave analyzer, a Tektronix X-Y oscilloscope for wave form display, and a Hewlett-Packard frequency spectrum analyzer. The AE monitor unit measures seven parameters (five AE parameters and two mechanical parameters) simultaneously and records information on solid state digital memories. Acceptance of AE signals is controlled by a source isolation feature which restricts accepted signals to only those originating from a predetermined source area. The source isolation circuit also controls which signals the transient wave analyzer will make available for display and spectral analysis. The AE measurement system is discussed in greater detail in two previous progress reports^(1,2). The key features are:

- ° source isolation which has proven very valuable in separating flaw growth AE from other similar acoustic signals generated by the physical testing system.
- ° digital memory recording which greatly facilitates data analysis by making possible a single direct numeric readout with all parameters directly related.

A Dunegan/Endevco (D/E) Model 920 commercial laboratory AE laboratory AE monitor was rented for two months to check performance of the primary system. The D/E 920 provided one parameter (AE event count) which could be

Figure 9. Test Setup for 3% Pre-Strain Plate Specimen.

FIGURE 10. Acoustic Emission Analysis System

directly compared with the BNW digital memory system. The need for such a check arose from concern over a virtual absence of AE from smooth tensile specimens. The D/E system consisted of:

- 1 - Model 920 distribution analyzer with power supply.
- 1 - Model 302A dual amplifier.
- 2 - Model 1801 preamplifier.
- 2 - Model 5140B/LP AE sensor.

The D/E 920 system generally showed fewer signals from the tensile specimen gauge section than did the BNW system for similar sensitivities - i.e., on one smooth tensile, the BNW count was 9 compared to the D/E 920 count of 3 and on a notched tensile, the BNW count was 192 compared to the D/E 920 count of 142. With such relatively small count totals, an absolute comparison of numbers is less important than the fact that they are of the same order of magnitude. These differences in absolute magnitude could be attributable to somewhat different circuitry and method involved in source discrimination. After comparing the two systems on six tensile tests, it was concluded that the BNW system was performing satisfactorily and that the low count from smooth tensile specimens was indeed legitimate.

In addition to the above systems, an NRC owned D/E 1032 computerized AE monitor system is available for use on this program. This is a 28 channel system with an integral minicomputer for data processing to produce point source location, AE event count and AE count data in both a visual display and a printout form. The system utilizes four-sensor arrays. This unit is designed primarily for monitoring relatively large structures such as pressure vessels. It is adaptable, however, to monitoring smaller test objects as discussed in a later section on "HSST Tests."

A method has been developed for rating the sensitivity of a complete AE monitor system. The rating is in terms of sensor front face pressure, in μ bar, required to produce a signal detectable by the monitor system. We call this "Effective Sensitivity." It takes into account sensor sensitivity, system gain and detection threshold. The purpose of such a rating is to

make results from this program relate to other AE monitor systems and tests. To illustrate, assume a monitor system operating with a total gain of 90 dB, a detection threshold of 1.5 volts peak, and sensor with an absolute sensitivity calibration of -65 dB re 1 volt/ μ bar in the frequency range being monitored. The minimum input voltage to the system from the sensor that the system would respond to is $\frac{1.5 \text{ volts}}{90 \text{ dB gain}}$ of 47 μ volts. Considering the sensor, it should produce 1 volt/ μ bar or 562 μ volts/ μ bar of front face pressure. If we now compare these two values, the total system should respond to $\frac{47}{562}$ or 0.08 μ bar pressure on the front face of the sensor. Thus 0.08 μ bar is called the effective sensitivity of the measurement system.

3.3 RESULTS

This section covers results of work conducted on 15 tensile tests, 3 fracture tests, 2 HSST tests, 3 fatigue crack growth tests and high temperature AE sensor evaluation. For purposes of continuity, the HSST tests are discussed and analyzed separately from the other tests which were conducted at PNL.

3.3.1 Tensile Tests

Fifteen tensile specimens (Figure 4) were tested as shown in Table 1. All were 0.250 inches diameter (nominal) except for heat treated specimens which required further reduction in gauge section area to assure that specimen maximum loads did not exceed the capacity of the Instron test machine.

Thirteen of the specimens were removed from the outer or "skin" surface material of which 4 included the HSST weldment in the gauge section. The remaining 2 were removed from the core or mid-thickness region of the 6-inch thick HSST material. One specimen was notched to about 0.005 inch maximum root radius. One specimen was heat treated to Rockwell "C" (Rc) 45-46 to investigate the effect of hardness (strength) on AE. Please note that this was improperly noted as Rc 52 in Reference 2. One base metal specimen was tested at 550°F (nominal). All of the unnotched tensile specimens were characterized by a relatively small amount of AE (1 to 25 event count with the average around 7 count per specimen). Some of the few AE event

TABLE 1
AE - TENSILE TEST DATA

Specimen No.	Material Condition	Test Temp (°F)	Notch Condition	Initial Crosshead Velocity (in/min)	Final Crosshead Velocity (in/min)	Σ Valid AE Count	Σ Total AE Count	Comments
A-1-5	SW (1)	RT	UN	0.002	0.02	5	258	
AA-1-1	CW (1)	RT	UN	0.002	0.02	10	236	
AA-2-1	CB (1)	RT	UN	0.002	0.02	25	710	
AET-21	SB (3)	RT	UN	0.002	0.02	6	-	
AET-25	SB (3)	RT	N	0.002	0.002	192	-	High count due to notch
AET-19	SB (3)	RT	UN	0.002	0.02	907	-	Heat treat-induced longitudinal defect in gage section
AET-22	SB (3)	RT	UN	0.002	0.002	7	-	Heat treated to Rc 45-46
A-1-4	SW (1)	RT	UN	0.002	0.02	11	158	
A-1-1	SW (1)	RT	UN	0.002	0.02	5	-	
AET-23	SB (3)	RT	UN	0.002	0.02	19	-	
AET-10	SB (3)	RT	UN	0.002	0.02	1	-	
A-2-2	SB (1)	RT	UN	0.002	0.02	1	-	AE Threshold decreased during test
A-2-3	SB (1)	RT	UN	0.002	0.02	1	296	
A-2-1	SB (1)	550	UN	0.02	0.02 and 0.0005	4(51)	-	() count due to crack-ing of cou-plant
5A-5-3	SB (2)	RT	UN	0.002		-	-	To determine mech props for prestrain of specimen

SW = Skin weld
SB = skin base
CW = core weld
CB = core base

RT = Room temperature
UN = Unnotched
N = Notched
(1) = 6" thick HSST material

(2) = 8 1/4" thick primary material
(3) = BNW CL 2 material

counts occurred around small, relatively uniform load drops following yielding, some around load increases associated with increasing heat travel rate. Some appeared during straining in elastic and plastic regions where the load was changing uniformly. Cross-head travel rates ranging from 0.0005 inch/minute to 0.02 inch/minute had no apparent effect on the few counts that were produced. It should be noted that no discontinuous or serrated yielding occurred in any of the specimens. The gauge section surfaces were also machined to an 8 μ inch finish to assist in detecting Luders bands, none of which were seen.

Differences in metallurgical condition, namely, Class 1 versus Class 2 material, skin versus core and base metal versus weld metal, hardness R_C 45-46 versus R_B 85-95, had no apparent affect in the small amount of AE event count that was produced. Testing at 550°F also had no significant affect on AE. It should be noted, however, that only one specimen was tested at an elevated temperature level.

Figure 11 is characteristic of all unnotched tensile-AE data. Eleven AE event counts occurred during the test. Most notable, however, is the amount of acoustic signals (158) originating outside the gauge section and which is detected by one of the pair of AE sensors. Generally, the acoustic noise, which was probably produced by the threaded grips, exceeded gauge section AE by a factor of about 15 to 20, and as high as about 300 in one test. This strongly points out how AE data can be masked and severely distorted by acoustic noise.

Figure 12 shows that increasing the yield and ultimate strength about a factor of 3 by heat treatment (R_C 45-46) caused no apparent change in AE over lower strength, quenched and tempered Class 2 material (R_B 85-95). Introduction of a notch can also increase the apparent yield and ultimate stress about a factor of 2 in Class 1 material, as shown in Figure 13. Now, however, AE is increased significantly by the presence of the notch (192 AE event count). AE diminishes rapidly after general yielding of the notch region, suggesting that the high strain gradient at the notch root and subsequent growth of a crack tip plastic zone through elastically strained material

Figure 11. AE from Tensile Test A1-4, Skin Weld Metal, A533B Room Temperature.

Figure 12. AE from Test AET-22, Skin Base Material, A533B Heat Treated to Rockwell C 45-46.

Figure 13. AE from Notched Tensile Test AET-25, A533B Material, Room Temperature.

could be responsible for the rapid increase in AE rather than the strength increase due to the notch. However, this result represents only one test. Metallurgical examination will be done to determine if an abnormal AE source existed at or near the notch.

Figure 14 gives assurance that the above AE results were not simply an instrument effect. A commercial system (Dunegan/Endevco 920) was rented and operated in parallel with the BNW source isolation system. Results from the two systems were quite similar. This was true for six of the tests that were monitored by both systems.

The largest amount of AE or possibly acoustic noise was produced by a heat treatment-induced axial or longitudinal flaw in the gauge section of a tensile specimen (AET-19). The flaw was not detected until the specimen was fractured. The specimen produced 907 AE event count primarily after the maximum load had been reached. The AE or noise was apparently produced by Poisson-induced rubbing of the flaw surfaces as the gauge section diameter and length were changing rapidly in the region of the longitudinal flaw.

In summary, the results of AE tensile tests show that within the range of conditions studied and in the absence of notches, AE is relatively unaffected by microstructure, temperature and strength level. No apparent difference was seen between skin base and core base metal, skin weld and core weld metal, Class 1 and Class 2 material, and Class 2 material heat-treated to $R_c 45-46$, cross-head travel rate and temperature. The presence of a notch in a tensile specimen gauge section dramatically increased AE. It may be due to a high strain gradient associated with the flaw and subsequent growth of the flaw plastic zone into elastically strained material, but this must be verified by metallurgical analysis. Examination of the effect of K_t on AE should be considered in the future to determine K_t threshold level for AE production.

3.3.2 Fracture Toughness Tests

Fracture toughness tests were conducted on three 1.75 inch thick 2T-CT specimens. Two specimens, B2-1B and B2-3B, were removed from "skin" HSST base metal (Figure 6). Specimen B2-3A was removed from the same "skin" material but included the 1.4 inch minimum width weld within the notched

AE MONITOR SENSITIVITY
 BNW SYSTEM - 0.1 μ bar
 D/E 920 SYSTEM - 0.06 μ bar

Figure 14. Comparison of AE Response for BNW Digital Monitor and Dunegan/Endevco 920 System, Specimen AET-25.

region. Specimens B2-3A and B2-3B were fatigue pre-cracked as shown in Table 2. Loads were decreased during cycling so that $\frac{\Delta K_f}{E}$ was less than $0.0012 \text{ in}^{1/2}$ when the crack length reached an a/W ratio of about 0.5.⁽³⁾

Specimen B2-1B had undergone fatigue crack (FCG) testing (see next section) prior to fracture. Thus da/dN and ΔK were higher at completion of FCG testing than were the two specimens that were only fatigue-precracked. Details on test procedure are included in the appendix.

The AE isolation system was used during the fracture tests. Non-isolated or total acoustic signals detected by one of the sensors was also recorded. AE data along with load are plotted against time for the three fracture toughness tests in Figures 15, 16 and 17.

With the geometry of the CT specimen, to avoid noise produced by the pins during loading, the isolation system was set to accept only those signals from an area about 3/8 of an inch wide centered on the crack plane. The region of acceptance was minimized to avoid including pin noise. In test B2-3B (Figure 15), it appears the accept zone was too narrow, because the "pop-in" is not reflected in the valid data. In this case, the valid data must be considered suspect. Two different geometries of the plate tension specimens (Figure 8) which will be used in subsequent testing eliminate the need for such stringent zone isolation.

Test B2-3B data in Figure 15 shows a rapid, almost linear increase in total AE early in the test leveling off at a point between the initial fatigue precracking load and general yielding. After "general yielding", both total and valid AE count increase slowly although the total AE count is increasing more rapidly. It is plotted on a scale 25 times as coarse as the valid event count. A ductile crack is estimated to be beginning to grow within 2 to 4 minutes into the test. Around 6-3/4 minutes a large "pop-in", or probably cleavage crack extension, occurs which is readily detected by a single sensor but is seen to be only several counts by the isolation system. Because of a timing error in the system, the load and total AE count system are thought to be out of phase. Thus, it is possible that the increase in total AE count may not have preceeded the large load drop as much as indicated; Palmer⁽⁴⁾ noted in his work on reactor pressure vessel steel that

TABLE 2

2T-CT FATIGUE LOADING CONDITIONS PRIOR TO FRACTURE AE

Spec No	Load		Average Crack Length Inches	Load Cycles (N)
	P _{max} (Kips)	P _{min} (Kips)		
B2-3A	21	2.1	1.20	0
	21	2.1	1.60	49,990
	17	1.7	1.60	49,990
	17	1.7	1.80	69,270
	14	1.4	1.80	69,270
	14	1.4	1.90	81,340
	11.6	1.16	1.90	81,340
	11.6	1.16	2.00	97,490
B2-3B	21	2.1	1.20	0
	21	2.1	1.60	63,610
	17	1.7	1.60	63,610
	17	1.7	1.80	85,160
	14	1.4	1.80	85,160
	14	1.4	1.90	107,480
	11.6	1.16	1.90	107,480
	11.6	1.16	~2.00	124,210

Figure 15. Fracture Test B2-3B Data - Base Metal.

Figure 16. Fracture Test B2-3A Data - Weld Metal.

Figure 17. Fracture Test B2-1B Data - Base Metal.

an increase in AE accompanied but did not precede rapid load drops.

In general, the 2T-CT fracture toughness tests show an AE event count behavior that is dominated primarily by plastic flow and ductile crack extension. Increasing amounts of valid AE occurred during slowly decreasing loading where ductile crack extension is the dominant fracture mechanism. Further work is necessary to clarify the nature of these effects.

3.3.3 HSST Tests

PNL participated in two HSST tests during FY-77, both of which were performed at Oak Ridge, Tennessee. The first of these was a thermal shock test (TSE-4) performed 1/19/77.⁽⁵⁾ The digital memory AE monitor system was used. 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 with predicted crack growth initiation.⁽⁵⁾
- ° 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.

The second test monitored was the V-7B intermediate vessel test on 7/14/77.⁽⁶⁾ The vessel consisted of a 54" long cylindrical test section 39" OD x 27" ID closed on one end by a welded hemisphere and a bolted flange on the other end. Material was ASTM A533 Grade B, Class 1 steel. This test involved a machined defect in the heat affected zone of a repair weld made in accordance with ASME Boiler and Pressure Vessel Code, Section XI.

There were two purposes in monitoring AE:

1. To provide real-time information to the test manager of any notable indications of distress in the vessel at locations other than the machined defect;

2. To acquire AE data for analysis relevant to development of AE/ flaw relationships for in-service reactor monitoring.

Two AE monitor systems were used to more effectively meet the two requirements. A Dunegan/Endevco (D/E) 1032 computerized monitor system (Figure 18) which provides point source location and a count of all AE signals received was used in support of the first objective. This system should be capable of detecting AE from any point in the vessel. The BNW multi-parameter digital memory AE monitor (Figure 19) was used to achieve the second objective. This unit measures five AE parameters (total event count and valid event count, energy, rise time and amplitude) plus a mechanical parameter (vessel pressure) simultaneously and stores the information in the digital memories. By means of a source isolation feature, "valid" signals are restricted to those originating from a predetermined area - in this case, the vicinity of the machined defect. Total event count is a count of all acoustic signals detected without limitation by source isolation.

Procedure. Location of the AE sensors on the test vessel is shown in Figures 20 and 21. Installed instrumentation prior to test is shown in Figure 22. Pressure coupled metal wave guide sensors 8 inches long were used with the D/E 1032 system and surface mounted PZT-5 sensors were used with the BNW system. Since the function of the D/E 1032 system was only to detect and locate AE sources, wave guide sensors with the attendant potential for wave form distortion were chosen for insurance against temperature effects. The vessel surface was about 200°F. Wave form is more critical to the BNW system for comparison with lab specimen data. Sensor calibration curves in Figure 23 were generated in the laboratory with the sensors mounted on a 12 inch x 12 inch x 6 inch steel block and using alumina grit blast excitation.

The AE sensors were connected to preamplifiers located within 15 inches of each sensor. Output of the preamplifiers connected to the monitor systems through cables about 100 feet long.

The ASME Guide for Acoustic Emission Examination During Application of Pressure was followed in setting up the instrument systems preparatory to testing. An electronic pulser was used to inject acoustic signals into the

FIGURE 18. D/E 1032 AE Monitor System

FIGURE 19. BNW AE Monitor System

FIGURE 20. Acoustic Emission Sensor Location HSST V-7B Test

FIGURE 21, AE Sensor Mounts on HSST V-7B Vessel

FIGURE 22. Installed AE Sensing
Instrumentation on HSST
V-7B Vessel

FIGURE 23. AE Sensor Calibration for HSST V-7B Test

vessel wall. The artificial signals served the functions of first verifying that the AE monitor systems were working and then to provide a reference for setting system gains and/or detection thresholds.

Source location accuracy of the D/E 1032 system was tested using the electronic pulser. The ASME Guide calls for the accuracy to be within 5% of the maximum distance between the affected sensors. This would be $.05 \times 28$ or ± 1.4 inch in the subject test. The maximum deviation was 2.0 inches and the average for ten signals was 1.2 inch.

The BNW digital system does not perform point source location. It selects AE signals on the basis of the indicated source being within a preselected area. The pulser was used to verify the source isolation zone limits.

Results. Tabulated AE data is summarized in Tables 3 and 4. Table 3 gives data produced by the BNW digital system with associated vessel pressure. Similarly, Table 4 shows data from the D/E 1032 system and corresponding crack-opening-displacement (COD) values. The column headed "Flaw Area" shows count from Array 0 which was associated with the flaw by the source coordinates given in the computer printout. The "All Array 0" shows the total count for Array 0 which encompassed the flaw. Array 1 showed only limited scattered indications and is ignored for analysis. Vessel pressure is a common parameter for cross correlating information in the two tables. It is evident that the total AE event count from the D/E system is roughly one third that from the BNW system. This is reasonable on the basis that the D/E system was purposely set up with about one-half the sensitivity of the BNW system. It was desirable to operate the BNW system with sensitivity similar to that used in laboratory specimen testing to facilitate data comparisons. This, however, made it relatively subject to possible problems with unexpected vessel test system noise. With this in mind, it was decided to make the D/E system less sensitive to minimize the possibility of total loss of AE data in the event that a noise problem did arise. In actuality, both systems operated without any problem.

TABLE 3

HSST V-7B Vessel Test
BNW Digital System AE Data

Press. Psig	Total Valid AE	Rise Time - usec.				Signal Amp. - Volts				Total Energy
		<1	1-5	5-10	>10	<1.3	1.3-2.5	2.5-5	>5	
PHASE 1										
0	0	0	0	0	0	0	0	0	0	0
1,000	13	6	5	1	1	7	4	1	1	1,736
2,000	21	11	7	1	2	12	4	3	2	3,247
3,000	64	33	20	8	3	34	15	6	9	9,241
4,000	126	78	31	12	5	79	21	9	17	17,111
5,000	221	128	65	22	6	136	34	27	24	29,776
6,000	324	180	100	30	14	197	46	46	35	41,665
7,000	421	228	127	45	21	255	58	62	46	54,687
8,000	516	278	159	57	22	301	73	81	61	67,318
9,000	665	369	194	70	32	389	89	102	85	84,216
10,000	782	430	230	87	35	455	97	125	105	99,168
10,500	821	448	239	98	36	475	102	135	109	103,945

PHASE 2

0	0	0	0	0	0	0	0	0	0	0
5,000	10	6	4	0	0	6	2	1	1	1,401
8,000	18	10	6	1	1	10	2	4	2	2,274
9,000	34	18	13	1	2	18	3	8	5	4,620
10,000	46	23	19	2	2	27	4	10	5	6,497
11,000	113	48	49	14	2	51	15	35	12	15,015
12,000	169	74	68	20	7	83	19	41	26	22,244
13,000	223	94	97	24	8	109	31	52	31	29,134
14,000	313	137	129	36	11	157	43	69	44	41,027
15,000	406	184	162	48	12	205	56	85	60	49,690
16,000	491	223	190	64	14	250	64	107	70	60,170
17,000	593	276	226	72	19	306	77	129	81	73,884
18,000	699	329	262	79	29	362	95	153	89	86,479
19,000	819	386	306	92	35	419	108	181	111	101,511
20,000	905	428	338	100	39	463	119	194	129	111,200
20,500	955	445	359	111	40	483	126	206	140	117,014
21,000	1,067	491	407	126	43	534	137	228	168	130,307
21,500	1,232	552	478	149	53	599	152	268	213	150,091
21,750	1,555	734	594	165	62	779	183	321	272	195,050
Failure	1,788	862	672	183	71	898	209	366	315	219,945

TABLE 4

HSST V-7B Vessel TestD/E 1032System AE Data

Press. Psig.	COD - Mils			AE Event Count	
	ZT-127	ZT-128	ZT-129	Flaw Area	All Array 0
<u>PHASE 1</u>					
0	1.00	0.50	1.00	0	0
1000	3.00	4.00	3.00	0	1
2000	6.00	8.00	6.00	1	3
3000	8.50	12.00	8.50	7	13
4000	11.50	16.49	11.50	14	26
5000				30	52
6000	17.49	25.49	17.49	51	87
7000	20.49	29.99	20.99	62	105
8000	24.49	35.99	24.99	81	118
9000	28.99	42.48	29.49	119	147
10000	29.99	43.98	30.49	157	231
10500	35.49	50.98	35.99	171	250
<u>PHASE 2</u>					
0	10.50	11.50	11.0	0	0
8000	28.99	41.48	29.99	1	1
9000	30.99	44.98	32.49	2	2
10000	33.99	48.98	34.99	5	9
11000	36.99	53.48	37.99	9	15
12000	42.98	61.98	44.48	58	70
13000	49.48	70.47	50.98	68	82
14000	56.48	79.97	58.49	93	114
15000	65.98	91.97	69.47	125	152
16000	75.97	104.46	80.47	145	178
17000	86.97	118.46	92.97	165	200
18000	99.46	133.95	107.96	195	232
19000	116.96	153.94	127.45	228	269
20000	135.95	175.94	148.45	264	327
20500	143.45	183.93	155.44	288	353
21000	164.94	205.42	175.94	343	429
21500	196.93	236.41	204.92	394	498
21750	229.92	267.90	235.41	519	666
Failure	339.38	307.89	334.38	556	711

A plot of AE count and vessel pressure vs. test time for each set of data is shown in Figures 24 and 25. In addition to the fact that the AE count parallels the pressure curve quite well, there are two other features in Figures 24 and 25. Going from Phase 1 into Phase 2, the influence of the Kaiser Effect is evident. In Phase 2, AE activity does not reappear to any degree until vessel pressure exceeds that of Phase 1. This is an AE phenomenon associated with repeat loading within the grossly elastic range to the same stress level where most of the detectable AE will be generated in the first load cycle. Dr. Kaiser in Germany first identified this in the early 1950's. Since that time, evidence has been gathered to show that the phenomenon is reversible under appropriate time and temperature conditions. Also, the effect does not hold with repeated loading to the extent that fatigue damage develops.

The other feature to note in Figures 24 and 25 is the sharp increase in AE as vessel failure at the flaw is approached. This provides a finite warning of impending failure. The detailed data shows that both systems showed the increase in AE at the same point - as the pressure exceeded 21,250 psig.

The visual display of AE source location indications on the D/E 1032 CRT screen relative to pressure increments is shown in Figures 26-33. These were generated by replaying test data from a digital cassette tape. Authenticity of the recorded data was verified by comparing the accompanying printout with the real-time printout from the test. The COD shown in the lower left corner of these illustrations is the increase in COD during a given pressure increment compared to the previous condition. Comparing Figures 26 and 27, the Kaiser Effect discussed previously is very evident. The same pressure range is involved with the second pressurization occurring within about 30 minutes of the first. The second pressurization produced very few AE indications.

The primary significance of Figures 26-33 is to demonstrate AE response to flaw development. Up to 18,000 psig, most of the AE is coming from the center section of the flaw. This AE could be evidence of plastic zone growth

FIGURE 24. AE and Pressure vs Test Time -
 HSST V-7B Vessel Test -
 BNW Digital AE System

FIGURE 25. AE and Pressure vs Test Time -
 HSST V-7B Vessel Test -
 D/E 1032 AE System

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 1
 PRESSURE RANGE
 0 TO 10,500 psig

COD SENSORS

FIGURE 26. HSST V-7B Test AE,
 Phase 1, 0-10,500 psig

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 2
 PRESSURE RANGE
 0 TO 10,500 psig

COD SENSORS

FIGURE 27. HSST V-7B Test AE,
 Phase 2, 0-10,500 psig

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 2
 PRESSURE RANGE
 10,500 to 15,000 psig

COD SENSORS

FIGURE 28. HSST V-7B Test AE,
 Phase 2, 10,500 - 15,000 psig

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 2
 PRESSURE RANGE
 15,000 TO 18,000 psig

COD SENSORS

FIGURE 29. HSST V-7B Test AE Phase 2, 15,000-18,000 psig

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 2
 PRESSURE RANGE
 18,000 TO 20,000 psig

COD SENSORS

FIGURE 30. HSST V-7B Test AE Phase 2, 18,000-20,000 psig

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 2
 PRESSURE RANGE
 20,000 TO 21,000 psig

COD SENSORS

FIGURE 31. HSST V-7B Test AE, Phase 2, 20,000-21,000 psig

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 2
 PRESSURE RANGE
 21,000 TO 21,750 psig

COD SENSORS

FIGURE 32. HSST V-7B Test AE Phase 2, 21,000-21,750 psig

HSST VESSEL V-7B TEST
 AE SOURCE LOCATION
 D/E 1032 SYSTEM
 PHASE 2
 PRESSURE RANGE
 21,750 TO FAILURE psig

COD SENSORS

FIGURE 33. HSST V-7B Test AE, Phase 2, 21,750-Failure psig

or crack extension or possibly both in the ligament region. As the pressure increases above 18,000 psig, the AE indications begin to move to the outer ends of the flaw. The last two photographs (21,000 - 21,750 and 21,750 - Failure) show evidence of potential crack extension from the ends of the flaw. Figure 34 shows that this did occur.

AE signal waveforms processed by the BNW system were obtained with an associated transient wave analyzer and oscilloscope. Samples of these are presented in Figure 35. An important observation is the fact that these are generally similar to AE signal waveforms observed during testing on laboratory specimens of the same type of material. This tends to lend credence to the usefulness of laboratory data in developing preliminary AE-fracture mechanics relationships for application to heavy section vessels. Signal No. 8 (Figure 35) is considered to be a noise signal from an unidentified source. It is classified as a noise signal on the basis of the gradual increase in amplitude without any sharply defined signal front. This is the type of signal observed previously from known noise sources such as movement at the interface of two metal objects. One noticeable difference between these signals and those observed from laboratory specimens is the predominance of lower frequency components (~ 300 kHz) in the signals from the vessel test. Signals from laboratory specimens show higher frequency components as well as the lower frequency. This is probably a combination of the influence of high frequency signal attenuation in the longer travel path in the vessel material and electronic system characteristics.

Analysis. The results are discussed in terms of relating AE to stress intensity factor and to COD.

Pressure levels, calculated stress intensity factors and AE data obtained during burst testing of vessel V-7B are given in Table 5. Note that the BNW AE event count is partitioned into signals of four different ranges of rise times (<1 , 1 to 5, 5 to 10 and >10 μ sec) and four different ranges of amplitudes (<1.3 , 1.3 to 2.5, 2.5 to 5 and >5 volts).

FIGURE 34. HSST V-7B Vessel Failure at Machined Flaw.

FIGURE 35. Sample AE Signals - HSST V-7B Vessel Test

TABLE 5. Acoustic Emission and Fracture Mechanics Data on HSST Vessel V-7B Burst Test*

Press. psig.	K_I ksi $\sqrt{In}$.	Total Valid AE	BNW AE COUNT								BNW Energy	D/E AE Count	
			Rise Time - μ sec				Signal Amp. - volts					Flaw	Total Array
			<1	1-5	5-10	>10	<1.3	1.3-2.5	2.5-5	>5			
0	0	0	0	0	0	0	0	0	0	0	0	0	
1,000	14.45	13	6	5	1	1	7	4	1	1	1.736	0	1
2,000	28.90	21	11	7	1	2	12	4	3	2	3,247	1	3
3,000	43.35	64	33	20	8	3	34	15	6	9	9,241	7	13
4,000	57.80	126	78	31	12	5	79	21	9	17	17,111	14	26
5,000	72.25	221	128	65	22	6	136	34	27	24	29,776	30	52
6,000	86.70	324	180	100	30	14	197	46	46	35	41,665	51	87
7,000	101.2	421	228	127	45	21	255	58	62	46	54,687	62	105
8,000	115.6	516	278	159	57	22	301	73	81	61	67,318	81	116
9,000	130.1	665	369	194	70	32	389	89	102	85	84,216	119	178
10,000	144.5	782	430	230	87	35	455	97	125	105	99,168	157	231
10,500	151.7	821	448	239	98	36	475	102	135	109	103,945	171	248
11,000	159.0	854	460	254	104	36	487	107	147	112	108,204	173	251
12,000	173.4	910	486	273	110	41	519	111	153	126	115,433	222	306
13,000	187.9	964	506	302	114	42	545	123	164	131	122,323	232	318
14,000	202.3	1054	549	334	126	45	593	135	181	144	134,216	257	350
15,000	216.8	1147	596	367	138	46	641	148	197	160	142,879	285	383
16,000	231.2	1232	635	395	154	48	686	156	219	170	153,359	307	412
17,000	245.7	1334	688	431	162	53	742	169	241	181	167,073	329	430
18,000	260.1	1440	741	467	169	63	798	187	265	189	179,668	354	462
19,000	274.6	1560	798	511	182	69	855	200	293	211	194,700	387	500
20,000	289.0	1646	840	543	190	73	899	211	306	229	204,200	425	558
20,500	293.2	1696	857	564	201	74	919	218	318	240	210,203	442	578
21,000	303.5	1808	903	612	216	77	970	229	340	268	223,496	481	625
21,500	310.7	1973	964	683	239	87	1035	244	380	313	243,280	534	700
21,750	314.3	2296	1146	799	255	96	1215	275	433	372	288,239	609	807
22,020	318.2	2529	1274	877	273	105	1334	301	478	415	313,134	720	953

*The AE data represents the cumulative AE obtained during two pressurization runs on vessel V-7B. During the first run the vessel was pressurized to 10,500 psi and then unloaded. On the next run the vessel was pressurized to failure. All AE data obtained below 10,500 psi on the second pressurization was subtracted from the accumulated AE obtained at higher pressures.

The stress intensity factors were calculated using an equation developed by Merkle, et al.⁽⁷⁾

$$K_I = C\left(\frac{r}{t}\right) p\sqrt{\pi a} \quad (1)$$

where C is the elastic shape factor for the flaw (= 1.572), r is the vessel radius (= 13.5 inches), t is the wall thickness (= 6 inches), a is the flaw depth (= 5.31 inches) and p is the internal pressure. Substituting the above values into equation (1) yields,

$$K_I = 14.45p \quad (2)$$

In order to delineate the relationship between AE and a fracture mechanics parameter, a graph of AE count versus the stress intensity factor was made (Figure 36). The D/E counts plotted in Figure 36 are in two forms: total array count and flaw count. The total array count represents the total AE count obtained in array "0" regardless of source location. The flaw count on the other hand represents a manual accumulation of AE count in array "0" from sources near the flaw as determined by their source coordinates. A linear relationship between AE count and stress intensity factor seems to exist over a broad range in stress intensity factor. Deviation from linearity occurs at the extreme low and high ends of the stress intensity factor range. Deviation at high stress intensity factor values is influenced by increasing AE associated with incipient fast fracture. The characteristic of rapidly increasing AE as a precursor to fast fracture has been observed by a number of AE investigators in several materials.^(8,9,10)

The lines drawn on Figure 36 were obtained by a least mean squares fitting of the data to an equation of the form,

$$\Sigma AE = a + b K_I \quad (3)$$

The calculated regression coefficients and the square of the correlation coefficients are listed in Table 6. It is evident from the data in Table 6

FIGURE 36. AE Count vs Stress Intensity Factor - HSST V-7B Vessel Test

TABLE 6. Least Squares Regression Coefficients and Correlation Coefficients for AE vs K_I Curves*

	Total Valid AE	BNW AE COUNT								BNW Energy	D/E AE COUNT	
		Rise Time - μ sec.				Signal Amp - volts					Flaw	Total Array
		<1	1-5	5-10	>10	<1.3	1.3-2.5	2.5-5	>5			
a	-221.8	-86.6	-94.7	-31.1	-9.3	-94.4	-23.0	-63.5	-40.5	-24,791	-105.0	-113.6
b	6.478	3.220	2.193	0.788	0.277	3.462	0.805	1.270	0.936	797.8	1.815	2.303
r^2	0.995	0.992	0.994	0.994	0.979	0.994	0.996	0.993	0.988	0.995	0.990	0.992

* $\Sigma AE = a + b K_I$

for K_I between 43.35 and 303.5 ksi $\sqrt{\text{in.}}$

that all AE parameters plotted in Figure 36 correlate well with the stress intensity factor. In addition, linear regression analysis was performed on BNW AE count data that was partitioned with respect to rise time and signal amplitude. The objective is to contribute to identification of AE parameters which most strongly relate to flaw growth*. Table 6 indicates that all the partitioned AE, except the slow rise time ($> 10 \mu$ sec) and high amplitude (> 5 volts), correlate well with the stress intensity factor.

The AE data is also compared to crack opening displacement as shown in Figure 37; here both BNW total AE and D/E flaw array "0" count and stress intensity factor are plotted against COD. The lines drawn through the AE data in Figure 37 were obtained by a least mean squares fitting of the data to an equation of the form shown on Table 7. The calculated regression coefficients and the square of the correlation coefficients are also listed in Table 7. It is apparent from the data that AE count correlates well with COD. In contrast to Figure 36, the AE data increases linearly up to failure with an intermediate change in slope, which occurs in the neighborhood of the initiation of general yielding of the vessel in the vicinity of the notch. The data suggests that COD is a better variable than K for correlation with AE. This may occur due to COD providing a better measure of crack tip plasticity and crack extension than the stress intensity factor where the crack length was, for calculation purposes, assumed not to change during the course of the test.

The exact reason for the change in slope of the AE versus COD curve is unclear. The first part of the curve could be related to AE occurring in the ligament region, the second part possibly due to a shift in plastic zone growth and crack extension toward the ends of the flaw and hence into thicker material. This needs further clarification, however, because it is not yet clear which process - plastic zone growth or crack extension - dominates

*The term growth is used in this work in a broad sense. It may represent flaw tip plastic zone growth, flaw growth or both.

Figure 37. AE Data and Stress Intensity Factor vs COD-HSST V-7B Vessel Test.

TABLE 7
Least Squares Regression Coefficients and Correlation
Coefficients for AE vs COD Curves*

	COD Range 0.008 in. to 0.053 in.			COD Range 0.053 in. to 0.308 in.		
	a_1	b_1	r^2	a_2	b_2	r^2
BNW AE Count	-165.7	19.60	0.988	537.3	6.404	0.995
D/E AE Count	-47.39	4.108	0.961	91.87	1.950	0.992

* $\Sigma AE = a + b (CDD)$

the production of detected AE, as well as to the nature of the AE process on a microscopic level.

Another observation should also be made at this point. That is, the AE behavior of the flawed vessel does appear different than corresponding fracture tests in the previous section (3.3.2). We do not know why the fracture tests displayed so little AE during gross elastic loading. It could be related to fatigue precracking. Vessel V-7B was not fatigue precracked but sharpened using electron beam welding. Flaw geometry may also be a significant factor. Further investigation is needed to resolve this possible paradoxical effect.

The results wherein AE correlates well with K and COD, however, are encouraging. They constitute an important input to the AE-flaw characterization program because they were derived from a flawed pressure vessel with a relatively thick wall (6 inches). The laboratory AE-flaw characterization work by necessity utilizes specimens up to about 1-1/2 to 2 inches thick.

Conclusions. Conclusions from the AE-hydrotest results include:

- o AE source location information which is indicative of flaw development can be obtained in the circumstances of this test.
- o Growth of a flaw in 6-inch thick A533B Class 1 material at 200⁰ F produced readily detectable AE.
- o The AE signal waveforms detected from the V-7B vessel are similar to those observed in laboratory testing of thinner A533B specimens.
- o AE data correlates well with stress intensity factor (K) and crack opening displacement (COD) indicating that AE can be related to flaw severity in this pressure vessel configuration.
- o The fact that the two separate AE monitor systems use substantially different approaches to isolating AE from the defect and yet the results are very similar gives reassurance that the AE data is not significantly contaminated with extraneous noise.
- o There was no detected AE indication of distress in the vessel at locations other than the machined defect.

3.3.4 Fatigue Crack Growth Tests

In this section, the results of fatigue crack growth (FCG) tests in two 2T-CT specimens and one single-edge notch (SEN) specimen are described. It should be noted at this point that the subsequent mathematical analyses of the AE-fatigue crack growth data have been done in two separate, but related ways. We have compared rate of change of AE and FCG parameters and compared total or summation of AE and FCG parameters. The analyses are separate in the sense that power-law curves have been empirically fitted to the rate data and linear curves empirically fitted to the summation data rather than curve-fitting the summation data then taking its rate derivative. The latter approach was not taken for several reasons. First, the fundamental metallurgical-based behavior of AE with respect to parameters that govern its production are not well known or universally agree upon. Second, separate empirical curve fitting, as the reader will see later, has allowed us to characterize the data and initially make some judgements as to how AE may be related to fracture mechanics parameters and show that in-service monitoring of fatigue crack growth is feasible. It is possible as more data is obtained, that the specific mathematical models will change. This will not, however, change the potential of the technique. It will be shown that the rate data analysis yields consistent relationships, thereby indicating that in-service monitoring of pressure vessels has an experimental basis.

3.3.4.1 FCG Test Results

Fatigue crack growth tests were conducted by applying cyclic sine wave-form loads between fixed minimum and maximum levels. The crack was measured on each side of a given specimen after incremental extensions (Δa) using a 32X traveling stage microscope. Details of the test procedure and raw data are found in Appendix A. Plots of fatigue crack length (a) and valid AE event count (C3) and valid energy (E) as function of load cycles are shown in Figures 38, 39 and 40. Figures 38 and 39 are derived from one HSST skin-base metal and one skin-weld metal 2T-CT specimen, respectively. Figure 40 is derived from an SEN specimen removed from the surface of the primary 8-1/4

Figure 38. Fatigue Crack Length, AE Data vs Load Cycles; Size 2T-CT Specimen (B2-1B) Base Metal.

Figure 39. Fatigue Crack Length, AE Data vs Load Cycles, 2T-CT Specimen (B2-1A) Weld Metal.

Figure 40. Fatigue Crack Length, AE Data, Fatigue Loads vs Cycles SEN Specimen (1-1A-2A), 3% Pre-Strain.

inch thick program material. In all three figures, AE event count and energy on the average, increase with increasing crack growth rate.

Before proceeding with a description of rate and summation data curve fitting, acoustic noise as shown in Figure 41 should be discussed. The bottom or isolation AE event count curve is the same data shown on a different scale in Figure 38. The upper or unisolated acoustic count curve of Figure 41 is a direct measure of the total acoustic information (noise + AE) that occurred during the FCG test of Specimen B2-1B. The isolation feature of the BNW instrument allowed separation of the AE data from the overriding amount of acoustic noise. By the end of the test, the total (noise + AE signals) exceeded actual AE data by a factor of about 10. This same effect was noted on all the other specimens but to a lesser degree. The other 2T-CT specimen produced about the same amount of AE event count (~50,000), but with about 250,000 noise count. This lesser noise is believed to be due to a better surface finish on the specimen holes and pins and the use of grease fittings in the specimen from the beginning of the test (see Appendix A). Figure 41 is a dramatic example of how acoustic noise, which is believed to be due primarily to contact stress-induced fretting-corrosion at the pin-specimen hole interfaces, can seriously distort AE data.

The SEN specimen produced even lesser amounts of noise (about 40% greater than AE event count) and is thought to be due to a reduced tendency for pin movement to occur during loading.

3.3.4.2 Rate Data Analysis, Unpartitioned AE Signals*

Fatigue crack growth rate (da/dN) data are characterized using the well-known Paris-Erdogan fatigue crack growth law,

$$\frac{da}{dN} = C(\Delta K)^m \quad (2)$$

*Analysis in this section uses the count of all signals determined to be valid AE. Section 3.3.4.3 analysis considers segments of the valid AE count which are partitioned out on the basis of rise time (peak time) and amplitude ranges.

Figure 41. Comparison of Unisolated Acoustic Count with Isolated AE Event Count - Specimen B2-1B.

where C and m are constants and, (for compact tension specimens)

$$\Delta K = \frac{\Delta P}{BW^{1/2}} \left[29.6\left(\frac{a}{W}\right)^{1/2} - 185.5\left(\frac{a}{W}\right)^{3/2} + 655.7\left(\frac{a}{W}\right)^{5/2} - 1,017\left(\frac{a}{W}\right)^{7/2} + 638.9\left(\frac{a}{W}\right)^{9/2} \right] \quad (3)$$

For the base metal and weld metal curves in 2T-CT Specimens B2-1B and B2-1A, $da/dN - \Delta K$ curves are shown in Figure 42. Both base metal and weld metal curves are essentially the same within normal data scatter observed in FCG tests. Both tests were halted near $a/W = 0.6$. The correlation coefficient 'r' is a measure of the "degree of fit" of the curve to the data points through which it is drawn (see Appendix A for a description of 'r').

The FCG data for the SEN specimen is shown in Figure 43. This specimen was prestrained 3.3% in the unnotched condition to simulate shakedown strains that might occur during vessel hydrotesting (see also Section 3.1.0) with subsequent fatigue crack growth occurring after hydrotesting.

The specimen was then notched and fatigue-tested. AE event count continued to increase uniformly up to the point where the notch edges showed 0.035 inch permanent set. At this point, the a/W ratio was about 0.52. The test was continued on to an a/W ratio of about 0.67, which is beyond the point (0.60)* where the governing K-equation⁽¹¹⁾ is considered to be valid,

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

where,

ΔP = load range.

Just prior to the 0.035 inch permanent set line in Figure 40, AE continued to accumulate, but at a lower rate. This might be due to increased plasticity in the remaining ligament.

* The last $da/dN - K$ point in Figure 40 was calculated at the point where $a/W = 0.6$.

Figure 42. Fatigue Crack Growth Rate vs Stress Intensity Factor Range for 2T-CT Specimens, B2-1A (Weld Metal) and B2-1B (Base Metal) $R=0.1$, 3Hz .

Figure 43. Fatigue Crack Growth Rate vs Stress Intensity Factor Range for 3% Pre-Strained SEN Specimen 1-1A-2A, R=0.1, 3Hz.

All three fatigue crack growth curves are essentially the same within normal data scatter, thus providing similar conditions for the production of AE. The knee in the 3% prestrain da/dN - ΔK curve may have been shifted to a slightly higher K value (about 32 ksi $\sqrt{in}$ to 38 ksi $\sqrt{in}$) but this, too could be within typical scatter.

Since fatigue crack growth data can be characterized quite well over a large range of da/dN values (up to 6 orders of magnitude in A533B)⁽¹²⁾ with power-law equations, we arbitrarily decided to also compare AE and FCG rate parameters with a power-law equation.

Figure 44 is a plot of dC_3/dN (AE event count/cycle) versus da/dN , with a corresponding least squares regression power-law equation. Because of data scatter in this, as well as other rate comparisons, it was decided to use a statistical method for rating the "goodness of fit" of the equation. The method used is described in Appendix A, where both correlation coefficient 'r' and the number of data points, N, are combined to yield a "percent chance of correlation." These percent correlation values provide a relative measure of the dependency of the two variables. In addition, while they do not provide a measure of the validity of the power-law relationship, they do allow a means of comparing or "weighing" one power-law relationship to another on a common basis. Based on the method described in Appendix A, the power-law equation,

$$\frac{dC_3}{dN} = 4.942 \times 10^5 \left(\frac{da}{dN} \right)^{1.123} \quad (5)$$

where C_3 = AE event count/cycle, a 99.9% chance of correlation is derived. (A comparison of numerous AE and FCG parameters are tabulated later in this report using the percent chance of correlation to provide an initial basis for weighing the correlation of the two sets of parameters. From these percent correlation values, some initial statements are made concerning the nature of the parameters that may affect the production of AE during FCG.)

Figures 45 (B2-1A) and 46 (1-1A-2A) are plots of the same two variables shown in Figure 44. Figures 45 and 46 display the effect of weld metal and 3% prestrained material, respectively.

Figure 44. AE Event Count/Cycle vs Fatigue Crack Growth Rate for 2T-CT Specimen B2-1B, Base Metal.

Figure 45. AE Event Count/Cycle vs Fatigue Crack Growth Rate for 2T-CT Specimen B2-1A, Weld Metal.

Figure 46. AE Event Count/Cycle vs Fatigue Crack Growth Rate for SEN Specimen 1-1A-2A, 3% Pre-Strain Base Metal.

The weld metal specimen shows a greater degree of scatter but retains a >99.9% chance of correlation. The pre-strained specimen behaved similarly, but only limited AE was detected prior to a da/dN of about 10^{-5} inch/cycle, whereas the other two specimens began to produce substantial amounts of AE around 3 to 6×10^{-6} inch/cycle. Since an effort was made to maintain similar AE system sensitivity in these various tests, sensitivity variations should be a relatively small factor in this phenomena. The 3% prestrain may have de-sensitized the material for production of AE at da/dN values less than 10^{-5} inch/cycle. Another comment should be made concerning the range of data in Figure 46. Lack of AE data until about 10^{-5} inch/cycle (which is equivalent to about 70,000 load cycles on Figure 40) and the rapid decrease in AE accumulation after about 104,000 cycles allowed only 17 data points for effective AE- da/dN analysis. The rapid decrease in AE accumulation has been observed to occur in other work we have done and seems to parallel the development of increased net section or ligament plasticity.

Many other comparisons of linear elastic fracture mechanics parameters are possible. Figure 47 shows a comparison of AE energy/cycle with da/dN for Specimen B2-1B. This curve is comparable to Figure 44. Even though the percent correlation is slightly higher for the energy curve, in reality it is about the same. There would need to be many more data points available to attempt to draw fine distinctions using the percent correlation method.

AE rate also compares well with ΔK as shown in Figure 48. This is not surprising as da/dN correlates very well with ΔK and hence, dC_3/dN should also compare favorably with ΔK as it does with da/dN .

Several initial comparisons can be made on the nature of AE rate data from two different specimen geometries and three different material conditions. First, all three specimens display an increasing AE event count/cycle with increasing da/dN , thus providing a measure of fatigue crack growth rate based on AE data alone. All three curves show about 1 count/cycle around 3×10^{-5} inch/cycle. The 1-3/4 inch thick weld metal and base metal specimen equations display power-law exponents of 1.233 and 1.833 respectively, while the thinner (about 1/2 inch) prestrained SEN specimen base metal shows a

Figure 47. AE Energy/Cycle vs Fatigue Crack Growth Rate for 2T-CT Specimen B2-1B, Base Metal.

Figure 48. AE Event Count vs Stress Intensity Factor Range for 2T-CT Specimen B2-1B.

lesser exponent, 0.9544. The decrease in slope of the SEN specimen curve could be due to a combined effect of the 3% prestrain and reduced thickness. Additionally, AE energy/cycle compares well with da/dN and also provides a measure of the "crack driving force" or stress intensity factor range.

Further comparison is made of AE rate and da/dN -type parameters below. Several other models are presented along with separation or partitioning of the AE data into different amplitude and rise-time categories. This separation provides further insight into those AE signal parameters that are most sensitive to fatigue crack growth rate. This is important in beginning to identify which AE parameters may be restricted in data acquisition on a reactor to screen out noise without destroying the basis for flaw evaluation by AE data.

3.3.4.3 Rate Data Analysis Using Other Models and Partitioned AE Data

Two other variables besides change in load cycles, dN , have been used to correlate AE with da/dN . They are, crack area swept out per cycle (dA/dN) and change in theoretical crack tip plastic zone volume dVp . Change in theoretical crack tip plastic zone area (dAp) was investigated several times and found to be consistently similar but slightly less accurate than dVp . Thus, dAp is omitted at this time in favor of dVp to expedite analysis. As our AE technology base increases, dAp will be periodically re-examined. Crack area swept out per cycle was selected as one model base because of its simplicity and direct measureable relationship to a crack in a laboratory specimen. Theoretical crack tip plastic zone factor was used because of its volumetric measure of region adjacent to the crack tip that could be responsible for AE production. Crack area, dA , simply involves,

$$dA \approx \Delta A = B(\Delta a) = \text{constant} (\Delta a) \quad (8)$$

where $a = \bar{a}_{i+1} - a_i$

for constant thickness specimens.

Crack tip plastic zone volume, dV_p , involves calculating the change in plastic zone volume from one crack length measurement to the next, as

$$dV_p \approx \Delta V_p = V_p(a_{i+1}) - V_p(a_i) \quad (7)$$

where $V_p(a_i) = \pi [r_p(a_i)]^2 B$

and $r_p = \frac{1}{2\pi} \left[\frac{K(a_i)}{\sigma_{ys}} \right]^2$

and $K(a_i)$ is either Equation 3 (compact tension geometry) or Equation 4 (SEN geometry). Please note that Equation 7 represents the change in plastic zone volume and not the volume swept out by the plastic zone of an advancing crack. Further analytical work will be conducted to characterize the latter effect.

Valid AE event count signals were partitioned into four levels of amplitude and four levels of rise time. These various valid AE signal parameters are:

C = AE count (no partitioning)

E = Energy, valid AE signals

H_1 = No. of AE signals with amplitude < 1.3 volts

H_2 = No. of AE signals with amplitude between 1.3 to 2.5 volts

H_3 = No. of AE signals with amplitude between 2.5 to 5.0 volts

H_4 = No. of AE signals with amplitude > 5.0 volts

R_1 = No. of AE signals with rise time < 1 μ sec

R_2 = No. of AE signals with rise time between 1 to 5 μ sec

R_3 = No. of AE signals with rise time between 5 to 10 μ sec

R_4 = No. of AE signals with rise time > 10 μ sec

Our AE system presently partitions signal amplitude and rise time separately. Thus, H_1 signals could be composed of signals of various rise times, etc. In this initial correlation evaluation, we used only the two extreme values of amplitude (H_1 and H_4) and rise time (R_1 and R_4) to attempt to bracket the significant values. The initial ranges selected for rise time and amplitude were somewhat arbitrary.

Consider Table 8, which gives the results of relating various of the above parameters to da/dN using the power-law curve fitting method. Each "AE parameter," eg., dC/dN , dC/dV , et., is correlated with da/dN , a least squares regression curve derived, and a percent correlation value determined. The numbers in each of the three columns for each test specimen are the percent correlation values between an "AE parameter" at the left side of the table and da/dN . The significance of percent chance of correlation values is based on the following criteria:

>99.9%	Highly significant
99.0 to 99.9	Significant
< 95 to 99	Marginal significance
95	Insignificant

Sample curves for Table 8 relationships are shown in Figures 49 through 51. Observations can be made from Table 8. In general, fatigue crack growth (da/dN) is characterized quite well using valid AE event count (C) per cycle and energy per cycle (numbers 1 and 4), low amplitude AE signals (H_1) per cycle, and fast rise time AE signals (R_1) per cycle (numbers 7 and 13). In addition, H_1 and R_1 related to dV_p compare well with da/dN (numbers 3, 6, 9 and 15). These comparisons suggest that fast rise time-low amplitude signals among the partitioned values examined give the best measure of crack growth rate. Further, examination of rise time and amplitude in combination is planned for FY 78. Table 8 also suggests that plastic zone volume may play a dominant role in generation of AE.

3.3.4.4 Summation Data Analysis

The same valid AE data shown in Figures 38, 39 and 4D that were rate-analyzed in a power-law form in the preceeding two sections are presented here in a linear summation form. Figure 52 is a plot of AE event count, plotted against maximum stress intensity factor (K_{max}) for all three FCG specimens. The summation data could also be plotted against ΔK as the two K's are related through,

TABLE 8

SUMMARY OF AE FUNCTIONS RELATED TO
FATIGUE CRACK GROWTH RATE (da/dN)
IN TERMS OF PERCENT CHANCE OF CORRELATION

	Test B2-1B Skin-Base Mat'l.	Test B2-1A Skin-Weld Mat'l.	Test 1-1A-2A Skin-Base, 3% Prestrain
dC/dN	>99.9	>99.9	>99.9
dC/dA	72.9	86.8	18.2
dC/dV	>99.9	97.5	>99.9
dE/dN	>99.9	>99.9	99.8
dE/dA	77.0	99.0	52.4
dE/dV	>99.9	96.3	>99.9
dH_1/dN	>99.9	>99.9	>99.9
dH_1/dA	99.9	88.2	54.1
dH_1/dV	98.5	98.4	>99.9
dH_4/dN	>99.9	99.7	1.8
dH_4/dA	99.8	87.5	94.4
dH_4/dV	27.8	7.9	>99.9
dR_1/dN	>99.9	>99.9	>99.9
dR_1/dA	79.5	94.8	14.6
dR_1/dV	>99.9	98.6	>99.9
dR_4/dN	97.8	>99.9	52.5
dR_4/dA	64.9	98.8	86.8
dR_4/dV	93.1	67.7	>99.9

Nomenclature

- C - AE event count₂ (<1.3 - >5.0 volts)
 E - AE energy-volt²-sec.
 H₁ - Number of lowest amplitude events (<1.3 volts)
 H₄ - Number of highest amplitude events (>5.0 volts)
 R₁ - Number of fastest rise time events (<1usec)
 R₄ - Number of slowest rise time events (>10usec)
 a - Crack length
 N - Number of load cycles
 A - Crack area
 V - Volume of the crack front plastic zone

Significance of Percent Numbers

This is based on a statistical evaluation with the following criteria:

- >99.9% - highly significant
 99.0 - 99.9% - significant
 95.0 - 99.0 - marginal significance
 <95.0 - insignificant

Figure 49. Low Amplitude (< 1.3 Volts) AE Signals/Cycle ($\frac{dH_1}{dN}$) vs Fatigue Crack Growth Rate ($\frac{da}{dN}$), Specimen B2-1B, Base Metal.

Figure 50. AE Event Count/Increase in Plastic Zone Volume (dC_3/dV_p) vs Fatigue Crack Growth Rate ($\frac{da}{dN}$), Specimen B2-1B, Base Metal.

Figure 51. AE Event Count/Increase in Plastic Zone Volume (dC_3/dV_p) vs Fatigue Crack Growth Rate ($\frac{da}{dN}$) Specimen 1-1A-2A, 3% Pre-Strain Base Metal.

Figure 52. Summation AE Event Count vs Stress Intensity Factor for 2T-CT and SEN Specimens.

$$K_{\max} = \frac{\Delta K}{1-R}$$

where $R = \text{load ratio} = \left(\frac{P_{\min}}{P_{\max}} \right)$

The plots in Figure 52 for data from the two compact tension specimens are nearly the same even though one was base metal and the other was weld metal. The weld metal curve (B2-1A) shows a slightly larger degree of scatter, but is essentially the same as that of the base metal. Interestingly, the knee in the $\Sigma \text{AE}-K_{\max}$ curve occurs at a ΔK level similar to the ΔK value for the knee in the $da/dN-\Delta K$ curve (Figure 42).

The 3% prestrain $\Sigma \text{AE}-K_{\max}$ curve in Figure 52 shows a functional relationship similar to the 2T-CT curves, but is displaced to the right. This could be due to the prestrain desensitizing some of the AE sources. The reason for the break or knee in the curve around $75 \text{ ksi } \sqrt{\text{in}}$ is not understood at this time.

Comparisons of ΣAE energy with maximum stress intensity factor are shown in Figure 53. Here the curves are of the same form as Figure 52 except that the base metal energy levels are slightly higher than weld metal for the two 2T-CT specimens. As in the rate data analysis section, the limited data of this section show AE event count and energy to be nearly equivalent in their correlation with $K_{\max}$.

3.3.4.5 Discussion of Rate and Summation Fatigue Crack Growth and AE Analysis

Two methods of analysis of fatigue crack growth-AE data have been presented. The two methods, rate and summation, as noted in the beginning of this section were analyzed separately.

The data thus far is encouraging from the viewpoint of potential for continuous monitoring. The rate data analyses show that AE alone can provide a measure of fatigue crack growth rate or the crack during force ΔK , namely $dC_3/dN = C(da/dN)^m$ or $D(\Delta K)^n$. Detailed analyses of the AE signal amplitude and

Figure 53. Summation AE Energy vs Stress Intensity Factor for 2T-CT and SEN Specimens.

rise time ranges show that low amplitude-fast rise time signals appear to describe the FCG process best because they yield the best correlation with da/dN . The analyses also indicate that the plastic zone size may influence AE production. This is encouraging because even the most complex-shaped flaws have plastic zones that precede and accompany fatigue crack growth. Even though the exact mechanisms that produce AE during FCG are not well known, the data indicate that AE monitoring is feasible, particularly during gross elastic behavior where growing flaws are small with respect to major vessel dimensions such as thickness.

The limited data also shows a behavior that, if backed up by further experimentation, could be extremely useful. That is, the AE-fatigue behavior of a code acceptable weld was essentially the same as its surrounding base metal. Of course, it remains possible that more gross variations in weldments, particularly those that are code-rejectable, may prove to be different than base metal. Future examination in this area is needed.

Points concerning the rate data analyses which remain to be examined are cyclic rate-effect and R ratio effect, if any, on the resultant AE data. If there is no cyclic rate-effect, then da/dt type data can be directly related to da/dN where the constant of proportionality is

$$\frac{da}{dt} = \frac{dN}{dt} \circ \frac{da}{dN}$$

It is anticipated that the majority of FCG in a reactor will probably occur around $R = 0.5$ rather than $R = 0.1$ where the laboratory tests were run. This must be examined for effect on AE generation.

Finally comparison of the AE-FCG data on a summation basis adds a "second equation" for assessing flaw driving force where,

$$\Sigma C_3 = A + BK_{\max}$$

where A, B = constants

$$\text{and } K_{\max} = \left(\frac{\Delta K}{1-R} \right)$$

Observation of the summation data suggest that, once the governing factors or parameters that control AE production in fatigue crack growth are resolved, it may be possible to derive the rate equations by taking appropriate rate derivatives of the summation data. That this cannot yet be done, however, does not limit assessing the feasibility of applying such an approach to the monitoring of an operating nuclear reactor.

Thus, rate data in particular and summation data to a lesser degree offer a potential basis for estimating flaw severity based on AE data alone.

3.3.5 High Temperature AE Sensor

Evaluation of high temperature sensors was initiated with the objective of determining availability of AE sensors suitable for long-term monitoring of reactor vessels and other components. Sensors have been calibrated at room temperature in preparation for high temperature laboratory testing. Results are shown in Figure 54. Of the three types of commercial sensors, sensor "C" lends itself to tuning with an inductance coil. This is an advantage for AE detection and location. It may or may not be an advantage for detecting AE information needed for flaw evaluation. The significance of preserving broadband frequency content will resolve this question. Data on a lithium niobate calibration reference sensor, a BNW sensor typical of ones being used in laboratory test work, and a BNW wave guide with various degrees of inductance tuning are also included for reference. In comparing these sensors, the reader is cautioned to observe the sensitivity scale on the right side of each photo rather than relating to the analyzer noise reference. Different analyzer sensitivity ranges were used in this work.

The commercial high temperature sensors appear to be 10 to 20 dB lower in sensitivity than most room temperature AE sensors. The significance of this lower sensitivity is dependent on the type of AE signal which proves to be most important to flaw evaluation - i.e., low amplitude or high amplitude. From the standpoint of minimizing reactor hydraulic background noise interference, sensor "B" of the commercial sensors shows the best characteristics.

FIGURE 54. Room Temperature Calibration of High Temperature AE Sensors

Its peak sensitivity covers a frequency span from 0.35 to 0.55 MHz. Metal waveguides with inductance tuning show good sensitivity and good low frequency (noise) cutoff. It is obvious, however, that the high sensitivity covers only a relatively narrow frequency band. Again, whether or not this is a detriment is dependent on the AE parameter(s) which prove important to flaw evaluation. If signal frequency content is not of primary significance, then a narrow band sensor should be acceptable.

High temperature sensor evaluation did not proceed as far as planned in FY-77 due to problems in sensor procurement and difficulties in assembling a test system suitable for long-term laboratory testing at 600°F. Some preliminary conclusions can be drawn, however:

- °Use of metal wave guides pressure coupled to the surface to be monitored are a proven means of sensing AE from a high temperature surface.

These have been used successfully at PNL for temperatures in excess of 600°F. They do have two possible disadvantages of physical protrusion from the side of a vessel (probably 3-4 feet) and a narrow frequency response band when tuned to achieve high sensitivity.

- °The manufacturer of one commercial high temperature sensor claims 5 years continuous test experience on a reactor vessel with no evidence of deterioration. Data supporting this has not yet been made publicly available, however, it could represent an important achievement toward a reliable system for continuous monitoring of AE on a reactor.

- °It appears at this time that a successful long-term high-temperature sensor must use a pressure coupling technique to couple acoustic information from the monitored surface to the sensor. To date, we have been unable to find a coupling material such as epoxies which could be expected to retain their acoustic coupling properties under long exposure (1-year minimum) to 600°F temperature plus nuclear radiation.

Testing of high temperature sensors will continue in FY-78.

3.3.6 AE Library

The purpose of the AE library is to search out published research results which have relevance to this program. Accomplishments include a visit to the Battelle-Frankfurt Germany Laboratory to discuss AE research work there related to the interests of this program, review of six publications of AE research results from England, Denmark, Japan, and the U.S., and review of technical discussions at the 17th Acoustic Emission Working Group Meeting. Reviews of a survey report on AE work in several countries from Denmark⁽¹³⁾ and a report on AE work in Japan,⁽¹⁴⁾ plus a trip report on the visit to Battelle-Frankfurt were included in the first progress report.⁽¹⁾ Reviews of reports on pressure vessel testing⁽¹⁵⁾ and AE parameter interpretation⁽¹⁶⁾ from England and a report on AE monitoring of pressurized water reactors⁽¹⁷⁾ from the U.S. were included in the second progress report.⁽²⁾ A review of a report concerning AE from testing a C/Mn steel pressure vessel⁽¹⁸⁾ and a summary of technical discussions at the 17th Acoustic Emission Working Group are included as Appendix B of this report.

3.3.7 AE Signatures

AE signal characterization in FY-77 was confined to searching for characteristics of signals from known crack growth which appeared unique compared to common noise sources such as movement at metal interfaces or hydraulic noise. Typical AE signals during fatigue crack growth in laboratory specimens appear in Figure 55. Signal characteristics with potential importance which can be observed are:

- ° AE signals in these tests fall into three general categories - fast rise time with low amplitude, fast rise time with high amplitude, slow rise time with various amplitudes. As discussed previously, fast rise time, lower amplitude signals show the best correlation with crack growth parameters. This combination also offers a potential for screening out many noise signals.

FIGURE 55. Samples of Different AE Signal Wave Forms - Fatigue Test B2-1B

- ° Observation of AE signal wave forms shows some evidence that they may characteristically start with a negative half cycle. (This assumes a fixed polarity of the sensing crystal.) If this can be verified by further testing, it would be a valuable tool for separating AE signals from other unwanted signals.
- ° AE signal frequency spectra tend to maintain a level up to about 600 kHz while for noise signals the level drops with increasing frequency above about 200-300 kHz. This is important in that it indicates that AE signal frequency content extends beyond the point where hydraulic background noise becomes quite low (350 kHz). Thus, hydraulic noise can be rejected on a frequency basis and still detect AE signals.

Signal wave forms observed during the HSST V-7B vessel test are shown in Figure 56. An important observation is the fact that these are generally similar to AE signals observed during testing on laboratory specimens of the same type of material. This tends to lend credence to the usefulness of laboratory data in developing preliminary AE-fracture mechanics relationships for application to heavy section vessels. Signal No. 8 in Figure 56 is considered to be a noise signal from an unidentified source. It is classified as a noise signal on the basis of the gradual increase in amplitude without any sharply defined signal front. This is the type of signal observed previously from known noise sources such as movement at the interface of two metal objects. One noticeable difference between these signals and those observed from laboratory specimens is the predominance of lower frequency components (300-400 kHz) in the signals from the vessel test. Signals from laboratory specimens show higher frequency components as well as the lower frequency. This difference may be due to a combination of the influence of high frequency signal attenuation in the longer travel path in the 6-inch thick vessel material plus electronic system characteristics.

FIGURE 56. Sample AE Signals - HSST V-7B Vessel Test

Special purpose analysis modules for the multiparameter digital AE monitor are planned for FY-78 to more positively confirm or deny some of the characteristics discussed above. One module will provide a count of validated AE signals which start with a negative half cycle. Another module will allow sorting signals by a combination of rise time and amplitude requirements.

The FY-78 program will also examine characteristics of acoustic signals from slag inclusions, oxide cracking and water in the crack. These will be compared with known AE signals from flaw growth to determine distinguishing differences.

Another AE characteristic has been observed very preliminarily in 3% plastic pretrained material. In addition to the primary AE monitor system (monitoring frequency 200 kHz to 1 MHz), a tuned narrow band system (monitoring frequency is tuned frequency $\pm$ about 25 kHz) was used. AE detection by the narrow band system was significantly less than the broadband primary system when tuning was at 600 kHz. With tuning at 400 kHz, the two were similar. In light of the spectral content of the AE signals shown in Figure 55, which were from material not pretrained, it appears this might be a characteristic of the pretrained material. This phenomenon will be investigated specifically in coming tests.

4.0 ACKNOWLEDGEMENTS

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APPENDIX A

EXPERIMENTAL PROCEDURE

- AE Test Procedure
- Mechanical Test Procedure
- AE-Fracture Mechanics Analysis Procedure

AE TEST PROCEDURE

The purpose of this section is to describe the basic AE test procedure applied to all tests. It does not include added procedures used in a given test for special reasons.

AE System

The AE system used is described in Section 3.2 of this report. Added information relevant to this section concerns sensors. Four similar broadband (100 kHz to >1 MHz), flat response (± 7 dB) sensors with nominal sensitivity of -70dB re 1 volt/ μ bar have been selected for use on this program. These same sensors are used in all tests to minimize sensor influence on any changes in AE.

Test Procedure

As the first step on any test, the AE sensors are mounted on the specimen with epoxy "tacking" points around the edge of the sensor. A viscous ultrasonic couplant is used between the sensor face and the specimen surface for acoustic coupling. Sensing system frequency response is then calibrated for the sensor output and the sensor plus preamplifier. An alumina grit blast directed onto the specimen surface according to a set method is used to generate a repeatable broadband input to the sensors. These calibrations become a part of the test log. The calibration information plus monitor system gain characteristics and detection threshold of the system ready for test are used to determine effective system sensitivity. Effective sensitivity is discussed in Reference 2 of this report on page 7. A minimum effective sensitivity of 0.1 μ bar has been adopted as standard based on experience. Sensors are remounted, if necessary, to meet the 0.1 μ bar requirement.

Prior to testing with the specimen in the test machine, proper adjustment of the source isolation circuit is achieved using an electronic pulser to produce pulse signals from various locations. The source isolation is set to accept only signals from the flaw area. The setting of all adjustable parameters on the monitor instrument is recorded in the test log. Commentary

during the test is recorded on a cassette recorder. Useful information is subsequently retrieved and entered in the test log.

At the end of a test run (completion of a fracture test or a crack growth increment in a fatigue test), data in the digital memories is readout on a teleprinter to produce a hard copy.

During testing, valid signal waveforms from the Biomation transient analyzer, their spectrum analysis profile, and samples of analog acoustic and load information is recorded photographically.

In addition to the other parameters, valid signal amplitude distribution is measured using a Nuclear Data distribution analyzer. This also is recorded photographically by test increments.

Following completion of a test, AE data is retabulated according to significant mechanical test parameters (load increments, crack growth increments, etc.) for subsequent fracture mechanics analysis. Copies of these tabulations for fatigue tests B2-1B, B2-1A, 1-1A-2A and fracture tests B2-1B, B2-3B, B2-3A follow.

Spec. No: 3-2-18

AE - FATIGUE DATA

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Address Range	Total Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PR/PH	PEAK Time - μ sec.				Pulse Height - V			
								A	B	C	D	A	B	C	D
	0														
	10,210	10,210	904	1120	7179	135,448		1064	33	11	12	325	739	45	11
	22,290	12,080	828	932		154,555		885	19	9	19	196	690	37	9
	24,480	2190	76	80	1130	9714		72	6	2	0	1	66	13	0
	35,710	11,230	1328	1454	20811	167,618		1338	15	44	57	276	974	145	59
	47,770	12,060	2026	2476	30318	269,711		2055	50	99	272	594	1312	322	248
	59,240	11,470	2856	3270	8918	223,926		2779	65	114	262	164	2518	523	65
	63,260	4020	282	452	2676	477,688		402	50	0	0	36	217	68	131
	71,750	8490	924	436	12,200	538,52		405	4	4	23	83	314	35	4
	79,850	8100	1884	2050	17,478	220,314		1825	103	20	102	205	1168	410	267
	88,360	8510	2232	2962	32,866	353,544		2488	326	118	30	2340	207	296	119
	95,330	6970	546	564	20,262	782,74		513	51	0	0	355	85	6	118
	101,000	5670	574	584	16,426	86,571		543	23	12	6	450	88	41	5
	106,000	5000	1780	2238	21,218	261,584		1835	201	157	45	1634	179	179	246
	108,940	2940	1842	2278	14,132	270,418		1845	296	91	46	1777	46	137	318

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Spec. No: B-2-1B

AE - FATIGUE DATA

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Address Range	Total Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/PH	PEAK Time - μ sec.				Pulse Height - V			
								<1	1-3	3-7	>7	<1.6	1.6-2.5	2.5-3.5	>3.5
108940															
110460		1520	620	786	8890	115052		542	189	39	16	479	55	55	197
119770		4310	2260	3204	46460	385296		2659	256	160	129	2083	513	224	384
118290		3520	860	950	48072	123430		874	76	0	0	627	143	76	104
121200		2910	1308	1704	26529	209748		1568	136	0	0	1329	102	51	222
129580		3380	2240	3722	31352	457550		2047	1005	521	199	1898	186	558	1080
131700		7120	4450	7008	93058	877310		6027	981	0	0	3224	631	981	2172
132750		1050	942	2574	17208	29206	$\downarrow$	2291	283	0	0	1519	154	154	747
133090		290	268	624	5612	65534	$\downarrow$	537	87	0	0	306	44	44	230
160220		27180	25892	59280	363220	5545808		5395	4150	593	592	44462	4742	2371	7707
162550		2330	1520	3052	37544	276784		2777	275	0	0	1862	427	275	488
164250		1700	1422	3926	24556	430090		2295	445	480	206	2364	103	171	788
165940		1690	1602	4650	21262	562215		2836	651	418	745	2743	139	232	1536
167490		1550	1470	3908	24604	444974		3400	508	0	0	2032	117	195	1564
168700		1210	960	4238	18754	470114		3645	593	0	0	2246	254	339	1399

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Spec. No: B21-A

AE - FATIGUE DATA

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Address Range	Total Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	Δ D/E Event	Rise Time - μ sec.					Pulse Height - V				$\frac{2.5}{V_{avg}}$
								1	1-3	3-7	7-11	11-15	15-25	25-50	50-100	100-250	
0-33	9953	9953	8	8	106	757		7	1				5	3			
0-40	21957	12004	95	96	958	11704	325	84	10	2			75	19	2		
42-70	30410	8410	410	3144	4874	52337	6577	2705	220	5	11		2762	270	112		
72-94	37120	6710	981	5517	9960	131831	27153	5398	64	26	29		5357	137	10	13	.0023
0-22	43730	6610	445	464	2081	52670	527	381	23	34	26		371	84	6	3	.0064
24-39	48260	4530	570	643	2201	56243	7335	572	36	18	17		566	51	14	12	.0186
41-64	55170	6910	1149	1239	38010	158451	16979	931	128	82	98		814	177	77	171	.1380
66-80	59380	4210	302	315	5369	39810	1325	227	61	13	14		199	55	36	28	.0885
82-98	64200	4820	704	755	35102	93024	93224	594	103	41	17		501	154	20	74	.0780
100-113	68160	3960	994	1109	31264	134917	95569	841	154	96	18		760	194	33	122	.1100

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Spec. No: B-2-1-A

AE - FATIGUE DATA

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Address Range	Total Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	Δ D/E Event	Rise Time - μ sec.				Pulse Height - V				≥ 5 12.570
								< 1	1-3	3-7	> 7	4-12	12-50	5-15	2-5	
	68150															
0-39	72090	3911	879	945	2184	94635	1479	829	35	61	25	718	215	10	2	.0021
41-73	75400	3310	317	333	1184	34710	175	247	29	43	14	224	84	21	4	.0120
75-117	79610	4210	1014	1154	3311	119568	4528	512	233	301	108	520	276	354	4	.0034
119-150	82720	3110	2244	3267	6593	334753	5133	2205	344	426	292	2395	606	208	58	.0077
152-184	85940	3220	1453	1805	4285	168257	1808	990	554	183	78	911	530	277	87	.0481
186-200	87250	1310	1093	1558	3614	188198	3142	466	1026	35	31	377	180	77	924	.5930
1-28	89980	2730	1052	1248	3368	172527	644	1135	53	45	15	1090	138	19	1	.0008
31-61	93030	3050	1223	1536	5453	166375	1307	1156	153	187	40	1015	475	43	3	.0019
63-87	95588	2558	456	516	2505	60802	1214	388	93	24	11	358	70	55	33	.0039
89-115	98040	2452	2253	3359	11211	121332	3578	2682	238	311	128	2439	649	209	62	.0184
117-137	100050	2010	1226	1703	7697	201909	845	1120	223	153	207	1043	445	192	23	.0135
140-161	102150	2100	1000	1439	8966	171138	1115	1154	153	70	62	1109	239	86	10	.0069
164-181	103860	1710	1288	2358	13278	287835	3834	1734	329	137	156	1558	510	134	156	.0061

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Spec. No: 1-1A-2A

AE - FATIGUE DATA

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Address Range	Total Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	Δ D/E Event	Rise Time - μ sec.				Pulse Height - V			
								1	2	3	4	5	6	7	8
0-13															
18-60	4733	4733	77	78	302	6571	52	50	8	20	0	49	28	1	0
65-110	8439	4206	52	56	361	5268	31	28	2	26	0	25	25	6	0
113-149	13487	4548	75	75	3390	7769	134	68	2	5	0	63	12	0	0
	17180	3693	11	11	4760	1578	535	10	0	1	0	9	2	0	0
0-40	21265	4085	39	41	537	4133	12	35	0	6	0	34	7	0	0
0-182	23803	2538	10	12	102	916	9	11	0	1	0	10	2	0	0
188-344	42106	18303	94	94	256	6873	213	14	20	23	37	32	60	2	0
346-373	57781	15675	1	1	173	20	135	0	1	0	0	0	1	0	0
375-398	60558	2777	340	353	2471	3759	34	334	4	15	0	327	25	1	0
0-20	62949	2391	52	52	450	4117	29	34	0	15	3	30	21	1	0
0-45	65049	2100	607	621	2063	42313	803	235	262	63	61	256	360	25	0
47-89	69446	4397	616	621	1123	40685	910	354	98	66	105	363	148	20	0
	73793	4347	538	544	811	38423	16	180	85	263	16	135	339	20	0

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AE - FATIGUE DATA

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Address Range	Total Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	Δ D/E Event	Rise Time - μ sec.				Pulse Height - V			
0-30	73793														
34-66	76880	3087	1685	2506	2717	205731	1179	932	116	306	1152	918	268	1126	194
69-122	80358	3478	892	1302	1972	86399	336	952	146	89	115	871	305	61	65
125-151	85577	5219	2451	2658	3205	150098	183	1974	98	215	377	1801	423	313	121
0-20	88186	2609	2268	3622	4434	237859	687	2593	223	287	519	2275	753	407	187
25-44	90270	2084	1884	3654	3960	400356	1752	1698	723	445	738	1759	721	666	508
50-66	92178	1908	1443	2814	3131	251877	140	1406	87	271	1050	1371	342	316	785
73-88	93974	1796	1273	2185	2849	188600	154	1661	212	184	128	1545	384	146	60
0-15	95559	1585	1554	3799	3968	337902	56	2795	242	577	185	2829	496	338	136
19-47	97015	1456	1014	1710	2187	135441	122	1320	121	119	100	1305	261	105	39
52-60	99935	2920	2258	3180	4397	241653	108	2658	309	92	121	2274	728	139	19
63-71	100054	722	681	1690	2053	138400	263	1091	254	152	193	990	323	173	204
75-83	101481	824	770	1967	2470	162766	385	1282	117	161	407	1085	416	214	252
	102166	885	741	1616	2418	119320	72	1359	147	62	48	1246	272	77	21

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Address Range	Total Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	Δ D/E Event	Rise Time - μ sec.				Pulse Height - V			
86-93	102366	712	536	876	3672	66905	35	761	47	44	24	666	174	26	10
97-157	103078	548	528	1160	1733	100379	103	980	82	49	49	857	245	49	9
160-219	103626	590	589	1371	1818	145512	124	898	146	209	118	808	360	116	87
0-54	104216	549	295	363	375	13477	37	320	35	6	2	290	55	16	2
57-99	104765	432	205	236	244	13897	57	216	12	5	3	202	27	6	1
0-106	105197	1063	192	199	228	16056	308	153	16	19	9	133	50	15	1
109-512	106260	1620	94	98	106	7810	60	66	16	10	6	58	30	9	1
0-33	107880	338	183	261	271	17782	41	219	19	20	5	197	50	10	4
35-58	108218	242	120	156	158	8789	41	114	25	9	8	106	39	10	1
62-89	108460	270	84	101	195	10669	107	69	10	14	8	69	13	12	7
93-114	108720	219	31	33	41	2423	24	24	5	3	—	23	7	2	1
117-147	108949	302	81	125	492	21257	47	28	25	44	28	5	62	39	19
0-257	109251	1481	859	1558	2043	128457	64	638	848	62	10	1092	171	293	2
	110732														

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Spec. No: 1-1A-29

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[illegible]

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Spec. No: B2-1BAE - FRACTURE DATADate: 4-22-77Page 1 of 1

Time-Sec	Load	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/PH	PEAK Time - μ sec.				Pulse Height - V			
								≤ 1	1-3	3-7	> 7	≤ 1.6	1.6-2.5	2.5-5	> 5
0	0			0	0	0		0	0	0	0	0	0	0	0
216	180			10	320	1350		10	0	0	0	8	2	0	0
320	2200			8	124	1574		8	0	0	0	8	0	0	0
480	3100			22	62	3012		22	0	0	0	16	0	0	6
640	3220	A	A	28	54	4192	A	24	4	0	0	16	0	0	12
800	2960	N	N	6	6	642	N	4	2	0	0	2	0	0	4
960	2980			118	166	13998		95	23	0	0	42	0	6	70
1120	1860			86	100	8612		66	20	0	0	32	0	4	50
1344	220 Failure														

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Spec. No: B2-3BAE - FRACTURE
DATADate: 6-30-77Page 1 of 2

Time Sec.	Load	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/FH	PEAK Time - μ sec.				Pulse Height - V			
								A	B	C	D	A	B	C	D
0	0														
30	14,500			6	11.70	831		2	4	0	0	1	2	1	2
60	24,500			3	250	270		1	1	0	1	2	1	0	0
90	37,500			1	93	86		1	0	0	0	1	0	0	0
120	43,500			0	104	0		0	0	0	0	0	0	0	0
150	45,500			5	38	786		2	0	0	3	2	2	0	1
180	46,500			4	9	384		0	0	2	2	0	0	1	3
210	47,000	A	A	3	30	168	A	0	1	0	1	0	0	0	3
240	47,500	N	N	5	12	577	N	0	2	1	2	0	0	1	4
270	47,750			8	18	803		3	2	0	3	3	0	0	5
300	47,600			3	8	376		2	0	0	1	2	0	0	1
330	47,500			7	16	753		5	0	1	1	1	2	0	4
360	47,400			2	4	180		1	0	1	0	0	0	0	2
390	47,200			2	92	284		0	0	1	1	0	0	0	2
405	47,000			1	537	214		0	0	0	1	0	0	0	1

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Spec. No: B2-3BFRACTURE
AE - DATADate: 6-30-77Page 2 of 2

Time - Sec	Load Range	Load	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PI/PH	PEAK Time - μ sec.				Pulse Height - V			
									A	B	C		A	B	C	
405		47000			3	144	388		1	1	0	1	0	0	0	3
420		18,750			6	262	757		2	0	0	4	2	0	0	4
450		16,500			7	21	724		2	1	0	4	2	0	1	4
480		14,000			9	42	920		6	1	0	2	5	0	0	4
510		14,500			18	108	2713		9	2	0	7	9	1	0	8
540		8500			19	76	2121		3	1	1	14	3	0	3	13
570		0														

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Spec. No: B2-3AFRACTURE
AE - DATADate: 8-11-77Page 1 of 6

Time - Sec.	Load	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/PH	PEAK Time - μ sec.				Pulse Height - V			
								A	B	C		A	B	C	
0	0														
40	22000				1										
56	30600				4										
56	30600				3										
66	35200				3										
76	38900				11										
92	45000	N	N		3		N								
98	46100	N	N		10		N								
106	47100				3										
114	47500				3										
122	47800			2	5	299		2	0	0	0	0	1	0	1
132	4800			1	1	63		1	0	0	0		0	0	1
138	48100				1										
152	48200														
154	48100			2	2	202		1	0	0	1	2	0	0	0

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Spec. No: B2-3AAE ^{FRACTURE} ~~DATA~~ DATADate: 8-11-77Page 2 of 6

Address Range	Total Load	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/PH	PEAK Time - μ sec.				Pulse Height - V			
								≤ 1	1-3	5-10	> 10	≤ 1.25	1.25-2.5	2.5-5	> 5
Time-Sec.															
154	48100			1	2	55		1	0	0	0	0	1	0	0
160	48200				0										
162	48300				0										
164	48200			1	2	35		1	0	0	0	0	1	0	0
192	48300				0										
200	48200	N/A	N/A		1		N/A								
212	48100	N/A	N/A		1		N/A								
220	48100				6										
228	47900				2										
234	47800			3	3	293		1	1	0	1	0	1	1	1
246	47610				2										
252	47400				0										
260	47200				1										
270	47000														

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Spec. No: B2-3AFRACTURE
AE - ~~xxxxxx~~ DATADate: B-11-77Page 3 of 6

Time-Sec	Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/ PH	PEAK Time - μ sec.				Pulse Height - V			
								≤ 1	1-5	5-10	≥ 10	≤ 1.25	1.25-2.5	2.5-5	≥ 5
270	47000				1										
278	46800				0										
282	46600				0										
290	46400				0										
295	46200				0										
304	46000				0										
316	45500	N	N		1		N								
330	45000				1										
344	44500				3										
356	44000			1	1	197		1	0	0	0	0	1	0	0
380	43000			1	1	110		1	0	0	0	0	1	0	0
402	42000			1	5	177		0	1	0	0	0	0	0	1
422	41000			4	1	452		3	1	0	0	3	0	0	1
444	40000														

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Spec. No: B2-3AFRACTURE
AE - DATADate: 8-11-77Page 4 of 6

Address Range	Load Amplitude	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/ FH	PEAK Time - μ sec.				Pulse Height - V			
								2-1	1-5	5-10	7-10	5-12.5	12.5-25	25-50	50
Time-sec.															
444	40000				0										
456	39100				1										
574	38000				0										
578	39100				1										
584	39500	N/A	N/A	2	2	433	N/A	0	2	0	0	0	0	0	2
592	39000	N/A	N/A		0		N/A								
604	38000			4	6	421		3	0	1	0	2	0	1	1
624	37000				0										
638	35900			2	3	24		0	2	0	0	0	0	0	2
646	35100				1										
656	34100			1	1	254		1	0	0	0	1	0	0	0
670	33000			3	3	330		2	1	0	0	2	0	0	1
680	31900			3	4	419		1	1	0	1	0	1	0	2
690	31100														

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Spec. No: 82-3AAE - FRACTURE DATADate: 8-11-77Page 5 of 6

Time-sec	Load Cycles	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/PH	PEAK Time - μ sec.				Pulse Height - V			
								<1	1-5	5-10	>10	<1.25	1.25-2.5	2.5-5	>5
690	31100			5	5	624		3	0	1	1	2	0	1	2
706	30000			3	4	296		1	2	0	0	1	0	1	1
712	28900				1										
720	28200			6	6	911		2	4	0	0	0	0	1	5
726	27100			15	17	1919		14	1	0	0	13	0	2	0
738	26000	NA	NA	9	11	979	NA	2	1	1	5	0	1	0	8
746	25000			6	6	560		1	2	0	3	0	2	2	2
756	24000			4	4	472		0	4	0	0	0	3	1	0
770	22900				1										
778	22100			8	12	888		6	2	0	0	1	1	0	4
788	21000			1	2	224		0	1	0	0	0	1	0	0
790	20600			2	5	231		1	1	0	0	1	0	1	0
798	18000			4	5	676		0	1	0	3	0	1	0	3
FOR	16200														

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Spec. No: 82-3AAE - DATADate: 8-11-77Page 6 of 6

Time-sec	Load	Δ Load Cycles	Δ Valid Cycles	Δ Valid Event	Δ Total Event	Δ Valid Energy	PT/PH	PEAK Time - μ sec.				Pulse Height - V			
								5-1	1-5	5-10	7-10	5-125	125-25	25-5	25
808	16200			7	12	811		6	1	0	0	2	2	0	2
818	14200			9	15	923		7	1	1	0	6	0	0	3
828	11900			12	31	1527		8	3	1	0	5	2	1	4
894	9900			4	21	425		0	3	0	1	0	1	0	3
902	8100	A	A	3	13	339	A	1	1	0	1	0	0	1	2
922	6500	N	N	2	14	590	N	0	1	0	1	0	1	0	1
926	4400			1	16	255		0	1	0	0	0	1	0	0
928	2000				32										
940	0														

MECHANICAL TEST PROCEDURE

This section describes the test procedures associated with tensile, fracture and fatigue crack growth specimens. In general, test procedures as well as specimen design were dictated by the need to produce the best possible conditions for AE detection and measurement.

Tensile Test Procedure

All tensile tests were conducted in an Instron Tension/Compression 10,000 pound capacity test machine. The tests were conducted using a constant head travel rate to some point in the plastic range (2 to 10%) then a higher head travel rate thereafter. The higher head travel rate was used because little, if any AE occurred throughout the plastic range. Initial head travel rate was usually 0.002 inch/min. This relatively low rate was used to assure that 10 or more AE data samples (or update periods on the memories) would occur during its elastic and early elastic-plastic region. It was originally anticipated that large amounts of AE would occur in this region. Actually, little AE occurred anytime during testing of unnotched tensile specimens.

For elevated temperature tests (550°F), a two inch long, three zone control quartz tube radiant heat furnace was used. This length furnace covered the entire gage section and a portion of each shank of the test specimen but did not contact the specimen. This size furnace was used because it allowed the AE sensors to be maintained at < 200°F. Before AE monitoring was done, the system was calibrated using one sample with thermocouples at three points along its reduced section and one thermocouple on each adjacent thicker shank section. The survey was repeated three times to determine average control settings for each of the three sets of quartz lamps. All subsequent tests were conducted without any thermocouples attached to a given specimen. Attachment of thermocouples along with spot-welded thin metal foil covers to minimize biasing thermocouple readout, would have produced acoustic noise during testing. Test temperature levels based on the three surveys were about 550°F $\pm$ 40°F.

Fracture Toughness Test Procedure

Fracture toughness tests were conducted on size 2T-CT specimens. All specimens were tested in a 100 Kip electrohydraulic servocontrolled horizontally positioned test machine. Loads were applied using stroke control rather than the usual load control. A constant stroke rate was used throughout both gross elastic and gross plastic regions of the test. Periodic holds at a constant stroke position were used to cursorily inspect and assess the progress of the test. Constant stroke rate was used because it allowed potential AE data to be spaced more uniformly throughout the test. Use of load control would tend to cause accumulation of possible plastic region AE data in a few update periods of the AE instrumentation because the hydraulic cylinder would accelerate to meet the demand of a constant load rate in the plastic region. Stroke rate, between hold periods, was maintained at 0.067 inch/min.

Crack opening displacement (COD) was measured as a function of load until the COD gage range was exceeded. The COD gage feet were attached to the specimen using nylon screws and a 0.010 inch thick teflon sheet was placed between the specimen and the COD gage feet. This was done to minimize possible acoustic noise produced by rubbing of the COD gage leaves in their respective metal feet.

Around the same time that the COD gage range was exceeded the stroke range over which linear stroke rate occurred was also exceeded. This point occurred after the maximum load was reached. From then on the hydraulic cylinder was moved using manual control either until the specimen slowly tore apart or the hydraulic cylinder bottomed out.

Fatigue Crack Growth Test, Procedure

Fatigue crack growth tests were conducted on two 2T-CT specimens and one SEN specimen. All tests were conducted in the same 100 Kip electrohydraulic test machine described in the fracture toughness test procedure above.

Prior to FCG testing of either the 2T-CT specimens or the SEN specimen, unnotched specimens of the same geometry were tested first to determine the nature of the acoustic noise generated by high contact stresses between loading pins and holes and general test system noise. This provided an opportunity to determine that the source isolation AE system did not accept such noises. Testing conditions for notched 2T-CT specimen B2-1B are shown in Table A. Briefly the specimen was cyclic loaded between 1.87 Kip min and 18.7 Kip max at 3 Hz. After 5,760 cycles a small crack was detected on the 'W' or west side of the specimen. [Note that the crack length is an average of the length on both 'West' and 'East' sides of the specimen.] At 10,210 cycles the crack was 1.1819 inches long; the pins were also rotated 60° to try to minimize pin-noise. At 17,400 cycles the test was halted and a small crack was measured on both sides. Testing was continued and a crack length of 1.2053 inches was measured at 22,290 cycles; pins were also rotated to decrease pin noise. At 59,240 cycles the loads were changed from 18.7 Kip to 15 Kip max and > 1.87 Kip min load, to see if the large amount of pin noise could be reduced. Finally, after cycling at the original load levels to 63,260 cycles, the test was stopped because of our concern that excessive noise might saturate the isolation system. The specimen was removed from the machine, and grease fittings added to the front face of the specimen to allow grease to be added to the center region of the pin hole during testing. In addition the pin holes were bored larger and polished to accept grease-soaked transformer paper around the pin periphery. This has been found to be successful in reducing pin noise.

After machining was complete, the specimen was put back in the machine and load cycling continued as shown in Table A. Several load decreases and increases were incurred by the specimen and are noted in the table. Testing was halted after 168,700 cycles.

For the purposes of ease of analysis, the AE associated with the load drop at 124,850 cycles, the overloads at 132,749 and 133,040 cycles, and the load decrease at 133,041 to 160,220 cycles were omitted from the analysis. Crack length during the test was measured with two travelling

TABLE A

FATIGUE LOADING CONDITIONS FOR 1.75 INCH THICK 2T-CT SPECIMEN B2-1B

P_{max}	Load (Kips)		Cycle Rate (Hz)	Crack Length - a (Inches)	Load Cycles N	Comments
	P_{min}					
18.7	1.87		3	1.1755	0	
18.7	1.87		3	1.1755	5,760	Small crack, 'W' side
18.7	1.87		3	1.1819	10,210	rotated pins 60° cc
18.7	1.87		3	>1.1819	17,400	small crack, each side
18.7	1.87		3	1.2053	22,290	Rotated pins 60° cc
18.7	1.87		3	1.2412	35,710	
18.7	1.87		3	1.2860	47,770	
18.7	1.87		3	1.3485	59,240	
15	>1.87		3	1.3485	59,240	Reduce max load to examine pin noise
15	>1.87		3		59,380	
18.7	>1.87		3	1.3485	59,380	
18.7	1.87		3	1.3532	63,260	
Test stopped. Specimen holes bored out, greased transformer paper wrapped around loading pins, zerk grease fittings put on front specimen face to allow more rapid greasing of specimen holes.						
18.7	1.87		3	1.4018	71,750	
18.7	1.87		3	1.4673	79,850	
18.7	1.87		3	1.5387	88,380	
18.7	1.87		3	1.6224	95,320	Rotated pins and added grease
18.7	1.87		3	1.6668	101,000	
18.7	1.87		3	1.7250	106,000	Rotated pins and added grease
18.7	1.87		3	1.7844	110,460	Rotated pins
18.7	1.87		3	1.8537	114,770	
18.7	1.87		3	1.9094	118,920	
18.7	1.87		3	1.9622	121,200	
18.7	1.87		3	2.0284	124,850	
15.0	1.50		3	2.0284	124,850	Reduced load
				2.0873	131,700	
				2.0873	132,749	
					132,750	
					132,750	
18.7	1.87		3	2.0873	132,750	
18.7	1.87				133,040	
					133,041	Overload to arrest crack growth

Load (Kips)	Cycle Rate (Hz)	Crack Length - a (inches)	Load Cycles N	Comments
0.0	1.0	2.0873	133,041	
0.0	1.0	2.1303	160,220	
3.7	1.87	2.1303	160,220	Rotated pins, grease added.
3.7	1.87	2.1848	162,550	
3.7	1.87	2.2363	164,250	
3.7	1.87	2.2921	165,940	
3.7	1.87	2.3691	167,490	
3.7	1.87	2.4338	168,700	

TABLE B

FATIGUE LOADING CONDITIONS FOR 1.75 INCH THICK 2T-CT SPECIMEN B2-1A

$P_{\max}$	Load (Kips)		Cycle Rate (Hz)	Crack Length - a (inches)	Load Cycles N	Comments
	$P_{\min}$					
18.7	1.87		1	1.1823	0	
18.7	1.87		1	1.1823	440	
18.7	1.87		2	1.1823	440	
18.7	1.87		2	1.1823	3,000	
18.7	1.87		3	1.1823	9,980	
18.7	1.87		3	1.1973	14,430	Crack detected.
18.7	1.87		3	1.2243	22,000	
18.7	1.87		3	1.2675	30,410	Grease added.
18.7	1.87		3	1.3077	37,120	Rotated pins and grease added.
18.7	1.87		3	1.3519	43,730	
18.7	1.87		3	1.3881	48,260	
18.7	1.87		3	1.4307	55,170	Rotated pins and grease added.
18.7	1.87		3	1.4660	59,380	
18.7	1.87		3	1.5146	64,200	
18.7	1.87		3	1.5509	68,150	
18.7	1.87		3	1.5873	72,090	Rotated pins and grease added and put new paper around pins
18.7	1.87		3	1.6307	75,400	
18.7	1.87		3	1.6821	79,610	
18.7	1.87		3	1.7224	82,720	
18.7	1.87		3	1.7706	85,940	
18.7	1.87		3	1.7867	87,250	
18.7	1.87		3	1.8339	89,980	Pulled pins; paper intact; paper rotated
18.7	1.87		3	1.8920	93,030	
18.7	1.87		3	1.9394	95,588	
18.7	1.87		3	1.9939	98,040	
18.7	1.87		3	2.0506	100,050	
18.7	1.87		3	2.1034	102,150	
18.7	1.87		3	2.1546	103,860	
18.7	1.87		3	2.2003	105,107	Rotated pins, grease added.
18.7	1.87		3	2.2448	106,380	
18.7	1.87		3	2.3038	107,690	
18.7	1.87		3	2.3650	108,810	
18.7	1.87		3	2.4132	109,710	Testing completed.

TABLE C

FATIGUE LOADING CONDITIONS FOR 3% PRESTRAIN SEN SPECIMEN 1-1A-2A

P _{max}	Load (Kips)		Cycle Rate (Hz)	Crack Length - a (Inches)	Load Cycles N	Comments
	P _{min}					
61	6.1		4	.5121	D	
61	6.1		4	.5405	4,730	
61	6.1		4	.5577	8,960	
61	6.1		4	.6305	13,530	
61	6.1		4	.6884	17,230	
61	6.1		4	.7616	21,490	
61	6.1		4	.8073	24,070	
40	4.0		4	.8073	24,070	Decreased load because initial da/dN too high
40	4.0		4	.8340	42,640	
40	4.0		4	.9318	58,330	
40	4.0		4		61,130	Rotate pins
40	4.0		4	.9904	63,530	
40	4.0		4	1.0091	65,900	Degreased pins and bushings
40	4.0		4	1.0594	70,380	
40	4.0		4	1.1153	74,730	
40	4.0		4	1.1567	77,550	
40	4.0		4	1.2097	81,350	
40	4.0		4	1.2975	86,580	
40	4.0		4	1.3457	89,260	
42	4.2		4	1.3457	89,260	Increased loads
42	4.2		4	1.3945	91,350	
42	4.2		4	1.4481	93,260	
42	4.2		4	1.5016	94,960	
44	4.4		4	1.5016	94,960	Increased loads
			4	1.5542	96,520	
			4	1.6105	97,980	
44	4.4		4	1.7308	100,900	
46	4.6		2	1.7308	100,900	Increased loads and decreased cycling rate because of high da/dN
			2	1.7835	101,620	
			2	1.8355	102,440	
			2	1.9017	103,330	
46	4.6		2	1.9557	104,040	
46	4.8		2	1.9557	104,040	
				2.0220	104,620	
48	4.8			2.0916	105,210	0.035" permanent set to C.O.D.
48	9.2			2.0916	105,210	Increase minimum load
48	9.8		2	2.2218	106,200	
48	20		1	2.2218	106,200	Increased minimum load
48	20		1	2.3195	107,820	

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stage 32X microscopes with a least dial division of 0.0001 inch.

Fatigue loading conditions for the 2T-CT specimen B2-1A are shown in Table B. This test was begun with grease fittings and grease-soaked transformer paper around the loading pins. Thus this test required fewer interruptions. Testing procedure and crack measuring equipment were the same as for specimen B-2-1B.

Prior to notching, SEN specimen 1-1A-2A's 18 inch long reduced section was elongated 0.590 inch or approximately 3.3%. Loading was conducted in a 440 Kip hydraulic test machine. After pre-straining the specimens width and thickness was 4.923 inches and 0.482 inch, respectively.

Fatigue crack growth testing was started after initial load cycling without a notch, (see above). Fatigue loading conditions and comments during testing are noted in Table C. The AE source isolation system was restricted during this test to accept acoustic signals generated 1/2 inch on either side of the notch.

AE-FRACTURE MECHANICS ANALYSIS PROCEDURE

The purpose of this section is to describe a statistical method used for comparing mechanical test data with AE data and rating the "goodness of fit" of the data to different models. This approach is important to our long term goal of establishing AE-flaw growth relationships that could be used for monitoring an operating reactor.

A statistical method is useful for several reasons. First there are no well-defined cogent analytical models for relating AE to flaw growth during fatigue. Thus, one can not know a priori, which fatigue crack growth (FCG) or linear elastic fracture mechanics (LEFM) parameters best describes and correlates with AE parameters. Second, the nature of acoustic and mechanical behavior of test specimens leads to comparing of AE data with its inherent scatter, to FCG (and fracture) data also with its inherent scatter. Thus statistical analysis of the data assists in AE-LEFM model development while simultaneously accounting for acoustic and mechanical test data scatter.

There are a number of AE and mechanical test variables that may be selected and compared for model development. So far we have considered:

AE energy

AE event count - total ($H_1+H_2+H_3+H_4$)

AE event count partitioned into four event signal amplitude ranges (H_1, H_2, H_3, H_4)

AE event count partitioned into four different ranges of event signal amplitude (R_1, R_2, R_3 , and R_4)

a, crack length

N, number of load cycles

A, crack area swept out

V_p theoretical volume of the crack tip plastic zone

K stress intensity factor, and

ΔK range of stress intensity factor.

Within this list of variables, we have, thus far, examined as many as 30 combinations of these variables (usually in a rate form) primarily with da/dN sometimes with ΔK or K_{max} (see section 3.3.4.3). For purposes of analysis an AE parameter is considered the dependent variable, and mechanical parameter as the independent variable. Sometimes both AE and mechanical parameters are combined and compared with a mechanical parameter such as da/dN . Here the latter is considered the independent variable, the former, dependent. Finally, after the statistical method is described below, an example is presented using fatigue crack growth data, da/dN and ΔK .

In fracture mechanics, the fatigue crack growth rate per cycle (da/dN) can be related to stress intensity factor range (ΔK) using the well known power law relation,

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

where C and m are constants.

Similarly, acoustic emission (AE) parameters may be related to fatigue crack growth rate (da/dN) using a power law equation

$$f(AE) = A(da/dN)^n \quad (2)$$

where A and n are constants and $f(AE)$ can be some AE parameter rate per cycle, per unit plastic volume ahead of the crack tip or per crack area change.

We have arbitrarily selected a power law relationship to fit AE and da/dN parameters because of the good power law fit between da/dN and ΔK . As more AE data is obtained over a wide range of da/dN values, it is possible that other models will have to be considered.

The power equation has a general form

$$\hat{Y} = AX^B \quad (3)$$

where $\hat{Y}$ is the estimated values of the AE parameter for an observed value of X or da/dN.

Equation (3) can be readily transposed in a linear form by logarithmic transformation

$$\log \hat{Y} = \log A + B \log X \quad (4)$$

The least-squares line corresponding to the transformation of (3) minimizes the squares of the deviations of $\log Y$ from $\log \hat{Y}$, and not the squares of the deviations of Y from $\hat{Y}$, where Y are actual recorded values of the dependent variable, da/dN in this case.

The normal equations of the least-squares regression line of $\log Y$ on $\log X$ are:

$$\sum \log Y_i = AN + B \sum \log X_i$$

$$\sum \log X_i \log Y_i = A \sum \log X_i + B \sum \log X_i^2$$

where N = number of data pairs $\log X_i$, $\log Y_i$, which yield:

$$\log A = \frac{(\sum \log Y_i) (\sum \log X_i^2) - (\sum \log X_i) (\sum \log X_i \log Y_i)}{N \sum \log X_i^2 - (\sum \log X_i)^2} \quad (4a)$$

$$\log B = \frac{N \sum \log X_i \log Y_i - (\sum \log X_i) (\sum \log Y_i)}{N \sum \log X_i^2 - (\sum \log X_i)^2}$$

From the least-squares solution, the correlation coefficient r can be calculated, using the formula

$$r = \frac{\sum (\log X_i)(\log Y_i) - \frac{(\sum \log X_i)(\sum \log Y_i)}{N}}{\left\{ \left[\frac{\sum (\log X_i^2) - \frac{(\sum \log X_i)^2}{N}}{N} \right] \left[\frac{\sum (\log Y_i^2) - \frac{(\sum \log Y_i)^2}{N}}{N} \right] \right\}^{1/2}} \quad (5)$$

where N = number of data pairs $\log X_i$, $\log Y_i$. When there is perfect correlation between $\log X$ and $\log Y$, there is no residual deviation of Y

from $\hat{Y}$, and r equals ± 1.0 . When there is no correlation, r equals 0. Negative values of the correlation coefficient indicate a negative slope.

The correlation coefficient now allows us a measure of the "degree of fit" between $\log X_i$ and $\log Y_i$. Because of varying numbers of points between tests (often less than 20) it is useful to use both ' r ' and the number of data points for comparing AE with mechanical data. This is statistically useful as a greater number of data points provide a greater degree of confidence for comparing the various AE-LEFM models. For example, for equal r 's and unequal data points, transformation of r to Student's ' t ' allows a quantitative measure of correlation.

If the hypothesis is made that the correlation coefficient is equal to zero, r is related to Student's t (RA Fisher, "Statistical Methods for Research Workers", Oliver and Boyd, Edaburgh and London, 1948) according to the following formula,

$$t = r \sqrt{\frac{N-2}{1-r^2}} \quad (6)$$

where N = number of data points. Then the probability level at the corresponding degree of freedom ($N-2$) based on the hypothesis that there is no correlation between the two variables involved can be calculated. This probability level (in percent) indicates the chance of getting a value of r as large as calculated (eq. 5) when there is no correlation. In other words, the hypothesis that there is no correlation may be rejected with the chance of being wrong equal to the calculated probability level in percent. An example using percent correlation and a power equation is shown in the example later in this section.

The physical meaning of the term ' r ' is best explained in the following discussion. In linear regression, it is assumed that the independent variable, X , is exact and that the dependent variable, Y , has a random error normally distributed throughout the range of the observations. This is called the regression line of Y on X . The line obtained when X is selected as the dependent variable is call the regression line of X on Y .

It can be shown that the slopes of these two lines are equal if, and only if, $r = \pm 1.0$. If $r = 0$, there is no correlation between the variables and the two lines are at right angles to each other. Thus, the correlation coefficient measures the departures of the two regression lines and can be used to establish confidence limits of the regression line.

In addition to using r , some statisticians utilize r^2 . This term is more general in nature and applies to all types of regressions.

The square of the correlation coefficient r^2 is called the coefficient of determination, and is the ratio of the variation explained by the linear model to the total variation, or

$$r^2 = \frac{(\log Y_{\text{est}} - \overline{\log Y})^2}{(\log Y_i - \overline{\log Y})^2} \quad (7)$$

where

Y (or $\log Y$) is the recorded value of the dependent variable

$\overline{Y}$ (or $\overline{\log Y}$) is the mean of Y (or $\log Y$)

Y_{est} (or $\log Y_{\text{est}}$) is the calculated value of the dependent variable from the regression line.

Equation 7 is algebraically equivalent to (5) in a more general nature.

Equation (5) is used herein because of its simplicity for computation using small, programmable calculators.

An example calculation using a listing of ΔK and $\frac{da}{dN}$ values from specimen B2-1B are shown in the following table.

$Y_i = \frac{da}{dN}$	$X_i = \Delta K$	$\text{Log } \left(\frac{da}{dN}\right)$	$\text{Log } (\Delta K)$	$\left[\text{Log } \left(\frac{da}{dN}\right)\right]^2$	$\left[\text{Log } (\Delta K)\right]^2$	$\frac{\text{Log } \left(\frac{da}{dN}\right)}{\text{Log } (\Delta K)}$
8.35×10^{-6}	33.20	-5.07831	1.52114	25.78923	2.31387	-7.72482
9.71×10^{-6}	34.61	-5.01278	1.53920	25.12796	2.36914	-7.71567
10.72×10^{-6}	36.03	-4.96981	1.55666	24.69901	2.42319	-7.73630
11.64×10^{-6}	37.43	-4.93405	1.57322	24.34485	2.47534	-7.76284
13.32×10^{-6}	38.93	-4.87550	1.59028	23.77050	2.52899	-7.75341
16.08×10^{-6}	40.64	-4.79371	1.60895	22.97966	2.58872	-7.71284
15.82×10^{-6}	42.35	-4.80079	1.62685	23.04758	2.64664	-7.81017
18.14×10^{-6}	44.07	-4.74136	1.64414	22.48049	2.70320	-7.79546
19.59×10^{-6}	46.04	-4.70797	1.66314	22.16498	2.76603	-7.83001
23.30×10^{-6}	52.18	-4.63264	1.71750	21.46135	2.94981	-7.95656
30.29×10^{-6}	54.71	-4.51870	1.73807	20.41865	3.02089	-7.85382
33.02×10^{-6}	57.26	-4.48122	1.75785	20.08133	3.09004	-7.87731
49.68×10^{-6}	60.96	-4.30382	1.78504	18.52287	3.18637	-7.68249
53.47×10^{-6}	65.11	-4.27189	1.81365	18.24904	3.28933	-7.74771
		-66.12255	23.13569	313.13750	38.35156	-108.95941

$$\text{Log } A = \frac{(-66.12255)(38.35156) - (23.13569)(-108.95941)}{(14)(38.35156) - (23.13569)^2} = \frac{-15.05181}{1.66169} = 9.05814$$

$$A = 8.747 \times 10^{-10}$$

$$B = \frac{(14)(-108.95941) - (23.13569)(-66.12255)}{(14)(38.35156) - (23.13569)^2} = \frac{4.35908}{1.66169} = 2.623$$

The equation relating da/dN to ΔK (eq. 3) is

$$\frac{da}{dN} = 8.747 \times 10^{-10} (\Delta K)^{2.623}$$

From equation (5) the correlation coefficient is,

$$r = \frac{(108.95941) - \frac{(-66.12255)(23.13569)}{14}}{\left\{ \left[\frac{(38.35156) - \frac{(23.13569)^2}{14}}{14} \right] \left[\frac{(313.13750) - \frac{(-66.12255)^2}{14}}{14} \right] \right\}^{1/2}} = \frac{.31135}{.31540} = .98719$$

from equation 6,

$$t = 0.98719 \sqrt{\frac{14-2}{1-(.98719)^2}} = 21.4337$$

From the table, a value of t as great as 21.4337 for 12 degrees of freedom indicates a change of correlation between da/dN and ΔK being much greater than 99.9%.

This approach has been applied to relating AE and LEFM data and for purposes of rating which model appears best. These percentage correlation values do not indicate that the functional relationship is exact; they are just a relative measure of the dependency of the two variables.

To obtain the term r^2 using equation (7), we utilize the same da/dN - ΔK data and the estimated value of da/dN from equation (3) where

$$\frac{da}{dN} = Y_{\text{est}} = 8.747 \times 10^{-10} (\Delta K)^{2.623} \text{ and,}$$

$$\log \frac{da}{dN} = -66.1225/14 = -4.72304$$

The following table is a compilation of terms necessary to obtain r^2 from equation 7. $\bar{Y}$ is taken from the previous table as $\bar{Y} = \frac{-66.12255}{14} = -4.72304$.

45.11	20.000000	7.000000	15.11
45.20	25.000000	7.000000	15.20
45.30	30.000000	7.000000	15.30
45.40	35.000000	7.000000	15.40
45.50	40.000000	7.000000	15.50
46.00	45.000000	7.000000	16.00
46.10	50.000000	7.000000	16.10
46.20	55.000000	7.000000	16.20
46.30	60.000000	7.000000	16.30
46.40	65.000000	7.000000	16.40
46.50	70.000000	7.000000	16.50
47.00	75.000000	7.000000	17.00
47.10	80.000000	7.000000	17.10
47.20	85.000000	7.000000	17.20
47.30	90.000000	7.000000	17.30
47.40	95.000000	7.000000	17.40
47.50	100.000000	7.000000	17.50
48.00	105.000000	7.000000	18.00
48.10	110.000000	7.000000	18.10
48.20	115.000000	7.000000	18.20
48.30	120.000000	7.000000	18.30
48.40	125.000000	7.000000	18.40
48.50	130.000000	7.000000	18.50
49.00	135.000000	7.000000	19.00
49.10	140.000000	7.000000	19.10
49.20	145.000000	7.000000	19.20
49.30	150.000000	7.000000	19.30
49.40	155.000000	7.000000	19.40
49.50	160.000000	7.000000	19.50
50.00	165.000000	7.000000	20.00
50.10	170.000000	7.000000	20.10
50.20	175.000000	7.000000	20.20
50.30	180.000000	7.000000	20.30
50.40	185.000000	7.000000	20.40
50.50	190.000000	7.000000	20.50
51.00	195.000000	7.000000	21.00
51.10	200.000000	7.000000	21.10
51.20	205.000000	7.000000	21.20
51.30	210.000000	7.000000	21.30
51.40	215.000000	7.000000	21.40
51.50	220.000000	7.000000	21.50
52.00	225.000000	7.000000	22.00
52.10	230.000000	7.000000	22.10
52.20	235.000000	7.000000	22.20
52.30	240.000000	7.000000	22.30
52.40	245.000000	7.000000	22.40
52.50	250.000000	7.000000	22.50
53.00	255.000000	7.000000	23.00
53.10	260.000000	7.000000	23.10
53.20	265.000000	7.000000	23.20
53.30	270.000000	7.000000	23.30
53.40	275.000000	7.000000	23.40
53.50	280.000000	7.000000	23.50
54.00	285.000000	7.000000	24.00
54.10	290.000000	7.000000	24.10
54.20	295.000000	7.000000	24.20
54.30	300.000000	7.000000	24.30
54.40	305.000000	7.000000	24.40
54.50	310.000000	7.000000	24.50
55.00	315.000000	7.000000	25.00
55.10	320.000000	7.000000	25.10
55.20	325.000000	7.000000	25.20
55.30	330.000000	7.000000	25.30
55.40	335.000000	7.000000	25.40
55.50	340.000000	7.000000	25.50
56.00	345.000000	7.000000	26.00
56.10	350.000000	7.000000	26.10
56.20	355.000000	7.000000	26.20
56.30	360.000000	7.000000	26.30
56.40	365.000000	7.000000	26.40
56.50	370.000000	7.000000	26.50
57.00	375.000000	7.000000	27.00
57.10	380.000000	7.000000	27.10
57.20	385.000000	7.000000	27.20
57.30	390.000000	7.000000	27.30
57.40	395.000000	7.000000	27.40
57.50	400.000000	7.000000	27.50
58.00	405.000000	7.000000	28.00
58.10	410.000000	7.000000	28.10
58.20	415.000000	7.000000	28.20
58.30	420.000000	7.000000	28.30
58.40	425.000000	7.000000	28.40
58.50	430.000000	7.000000	28.50
59.00	435.000000	7.000000	29.00
59.10	440.000000	7.000000	29.10
59.20	445.000000	7.000000	29.20
59.30	450.000000	7.000000	29.30
59.40	455.000000	7.000000	29.40
59.50	460.000000	7.000000	29.50
60.00	465.000000	7.000000	30.00
60.10	470.000000	7.000000	30.10
60.20	475.000000	7.000000	30.20
60.30	480.000000	7.000000	30.30
60.40	485.000000	7.000000	30.40
60.50	490.000000	7.000000	30.50
61.00	495.000000	7.000000	31.00
61.10	500.000000	7.000000	31.10
61.20	505.000000	7.000000	31.20
61.30	510.000000	7.000000	31.30
61.40	515.000000	7.000000	31.40
61.50	520.000000	7.000000	31.50
62.00	525.000000	7.000000	32.00
62.10	530.000000	7.000000	32.10
62.20	535.000000	7.000000	32.20
62.30	540.000000	7.000000	32.30
62.40	545.000000	7.000000	32.40
62.50	550.000000	7.000000	32.50
63.00	555.000000	7.000000	33.00
63.10	560.000000	7.000000	33.10
63.20	565.000000	7.000000	33.20
63.30	570.000000	7.000000	33.30
63.40	575.000000	7.000000	33.40
63.50	580.000000	7.000000	33.50
64.00	585.000000	7.000000	34.00
64.10	590.000000	7.000000	34.10
64.20	595.000000	7.000000	34.20
64.30	600.000000	7.000000	34.30
64.40	605.000000	7.000000	34.40
64.50	610.000000	7.000000	34.50
65.00	615.000000	7.000000	35.00
65.10	620.000000	7.000000	35.10
65.20	625.000000	7.000000	35.20
65.30	630.000000	7.000000	35.30
65.40	635.000000	7.000000	35.40
65.50	640.000000	7.000000	35.50
66.00	645.000000	7.000000	36.00
66.10	650.000000	7.000000	36.10
66.20	655.000000	7.000000	36.20
66.30	660.000000	7.000000	36.30
66.40	665.000000	7.000000	36.40
66.50	670.000000	7.000000	36.50
67.00	675.000000	7.000000	37.00
67.10	680.000000	7.000000	37.10
67.20	685.000000	7.000000	37.20
67.30	690.000000	7.000000	37.30
67.40	695.000000	7.000000	37.40
67.50	700.000000	7.000000	37.50
68.00	705.000000	7.000000	38.00
68.10	710.000000	7.000000	38.10
68.20	715.000000	7.000000	38.20
68.30	720.000000	7.000000	38.30
68.40	725.000000	7.000000	38.40
68.50	730.000000	7.000000	38.50
69.00	735.000000	7.000000	39.00
69.10	740.000000	7.000000	39.10
69.20	745.000000	7.000000	39.20
69.30	750.000000	7.000000	39.30
69.40	755.000000	7.000000	39.40
69.50	760.000000	7.000000	39.50
70.00	765.000000	7.000000	40.00
70.10	770.000000	7.000000	40.10
70.20	775.000000	7.000000	40.20
70.30	780.000000	7.000000	40.30
70.40	785.000000	7.000000	40.40
70.50	790.000000	7.000000	40.50
71.00	795.000000	7.000000	41.00
71.10	800.000000	7.000000	41.10
71.20	805.000000	7.000000	41.20
71.30	810.000000	7.000000	41.30
71.40	815.000000	7.000000	41.40
71.50	820.000000	7.000000	41.50
72.00	825.000000	7.000000	42.00
72.10	830.000000	7.000000	42.10
72.20	835.000000	7.000000	42.20
72.30	840.000000	7.000000	42.30
72.40	845.000000	7.000000	42.40
72.50	850.000000	7.000000	42.50
73.00	855.000000	7.000000	43.00
73.10	860.000000	7.000000	43.10
73.20	865.000000	7.000000	43.20
73.30	870.000000	7.000000	43.30
73.40	875.000000	7.000000	43.40
73.50	880.000000	7.000000	43.50
74.00	885.000000	7.000000	44.00
74.10	890.000000	7.000000	44.10
74.20	895.000000	7.000000	44.20
74.30	900.000000	7.000000	44.30
74.40	905.000000	7.000000	44.40
74.50	910.000000	7.000000	44.50
75.00	915.000000	7.000000	45.00
75.10	920.000000	7.000000	45.10
75.20	925.000000	7.000000	45.20
75.30	930.000000	7.000000	45.30
75.40	935.000000	7.000000	45.40
75.50	940.000000	7.000000	45.50
76.00	945.000000	7.000000	46.00
76.10	950.000000	7.000000	46.10
76.20	955.000000	7.000000	46.20
76.30	960.000000	7.000000	46.30
76.40	965.000000	7.000000	46.40
76.50	970.000000	7.000000	46.50
77.00	975.000000	7.000000	47.00
77.10	980.000000	7.000000	47.10
77.20	985.000000	7.000000	47.20
77.30	990.000000	7.000000	47.30
77.40	995.000000	7.000000	47.40
77.50	1000.000000	7.000000	47.50
78.00	1005.000000	7.000000	48.00
78.10	1010.000000	7.000000	48.10
78.20	1015.000000	7.000000	48.20
78.30	1020.000000	7.000000	48.30
78.40	1025.000000	7.000000	48.40
78.50	1030.000000	7.000000	48.50
79.00	1035.000000	7.000000	49.00
79.10	1040.000000	7.000000	49.10
79.20	1045.000000	7.000000	49.20
79.30	1050.000000	7.000000	49.30
79.40	1055.000000	7.000000	49.40
79.50	1060.000000	7.000000	49.50
80.00	1065.000000	7.000000	50.00
80.10	1070.000000	7.000000	50.10
80.20	1075.000000	7.000000	50.20
80.30	1080.000000	7.000000	50.30
80.40	1085.000000	7.000000	50.40
80.50	1090.000000	7.000000	50.50
81.00	1095.000000	7.000000	51.00
81.10	1100.000000	7.000000	51.10
81.20	1105.000000	7.000000	51.20
81.30	1110.000000	7.000000	51.30
81.40	1115.000000	7.000000	51.40
81.50	1120.000000	7.000000	51.50
82.00	1125.000000	7.000000	52.00
82.10	1130.000000	7.000000	52.10
82.20	1135.000000	7.000000	52.20
82.30	1140.000000	7.000000	52.30
82.40	1145.000000	7.000000	52.40
82.50	1150.000000	7.000000	52.50
83.00	1155.000000	7.000000	53.00
83.10	1160.000000	7.000000	53.10
83.20	1165.000000	7.000000	53.20
83.30	1170.000000	7.000000	53.30.

$x_i = \Delta K$	$y_{est} = \frac{da}{dN}$	$\text{Log } y_{est}$	$\text{Log } y_{est} - \bar{Y}$	$(\text{Log } y_{est} - \bar{Y})^2$	$\text{Log } y_i = \frac{da}{dN}$	$\text{Log } y_i - \bar{Y}$	$(\text{Log } y_i - \bar{Y})^2$
33.20	8.555×10^{-6}	-5.06777	-.34473	.11884	-5.07831	-.35527	.12622
34.61	9.541×10^{-6}	-5.02039	-.29735	.08842	-5.01278	-.28974	.08395
36.03	10.603×10^{-6}	-4.97458	-.25154	.06327	-4.96981	-.24677	.06090
37.43	11.718×10^{-6}	-4.93115	-.20811	.04331	-4.93405	-.21101	.04453
38.93	12.990×10^{-6}	-4.88638	-.16334	.02668	-4.87550	-.15246	.02324
40.64	14.541×10^{-6}	-4.83741	-.11437	.01308	-4.79371	-.07067	.00499
42.35	16.201×10^{-6}	-4.79045	-.06741	.00454	-4.80079	-.07775	.00605
44.07	17.985×10^{-6}	-4.74510	.02206	.00049	-4.74136	-.01832	.00034
46.04	20.171×10^{-6}	-4.69528	.02776	.00077	-4.70797	.01507	.00023
52.18	28.012×10^{-6}	-4.55265	.17039	.02903	-4.63264	.09040	.00817
54.71	31.717×10^{-6}	-4.49871	.22433	.05032	-4.51870	.20434	.04175
57.26	35.743×10^{-6}	-4.44681	.27623	.07630	-4.48122	.24182	.05848
60.96	42.124×10^{-6}	-4.37547	.34757	.12080	-4.30382	.41922	.17574
65.11	50.068×10^{-6}	-4.30044	.42260	.17859	-4.27189	.45115	.20354
$\Sigma_{i=1}^{14}$				.81494			.83813

From Equation (7)

$$r^2 = \frac{.81444}{.83813} = .97173 \text{ (} r = .98577 \text{)}$$

The difference in 'r' value from equation 7 as compared to 'r' from equation 5 is due to rounding off of Y_{est} values and its logarithmic values.

Equation (1)

$$h = \frac{0.001}{0.001 + 0.001} = 0.5$$

The difference in h value from equation 2 is compared to the h value from equation 1. The difference is 0.5, which is the same as the h value from equation 1. This is due to rounding off of h values and the logarithmic values.

APPENDIX B
AE LIBRARY SUMMARIES

17TH ACOUSTIC EMISSION WORKING GROUP MEETING
LAWRENCE LIVERMORE LABORATORY
LIVERMORE, CA, 6/14-16/77

The purpose here is to summarize topics discussed at the subject meeting which are relevant to the NRC-PNL program for AE flaw characterization.

- ASME Code - J. G. Rawlings

ASME feels that more application data is essential prior to incorporating AE methods in a code. Action is being taken to initiate a "data bank" to accumulate pertinent application data from any source.

- On-Line AE Monitoring at the Peachbottom Nuclear Power Plant - W. F. Hartman

A 26-channel computerized Trodyne AE monitor system installed on Peachbottom III piping. Plan a one-year experimental study of how AE can benefit availability of a nuclear power plant. Data (signal Δ time, amplitude, count and location of AE signals plus vibration and temperature) will be collected and correlated with other information from normal inspection. Using high temperature pressure coupled sensors with no intermediate couplant. Started with 200-800 kHz sensors but are changing to 400-800 kHz sensors to alleviate a background noise problem.

- AE Application Update for Nuclear Plants - R. Gopal

Westinghouse has had an eight-year program on application of AE to reactor monitoring. The objectives are to develop:

- leak detection and location,
- crack growth detection and location, and
- loose parts detection and location.

Also studying AE data interpretation focusing on relation to stress intensity factor "K."

Claim five years experience with sensors pressure coupled on a reactor. No deterioration of sensitivity evidenced.

- AE Detected, Located, and Ultrasonically Confirmed on a Reactor Vessel - A. E. Green

Described Acoustic Emission Technology work in monitoring a reactor vessel hydrotest. Showed very high correlation between AE indications and subsequent ultrasonic confirmation. Details of work contained in Electric Power Research Institute Report No. RP-488.

- NRC Program for AE Flaw Characterization - P. H. Hutton

Described the NRC-PNL program and its objectives. Described specifically the method developed for rating AE system sensitivity in terms of μ bar input to the sensor. There were no negative comments. Purpose of rating is to make test results generally relatable to other AE systems.

- Acoustic Emission Monitoring of Fatigue Crack Growth - I. G. Palmer

Described work being done at Lockheed Palo Alto Research Lab on study of fatigue crack growth. Raw data appeared very similar to that observed in PNL work. Palmer has been working with signal amplitude. Finds that it appears to fit a power law relation to crack growth. Attributed signals occurring near minimum load on rising load side to crack interface noise. This triggered considerable discussion. Although no one had positive evidence of the source of these signals, there was substantial agreement that circumstantially they did not fit a logical pattern for crack interface noise.

- Metallurgical Effects on AE - S. H. Carpenter

Work done at the University of Denver with 1018 steel shows AE to be a function of internal damping and strain rate. Relation holds for samples both parallel and perpendicular to the rolling direction. Does not appear to apply to non-ferritic materials.

- AE Source Identification in Low Alloy Steels - K. Ono

UCLA work with 1018 steel leads Ono to the conclusion that inclusions are a major contributor to burst AE.

- Experimental Consideration for AE Proof Testing of Composite Pressure Vessels - M. Hamstad

Although this work at Lawrence Livermore Lab concerned composites, two points were of general applicability. The sensitivity of a standard Dunegan/Endevco S140A sensor was increased by a factor of 2-1/2 by machining away part of the wear face to leave a pedestal about 1/4" in diameter in the center of the sensor face. He did not have any information on whether this changed the sensor frequency characteristics.

A unique method of AE energy measurement had been developed using a Hewlett-Packard 3400A voltmeter. Although there are limitations on

signal density that can be processed, it is a relatively simple method for measuring AE energy. Details of the work are contained in LLL Report No. UCRL-79356.

- A Comparison of Optically and Piezoelectrically Sensed AE Signals - R. A. Kline

In this work being done at John Hopkins University, to date, there has appeared to be little difference between optical and piezoelectric AE signals. Piezoelectric signals tend to "ring down" longer. Material is 4340 steel. Out of 200 signals examined so far, 500 KHZ seems to be about the upper limit of significant components in the frequency regime.

- Continued Work on AE Weld Monitoring - W. Lichodziejewski

Reviewed the work being done by GARD under NRC sponsorship for nuclear weld monitoring. Feel that delay time and signal amplitude are useful parameters in defect identification. Showed very impressive success statistics for work to date.

- Transient Response of an Elastic Plate - J. Simmons

Described the EPRI-NBS program investigating detail signal analysis techniques for definition of AE sources. They will be working only with idealized mediums--not structural materials--for the present. This is a long term and very basic investigation. It does not appear that there will be an early return in the practical area.

NRC ACOUSTIC EMISSION CHARACTERIZATION PROGRAM
LIBRARY AE R&D LITERATURE

Acoustic Emission from a Defective C/Mn Steel Pressure Vessel

A.C.E. Sinclair, C.L. Formby, D.C. Connors, Central Electricity Generating Board, Research Department, Berkeley Nuclear Laboratories, UK, April 1974, Report No. RD/B/N2976

Work discussed in this report concerns measurement and analysis of AE from a steel pressure vessel tested to failure. The vessel was 5 ft in diameter by 12 ft long with a 1 in. wall thickness. A defect was machined in the outer surface along the longitudinal axis. The defect was 0.65 in. deep by 14½ in. long. Specification of the steel is:

Composition	C	Si	S	P	Mn	Ni	Cr	Mo	Cu	Sn
Wt. %	.145	.21	.023	.024	.90	.12	.185	.025	.23	.021

Yield Stress - 35.8 Kip

Ultimate Stress - 62.9 Kip

In the introduction, the authors state that attainment of remote assessment of defect severity by AE requires determination of the character and amplitude of emissions plus dependence on material, stress conditions, thermal history, corrosion effects, and nuclear effects.

A four sensor array of surface mounted PZT-5-A sensors located near the defect was used. Pressure, crack opening, and AE event rate from one sensor were recorded during pressurization. Three sensors were used for source location. Peak sensor response was at 165 kHz with a 30 kHz bandwidth. Sensors were magnetically mounted with a grease couplant. A discriminator circuit limited accepted signals to those > 25 µsec. long above a preset threshold. The discriminator also required that there not be a detected signal within 2.5 milliseconds prior to an accepted signal. These limits were used to eliminate multiple counts from a single multiple peak signal. Stated that only Lamb wave mode signals were detected by the sensors. A time window of 800 µsec. after signal detection by the master sensor for detection by slave sensors was used to control accepted signals.

Acoustic Emission from a Defective C/Mn Steel Pressure Vessel

Determined that the peak AE energy traveled at a velocity of 2.95×10^3 m/sec (116,147 in./sec) and that the received signal amplitude "a" was:

$$a = a_0 r^b$$

where a_0 is the source amplitude, r is propagation distance, and b is 0.9 for the plate tested. For thick plates, r approaches 0.5. Established an attenuation value of 0.2 dB per meter at the monitoring frequency in the material tested.

Vessel was tested at room temperature. It was pressurized to 1000 psi prior to machining the defect. Maximum test pressure was 990 psi. Maximum pressure was held until the crack opening had increased by 0.45 mm at which time pressure was released.

In the course of the vessel pressurization, AE source location results were:

Up to 200 psi -- little AE
240 to 450 psi - length of defect active
450 to 650 psi - ends of defect active
above 700 psi -- slight activity from defect - scattered background indications

The authors interpret the test results to indicate that the AE was produced by deformation. Cumulative emission count did not correlate well with crack opening values. By calculating the estimated plastic zone volume vs pressure, a curve is developed which fits relatively well with the cumulative AE count. Application of these results to defect detection on inservice vessels is suggested on the basis of detecting plastic zone formation ahead of a crack.

Observations pertinent to the NRC-PNL AE-flaw characterization program are:

1. The conclusions reached in this report reinforce the recognized need to positively assess deformation vs crack growth as a source of AE.
2. Comparing AE - crack opening correlation from this test with that for the HSST V-7B vessel test could provide some very useful indications relative to material differences and/or AE monitoring technique effect.

3. Inconsistencies between the results of this work and our test results viewed in light of monitoring frequency (30 kHz band centered on 165 kHz in this work vs 200 kHz to 1 MHz band in our work) may suggest that monitoring frequency has significance beyond just considerations of signal attenuation and reducing background noise interference.
4. The need to be aware of possible differences in AE characteristics even between different types of steels is reinforced by the discussion in this report.