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NUREG-0250-2

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

Progress Report
February 1 - July 1, 1977

Battelle Pacific Northwest Laboratories
for
U. S. Nuclear Regulatory Commission

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

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P. H. Hutton
E. B. Schwenk

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PROGRAM TO DEVELOP

ACOUSTIC EMISSION-FLAW RELATIONSHIP FOR

INSERVICE MONITORING OF NUCLEAR PRESSURE VESSELS

Progress Report

February 1 - July 1, 1977

ABSTRACT

The purpose of the program is to evaluate experimentally the feasibility of further assuring reactor safety by detecting and analyzing flaw growth in reactor pressure boundaries through continuous monitoring for acoustic emission (AE). Program objectives are:

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

This report covers program work period February 1, 1977 to July 1, 1977.

Steel plate required for the program has been procured and test specimens are being fabricated.

Specimen test system has been assembled and calibrated. A technique for rating AE monitor system sensitivity has been developed.

Smooth tensile specimens of A533B steel show little detectable AE when tested to failure. A similar specimen notched produces readily detectable AE as also do fracture and fatigue crack growth specimens.

Fracture mechanics - AE power law relationships suggest high amplitude signals may represent cracking and low amplitude represent plastic zone growth.

An HSST pressure vessel test has been successfully monitored for AE and data analysis is in progress.

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

Progress Report No. 2

P.H. Hutton
E.B. Schwenk

Battelle
Pacific Northwest Laboratories

INTRODUCTION

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

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

The purpose of the program is to build an experimental evaluation of the feasibility of detecting and analyzing flaw growth in reactor pressure boundaries on a continuous basis using AE.

SUMMARY

Topics relate to the FY-77 program letter.

Material & Test Specimens

Sufficient A533 Grade B, Class 1 steel for the total program has been obtained. Specimen fabrication is proceeding with final delivery scheduled for mid-September 1977.

Instrumentation & Test System

The total test system has been calibrated. The instrumentation system analyzes AE count, energy, signal rise time, signal amplitude, wave form, and frequency spectrum.

An AE system sensitivity rating method has been devised to assist in relating test results to other systems and other tests.

NRC owned equipment to be transferred from Dunegan/Endevco to PNL has been received.

Development of AE Signatures

Fourteen tensile specimens, one fracture specimen and one fatigue crack growth specimen were tested this period. Smooth tensile specimens produced virtually no detectable AE. Notched tensile specimens, fracture specimen and the fatigue crack growth specimen all produced readily detectable AE. The stress state around the notch or crack front appears to be instrumental in producing AE.

A totally independent commercial AE monitor was used in parallel with the BNW system to verify that the lack of detected AE from smooth tensiles was not just a function of inadequate sensitivity in the BNW system. The two systems agreed closely.

The primary signal characteristics for AE identification suggested by work to date are:

- Rise time and amplitude discrimination to isolate deformation AE and cracking AE
- Rise time and frequency filtering to discriminate against general noise
- There is some indication that detected AE signals may uniquely start with a negative half cycle out of a sensor which produces a positive half cycle for other types of impulse such as striking the specimen surface.

Fracture Mechanics - AE Model

Fracture mechanics - AE analysis so far has shown through power law development that AE event count and AE energy both correlate with crack growth rate and crack driving force (stress intensity "K").

Power law comparisons begin to show evidence that a distinction between AE from plastic zone growth and AE from cracking may be distinguishable on the basis of AE signal amplitude.

Evaluate Commercial High Temperature Sensors

Specimens of all of the high temperature AE sensors desired for testing are now on hand.

Collect & Analyze AE Data from HSST Tests

An HSST pressure vessel test (V-7B) involving a machined defect in the heat affected zone of a repair weld has been successfully monitored for AE. A Dunegan/Endevco 1032 computerized system and the BNW digital memory system were both used and both performed well. Data is currently being analyzed.

AE Library

Three AE reports have been reviewed and summarized. They concern:

- Testing a pressure vessel with a machined defect
- Interpretation of AE data
- Experience in monitoring reactor pressure vessels during operation.

DISCUSSION

The discussion is structured to follow the topical format of the FY-77 Program Letter.

Material & Test Specimens

Material (A533 Grade B, Class 1 steel) for specimens has been obtained from two sources:

1. A 6 in. x 20 in. x 23 in. HSST weldment specimen described in Progress Report No. 1[(1)]
2. 80 ft^2 of 8¼ in. thick plate from Lukens Steel

Item 1 above yielded 16 tensile specimens, and four 2T compact tension specimens. These included specimens with the test section from base metal and from weld metal. The specimens facilitated initiation of testing in March 1977 and provided specimens for five of the eight types of tests planned for FY-77.

Item 2 above will provide for all of the remaining specimens needed for FY-77 and FY-78 on this program plus archive material (21½ ft^2). Details of the material characteristics are included as Appendix A of this report. Test specimens from the current program are being fabricated from the outer "skin" material of the plate in accordance with an earlier NRC-PNL decision. Tooling Specialists in Latrobe, PA is performing test specimen fabrication. There are a total of 42 specimens with delivery to start in mid-July and be completed by mid-September.

Instrumentation & Test System

The AE test instrumentation currently being used on the program is shown in Figure 1. The digital memory multiparameter AE monitor which is the primary instrument was described in detail in Progress Report No. 1.[(1)] A valid signal verification pulse from the digital memory monitor triggers the Biomation 8100 transient wave analyzer to display the valid signal on an X-Y oscilloscope for wave form examination.

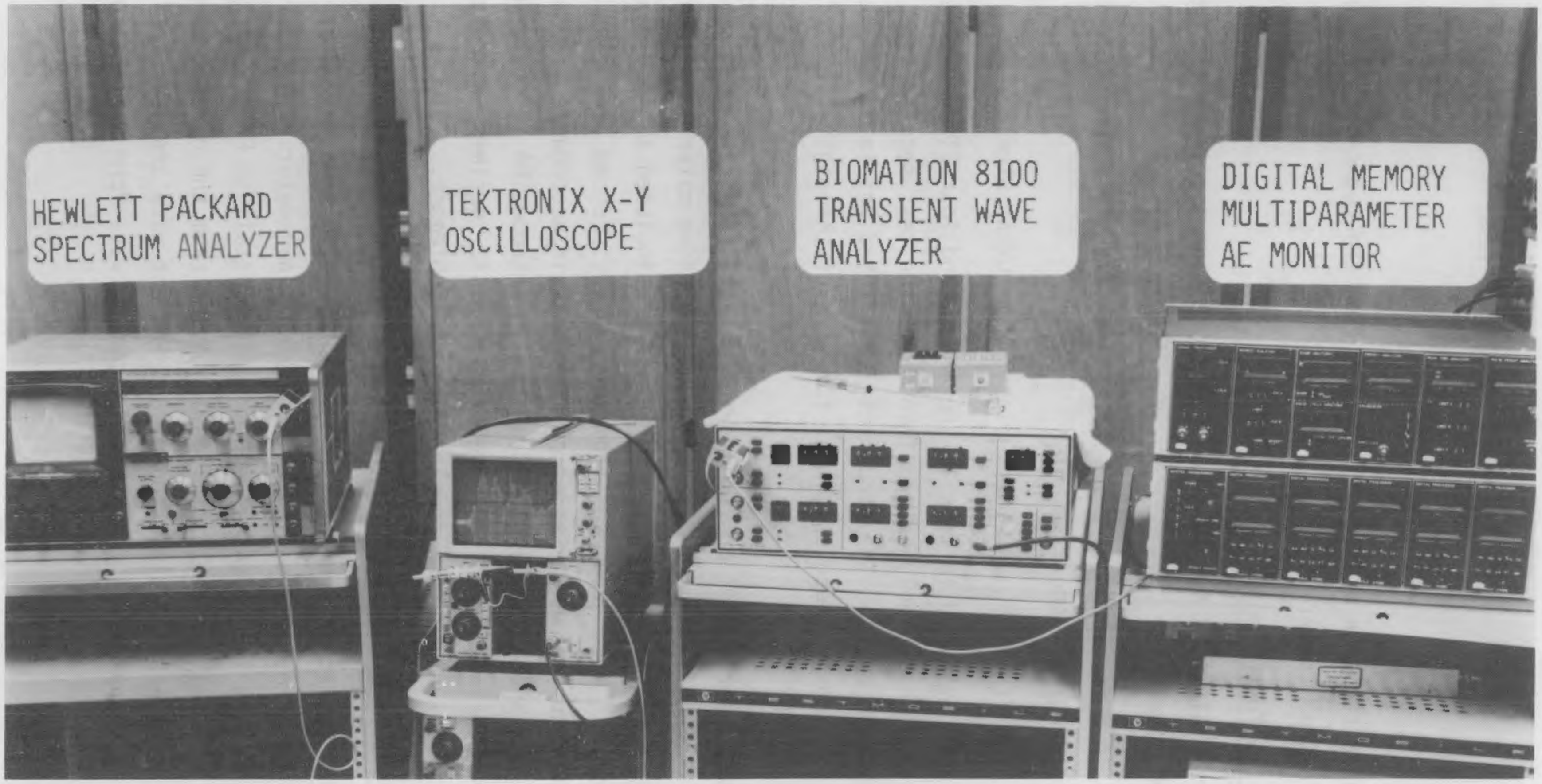


FIGURE 1. Acoustic Emission Analysis System

The same information is also routed to a Hewlett Packard Spectrum Analyzer for frequency analysis.

Initially, the AE monitor system, including preamplifiers, showed excessive electronic background noise - nominally 66 μ volts peak referred to input. This has been reduced to a nominal value of 32 μ volts peak. These values should not be confused with the averaged rms value commonly used in the electronics industry for measuring noise. The rms measure is very meaningful in many applications, however, it does not give a direct measure of the susceptibility of a threshold detection system (AE system) to noise encroachment as does the measure of peak volts noise quoted above.

In an effort to make the results of this program relatable to other AE monitor systems and tests, a method for rating the sensitivity of the entire AE monitor system has been devised. We call it "Effective Sensitivity". Tensile test A1-4 which is discussed later in this report, has been selected arbitrarily to illustrate derivation of Effective Sensitivity rating. In test A1-4, a total system gain of 90 dB and a detection threshold of 1.6 volts peak was used. Thus, the minimum input voltage to the system from an AE sensor that the system would respond to is $\frac{1.6 \text{ volts}}{90 \text{ dB gain}}$ or 51 μ volts. Referring now to the sensor calibration curves in Figure 2, the nominal maximum sensitivity of the least sensitive sensor in the frequency range being monitored (0.2 to 1.0 MHz) is -65 dB re 1 volt/μ bar. The least sensitive sensor is used because in this system, signal output from both sensors must be detected to produce a valid AE signal verification. The sensor should thus produce $\frac{1 \text{ volt}/\mu \text{ bar}}{65 \text{ dB}}$ or 562 μ volts for 1 μ bar front face pressure. Since the AE monitor will respond to an input of 51 μ volts, it follows that the system should respond to $\frac{51}{562}$ or 0.09 μ bar pressure on the front face of the sensor. Effective Sensitivity thus provides a comparable rating of total system sensitivity from test to test even though system gain, threshold, and sensor sensitivity may vary.

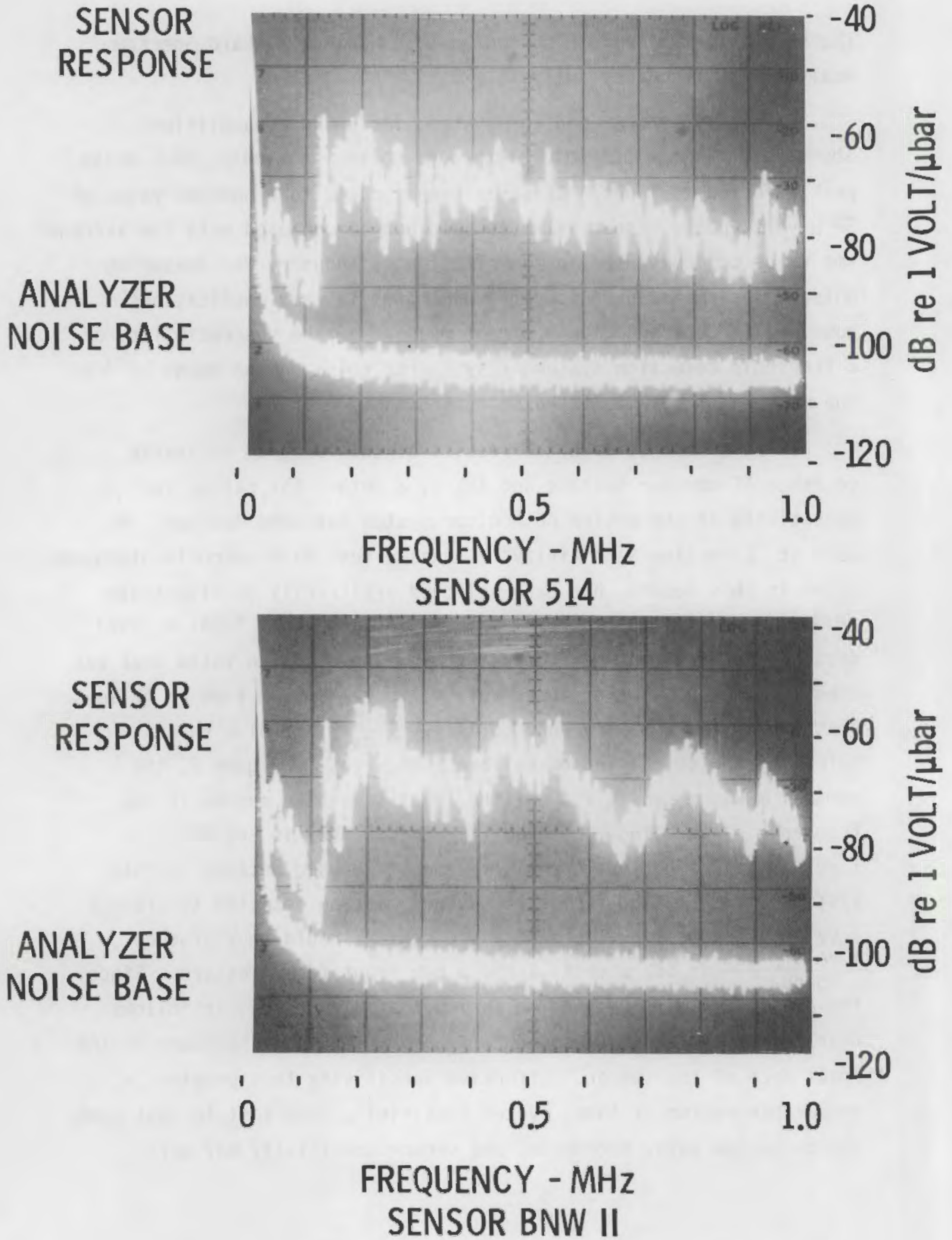


FIGURE 2. Sensor Calibration Curves, Tensile Test A1-4.

All NRC-owned equipment to be transferred from Dunegan/Endevco (D/E) to PNL has been received. The equipment is being inventoried for record purposes. A three-day training session on operation of the computerized D/E 1032 AE monitor system was conducted at PNL June 22, 23 & 24. Four PNL staff members participated.

Development of AE Signatures

A total of 14 tensile specimens have been tested. Basically, these were all 0.250 in. diameter test section. Figure 3 shows a typical test arrangement. A breakdown on the tests is as follows:

No. Tests	Material	Special Conditions	Temp.
6	Skin-Base	None	Room
1	Skin-Base	None	550^{0} F
1	Skin-Base	Heat Treated to R -52	Room
1	Skin-Base	Notched	Room
3	Skin-Weld	None	Room
1	Core-Base	None	Room
1	Core-Weld	None	Room

All of the smooth tensile specimens were characterized by a very small amount of AE. The results obtained from a skin-weld material specimen shown in Figure 4 are typical of the smooth tensile specimen tests. The small amount of AE detected generally appeared in the vicinity of engineering yield. In the course of these tests, strain rates ranging from 0.0005 to 0.02 inches per minute were used with no noticeable effect on the detected AE. In Figure 5, it is evident that the specimen tested at 550^{0} F was very similar to the room temperature tests. One skin-base material specimen was heat treated to a RC-52 hardness (normal for this material is $\sim$ RB-85) to investigate the effects of ductility. Again, (Figure 6) there was no significant effect.

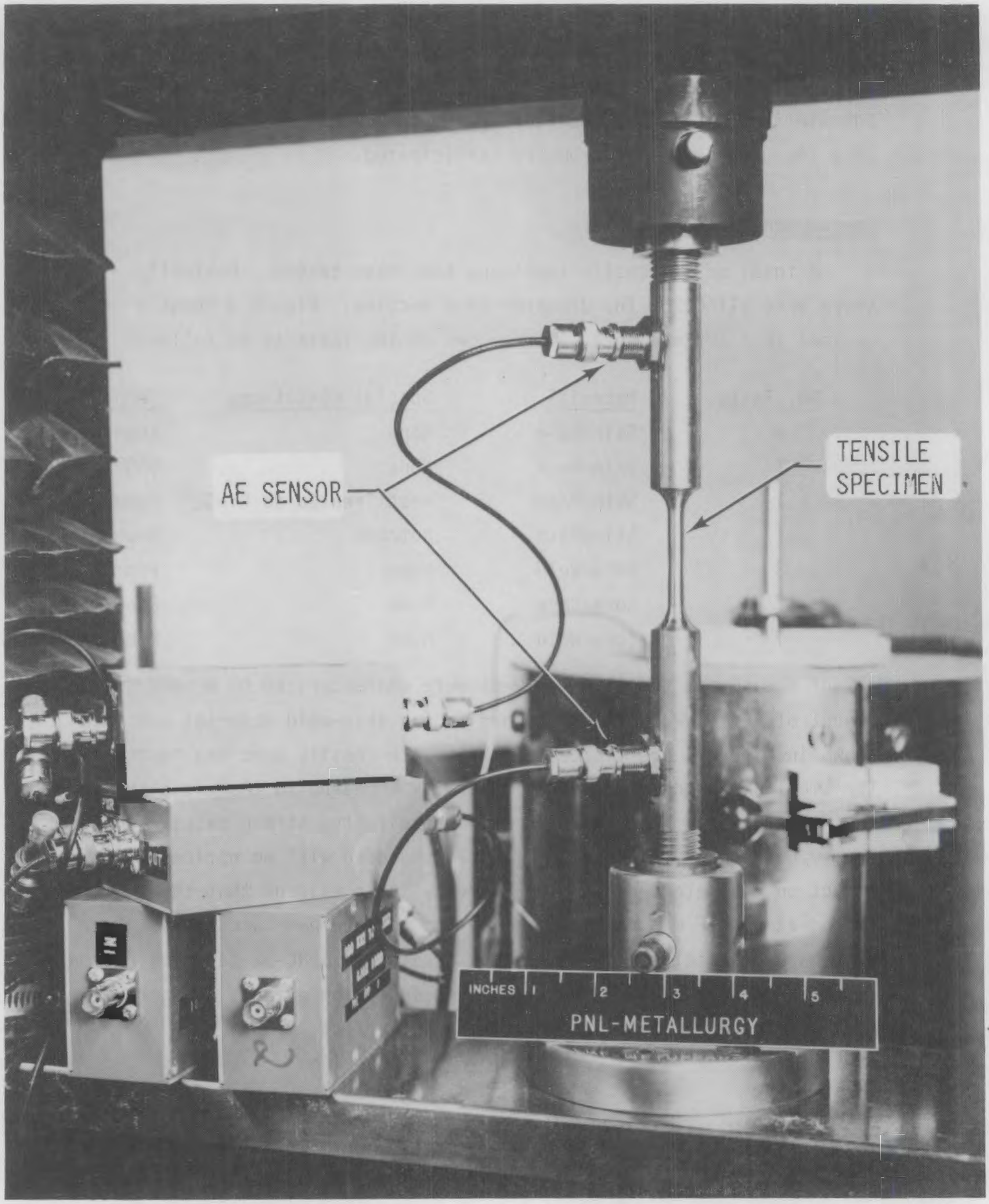


FIGURE 3. Acoustic Emission - Tensile Specimen Setup

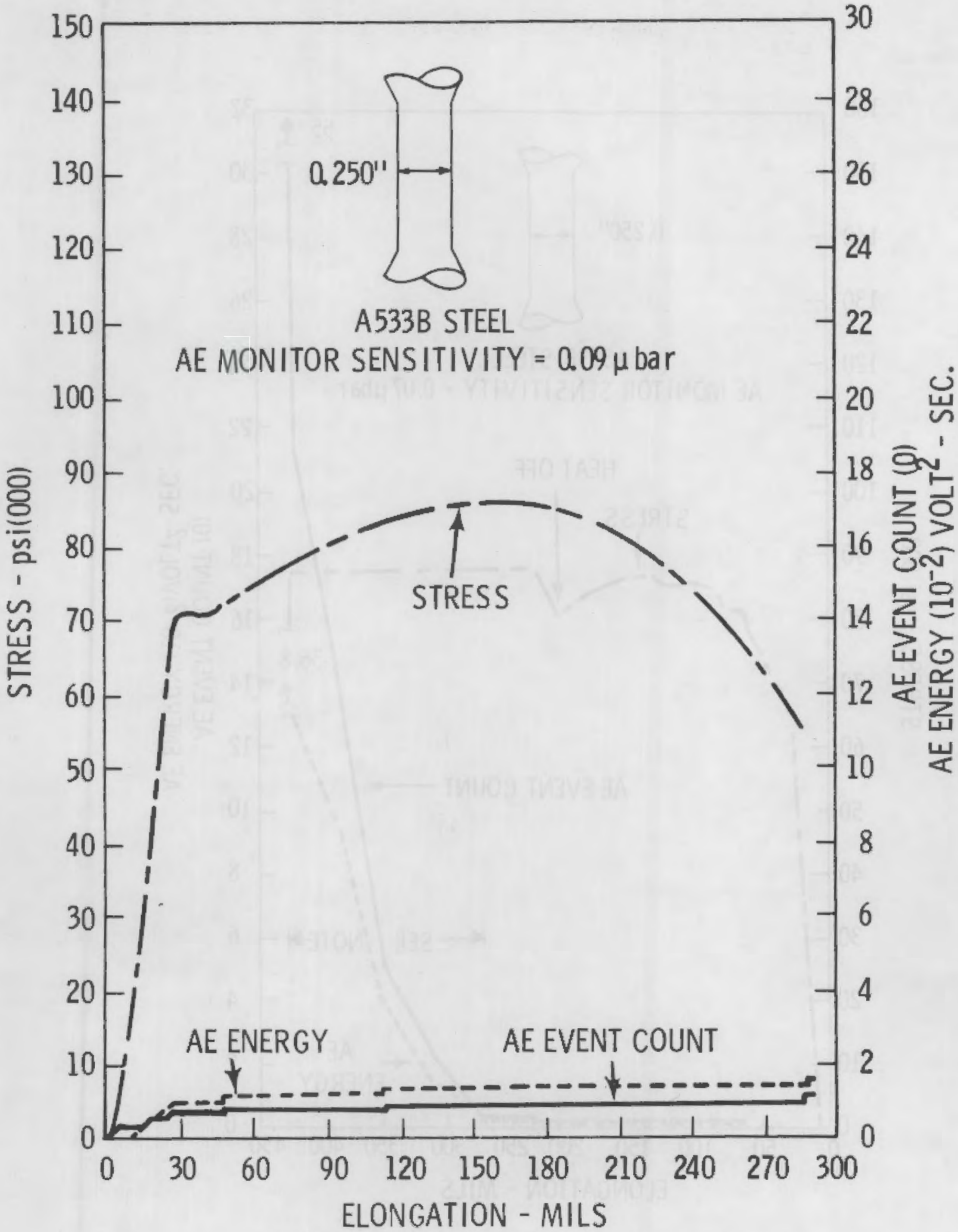
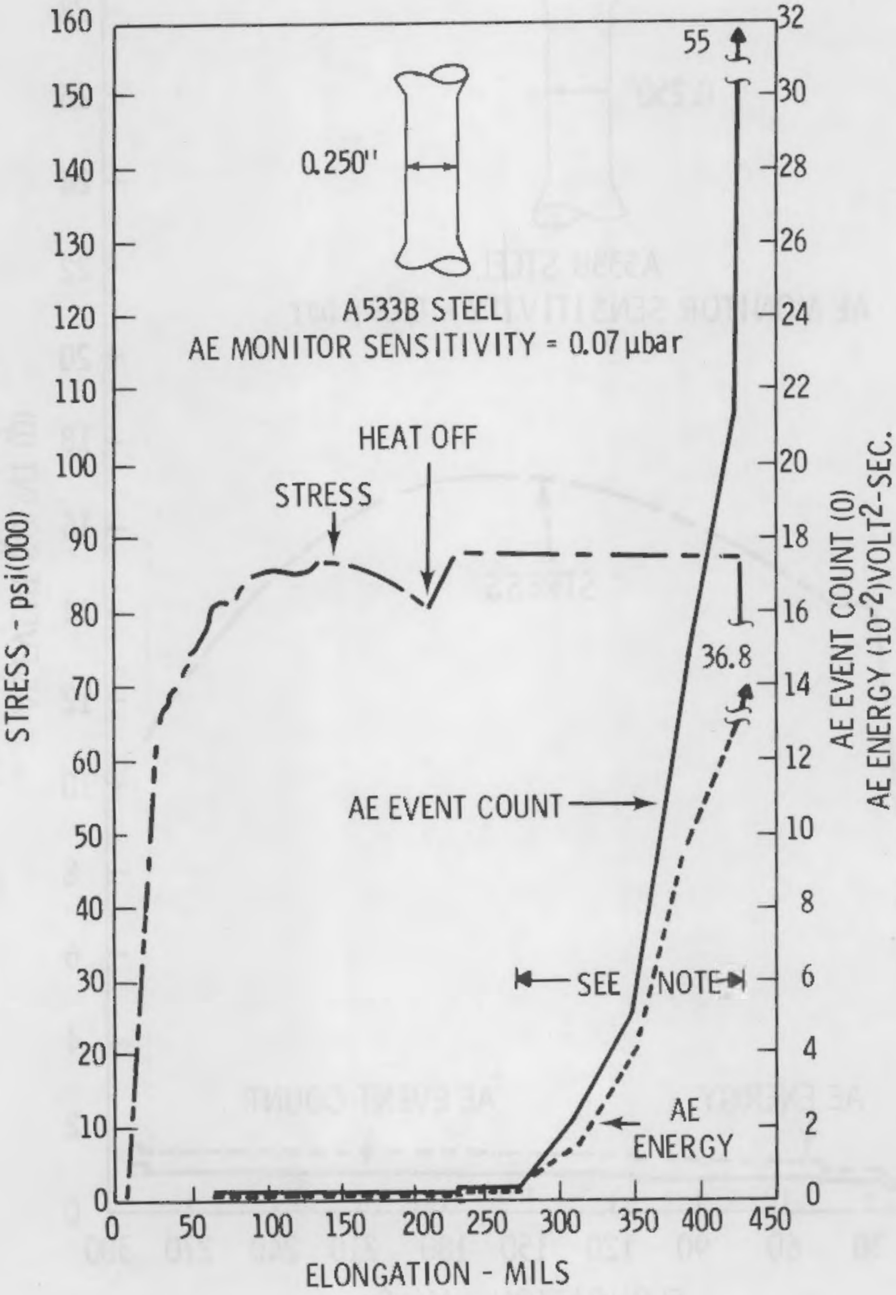


FIGURE 4. AE from Tensile Test Al-4, Skin-Weld Material, A533B, Room Temperature



NOTE: ACTIVITY DETECTED IN THIS REGION CAME FROM A DROP OF COUPLANT WHICH RAN DOWN ONTO TEST SECTION, CHARRED, AND CRACKED UPON COOLING

FIGURE 5. AE from Tensile Test A2-1, Skin Base Material, A533B Steel, 550°F

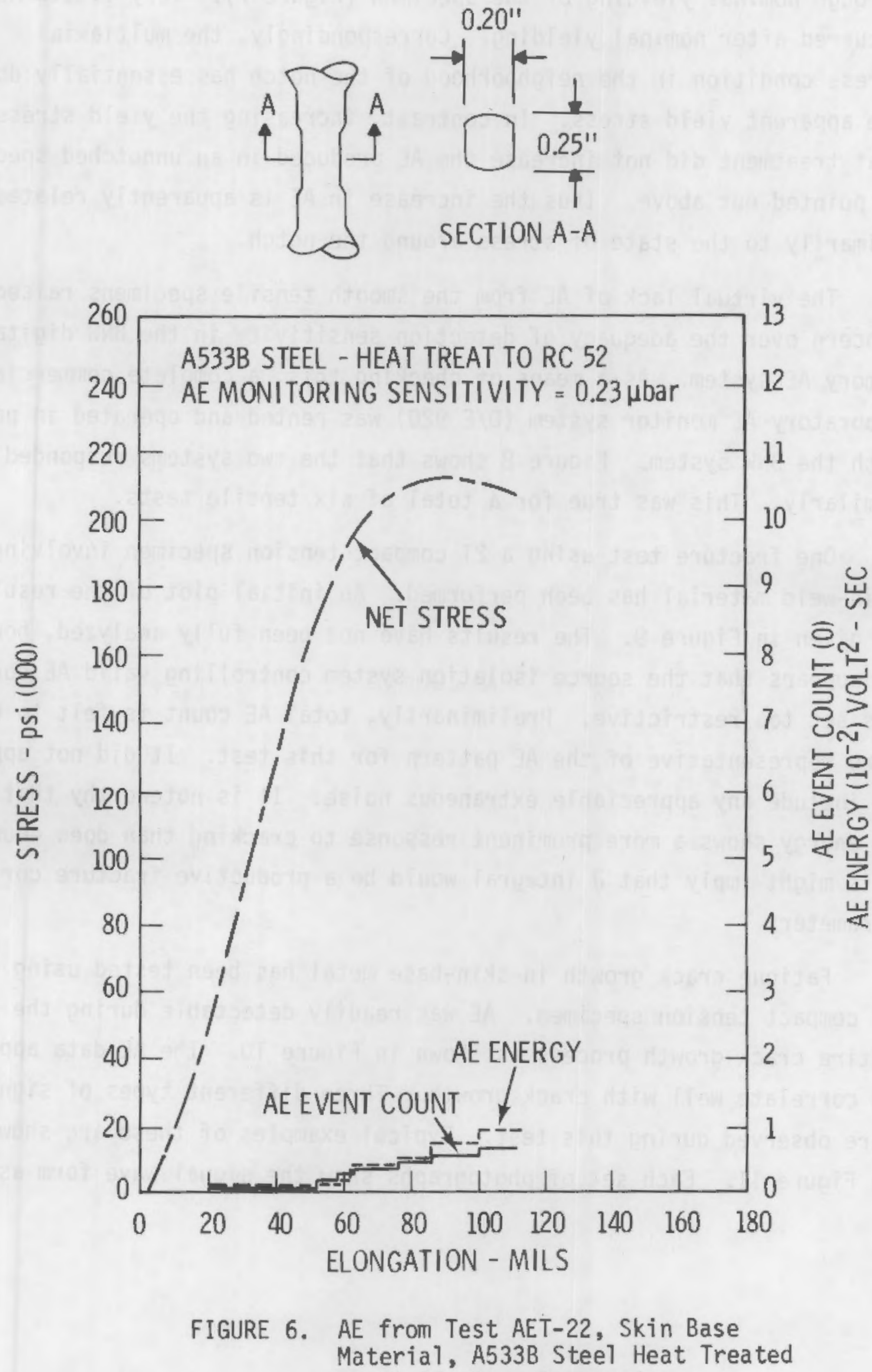


FIGURE 6. AE from Test AET-22, Skin Base Material, A533B Steel Heat Treated to RC-52, Room Temperature.

Addition of a sharp circumferential notch to the same size tensile specimen, however, substantially increased AE event count and energy up through nominal yielding of the specimen (Figure 7). Very little AE occurred after nominal yielding. Correspondingly, the multiaxial stress condition in the neighborhood of the notch has essentially doubled the apparent yield stress. In contrast, increasing the yield stress by heat treatment did not increase the AE produced in an unnotched specimen as pointed out above. Thus the increase in AE is apparently related primarily to the state of stress around the notch.

The virtual lack of AE from the smooth tensile specimens raised concern over the adequacy of detection sensitivity in the BNW digital memory AE system. As a means of checking this, a complete commercial laboratory AE monitor system (D/E 920) was rented and operated in parallel with the BNW system. Figure 8 shows that the two systems responded very similarly. This was true for a total of six tensile tests.

One fracture test using a 2T compact tension specimen involving skin-weld material has been performed. An initial plot of the results is given in Figure 9. The results have not been fully analyzed, however, it appears that the source isolation system controlling valid AE count was set too restrictive. Preliminarily, total AE count is felt to be more representative of the AE pattern for this test. It did not appear to include any appreciable extraneous noise. It is noteworthy that the AE energy shows a more prominent response to cracking than does count. This might imply that J integral would be a productive fracture correlation parameter.

Fatigue crack growth in skin-base metal has been tested using a 2T compact tension specimen. AE was readily detectable during the entire crack growth process as shown in Figure 10. The AE data appears to correlate well with crack growth. Three different types of signals were observed during this test. Typical examples of these are shown in Figure 11. Each set of photographs show the signal wave form as

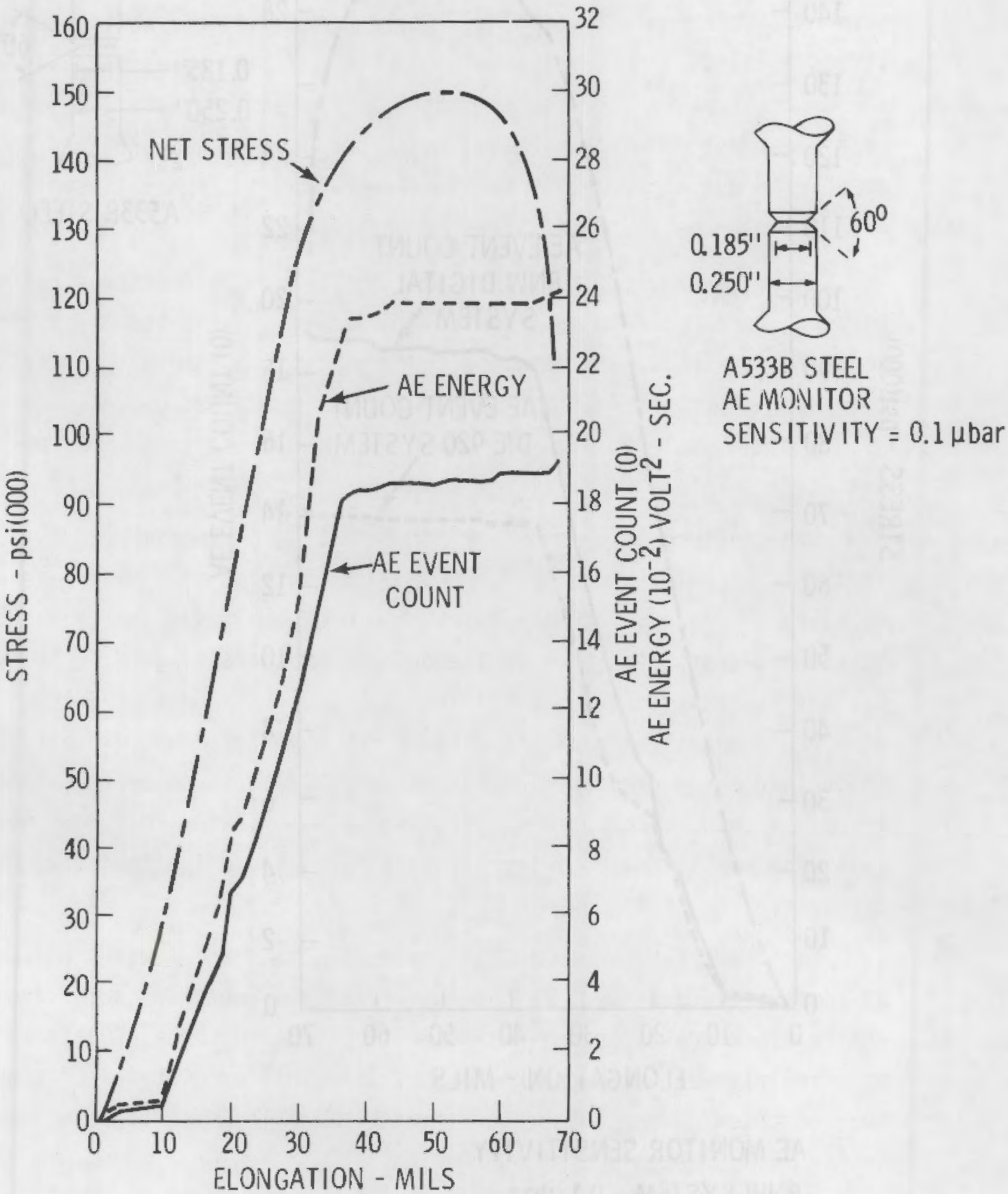


FIGURE 7. AE from Notched Tensile Test AET-25, A533B Material, Room Temperature

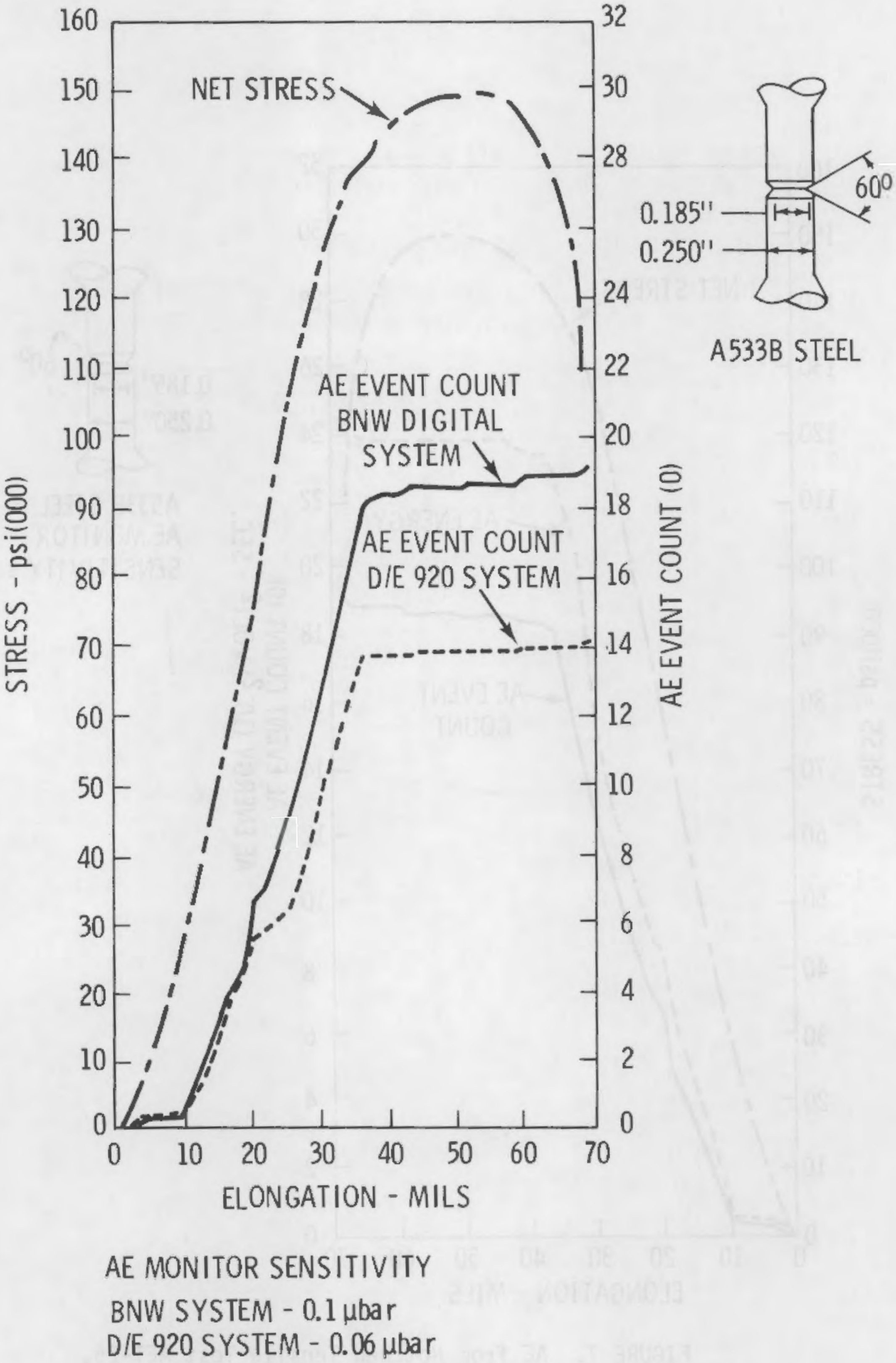


FIGURE 8. Comparison of AE Count Response for BNW Digital Monitor and Dunegan/Endevco 920 System - Test AET-25

TEST SPECIMEN - 2T COMPACT TENSION - B2-3B
AE SYSTEM EFFECTIVE SENSITIVITY = 0.19 μbar
CROSSHEAD TRAVEL - 0.067 IN./MIN.
FREQUENCY RANGE - 0.2-0.8 MHz

NOTE: VALID AE COUNT - CONTROLLED BY SOURCE ISOLATION
TOTAL AE COUNT - NOT CONTROLLED BY SOURCE ISOLATION

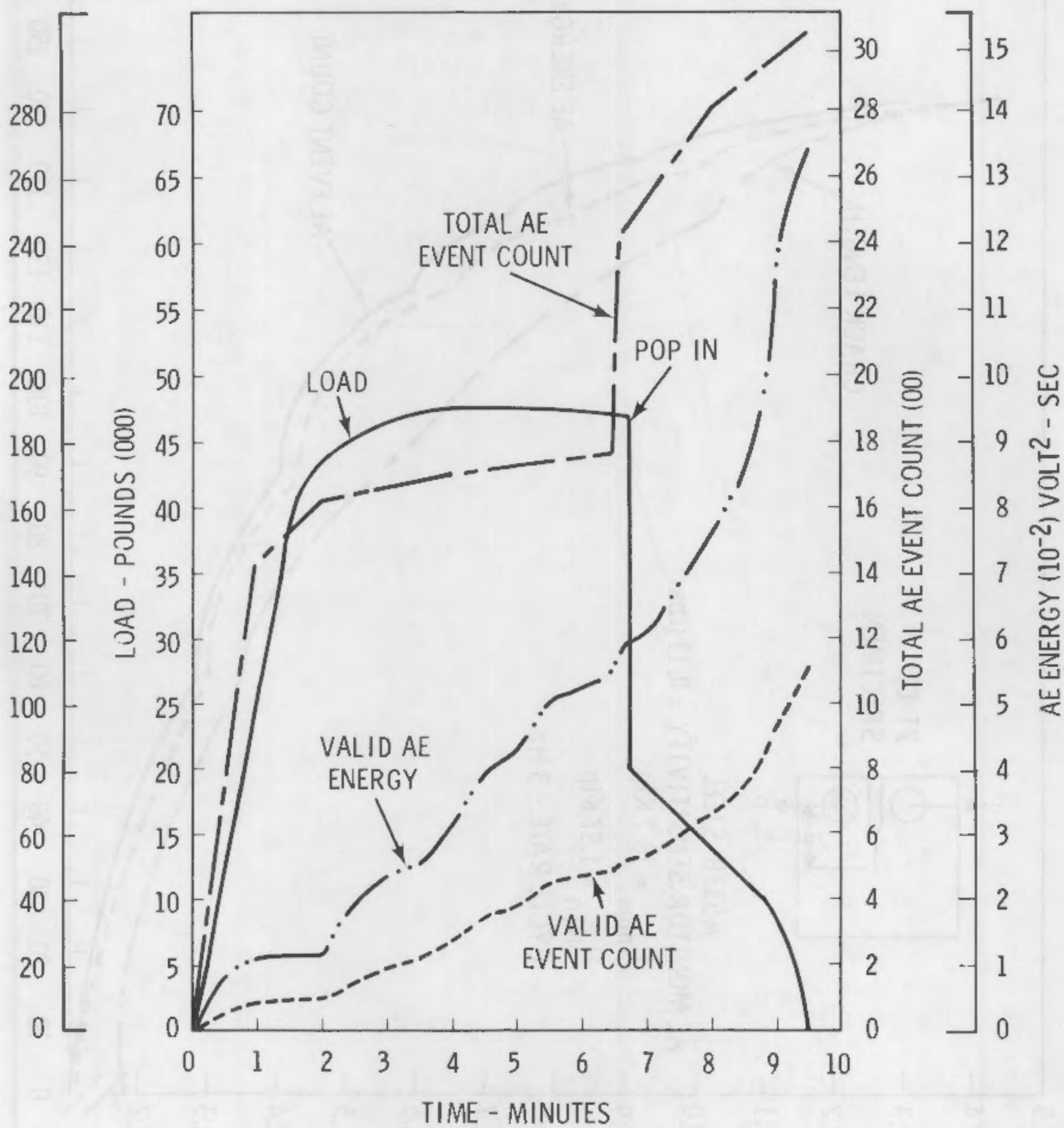


FIGURE 9. AE Results from Fracture Test B2-3B, Skin-Weld Material, A533B Steel, Room Temperature.

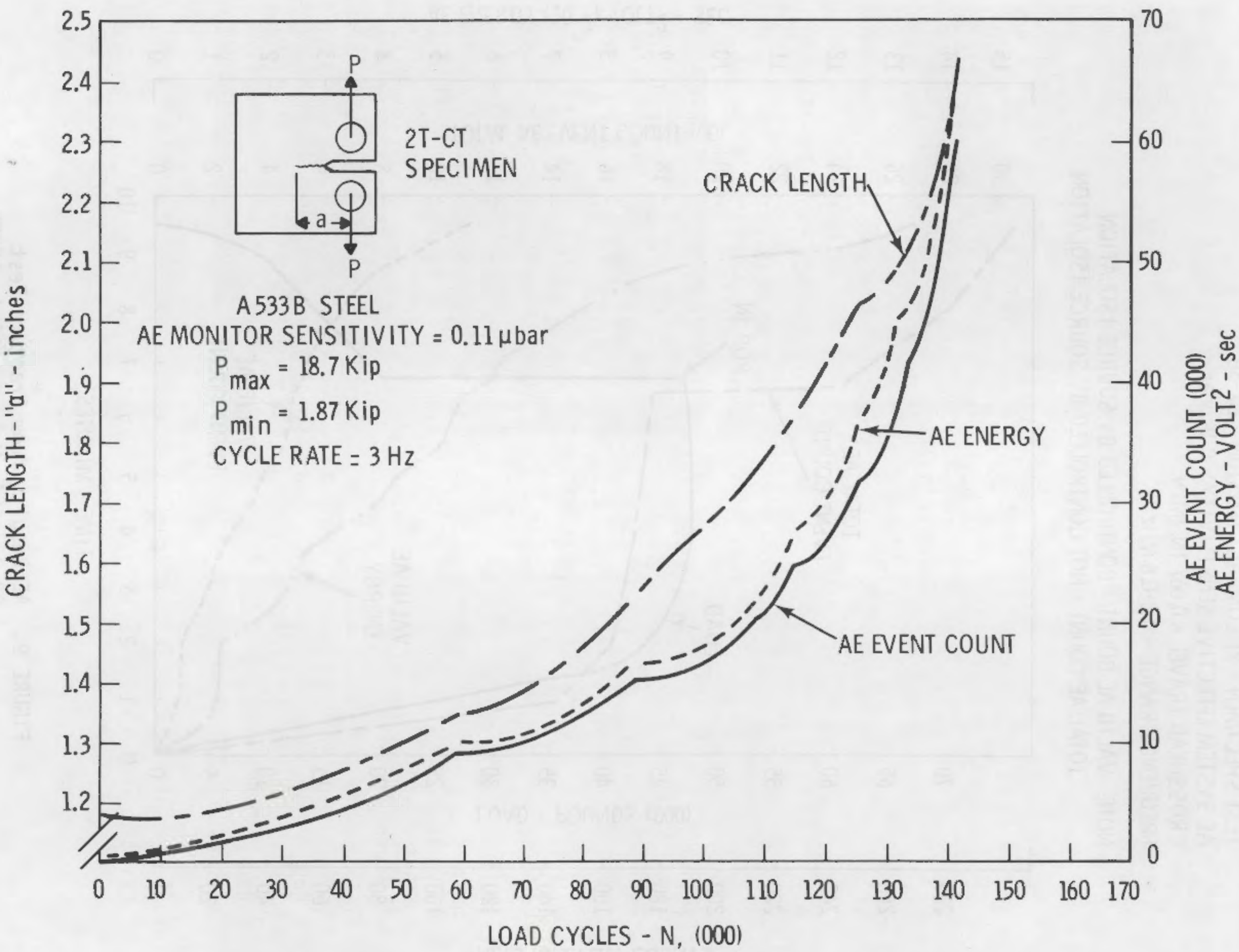


FIGURE 10. Fatigue Crack Length, AE Event Count, AE Energy vs. Load Cycles, Skin Base Material, Test B2-1B

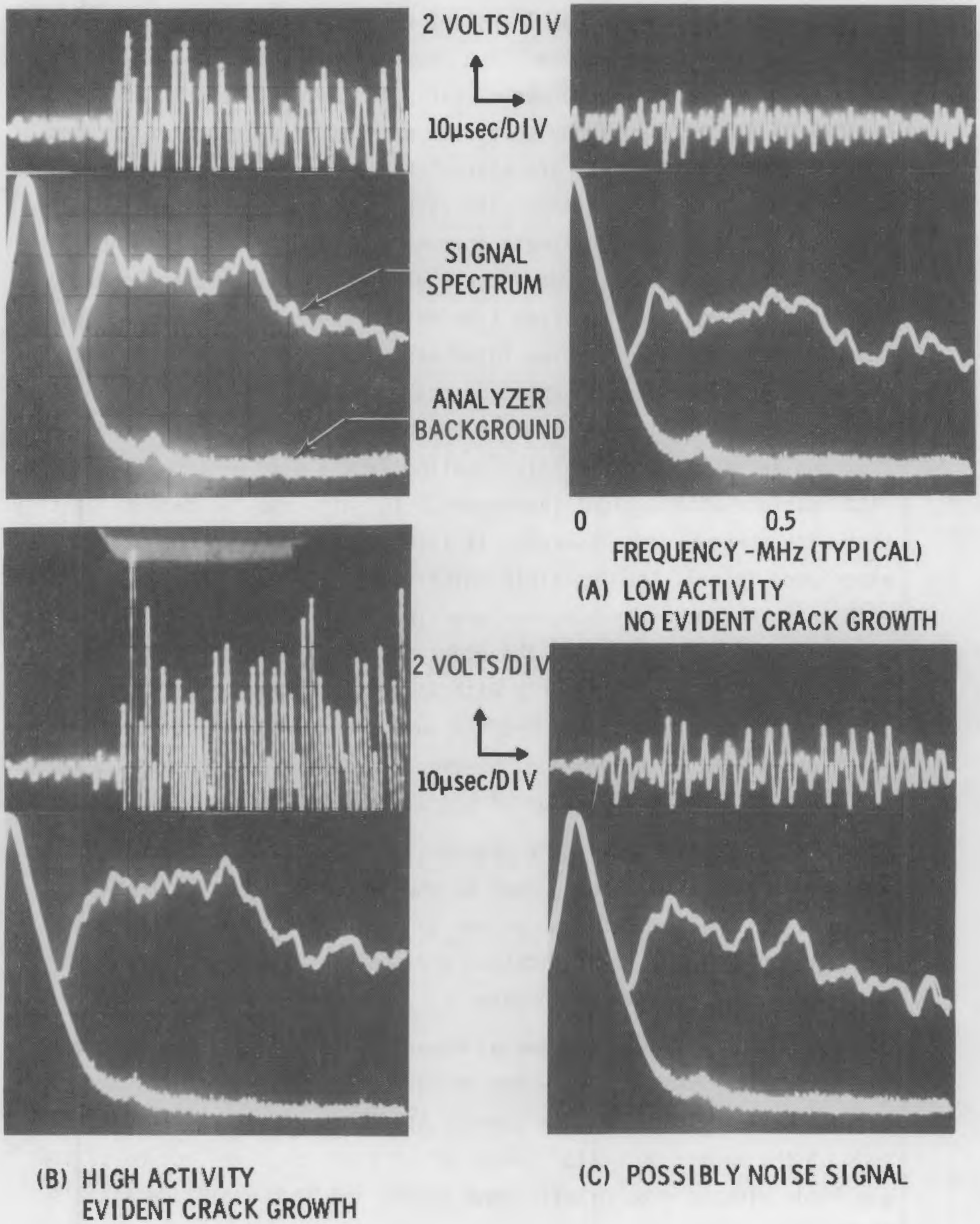


FIGURE 11. Samples of Different AE Signal Wave Forms
Fatique Test B2-1B

displayed from the Biomation Transient Wave Analyzer on top with the signal spectral content below. The type A signals made up a high percentage of the signals observed early in the test before crack growth was evident, but they were also present to a lesser proportion throughout the test. They are characterized by a low amplitude and short duration. It is difficult to visually identify them in the noise background. Type B signals were common during periods of high AE activity when there was evident crack growth. They are characterized by high amplitude and fast rise time on the front of the signal. The third signal type (C) appeared intermittently. The characteristics of this signal are medium amplitude and slow rise time. These signals are similar to signals observed in the past which were associated with known noise sources such as slag peeling from a weld or impact on a metal surface with a blunt instrument. In this case, we cannot identify them with a known noise source. It is speculation based on past experience to call them possible noise signals. It is interesting to note that the frequency spectrum profile of the possible noise signal differs from the spectrum of the other signals. The noise signal spectrum decays almost linearly with increasing frequency. The other signals show a somewhat flat profile out to about 600 kHz before they start to decay. At this stage, however, frequency spectra are considered to be a questionable indicator of signal identity.

A potentially significant observation from examining AE signal wave forms is that a large number of the Type B signals start with a negative half cycle. If this proves to be consistent, it would be important for signal identification and could provide new insight to the nature of the AE pressure wave.

Figure 12 presents samples of signal amplitude distribution from the fatigue test. These show two things - that the distribution varies during the test, and that the signals tend to group at the low and high ends of the amplitude scale. This latter could be a reflection of low amplitude signals from plastic zone growth and high amplitude signals from crack growth.

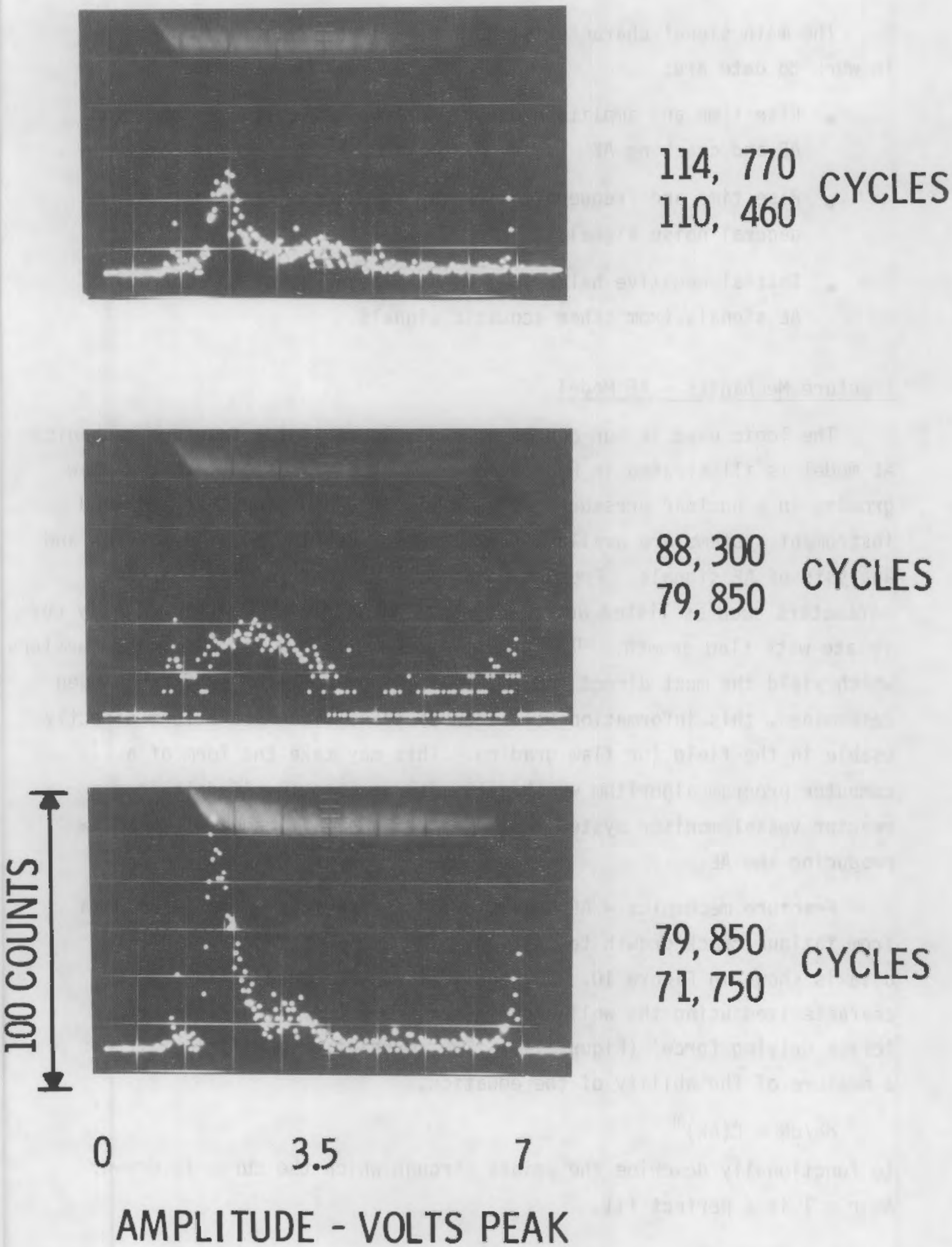


FIGURE 12. Samples of AE Signal Amplitude Distribution, Fatigue Test B2-1B

The main signal characteristics for AE identification suggested in work to date are:

- Rise time and amplitude discrimination to isolate deformation AE and cracking AE
- Rise time and frequency filtering to discriminate against general noise signals
- Initial negative half cycle might provide a key to separating AE signals from other acoustic signals.

Fracture Mechanics - AE Model

The logic used in our approach to development of a fracture mechanics-AE model is illustrated in Figure 13. This logic considers that a flaw growing in a nuclear pressure vessel will produce AE and that advanced instrument systems are available at least for developmental detection and analysis of AE signals. Present emphasis is on determining which AE parameters such as listed under "Current Development" most effectively correlate with flaw growth. When the AE parameter or combination of parameters which yield the most direct and reliable measure of flaw growth has been determined, this information will then be translated into a form directly usable in the field for flaw grading. This may take the form of a computer program algorithm which will analyze incoming AE data from a reactor vessel monitor system to indicate the significance of the flaw producing the AE.

Fracture mechanics - AE analysis to date has concentrated on data from fatigue crack growth test B2-1B. The basic AE and crack growth data is shown in Figure 10. Fatigue crack growth rate (da/dN) is characterized using the well known intensity factor range (ΔK) or 'crack driving force' (Figure 14). The correlation coefficient (r) is a measure of the ability of the equation,

$$da/dN = C(\Delta K)^m$$

to functionally describe the points through which the curve is drawn. An $r = 1$ is a perfect fit.

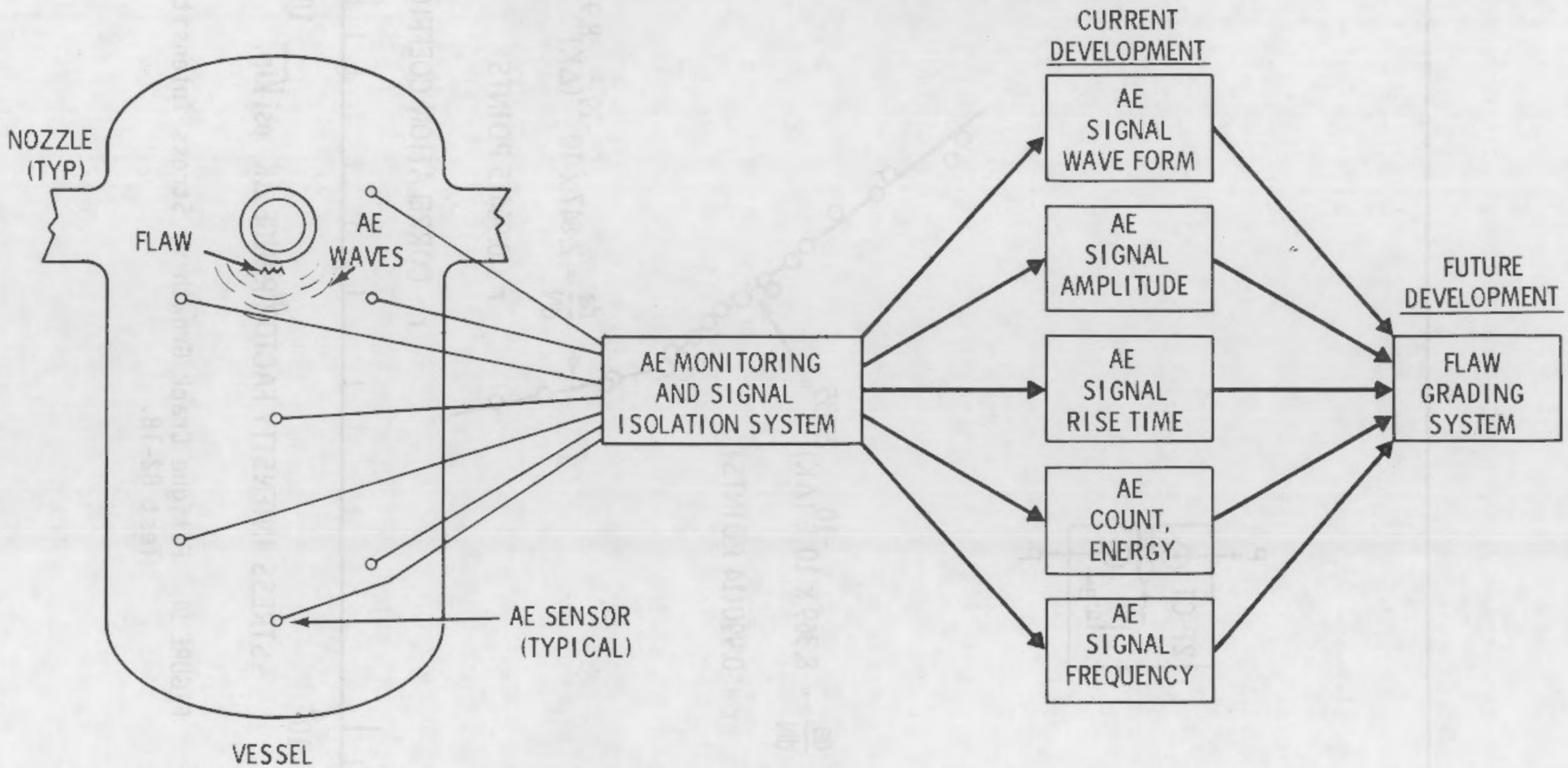


FIGURE 13. AE-Flaw Relationship Development Concept

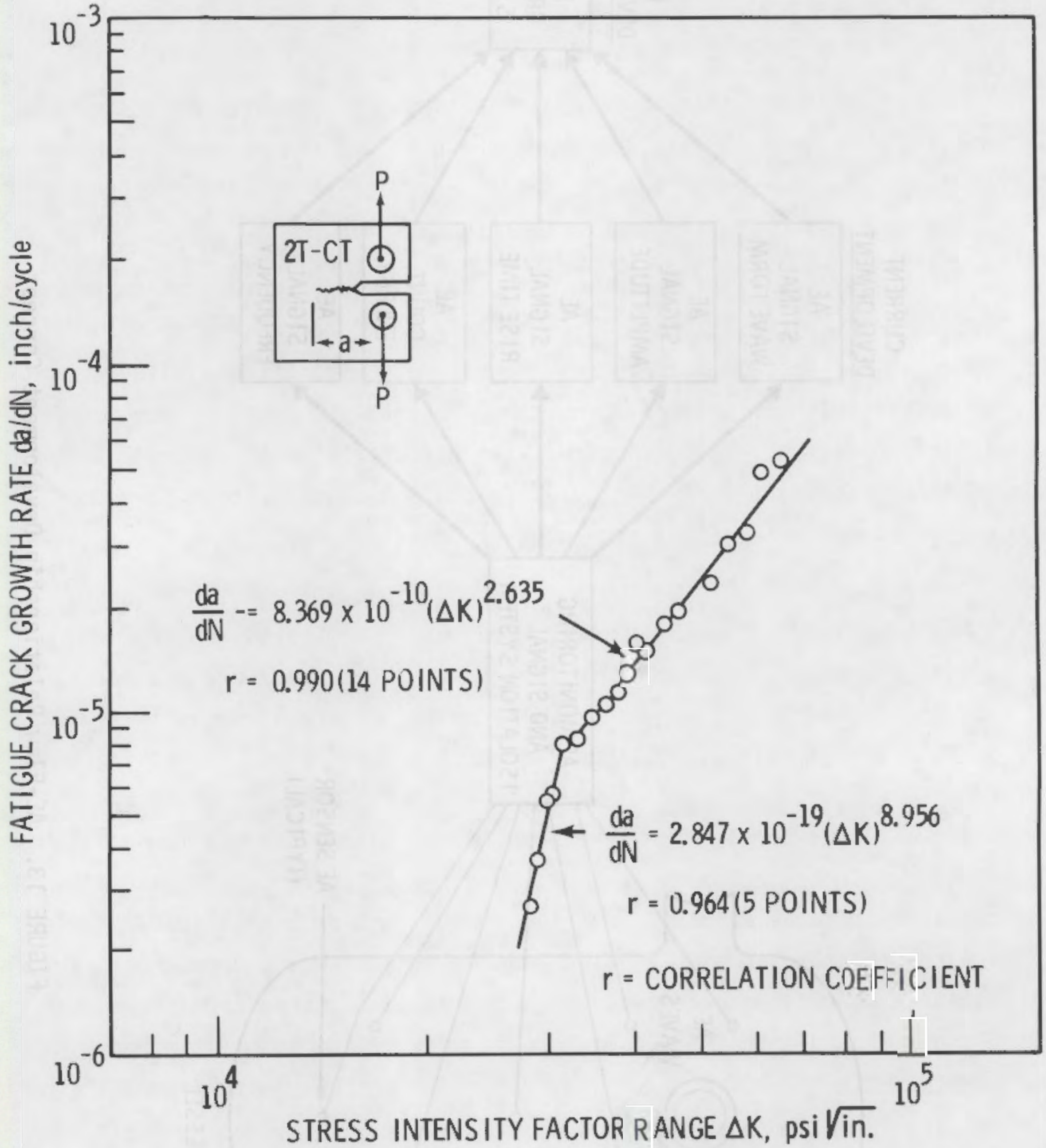


FIGURE 14. Fatigue Crack Growth vs Stress Intensity Test B2-1B.

If one compares the number of AE event counts/cycle (dC3/dN) with fatigue crack growth rate (da/dN), the data of Figure 15 results. A similar power-law relationship was derived where,

$$dC3/dN = 4.942 \times 10^{-5} \, (da/dN)^{1.233}$$
$$r = 0.826 \text{ (19 points)}$$

Figure 16 shows the same dC3/dN data except compared with the crack driving force, ΔK. This figure and the previous figure indicates that AE event count does reflect the range of the crack driving force as well as being a measure of fatigue crack growth rate.

AE energy data of the same form, namely dE3/dN versus da/dN and ΔK are shown in Figures 17 and 18. The "r" values for AE energy are somewhat better than that for AE count. Recognizing the limited amount of data involved, the results must be treated with caution, however, it is an indication. This, together with discussions with other AE experimentors suggests that AE energy vs fracture mechanics (both stress intensity and J integral) should be examined further.

Another avenue of analysis examined is partitioning AE count by signal amplitude. The BNW digital monitor system sorts signals into preset ranges of amplitude. In this test, the ranges were set for <1.6, 1.6-2.5, 2.5-3.5 and >3.5 volts peak. Figure 19 shows the results of relating signals by amplitude to crack growth rate. The solid curve is a repeat of the curve in Figure 15 which includes all AE signals. The two dashed curves were developed using minimum and maximum amplitude signals. These both show an improved fit with crack growth rate as compared to total AE count. In Figure 20, the lower amplitude signals are related to change in plastic zone volume and crack growth rate. This again shows quite a good fit. Figures 19 and 20 taken together appear to support the idea that low amplitude signals relate to plastic zone growth and high amplitude signals relate to cracking. In Figure 19, both physical phenomenon are present and low and high amplitude signals both

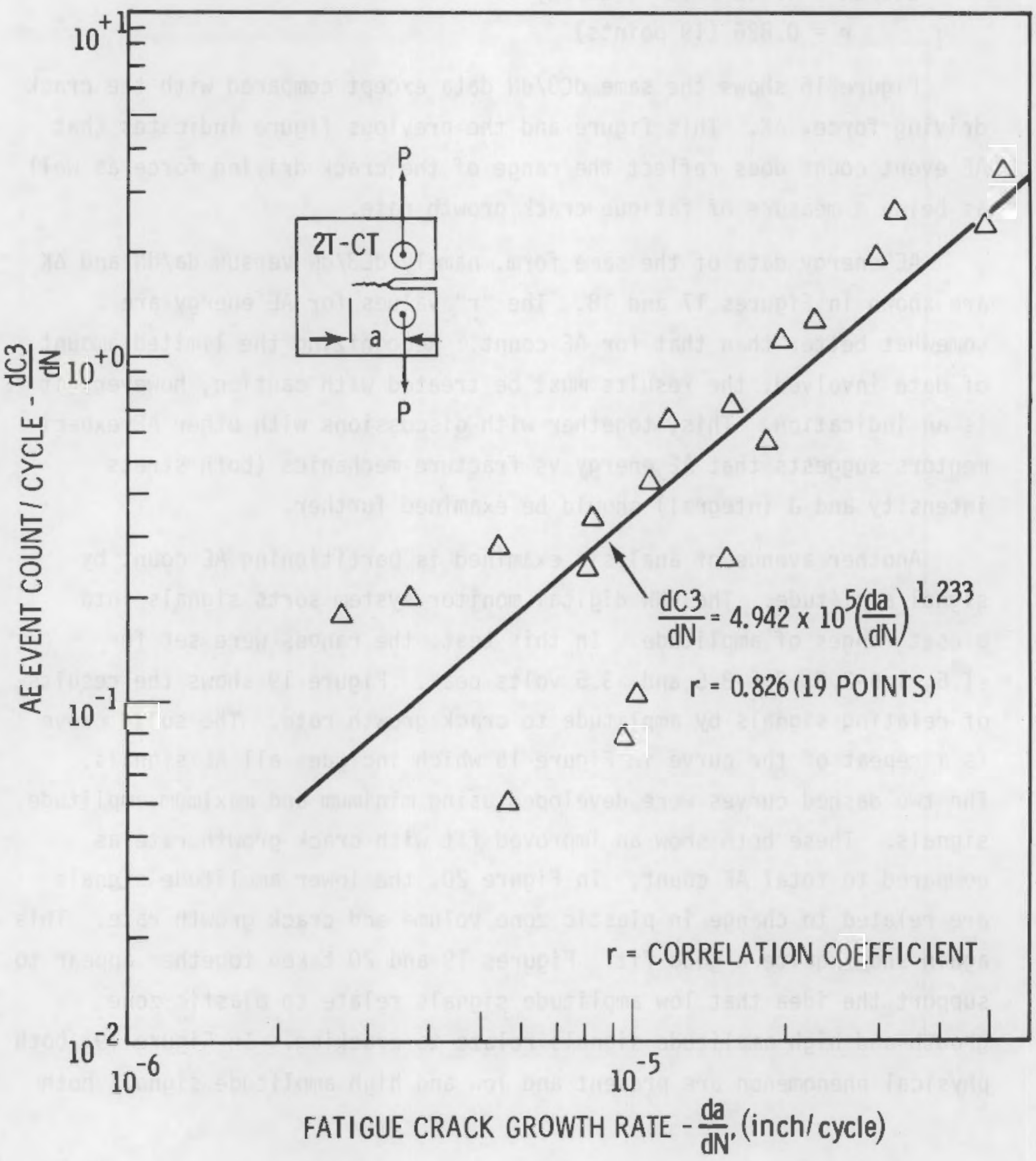


FIGURE 15. AE Event Count/Cycle vs Fatigue Crack Growth Rate - Test B2-1B.

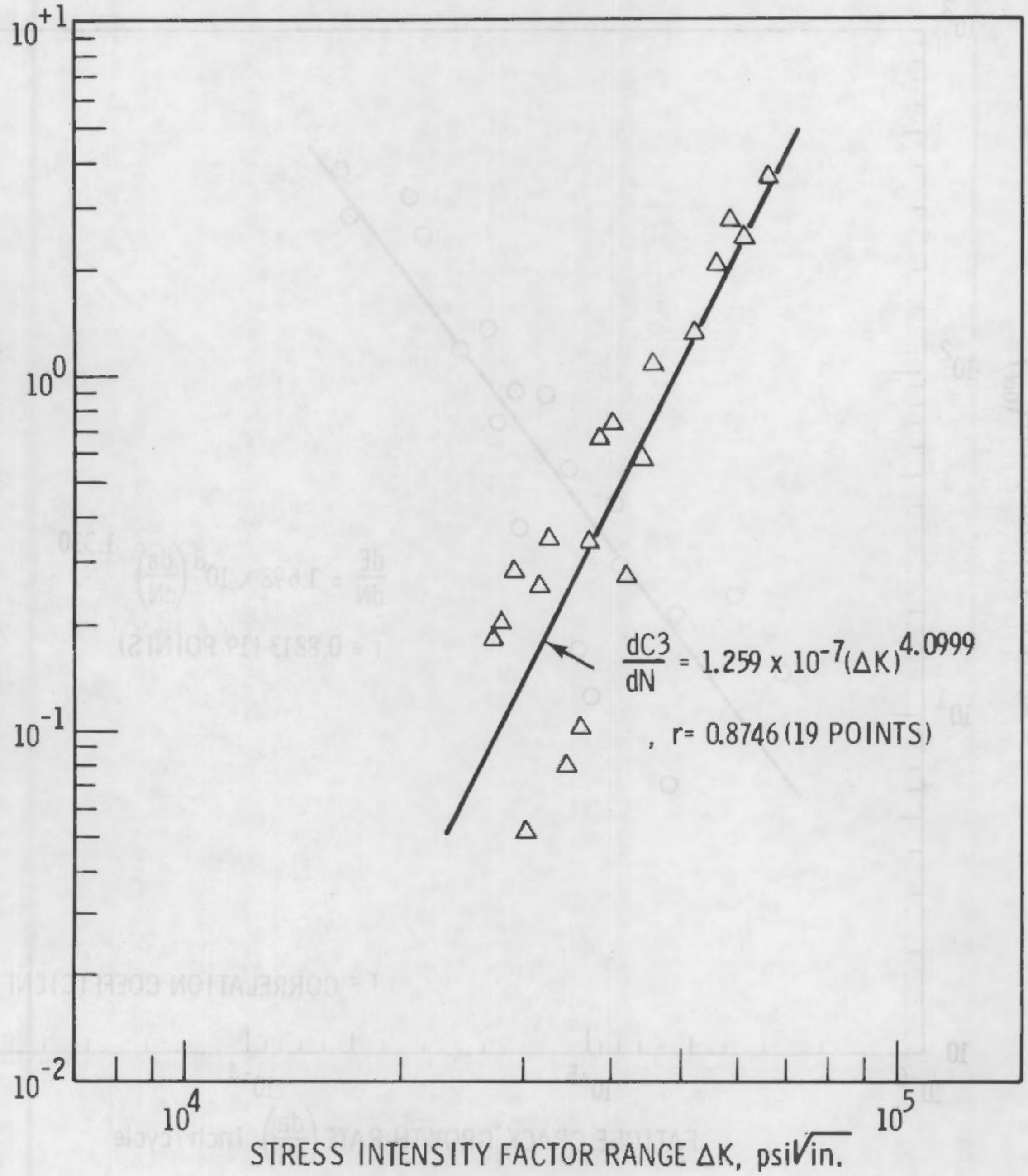


FIGURE 16. AE Event Count/Cycle vs Stress Intensity Factor - Test B2-1B

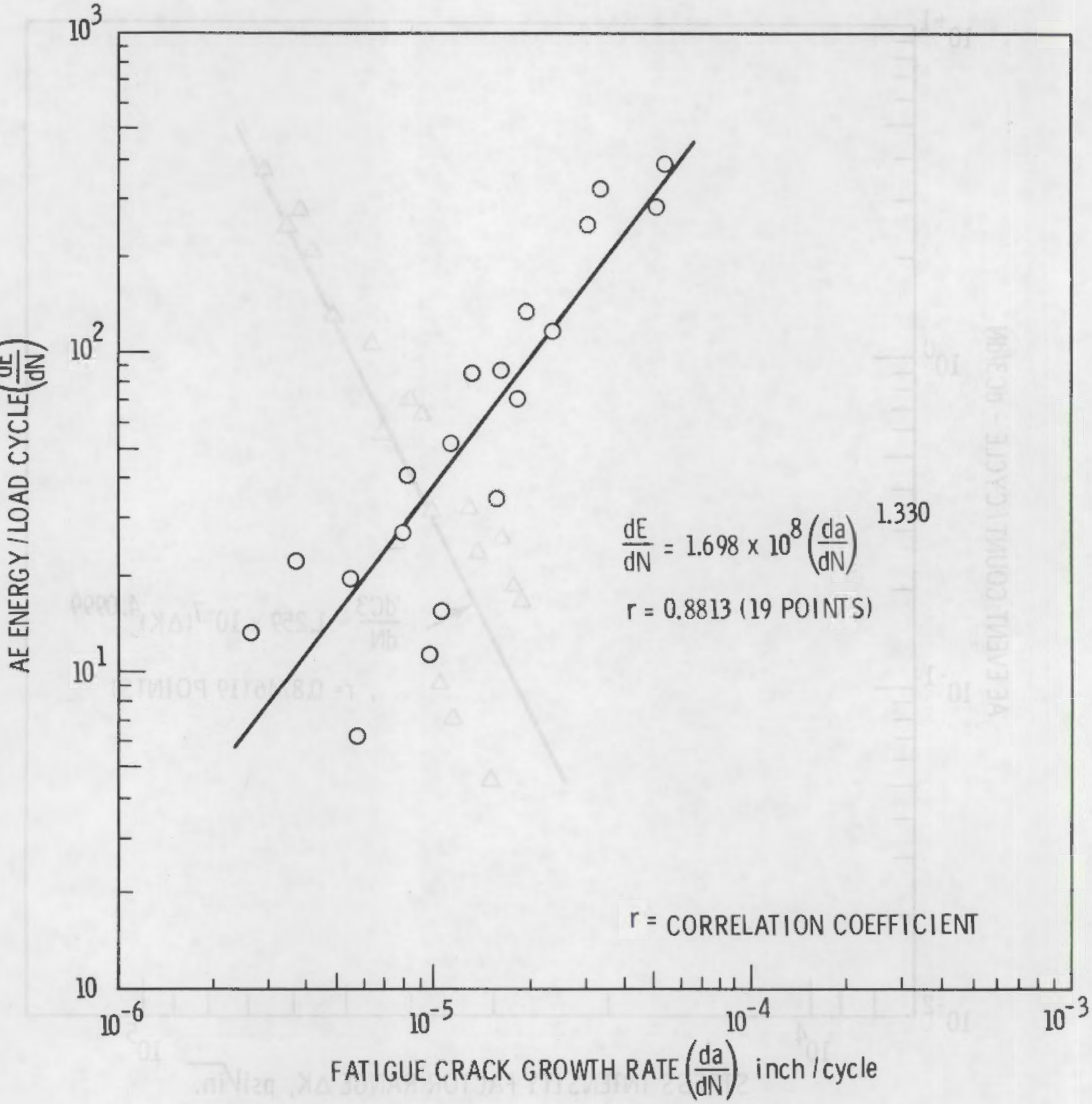


FIGURE 17. AE Energy/Cycle vs. Fatigue Crack Growth Rate, Test B2-1B

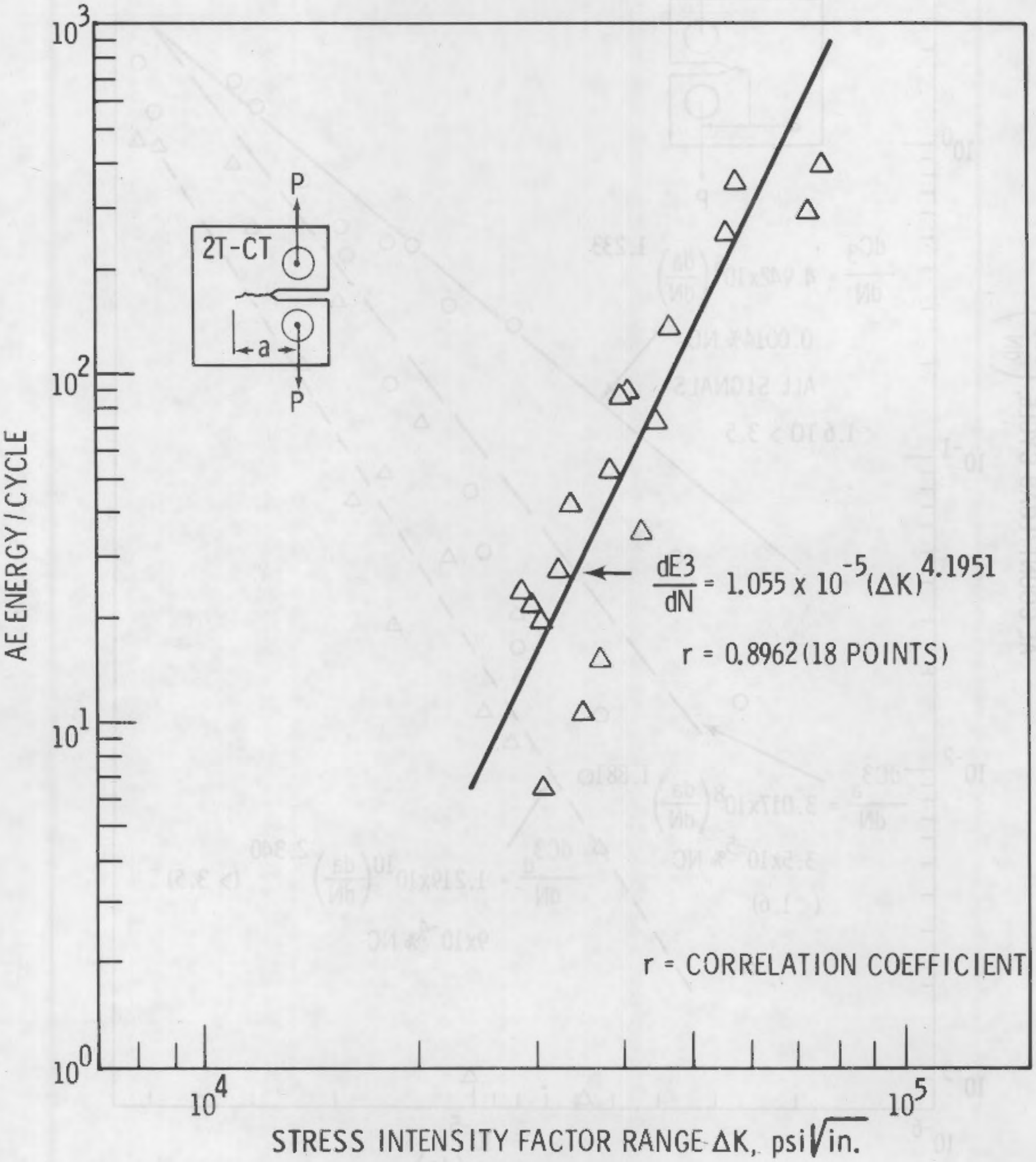


FIGURE 18. AE Energy/Cycle vs Stress Intensity Factor - Test B2-1B

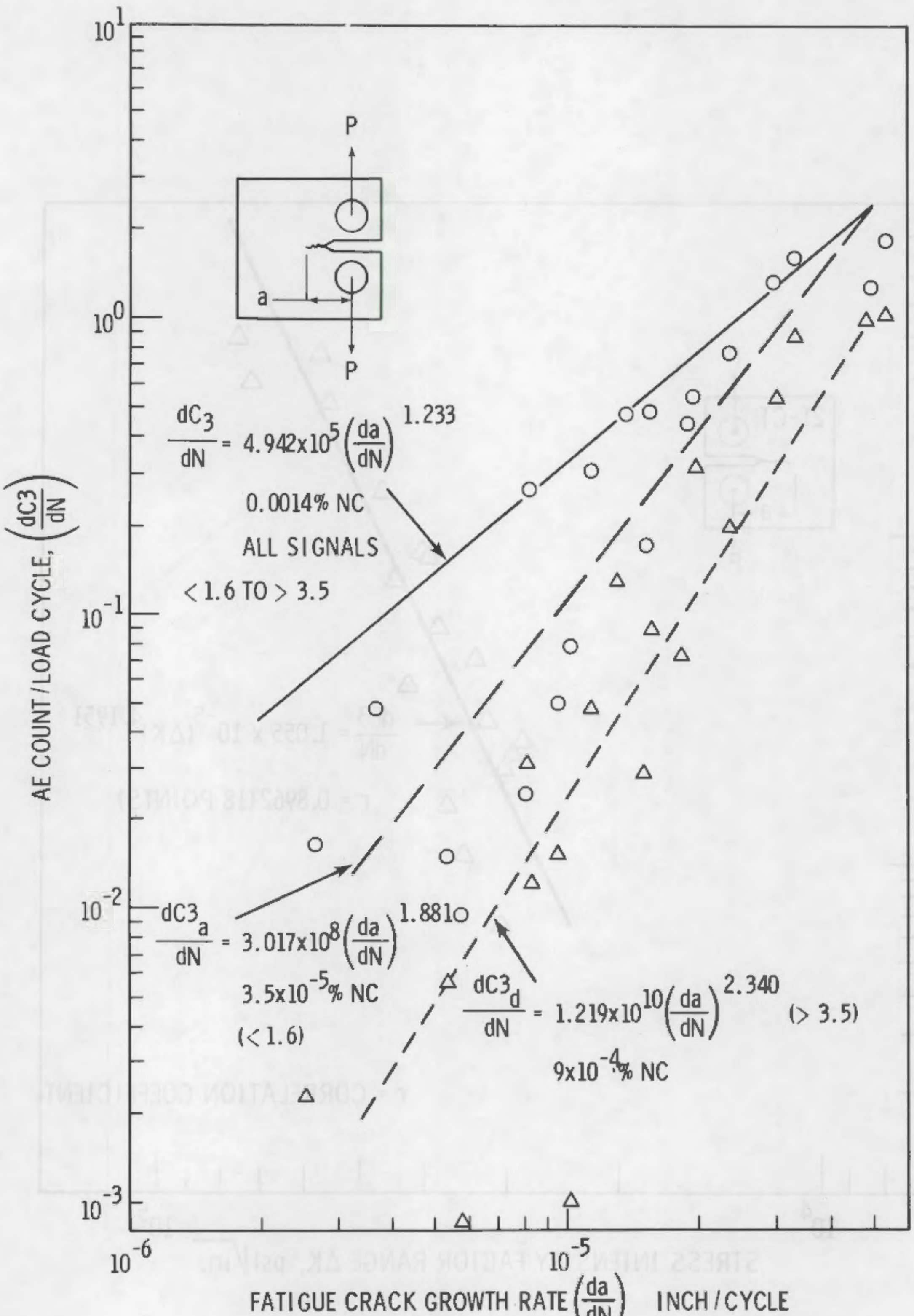


FIGURE 19. AE Count/Cycle Partitioned By Amplitude vs. Fatigue Crack Growth Rate, Test B2-1B

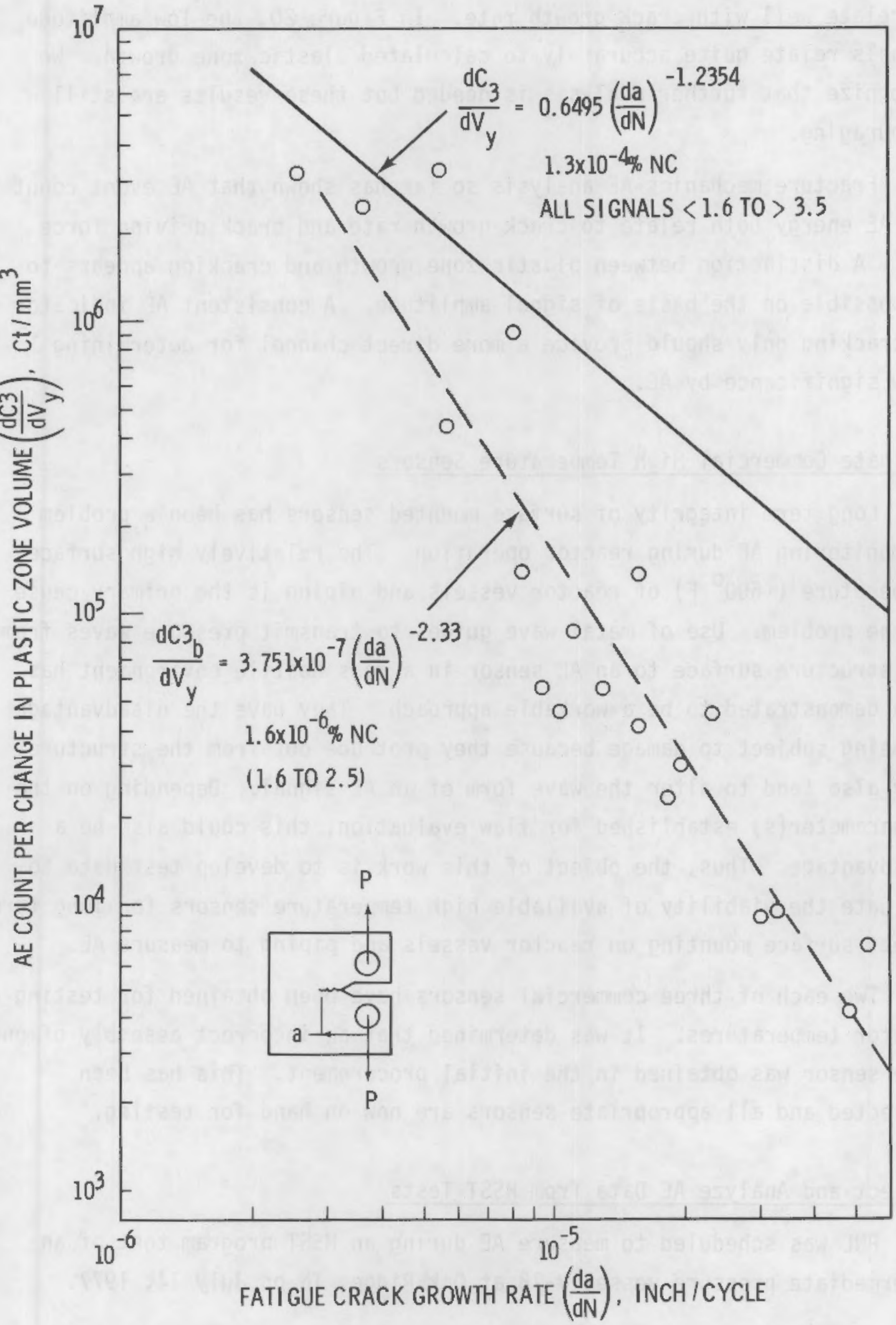


FIGURE 20. Total and Low Amplitude AE Signals/Increment in Plastic Zone Volume vs. Fatigue Crack Growth Rate, Test B2-1B

correlate well with crack growth rate. In Figure 20, the low amplitude signals relate quite accurately to calculated plastic zone growth. We recognize that further analysis is needed but these results are still encouraging.

Fracture mechanics-AE analysis so far has shown that AE event count and AE energy both relate to crack growth rate and crack driving force "K". A distinction between plastic zone growth and cracking appears to be possible on the basis of signal amplitude. A consistent AE indicator of cracking only should provide a more direct channel for determining flaw significance by AE.

Evaluate Commercial High Temperature Sensors

Long term integrity of surface mounted sensors has been a problem to monitoring AE during reactor operation. The relatively high surface temperature ($\sim 600^{0}$ F) of reactor vessels and piping is the primary cause of the problem. Use of metal wave guides to transmit pressure waves from the structure surface to an AE sensor in a less hostile environment has been demonstrated to be a workable approach. They have the disadvantage of being subject to damage because they protrude out from the structure. They also tend to alter the wave form of an AE signal. Depending on the AE parameter(s) established for flaw evaluation, this could also be a disadvantage. Thus, the object of this work is to develop test data to evaluate the viability of available high temperature sensors for long term direct surface mounting on reactor vessels and piping to measure AE.

Two each of three commercial sensors have been obtained for testing at reactor temperatures. It was determined that an incorrect assembly of one type sensor was obtained in the initial procurement. This has been corrected and all appropriate sensors are now on hand for testing.

Collect and Analyze AE Data from HSST Tests

PNL was scheduled to measure AE during an HSST program test of an intermediate pressure vessel V-7B at Oak Ridge, TN on July 14, 1977.

Two AE systems were used in this work. One was the NRC owned D/E 1032 computerized system to provide point source location and count of AE events. The other system was the BNW digital memory AE monitor to obtain data on AE parameters (count, energy, rise time, and signal amplitude) parallel to those being measured with the same instrument on laboratory test specimens. Both AE systems performed quite satisfactorily. Analysis of the resulting data is in progress and will be included in the next quarterly report.

AE Library

Review of AE research reports relevant to the objectives of this program is continuing. Three reports[2,3,4] have been reviewed in this period and summaries are attached as Appendix B of this report.

REFERENCES

1. P.H. Hutton, E.B. Schwenk, Program to Develop Acoustic Emission-Flaw Relationships for Inservice Monitoring of Nuclear Pressure Vessels, Progress Report No. 1, July 1, 1976 to February 1, 1977, NUREG 0250-1, BNWL 2232-1, March 1977.

2. P.G. Bentley, et al, Acoustic Emission Test on a 25 mm Thick Mild Steel Pressure Vessel with Inserted Defects, UKAEA Risley Engineering & Materials Laboratory, Warrington, England, March 1976.

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APPENDIX A

DETAILS - TEST SPECIMEN MATERIAL

DETAILS - TEST SPECIMEN MATERIAL

Purchase of specimen material from Lukens Steel for this program was done in collaboration with the Naval Research Laboratory (R. Hawthorne and F. Loss). To expedite handling and subsequent machining of specimens from the 8 1/4 in. thick plate, R.T. Landsiedel, Senior Technician, PNL, traveled first to NRL to discuss plate marking details and then to Lukens Steel at Coatesville, Pennsylvania where he followed the 8 1/4 in. x 104 in. x 175 in. plate through the heat treatment, marking for flame cutting, and marking and steel stamping for subsequent PNL specimen removal.

The plate was marked for flame cutting as shown on page 1 of the attached, "Flame Cutting and Specimen Machining Layout". Photos of the layout and flaw cutting process are shown in Figures A and B. Figure A shows the entire plate. The round cutout was apparently done to remove a localized defect that was detected during preliminary ultrasonic examination. Tensile, charpy and drop weight test specimens were fabricated from the other smaller cutout in the background. Figure B shows the flame cutting proceeding on plate sections III-1 and III-2.

The plate was first cut to size (104 in. x 175 in.) by removing the end containing cutouts. Chalk lines for flame cuts, at the positions shown on page 1 of the attachment are barely perceptible in Figure A.

Page 2 of the attachment shows the steel stamp layout for each major sub-plate. Sub-plate I-1 was stamped as I-1 in its upper left and lower right corners. In addition, each corner was identified respectively as A, B, C and D as shown. The word "edge" was stamped on all those edges that experienced a quenched-edge effect. The letters BNW were stamped in the center of the sub-plate along with a Lukens designation.:

Lukens
A533-1 Type B
MT Mn Mo M
A5401-2
⟶

The arrow designates the rolling direction and also points to the right end of the plate in Figure 2 of the attachment. The right end is also the top of the ingot from which the plate was rolled. Correspondingly the left end of the plate is from the bottom of the ingot.

Each additional sub-plate (I-2, II-1 & 2, III-1 & 2 and IV) were marked in the same manner as sub-plate I-1, except for those subplates that were to be delivered to NRL, viz III-2 and IV.

The disposition of the plates at present is:

Sub-plate	Location	Purpose
I-1	Tooling Specialists, Inc. Latrobe, PA	Cutting & machining of specimens
I-2	"	"
II-1	"	"
II-2	NRL	In storage for BNW by NRL for future welding by a pressure vessel company
III-1	PNL	Storage at PNL
III-2	NRL	-
IV	NRL	-

Cutting of the sub-plates into the blocks shown on pages 3, 4 and 5 is complete and machining of specimens has begun. Two of the 1 x 9 x 41 inch plate specimens are expected to be delivered by July 14 and 18 respectively.

The block cutting layout on page 5 of the attachment supercedes all previous layouts.

Based on discussion with NRC, sub-plate III-1 is being held as archive base metal rather than welding it as originally intended. A piece of 2 in. thick A533B Class 1 material is being substituted for welding.

Material Properties

Chemical analysis, physical properties and heat treatment information were provided by Lukens Steel as follows:

Matl: A533-74 Cl 1, Type B

Mill Order No: 74564-2

File No: 8185-45-99

Melt No. A5401

Chemical Analysis (%)

C	Mn	P	S	Si	Ni	Mo
0.23	1.40	0.005	0.004	0.25	0.70	0.57

Physical properties for melt no. A5401, slab no. 2 are:

Mechanical (Transverse to rolling direction)

Yield stress (KSI)	72.6
	71.6
Ultimate Stress (KSI)	93.0
	92.9
% Elongation (2 in.)	22
	24

Charpy Impact

Transverse V-notch tests were run at +20°F. The results were:

Ft - lbs	56	64	62
Lateral expansion (in.)	0.052	0.058	0.055
Fracture Appearance (% shear)	60	60	60

The transverse drop weight transition curve results per ASTM E208 (size P3) were:

Temp. (°F)	Results
0	No break
-10°	"
-20°	"
-30°	2 No break
-40°	No break

NDT is -40°F Reference temp: -40°F

Heat Treatment

Sub-plates and Lukens test specimens were heated to 1625 - 1675^{o} F, held 1/2 hour per inch minimum and water quenched. Tempering occurred at 1220^{o}F, holding at 1/2 hour per inch minimum and water quenched. Sub-plates were stress relieved after flame cutting by heating to 1025 - 1075^{o}F held 1/2 hour per inch minimum (actual time about 12 hours) and air cooled.

Lukens test specimens were stress relieved by heating to 1100 - 1175^{o} F, held 40 hours and furnace cooled to 600^{o} F, then air-cooled.

The full plate was ultrasonic tested. The 104 x 125 plate was acceptable per SA 578 level 1.

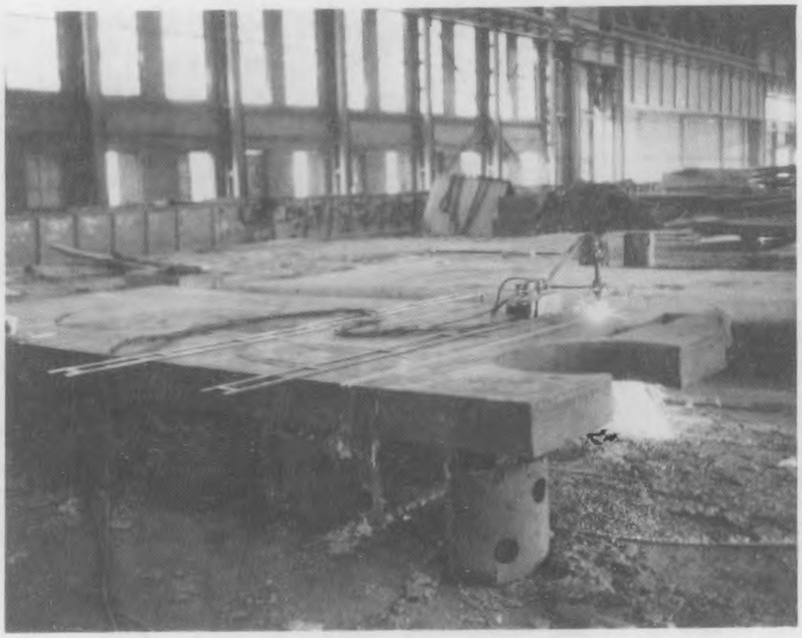


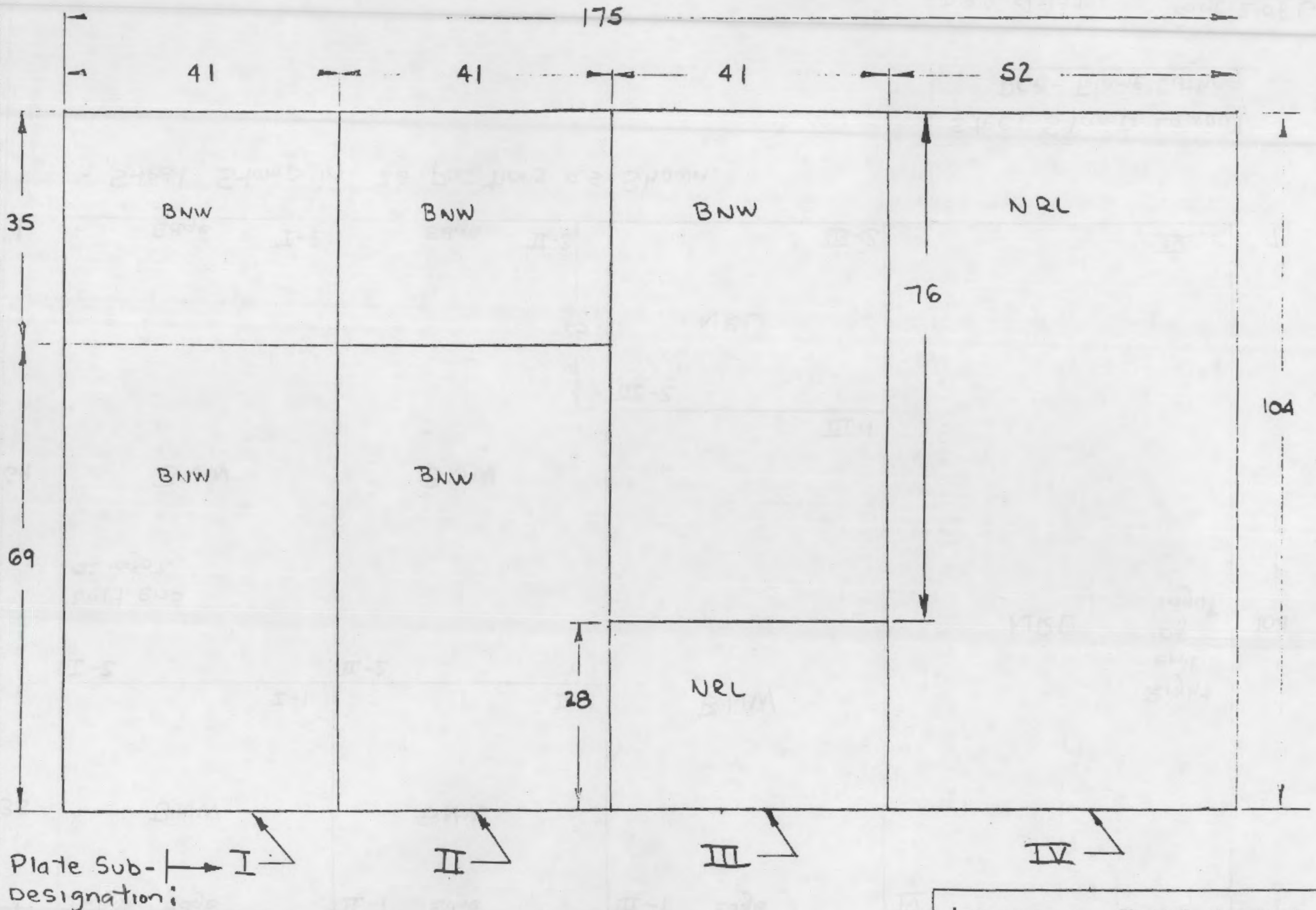
FIGURE A. Flame cutting of 8 1/4 inch A533B Cl-1 plate, dropout section

Figure B. Flame cutting of sub-plates III-1 and III-2 of 8 1/4 inch A533B CL-1 plate

FLAME CUTTING and SPECIMEN MACHINING LAYOUT

Battelle - Northwest
PO Box 999
Richland Wash 99352
E B Schwenk & R T Landsiedel

5/13/77

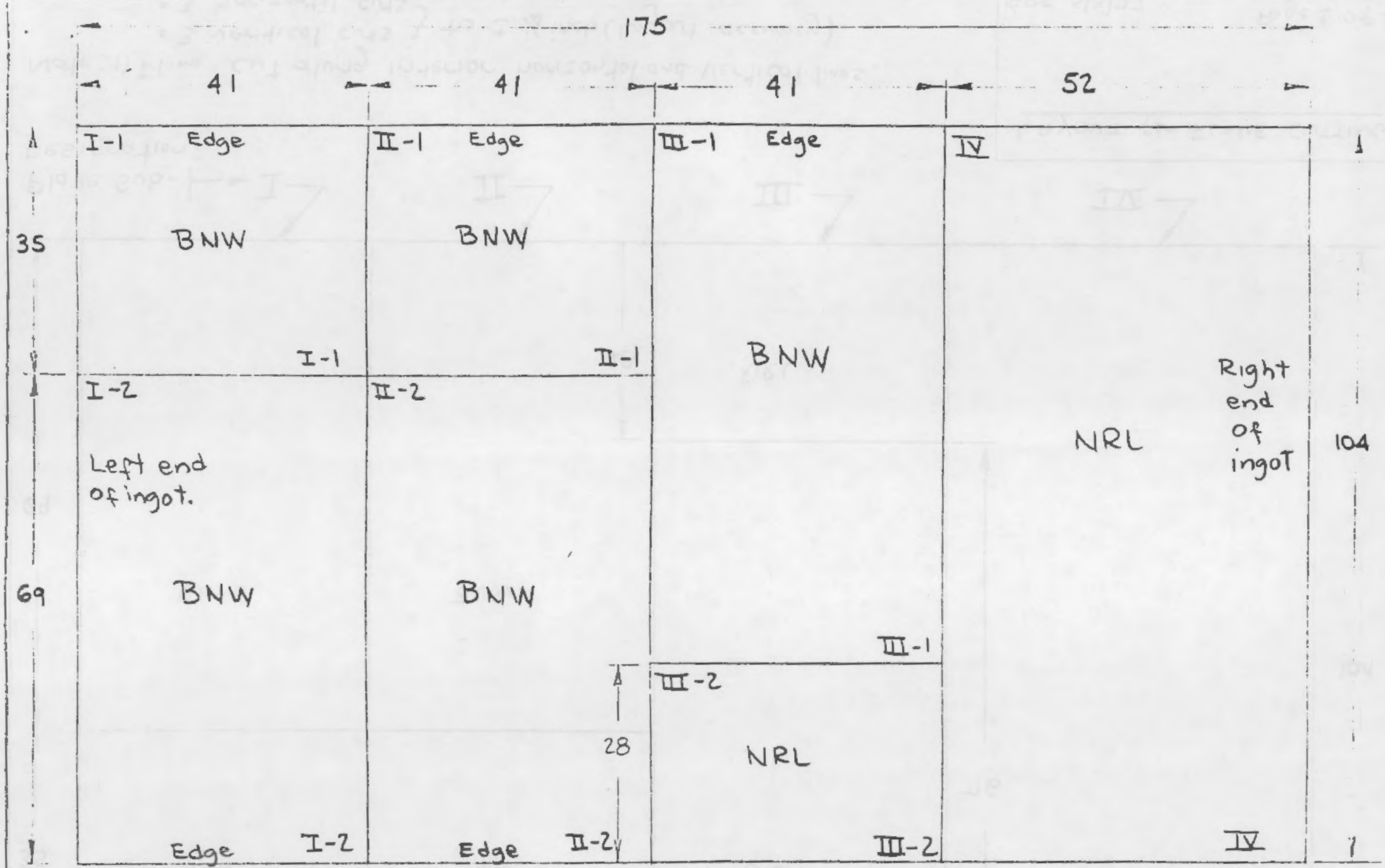


Note: 1) Flame cut along interior horizontal and Vertical lines.
- 3 vertical cuts } to ± 1/4 inch (Layout accuracy).
- 3 horizontal cuts

LAYOUT for FLAME CUTTING

EBS 5/3/77

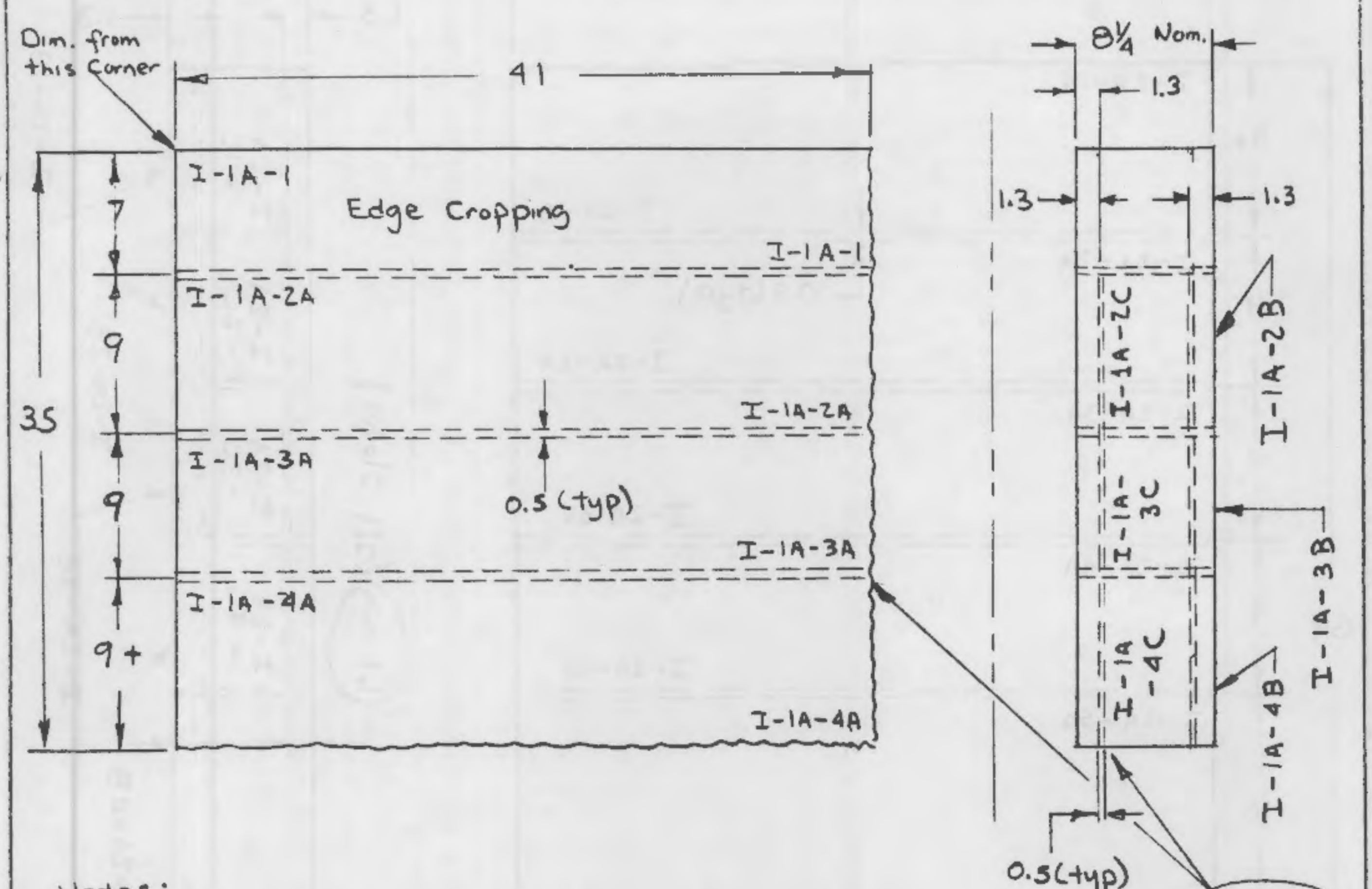
Page 1 of 6



• Steel Stamp in 26 positions as Shown.

Steel Stamp Layout
Pre- Flame Cutting

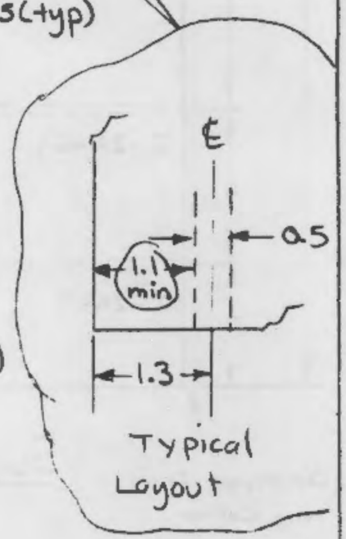
EBS 5/3/77



Notes:

1) Steel Stamp Spec. no's. Eight(8) places face side, Six(6) places back side.
Note that bottom no's are different.
SS "edge cropping" on face side only.

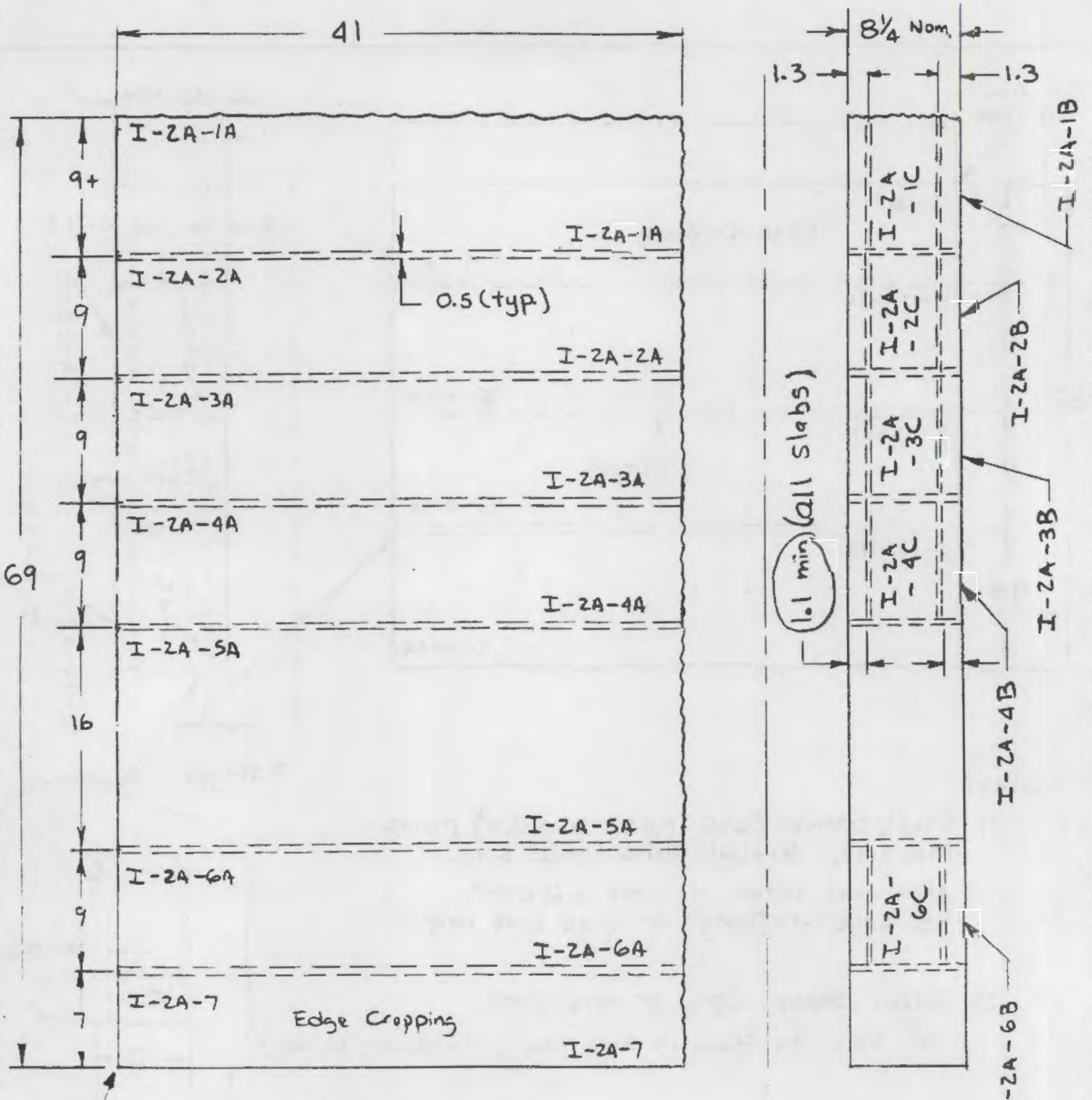
2) Steel Stamp core or mid-plate on side as shown in side view (I-1A-2C, 3C, 4C)



SUB PLATE I - 1

Specimen No. Identification & Pre-Saw cutting Layout

EBS 5/3/77



SUB PLATE I-2

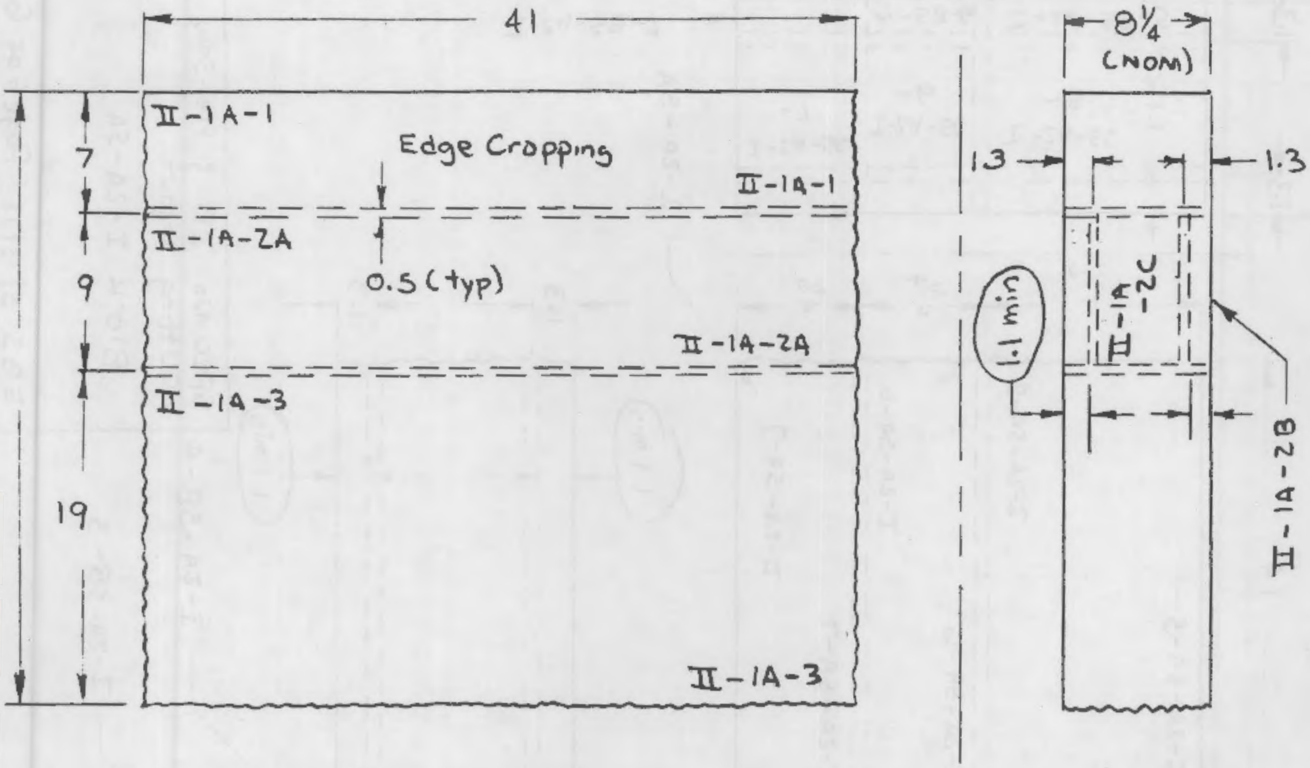
Dimension from this Corner.

Note: 1) SS No's 14 places on face side; 12 places on back side.

2) SS No's 5 places on Right edge; edge cropping on face side only.

A-10

Spec. No. Identification & Pre-Saw Cutting Layout



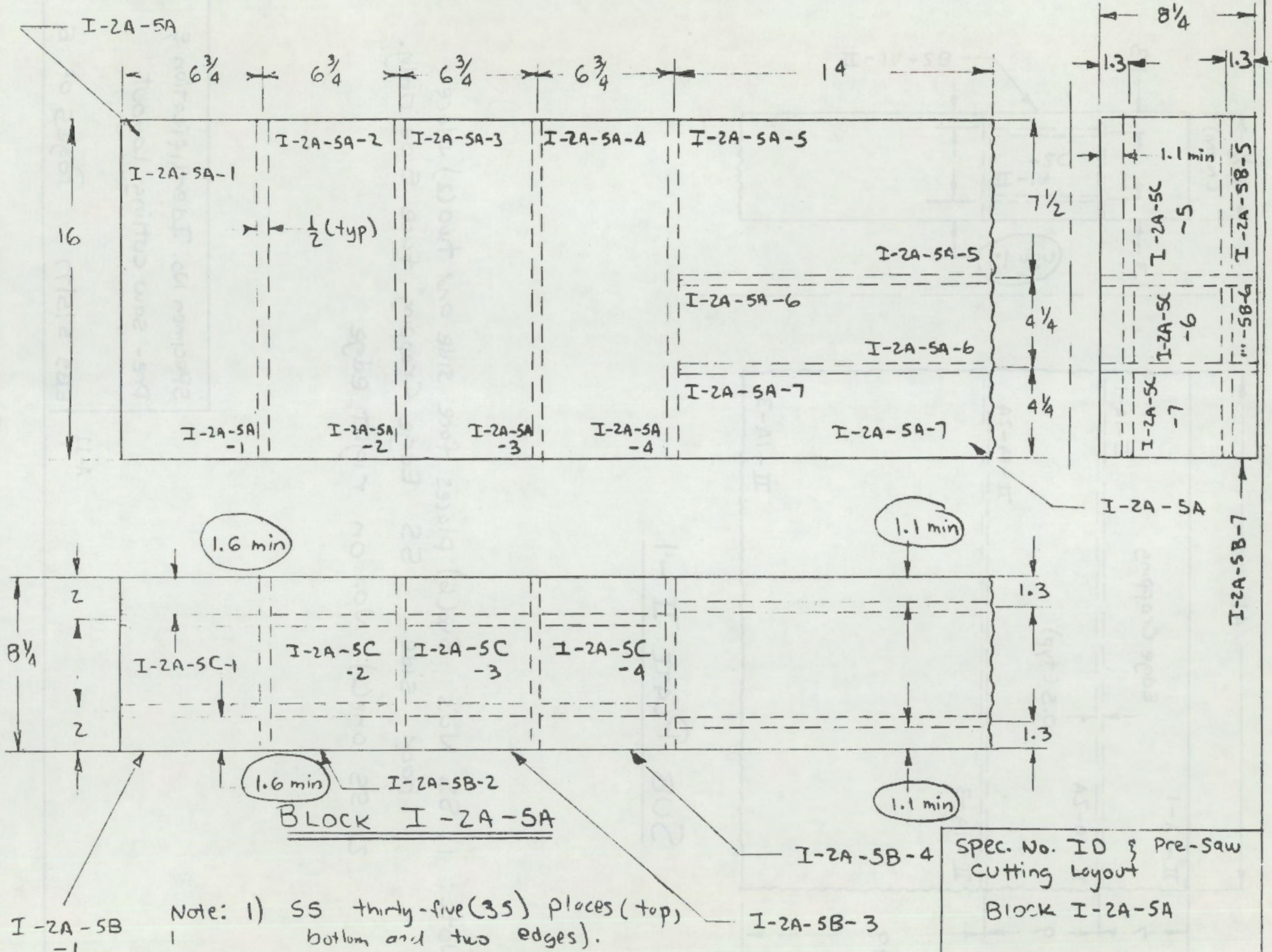
SUB PLATE II-1

Note: 1) SS No's Six(6) places face side and two(2) place back side. SS "Edge Cropping" face side only.

2) SS one(1) No. on right edge

Specimen No. Identification & Pre-saw cutting Layout

EBS 5/5/77 Page 5 of 6



BLOCK I-2A-5A

Note: 1) SS thirty-five (35) places (top, bottom and two edges).

Spec. No. ID & Pre-Saw Cutting Layout
Block I-2A-5A

EBS 5/13/77 Page 6 of 6

APPENDIX B

REVIEWS OF AE RESEARCH REPORTS

NRC ACOUSTIC EMMISSION CHARACTERIZATION PROGRAM
LIBRARY AE R&D LITERATURE

Experience in Acoustic Monitoring of Pressurized Water Reactors

R. Gopal, J. R. Smith, G. V. Rao, Westinghouse Power Water Reactor Systems Division, Pittsburg, Pennsylvania, March 1976.

The Westinghouse R&D programs to develop application of acoustic emission and related acoustic techniques to reactor surveillance are discussed in this report. Topics included are monitoring operating plants, shop hydrostatic and vessel rupture tests, and laboratory work on AE signal interpretation. The paper was presented at the Third Conference on Inspection of Pressurized Components, London, England, September 20-22, 1976.

Key items noted in this paper are:

- Wide acceptance of AE for in-service inspection of pressure boundaries is contingent on developing a method of interpreting AE data.
- Westinghouse program to develop an AE system for in-service monitoring of nuclear reactor primary system has been active for six years.
- System provides two measurements--detection and location of leaks and detection and location of crack growth.
- Strong emphasis on elimination of mechanical and electrical noise interference.
- AE system is computerized with CRT display and hard copy record capability. Uses a resolution element-- "look-up-table" source location technique as opposed to performing hyperbolic calculations. Size of resolution elements can be made comparable to area accuracy limits of hyperbolic calculations.
- AE system simultaneously measures two functions--rms background noise level for leak detection and AE burst signals by threshold discrimination for crack growth detection.

Experience in Acoustic Monitoring of Pressurized Water Reactors

- Sensors are pressure coupled piezoelectric with a primary frequency range of 0.3 to 1.0 MHz. Absolute sensitivity is -90db re 1 volt/ μ bar at 0.5 MHz. A line driver technique is used to allow preamplifier location several hundred meters from the sensor.
- AE system has been evaluated at nine nuclear power plants. At two plants, AE monitoring equipment was permanently installed during construction.
- Cold hydrotests, hot functional tests, precritical heat-ups, and steady-state operation have been monitored.
- Objectives of plant tests have been study of AE, characterization of leaks, wave propagation, background noise levels, elimination of noise interference, and reliability of system components in nuclear environment.
- Acoustic leak detection has been proven. Detection of AE from all regions of pressure boundary can not be guaranteed yet during plant operation due to combination of hydraulic noise and inaccessibility of certain regions for sensor mounting.
- Conducting laboratory tests to develop AE-flaw growth characterization. Relating AE count N to stress intensity factor K in the form $N = AK^n$. Data indicates n equals about 7 for unirradiated and 3.4 for irradiated A533B steel.
- Indicate conclusion that plastic zone at front of crack is source of AE.
- Developed a nickel-iron system to provide metallurgical source of AE for system calibration.
- AE monitored five HSST vessel rupture tests. AE data correlated well with strain and crack extension data.

Observations from this paper with major relevance to the NRC-PNL AE program include:

1. Westinghouse program should provide valuable insight to reliability of AE system components in a nuclear reactor environment and unique

problems attendant with in-service monitoring.

2. Westinghouse experience with long term sensor installation on reactor pressure systems will provide important input to definition of a viable high temperature sensing system.

3. A significant variation in AE signal rise time was observed ("very short--up to 300 μ sec"). This was attributed to surface defects versus subsurface defects and attendant differences in wave propagation modes. This does not appear to be totally consistent with the conclusions by the Germans (Battelle-Frankfurt) that AE from any source in heavy section plate propagates by surface wave beyond about three plate thicknesses from the source. This subject is important from two considerations--measurement of time of arrival difference for source location and measurement of rise time as an AE signal characterization parameter.

4. Plastic zone growth is indicated to be the source of AE in crack growth. This is still open to question and early tests in the NRC-PNL program should provide further definition. Resolution of the question of plastic zone growth versus crack area increase as the source of primary AE in crack growth could be very important to developing reliable AE data interpretation relationships.

Acoustic Emission Test on a 25mm Thick Mild Steel Pressure Vessel With Inserted Defects

P. G. Bentley, D. G. Dawson, D. J. Hanley, N. Kirby, UKAEA Risley Engineering and Materials Laboratory, Warrington, England, March 1976.

Acoustic emission (AE) measurements on a mild steel pressure vessel containing four artificial defects which was tested to failure by internal pressure is the subject of this paper. The primary feature of this work is the fact that no AE was detected from the artificial defects during any part of the test even though the largest defect extended through the vessel wall to produce failure. The paper was presented at the Third Conference on Inspection of Pressurized Components, London, England, September 20-22, 1976.

The following observations are drawn from the paper:

- Test arrangement consisted of a mild steel (BS1501-224, Grade 32A) pressure vessel 1.5 m I.D. x 4.3 m long x 25 mm wall. Three defects were produced in a 1.5 m x 1.2 m implant panel in the vessel wall and one defect in the base vessel wall. Depth of defects ranged up to 90% of wall thickness (in the implant panel).
- No special effort was made to assure a high quality weld between the implant and the vessel wall.
- The AE monitor system used was capable of detecting an 8 μV signal. A bandwidth of 130-300 KHz was used with primary sensitivity at 190 KHz.
- Fatigue bars were welded to one end of the vessel for pretest calibration of the AE system.
- Fatigue cracking the bars was readily detected by the AE system and source located to the bar.
- Two of the panel defects were fatigue cracked prior to test. During the fatigue cracking of one defect, AE was monitored

periodically for a total of 98 cycles out of 1155 fatigue cycles used. No AE was detected.

- The main test consisted of 13 internal hydraulic pressure cycles total to three successively higher pressure levels. The 90% through wall defect in the implant panel caused failure.
- 3600 AE events were detected during the test with none indicated to be from the four installed defects.
- During the final pressure ramp, ten large AE signals were observed ten seconds before failure. Signal distortion prevented any source location on these signals.
- Plastic flow occurred at all defects and the ligament at the bottom of the deepest defect (90% through wall) cracked to cause failure.
- Several weld defects (slag inclusions) in the implant panel weld were detected and located by AE.
- Four point bend tests on notched specimens cut from the implant panel after testing showed an abundance of relatively low level AE.
- Post test investigation indicated that a signal attenuation of 18 to 26 db could occur between the defects and the AE sensors due to attenuation in the material and signal dispersion. Based on specimen bend test results, it was estimated that a 26 db attenuation would result in only 1% of the signals being detected.
- Conclude that non-planar defects such as slag inclusions in welds can be detected by AE during stressing but that planar defects of a relatively large size will not necessarily be detected.

On the surface, the test results described above could appear discouraging in the context of the NRC-PNL AE program. There are several factors which must be considered, however, in weighing the test results.

1. The weld joining the implant plate to the vessel wall was by description a low quality weld. Porosity, slag inclusions, and voids from lack of side wall fusion were identified by inspection.

This weld could be contributing to AE signal attenuation and also signal distortion which would make source location difficult.

2. The primary mechanism operating during the test to produce AE was plastic flow. Very little cracking occurred and most of this in a very short period as the ligament at the bottom of the deepest defect cracked. As pointed out in the paper, the AE signal from plastic flow is very low in amplitude. Thus, it is not surprising that no emission was detected from the defects.

3. The fact that no AE signals were detected during fatigue precracking of one of the defects is again not surprising. A total of 98 load cycles were monitored out of 1155 used to grow the crack. The 98 cycles were monitored at 9 different points in the crack growth process for an average of about 11 cycles per monitoring period. We have consistently observed that AE from fatigue crack growth is intermittent. It is thus quite possible that the nine very brief monitoring periods would not see AE.

4. The conclusion of the authors states, "In conclusion therefore, the tests show that small natural non-planar defects in welds can be found by acoustic emission but that very large artificial planar defects up to 90% of plate thickness cannot necessarily be reliably detected."

   The implications of this conclusion are rather disquieting but of questionable justification. In the case of a reactor pressure vessel, shallow defects (certainly far less than 90% through wall) that start to grow would be the type of deterioration we would expect to detect by in-service AE monitoring. Since these defects would proceed by cracking rather than primarily plastic flow, the assurance of detecting them by AE would be much greater than in the case of the very large defect used in the subject test work.

5. The effect of signal attenuation in the vessel wall, although it may not be as severe as measured in the subject tests, is a factor that certainly must be taken into consideration in in-service monitoring.

<u>Acoustic Emission Test on a 25 mm Thick Mild Steel.....</u>

In summary, considering the above factors, the results of the subject test work are not considered discouraging to our program but they do point out aspects such as signal attenuation which must be carefully considered in in-service AE monitoring.

Acoustic Emission Parameters And Their Interpretation, D.E.W. Stone and P.F. Dingwall, Structures Dept., Royal Aircraft Establishment, Farnborough, Hants, England. Published in NDT International, Vol. 10, No. 2, April, 1977, pgs. 51-62.

The article approaches the subject from the basis that one would like to use acoustic emission (AE) as a technique to answer the following questions concerning a specimen or a structure:

(1) Has a failure event occurred? (Failure here is taken to mean on a localized, perhaps micro scale; not gross structural failure in the normal sense)

(2) Where has it occurred?

(3) What type and severity of event has occurred?

The authors point out that within definable practical limits, the capability is in hand to use AE to answer the first two questions. In the case of the third question, however, much of the technology remains to be developed. The paper discusses avenues of approach to meeting this technology need both from a theoretical and a practical standpoint.

Highlights extracted from the paper are:

- In the context of AE source identification and evaluation, four aspects are considered - sensor response, signal frequency spectrum, signal amplitude, and signal energy.

Sensor

- Relating sensor electrical output to the strain induced in the crystal to produce the output is quite complex. Several methods are currently being used in an attempt to obtain absolute calibrations for practical sensors.
- Ideally, one would like to derive the original stress pulse in the material from examination of the sensor output signal. To date, there has not been an unambiguous definition of the transfer functions.

Acoustic Emission Parameters and their Interpretation

- An emperical method for relating sensor response to the wave producing it is being investigated by McBride and Hutchinson (Can. J. Phys. 54 No. 17, 1976, pp 1824-1830). This involves comparing the sensor spectral response to a gas jet and to a real AE producing event under known conditions. The gas jet is then applied to a structural monitoring circumstance to establish sensor response to the gas jet at various locations on the structure. The resulting information together with results from the known condition calibration would provide a basis for predicting sensor response to the real AE producing event in the structure at the various locations. Efficiency of the method is yet to be demonstrated in practice.

Frequency

- Frequency spectrum of a sensor response to AE pulse excitation is conditioned by sensor characteristics and the resonances of the physical object being monitored.
- Ono and Ucisik (Acoustic emission behavior of aluminum alloy, Mater. Eval. 34 No. 2, Feb., 1976, pp 32-44) concluded from testing aluminum alloys that identifiable changes in the spectrum were due to sensor and specimen resonances. A characteristic spectrum of fracture events could not be identified.
- Graham and Alers (Acoustic emission in the frequency domain, ASTM, STP 571, 1975, pp 11-39) concluded from testing A533 B steel that different spectra were observable for different failure events. They related low frequency spectra with crack extension and high frequency spectra with plastic deformation. They also concluded that spectral content was not altered by either geometric reflection or wave propagation mode.
- A great deal more investigation is needed before interpretation of AE by frequency content can be reliably applied to structural monitoring.

Amplitude

- Sensor response amplitude is not only a function of the amplitude of the original stress pulse, but also piezoelectric constants of the sensor crystal, pulse duration, the Q-factor of sensor resonances, and propagation distance through the material.

- Considers the best approach to evaluating amplitude correlation with AE source is to use a damped sensor and sort the sensor output into multilevels of amplitude.
- Pollock derived an exponent factor termed "b" (Acoustic emission-2. Acoustic emission amplitudes, Non-destructive Testing 6, No. 5, 1973, pp. 223-286) for interpreting the meaning of a given amplitude distribution. A useful feature of this presentation is that the value of "b" does not change if the amplitude of all signals involved are changed by a common factor.
- Effective application of amplitude interpretation would be sensitive to stress pulse propagation distance in the material and the associated attenuation.

Energy

- Measurement of the energy in an AE event offers the possibility of direct comparison with the work of fracture and with standard fracture mechanism parameters.
- The energy spectrum will extend from zero up to a frequency inversely proportional to the duration of the source event.
- Theoretically, the upper end of the energy spectrum may be 20 MHz or higher.
- In practical measurements of AE, the total energy spectrum is curtailed by material attenuation at high frequencies and filtering at low frequencies to avoid noise interference.
- There are two sources of energy in a given event - high level, short term energy packet due to the event itself and a low level longer term energy from decaying oscillations of nearby material. The first is much predominant.
- Use of a narrow frequency band system appears advantageous in practical energy measurements. Although only a fraction of the total energy spectrum is measured, it removes the complexity of determining the frequency function in the measured energy. Ishikawa and Kim (Stress Wave Emission and Plastic Work of Notched Specimens,

J. Mater. Sci., 9, 1974, pp 737-743.) have shown on notched structural steel specimens that energy so measured is a constant proportion of the J integral which is a measure of the work done per unit increase in crack length.

- Measured AE energy will be influenced by propagation distance, the number of wave reflections measured, frequency bandwidth, and propagation mode measured.

There are several implications from this paper which are of interest in the NRC-PNL AE-flaw characterization program. These are:

(1) Use of frequency spectrum information for evaluation of AE data must be treated with caution. There is, however, enough positive results that it should not be discarded as a parameter to be examined.

(2) The method for measuring signal amplitude recommended in this article is very similar to that being used in the NRC-PNL AE program.

(3) Based on discussion in this article, we may want to consider measurement of AE energy in a series of consecutive frequency bands spanning the total bandwidth currently used in our work. We presently measure the composite energy in the total bandwidth.

(4) Based on comments concerning correlation between AE energy and J integral, energy measurement may warrant special attention in measuring AE from HSST irradiated fracture specimens.

(5) The effect of geometric reflections on energy measurement should be easier to control in heavy sections such as a pressure vessel wall. The reflected information should be separated more in the time domain from the initial wave than is the case in smaller laboratory specimens.

(6) There were several comments concerning adverse effects of varying AE detection distance on the consistancy of AE parameter measurements. This reinforces the possibility that on line monitoring may, at lease initially, need to be approached on the basis of restricted area monitoring rather than total volumetric monitoring of a vessel.

Acoustic Emission Parameters and their Interpretation

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