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

Progress Report
October 1, 1977 - January 1, 1978

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

Battelle-Pacific Northwest Laboratories

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PROGRESS REPORT

October 1, 1977 to January 1, 1978

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February 1978

ABSTRACT

This program is directed to providing an experimental evaluation of detecting and analyzing flaw growth in reactor pressure boundaries through continuous monitoring for acoustic emission (AE). The investigation is currently limited to A533B, Class 1 material. Program primary objectives are:

- 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 October 1, 1977 to January 1, 1978.

A room temperature fracture test was performed on a one-inch thick by six-inch wide single-edge notch (SEN) specimen. The results were similar to AE-fracture test data obtained on 2T-CT laboratory specimens in that the majority of AE occurred during crack propagation.

Continuous elevated temperature (500^{0} F) testing of high temperature AE sensors was initiated.

Four reports on program results were completed during this period.

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1.0 INTRODUCTION

The purpose of this program is to provide an experimental evaluation of the feasibility of detecting and analyzing flaw growth in reactor pressure boundaries on a continuous basis using acoustic emission (AE). Type A533B, Class 1 steel is being used in all experimental testing. The 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.
- Make available a characterized high temperature AE sensor.

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2.0 SUMMARY/CONCLUSIONS

A room temperature fracture test of a one-inch thick by six-inch wide SEN base metal specimen has been completed. The specimen was fatigue precracked prior to fracture toughness testing. AE data for the fatigue precracking portion of the experiment were only partially comparable to earlier work[1] because bending of the specimen occurred during fatigue loading. This resulted from specimen bowing (about 0.070 inches at the center) caused by the stress-relief heat treatment ($1150^{o} \pm 25^{o}$ F, 40 hrs).

Fracture test results compare favorably with earlier results derived from size 2 compact tension (2T-CT) specimens. As with the 2T-CT specimens, this specimen emitted very little valid AE during gross elastic loading. Most of the AE was observed during crack extension, following "general" yielding. In contrast, a relatively large amount of AE occurred during gross elastic loading of the HSST vessel V-7B burst test. Differences between laboratory specimen AE-fracture data and the HSST V-7B vessel data[1] have not been explained.

Continuous elevated temperature testing of high temperature AE sensors was initiated in late December 1977. Sensors are being cycled between room temperature, 320^{o} F (160^{o} C) and 500^{o} F (260^{o} C).

Four reports on program results were completed during the report period.

3.0 DISCUSSION

Discussion of results is presented under the format of Experimental Procedure, Experimental Results and Analysis, as appropriate to each topic.

3.1 AE/Fracture Mechanics Testing

3.1.1 Experimental Procedure

Preparations for room temperature fracture testing of SEN specimens 1-2A-2B (base metal) consisted of machining an initial notch approximately .030 inches wide by 2.8 inches long, polishing the

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specimen surfaces near the notch root, and mounting and calibrating the AE sensors. The locations of the notch and AE sensors relative to the centerline of the specimen are shown in Figure 1. The reason for locating the notch and AE sensors asymmetrically about the specimen centerline was to enhance pin noise rejection. With a symmetrical arrangement, it is possible for acoustic noise signals emmanating from each pin at the same instant to be misinterpreted by the instrumentation as originating at the center of the specimen (flaw area) because the Δ time of signal detection at the sensors would be zero. We do not have evidence that this has occurred with previous symmetrical arrangements but it is possible. The AE acceptance zone was restricted to a region about one-inch on each side of the flaw.

In order to sharpen the notch root radius prior to fracture testing, the specimen was subjected to sinusoidal fatigue loading. Table I lists the fatigue pre-cracking (FPC) conditions employed. Low stress intensity levels were utilized to provide a relatively slow crack growth rate and to minimize possible effects of FPC on AE behavior during subsequent fracture toughness testing. The specimen was FPC until the average crack length was approximately 2.94 in. The tendency of the specimen to straighten during loading induced some bending stresses through the specimen thickness. This is evidenced by the non-uniform growth of the fatigue pre-crack as seen later. At the completion of FPC the fatigue crack was about 3.074 inches long on one specimen face and 2.813 inches long on the opposite face. Note also that a secondary fatigue crack apparently began to grow later in the test. It eventually intersected the main fatigue crack resulting in a vertical step in the fatigue fracture surface. Throughout FPC the specimen was AE monitored.

AE monitor system parameters for the 1-2A-2B fatigue pre-crack monitoring were:

Sensor sensitivity: -70 dB re 1 volt/μ bar
System gain: 91 dB

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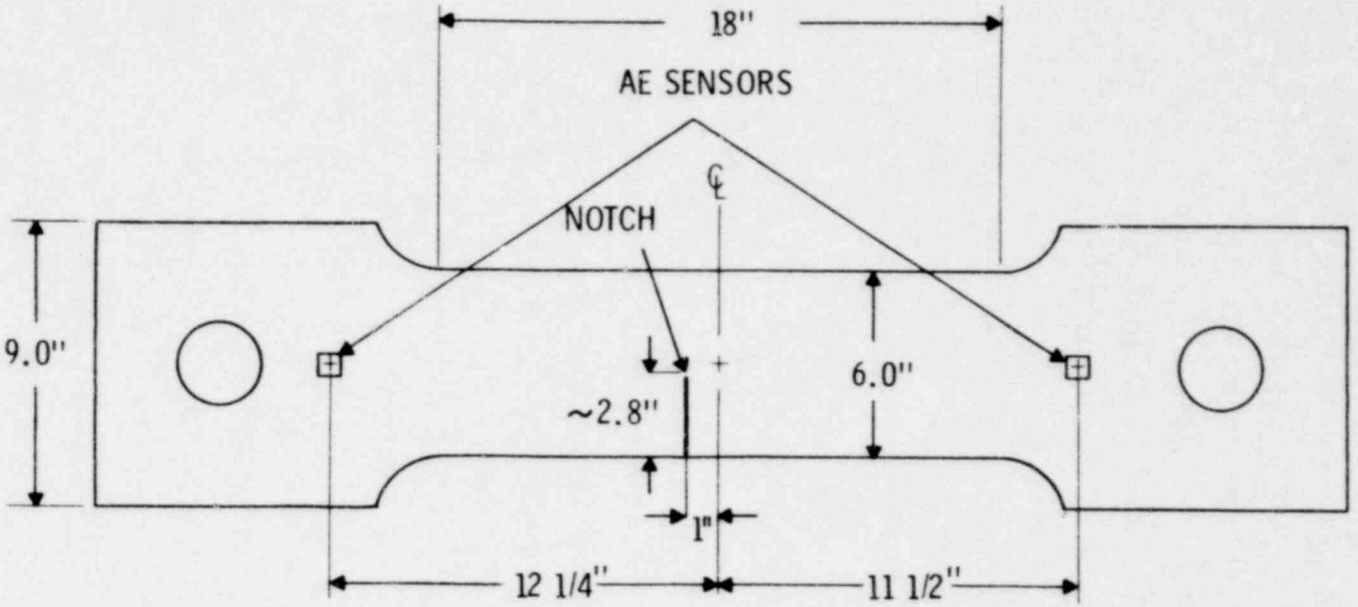

Figure 1. Notch and AE Sensor Locations for Fatigue Pre-Cracking and Fracture Toughness Testing for SEN Specimen 1-2A-2B (Base Metal).

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Detection Threshold: 1.35 volts (0-102,210 cycles)
1.25 volts (102,210 cycles to the end of precracking)

Effective Sensitivity: 0.12 μ bar (0-102, 210 cycles)
0.11 μ bar (102,210 cycles to the end of precracking)

Contrary to normal practice, the threshold was lowered at 102,210 load cycles because it appeared that some low level valid data was being missed.

Following FPC a fracture toughness (FT) test was conducted. A crack opening displacement (COD) gauge was installed on the specimen and a constant displacement rate applied to the specimen. The calibrated range of the COD gauge was about 0.250 in. An initial loading to 110 Kips in an MTS test frame rated at 100 Kips produced neither detectable AE nor crack extension. The specimen was relocated in a 440 Kip Baldwin tensile test machine and reloaded to failure, which occurred around 175 Kips.

AE monitor system parameters for the 1-2A-2B fracture test were:

Sensor sensitivity: -70 dB re 1 volt/μ bar
System gain: 91 dB
Detection Threshold: 1.25 volts
Effective Sensitivity: 0.11 μ bar

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TABLE I. Fatigue Pre-Cracking Conditions for SEN Fracture Specimen 1-2A-2B (Base Metal)

Load, Kips		Cycle Rate, Hz	Total Load Cycles	Average Crack Length, Inches	Comments
P_{max}	P_{min}				
21.75	2.18	3	0	2.8085	
21.75	2.18	3	900	2.8085	
21.75	2.18	5	900	2.8085	
21.75	2.18	5	4,000	2.8085	
21.75	2.18	7	4,000	2.8085	
21.75	2.18	7	10,000	2.8085	
21.75	2.18	10	10,000	2.8085	
21.75	2.18	10	26,720	2.8258	
15.0	1.50	10	26,720	2.8258	Pins Rotated*
15.0	1.50	10	75,700	2.8457	
15.0	1.50	10	102,210	2.8661	Pins Rotated
15.0	1.50	10	122,500	2.8835	Pins Rotated
15.0	1.50	10	140,600	2.8978	Pins Rotated
15.0	1.50	10	157,550	2.9132	Pins Rotated
15.0	1.50	10	179,250	2.9315	Pins Rotated
15.0	1.50	10	185,700	2.9397	

*The pins were periodically rotated to help reduce noise generated at the load-bearing surfaces.

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3.1.2 Experimental Results

Condensed experimental results for the FPC and FT phases of the experiment are given in Appendix A.

Fatigue crack length measurements and valid AE count versus load cycles are plotted in Figure 2. A plot of valid AE energy versus load cycles was not included in Figure 2 because a profile nearly identical to the A_E count versus load cycles curve was observed. Note the discontinuous nature of the AE count data as compared to the smoothly increasing crack length versus load cycles relationship. These data suggest that the sources of AE may not be uniformly distributed or a finer resolution of crack growth behavior is necessary or both.

Results of the second fracture toughness test are plotted in Figure 3. Very little AE was detected throughout the majority (about 710 seconds) of the test which included initiation of "general" yielding of the net section. About 27 percent of the total AE count occurred during this portion of the test (see Table A.2). Prior to reaching maximum load little, if any, crack extension, as well as AE, was observed. Beyond maximum load the crack advanced by a series of alternating rapid and "slow" crack extensions. The rapid extensions correspondingly resulted in rapid load drops, exceeding the response of the load dial for following the loads. During the "slow" crack extensions the load was relatively stable, sometimes increasing until the next rapid load drop occurred. The majority of AE (about 73%) occurred during the alternating rapid and slow crack extensions which in turn occurred in the last 50 to 60 seconds of the test. Extensive net section yielding and plastic flow also preceded growth of the crack. The topography of the fracture surfaces is shown in Figure 4 by the alternating "bands" of fast and slow crack growth.

Unfortunately, load and COD readings were not obtained when most of the AE was produced, due to frequency response limitations in the Baldwin load measuring system and the limit of the COD gauge being

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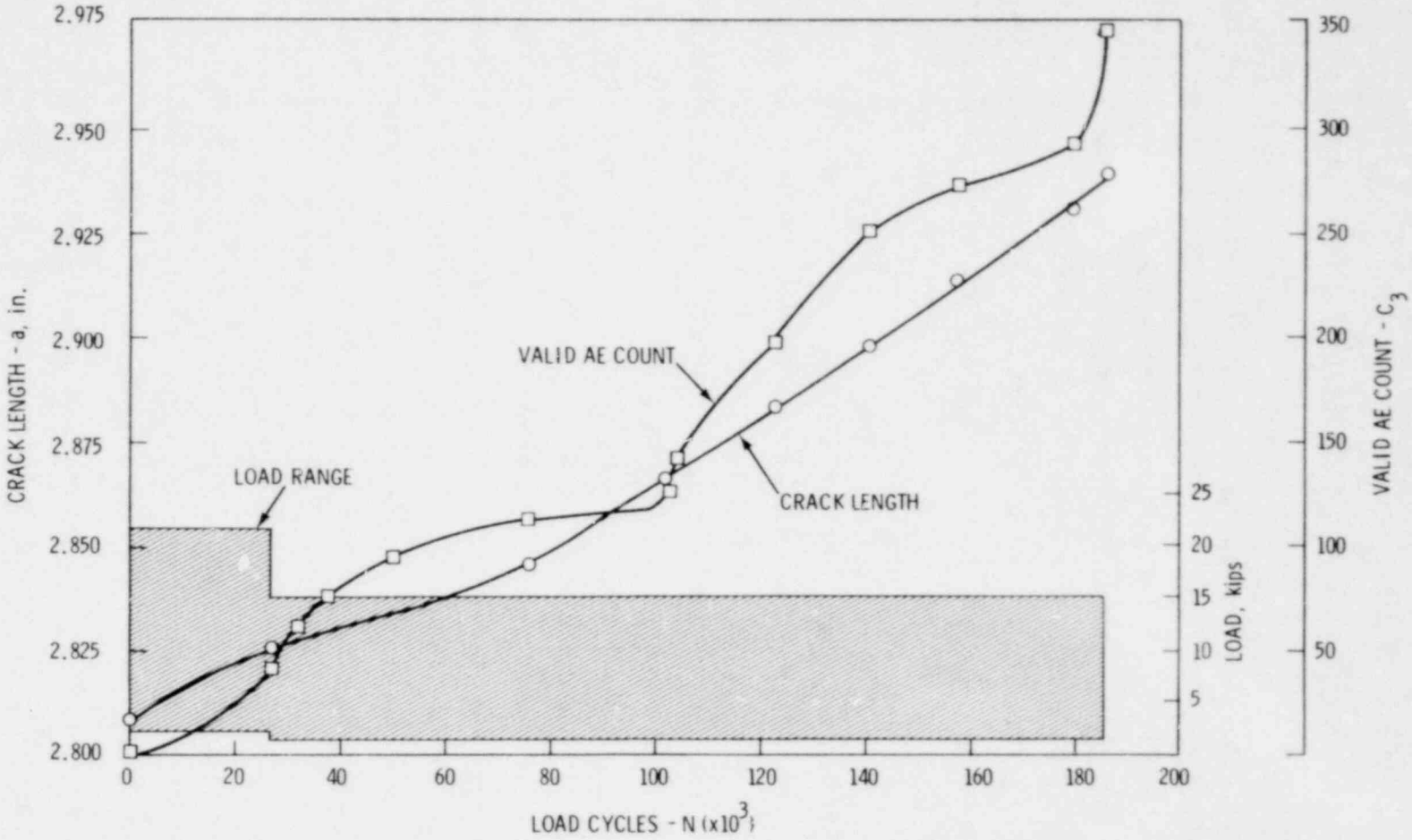

Figure 2. Crack Length Measurements and Valid AE Count versus Load Cycles for Room Temperature Fatigue Pre-Cracking of SEN Specimen 1-2A-2B (Base Metal).

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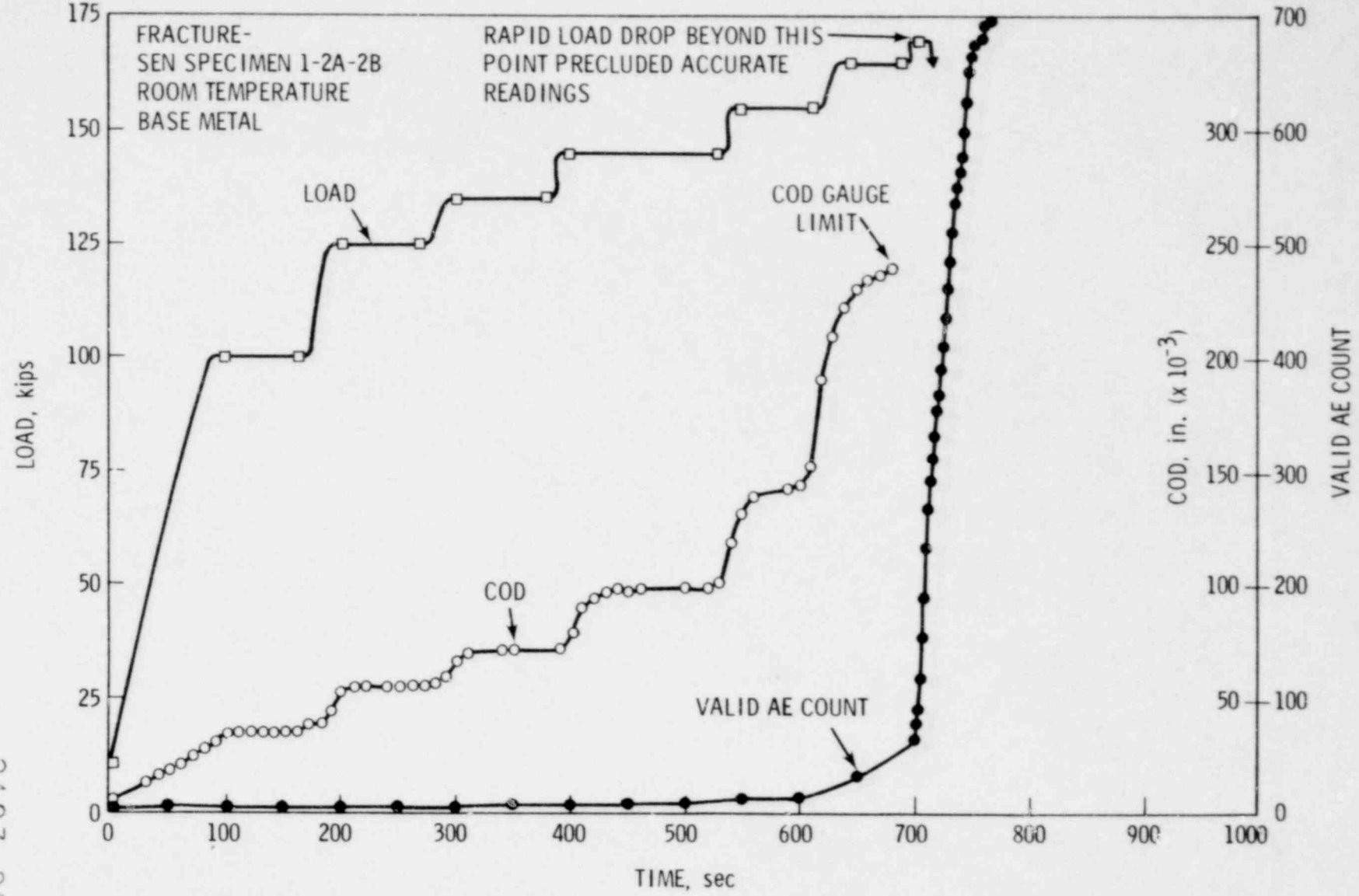

Figure 3. Load, Crack Opening Displacement and Valid AE Count versus Time for Room Temperature Fracture Toughness Testing of SEN Specimen 1-2A-2B (Base Metal).

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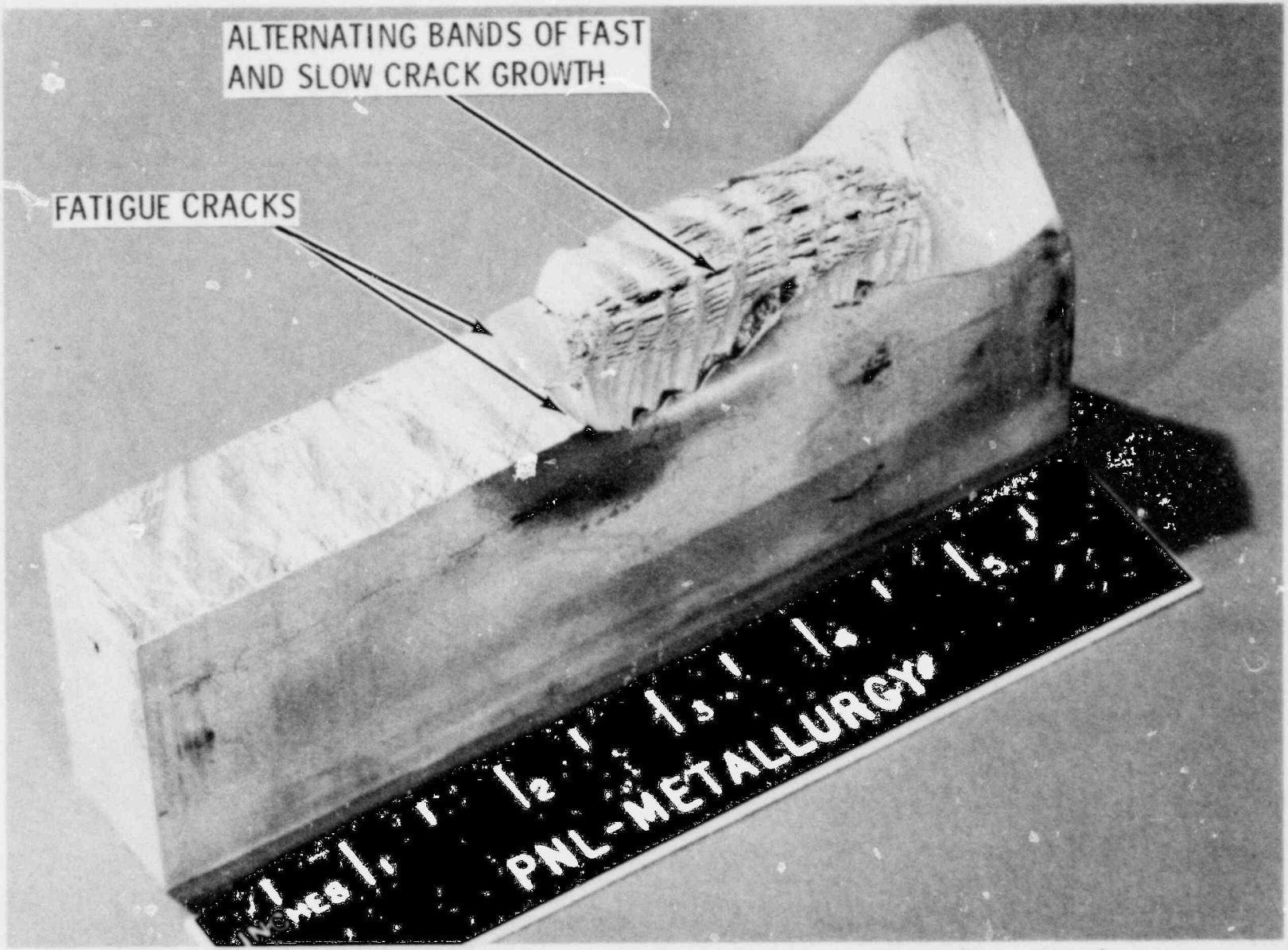

Figure 4. Photograph of the Fracture Surface of SEN Specimen 1-2A-2B (Base Metal).

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exceeded. Improvements to the test setup designed to provide continuous load monitoring and a COD gauge with a broader range are currently being assembled.

3.1.3 Analysis

Rate and summation analyses were performed on the FPC data obtained on SEN specimen 1-2A-2B. The results of these analyses indicated that summation of AE event count versus the maximum stress intensity factor yielded a reasonably linear relationship (see Figure 5) but the rate data (e.g., dC_3/dN vs da/dN, da/dN vs ΔK, etc.) yielded very poor correlations. The reason for this behavior was probably due to the fact that specimen 1-2A-2B was warped (~.070" at center) following a 40-hour stress-relief heat treatment at 1150^{0} F. As a consequence, bending of the specimen near the notch resulted during fatigue loading. The curved crack front and presence of two fatigue cracks (see Figure 4) indicate the bending of the specimen did influence crack growth behavior during fatigue precracking. The fatigue crack most likely initiated at one corner of the notch and then advanced in a somewhat elliptical shape. Thus the average crack length measurements reported are not indicative of true crack growth. This effect was not considered a significant problem since the primary purpose of this test was to evaluate AE during fracture.

Analysis of the fracture toughness test was hindered by the lack of either load or COD measurements during the time interval when most of the AE was obtained. However, two significant observations may be obtained from the data. The first was that almost all of the AE was associated with rapid load drops. This result lends support to the notion that AE in a planar specimen is produced during crack extension rather than plastic zone volume expansion. (In contrast, a relatively large amount of AE was detected in the HSST V-7B test[1] throughout the loading history.) Secondly, almost all of the AE was observed when the specimens' net section was essentially in a gross plastic rather than a gross elastic state. About 73% of the AE occurred after

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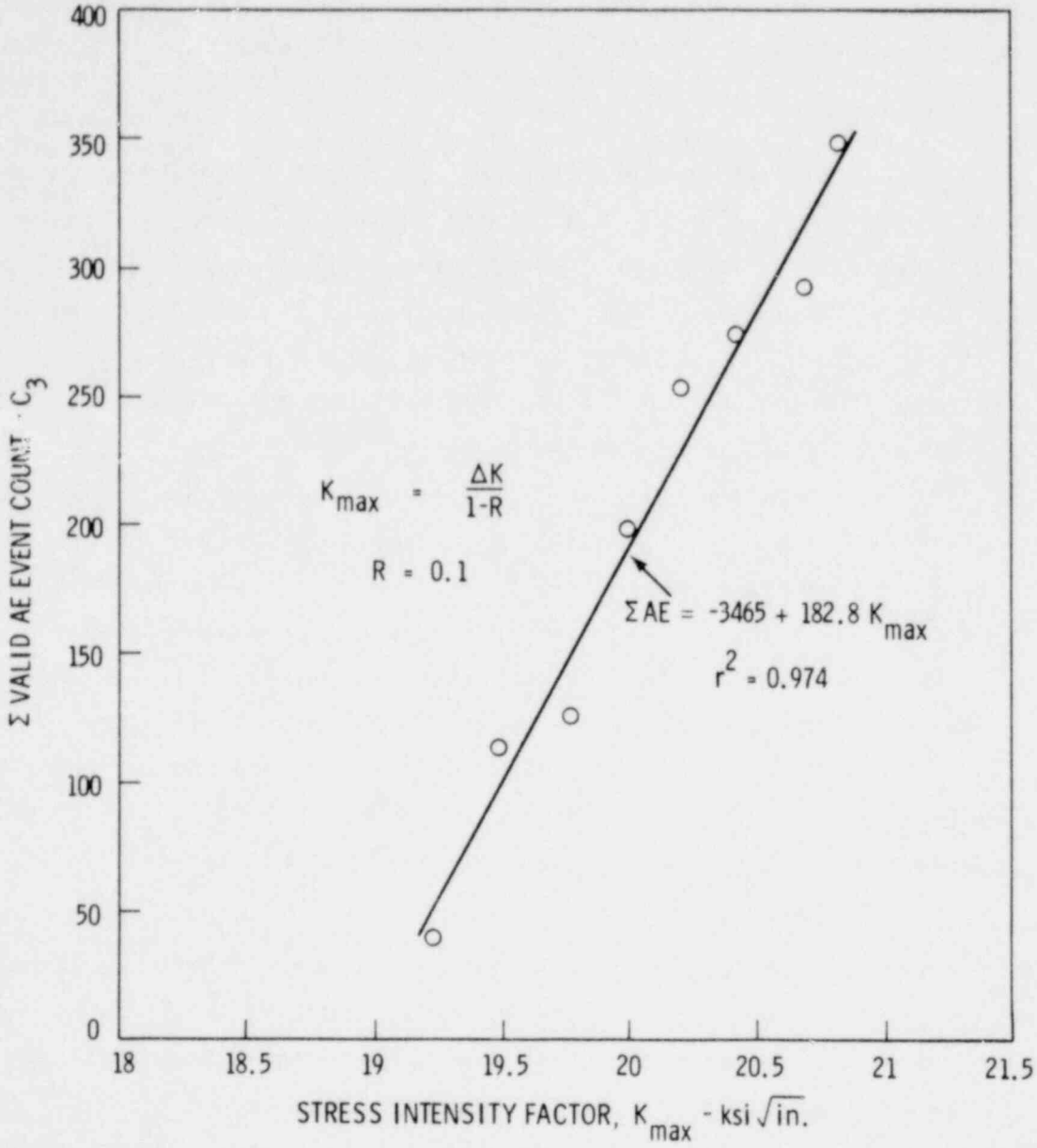

Figure 5. Summation AE Count versus Stress Intensity Factor for SEN Specimen 1-2A-2B (Base Metal).

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the last point shown on the load versus COD curve of Figure 6. This result also supports the idea that crack extension tends to influence AE production more strongly than the state of stress or strain at the crack tip. These data also compare favorably with AE-fracture behavior observed in the laboratory on 2T-CT specimens even though the 2T-CT specimens displayed more slow, continuous-type crack growth than specimen 1-2A-2B.

3.2 High Temperature AE Sensor Testing

This part of the program has an objective of making available a characterized high temperature AE sensor suitable for use in continuous monitoring of reactor pressure boundaries. The adequacy of presently available sensors is being evaluated as a first step.

3.2.1 Experimental Procedure

Three different high temperature AE sensors have been purchased. These, together with a PNL metal wave guide sensor, are being tested simultaneously to evaluate ability to withstand exposure to light water reactor temperature environment. Figure 7 shows the physical arrangement of the sensors on a test block. The test block is placed inside a radiant heat oven with output connectors extending through a port in the oven. Sensor output is fed into an amplifier and then to an oscilloscope where sensor response is recorded photographically. The center waveguide shown in Figure 7 is used to transmit an electronically produced transient signal from a transducer on the outer end of the wave guide into the test block. Response of the AE sensors to this input signal is recorded.

Sensors A, B and C are pressure coupled to the surface of the test plate with front face pressures shown in Figure 7. The differences in front face pressure are a function of sensor design and pressure values recommended by the sensor manufacturers. The two wave guides are mounted into threaded holes.

Amplification of the output of the various sensors is 35 dB with the exception of sensor A, where the gain is 59.6 dB. This difference in gain is a function of the readout system requirements and is accounted for in evaluating results.

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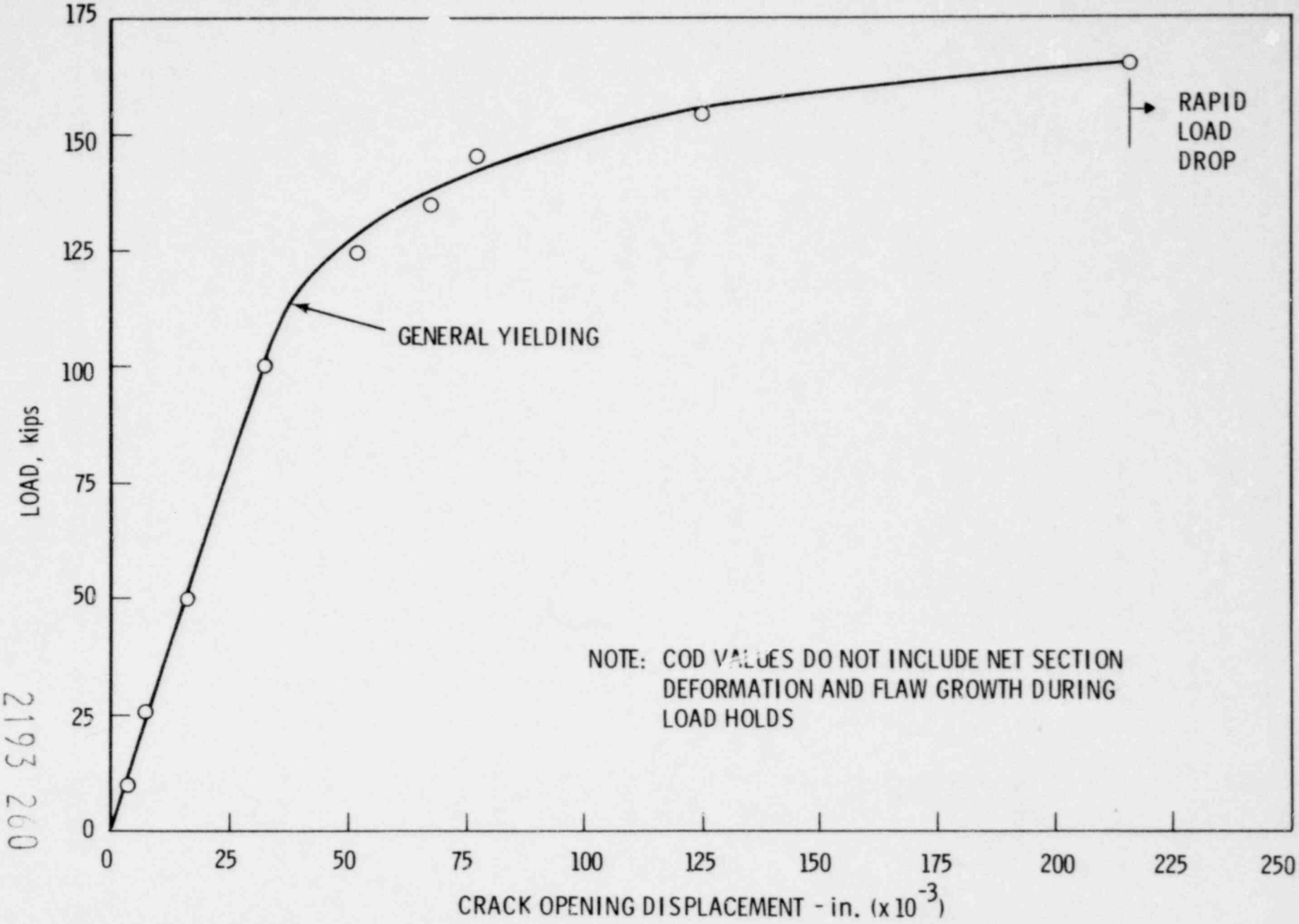

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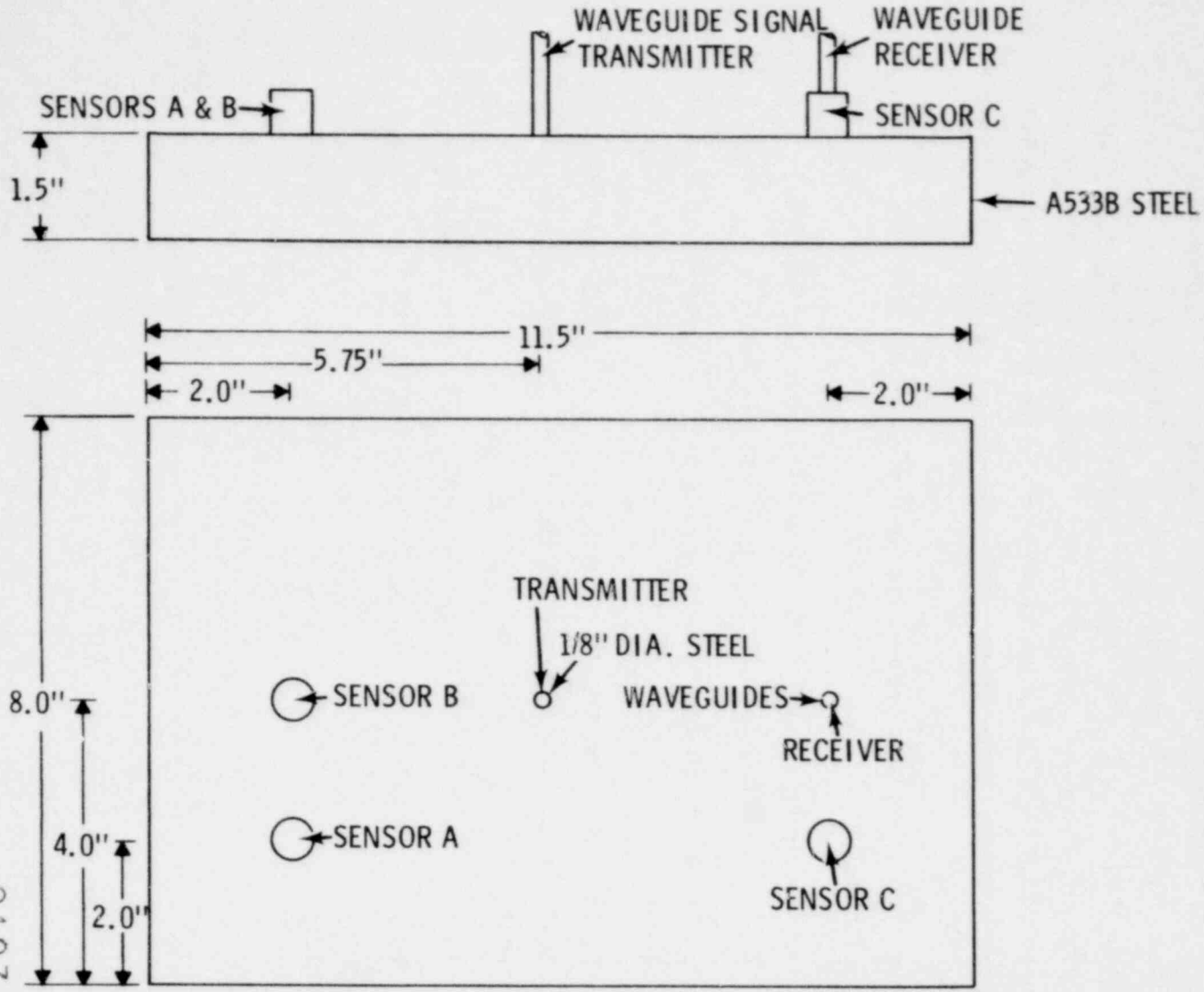
FIGURE 6. Load versus Crack Opening Displacement for Room Temperature Fracture Toughness Testing of SEN Specimen 1-2A-2B (Base Metal).



SENSOR MOUNTING

SENSORS A, B AND C ARE PRESSURE COUPLED USING SPRING LOADING. FRONT FACE PRESSURE IS:

A - 110 psi
B - 3000 psi
C - 190 psi

WAVE GUIDES ARE BOTTOMED IN A DRILLED AND TAPPED HOLE # 5-40 BY 3/8" DEEP.

FIGURE 7. High Temperature AE Sensor Test Arrangement

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The test sequence to be repeated on a weekly basis is:

- 16 hours at 320° F (160° C) Monday through Friday
- 8 hours at 500° F (320° C) Monday through Friday
- 48 hours at room temperature on Saturday and Sunday.

3.2.2 Experimental Results

High temperature testing was started in late December. Thus, no significant results were developed during this quarter. Room temperature calibration results for the high temperature sensors were reported previously.[1] The commercial high temperature sensors appear to be 10 to 20 dB less sensitive than most room temperature AE sensors.

3.3 Reports

Four reports on program results were generated during this quarter. These included:

- Participation in the Fifth Annual U.S. Nuclear Regulatory Commission's Water Reactor Safety Research Information Meeting
- Contribution to the Metallurgy and Materials Research Branch Annual Report
- Documentation of the AE results and analysis for the HSST V7-B vessel test for inclusion in the forthcoming ORNL topical report on that test
- An annual report[1] for this program summarizing results from program initiation (July 1, 1976) to the end of FY-77.

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REFERENCES

1. P.H. Hutton, E.B. Schwenk, R.J. Kurtz, C. Pavloff, Program to Develop Acoustic Emission-Flaw Relationships for Inservice Monitoring of Nuclear Pressure Vessels, Annual Report No. 1, July 1, 1976 to October 1, 1977, NUREG 0250-3, January 1978.

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APPENDIX A

Condensed Experimental Results

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TABLE A.1 Acoustic Emission Data for Fatigue Pre-Cracking of SEN Specimen 1-2A-2B (Base Metal)

Total Load Cycles	BNW AE Count									BNW AE Energy	Unisolated AE
	Valid Total	Peak Time-μsec				Signal Amp. - Volts					
		<1	1-3	3-6	>6	<1.35	1.35-2.3	2.3-4.3	>4.3		
0	0	0	0	0	0	0	0	0	0	0	0
26,720	41	29	7	4	1	25	14	2	0	2,926	331
31,700	61	42	14	4	1	34	21	6	0	4,477	733
37,200	76	53	18	4	1	42	25	9	0	5,499	786
49,700	95	70	19	5	1	59	27	9	0	7,357	1,646
75,700	113	84	19	7	3	69	31	13	0	9,427	10,083
102,210	126	96	20	7	3	78	34	14	0	10,705	13,775
103,670	142	105	24	10	3	89	39	14	0	12,601	15,723
122,500	198	151	33	10	3	134	45	16	1	15,741	20,635
140,600	252	202	36	10	3	175	58	16	1	21,996	32,577
157,550	273	220	38	10	4	190	63	17	1	24,437	51,690
179,250	293	238	39	11	4	202	70	17	1	26,886	94,707
185,700	348	273	57	11	6	225	96	23	1	33,490	105,540

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TABLE A.2 Acoustic Emission - Mechanical Data for Fracture Testing of SEN Specimen 1-2A-2B

Time, sec	Load, Kips	Crack Opening Disp., in. ($\times 10^{-3}$)	BNW AE Count									BNW AE Energy	Unisolated AE
			Valid Total	Peak Time-μsec				Signal Amp. - Volts					
				<1	1-3	3-6	>6	<1.35	1.35-2.3	2.3-4.3	>4.3		
0	10	4.81	0	0	0	0	0	0	0	0	0	0	0
50	05.5	17.35	0	0	0	0	0	0	0	0	0	0	0
100	100	33.41	1	1	0	0	0	1	0	0	0	131	79
150	100	34.17	1	1	0	0	0	1	0	0	0	131	92
200	125	51.73	3	2	0	0	1	2	0	0	1	400	131
250	125	54.24	4	3	0	0	1	3	0	0	1	615	141
300	135	65.28	4	3	0	0	1	3	0	0	1	615	147
350	135	70.55	4	3	0	0	1	3	0	0	1	615	154
400	145	77.57	4	3	0	0	1	3	0	0	1	615	158
450	145	96.64	7	5	0	0	2	5	0	0	2	1,043	168
500	145	97.89	7	5	0	0	2	5	0	0	2	1,043	168
550	155	130.01	10	6	1	0	3	6	1	0	3	1,377	176
600	155	142.80	12	8	1	0	3	8	1	0	3	1,689	179
650	165	230.30	31	17	3	2	9	18	2	3	8	4,257	205
700	165	-**	62	26	7	5	24	27	2	10	23	7,439	238
710	170	-	188	67	28	15	81	92	8	30	79	23,597	394
720	-*	-	329	116	44	29	143	119	13	50	147	41,601	594
730	-	-	434	157	68	37	175	163	24	63	184	55,253	745
740	-	-	549	191	94	45	222	201	27	79	242	69,973	939
750	-	-	651	226	110	51	272	230	33	93	295	83,435	1,114
760	-	-	678	233	115	52	282	236	35	96	311	87,319	1,212
768	-	-	699	236	116	53	302	238	35	97	329	89,653	1,411

*Load readings uncertain due to rapid load drops
**COD gauge limit exceeded

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