ACOUSTIC EMISSION-FLAW RELATIONSHIP FOR IN-SERVICE MONITORING OF NUCLEAR PRESSURE VESSELS[(a)]

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INTRODUCTION

This program is to develop an experimental evaluation of the feasibility of detecting and analyzing flaw growth in reactor pressure boundaries by means of continuously monitoring acoustic emission (AE). Major objectives are:

- Develop an AE-flaw growth model for relating in-service AE to flaw significance.
- Develop criteria to distinguish flaw growth AE from innocuous acoustic signals.
- Demonstrate application of program results through both off-reactor and on-reactor testing.

APPROACH

The experimental investigation has been limited to characterizing the AE response of ASTM Type A533, Grade B, Class 1 material. The basic approach to gathering AE-flaw growth data has been to test

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1 to 1-3/4 inch (25.4 to 44.5 mm) thick fracture mechanics specimens in tension-tension fatigue crack growth (FCG) and fracture at room temperature (RT) and 550°F (288°C). AE data obtained from fracture testing of 6 inch (152 mm) wall pressure vessels under the HSST Program at Oak Ridge has also been incorporated in the analysis. Work to date has concentrated on characterizing the effect of base and weld metal, flaw geometry, R-ratio and cyclic frequency upon the AE response.

RESULTS

AE/FLAW GROWTH RELATIONSHIP

A preliminary relationship for evaluating flaw severity during fatigue crack growth has been developed. This takes the form shown in Figure 1. The AE rate is related to the fatigue crack growth rate and the crack growth rate is in turn related to the stress intensity factor range, ΔK. ΔK then provides a measure of flaw severity in terms of fracture mechanics. In Figure 2, all of the current AE data from laboratory tests encompassing variables in temperature (RT and 550°F), R-ratio (0.1 and 0.5), cycle rate (0.1, 1.0 and 2.0 Hz), flaw geometry (through wall and surface notch), material (base metal and weld metal) and thickness (0.5, 1.0 and 1.75 inches) is cast into the AE rate-crack growth rate relation.

Even though there is scatter in the experimental relationship between AE rate and crack growth rate on an absolute basis, AE does increase with crack growth rate. It also appears that there is less statistical scatter between the change in AE rate and the change in crack growth rate for the laboratory results thus far than for the relationship between AE and crack growth rate. This simply means that the slope between AE rate and crack growth rate describes the phenomenon better (less scatter) than the absolute relationship and offers a potential method of interpreting changes in AE rate with respect to the estimated change in flaw growth rate.

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Data obtained while monitoring fracture tests of two different 6 inch (152 mm) wall, intermediate scale test vessels (Figure 3) suggests that AE may be used to evaluate flaw severity during fracture type loading conditions. The two tests represent substantially different conditions in temperature and flaw dimensions. The tests are described in greater detail in other reports (Ref. 1, 2). Briefly, the V-7B test was performed at 200°F (93.3°C) with a longitudinal O.D. flaw 18 inches long by approximately 5-3/8 inches deep (457 x 136.5 mm). The flaw was located in the heat-affected zone of a repair weld. Test V-8 was performed at -5°F (-20.6°C) with a longitudinal O.D. flaw 8 inches long by 2 inches deep (203 x 51 mm) which was located in an area of high residual stress in a repair weld.

Comparison of the AE versus K curves for the two tests indicates that the behavior of the V-8 vessel after the first pop-in appears to be the same as V-7B vessel over a limited range of K and AE does appear to rationally parallel changes in fracture behavior of the two vessel tests.

CHARACTERIZATION OF FLAW GROWTH AE SIGNALS

Pattern recognition analysis is being investigated as a means of characterizing AE signals from crack growth to distinguish them from other acoustic signals (transient noise signals, slag inclusion cracking, etc.) (Ref. 3). The initial evaluation was done using 223 waveform samples of noise and of AE taken during a fatigue crack growth test. The example in Figure 4 shows the overt similarity of the two types of signals. A time domain autocorrelation technique illustrated in Figure 5 was the most effective method for classifying these signals. Classification by this technique of all waveform samples was 96% correct (Figure 6).

AE signal characterization by energy and peak time partitioning of AE data obtained during FCG testing of weld metal specimen 2W-1B was also performed. The total energy range (0-500 energy units) was partitioned into 20 equal increments. Similarly, the peak time range from 0-30 μsec was partitioned into 31 increments. The partitioned data sets containing more than about 5 percent of the total AE count were then least mean squares curve fit to an equation of the form:

$$\frac{dN}{dn} = C\left(\frac{da}{dn}\right)^m \qquad (1)$$

where dN/dn is the partitioned AE rate data (count/cycle), da/dn is the fatigue crack growth rate (in./cycle), and C, m are constants. Correlation coefficients for unpartitioned room temperature and 550°F data were 0.571 and 0.221, respectively. Figure 7 shows a plot of the correlation coefficients obtained from the regression analyses versus the partitioned AE energy data. A much improved correlation coefficient was obtained for the 550°F data when the data set was restricted to those signals with energies ranging between 25 and 50 energy units. For the RT data, the maximum correlation coefficient was obtained with the $50<E\leq75$ energy range. These results suggest that energy partitioning of the AE data may be useful for improving the AE rate versus FCG rate correlation.

The peak time partitioned information (Figure 8) shows limited improvement in correlation coefficient for either RT or 550°F data sets. It does show a shift to somethwat longer peak time values for maximum correlation with increased temperature. This suggests caution in attempting to generally restrict AE signals to a single peak time partitioning criterion.

DEMONSTRATE APPLICATION

Expanding from simple laboratory specimens, a pipe bend test designed to incorporate more realistic environmental conditions is in progress. The specimen (shown in Figure 9) is an 8 inch O.D. by 2 inch I.D. cylindrical section of A533B, Class 1 steel with a circumferential I.D. notch 0.875 inch wide by 1 inch deep. The specimen is being sinusoidally loaded in tension-tension bending at 0.5 Hz and R=0.1. It can be internally exposed to either RT air or 550°F water at 1350 psig. Initial results are plotted in Figure 10. They show that introduction of pressurized high temperature water did not significantly affect AE detection. The AE data shown in Figure 10 includes unpartitioned and peak time partitioned data. The two curves are very similar during fatigue testing in RT air but with introduction of 550°F water, what appears to be abnormal signals are included in the validated data. Eliminating these long rise time signals produces a data curve at 550 F which is consistent with the room temperature data. The source of the long rise time signals is not clear at this time. Resolution of this question awaits additional testing and analysis. The most significant aspect of these results is that AE was detected under conditions relevant to the nuclear reactor operating environment.

The concept for a prototypic reactor monitoring AE system has been developed, as shown in Figure 11. It can be defined in two sections: 1) data acquisition and source location, and 2) data analysis. The data acquisition section would either be acquired commercially or fabricated in-house and installed on a reactor as soon as possible. This allows initiation of longevity testing in the full reactor environment, evaluation of background noise control and gathering various waveform samples for pattern recognition development. Two types of high temperature sensors - a commercial surface mount and a metal wave guide - are being used in parallel during current testing to develop a performance data base.

The data analysis section as shown is a semi-breadboard system in the sense that it provides for recording pattern recognition waveforms in parallel with pattern recognition processing. This is to allow refinement of the pattern recognition function from initial tests. Subsequently, the waveform recorder would be eliminated and pattern recogntion would become a "black box" element. In this concept, the pattern recognition function would operate to determine whether a located signal was a crack growth AE signal or a noise signal. If it was AE, the signal would go to the flaw analysis section; if not, it would be rejected. It is necessary to operate the source location and pattern recognition functions in parallel due to timing requirements.

CONCLUSIONS

We feel that the laboratory results obtained justify optimism that AE monitoring can be successfully applied to continuous flaw detection and evaluation on an operating reactor vessel. The major items planned for continued development in FY-80 are:

- Assemble a prototype instrument system for reactor monitoring.
- Perform an evaluation of system and current analysis methods by a vessel test simulating reactor conditions.
- Install a limited data acquisition system on a reactor.

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CREDITS

Primary among those Battelle staff members contributing to this work are: J.R. Skorpik, J.F. Dawson, R.T. Landsiedel, G.D. Shearer, P.G. Doctor and T.P. Harrington. Their contributions are gratefully acknowledged.

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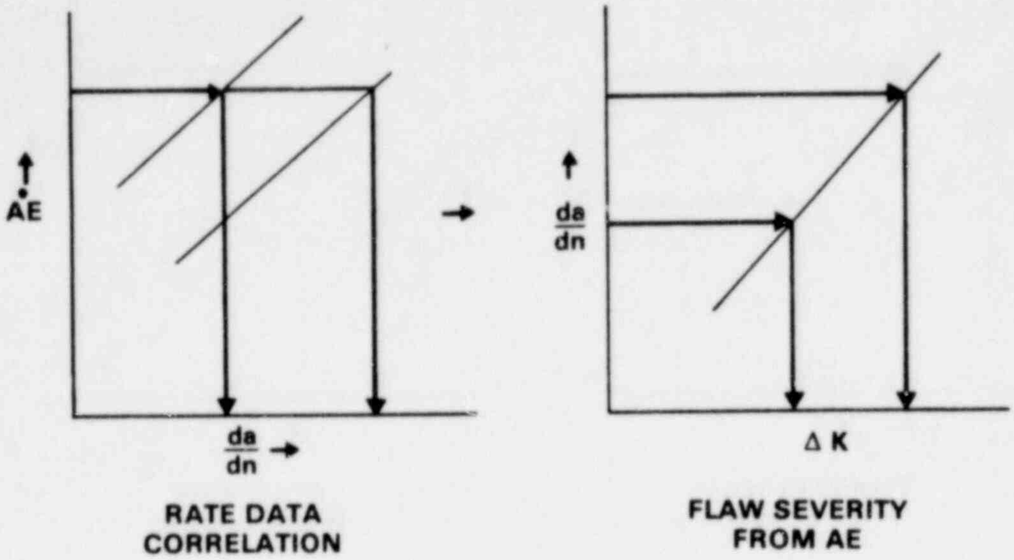

FIGURE 1. AE - Fatigue Flaw Severity Correlation.

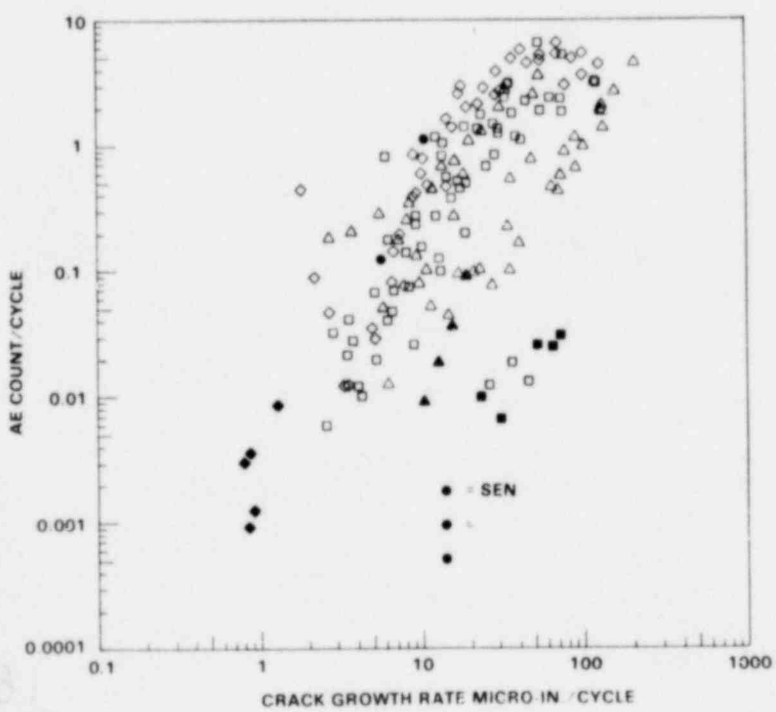

FIGURE 2. Experimental Data - AE Rate vs. Fatigue Crack Growth Rate.

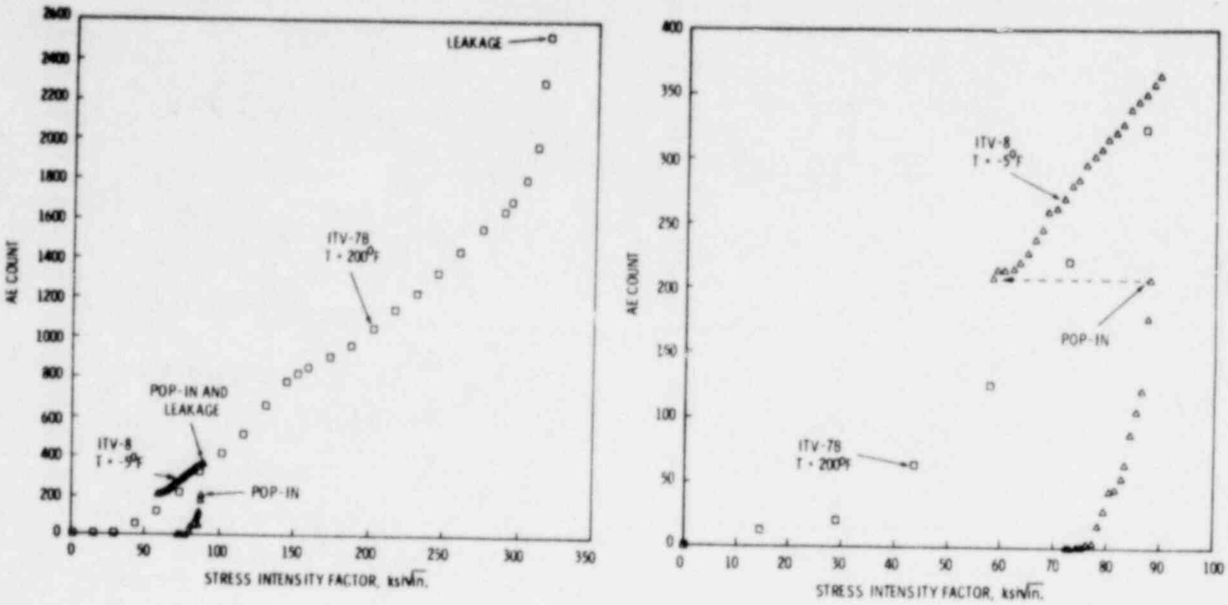

FIGURE 3. AE vs. Stress Intensity - Intermediate Vessel Tests.

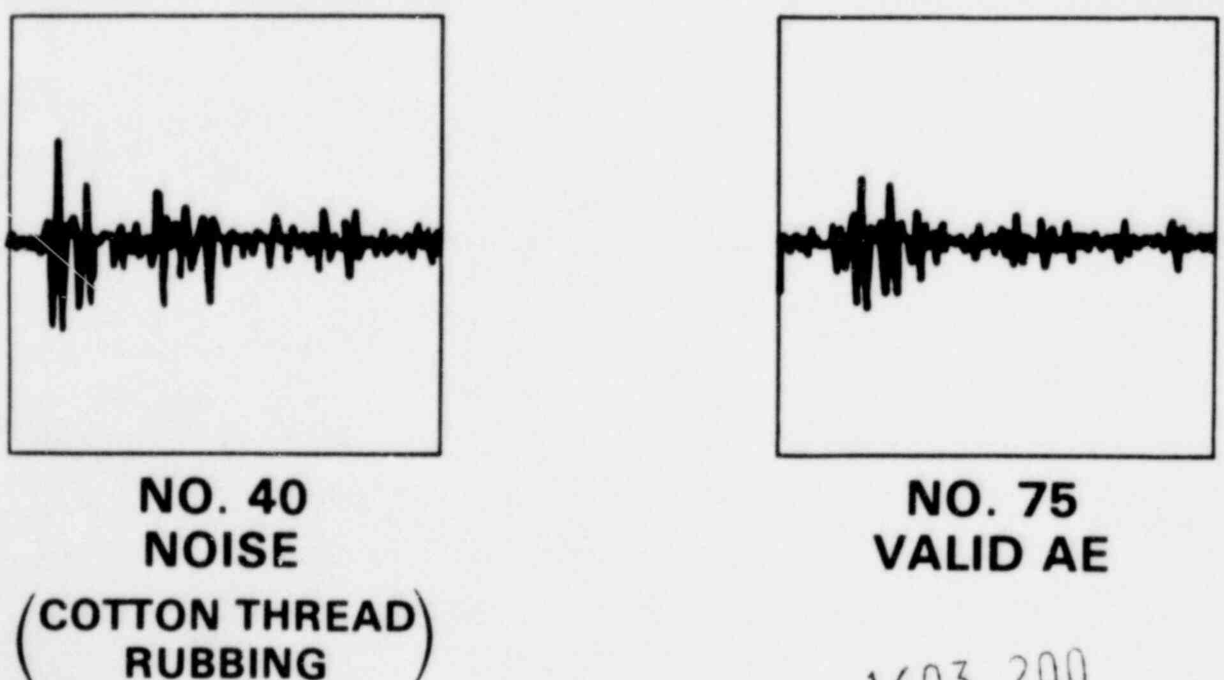

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FIGURE 4. Sample Digitized Waveforms.

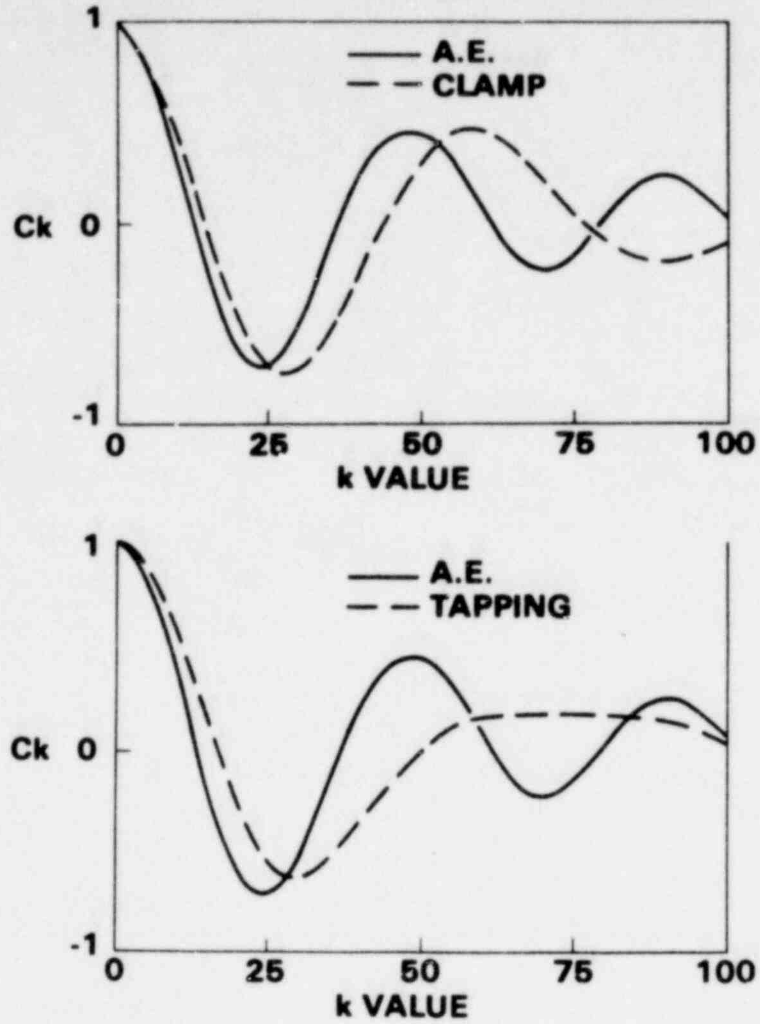

FIGURE 5. Autocorrelations for AE and Noise Waveforms.

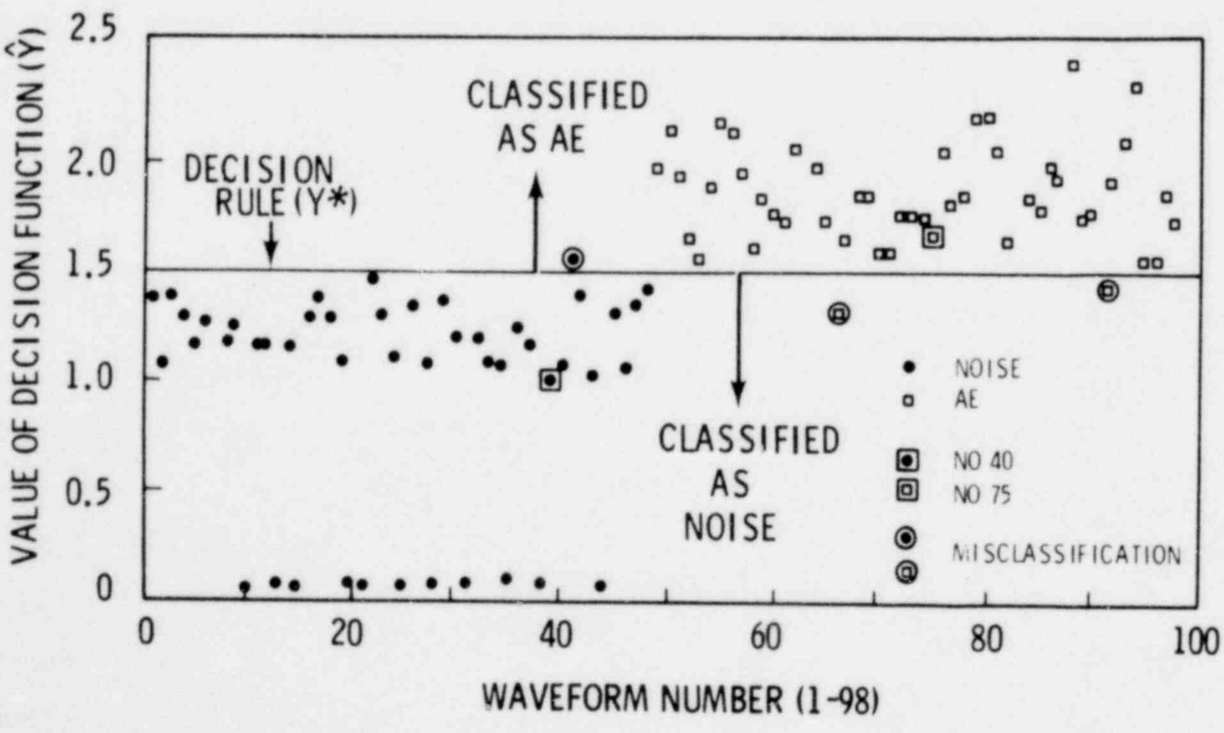

FIGURE 6. Pattern Recognition Classification of AE and Noise Signals.

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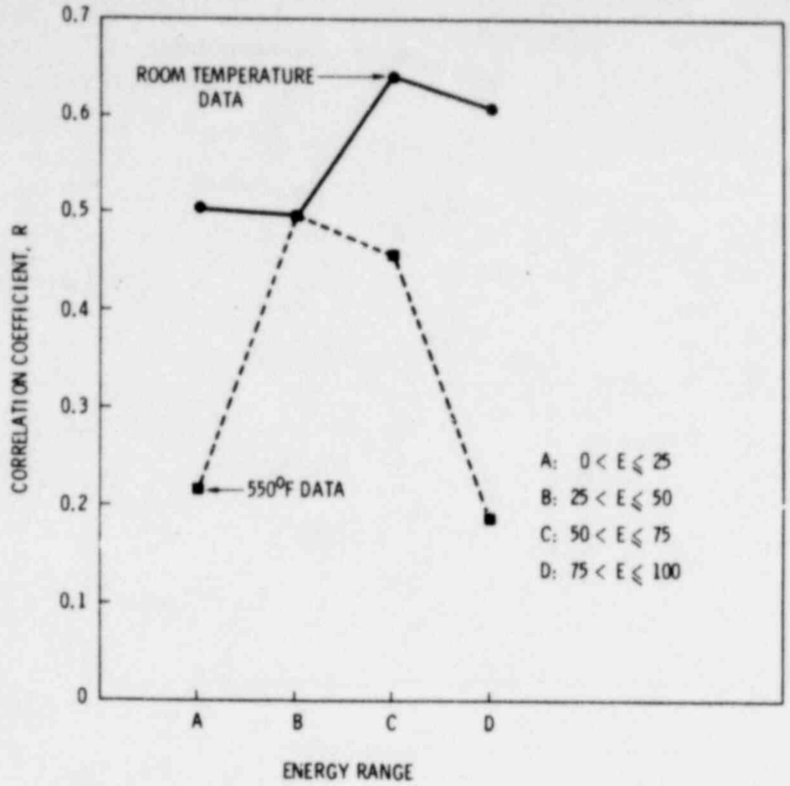

FIGURE 7. Correlation Coefficient vs. Energy Range for FCG Testing of Weld Metal Specimen 2W - 1B.

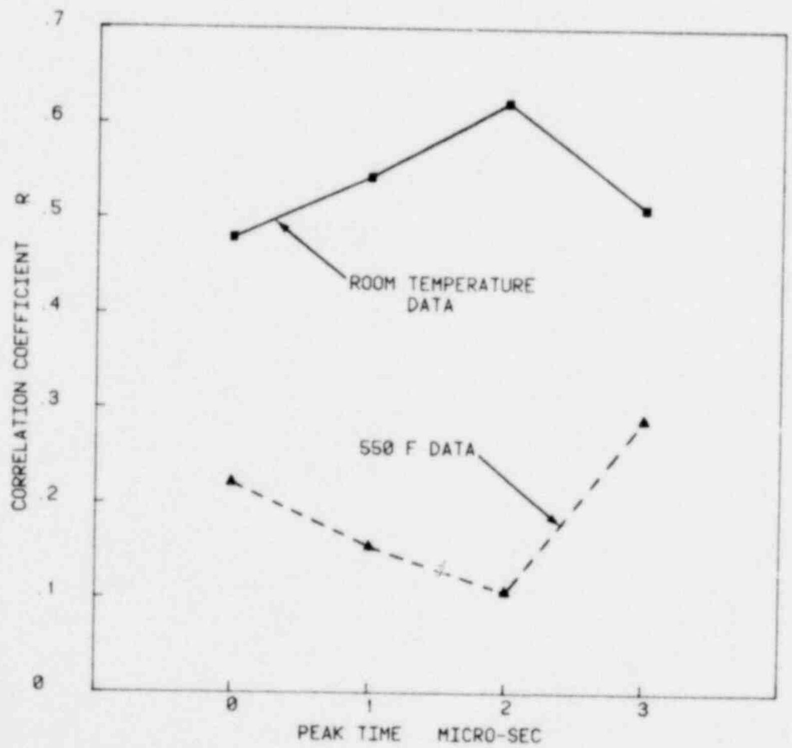

FIGURE 8. Correlation Coefficient vs. Peak Time for FCG Testing of Weld Metal Specimen 2W - 1B.

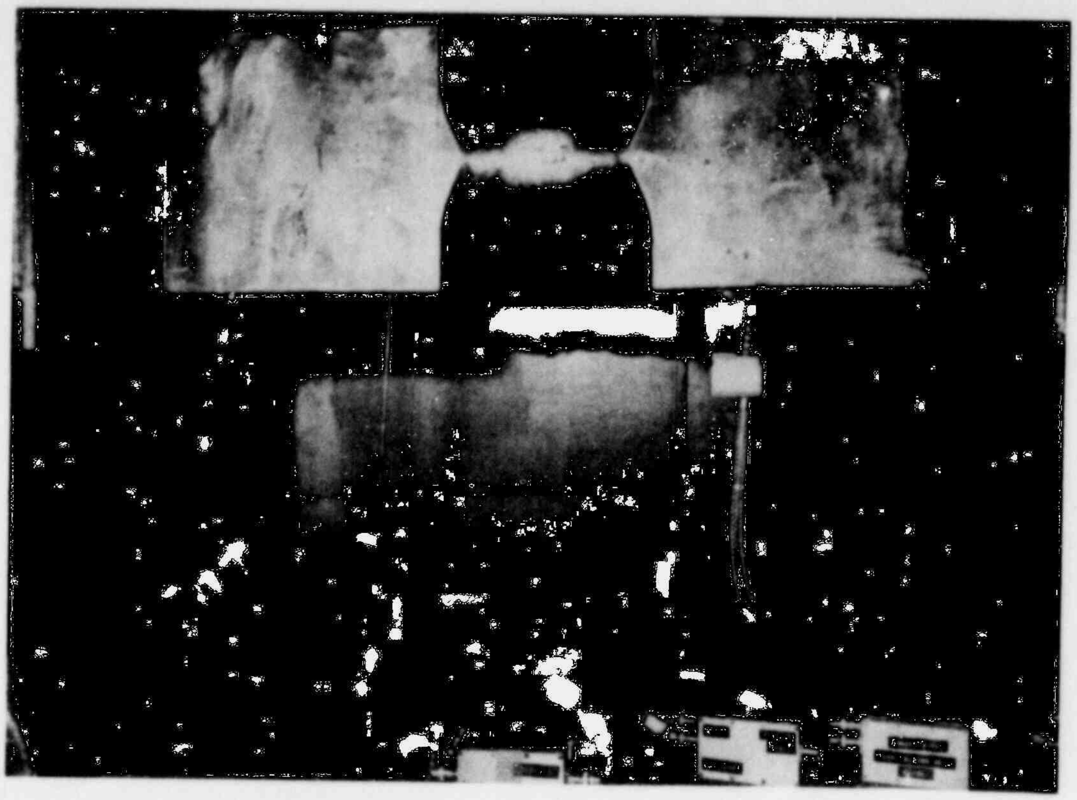

FIGURE 9. Photograph of the Pipe Bend Test Specimen.

POOR ORIGINAL

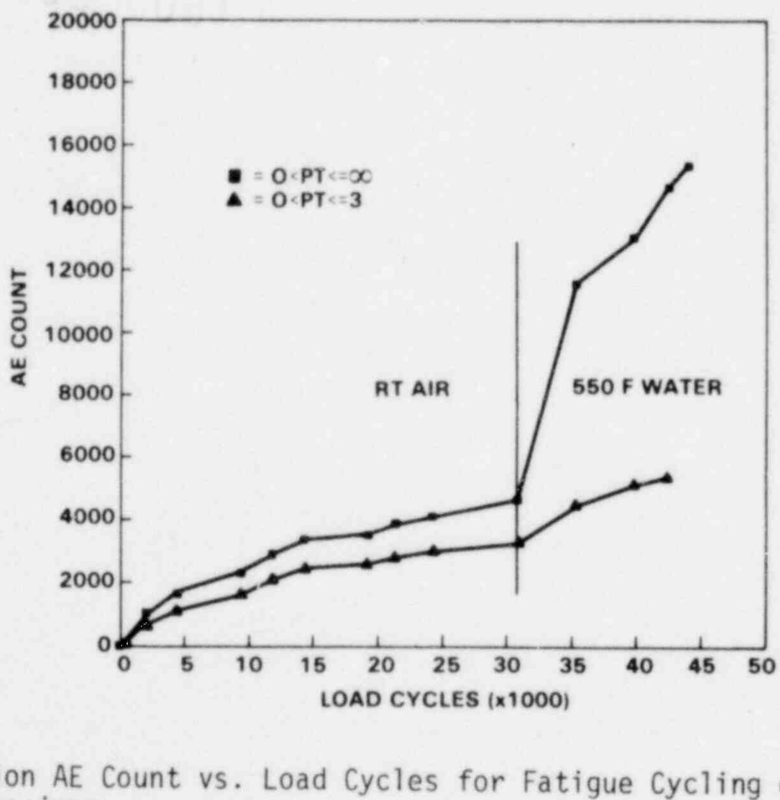

FIGURE 10. Summation AE Count vs. Load Cycles for Fatigue Cycling of a Pipe Specimen.

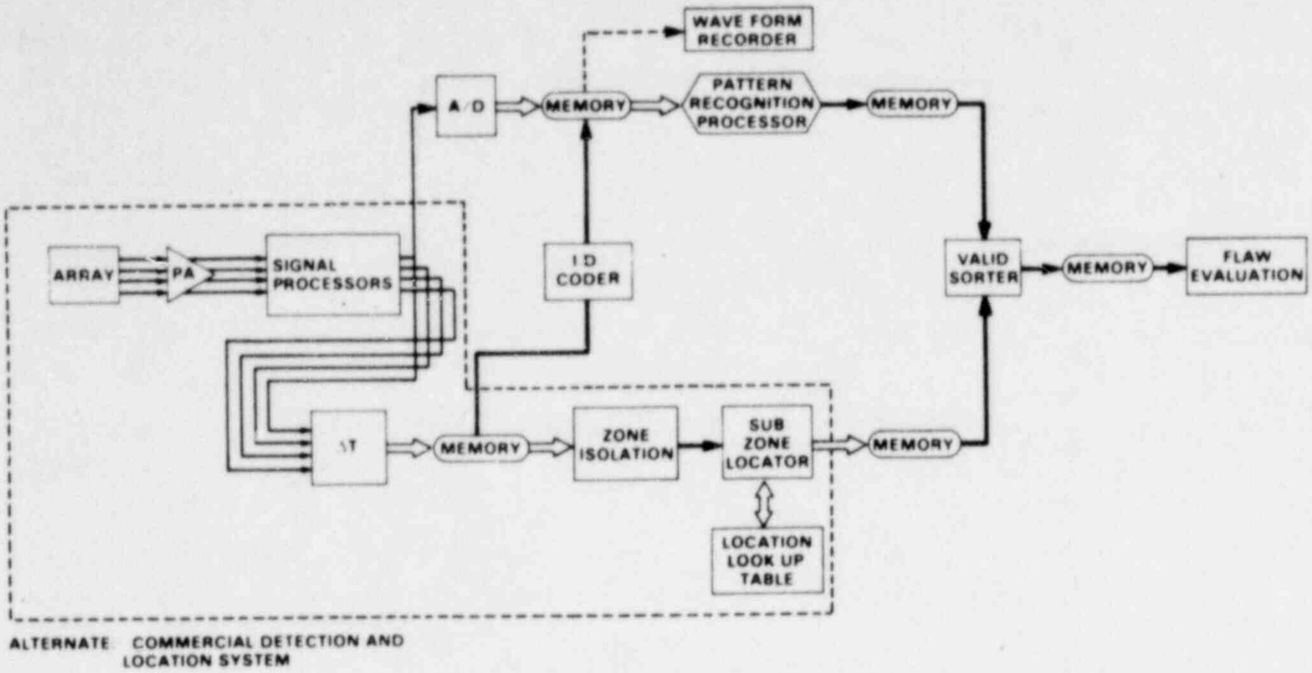

FIGURE 11. Concept on Reactor AE Monitor for Flaw Detection and Evaluation.

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