INTERIM REPORT

Accession No. ____________

Contract Program or Project Title: ACOUSTIC EMISSION/FLAW RELATIONSHIPS FOR INSERVICE MONITORING OF NUCLEAR PRESSURE VESSELS

Subject of this Document: MONTHLY PROGRESS - January, 1980

Type of Document: INFORMAL LETTER REPORT

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Date of Document: February 19, 1980

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Prepared for
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

INTERIM REPORT

NRC Research and Technical
Assistance Report

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February 19, 1980

Dr. Joe Muscara
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NRC Research and Technical Assistance Report

Dear Joe:

MONTHLY LETTER REPORT - JANUARY, 1980
ACOUSTIC EMISSION CHARACTERIZATION OF FLAW GROWTH IN A533B PRESSURE VESSEL STEEL
FIN. NO. B2088

ACCOMPLISHMENTS

- Developed a matrix for considering approach to vessel test.
- Submitted proposed revisions to NRC Branch position paper on AE applied to hydrotest.
- Initiated design of AE monitor system for use on vessel test.
- Completed preparation of method for AE monitoring HSST 4T irradiated fracture specimens.
- Obtained a new commitment for installing high temperature sensors on N Reactor for test.
- Continued development of pattern recognition method for characterizing AE signals.
- Conducted a review of program status and plans for FY-80 for the NRC contract manager.

In support of developing an information matrix upon which to base a decision concerning preparation of a vessel test for evaluating AE identification and interpretation relationships, information was obtained from ORNL and J.A. Jones. At a meeting with ORNL, HSST staff, requirements were identified and a cost and time estimate was obtained for vessel preparation and testing. Cost and time estimates were also obtained for vessel preparation by J.A. Jones and for vessel testing at PNL. Since this information did not support a clear cut decision, additional estimates for vessel preparation will be obtained with the objective of reaching a final decision in early February.

A proposed NRC, DOR branch position paper concerning use of AE for pressure vessel inspection during hydrotest was reviewed. Proposed modifications submitted earlier are contained in Attachment 1 of this report.

Design of a "breadboard" AE monitor system with which to evaluate AE/flaw severity models and AE signal identification methods on the vessel test has been initiated. Use of an existing NRC-owned computerized monitor system upgraded to meet requirements is planned for the data acquisition and source location subsystem. Analytical subsystems will be established in software in a minicomputer to maximize flexibility for change and improvement. In addition to real time data analysis, raw data will be recorded in analog and/or digital form to allow reprocessing the data by modified methods. The "breadboard" approach maximizes use of existing equipment to test a function and guide design of a prototypic final system.

Preparation of a method for AE monitoring HSST irradiated fracture specimen tests has been completed. The schedule for the tests is still indefinite.

Installation of high temperature sensors on the discharge face of N Reactor for environmental testing is scheduled for late February.

Development of the pattern recognition method for crack growth AE signal identification continued with analysis of signals recorded to date during the heavy section cylindrical bend specimen tests.

57 waveforms from a high temperature surface mounted AE sensor were selected for analysis. Included are:

Valid AE	36
C-clamp	3
Tapping	14
Pentel	4
	57

The format of the pattern recognition analysis followed the one used in earlier work. The waveform features generated for this test were the same as before. They are:

Mean
Standard deviation
Skewness
Kurtosis
Autocorrelation at Lag 13
Autocorrelation at Lag 37
Maximum frequency response
Frequency of the maximum response
Total power (0 Hz - 1 MHz)
First moment of the power spectrum
Second moment of the power spectrum

With only 57 waveforms, the complete analysis using training and test sets would have little meaning, therefore, the analysis included only the necessary steps to produce a decision rule. The steps were:

Feature scaling
Feature reduction and orthogonalization
Least squares decision rule

The features were autoscaled, and a correlation to property feature reduction algorithm was used. The five features which contained the most of the signal-source information were:

Kurtosis
Autocorrelation at Lag 37
Mean
Total power
First moment of power spectrum

These five features were orthogonalized and fed into the least squares fitting algorithm to produce a decision function. The value of the decision function is plotted in Figure 1. Waveform number is listed on the abscissa and is arbitrary. The horizontal line represents the value of the decision rule; all those points above the line are classified as noise and those below the line as valid AE. The decision rule was located to minimize the number of valid AE waveforms misclassified as noise. The result is that only one noise and no valid AE were misclassified.

When the test resumes, additional waveform data will be gathered to use as a test set for the decision function.

Program progress and plans for FY-80 were reviewed for the NRC contract manager at PNL on January 30. The major topic in program plans concerns a decision on the approach to achieving a vessel test for AE monitoring under simulated reactor conditions.

WORK PLANS FOR FEBRUARY

- Resolve plans for vessel test preparation.
- Continue monitor system breadboard design.
- Complete definition of a total AE monitor system calibration/verification method.
- Modify heavy section cylindrical bend specimen test to include simulated reactor flow noise.
- Install high temperature test sensors on N Reactor.

Yours very truly,

P.H. HUTTON
Program Manager

Attachments

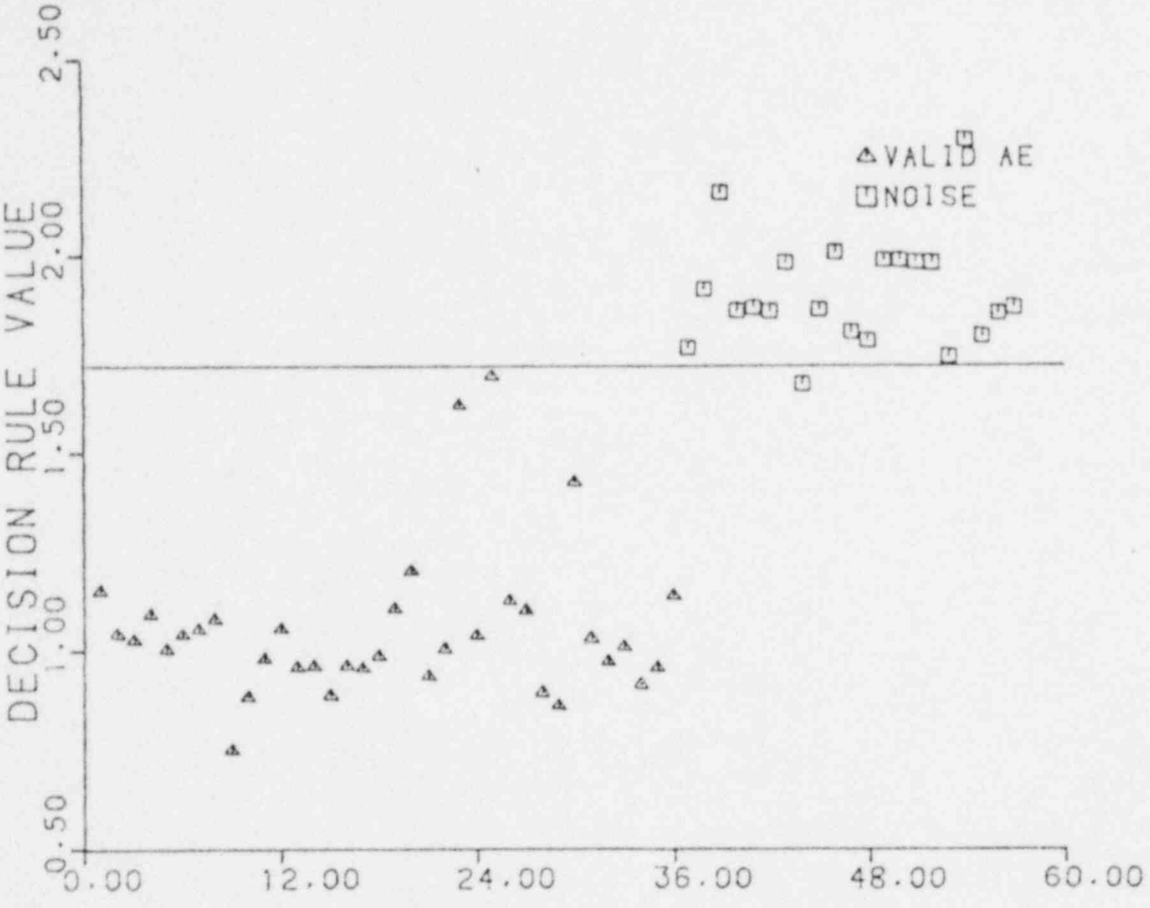

FIGURE 1. Pattern Recognition Segregation of Bend Specimen Acoustic Data.

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January 18, 1980

R.W. McClung
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Oak Ridge, TN 37830

Subject: Union Carbide Purchase Order No. 19X-31524V; Review of NRC Branch Position Paper on Acoustic Emission

Dear Bob:

Our comments and suggested changes to the subject branch position paper are listed below. These comments are referenced to the draft which is circulating in NRC for review.

The following substitutions are proposed in place of the referenced sections in the Branch Position Paper draft.

A. Background

Second Paragraph, Fourth Sentence: Acoustic emission can detect the presence of a flaw when local stresses reach a level in excess of recently applied stresses to produce elastic strain, plastic zone growth or flaw growth.

Third Paragraph: The strength of acoustic emission is that it can detect and locate a growing flaw by monitoring with fixed sensors located remotely from the flaw site. AE count and energy can be used to estimate the severity of the flaw.

2.3 Calibration

A calibration of sensor sensitivity versus spectral frequency which is traceable (either primary or secondary) to the National Bureau of Standards shall be performed for each sensor prior to use in a hydrotest monitor. The sensors shall be similarly calibrated following completion of the hydrotest. A copy of these calibration records shall be made a part of the test report.

Calibration of the AE monitor system after installation on the reactor shall be performed in accordance with procedures outlined in ASTM E569-76, Standard Recommended Practice for Acoustic Emission Monitoring of Structures During

Controlled Stimulation, Section 5.0, with additional requirements as stated below.

A constant AE simulator pulse will be used for installed AE system calibration. The response of any AE monitor channel to the simulator pulse input shall be no greater than 10:1 over system electronic background noise when applied in the context of Section 5.1.1 of referenced ASTM E569-76.

Under hydrotest conditions, the same AE simulator pulse input applied in the same manner shall produce a minimum signal to noise ratio of 4:1 where noise is defined as total hydrotest background noise. Sensors that fail to meet the 4:1 ratio shall be replaced or rebonded and recalibrated to meet the required sensitivity.

All instruments used for AE monitoring and data interpretation shall be calibrated within one week prior to and following the hydrotest.

(The intent of the proposed substitution is to provide more specific guidelines for calibration.)

2.4 Loading

We propose that a maximum pressure 115% of normal operating pressure be used.

2.5 Examination Frequency

Subsequent AE examination frequency will be determined on the basis of AE source characterization derived from a given hydrotest by joint NRC and utility review.

(The present state-of-the-art does not support the criteria perviously expressed.)

3.0 AE Source Characterization

The source characterization to be applied is presented in Appendix A of this document.

Considering the fact that AE technology is still in a developmental stage, application of additional characterization methods for comparison is encouraged providing a definitive criterion for interpretation can be established. The criterion(s) used in characterizing AE sources shall be defined as part of the test report.

4.0 Acceptance Criteria

In view of the fact that AE technology is still in the developmental stage and is not yet recognized by the ASME Codes, action required by the AE results from a given hydrotest must be determined by joint review of these results by NRC and the utility.

(Comments on Section 3.0 and 4.0 again reflect the feeling that the state-of-the-art does not support a specific criteria to be generally applied at this time. It is, however, important to introduce the best engineering criteria that can be supported by available data. This we have attempted to do. Since the criteria is still semi-qualitative, results must be reviewed by NRC and the utility on a case-by-case basis to arrive at a sound judgment on the indicated course of action.)

If there are questions concerning this material, please call me.

Yours very truly,

P. H. Hutton
P.H. HUTTON
Associate Manager
Nondestructive Testing Section

RJ Kurtz
R.J. KURTZ
Research Engineer
Metallurgy Research Section

PHH:dd

cc: J. Muscara (NRC)

APPENDIX A

IN-SERVICE FLAW ASSESMENT OF NUCLEAR PRESSURE VESSELS DURING HYDROTEST BY ACOUSTIC EMISSION

Purpose

To provide an initial framework for the application of acoustic emission (AE) as a basis for locating and assessing regions of structural degradation in a pressure vessel during a hydrotest.

Introduction

Section XI of the ASME Boiler and Pressure Vessel Code contains rules and procedures for performing pre-service and periodic in-service inspections of nuclear power plant components and for evaluating flaw indications detected during the inspections. This paper discusses a possible method for flaw assessment, based on in-service acoustic emission monitoring during a hydrotest. It is presented as a basis for a possible future adjunct to flaw evaluation procedures contained primarily in a non-mandatory appendix (Appendix A) of Section XI.

Background

The flaw evaluation procedures of Section XI are based on the concepts and principles of linear elastic fracture mechanics. The potential application of AE to flaw assessment, described here, is also based on linear elastic fracture mechanics using Section XI, Appendix A, as a foundation for developing the method of application.

Although the concept of linear elastic fracture mechanics (LEFM) is well known, a brief review of the basic features may be useful. The significant quantity is the stress intensity factor, K_I, for the opening mode loading of a sharp-tipped crack. K_I is related to the stress, σ, remote from the crack and a characteristic dimension, a of the crack through an equation of the form

$$K_I = C\,\sigma\sqrt{a} \qquad (1)$$

where C is a numerical factor whose value depends on the geometry of the crack, the ratio of the crack size to the section size of the component containing the crack, and the type of loading. As a simple example, $C = \sqrt{\pi}$ for the case of tensile loading of a very wide plate containing a through-thickness crack of length 2a. The brittle fracture criterion is that initiation of unstable crack propagation occurs when K_I attains a critical value. This critical value is denoted as K_{Ic} and is identified as the fracture toughness of the material. Thus, fracture mechanics principles enable the formulation of a fracture analysis methodology in terms of applied stress, flaw size, and a material property.

Although extremely useful, linear elastic fracture mechanics is properly limited to characterizing non-ductile failures. These limitations may be minimized by advanced techniques of elastic-plastic fracture mechanics. To date, these advanced techniques have not been incorporated into Section XI analysis procedures.

Acoustic emission denotes a phenomenon whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material under strain. In metals, deformation and crack growth can produce AE. As an emerging non-destructive testing technique, AE has a unique feature for flaw surveillance -- the capability to detect and locate flaws during a hydrotest by using a fixed array of AE sensors. Inherent in this is also the potential for continuous long-term surveillance during service operations.

Acoustic emissions are usually discrete, discontinuous in nature, usually inaudible and are sensed as minute displacements at a material's surface. A common method of detecting AE employs a piezoelectric sensor mounted on the surface of the object. The piezoelectric material generates an electrical pulse that is dependent on the strain wave passing under the sensor. The resulting AE analog signals are amplified, conditioned, and analyzied to measure parameters such as signal counting, signal energy, etc.

The AE signal voltage varies with time, usually in a complex manner believed to depend upon such factors as the AE source mechanism, the sensor couplant, the sensor mechanical to electrical conversion, the AE path length, and geometry of the body (specimen or structure) between the AE source and the sensor. This complex relationship is not yet clearly understood because critical problem areas associated with the detected AE signal remain to be solved. These problem areas include:

- Identification of the relationship between AE analog signals and the causative mechanisms.
- Quantification of a wave propagation process through the material structure.
- Characterization of the sensor response and its relationship to propagating elastic waves.

Because of these limitations, primary standards for calibrating AE systems do not exist and unambiguous separation of AE from innocuous noise signals has not been achieved.

In addition, experiments conducted by different investigators on nominally the same test material have yielded divergent results.

In spite of the foregoing difficulties, AE techniques are being successfully used to detect and locate flaws during pressure system testing (e.g., hydrotesting of pressure vessels and piping.) Also progress in the areas of pattern recognition and signal deconvolution may permit an empirical segregation of AE from other transient acoustic signal sources (viz., mechanical and electrical noise.) We believe the long term potential of AE technology far outweighs the present limitation and with adequate investigation these problems can be overcome.

Potential Application Method

To relate AE to K_I during a hydrotest requires that experimental AE-K_I data exist for the relevant material conditions anticipated during pressure vessel service. This implies that the influence of environmental and loading conditions upon the material and, hence, the AE response from that material, be known. Data from surface notch flaws in 6 inch thick HSST vessel hydrotests has been obtained and is shown in Figure 1 in terms of AE even count versus K. These data, while showing the positive potential for vessel flaw assessment by AE, represent a limited data base for flaw severity assessment. Only a limited range of test conditions are represented by the curves shown in Figure 1. Nevertheless, a concept for a quantitative flaw evaluation procedure during hydrotest can be delineated from the HSST vessel test data if the following assumptions are made:

- Separation of AE from noise signals may be achieved.
- The response of the AE monitoring system is known and is similar to that used in the HSST tests as determined by the following criteria:

  $$\frac{\text{T.H.}}{\text{G.}} \Big/ \frac{1\ \text{volt}/\mu\text{bar}}{\text{S}} = 0.1 \text{ to } 0.15\ \mu\text{bar}$$

  where "T.H." is system detection threshold in volts; "G." is system gain and "S" is sensor peak sensitivity in the frequency range of 150 to 300 KHz in terms of dB re 1 volt/ µbar.
- The flaw dimensions remain essentially constant during a hydrotest, such that the K_I descriptor is valid up to the hydrotest pressure.
- Figure 1 depicts the experimental relation between flaw severity and AE for the pressure vessel material under consideration and adjustment factors to compensate for flaw distance from the AE sensors and for geometric disturbances in the transmission path have been determined.

Using equation (1), the stress intensity factor resulting from a stressed flaw in a reactor pressure vessel during a hydrotest may be expressed as:

$$K_I = C_1 P_h \qquad (2)$$

where P_h is the maximum hydrotest pressure which is taken as 115% of the nominal reactor operating pressure and C_1 is a constant which includes all flaw and vessel geometry terms and structural loading (e.g., conversion of pressure to stress) type factors. Equation (2) may be rearranged to yield:

$$K_I = C_1P_o + C_1\ (P_h-P_o) \qquad (3)$$

where P_o is the nominal reactor operating pressure.

Figure 2 shows a hypothetical AE versus test pressure curve for a hydrotest. The number of AE count obtained from a particular flaw during the hydrotest, δN, may be used in conjunction with the data in Figure 1 to determine the change in stress intensity factor, δK_I, of the flaw due to changing the pressure from P_o to P_h.

The change in stress intensity factor due to the overpressure of the hydrotest is given as the second term in equation (3) or:

$$\delta K_I = C_1\ (P_h-P_o) \qquad (4)$$

Hence, for a particular quantity of AE from a flaw at a given location that relation can be expressed:

$$\delta N = f\ (\delta K_I) \qquad (5)$$

where $f(\delta K_I)$ represents the mathematical relationship for the flaw severity - AE data shown in Figure 1. Over the range of expected values for K_I (i.e., 15-200 ksi$\sqrt{\text{in.}}$) this relationship may be taken as an equation of the form:

$$\delta N = C_2\ \delta K_I \qquad (6)$$

where C_2 is the slope of the nearly linear relationship between AE and K_I.

Substituting the right-hand-side of equation (4) into equation (6) produces:

$$\delta N = C_2C_1\ (P_h-P_o) \qquad (7)$$

Solving for C_1 and substituting back into equation (3) produces the final result:

$$K_I = \frac{\delta N}{C_2}\ \frac{P_h}{P_h-P_o} \qquad (8)$$

The resulting stress intensity factor represents a quantitative measure of the flaw severity which may be used to calculate the degree of structural degradation. Furthermore, this K value may be used in a fatigue crack growth analysis to predict end-of-life for a given structural element.

This analysis has illustrated in principle how an assessment of flaw severity based upon AE data alone may be obtained. The analsysis is based upon a very limited amount of experimental data and should not be construed as anything more than a qualitative measure of flaw severity at this time.

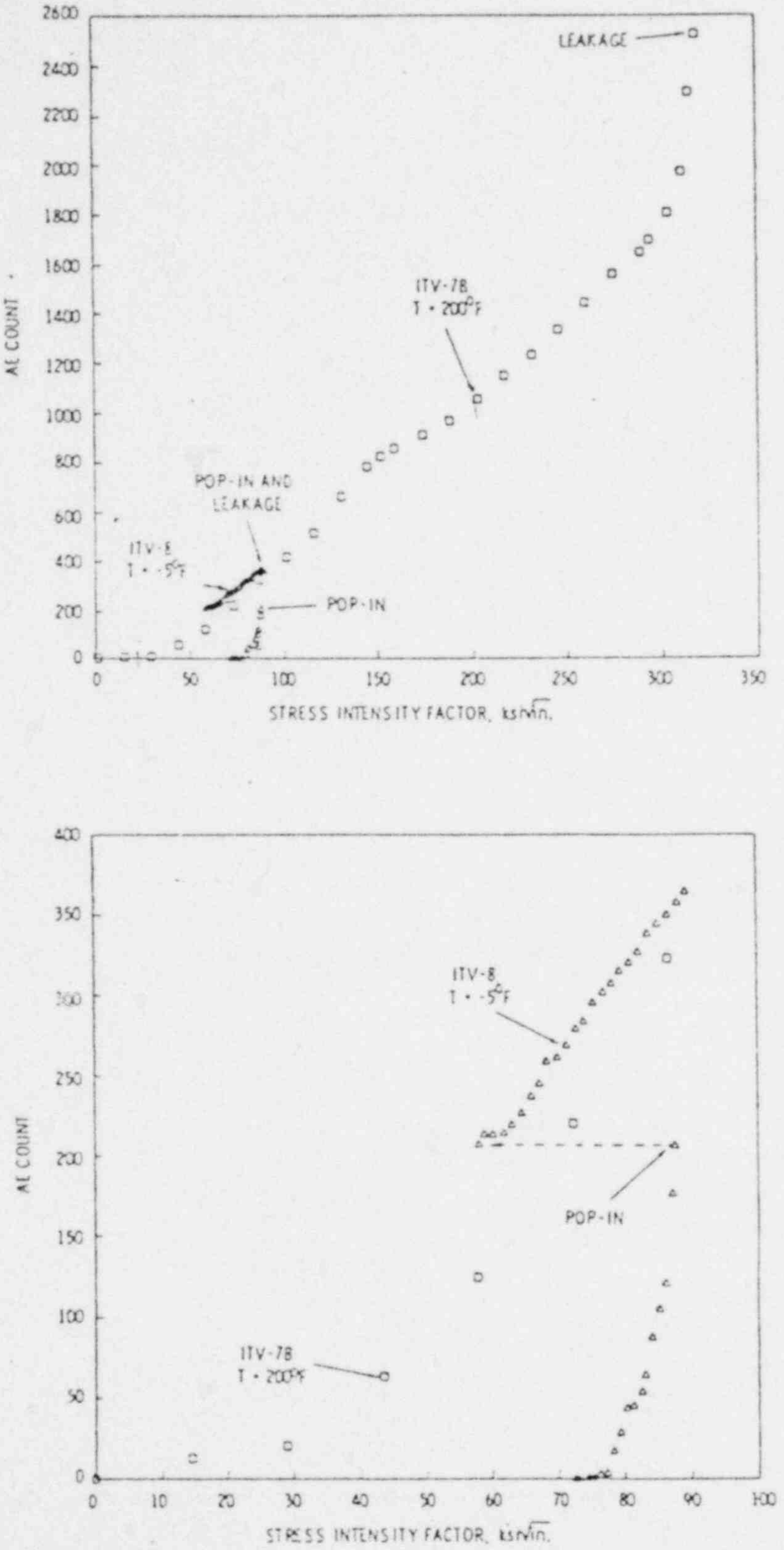

Figure 1. AE Versus Stress Intensity Factor for HSST Vessels V-7B and V-8.

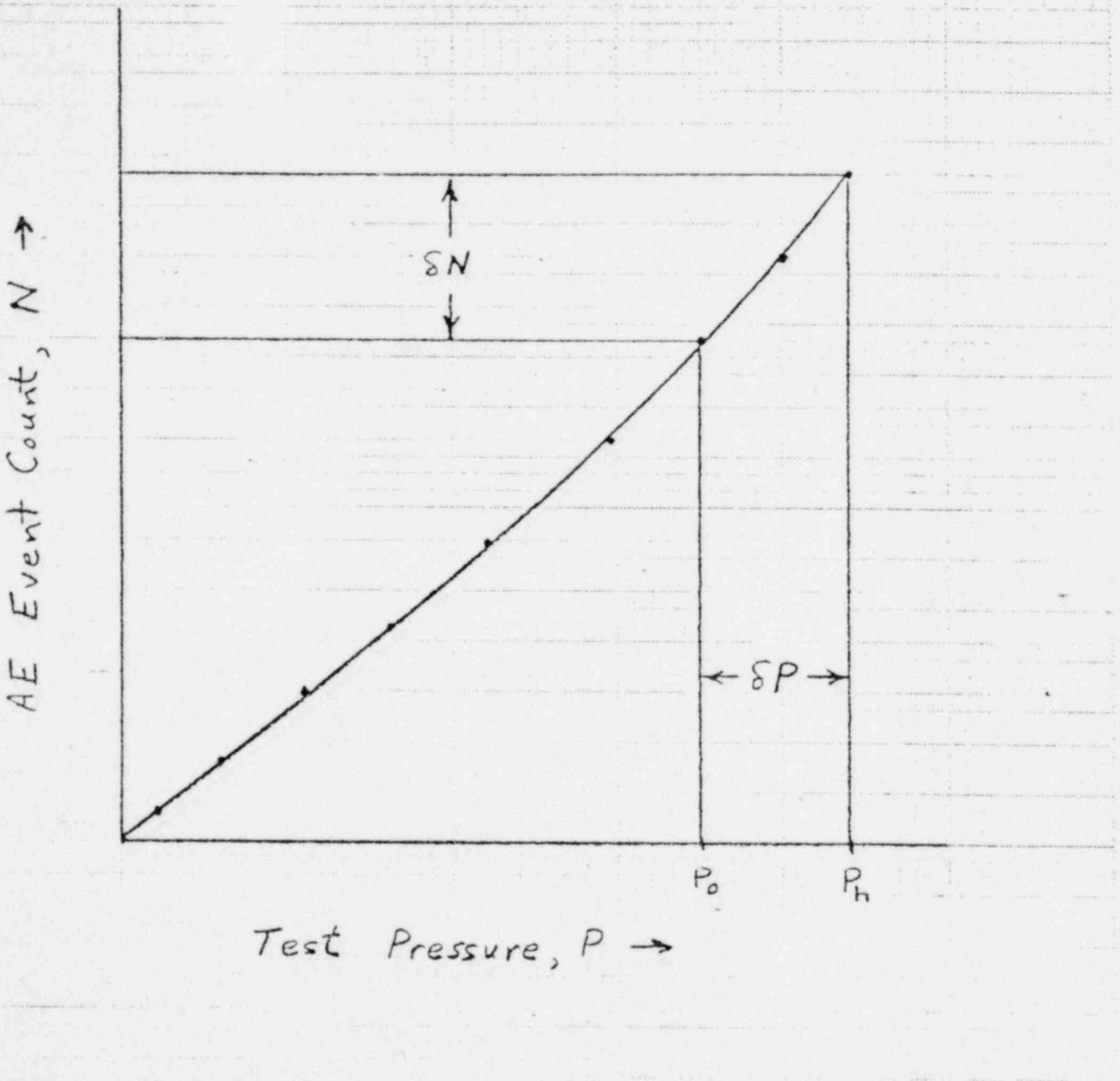

Figure 2. Hypothetical AE versus Test Pressure Curve for a Nuclear Pressure Vessel Hydrotest.