# A NOTE ON ACOUSTIC EMISSION MEASUREMENTS AT REML

by

N Kirby and P G Bentley

Risley Engineering and Materials Laboratory
United Kingdom Atomic Energy Authority
Wigshaw Lane
Culcheth
Warrington
Lancs.

## Abstract

The development of high sensitivity instrumentation for detecting and processing acoustic emission signals is outlined. Details are given of tests on fracture toughness test pieces of low strength steels and the benefits and limitations of such data are discussed. A summary of development work to establish location techniques is given.

## INTRODUCTION

The ability of metals to emit sounds when deformed has long been recognised but it is only in comparatively recent years that the full technological implications of acoustic emission phenomena have been appreciated. Of the varied applications that have been proposed, one of the most important is the assessment of structural integrity(1,2).

Work on acoustic emission within the UKAEA Reactor Engineering and Materials Laboratory began in 1968. At that time some exploratory studies were made on artificially flawed pressure vessels(3). A long term programme was then initiated to develop a technique suitable for use primarily on pressure vessels, during proof pressure tests. The separate parts of the programme may be described as follows:

(1) Development of a high sensitivity instrumentation for detecting and processing emission signals.

(2) Development of instrumentation and analysis for defect location.

(3) Characterisation of emissions and patterns of emission for low and medium strength pressure vessel steels.

This paper describes some of the work done in parts (2)-(3) of the programme.

## BASIS OF THE ACOUSTIC EMISSION APPROACH

When a metal containing defects is stressed, a stress concentration occurs at the tips of the defects. Under increasing stress, relaxation first occurs in these regions and may take the form of plastic flow, micro cracking or in the extreme large scale cracking. Acoustic emission is part of the energy released by these processes and so provides an indication of the presence of defects.

Emissions can be detected remote from their source and so it is possible to inspect a large area of a structure with a single detector and provide complete inspection coverage with a number of detectors.

## EQUIPMENT

The emission is converted to an electrical signal by means of a piezo electric transducer. The transducer used is generally a 1 in. diam. x $\frac{1}{4}$ in. disc (70-100 KHz resonant frequency) which is contained in a metallic housing, Fig 1, and may be bonded to the test specimen with adhesive or a thin film of grease. The signal is then amplified often using a pre-amplifier near the transducer, filtered to remove low frequency electrical and mechanical noise and then recorded or analysed directly.

Stressing of a metal can produce continuous emission or discrete bursts of higher amplitude, Fig 2. Analysis of these signals can be made in a number of ways. Each ring of the transducer above a set threshold level may be counted (ring down count) or alternatively each burst type emission may be counted as a discrete pulse. The number of counts per second or the integrated count is then compared with some other parameter such as applied load, pressure or strain. The trends may be displayed graphically on a chart recorder or X-Y plotter by converting the digital output from the counter to a simple voltage. A single transducer system used for monitoring small scale tests is shown diagrammatically in Fig 3.

A source of emission can be located by using a series of transducers at known locations and by measuring the differences in the times taken for a given emission to reach the transducers. A small computer is used to record and store the time data which can then be printed or plotted automatically using a conventional plotter or, for greater speed, displayed on an oscilloscope. To calculate the position of a defect, the time delays are converted to distances either manually or with the aid of the computer. Fig 4 shows a system of 10 transducer channels which provides for on line location with any 4 channels as well as tape recording, and subsequent analysis. The system has recently been mounted in a trailer unit to facilitate its use in on site tests on plant and structures.

## CHARACTERISATION STUDIES

The possible use of acoustic emission to estimate defect severity and proximity to failure is being examined using notched test pieces and artificially flawed pressure vessels. This work is still in progress and the observations are mainly qualitative.

## TESTS ON SMALL SPECIMENS

Notched bend specimens and compact K specimens(4) (CKS) generally 1 in. (2.5 cm) thick have been used in the investigations. These were fatigue cracked and then tested according to the recommended procedure for plane strain fracture toughness measurement(4). The tests were done in an hydraulic tensile machine which was manually controlled to give a steady rate of loading. A CKS specimen mounted ready for testing with a clip gauge and an acoustic emission transducer is shown in Fig 5. During test the rate of emission (or cumulative emission) and the opening of the notch (indicated by the clip gauge) were recorded as a function of the applied load using a 2 pen X-Y plotter.

Steels ranging from 30 ton/in (4.7x10kg$^{3}$/cm$^{2}$) to 100 ton/in$^{2}$ (15 x 10$^{3}$ kg/cm$^{2}$) ultimate tensile strength have been studied. At the highest strength levels a maraging steel and a medium alloy quenched and tempered steel were tested. These gave large burst type emission signals and in some tests there was an audible release of energy when a 'pop in' occurred at the end of the crack. Clear warning of impending failure was given by a dramatic rise in the emission count which began at about 80% of the ultimate failure load. In the low and medium strength steels of 15 tons (2.3 x 10$^{3}$ kg/cm$^{2}$) to 30 tons yield strength (4.7 x 10$^{3}$ kg/cm$^{2}$) the emission signals were basically similar to those of the high strength steel but had generally lower amplitudes; also the proximity to failure was not always characterised by a rapidly increasing rate of emission.

Correlation of the emission occurring during loading with the load displacement curves showed that the increasing rate of emission given by the ultra high strength steels had taken place under linear elastic plane strain conditions whereas the low and medium strength steels had failed in non plane strain and had given a sharply rising emission rate only when there was gross plastic flow at the root of the notch.

Observations made on the latter steels can be summarised using the result from a C-Mn steel specimen Fig 6a. Specimens having the least ductility and failing between the equivalent of points A and B on the load displacement curve gave a constant rate or a steadily rising rate of emission through to failure; specimens having greater ductility and failing between B and C on the curve showed a sharp rise before failure; at still higher levels typified by the C-Mn steel specimens, the emission rate rose and then decreased again before failure. In some tests there was a further increase in emission rate at failure, also, when specimens failed entirely by slow tearing there was a continuously high level of noise (possibly due to rotation of the specimens on the loading grips) as the failure was occurring.

Failure of the specimen used to obtain the result shown in Fig6a was predominantly brittle but was preceded by a small amount of fibrous tearing. (This subcritical crack extension is represented by a dark fracture region adjacent to the slightly bowed fatigue crack (Fig 6a & b)). The influence of the tearing was investigated by means of a series of tests in which similar specimens were loaded part way to failure, unloaded and then broken at a brittle temperature to reveal whether or not a crack had initiated during the loading operation. By these tests, the tear was shown to have developed mainly during the relatively quiet period before final fracture and to have made no significant contribution to the peak in acoustic activity occurring in the earlier part of the test. The results therefore lend support to the view that the emission observed in the low and medium strength steels tested was caused chiefly by the occurrence of plastic flow.

Studies have also been made of relationships which may permit quantitative assessment of defect/stress combinations using acoustic emission. The approaches examined have been based on the cumulative emission count $\Sigma E$ and the fracture mechanics parameters, stress intensity factor, K,(5) or the crack opening displacement COD or $\delta$(6). For conditions of limited plasticity before failure the emission can be expressed in terms of the relationship

$$\Sigma E = A K^{n}$$

where A and n are constants(7).

However for conditions of greater plasticity appropriate to low and medium strength steels in thin sections and exposed to normal design and operational conditions the crack opening displacement approach has appeared more relevant.

Plots of $\Sigma E$ against $\delta$ for three steels of differing yield strengths are shown in Fig 7. Since the axes are logarithmic the approximately linear variation shown by each of the steels implies a relationship $\Sigma E = A' \delta^{n'}$.

where A' and n' are constants.

This is similar to the linear elastic expression, and is to be expected as K and $\delta$ can be shown to be directly related when the plastic zone at the tip of the crack is small(8). The values of n (derived by regression analysis) given in the figure suggest no appreciable material dependency, however, further work is needed to investigate whether or not this is true for different steels and test conditions.

## SMALL VESSEL TESTS

Tests on small mild steel vessels were made early in the test programme with the objectives of developing techniques and making a preliminary investigation of emission phenomena in a vessel containing a flaw.

The vessels were essentially tubes, 12 cm thick x 150 mm diam. x 100 cm long. Each vessel contained an axial through wall thickness defect sealed to prevent water leakage by applying a patch of neoprene rubber reinforced with stainless steel sheet to the inner circumference of the tube. The ends of the tube were sealed with metal end plugs and rubber sealing rings. These end seals proved to be a potent source of emission, particularly during the early part of the test. However during repeated pressurisation the noise from the end fittings became negligible so that in pressure cycling tests it was possible to study emission with greater confidence.

It is well known that a metal once stressed gives little or no emission during a subsequent stressing unless there has been some increase in stress concentration within the metal, (for example due to the growth of a defect). This so called Kaiser effect(9) can give considerable operational confidence if observed, for example, in a repeat proof test on vessel after a period of service. Conversely the release of acoustic emission could imply that new defects had been introduced or that existing defects had grown since the previous pressurisation. However in some steels recovery can occur so that emission in a repeat test does not necessarily imply the growth or appearance of a new defect.

Two of the mild steel vessels were cyclicly pressurised 9 and 18 times respectively, with delays of up to 5 weeks between cycles. During most of the cycles the vessels gave negligible emission so that there was no evidence of any progressive recovery of emission. In one cycle of each series, however, appreciable emission was detected, and in this cycle the defect had grown significantly by widening at the tip of the notch, Fig 8. In the other cycles where there was virtually no emission, there was no significant widening. Although the widening was thought to indicate the initiation of a fatigue crack, the evidence on this point was inconclusive. Nevertheless the result served to demonstrate the sensitivity of emission to relatively small changes occurring at a defect.

These tests also demonstrated the effect that stress cycling can have on the emission that occurs subsequently at higher stresses. When pressurised to failure the vessels were exceptional in giving a much greater emission than any of the many other vessels tested. Specifically, the maximum rate was 10,000 counts per 1000 psi compared with rates generally of 500 counts per 1000 psi. The steep rise in emission is shown in Fig 9.

## LOCATION STUDIES

Initial development of the source location system was done in the laboratory with the aid of a steel plate test bed and artificial emission sources generated either electrically or by some mechanical means. Since that time experience has been gained from tests on large plate specimens and on experimental pressure vessels containing machined slits to represent natural defects. More recently a number of field trials have been conducted.

An example is a test made on a low alloy steel plate, 2.5 cm thick x 100 cm x 150 cm, which contained a 10 cm long central transverse slit. The plate was being stressed to failure in a machine of 4000 ton ($40 \times 10^5$ Kg) load capacity for fracture evaluation purposes. Fig 10 shows the plate mounted in the machine between two end lugs. Cooling trays were attached to the plate for cooling to the test temperature of -80°C. Four transducers were used all being glued to the accessible area on the upper end lug. Analysis of the emissions released as the specimen was loaded revealed three sources. Each source was diffuse indicating that the emissions came from an area rather than a specific point on the plate. One source was associated with the slit and its computed position was close to the actual position of the slit. The other sources were situated at opposite edges of the plate and since no defects were confirmed ultrasonically in these regions it seemed probable that these emissions had been caused by some local yielding of the plate.

The opportunity to examine the problems of field operation was taken when an experimental, 3 in. thick pressure vessel had been repaired and was about to be pressure tested at the fabricators. Although the vessel was situated centrally in a boiler making shop, where the normal activities of grinding, welding etc were in progress, no special problems due to interference from transmitted mechanical noise or spurious electrical signals were encountered and it was possible to check and calibrate the acoustic emission system without the need to halt production work. During the pressure test several leaks developed which were immediately sensed by the instrumentation and so demonstrated the known value of acoustic emission in leak detection. However, the noise from the leaks was sufficient to obliterate any genuine emission in the vessel. A later test was made to a higher pressure at RNL and emissions were detected satisfactorily.

The vessel currently contains a slit to represent a flaw and is being cyclicly pressurised to promote growth of a fatigue crack. Emission from the growing crack is being used for further development and proving of the source location techniques and to study the factors which can complicate the quantitative measurement of acoustic emission (eg count rate).

Other work has involved measurements during a proof test on a thick walled nuclear reactor pressure vessel and the investigation of problems associated with the monitoring during the return to operating conditions of a 50 ft. diam. gas cooled reactor pressure vessel. Details of this work are to be published shortly(10).

## DISCUSSION AND CONCLUSIONS

Acoustic emission provides a means of inspecting all parts of a vessel simultaneously and, applied in a final proof test it permits a full assessment of the vessel in its condition immediately before operation. Development of instrumentation and analysis for detecting and locating emission sources in the relatively quiet conditions of a proof test is well advanced although scope remains for improvement of detail.

Having located regions of above average activity, these may be related to physical features on the vessel; from this it may be possible to decide whether the emission has originated in the vessel itself and is, therefore, likely to be due to the presence of a defect or whether it has come from some extraneous source such as a bolted connection, support structure etc. Further deductions on the nature of the source may be made from the shape and size of the emitting region.

Interpretation of the strength of an emission source in terms of the severity of a possible defect isat present qualitative and based on experience. For instance, a sharp increase in the rate of emission under steadily rising load conditions might be taken as an indication of a severe defect and the likelyhood of imminent failure. Quantitative analysis of large vessels is not yet possible and regions of possible weakness indicated by acoustic emission would normally be examined further by conventional NDT methods.

Progress towards a more quantitative approach may be possible by relating acoustic emission to the fracture mechanics parameters K and δ - both a function of applied stress and defect size and geometry. The derivation of such relationships and proof of their general validity may be obtained in the course of monitoring commercial pressure vessels; however, information from such tests will be slow to accumulate and tests on experimental vessels with known sizes of defect subjected to known stress fields appear a necessary supplement.

Acoustic measurements on test pieces have the advantage that many parameters can be investigated using available equipment. Although there are inherent difficulties in applying quantitatively the results from a test piece to a structure, a useful qualitative indication of structural behaviour may be obtained. Specimen geometies are required which simulate reasonably closely the state of stress or strain in a structure. For conditions of plane strain test piece thickness may differ from that of the vessel, whereas for conditions of non plane strain, specimen size may be a critical factor and an adequate representation of the emission in structure may require the use of specimens of full plate thickness.

These geometry requirements are generally met in specimens used to measure the fracture toughness of a material ($K_{Ic}$ or $\delta_c$). Hence, the monitoring of fracture toughness tests is a convenient way to obtain relevant acoustic emission data. In addition, the emission detected may be useful as an aid to define the onset of fracture in the specimen and so permit a more accurate measurement of the fracture toughness. This could be particularly important in tests to measure critical values of COD ($\delta_c$) where the onset of fracture by a slow growth process is difficult to determine by other methods.

## REFERENCES

1. HUTTON P H and PARRY D L. Materials Research and Standards. MTRSA Vol 11. No. 3, p25.

2. NICHOLS R W and COWAN A. Preprints of 1st Int. Conf. on Structural Mechanics in Reactor Technology, Berlin 1971. Vol 5, pL61.

3. NIELSEN A, LATHAM F G, KIRBY N. Acoustic Emission from Steel Pressure Vessels. UKAEA TRG 1983(C).

4. Proposed Recommended Practice for Plane Strain Fracture Toughness Testing of Metallic Materials. ASTM Standards Pt 31, ASTM, Philadelphia USA (1969) p1099.

5. Fracture Toughness Testing and its Applications ASTM Special Tech. Publ. No. 381 ASTM Philadelphia USA 1965.

6. BURDEKIN F M in Proc. Symp. on Fracture Toughness Concepts for Weldable Structural Steel (Practical Fracture Mechanics for Structural Steels) UKAEA Risley and Chapman and Hall, London 1969, pC1.

7. DUNEGAN H L, HARRIS D O and TAHO C L. Engineering Fracture Mechanics 1968 p105.

8. BURDEKIN F M, STONE D E W. J. Strain Analysis Vol 1, No. 2 1966, p145.

9. KAISER J. "Untersuchungen Uber das Auftreten von Gerauschen biem Zugversuch". A doctoral dissertation presented to Fahultet fur Maschinen wesen and Electrotechnik · Der Tehnischen Hochschule Munchen, Munchen, Germany 1950.

10. BURTON E J, BENTLEY P G, BURNUP T E, COWAN A, KIRBY N. Paper to be presented at Conf. on Periodic Inspection of Pressure Vessels to be held 9-11th May. I.Mech. E. London 1972.

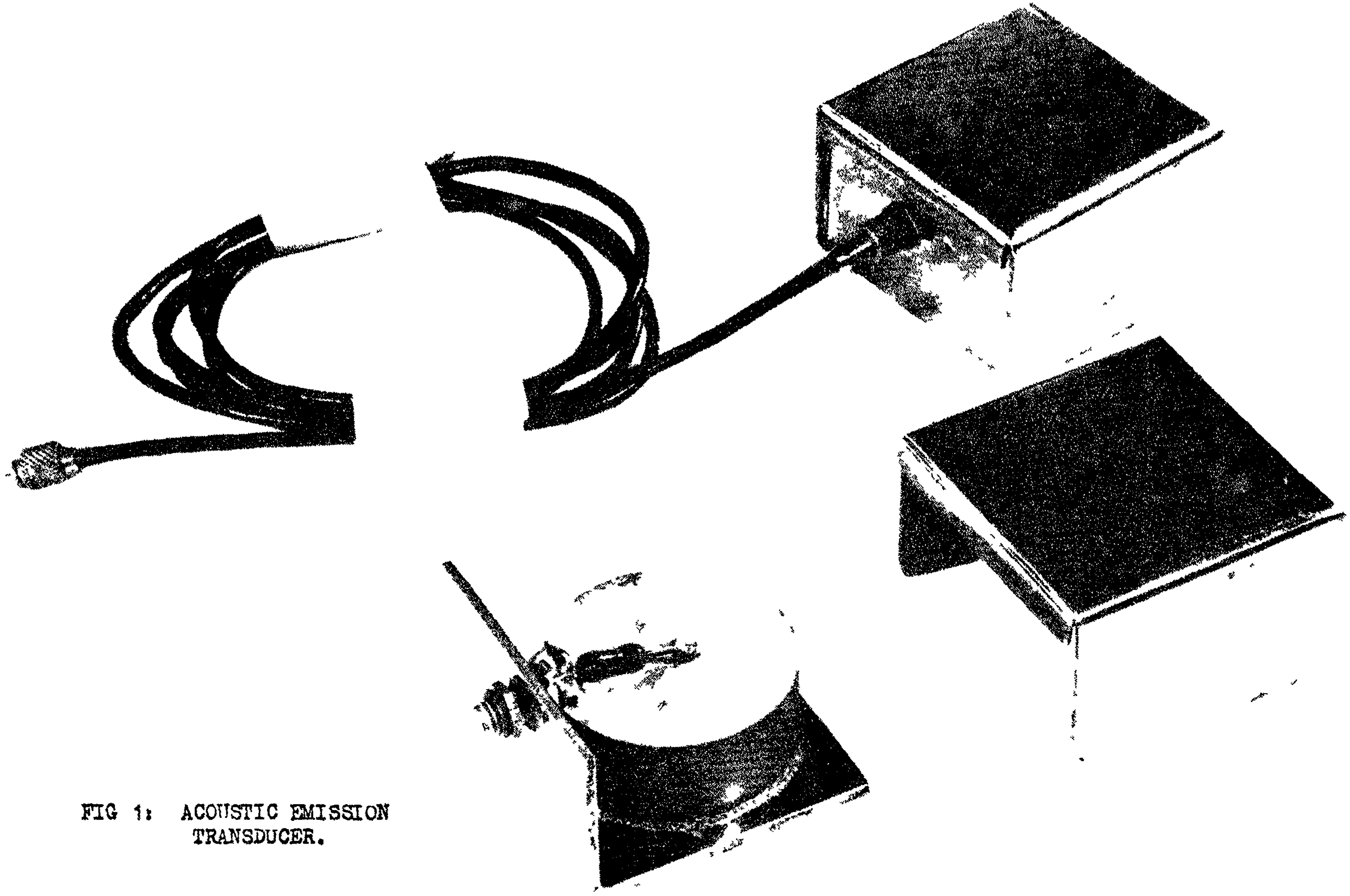

FIG 1: ACOUSTIC EMISSION TRANSDUCER.

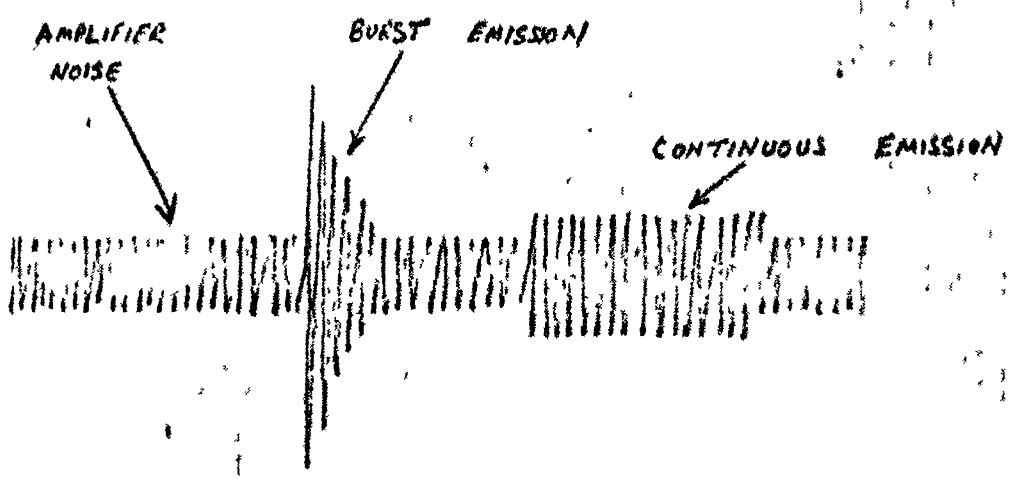

FIG 2. ACOUSTIC EMISSIONS.

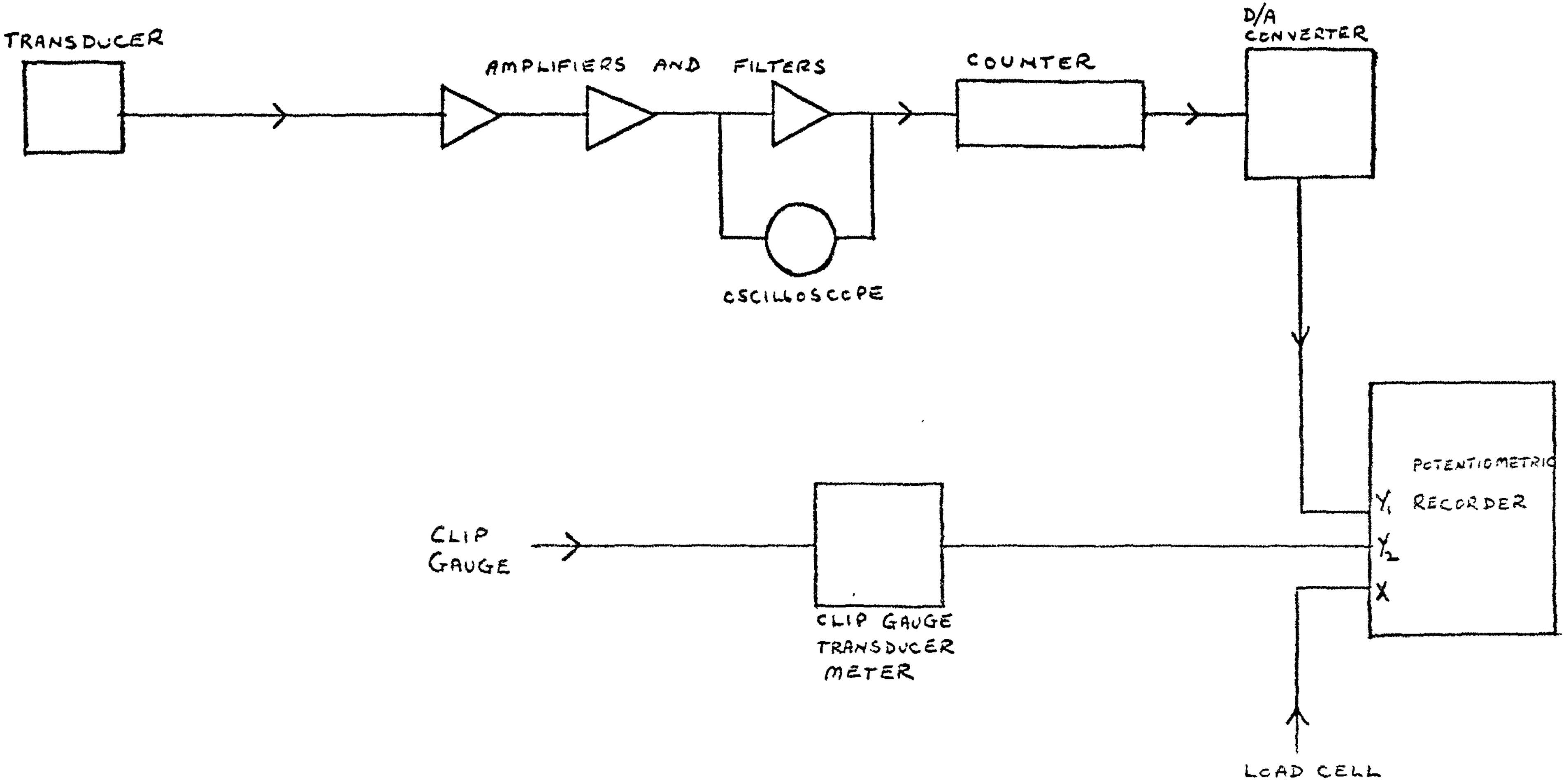

FIG. 3 INSTRUMENTATION FOR ACOUSTIC EMISSION DETECTION AND ON LINE DATA PRESENTATION

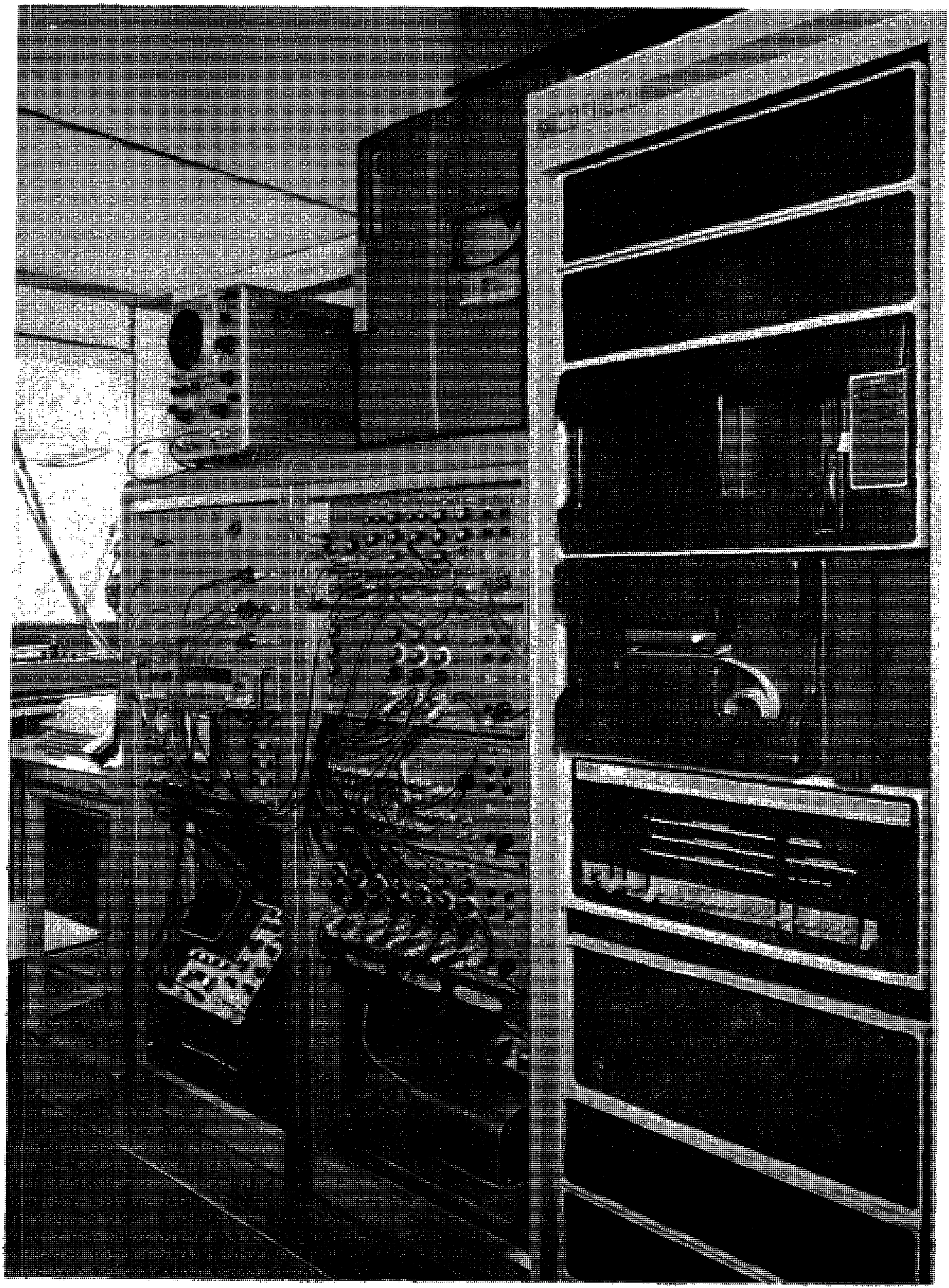

FIG 4: INTERIOR OF THE SWEL MOBILE TRAILER
(STRESS WAVE EXPERIMENTAL LABORATORY).

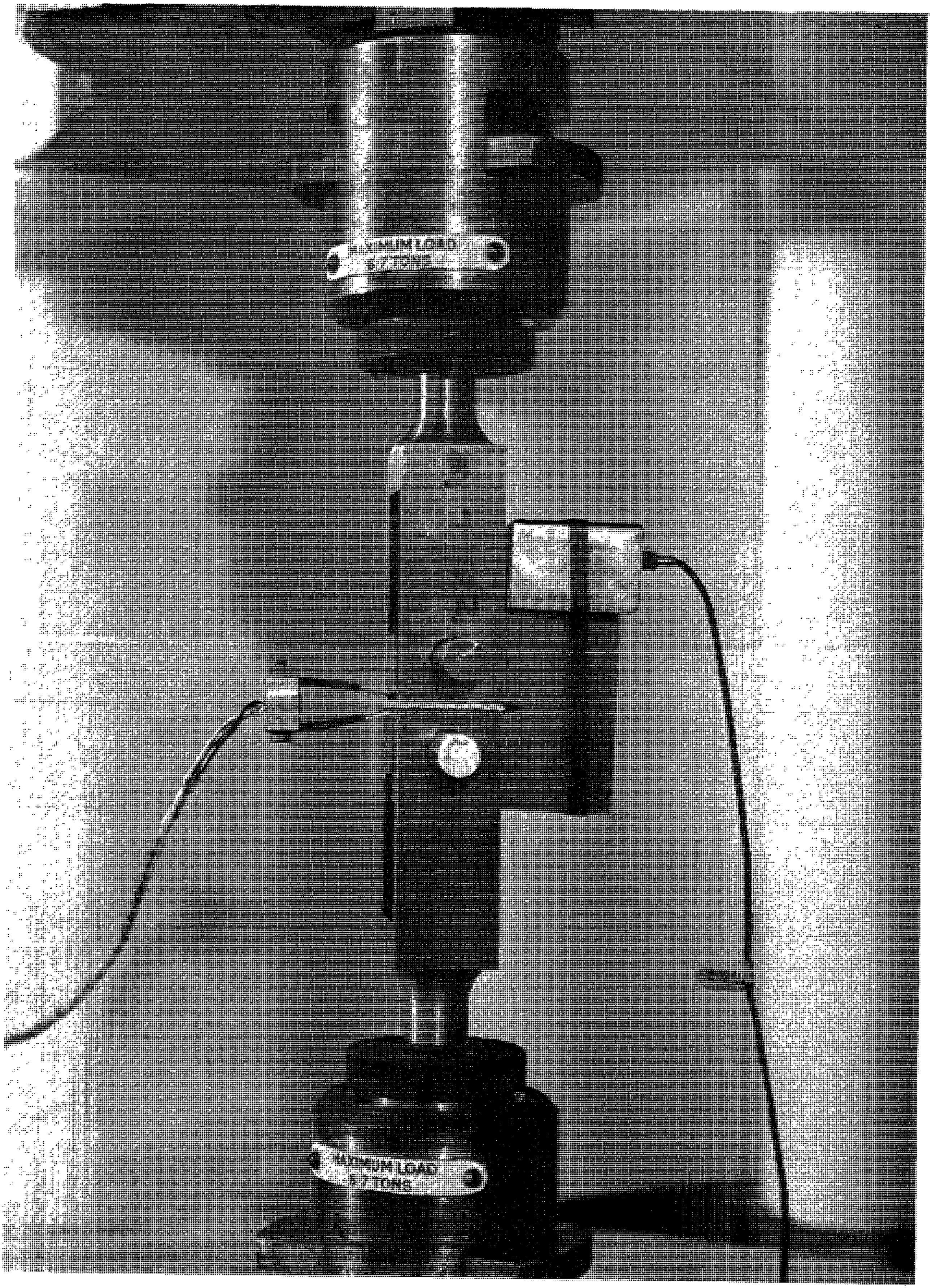

FIG 5: ASSEMBLY FOR TESTING CKS SPECIMENS.

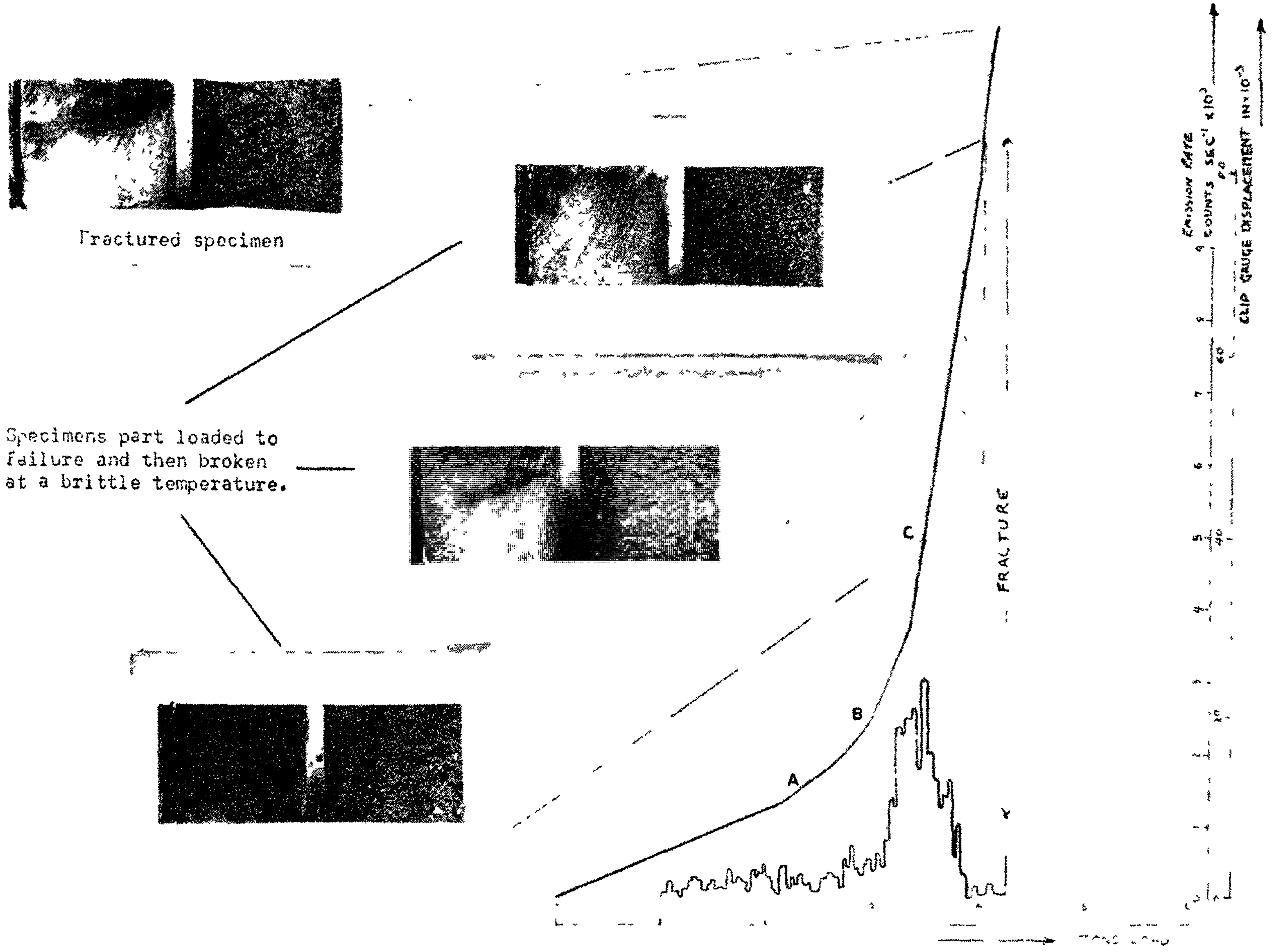

FIG. 6a: ACOUSTIC EMISSION FROM 0.25%C-0.75%Mn STEEL CKS SPECIMENS.

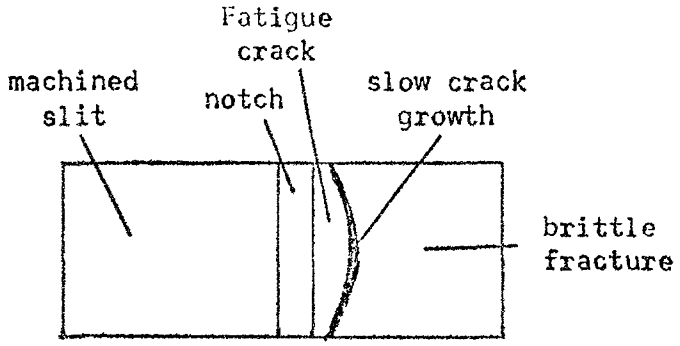

FIG. 6b: DIAGRAM OF FRACTURED SPECIMENS SHOWN IN FIG. 6a

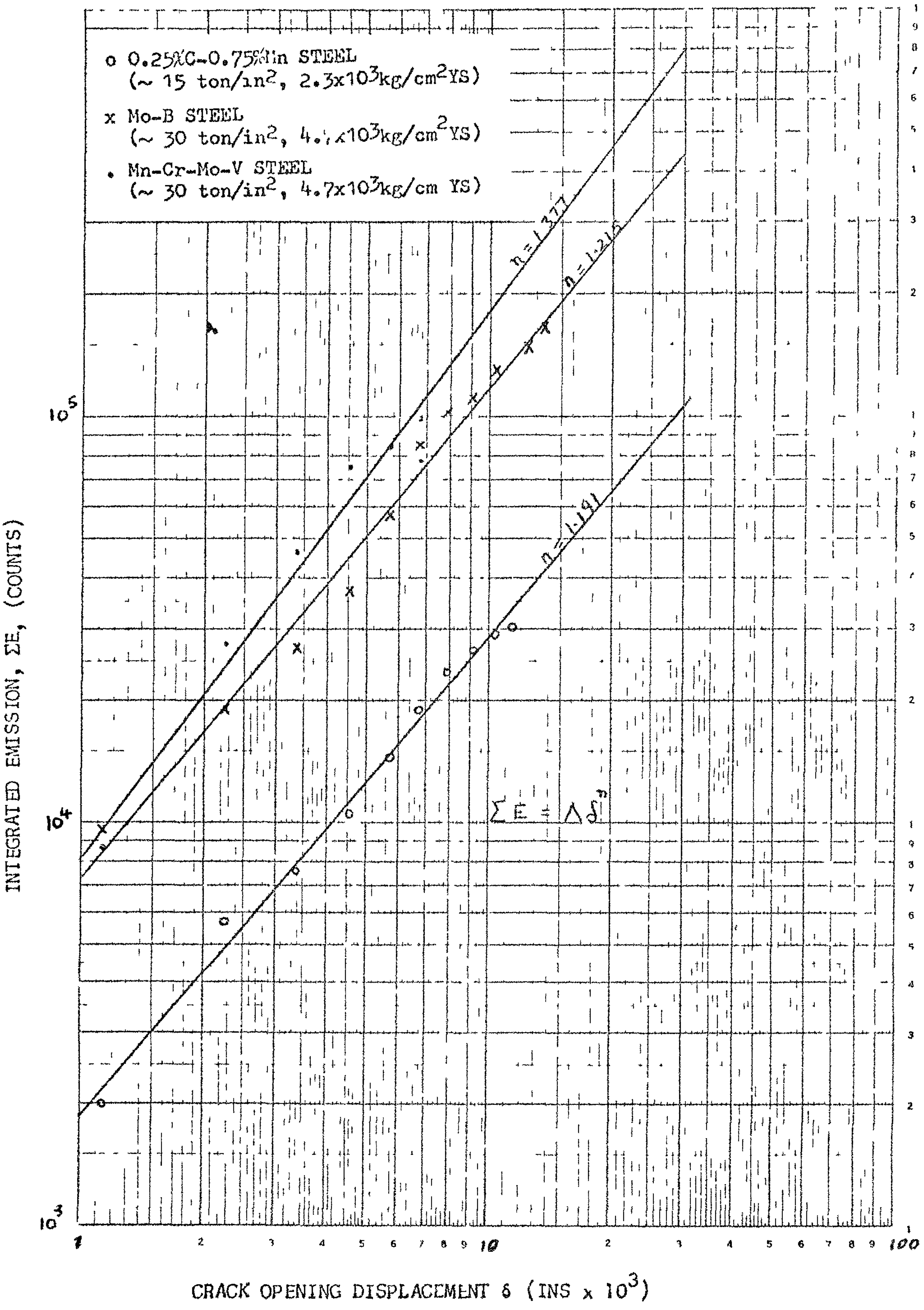

FIG. 7: INTEGRATED EMISSION AS A FUNCTION OF CRACK OPENING DISPLACEMENT FOR CKS SPECIMENS OF LOW AND MEDIUM STRENGTH STRUCTURAL STEELS.

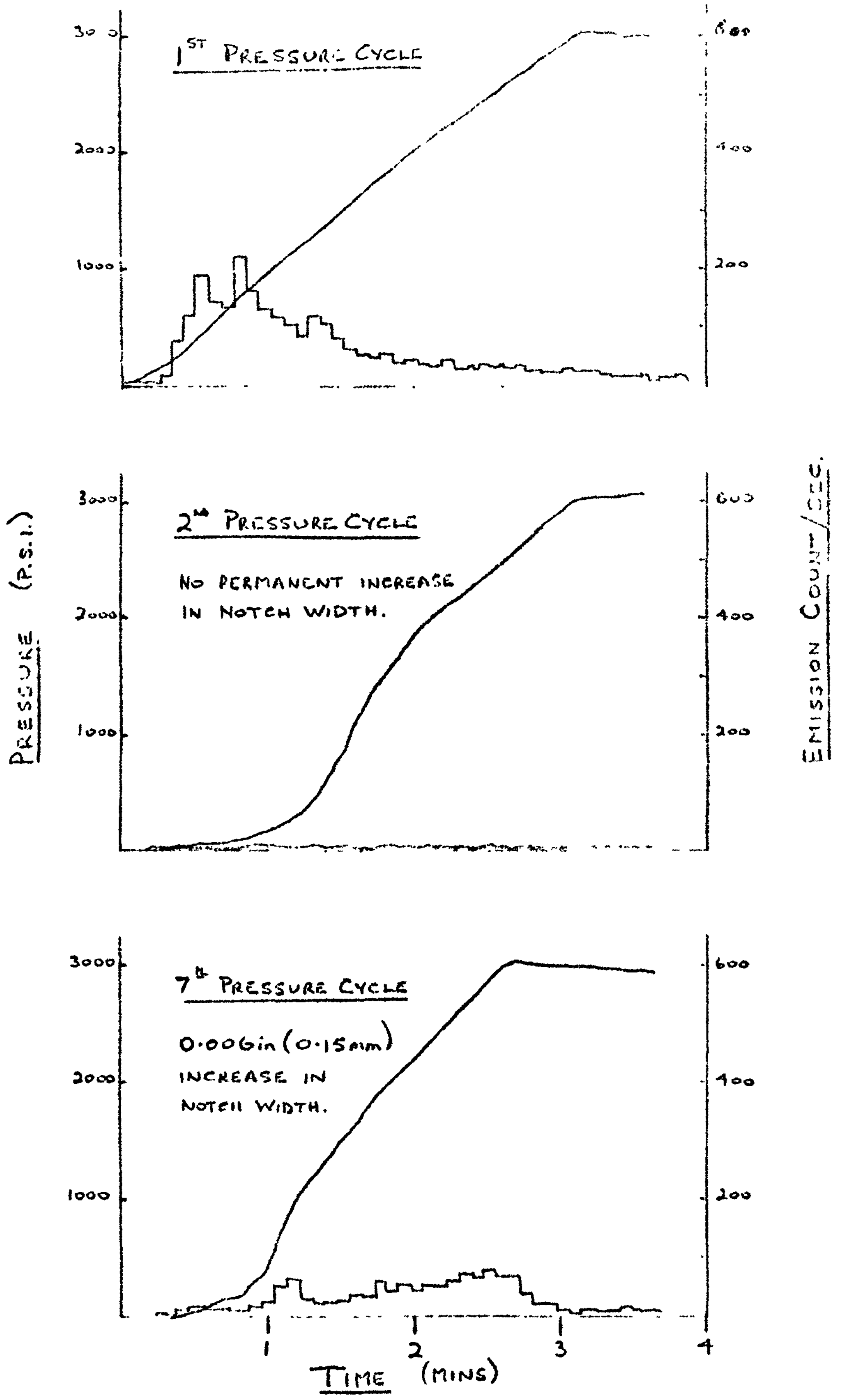

Fig 8. Acoustic Emission occuring During Pressure Cycles on A ½ in. Thick C-Mn Steel Tube Containing A 4 in. Long Defect.

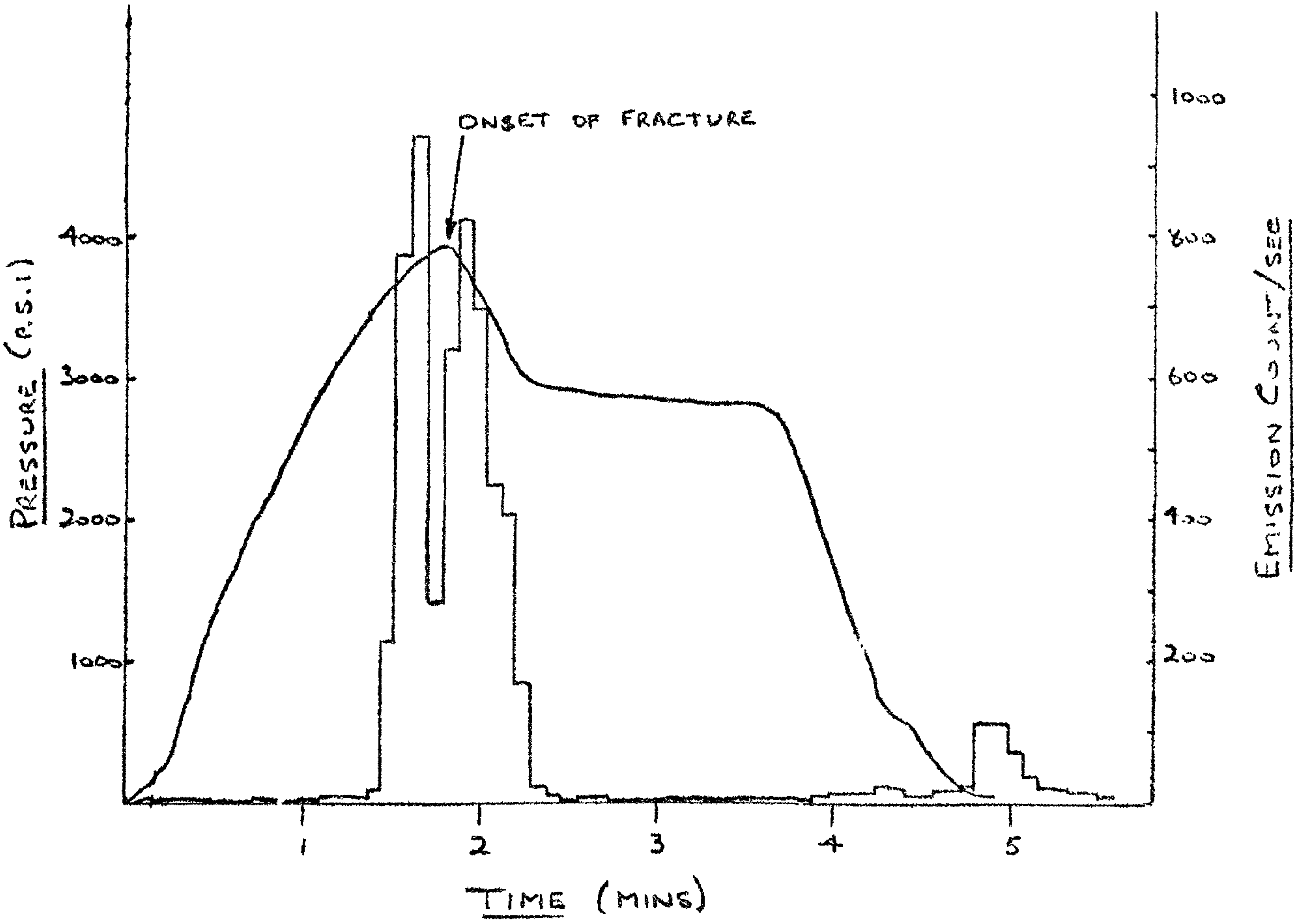

FIG. 9. RISE IN ACOUSTIC EMISSION OCCURING TOWARDS FAILURE OF A C-Mn STEEL TUBE PREVIOUSLY PRESSURE CYCLED TO 3000 P.S.I.

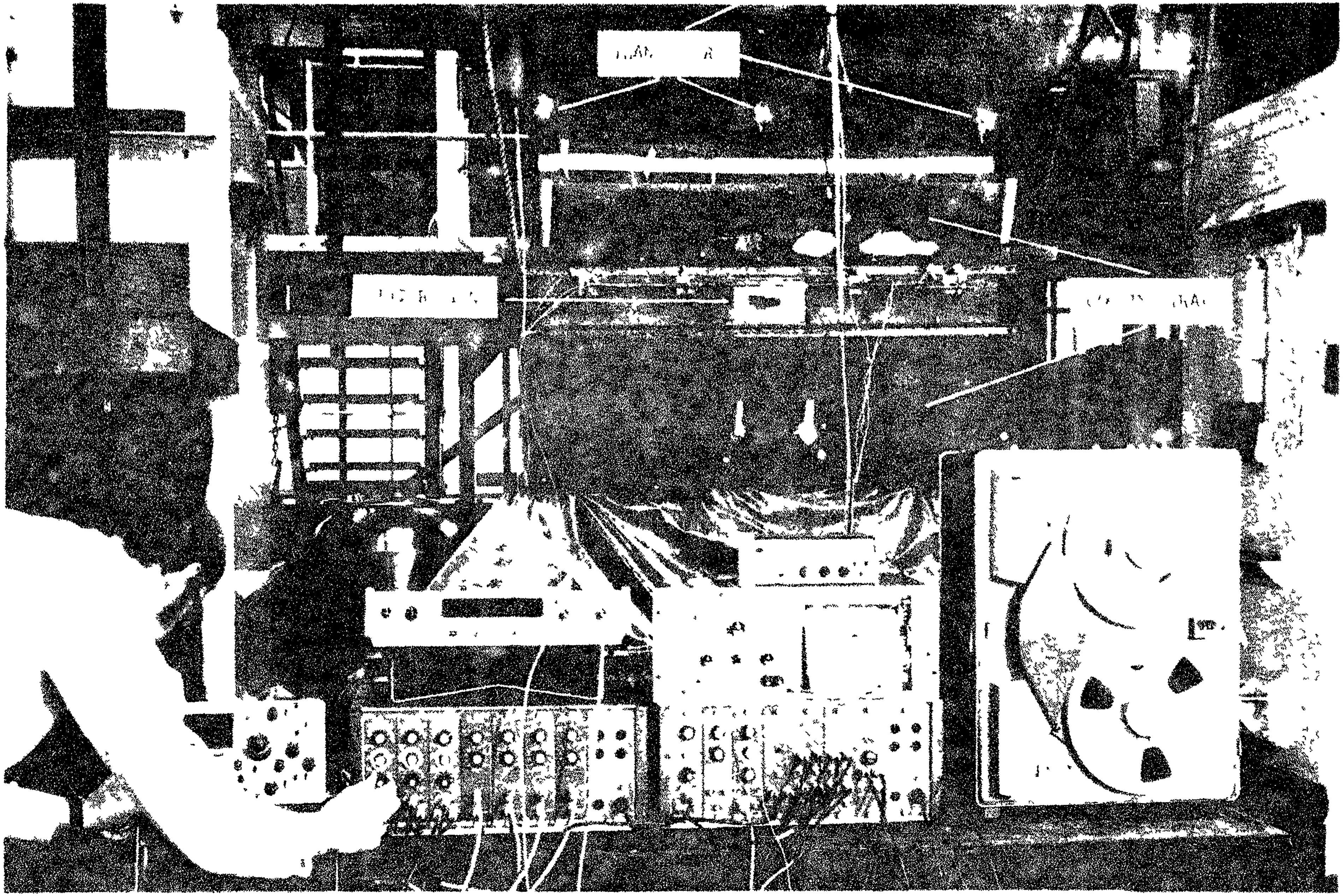

FIG. 10: ACOUSTIC MONITORING OF A FLAT PLATE TEST PIECE CONTAINING A CENTRAL SLIT.