

THE APPLICATION OF ACOUSTIC EMISSION MEASUREMENTS ON LABORATORY TESTPIECES TO LARGE SCALE PRESSURE VESSEL MONITORING

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SUMMARY

The development of laboratory acoustic emission testing at REML is outlined. Tests using single sensors have indicated that emission activity in pressure vessel steels could be related to toughness and strength; however, emission data from this type of test could not be related to structural monitoring.

A more detailed series of measurements using an emission location technique was made on BS1501/151/Grade 28A mild steel to relate specimen activity with that of large structures.

A test pressure vessel containing 4 artificial defects was monitored for emission whilst pressure cycling to failure. Testpieces cut from both the failed vessel and from as-rolled plate material were tested in the laboratory.

No emission was reliably detected from the defects in the pressure vessel whereas emission was easily detected from both types of testpiece.

A marked difference in emission characteristics was observed between plate and vessel testpieces. Activity from vessel material was virtually constant after general yield and emission amplitudes were low. Plate testpieces showed maximum activity at general yield and more frequent high amplitude emissions.

An attempt has been made to compare the system sensitivities between the pressure vessel test and laboratory tests. In the absence of an absolute calibration device, system sensitivities were estimated using dummy signals generated by the excitation of an emission sensor. The measurements have shown an overall difference in sensitivity between vessel and laboratory tests of approximately 25db. The reduced sensitivity in the vessel test is attributed to a combination of differences in sensors, acoustic couplant, attenuation, and dispersion relative to laboratory tests and the relative significance of these factors is discussed.

Signal amplitude analysis of the emissions monitored from laboratory testpieces showed that, with losses of the order of 25 to 30 db, few emissions would be detected from the pressure vessel test.

It is concluded that no reliable prediction of acoustic behaviour of a structure may be made from laboratory tests unless testpieces of the actual structural material are used. A considerable improvement in detection sensitivity is also required for reliable detection of defects in low strength ductile materials and an absolute method of system calibration is required between tests.

Introduction

Many organisations throughout the world have developed equipment for on-line analysis of acoustic emission from large scale structures. Tests on pressure vessels have shown that currently available equipment is not suited to continuous monitoring because of difficulties associated with adverse environments and the high background electrical and mechanical noise levels usually found under service conditions[1]. It is accepted that maximum benefit can be obtained by applying acoustic emission during periodic proof (overpressure) tests where operation difficulties and background noise levels will be much lower[2] [3].

Measurements of acoustic emission during proof testing have shown that low stress crack growth processes eg stress corrosion cracking, hydrogen embrittlement can be identified with comparative ease [3], but the yielding and slow crack extension associated with ductile (leakage) failures is not readily detectable in typical experimental pressure vessels [1][4]

A common factor associated with many reported pressure vessel tests is that a large number of signals are subsequently found to originate at natural welding defects [1] [4] (eg slag, lack of fusion) which would often be considered to be innocuous in terms of pressure vessel integrity. If emissions from different materials and types of defect can be characterised and the significance of the different defect types is known, then some form of automatic rejection system might be possible which could lead to more reliable coverage in an acoustic emission test.

Background information on the acoustic emission characteristics of materials can be obtained from laboratory tests. The objective of laboratory testing should be to provide data which can be applied directly to the particular pressure vessel under investigation. It is now recognised that this will not be possible until the results of structural and laboratory tests can be compared directly through an absolute calibration. Calibration techniques have yet to be standardised and at the moment laboratory data can only be used qualitatively. However, simple laboratory tests have indicated a number of aspects of relevance to pressure vessel testing, some of which will be dealt with in this paper.

The paper outlines briefly the development of laboratory acoustic emission testing at REML and describes the results of recent tests using a laboratory facility capable of emission location. These tests were done in conjunction with a full scale pressure vessel experiment and acoustic emission data from small scale and large scale tests are presented and discussed.

Single Sensor Laboratory Tests

Experience in laboratory acoustic emission testing at REML has been acquired over the past 3-4 years. In the early work, tests were monitored using a single sensor system where it was not possible to distinguish between emissions from test piece deformation and spurious signals from testing fixtures. Although these simple tests do not provide quantitative data applicable to structural testing they do provide a useful method of comparing acoustic activities in different steels.

A range of pressure vessel steels have been monitored using a single sensor pulse counting technique. Acoustic activities obtained using both tensile and fatigue pre-cracked fracture toughness (three point bend) test pieces have shown that steels could be rated in terms of strength and ductility or fracture toughness. Full details of these tests have been presented elsewhere [5] and only the general conclusions are given here.

- 1) Tensile tests showed that maximum emission was associated with yielding phenomena. In general, acoustic emission increased with increasing tensile strength and decreasing elongation although steels which showed well defined discontinuous yielding produced higher acoustic activity than would be inferred from strength and ductility alone.
- 2) Fracture toughness tests have shown that acoustic emission increases with decreasing toughness. The tests demonstrated two distinctive types of behaviour. Steels which failed by brittle fracture were characterised by a rising emission rate at failure, whereas steels which failed by ductile fracture showed similar characteristics to those found using tensile test pieces, i.e. a peak in emission at general yield followed by a decrease in emission rate as gross yielding spread through the ligament area of the test pieces.
- 3) Fracture toughness tests on test pieces of differing size showed that acoustic emission was proportional to the volume of material undergoing deformation.
- 4) Fracture toughness test pieces containing heavily oxidised notches produced many "spurious" emissions in the elastic range due to break up of the oxide film.

Workers in other laboratories have shown that acoustic response in steels is also dependent on many other factors, for example, the precise heat treatment of the steel [6] and the strain rate of the test [7].

Coincidence detection

Single sensor monitoring is restrictive, in that, other than in the broadest terms, the data acquired cannot be related to large scale test behaviour. Ideally, laboratory tests should be monitored using a location system similar to that used in the full scale test so that validated emissions from the test-piece can be compared with validated emissions from the structure. This approach has been adopted for the more recent work at REML. Since the source of acoustic emissions is known in any laboratory test system, the REML SWEL [8] source location system is unnecessary and a 'co-incidence' technique has been developed specifically for laboratory work. In the co-incidence method, two transducers are placed equi-distant from the acoustic emission source and only those signals which trigger both transducers within a fixed gate time are validated. By testing in four point bending (as opposed to three point bending used in the single sensor work) load point emissions will be rejected providing the difference between arrival times of signals originating at the inner load supports (minor span) is greater than the co-incidence gate time. With the REML system, discrimination between acoustic emissions from the notch tip of a fracture toughness test-piece and the minor loading span supports can be achieved providing that the minor span is greater than 3in. Simultaneous monitoring of fracture toughness test-pieces using the co-incidence unit and the SWEL location system has shown good correspondence in validated emissions monitored using the two systems.

The co-incidence unit has been used to monitor emissions in laboratory test-pieces machined from both the original as-rolled plate used in the fabrication of large scale (5ft dia, 1in thick) pressure vessel and from the actual pressure vessel after it had been tested to failure.

Laboratory tests on Pressure Vessel Material

Four point bend tests were made using the test-piece types shown in Fig 1. 'Plate' test-pieces machined from original vessel plate material had been prepared prior to the pressure vessel programme and were used to assess the emission characteristics of BS1501-151

steel. 'Vessel' test pieces were machined from a curved patch of BS1501-151 steel removed after completion of the vessel test. 'Plate' test pieces were notched on the through thickness face ie the standard orientation for material evaluation. 'Vessel' test pieces were notched on the plate surface ie corresponding to the orientation of the artificial surface defects in the pressure vessel test. The notches of 'plate' and 'vessel' test pieces were sharpened by fatigue pre-cracking to provide crack length/test piece depth (a/w) values of 0.5 and 0.3 respectively (Fig 1).

Emissions were monitored using 190 KHz resonant sensors mounted inside machined cylindrical cases. The sensors were screw attached to the test pieces and grease was used as the acoustic couplant.

Detected signals from the sensors were pre-amplified in a bandwidth 130-300 KHz and fed to automatic gain setting detector modules where further filtering passed signals above 120 KHz. The discriminator level was set to 1.3 times peak background noise level and maintained at this level by automatic gain control to compensate for any changes in noise level. Acoustic emissions validated by the system were shaped to convert the oscillatory response of the sensors to a single pulse of fixed amplitude.

A schematic of the testing arrangement is shown in Fig 2 and Fig 3 shows a photograph of the REML acoustic emission instrumentation.

Measurements were made of load/COD*, ringdown count rate/COD (X-YY), located emission rate/Time (X-T), ringdown count rate/Time (X-T). Reference load values were included on the constant speed (X-T) recorders via an event marker. The tape recorder was used on some tests to record emission for future reference and off line pulse height analysis.

Results

Typical test records for 'plate' and 'vessel' test pieces are shown in Figs 4 and 5. Fig 4 shows plots of load/COD and ringdown count/COD. Single sensor ringdown counting was monitored as a means of identifying the onset of ductile crack extension which has been identified previously [1] with the attainment of a minimum count rate in the COD/emission record. The records show a marked difference in emission rates between 'plate' and 'vessel' test pieces where maximum count rates associated with general yield were respectively 60,000 and 5000 counts sec^{-1} . Although the onset of crack extension could be inferred from the 'plate' test piece, no value could be inferred from the 'vessel' test piece which showed no significant decrease in emission rate after general yield. Fig 5 shows located emissions (pulse, not ringdown) for the two types of test. The load/time curves were obtained from voice comments and, although not strictly accurate, are a close representation of test conditions. The located emissions provide similar characteristics to the ringdown counts but the difference in emission rate is not so marked. 'Plate' material gave a maximum activity at general yield, low activity during ductile crack extension and an increased activity at maximum load. The increase in activity towards the end of the test was probably associated with gross tearing and delamination, evidence of which could be seen on the fracture surface. 'Vessel' material, on the other hand, gave almost uniform activity between general yield and maximum load.

*COD - crack opening displacement (a measure of fracture toughness in ductile materials)

All test pieces were copious emitters and signals were of 'burst' type throughout the tests. 'Plate' material was extremely active at general yield, with emission bursts overlapping. 'Vessel' material, throughout the tests, and 'plate' material, post yield, gave intermittent burst emissions. Typical emissions from both test pieces at general yield load (maximum count rate) and 1.25 general yield load (minimum count rate in 'plate' material) are shown in Figs 6 and 7 respectively. The totalised emissions at three load levels ie general yield, 1.25 x general yield and the maximum load (load at which the test was stopped) are shown in Table 1. A comparison of data up to 1.25 x general yield load suggests that the plate test pieces were at least twice as active as vessel test pieces.

Pulse height analysis obtained using SWEL are presented in Fig 8 which gives the amplitude distributions at progressively increasing load. At all levels, peak signal amplitudes were lower from 'vessel' than 'plate' test pieces and signals greater than 30 times (30 db) instrument noise level were infrequent from either type of test.

Pressure Vessel Test [9]

The pressure vessel was fabricated using BS 1501-151 Grade 28A, a low strength C-Mn pressure vessel steel. Three axial partial penetration defects were introduced into the vessel surface and the vessel was pressure cycled to 525 psi to promote fatigue crack growth at the most severe defect. This defect was initially 8 inches long and 0.8 inches deep and after 1142 pressure cycles the defect depth had increased by an estimated 0.08 inches. Of the 1142 pressure cycles, 91 were monitored using the SWEL system but the first cycle was not monitored.

Only the defect known to be growing under the cyclic load was monitored for acoustic emission. Emissions were monitored using an array of 190 KHz resonant emission sensors mounted with araldite adhesive. Detection system sensitivity was checked using dummy emission pulses generated by driving an emission sensor with an electrical impulse.

During the 91 cycles monitored using SWEL, acoustic emission from the defect region was low; approximately 200 emissions (including background activity) were observed. No localised emission source could be identified positively with the machined defect.

After fatigue pre-cracking the severest defect, a fourth partial thickness defect was machined into the vessel wall. The vessel was then subjected to 13 progressively increasing pressure excursions until the 0.88 inch deep fatigue pre-cracked defect penetrated the vessel wall at a pressure of 950 psi and the vessel failed by leakage. The whole vessel was monitored for emissions during this phase of the test. Throughout the test no statistically significant emission source was identified either from the fatigue pre-cracked defect which failed by tearing through the remaining ligament or from any of the other three machined defects, at least two of which were calculated to be yielding. [10]

Comparison of System Sensitivities

In order to assess the significance of the laboratory emission data an effort was made to compare the system sensitivities on vessel and test pieces.

In the absence of an absolute method of calibration, comparisons were made using dummy resonant signals generated by exciting an emission sensor with pulses 10 μ sec wide of amplitude 50 mV (test pieces) and 200 mV (pressure vessel). The lower input pulse amplitude in laboratory tests was used after calibration checks of the pulser system had shown that the received signal amplitude varied linearly with input pulse amplitude for the range of inputs

used.

Measurements on the pressure vessel were made both by exciting sensors in the detector array and also by exciting separately attached pulsing sensors. This is normal practice on vessel tests to check the emission location system. Signal attenuation was measured on the pressure vessel using a 'ring round' method and sensitivity corrected before comparison with test piece sensitivity. Vessel attenuation was 2.2 db/metre in agreement with previously quoted values [8]. Maximum attenuation at the most remote sensor from any of the defects was 6 db.

Sensitivity checks on test pieces were made by exciting each sensor in turn and measuring the peak received signal at the other. For comparison purposes, attenuation was assumed to be zero on the test pieces.

Since the construction and coupling of sensors used on the pressure vessel and in laboratory tests was different, a number of sensors of the type used on the pressure vessel test were calibrated on laboratory test pieces. Comparison between vessel and test piece sensors using a grease couplant showed a sensitivity difference of 4 db. Comparison of a number of vessel sensors mounted in various positions on test pieces using araldite as the acoustic couplant showed a sensitivity difference of 7 db.

The results of these sensitivity measurements are given in Table 2. The difference in system sensitivity between vessel and test pieces was 19 db, or 25 db including maximum attenuation in the vessel array.

Discussion

The difference in emission count rate and signal amplitude characteristics for plate and vessel test pieces (Figs 5 and 8) have yet to be explained. Tests are in hand to determine the effect of differences in test piece size, curvature and notch orientation but contributions from these factors are not expected to account for the significant differences between plate and vessel tests particularly at general yield. Differences in emissions at general yield are not thought to be attributable solely to the amount of prior stress seen by the 'vessel' test pieces for the following reasons. Since the vessel failed at a hoop stress of approximately 13 tsi and the yield strength of the material under investigation was 16 tsi, regions remote from the artificial defects from which the test pieces were machined would have suffered no plastic deformation. Prior elastic deformation will influence acoustic response providing that no recovery in emission occurred in the time between vessel and laboratory tests. Thus, no emission would be expected to occur in laboratory tests on vessel test pieces until a stress of 13 tsi was exceeded; the presence of a fatigue pre-crack in the test piece would result in local crack tip stresses exceeding this value at approximately one-half of the general yield load. The generation of a well defined yielding plateau (which is indicative of freshly yielding material) can be seen clearly in the load/COD test record for the vessel test piece shown in Fig 4.

Metallurgical examination of plate and vessel samples indicated that there were no significant differences between the two samples. However, the most likely reason for the differences in emission rates at general yield is the different heat treatments seen by plate and vessel material. The plate material was in the 'as rolled' condition whereas the pressure vessel had been formed and stress relieved for 2 hours at 625°C after fabrication. Removal of microscale residual stresses could be the most significant factor when considering

differences in acoustic behaviour in the two materials. This is supported by observations at CERL [6] where only slight changes in heat treatment of a C-Mn steel produced significant differences in acoustic response.

The results obtained have particular relevance to the use of laboratory tests to predict emission in large scale engineering structures.

Firstly, it is apparent that no data relevant to a large structure can be obtained from laboratory tests unless test pieces of the actual structural material are tested. Secondly, there is shown to be a large discrepancy between the emission activity of laboratory vessel test pieces and emission from defects in the test vessel. Even though the general yield emission was low in comparison to plate test pieces, the 'vessel' test pieces showed approximately the same count rate for most of the duration of the test (Fig 5). In terms of count rate alone the laboratory tests would indicate that some thousands of emissions should have been detected in the vessel test, and this number would be increased further for the 8 inch long defect if acoustic activity is proportional to the volume of material undergoing deformation (compare Table 1 for 1 inch defects). In fact no emission could be positively identified with the artificial defects in the pressure vessel during pressurisation to failure.

The results therefore show that there is considerable difference in detection sensitivity between laboratory and large scale tests. A useful approximation of the difference in detection sensitivity existing between vessel and laboratory tests can be made from the results of the pulse height analyses. Examination of the emission pulse height distributions (Fig 8) show that the signals are small, a result which agreed with visual observations of the signals (Figs 6 and 7). Only approximately 1% of signals from the vessel test piece exceed background noise level by 26 db (x20) and less than 0.2% of the signals by 30 db (x30). Even allowing for anticipated greater activity from the large vessel defects a sensitivity difference of the order 25-30 db would lead to only a few signals of low amplitude being detected on a vessel test. These few would be obscured by scattered surface activity and scattering due to errors in location analysis. Under ideal conditions, the detection of yielding defects in low strength steel is certainly possible, a good example of this being the work at CEGB BNL [11] where the yielding process was located and monitored as it progressed along the length of a long partial thickness defect. However, for this test, the region surrounding the defect was very well prepared and normally defects have to be detected against a background of scattered surface activity and activity from innocuous weld defects.

Some of the factors which may lower sensitivity on vessel tests are:-

- 1) Attenuation
- 2) Dispersion
- 3) Differences in sensor sensitivity

The individual contributions from these effects can be assessed from the dummy signal measurements:-

Attenuation (the absorption of energy from the signal by the material) is dependent on the separation of source and sensor, and on the vessel varied from 2 to 6 db. The difference in sensitivity between test piece and vessel sensors was 4 db and the overall loss was 7 db when the lower sensitivity sensors were used as transmitters and receivers. After correction of the indicated maximum loss in sensitivity of 25 db (Table 2) for attenuation and sensor differences, a loss of 12 db remains. This is attributed to dispersion of the signal with

distance.

For loads up to 1.25 x general yield the 18 db combination of dispersion and attenuation on the 1in vessel is sufficient to reduce the number of detected signals almost to zero. (Fig 8).

Finally, unambiguous emission location on a vessel requires the signal to be detected by the least sensitive of an array of sensors. The measurements made (Table 2) show that sensor variations may be ± 4 db about the mean. Recent work at REML [12] has shown that these variations may be caused by a combination of coupling variations and interference of different modes of signal transmission.

The dummy signal measurements thus indicate that maximum losses due to attenuation (6 db), dispersion (12 db), sensor sensitivity difference (4 db) and coupling (4 db) were 26 db and would not be less than 18 db. Considering that an absolute calibration device was not available and the dummy pulse method does not simulate an actual emission pulse, these results are in good agreement with the value inferred from pulse height analysis.

At first sight, it would appear that an improvement in detection sensitivity of approximately 26 db (x20) would lead to the easy identification and monitoring of growth of defects in ductile pressure vessel steels. An increase in sensitivity could possibly be achieved by improving the amplifier (ie producing lower noise amplifiers) and increasing sensor sensitivity. However, it should be noted that should an improvement in sensitivity of this magnitude be possible, it may also lead to an increase in the amount of background activity detected. This could lead to no net improvement for flaw detection.

Conclusions

1. Prediction of the emission behaviour of a structure from small scale tests, requires tests to be made on the actual structural material.
2. Prediction of the emission activity of a structure from specimen tests requires some means of comparing detection system sensitivities between tests. A dummy pulse injection technique has shown differences in overall sensitivity between vessel and laboratory tests of approximately 26 db.
3. A considerable improvement in emission detection sensitivity is required to detect defects in parent plate materials in lower strength structures. Measurements indicate that an improvement of approximately 26 db is necessary.

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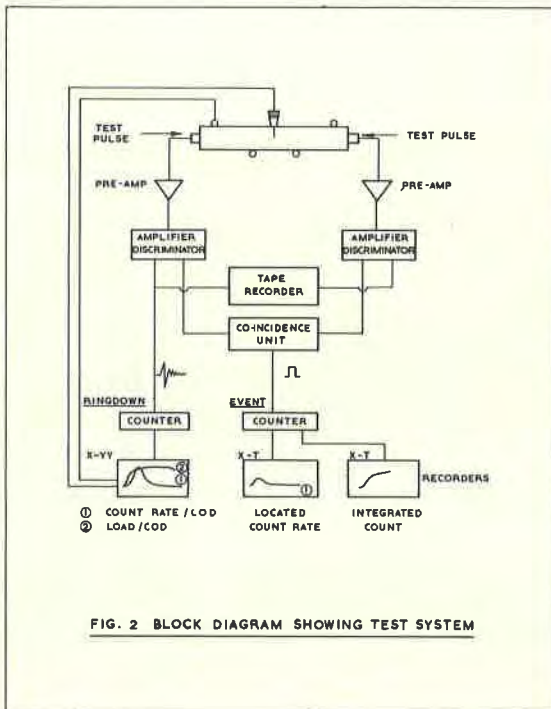
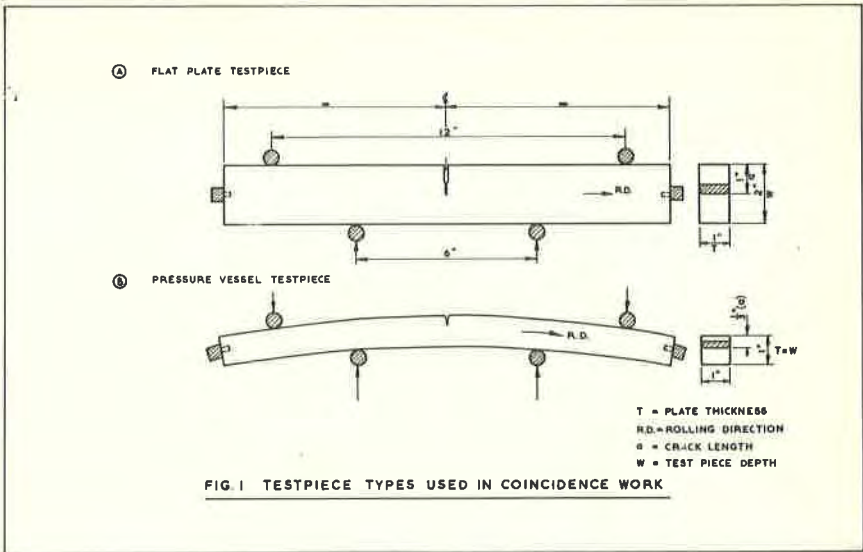
TABLE 1
EMISSION ACTIVITY OF BS 1501-151/28A MILD STEEL 4 POINT BEND SPECIMENS

Test piece Type	No of emissions from notch			
	LOAD			
	Yield	1.25 Yield	Maximum	
Flat Plate	RY1	2770	8150	14544
	RY2	*	*	24182
	RY6	3800	7970	10900
	RY8	5800	16100	22000
	RY9	3545	9000	13250
	RY10	2560	5600	11640
			Mean 9364	Mean 16086
Vessel Plate	AD1	1460	4800	14722
	AD2	1330	4800	14660
	AD4	1120	4500	10947
	AD10	910	4130	15910
	AD11	1060	4000	13936
			Mean 4846	Mean 14035

* Not estimated Non uniform strain rate

TABLE 2
MEASUREMENT OF SYSTEM SENSITIVITIES
COMPARISON BETWEEN LABORATORY TEST PIECES AND PRESSURE VESSELS

Test	Mean signal loss relative to test pieces db	Sensitivity variation 2 standard deviations db	Maximum signal loss on vessel test (including attenuation) db
1 inch vessel	19	± 4	25
Comparison of test piece and vessel sensors	4	± 3	-
Comparison of vessel sensors with one another	7	± 4	-



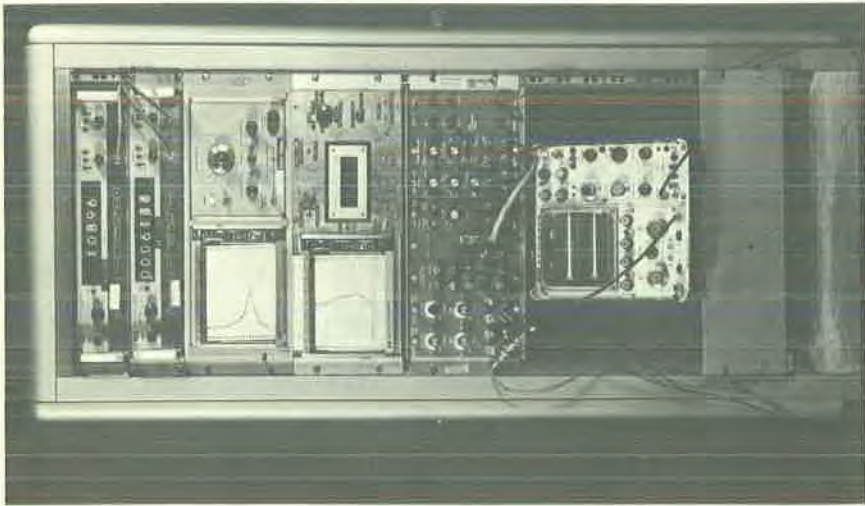


FIG. 3 LABORATORY EMISSION EQUIPMENT

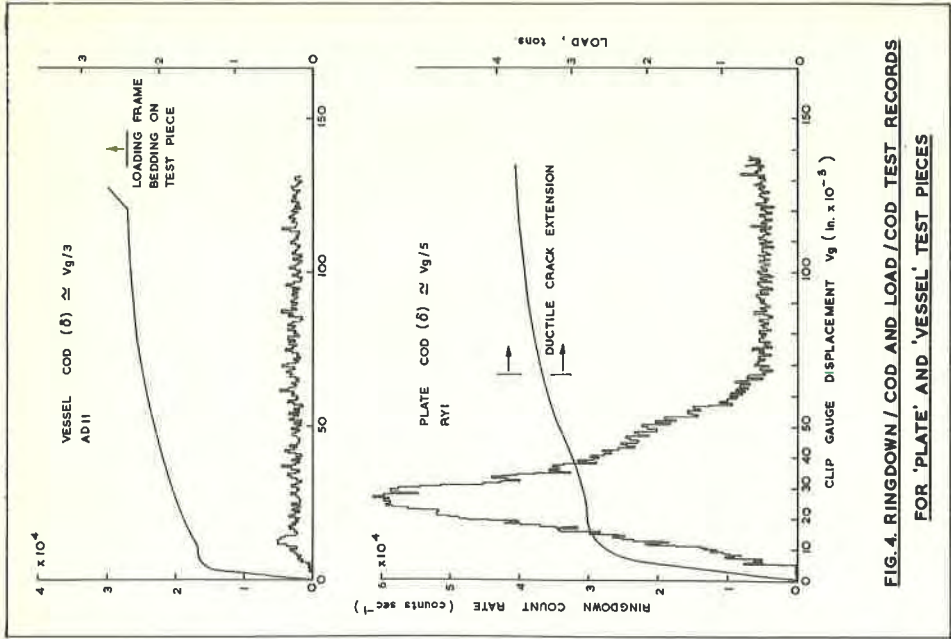


FIG. 4. RINGDOWN / COD AND LOAD / COD TEST RECORDS FOR 'PLATE' AND 'VESSEL' TEST PIECES

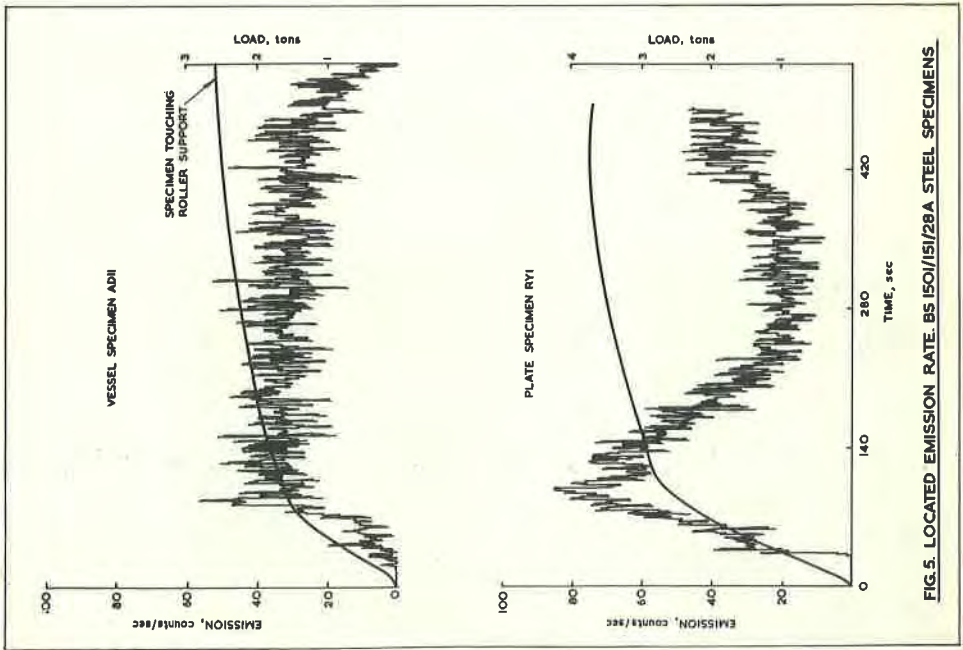


FIG. 5. LOCATED EMISSION RATE. BS 1501/151/28A STEEL SPECIMENS



TESTPIECE CUT FROM 'AS-ROLLED' PLATE (RYI)



TESTPIECE CUT FROM PRESSURE VESSEL (ADII)

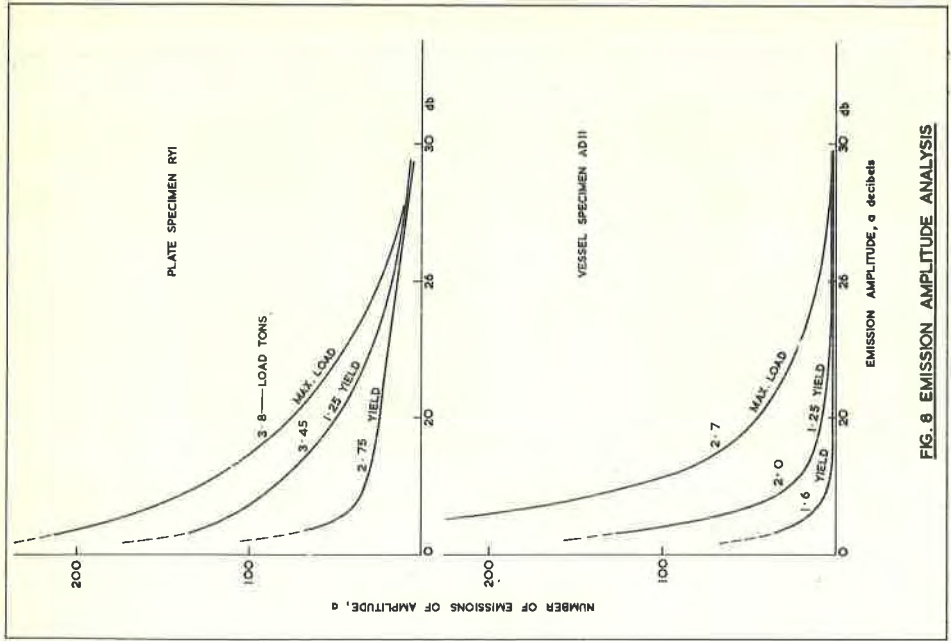


FIG. 8 EMISSION AMPLITUDE ANALYSIS



TESTPIECE CUT FROM 'AS-ROLLED' PLATE (RYI)



TESTPIECE CUT FROM PRESSURE VESSEL (AD II)

FIG. 7 POST YIELD EMISSION BURSTS