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ABSTRACT

As part of the first stage of an Australian Welding Research Association co-operative research project, acoustic emission monitoring has been applied to a steam receiver vessel withdrawn from service owing to severe weld cracking. This technique is used to check acceptance standards for defects in nozzle welds and to apply modern methods of assessing the integrity of pressurised plant. Acoustic emission monitoring has been used, together with strain gauge measurements and ultrasonic scanning, to detect the occurrence of any significant defect growth during cyclic pressurisation of the vessel. During this first stage, no significant defect growth has been produced by 1000 cycles of pressure up to 24.1 MPa (3500 psi), subsequent pressurisation up to 35.8 MPa (5200 psi), or 97 per cent of the expected yield stress of the vessel shell. The small amount of acoustic emission detected was consistent with this result.

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ACOUSTIC EMISSION TESTING; DEFECTS; NOZZLES; PRESSURE VESSELS; STEAM GENERATORS; WELDED JOINTS

CONTENTS

1. INTRODUCTION

This project was initiated when a power station steam receiver vessel, withdrawn from service by the State Electricity Commission of Victoria because of cracked nozzle welds, was offered to the Australian Welding Research Association (AWRA) for testing purposes. The manageable physical size of the vessel, and the presence in it of defects produced during manufacture and service, made it suitable for practical tests of the behaviour of weld defects and the application of techniques to assess structural integrity.

A full assessment of structural integrity requires a knowledge of the properties of the material, the defects that are present and the stresses operating on them. Modern techniques of fracture mechanics, nondestructive inspection and finite element stress analysis have been developed for this purpose, but application to real components presents several problems, particularly in the codification of their use.

Acoustic emission monitoring should play an important role in structural integrity assessments because of its potential to locate the growth of defects under the influence of applied loads. Although considerable progress has been made in other countries towards achieving this objective, only limited experimental testing has so far been performed in Australia. The equipment currently available here precludes any role for the technique other than to complement established nondestructive testing methods. In the present project, acoustic emission has been used to monitor the behaviour of defects that were initially located by ultrasonic and surface inspections.

2. OBJECTIVES

This report details only the acoustic emission aspects of a cooperative project; however, it is appropriate to outline briefly the objectives of the other participants. For the tests either completed or in progress, these were:

- To locate defects in the welds of five nozzles on the steam receiver, using ultrasonic and magnetic particle inspection (Electricity Commission of New South Wales (ECNSW)).
- To apply two- and three-dimensional finite stress analyses to the nozzle configuration to determine the stresses operating on the defects and, on the basis of assumed material properties, to predict the behaviour of the defects under pressure loading

(ECNSW, AWRA, AAEC).

- To subject the vessel to a program of pressure tests in an attempt to extend one or more of the weld defects to a critical size for catastrophic failure to occur (Snowy Mountains Engineering Corporation (SMEC)).
- To monitor acoustic emission from the vessel during testing to provide an indication of any impending failure situation and, by post-test analysis of recorded signals, to identify those defects which were active (AAEC).
- To collect strain gauge data from the pressurised vessel to check the prediction of the finite element analysis (SMEC).
- To perform further ultrasonic and visual inspections of defects at times during the tests suggested as appropriate by acoustic emission data and vessel behaviour (ECNSW).
- In the event of vessel failure, to measure the properties of the steel, to correlate actual and predicted fracture behaviour, and to draw appropriate conclusions about the severity of the defects.

A preliminary discussion of the background to the project and the nondestructive testing to be applied has been published by Vetters *et al.* [1974]. Reports on the completion of the other objectives are being prepared by the relevant organisations concurrently with this report of the acoustic emission results.

3. VESSEL AND TESTING SPECIFICATIONS

The plan view of the vessel, including typical detail of the nozzles, is shown in Figure 1. Full information on the parent metal (1.0% Cr - 0.5% Mo) and weld metals (0.3% Cr - 0.5% Mo) and (0.5% Mo) in the vessel is not known, but chemical and hardness tests carried out with a portable spectrometer and a hardness tester, indicated that the steels were consistent with the specifications originally nominated for the vessel. After the vessel has been pressurised to failure, material will be tested for composition, conventional mechanical properties and fracture toughness properties.

The receiver was forged in the UK and fitted with nozzles fabricated in Australia to a standard design. It had been in service, nominally at 9.6 MPa (1400 psi) and 500°C, for approximately 10 years when withdrawn from service.

The vessel was prepared for testing by blanking off the nozzles. Ultrasonic inspections were only practical from the interior of the nozzles, so access was provided *via* a removable manhole cover at one end of the vessel. For ambient temperature operation, the effective design pressure of the vessel was 26.2 MPa (3800 psi). The test sequence chosen for the phase of the work reported here was:

(i) Pressurise in steps up to 27.6 MPa (4000 psi) while monitoring acoustic emission and strain gauges.

(ii) Cyclically pressurise between 6.0 MPa (1000 psi) and 24.1 MPa (3500 psi) for 1000 cycles, monitoring the first few and last few as before.

(iii) Carry out ultrasonic inspection.

(iv) Pressurise in steps to 35.8 MPa (5200 psi), again with acoustic emission monitoring. Because the final pressure was expected to stress the vessel shell nearly to yield, it was necessary to exercise stringent safety precautions and house the vessel in an underground concrete bunker.

4. BACKGROUND TO ACOUSTIC EMISSION

Deformation and fracture processes in materials are accompanied by energy release which generates propagating elastic waves. This phenomenon is known as stress wave or acoustic emission. Detection and interpretation of these stress waves provides the basis of a potentially powerful nondestructive testing system for locating defects in a structure and for assessing their significance to structural integrity. The technique involves the detection, with band-limited piezoelectric sensors, of broadband emissions whose spectra are modified by complex reflections in the structure being tested and by the vibration characteristics of the sensors.

Observed acoustic emission signals are usually in the form of complex decaying fast transients, or bursts, since they result from the impulse response of a vibrating system (the sensor and a structure or testpiece), which behaves as a damped oscillator. A typical source of burst emissions would be a developing crack or a plastic yield front. In addition, there are also signals of much smaller amplitude, typically from dislocation activity, which are believed to consist of trains of burst signals occurring closely enough together for their waveforms to overlap [Pollock 1971, Fisher & Lally 1967]. In the present study, the great majority of signals detected and processed were of the burst type. Their occurrence in time is random but, because they are discrete events, they are the input signals for defect location systems.

This is believed to be the first research project of its kind in Australia to use acoustic emission as a nondestructive testing technique. An acoustic emission monitoring system, such as the one described here, supplements information from traditional inspection techniques in several important ways. A fixed array of sensors can, by means of triangulation techniques, identify and monitor sites where deformation is occurring or cracks are extending, without the need to physically scan the structure. Remote and continuous monitoring of critical components for impending failure becomes feasible. Furthermore, other techniques do not readily discriminate innocuous flaws from potentially deleterious ones. By concentrating attention on the latter, acoustic emission monitoring can guide the more selective and efficient application of other techniques to delineate the precise location and nature of the critical defects. This is the main use for acoustic monitoring in the present tests, although the equipment available locally does not allow the technique as a replacement for complete radiographic or ultrasonic inspection prior to pressurisation. In the present case, the location and dimensions of defects in welds was established by thorough ultrasonic probing before and after pressurisation, and acoustic emission data provided confirmatory evidence.

5. INSTRUMENTATION

In typical acoustic emission systems, the detected emissions are amplified (usually 10^3 - 10^5 times), selectively filtered to suppress extraneous low frequency background noise, then processed directly or recorded on magnetic tape for subsequent analysis. The system used for the present project (Figure 2) required that all analysis be done post-test from data recorded on a high-fidelity seven-channel tape recorder (Ampex FR1300).

The seven sensors were piezoelectric devices (Dunegan S-140A) rigidly bonded to the vessel at locations selected to give optimum coverage of the whole vessel (Figure 3). Their fundamental resonance frequency of approximately 150 kHz was conveniently centred in the 75-300 kHz passband of the electronic system employed. Visual (cathode ray oscilloscope) and audible (envelopes of bursts fed to a loudspeaker after amplification) monitoring was used during the test as possible indicators of the onset of vessel failure.

5.1 Measurement of Acoustic Emission Energy

Since a large amplitude burst is indicative of a larger release of energy than a small amplitude burst, it is usual to weight each burst accordingly. This is done either by counting the number of oscillations of the burst waveforms per second above a predetermined threshold level, usually the electronic noise level, to give a count rate (dN/dt), or by integrating all the count rates over an arbitrary stressing regime, here a step in pressure, to give a cumulative count (Σn). Modular units produced commercially for measuring these parameters were not available for this project; instead, a standard nucleonic counter (128-channel Nuclear Data ND-110) operating in the multiscale mode was used.

5.2 Location of Acoustic Emission Sources

The detection of individual emission bursts is the basis for locating emission sources. The essential requirement is to identify a burst arriving at one sensor, and to determine the time delay for its arrival at at least two other sensors so that the emission source can be located by triangulation.

Organisations in other countries have developed on-line computer-based systems for the correlation of data from many sensors as testing proceeds. Such a facility was not available for this project, and only a restricted post-test analysis of data from seven sensors was feasible.

Time delays between the arrival of bursts at different sensors were obtained using several methods, including photography of burst signals on an oscilloscope screen using ultra-fast film, cross-correlation using a Hewlett-Packard 3721A correlator and replaying recorded signals into an EA1 1910 pen-recorder. The first two methods had the disadvantages that resolution was poor, and only one pair of recorded channels could be correlated at a time and were, therefore, very slow. The third method was also slow because it was first necessary to re-record the signals using an auxiliary tape recorder to reduce the frequencies to an acceptable bandwidth for the pen-recorder; but it had the advantage that a permanent pictorial record of the signals was obtained which gave, in one run, all the time delays possible. For the seven sensors used here, there were 21 associated time delays. The triangulation procedure involves constructing two intersecting hyperbolae each of which represents the locus of points having a constant time difference from two sensor locations. A detailed description of this construction is given by Cross *et al.* [1972].

The resolution on the pen-recorder paper for burst signals time-expanded by a factor of 1024 was 10 μs mm^{-1}. When multiplied by the measured velocity of propagation of bursts in the vessel wall of $2.95 \times 10^5 cm\ s^{-1}$ (or 2.95 mm μs^{-1}), this represented a potential accuracy of about 3 cm in distance on the vessel although, in practice, the accuracy was no better than ± 6 cm.

A pre-test calibration of the vessel and monitoring system provided some alleviation of the emission source location problems. Signals were injected into the vessel and nozzles over a pre-selected grid of 686 sites, so that the time delays for arrival at the seven sensors could be measured. The sites of major defects were known from ultrasonic tests and could be related to various grid sites for which time delay patterns had been determined. Particular significance was given to the observation of these time delays during analysis of the tape-recorded acoustic emission bursts generated during pressurisation of the vessel. This is a positive method of source location and has the advantage that it lends itself to off-line computer analysis [Bentley *et al.* 1973].

6. RESULTS

Results and observations reported here apply to pressure increases up to 35.8 MPa (5200 psi) or 97 per cent of the expected yield stress of the vessel shell. The pressure-time history of the vessel during the period of the tests is shown in Figure 4, together with recording periods (hatched areas). It was impractical to monitor acoustic emission during the cyclic loading sequence.

Because of the diverse acoustic responses of metals in different metallurgical conditions, it was necessary to qualify the results of pressure tests on the vessel by carrying out a characterisation study on testpieces having similar specifications to those of the vessel steel. The precise mechanical properties of the vessel will not be known until after catastrophic failure.

6.1 Characterisation Study

The aim of this laboratory study was to bracket the potential range of properties in the vessel shell and nozzles, excluding coarse grain regions which might exist in welds, in order to provide a better assessment of the vessel's acoustic emission response. It is expected that if the vessel material is in a soft condition, then defect growth would generate little emission, but if hardened zones exist, then defect growth would produce much more emission. Two testpieces were used in an untreated state to simulate properties near the bottom end of the specification range of the vessel material; two other testpieces were subjected to a hardening procedure which involved heating to 975°C for 30 minutes, oil quenching, then tempering at 400°C for a further 30 minutes. This procedure was designed to simulate welding and subsequent stress relief, and produced material with more than double the tensile strength of the untreated steel.

The four testpieces used for this study are designated as follows:

Testpiece A	un-notched, untreated
Testpiece B	notched, untreated
Testpiece C	un-notched, hardened and tempered
Testpiece D	notched, hardened and tempered

The design of testpieces A and C was according to ASTM Standard E8-69, although some of the dimensions were modified [Schuyler & Feirtag 1972] to accommodate the sensor (Figure 5). The design of testpieces B and D, each having notch widths of 0.75 mm (Figure 6), was not according to any recognised standard.

Before testing, the load-bearing areas around the testpiece grips were loaded by compression to beyond the expected maximum test loads [Dunegan & Tatro 1971] so that, as a consequence of the Kaiser [1958] irreversibility effect, any emission detected during tensile testing would be generated only in the gauge lengths of testpieces A and C and at the notch roots of testpieces B and D. All four testpieces were loaded in an Instron machine operating at a constant crosshead speed of 0.51 cm min^{-1}.

Testpiece A was very ductile and so 'quiet' that emission was detected only during elastic extension; no emission was detected after yield. By contrast testpiece C, which because of heat treatment had more than twice the tensile strength of testpiece A, was a copious emitter, with most of the emission occurring during elastic deformation (Figure 7). The cumulative count for testpiece C was approximately 16 times greater than for that of testpiece A.

The arbitrary notch root separation 'd' of testpieces B and D (Figure 6) was progressively reduced during testing, until a load within the normal capacity of the Instron machine (4535 kg) could initiate cracking. The load-time curves and associated count rates and cumulative counts for these two testpieces are shown in Figures 6 and 8. Again, the heat-treated testpiece had an associated cumulative count an order of magnitude greater than that for the untreated testpiece. The essential baseline information obtainable from these tests is:

(i) count rates for ductile or soft metal are in the range 0 to 300, but mostly they are less than 100; and

(ii) count rates for brittle or hardened metal are in the range 0 to 900, but mostly they are greater than 100.

Although it is difficult to correlate these figures with count rates obtained from tests on the steam receiver vessel, because of differences in mechanical properties and also in strain rate, they do provide interpretative guidelines. Cracking in or close to a weld, for instance, would normally produce much larger count rates than from defect extension in the vessel shell but, in view of the history of the vessel as a steam receiver operating at 500°C for 10 years, it is expected that the most critical defects would extend in brittle jumps and generate sudden increases in emission count rates. Prediction of *unstable* crack growth leading to catastrophic failure was not considered possible (and has not been achieved elsewhere) because emission from any event can only be detected after the event has occurred.

6.2 Acoustic Emission Energy Measurements

During analysis of recorded signals, the count rates were usually averaged over 1-second intervals, but the averaging time was 5 seconds for the examples shown in Figure 9 and 10. The count rates would be produced by any source in the vessel, but were expected to be dominated by contributions from any extension of defects. However, during all pressure increments the average count rate remained at the same order of magnitude, usually less than ten counts per second. The low count rates implied that no significant defect growth occurred during the tests. This is consistent with the laboratory characterisation study.

In general, the Kaiser effect was apparent, because emission was observed on a given cycle only after the pressure had been increased above the previous maximum pressure. This was observed to be the case only for pressure cycles close together in time. In pressure step 14 (Figure 9), count rates begin only at 24.1 MPa (3500 psi), which was the highest pressure attained in step 13. However, for long delays of the order of a week or more, there appeared to be some recovery of the vessel (Figure 10), a phenomenon which has also been observed during similar tests at UKAEA Risley [Neilsen *et al.* 1973]. For example, on pressure step 1014, emission began at 10.3 MPa (1500 psi), well below the previous maximum pressure of 24.1 MPa (3500 psi), after a delay of a week. It may be significant, however, that during this period the manhole at one end of the vessel was removed and replaced again; thus some of this emission may be accounted for by its resettling.

6.3 Defect Location

A complication with the steam receiver is that it contains five nozzles which are quite large compared with the spacing between them and the overall vessel size. All the nozzles were cracked at the outset of the tests, three of them extensively. Thus there were many closely-spaced and potentially active sites for acoustic emission spread widely over the vessel. The low count rates and small amplitudes of the burst signals made time delay measurements difficult because the signal levels for most bursts were barely above the electronic background level. Thus discriminator settings for the monitoring system, if set too high, prevented the triggering of any recording devices.

A further problem with the time delay measurements was that the rise times of the observed bursts were often 'long' (compared with the time delays between different sensors); they were, in some cases, of the order of 100 and 200 μs making it difficult to establish the precise time when a given sensor was triggered. Figure 11 shows a typical pen-recorder chart from which time delay measurements were made. It is clear that the sensors were receiving signals many vibration cycles before peak signal levels were established; however, the accuracy of measurements for the larger amplitude bursts was still very good, being of the order of ± 20 μs in time or ± 6 cm in distance on the vessel. This was considered to be of sufficient accuracy for the acoustic emission technique to be an effective non-destructive testing tool in these tests, because the location of the defects being monitored had been established ultrasonically and could be subsequently checked.

During the first three pressure steps, about 200 discrete bursts were observed, mostly of very small amplitude. Time delay measurements for the largest of these showed that they were generated from the new weld joints on the end nozzle (N6 in Figure 1) to which sensor S7 was attached. Contrary to these initial findings, more emission sources had occurred at the opposite end of the vessel for the rest of the tests. In total throughout the tests, about four times as many bursts derived from the general area of nozzles N1 and N2 as from the general area of N3, N4 and N5, especially at pressures up to 27.6 MPa (4000 psi). This was consistent with the larger and more extensive defects in the welds of nozzles N1 and N2 compared to the others. However, the sources were randomly distributed on and around the nozzles. For pressure tests above 27.6 MPa, two extra sensors S8 and S9 were bonded to N1 to obtain better 'fixes' on bursts emanating from this nozzle, the 'worst', S6 and S7,being disconnected. Again there was random distribution of sources around the vessel, both on the shell and on the various nozzles, with only a small percentage that could be traced to nozzle N1. Thus there was no definite evidence of significant growth of any of the defects.

7. CONCLUSIONS AND RECOMMENDATIONS

Acoustic emission was monitored and recorded on magnetic tape during pressurisation of a large steam receiver vessel. In a post-test analysis, count rates were measured and emission sources were located for various pressure steps up to 35.8 MPa (5200 psi) which was 97 per cent of the expected yield stress of the vessel shell. There was no indication of any significant defect extension because the count rates remained low and of the same order of magnitude throughout the tests, and emission sources were randomly distributed. The source location capability was accurate to ± 6 cm, but the method used was very time consuming, since it required time delay measurements from pen-recorder charts. In future tests, it is recommended that a transportable commercial acoustic emission source location system is used so that real-time signal processing becomes possible. Such a system, employing an arrival time difference calculator, an analogue computer programmed to solve the intersection of two hyperbolae, and a storage oscilloscope for displaying the emission sources, may be obtained comparatively cheaply compared with the digital computer-based systems.

8. ACKNOWLEDGEMENTS

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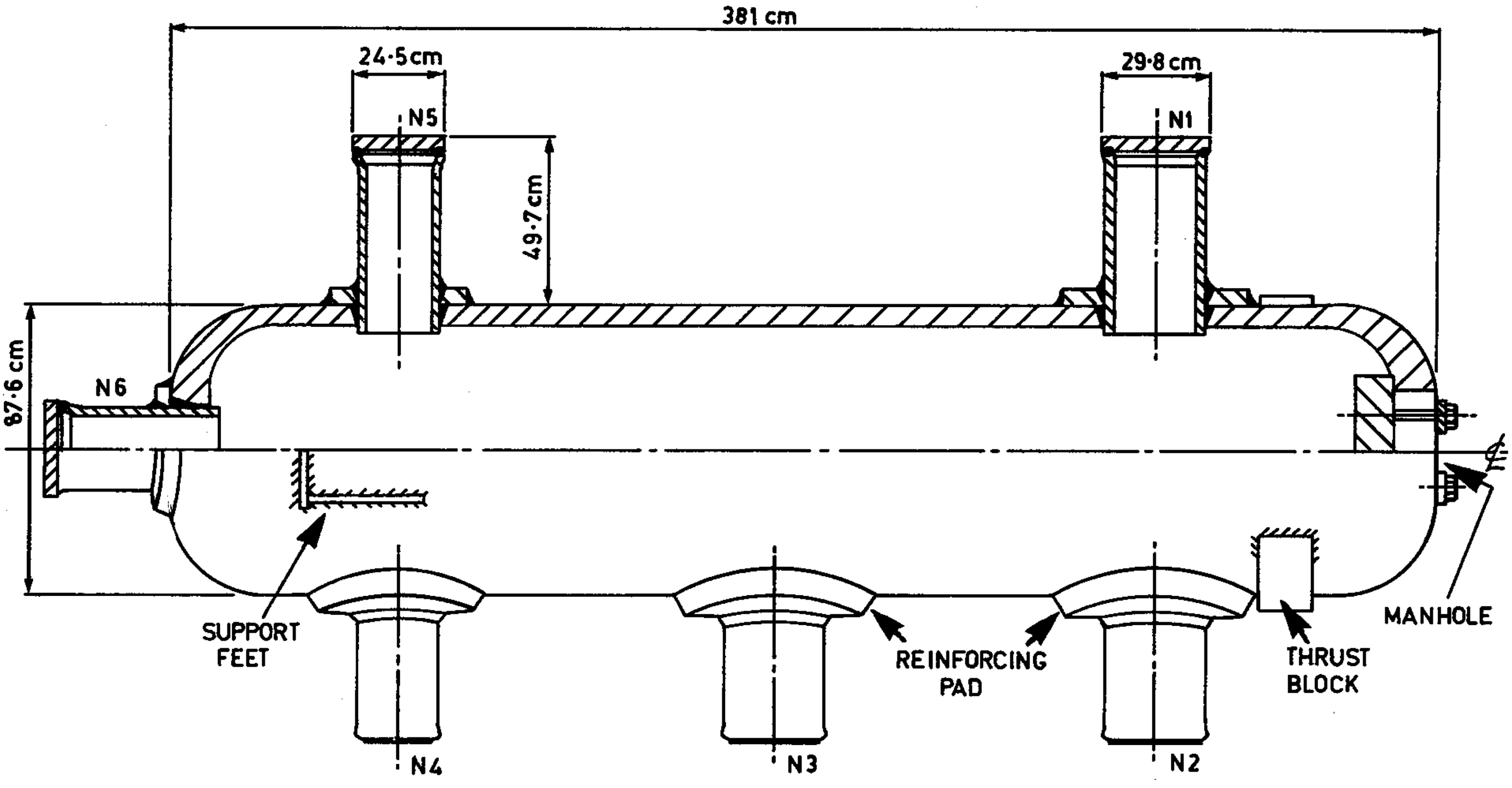


FIGURE 1. HALF-SECTION, PLAN OF STEAM RECEIVER VESSEL

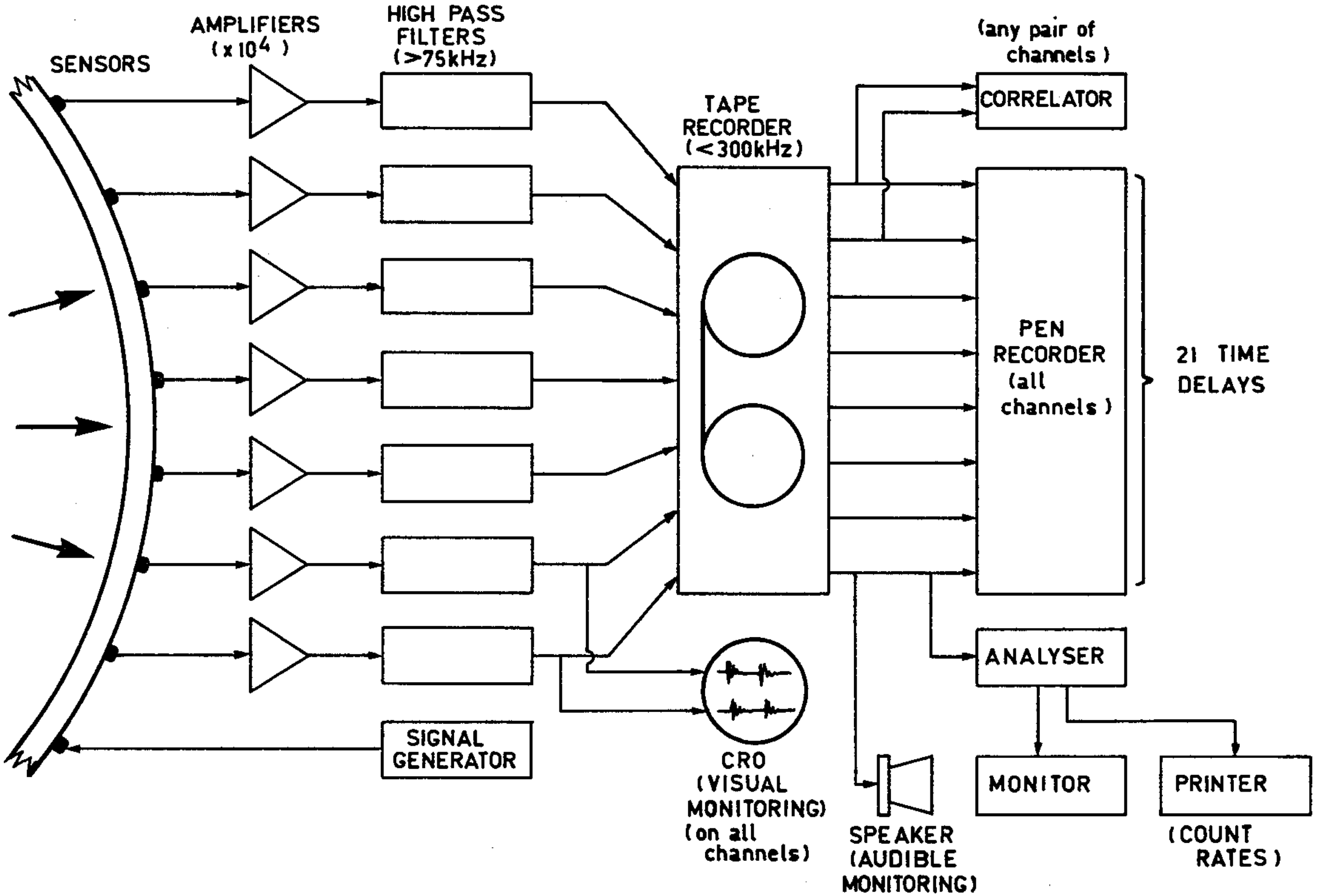


FIGURE 2. ACOUSTIC EMISSION INSTRUMENTATION

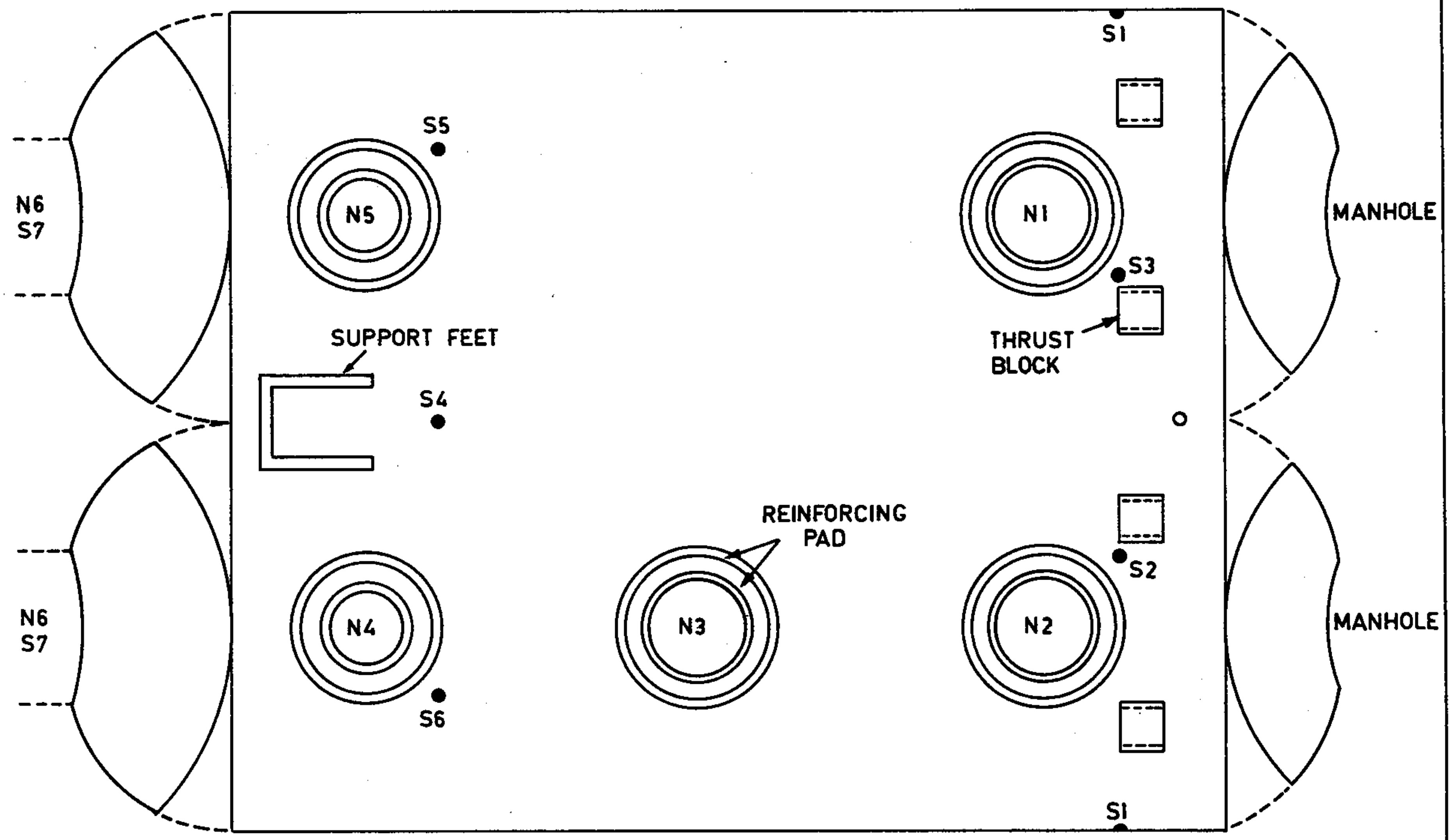


FIGURE 3. 'EXPLODED' PLAN OF VESSEL

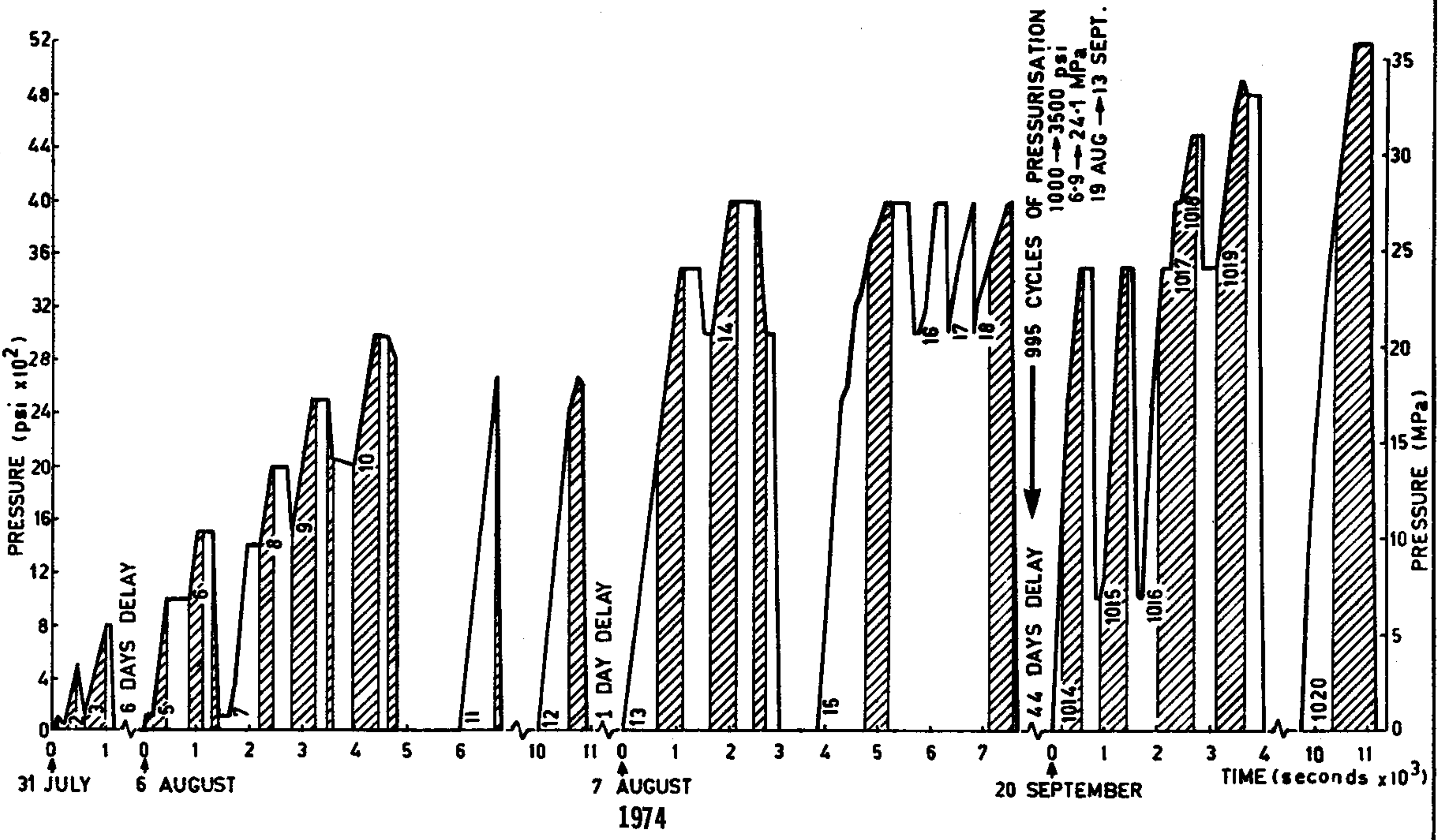


FIGURE 4. PRESSURE-TIME HISTORY OF VESSEL

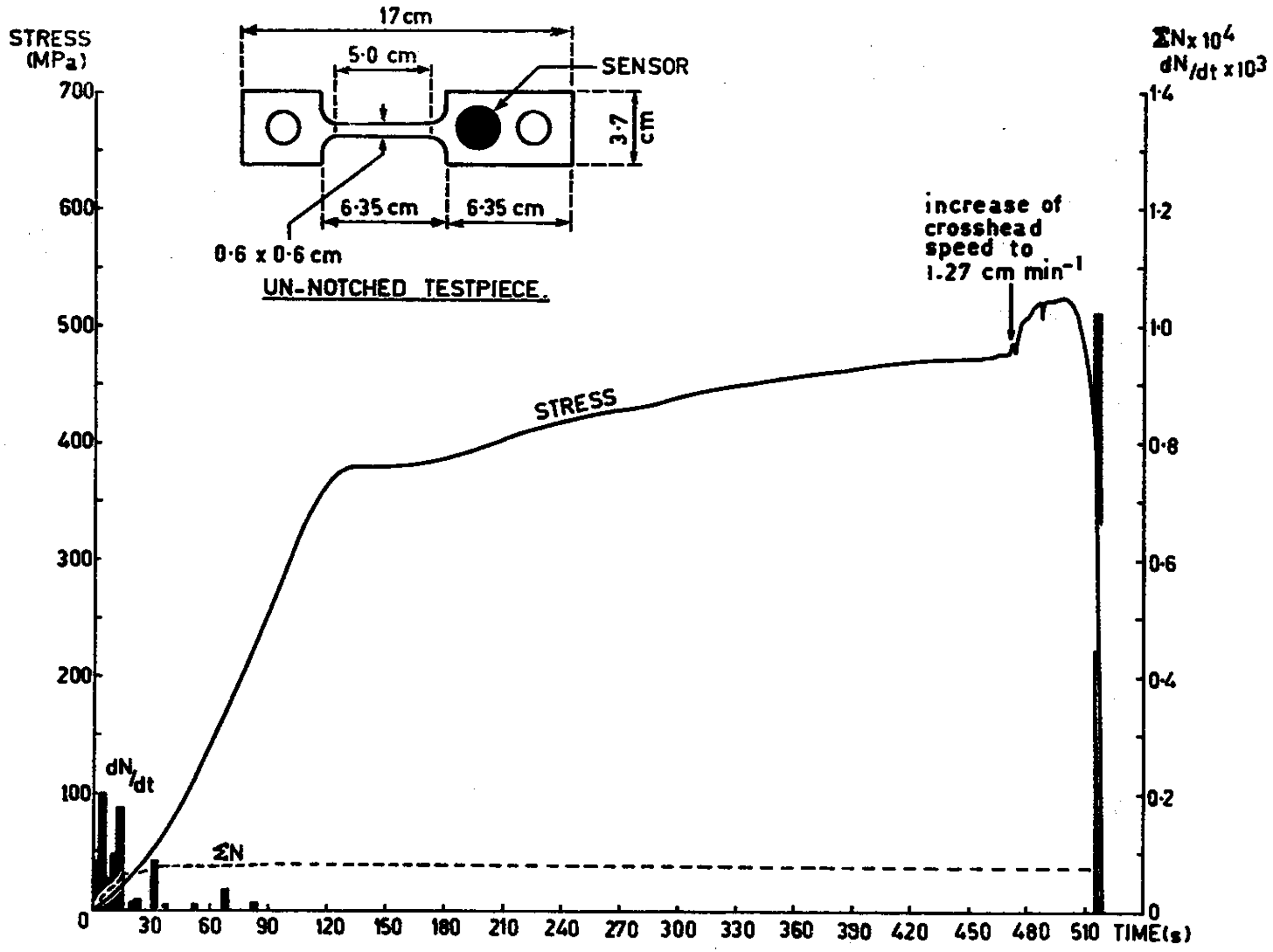


FIGURE 5. TESTPIECE A: UN-NOTCHED AND UNTREATED

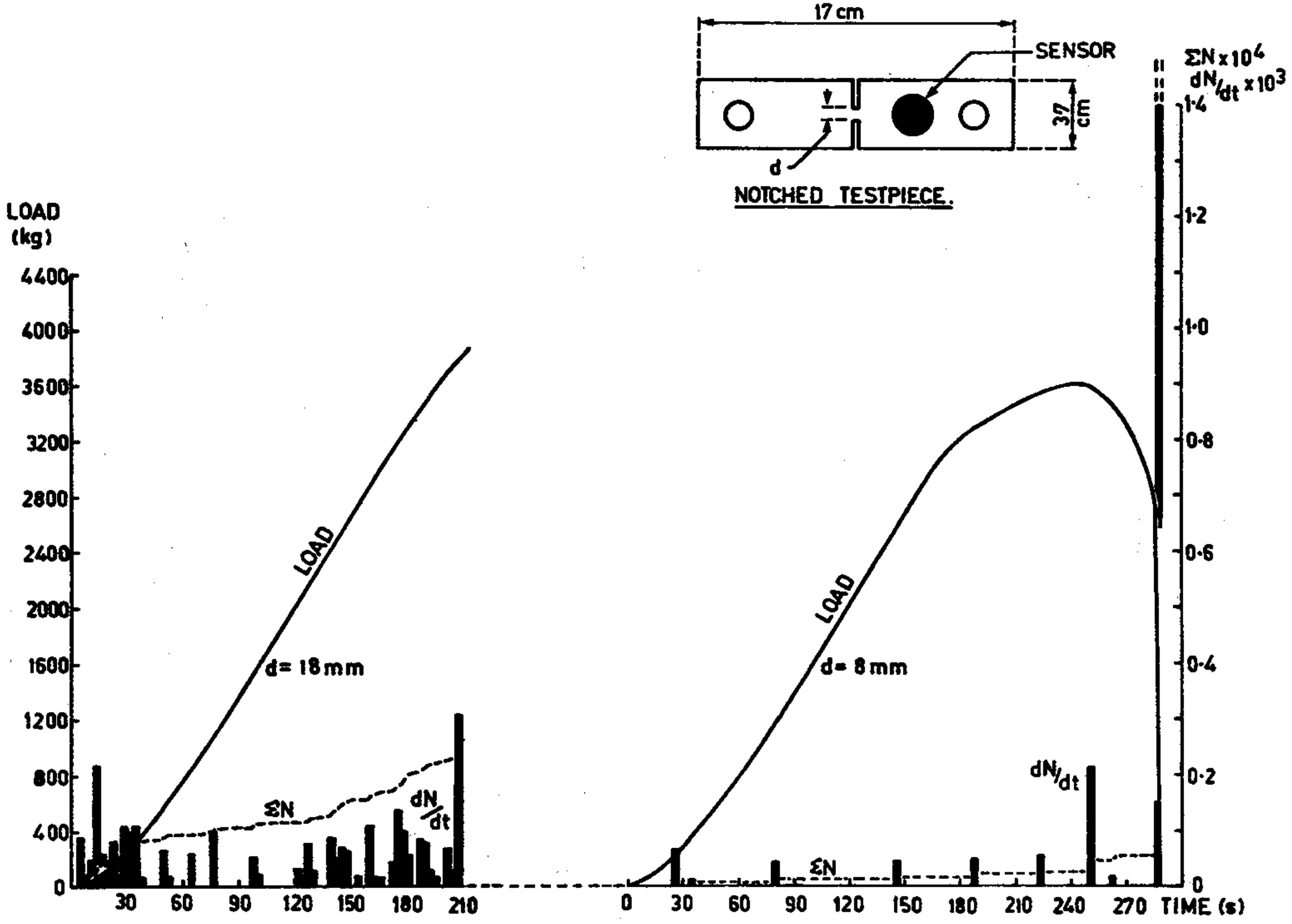


FIGURE 6. TESTPIECE B: NOTCHED AND UNTREATED

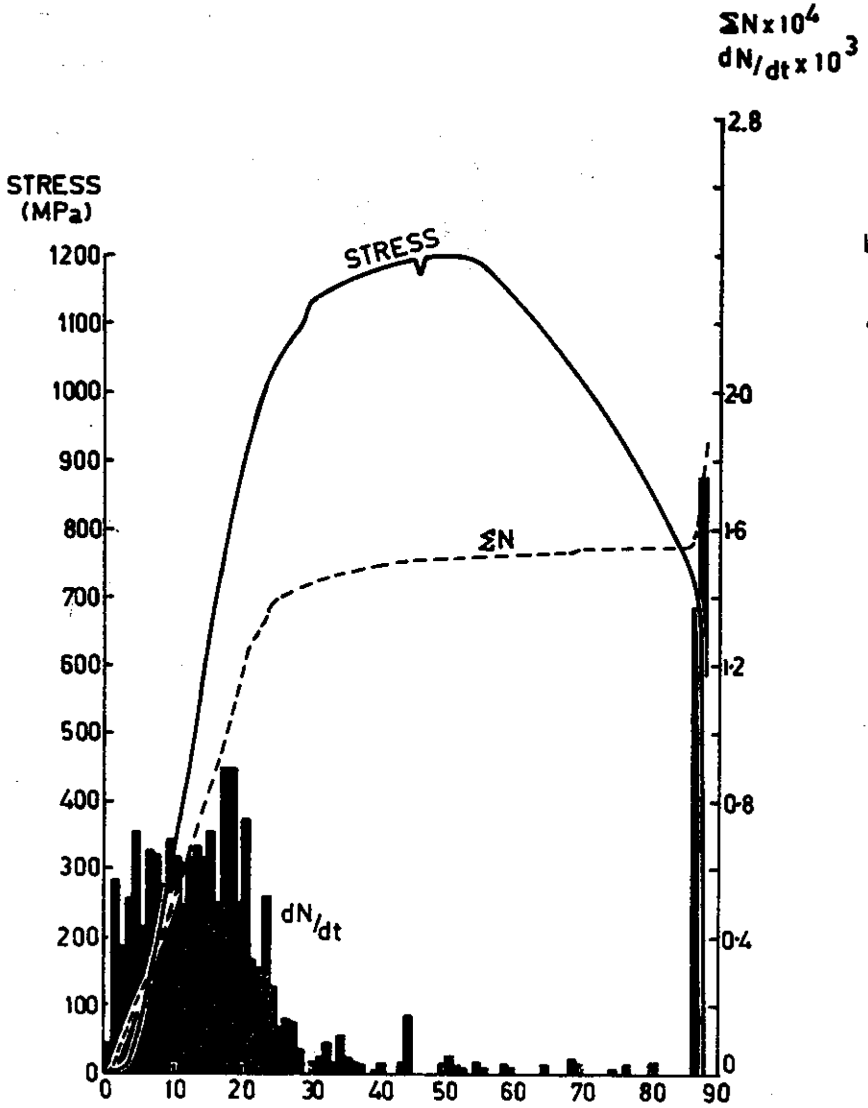


FIGURE 7. TESTPIECE C: UN-NOTCHED, HARDENED AND TEMPERED

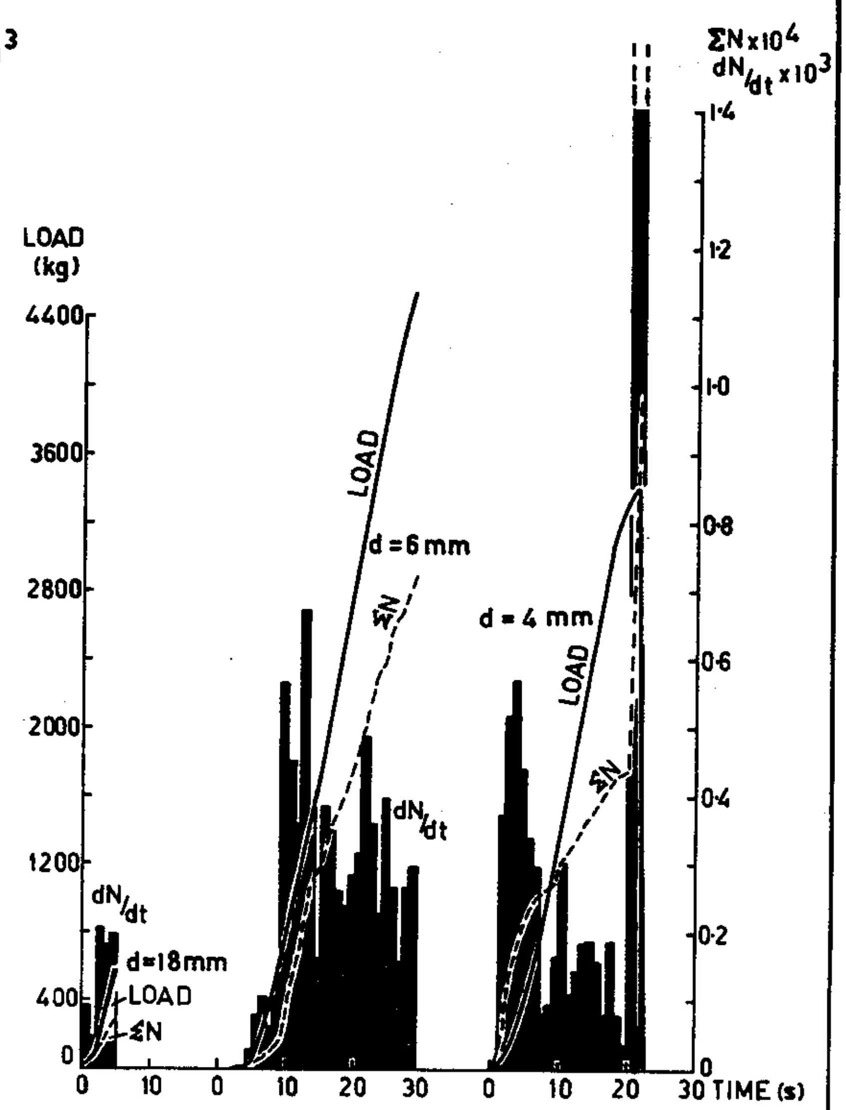


FIGURE 8. TESTPIECE D: NOTCHED, HARDENED AND TEMPERED

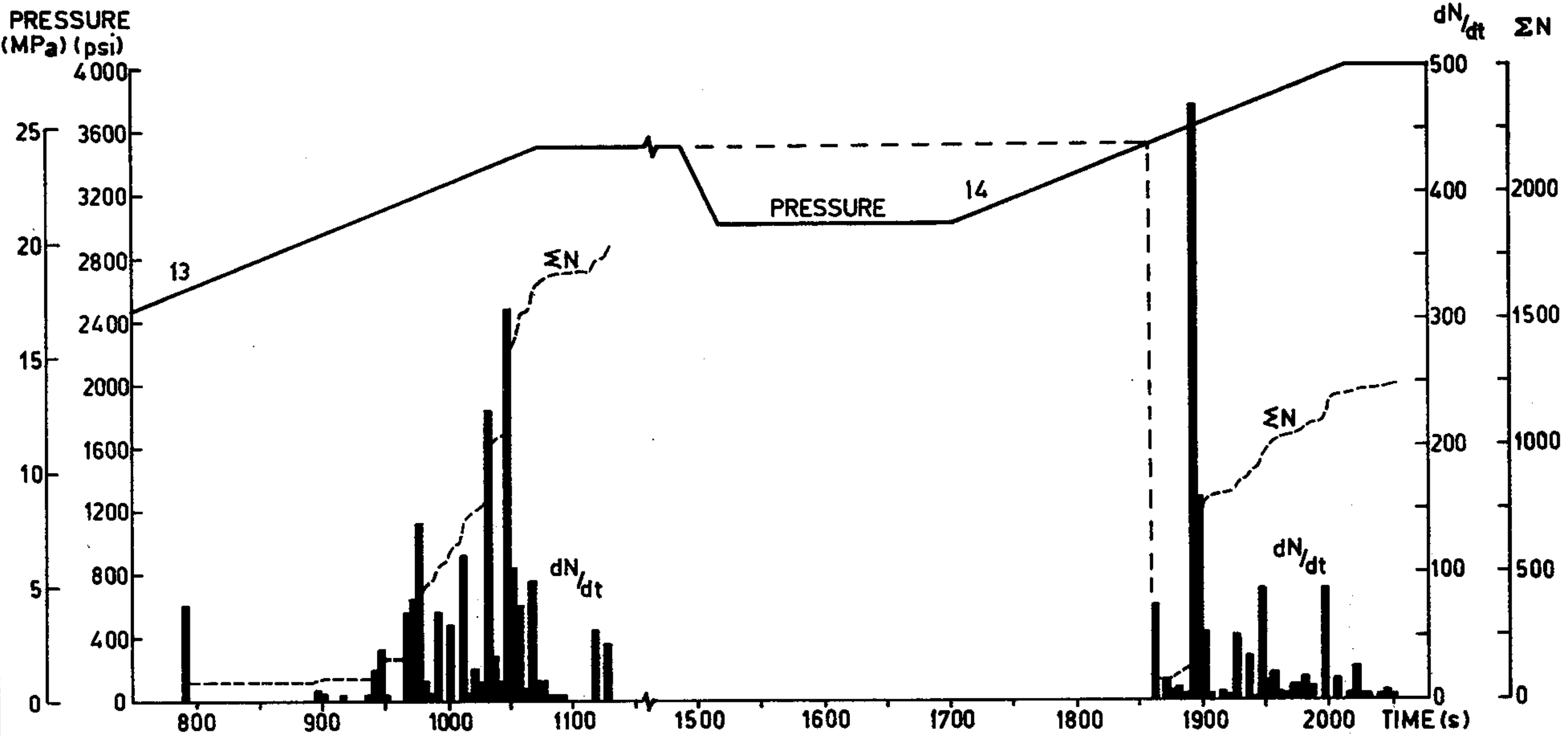


FIGURE 9. PRESSURE STEPS 13 AND 14 SHOWING COUNT RATES AND CUMULATIVE COUNTS

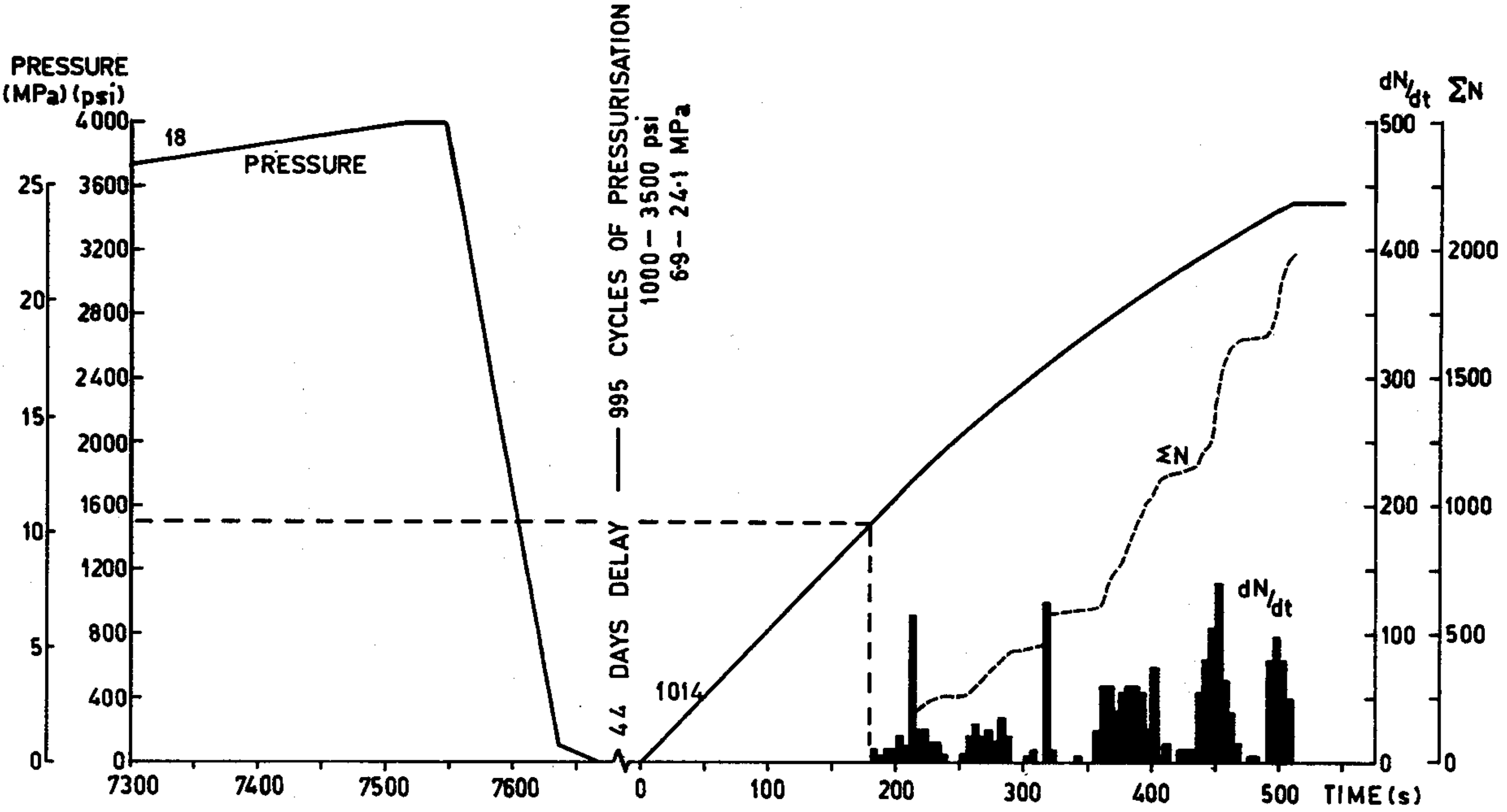
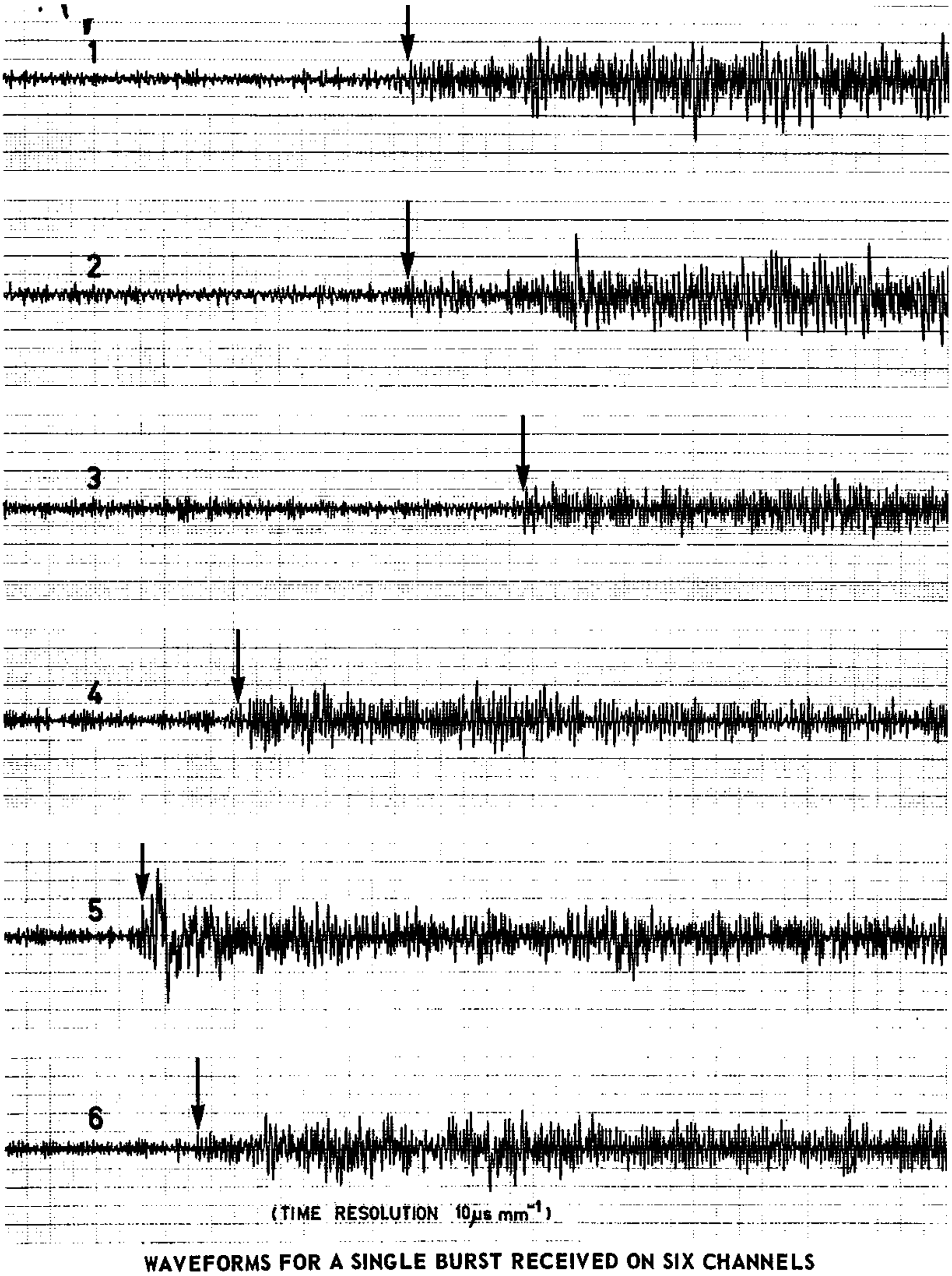


FIGURE 10. PRESSURE STEPS 18 AND 1014 SHOWING COUNT RATES AND CUMULATIVE COUNTS



WAVEFORMS FOR A SINGLE BURST RECEIVED ON SIX CHANNELS

FIGURE 11. PEN-RECORDER CHART SHOWING TIME DELAYS