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AN ACOUSTIC METHOD FOR DETECTING ICE PLUG FORMATION IN CRYOGENIC PIPE FREEZING.

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Introduction:

When a leak occurs in a pipeline, or a valve becomes seized and cannot be fully closed, a repair is usually effected by first draining the fluid from the line. This process can be costly both in terms of the time needed to drain the fluid and in the disruption to major parts of the plant, which may include total shut down. A much better way of dealing with such repairs or maintenance is to locally isolate the repair site or component needing repair. This is the basis of the technique of Cryogenic Pipe Freezing. With this technique the fluid in the pipe is frozen into a solid plug which adheres to the inner pipe wall and forms an effective seal between the fluid on either side. This process is shown schematically in figure 1.

By freezing plugs on either side of the site a section of pipe can be isolated from the rest of the line. This is achieved by attaching a container or jacket around the pipe which is then filled with a cryogenic liquid, such as liquid nitrogen or a solid CO_2/methanol mixture. Frozen plugs can also be used to allow pressure tests on a line up to a given position, or over a small section of line between two plugs. Frozen plugs can have considerable strength and have held pressures in excess of 240 bar.

The plug forms in two stages; first it grows radially inwards from the pipe wall with the greatest growth rate usually occurring in the axial central region; eventually the plug will close off at the narrowest point and then growth will be in an axial direction, initially at a high rate. Finally the plug will reach a stable shape when the heat transfer to the plug from the adjacent fluid is balanced by the heat removed from the plug by the coolant at the outer wall of the pipe.

Since the technique was first developed it has been used on a wide range of fluids and on pipes up to 1m diameter. In many applications the fluid to be frozen is water, either because it is the fluid normally in the line or because it has been introduced in order to effect the freeze.

The range of conditions over which the technique can be applied varies considerably: at one extreme there may be no flow in the pipe, at the other a substantial flowrate may be present. The temperature of the fluid may also be variable. Orientation can vary between horizontal and vertical. Combinations of these conditions can lead to considerable variation in the time needed, and indeed the potential success, for a given freeze. Clearly, in any given case, attempts will be made to reduce the conditions in the pipe to those most likely to promote success, eg minimising the flowrate and/or reducing the temperature. However, there are limits to these measures and some freezes will be unsuccessful. Under these more critical conditions it is desirable to be able to monitor the progress of plug development within the pipe in order that a potentially unsuccessful freeze may either be abandoned or external conditions changed to improve the chance of success. If the freeze is successful, and the plug closes off, it is desirable to know when this occurs as early as possible so that the repair can be carried out.

From outside the pipe there are few indications of how the plug is developing, although pipe freezing contractors usually have a "feel" for how well it is progressing, however this is far from quantitative. Under many conditions it is possible to test for plug closure by pressure testing across the plug zone or, if the freeze is near a valve or flange, the bolts may be slackened and the joint loosened to see if the flow has stopped or the pressure fallen.

Under some circumstances pressure tappings may not be available or the freeze may be being carried out away from any flanges. Under these conditions it would be desirable to have a non-invasive method of monitoring plug development and a positive indicator of plug closure.

It has been found that when an ice plug forms under the severe thermal conditions imposed by the application of a cryogen to the outside of the pipe, the ice develops cracks which appear to depend on the rate of ice formation. For example, in the early stages of a freeze when the ice layer is thin cracks occur quite frequently, however once a steady shape has been achieved, closed or not, the activity falls to almost zero. This behaviour is currently the subject of a study which aims to explore whether there is any quantifiable correlation between cracking and the development of the plug, or its final closure.

A research programme is being carried out at Southampton with the aim of studying many different aspects of the pipe freezing technique. Most of this work has been centered around an experimental facility which allows ice plugs to be grown under a wide range of conditions of flow, temperature pipe size and orientation. The rig will accept test sections from 10 cm to 25 cm diameter and has been instrumented to provide temperature, heat flux and plug profile data during plug growth; visual access from the ends allows the progress of the plug to be followed. Much of the work carried out to date has been concerned with the heat transfer processes [1,2] but part of the brief has been to investigate non-invasive methods of plug monitoring and detection.

Several methods of sensing the formation of an ice plug within a steel pipe have been investigated. The techniques used include the measurement of changes in the acoustic impedance of the pipe, the use of ultrasound, and monitoring the rate of acoustic emissions from the ice within the pipe. Although the other approaches met with some limited success, the acoustic emission technique proved to be the most promising method of plug detection.

Experimental method:

Experiments into the acoustic emissions from cracking ice were conducted using the freezing facility with a vertically mounted 20 cm diameter stainless steel pipe. Several runs were carried out with different flow rates and bulk fluid temperatures. Under these conditions the ice plug takes upwards of one hour to fully form. The procedure was to fill the jacket with liquid nitrogen and keep it topped up to a constant level while the plug developed. The progress of the plug was followed through heat flux and plug profile measurements as well as by visual observation. The acoustic emissions were monitored using an accelerometer and a piezoelectric strain gauge mounted on the pipe outer surface away from the freezing zone.

Acoustic methods of detecting plug formation:

Applying the acoustic emission (AE) technique to a pipe undergoing cryogenic freezing is extremely simple. A sensor is attached to the outside of the pipe to pick up the elastic waves induced in the pipe wall by acoustic emissions from the ice. Since the damping of elastic waves in the pipe wall is low for steel pipes, the sensor may be attached at some distance from the jacket. This avoids many of the problems associated with other plug detection methods, where the sensor has to be attached to the pipe close to or within the cryogenic region.

The AE signals are of the "burst" type [3], and resemble decaying sinusoids due to resonances in the pipe and the transducer. A typical example is shown in figure 2. Rather than use the traditional AE technique of ringdown counting [4], where each AE event generates a number of counts (effectively corresponding to the number of cycles having a detectable amplitude), signal conditioning circuits were used to ensure that each emission only incremented the count by one. This greatly simplifies the subsequent signal analysis [4]. The most effective AE technique for monitoring the progress of cryogenic pipe freezing was found to consist of monitoring the rate of acoustic emissions during a freeze. The AE signals were counted over a period of 10 or 100 seconds, and the resulting totals plotted as the freeze progressed. The energy distribution of the AE signals was also studied, and was found to change slightly as plug closure took place.

Instrumentation:

Two sensors were used to detect the elastic waves produced by the acoustic emissions from the ice: an accelerometer with a wideband response (uniform up to 40kHz); and a piezoelectric plastic strain gauge manufactured from a commercially available material known as PVDF film [5]. Both sensors gave good results, although the sensitivity of the PVDF film was lower and necessitated the use of a high-gain amplifier. However, PVDF film may be preferable for routine use since PVDF sensors are much cheaper than accelerometers. In addition, these sensors have a uniform frequency response to around 1MHz. PVDF sensors are easily applied to the test object using double-sided adhesive tape, whereas a mounting stud has to be provided for the accelerometer.

Both sensors produced a low-level signal which had to be amplified by a charge amplifier. A 1kHz high-pass filter was used to remove mains-borne low frequency noise from the signal.

A tape recorder (Racal Store 7) with Direct and FM record/replay electronics was used to record the acoustic emission pulses for subsequent analysis. The use of FM electronics permits simultaneous recording of slowly-varying engineering parameters such as temperature, flow rate etc. The recording modes and tape speed controlled the upper and lower frequency limits. With the Direct channels the upper frequency limit was 75kHz at a tape speed of

15ips. For the FM channels the upper frequency was 10kHz. (It was shown by using a spectrum analyser that the upper frequency of the acoustic emission ringdown waveforms was around 20kHz). The low frequency limit for both recording modes was substantially less than the high-pass filter cutoff of 1kHz.

The main signal analysis technique used was to measure the acoustic emission count rate as described above. An electronic counter was specially developed to count each rise of emission pulses above a preset waveform. A Schmitt triggered input and an adjustable gate delay were used to ensure that each acoustic emission only incremented the count by one. The counts were accumulated over a preset period of 1, 10 or 100 seconds, and at the end of each period the total was plotted on a chart recorder. The digital count was also data logged. Figure 3 shows some typical results; it will be noted that the AE rate rises at or immediately after the time the plug finally closes off.

Pulse height analysis was also used to examine the energy distribution of the acoustic emissions. It was found that the acoustic emissions had a larger energy range at the point of plug closure than during the earlier stages of plug growth. Typical pulse height analysis results are shown in figure 4. The numbers on figure 4 refer to the points on figure 3 at which pulse height analysis was undertaken.

Frequency analysis by means of the Fast Fourier Transform was also used to study the frequency content of the acoustic emission signals. It is thought that most of the observed frequency content arises from resonances of the pipe or of the sensor or its mounting.

A block diagram of the acoustic emission instrumentation used is shown in figure 5.

Discussion:

As indicated earlier, ice-plug closure is primarily detected by observing the characteristic shape of a graph of count-rate vs. time, plotted as the freeze takes place. Figure 3 shows two such graphs, one for a successful freeze (labelled RUN 54 on figure 3) where an ice plug closed off, and one for an unsuccessful freeze (labelled RUN 52) where the initial flowrate and temperature were such that the ice plug failed to close. The figure shows the three characteristic features observed in the acoustic emissions from a successful freeze. The rate of acoustic emissions is at its highest during the early part of a freeze (i.e. in the region marked 1 on figure 3). This is followed by a period during which the emission rate is at a minimum and is almost unchanging (regions 1 and 2 on fig. 3). Finally, as the point at which the plug closes is approached the emission rate rises, giving the characteristic peak (marked as 4) on the right of figure 3 for the successful freeze.

One of the most useful features of the technique is that in addition to detecting the point at which the plug closes, it clearly indicates those cases where plug closure has not occured. This may be due to the initial conditions. Thus, the technique may be used to prevent inadvertent opening of an unplugged pipe.

A possible mechanism for AE in cryogenic pipe freezing:

The mechanism which gives rise to the acoustic emissions from the ice within a pipe is the subject of further study. However, it seems likely that the cracking which produces the acoustic emissions arises from thermal stresses within the ice. These stresses are produced by the temperature gradient. The ice adjacent to the pipe wall is at a temperature close to that of liquid nitrogen (-196 deg C), while at the ice/water interface the temperature is 0 deg C. Thus, the radial temperature gradient within the ice will be large and changing rapidly at the beginning of the freeze, when the layer of ice adhering to the pipe wall is thin, and we should expect a large number of acoustic emissions at this stage in the freeze. This is borne out in the experimental data of figure 3.

Towards the end of a successful freeze the water in the region of the ice plug often narrows to a thin, pencil-like column through the centre of the ice plug. When the plug finally closes off, this column freezes as the ice/water interface rapidly grows in an axial direction towards the ends of the plug. The formation of this ice is very rapid and is accompanied by a rapid reduction in temperature. This gives rise to a correspondingly large number of acoustic emissions and a peak in the AE rate is seen as the plug closes, as shown in figure 3.

Conclusions:

The use of AE rate measurement on a steel pipe undergoing cryogenic pipe freezing has been shown to be a promising indicator of the formation of a solid ice plug under laboratory conditions. The technique is simple to use and the results need little skill to interpret, thus making the method suitable for use in routine plant maintenance. The mechanism that gives rise to the acoustic emissions within the ice is still uncertain, but it seems likely that it is associated with thermal stresses and the rate of ice formation.

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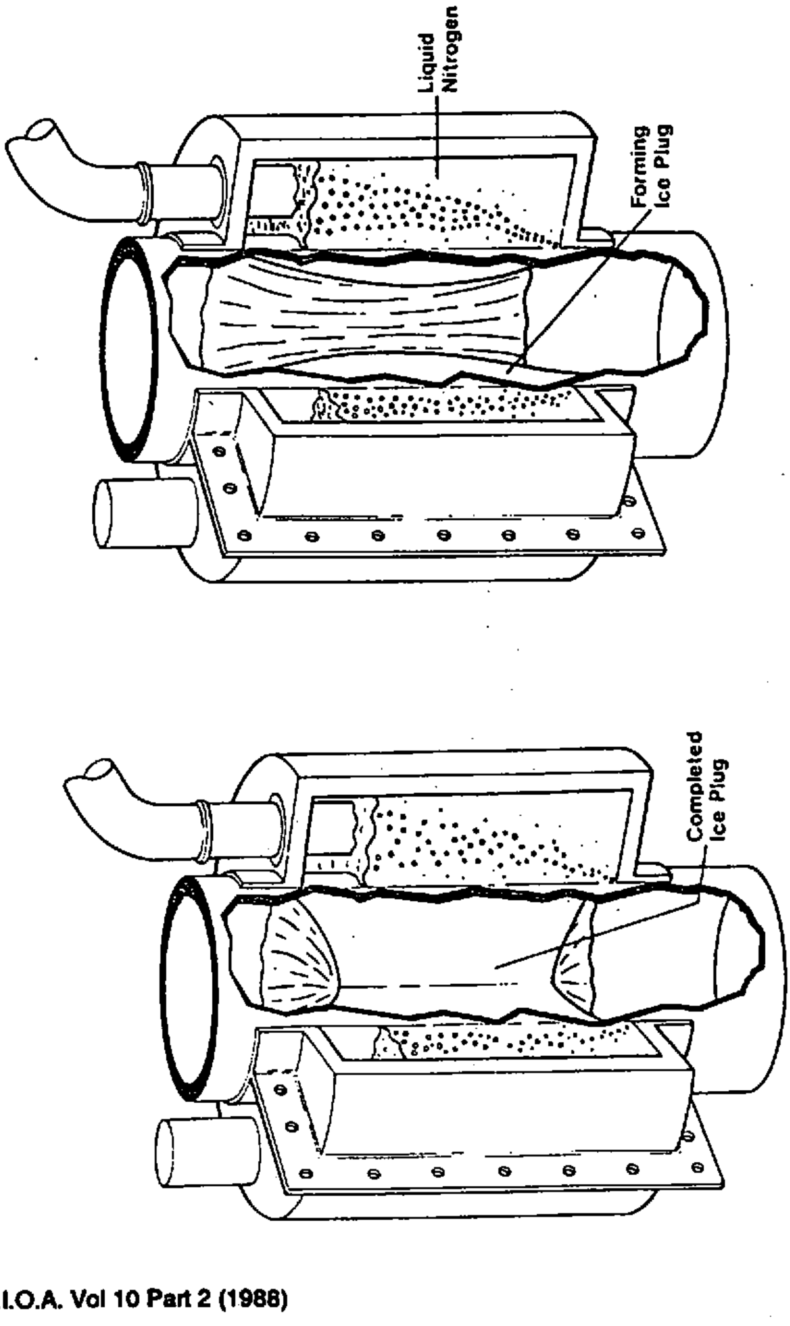

Figure 1

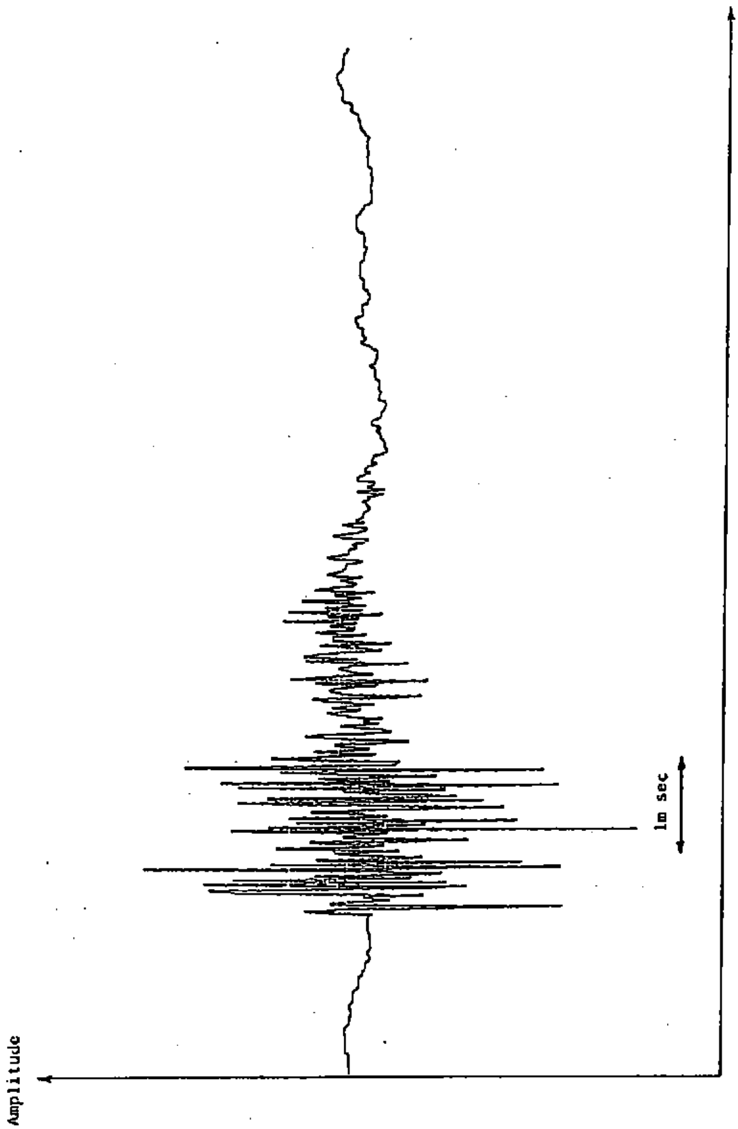

Figure 2: Typical Acoustic Emission Waveform

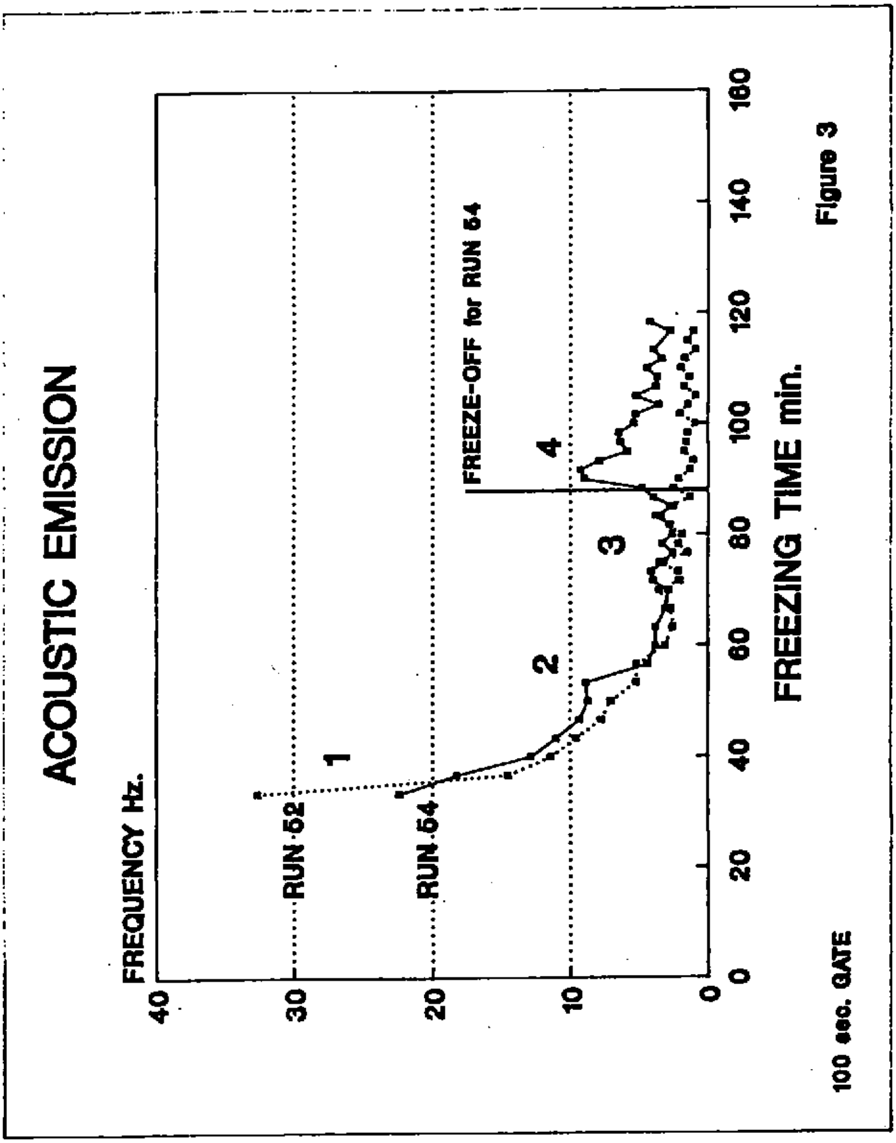
ACOUSTIC EMISSION
FREQUENCY Hz.
40
30
20
10
0
RUN 52
RUN 54
1
2
3
4
FREEZE-OFF for RUN 54
0
20
40
60
80
100
120
140
160
FREEZING TIME min.
100 sec. GATE

Figure 3

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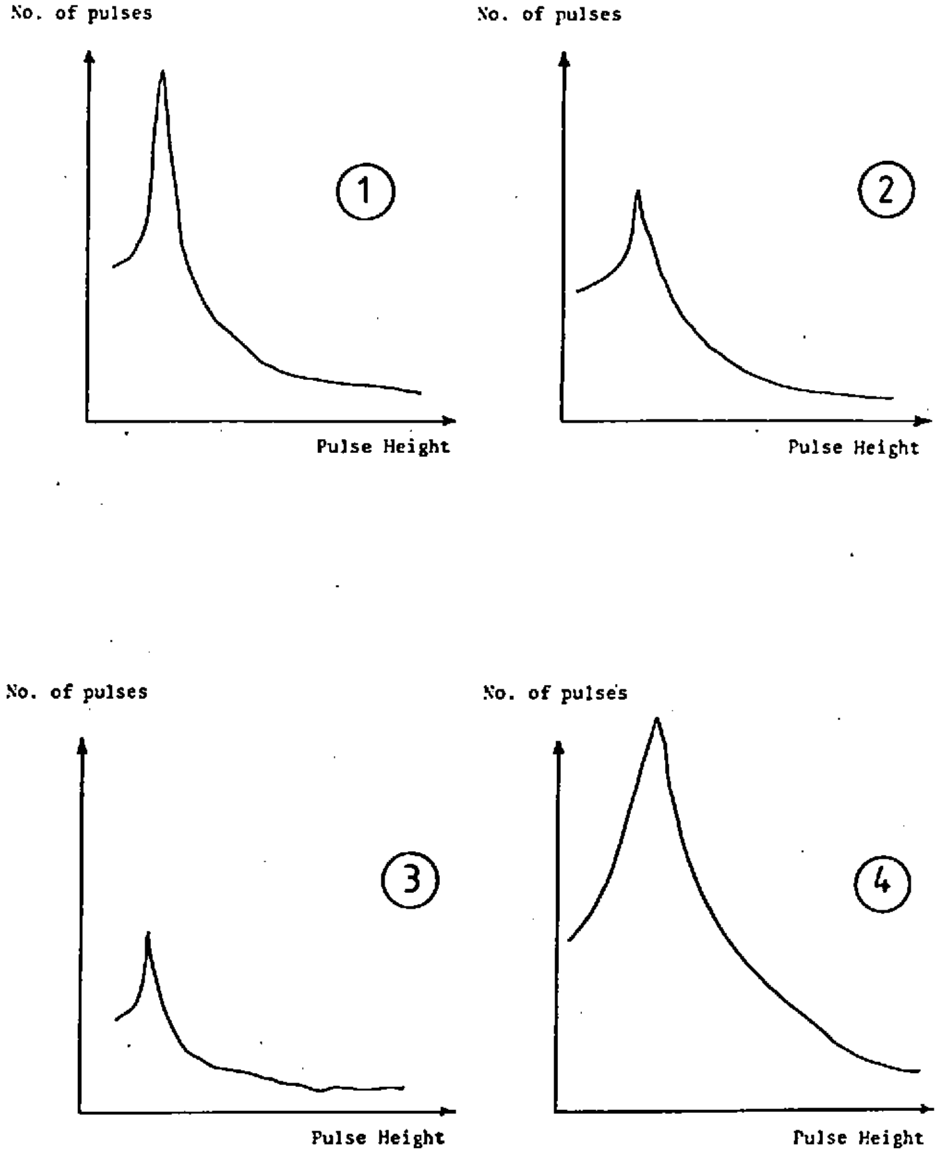

Figure 4: Pulse Height Analysis Results. (The numbers 1 - 4 relate to the points on figure 3 at which the above analyses were carried out)

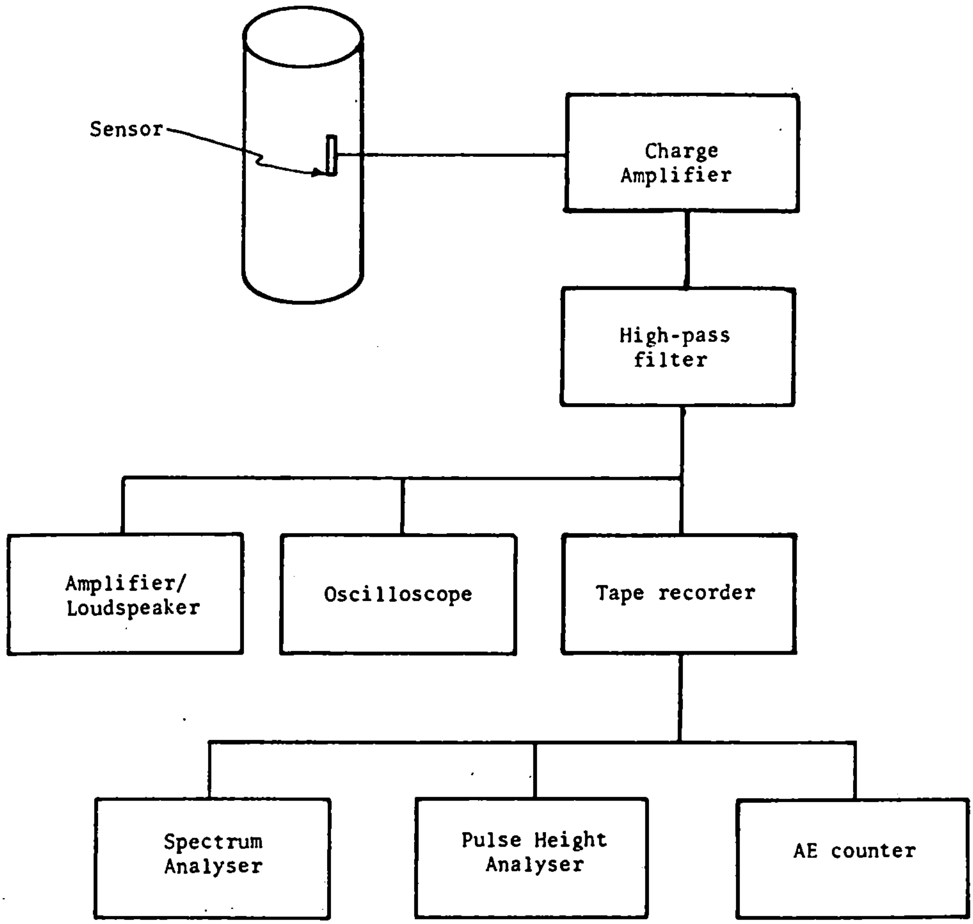

Figure 5: Acoustic Emission Instrumentation