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ACOUSTIC SURVEILLANCE TECHNIQUES FOR SGU LEAK MONITORING.

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SUMMARY

Acoustic techniques for the detection of steam leaks in Fast Reactor SGUs fall into one of two categories:

a) Passive techniques which listen to the noise produced by the leak. This can be the noise due to the velocity of the steam jet (which can increase if it impinges on a target), noise from the sodium/water reaction itself or, under severe leak conditions, noise from the boiling of the sodium. Further sources of noise include the movement of hydrogen bubbles through grids. Hydrogen bubbles also have a markedly detectable effect in the absorption of certain background frequencies.

b) Active techniques which rely on the modification of the sonic transmission path by hydrogen bubbles or heating caused by the leak.

Passive techniques depend on an accurate assessment of the signal to noise ratio to be expected at the receiving transducers when a leak occurs. Thus, in the absence of a full-scale SGU test facility that matches the expected fast reactor design, there are three aspects that have to be studied separately and then combined. These are the acoustic signal generated by the leak, the transmission of the sound to the transducer, and the level of background noise expected.

Information concerning the acoustic source signal generated can be judged from measurements taken from sodium/water reaction tests. Transmission problems can be studied using either existing SGUs, or from water models. Since transmission characteristics are the most likely to change from design to design, a theoretical support to this work is most important. Finally, background signals can also be judged by direct measurements on existing plant. (These individual factors are discussed in companion papers).

Detection of a small leak in the presence of substantial noise depends very much on recognition of the peculiar characteristics of the sound. Experience in working with difficult signals is being obtained through an International Bench-Mark test, being organised through the IWGFR. At present, the estimate of sensitivity due to UK work alone is that in an EFR SGU a leak rate of 3 g/s would not be difficult to detect, and that higher sensitivities would be attainable through more sophisticated signal processing. One such technique uses a number of transducers on the SGU: by treating them as an array the signals can be processed to yield the approximate position of the leak, at the same time the sensitivity is increased.

Active techniques can also be used to locate the source of a leak. Again, by using a multiplicity of transducers sensitivity is also improved. The transducer array can be used for tomographic processing, a method which is known to be quite sensitive to temperature disturbances, and extremely sensitive to gas voidage. Application of the technique, however, is very dependant on the details of the complex internal structure of the SGU itself.

Thus it is concluded that acoustic techniques offer a number of options for detection and location of steam leaks in SGUs. The choice depends in part on precise knowledge of the intended SGU design, but also in obtaining more information about the performance expected from the various techniques. The present programme of work is framed to answer these questions.

INTRODUCTION.

The following paper is intended as a brief review of the acoustic techniques applicable to the detection of SGU leaks that have been studied in the UK. Any development, however, should be preceded by a target performance specification. Unfortunately, the definition of a specification for a system is a difficult task, often requiring assumptions to be made due to the lack of detailed information. This is especially true when assessing the overall requirements of a complete detection package to protect the Steam Generator Units from damage. Despite such problems a simple reference representation of the required performance as developed in the UK will be given before discussing details of the acoustic detection methods.

TARGET PERFORMANCE SPECIFICATION

A target performance specification has three aspects which need to be addressed. These are response, reliability and spurious trip rate.

System response.

The required detection system response is determined by the type and consequences of leaks within the SGU. From the limited data available both for the proposed EFR tube alloy, T91 and for 21/4CrMo ferritic steels, two different leak mechanisms appear to dominate:

a) Leaks develop in the range 10^{-2} to 10^{-1} g/s and remain open over a relatively long period of hours. These then escalate in a few seconds into leaks in the g/s range.

b) Small leaks develop in the range < 10^{-2} g/s. These then effectively block for an indeterminate period before escalating rapidly into the g/s range.

The effect of such leak behaviour is governed by many independent variables and any assessment of the likely damage can only be based on a best estimate approach at this stage. There are two distinct damage functions to be considered, either of which could lead to secondary failure and hence the SGU tube bundle being damaged beyond repair. The first is wastage damage resulting from leaks in the range 10^{-2} up to at least 100 g/s. An important transition appears at about 3 g/s leak rate where experimental data suggests a transition from pit to toroidal wastage. The second damage function is the overheating damage significant for leaks above 10 g/s leak rate. The consequent complete failure of a single tube can result in an irrevocable cascade of secondary ruptures, the so-called "Multiple Tube Rupture" (MTR).

The conclusion of a typical damage study is that leak rates of the order of 3 g/s should be detectable with a response rate of about 1 sec if MTR is to be avoided in all cases. Smaller leaks, down to 10^{-2} g/s would ideally be detectable, but the response rate is less important. Although the sensitivity of hydrogen detection systems can be high, and so meet the latter requirement, their response will be too slow for the some types of failure. The devices on PFR, for example, have a response time of about 70s. Thus the primary role for acoustics could be for the faster detector, and may not necessarily have to meet the higher sensitivities.

Reliability.

Despite current uncertainties about the level of reliance placed on detection systems, it is an essential exercise to illustrate the effect of detector system reliability on the safety and economic consequences. An illustrative analysis is shown in fig. 1, based on best estimates at the present. It examines the probability of a primary containment failure (IHX failure - Safety Consequence, SC), major damage to the plant (Economic Consequence, EC), or successful shut-down for repair (OK). The analysis assumes a failure rate within the SGU of one tube per year, which fails in one of the two ways mentioned earlier. A somewhat arbitrary reliability of detection for both Hydrogen Leak Detection (HLD) and Acoustic Leak Detection (ALD) is set at 10^{-1} for events falling within the operating range of the detector.

For comparison, there is a general agreement that the upper limit of the probability of a nuclear release (SC) is 10^{-7} events per year, and that for an economic write-off (EC) would be about 10^{-4} events per year. From the diagram it is clear that the reliability figure of 10^{-1} for ALD is reasonable safety-wise but inadequate for economic protection. It should be better than 10^{-3} in practice.

Spurious Trip rate.

The frequency with which the protection system falsely indicates a tube leak affects its credibility and leads to expensive down-time. The tolerable level of such indications is best defined by the Reactor operations or design and construction groups. A trade off exists between sensitivity and response time and spurious trip rate. A figure of less than one in ten years is felt the minimum target.

ACOUSTIC LEAK DETECTION METHODS.

Acoustic techniques for the detection of steam leaks in Fast Reactor SGUs fall into one of two categories:

a) Passive techniques which listen to the noise produced by the leak. This can be the noise due to the velocity of the steam jet (which can increase if it impinges on a target), noise from the sodium/water reaction itself or, under severe leak conditions, noise from the boiling of the sodium. Further sources of noise include the movement of hydrogen bubbles through grids. Hydrogen bubbles also have a markedly detectable effect in the absorption of certain background frequencies.

b) Active techniques which rely on the modification of the sonic transmission path by hydrogen bubbles or heating caused by the leak.

PASSIVE ACOUSTIC TECHNIQUES.

Passive techniques depend on an accurate assessment of the signal to noise ratio to be expected at the receiving transducers when a leak occurs. Thus, in the absence of a full-scale SGU test facility that matches the expected fast reactor design, there are three aspects that have to be studied separately and then combined. These are the acoustic signal generated by the leak, the transmission of the sound to the transducer, and the level of background noise expected. The current range of information sources are indicated in fig 2.

Information concerning the acoustic source signal generated has been obtained from sodium/water reaction experiments at Dounreay, in both the "small water leak rig" (SWLR) or Super Noah, as described in a companion paper [1]. So far, the SWLR rig tests are virtually complete, actual steam injection rates from 0.3 to 17.3 g/s from each of five injection orifices were achieved. Four receiving accelerometers were fitted to waveguides welded to the test section and there was also an immersed transducer within 300 mm of the orifices. Because of the closeness of the detectors to the sources, there was little difficulty in recording significant acoustic signals in all cases. Two further points may be made; first the tests are similar in geometry to the CEA leak evolution tests already completed in the same facility, and secondly, each test was preceded by an argon injection to provide a calibration reference.

The PFR SGUs are providing a continuous source of data concerning typical background noise levels, and this is also described in a companion paper [2]. The main problem in assessing acoustic leak detection response is combining the two kinds of data to give a realistic signal/noise background ratio that would apply in a real SGU, should a leak occur. To do this, one has to estimate the transmission losses experienced by the leak signal before it reaches the detector, and these are assumed fairly liberally distributed about the containment vessel. The transmission has been estimated from the PFR SGUs, from water tests and from a developed theory to give a first estimate. (See companion papers [3,4]. The estimation indicates that a typical signal level would be about 10 db above background for a leak rate of 50 g/s, a figure that would ensure detection within a few seconds with a high degree of confidence.

This sensitivity is still below what is required, but so far no special processing of the signal has been considered; there is as yet no attempt to take advantage of the unique features of the leak noise. In fact a number of techniques already exist that would do this, and it is confidently predicted that a sensitivity of 3 g/s can be readily achieved.

Advanced Processing techniques

IWGFR Bench Mark tests.

Development of special signal processing techniques for SGU leak detection is still at an early stage, but similar work for an allied problem for use in Fast Reactor Primary vessels, Acoustic Boiling Noise Detection, are well advanced. An international bench mark test organised by the IWGFR has been reported [5]. Of significance in these tests is that all contributors had no difficulty in detecting the test signals despite having the signal/noise ratio worsened by 17 db; as a consequence an extension to the programme was agreed, and participants are currently working on test data with signal/noise ratios down to -21 db. After this work is completed, before the end of 1990, a further test is planned, this time using signals from sodium/water leaks. Data has already been supplied by the USSR covering the range from 0.1 to 1 g/s, and it is planned to add data from UK sources for the higher leak rates.

At this stage, it would be imprudent to anticipate the results of these tests. However, the techniques developed in the UK are described below. The most promising methods have been a) Pattern Recognition, and b) Location Techniques.

Pattern Recognition Analysis

This is a powerful method of distinguishing between a signal and background noise. Techniques involve the measurement of certain features of a data sample which may be used to separate the data sample into one of a number of classes. Data samples from various experimental conditions or from various sources can be used to define different classes and algorithms exist which can identify the most significant features to separate the classes. New samples of data can then be assigned to one of the classes using various recognition algorithms. The UK work in this area has already been reported[5,6,7].

An illustration of this type of processing comes from the analysis of the acoustic signals obtained during a multipin boiling experiment in the KNK2 reactor carried out by KfK Karlsruhe[8]. The principles apply equally well to analysis of acoustic data from SGUs.

The detection of in this case the boiling signal from these experiments was made difficult by the presence of a strong interfering signal which contained many spikes as big as or larger than the boiling noise pulses. It was shown that this interference arose from the electrical supply to the heater pins and so will not be a part of normal reactor background noise. Nevertheless this experiment provided an opportunity to test methods of discriminating between the interference and boiling noise pulses.

Analysis

Samples of the signals of about 10 milliseconds duration were digitised for three different conditions, low and high heater powers without boiling and high heater power with boiling. Approximately eighty data samples were taken for the non-boiling conditions and about thirty data samples with boiling. Each data sample was then analysed to produce a set of twelve features which defined the energy in various frequency bands, the spectral shape of the noise signal and the standard deviation and kurtosis of the data sample. A principal components analysis based on the Fisher Linear Discriminant was then made which combined the twelve features using an algorithm which optimised the separation between the three classes. Fig. 3 shows a scatter plot of the first and second principal components obtained in this way and it can be seen that the three classes, low power background (A), high power background (C) and high power boiling (B), are clearly separated. The ellipses in the figure are at two standard deviations from the mean of each class.

The probability of false classification can be estimated by fitting a probability curve to the data in each class and then calculating the degree of overlap of the distributions. An illustration is shown in fig. 4 obtained using the first principal component for classes B and C in fig. 3 (boiling and non-boiling data samples at high heater power) and assuming a Gaussian distribution. In fig. 4 the probability of wrongly classifying background as boiling is proportional to the area under the background distribution and above the chosen discrimination level and failure to detect boiling is proportional to the area under the boiling distribution below that point. For the data in fig. 4 the probability of false acceptance of a 10 millisecond sample of background noise as boiling is estimated to be $3.67\ 10^{-03}$. In the KNK2 experiment, during the highest levels of boiling, typically fourteen boiling pulses were detected in an approximately six second analysis period. The probability of fourteen 10 millisecond background samples being classified as boiling in a corresponding analysis period would be about $7\ 10^{-09}$ (using the Poisson distribution) corresponding to one spurious trip in about four years. This is a relatively high figure but would be reduced significantly by increasing the period over which the pulse rate must be maintained.

The above results illustrate that pattern recognition techniques could be used as part of an automatic acoustic surveillance system on a fast reactor, such as an SGU leak detection system, and provide a means of specifying detection levels and spurious reactor trip rates.

Location Techniques

Location methods are of value for two main reasons. First it is obviously of interest to the reactor operator to know the position from which an anomalous acoustic indication is coming. This information is also clearly of value after shutdown as an aid to correcting the problem. Secondly if the acoustic detectors can be focused on a particular region then the background noise from elsewhere in the system is excluded. This improves the signal to noise ratio and is a valuable aid to detection. Again, development in the UK has concentrated initially on instruments for the FR primary vessel, and these results are reported here.

Pulse Timing

When the signals are clear, for example a large anomalous pulse, location can often be determined by a direct comparison of the signals from the detectors to determine the difference in the transmission time of the signal to each of a pair of transducers. In a two dimensional system this enables a semi-hyperbola to be drawn, with the detector which received the signal earlier as focus, on which the source must lie. A second pair of transducers allows a second semi-hyperbola to be drawn and the source will be located at an intersection of these. Additional pairs of transducers allow ambiguities to be clarified. An example of this location method from an experiment carried out in a model of part of the PFR core is shown in fig. 5. Six transducers located above the outer corner subassemblies were used to locate the source of an electrically generated signal. This technique is appropriate when there is good signal to noise ratio. The method can be extended to three dimensions by plotting hyperboloids. A minimum of four transducers is required.

When the signal cannot be readily discriminated from the noise by inspection a correlation method is required to determine the relative delays. This is in effect the basis of beamforming techniques.

Delay and Sum Beamforming

In the simplest beamformer, the delay and sum beamformer, the correlation value is obtained by calculating the distance from the point of focus to each of the hydrophones. These distances are divided by the velocity of sound to give the transit times which in turn are divided by the sampling interval used in the digitising process to express the transit times as numbers of time points in the digitised records. The records can then be shifted by these amounts so that a signal emanating from the focus will appear at the same timepoint in all records. The records are then added and squared to give a measure of the acoustic power from that point. This technique has been applied to data obtained on the half scale model of the PFR core. A plan view of the model showing the position of the hydrophones is shown in fig. 6. A transducer driven from an electrical oscillator was used as the source and the results in the form of Isometric plots are shown in fig. 7. It is seen that the source is always located correctly in the central subassembly and that the sharpness of the location improves with frequency. At high frequencies the wavelength becomes less than the space between transducers and spurious locations are indicated due to aliasing. The spurious indications vary with change in frequency and so can be distinguished from the true location.

An advance on the above technique can be obtained using adaptive methods[6] as explained below.

Adaptive Beamforming

Adaptive array processing can significantly suppress the contribution from noise with high spatial correlation. Unpredictable physical features such as entrainments of gas or vapour within the reactor core may cause high signal attenuation at some sensors. We require the additional capability to suppress contributions from sensors with low signal to noise ratio.

An adaptive array processing strategy which satisfies these requirements is the orthogonal beamforming or eigenvalue decomposition technique[9,10]. This technique is summarised below.

Define the following quantities:
a. Estimated cross spectral density matrix **B**. In practice there are a finite number of matrices **R** at discrete frequency values **f**. Each matrix has dimensions n x n (where n is the number of sensors) and is positive definite. The matrix is subject to statistical variability due to the finite length of sample used to estimate it.

b. Estimated cross-spectral density matrix **N** for the noise (again positive definite).

c. Steering vector $\underline{s}$. This vector contains the phase lag information corresponding to the current array focal point. It is a function of frequency.

The array output power at frequency **f** for a non-adaptive beam former may be expressed as

$$P\ (f,\underline{s}) = \underline{s}^{H}R\underline{s} \qquad (1)$$

where the superscript H denotes the conjugate transposed.

Generally adaptive methods replace expression (1) by

$$P(f) = \underline{w}^H R \underline{w} \qquad (2)$$

where $\underline{w}$ is a "weight vector". The relative amplitudes and phases of w are now chosen to optimise some measure of the array performance subject to some constraint on $\underline{w}$.

In the orthogonal beamforming approach we require to maximise the total array output power subject to the constraint that the array response to the "noise" is unity, i.e.

$$\underline{w}^H N \underline{w} = 1 \qquad (3)$$

The maximum value of P(f) may now be shown to be given by

$$P_{max}(f) = E_1 \qquad (4)$$

where E_1 is the maximum eigenvalue of the equation

$$R\underline{w} = EN\underline{w} \qquad (5)$$

The optimum weight vector is the eigenvector $\underline{w}_1$ corresponding to E_1.

If there is no "signal" present and furthermore **R** and **N** are estimated exactly then **R** = **N** and all of the eigenvalues of equation (5) are equal to 1. This does not happen in practice because of sampling errors and in this case the eigenvalues are clustered randomly in the neighbourhood of 1. If a single source "switches on", one eigenvalue emerges from this cluster and assumes some larger value. Thus E_1 may be used in the "detection" role and some detection threshold set.

To "locate" a single source the correlation

$$C(\underline{r}_F) = |\underline{s}^H \underline{w}_1|^2 \;/\; \{ (\underline{s}^H N^{-1} \underline{s}).(\underline{w}^H N \underline{w}_1) \} \qquad (6)$$

may be tabulated or plotted over all candidate source positions $\underline{r}_F$ (NB $\underline{s}$ depends on $\underline{r}_F$). The maximum is located in order to give an estimated source position.

An experimental result of the application of these techniques to data from the PFR model in the case where the signal to noise ratio on each of the transducers used was -9db on average, is shown in figs 9 & 10. The benefit of the orthogonal beamforming technique in distinguishing the new source from the normal background is clearly seen.

ACTIVE ACOUSTIC DETECTION TECHNIQUES.

These methods depend on a sodium/water leak generating an anomaly in the acoustic transmission path local to the leak which can be detected by sending and receiving acoustic signals. The simplest anomaly would be that of a local temperature rise caused by the reaction, but the appearance of clouds of hydrogen gas would have a major effect that would be fairly readily detectable. The following technique, acoustic tomography, has been developed to a practical state for use in a Fast Reactor primary vessel. Its application to a SGU would be modified by the transmission losses caused by the tube bundle, and its precise performance would require more precise information about the EFR SGU design than is available at present.

Anomaly detection by acoustic tomography

Acoustic tomography is being developed as a general technique to monitor certain conditions within a plane area of a fluid by measuring the variation in the acoustic transmission properties over the area. The method could be used to determine the distribution of any effect which produces an associated detectable change in the acoustic properties; for example, the measurement of the temperature distribution across a region of fluid by the variation in the transmission velocity, or the gas bubble content in a liquid by the variation in the acoustic attenuation.

A square array of acoustic transducers, able to both transmit and receive, are mounted around the periphery of the area of interest, as illustrated in fig. 10. Each transducer, in turn, transmits a pulse of high frequency sound which is received by each of the other transducers, and the transmitted and received signals are recorded by a high speed digital transient recording system. From these waveforms, acoustic properties are determined such as the transit time between transducers, and the attenuation of sound along each path. The region enclosed by the transducer array is divided into a square grid such that each grid cell is traversed by at least one sound path between transducers. The measured data is then used to compile a set of linear simultaneous equations, each such equation being the sum of the partial transmission over the grid cells for each path.

For example, the velocity equation for the path from T1 to T4 in fig. 10 is:

$$T_{14} = L_{11}/V_{11} + L_{12}/V_{12} + L_{23}/V_{23} + L_{24}/V_{24} + L_{35}/V_{35}$$

where T_{14} is the transit time between transducers 1 and 4;
Lij is the distance travelled in cell (i,j);
Vij is the velocity of sound in cell (i,j).

These equations are solved to determine the acoustic characteristics in each of the cells, from which other fluid properties can be deduced; for example the distribution of temperature over the region can be calculated if the velocity of sound is known as a function of temperature.

A demonstration experiment has been set up in a large tank facility to assess the technique in water at room temperature. Eight transducers were arranged to form a square 400mm across and this region was notionally divided into a 5x5 grid. (8 transducers yield 8x7/2 = 28 independent acoustic paths giving that many equations to solve for 5x5 = 25 unknown values.) The layout of the transducers and the grid is as shown in fig. 10

Fig. 11 shows a plot of the successive computed values of temperature for all the cells when hot water was injected into the tank at a position vertically below cell (2,3). The temperature for that cell can be seen to increase by 6 or 7 degrees centigrade as the hot flow passes up through the monitoring plane. An increase can also be seen in cell (2.2) which was probably due to leakage of the flow into that grid square.

The comparison between the computed 'tomographic' temperature and that measured by a standard chromel-alumel thermocouple for cell (2,3) during two periods of hot water injection, is shown in fig. 12 which indicates very good agreement between the two measurements.

These test results show that, in static water at ambient temperature, an increase of 2°C over a square 80mm across, can be reliably detected. Currently, one full cycle of pulsing all transducers, capturing the waveforms, deriving the parameters and solving the simultaneous equations takes approximately 2.5 seconds which is the minimum time achievable with the present configuration.

Future work on the technique will include the development of dedicated hardware to reduce the processing time per measurement to less than 1 second, and the extension of the analysis to larger transducer arrays to improve the resolution by increasing the number of grid cells and thus reducing their size for a given monitoring area.

CONCLUSIONS

A preliminary specification for the acoustic leak detection of sodium/water leaks in steam generating units suggests that it will be necessary to detect better than a leak rate of 3 g/s within a few seconds. Whilst leak experiments have so far not been done in a realistic SGU tube bundle geometry, it has been possible to assess performance of passive acoustic techniques by combining known leak noises with typical backgrounds, using a knowledge of the tube bundle acoustic transmission properties deduced from water tests and developed theory. Simple detection of signal above background suggests a detection sensitivity of only 50 g/s. However it is confidently claimed that application of advanced techniques, currently being assessed by an IWGFR bench mark test, would increase the sensitivity to much better than that required, possibly 1 g/s.

The use of active acoustic techniques such as tomography offers further discrimination of the signal, but its accurate assessment will require testing with an accurate model of the tube bundle once the SGU design has been established.

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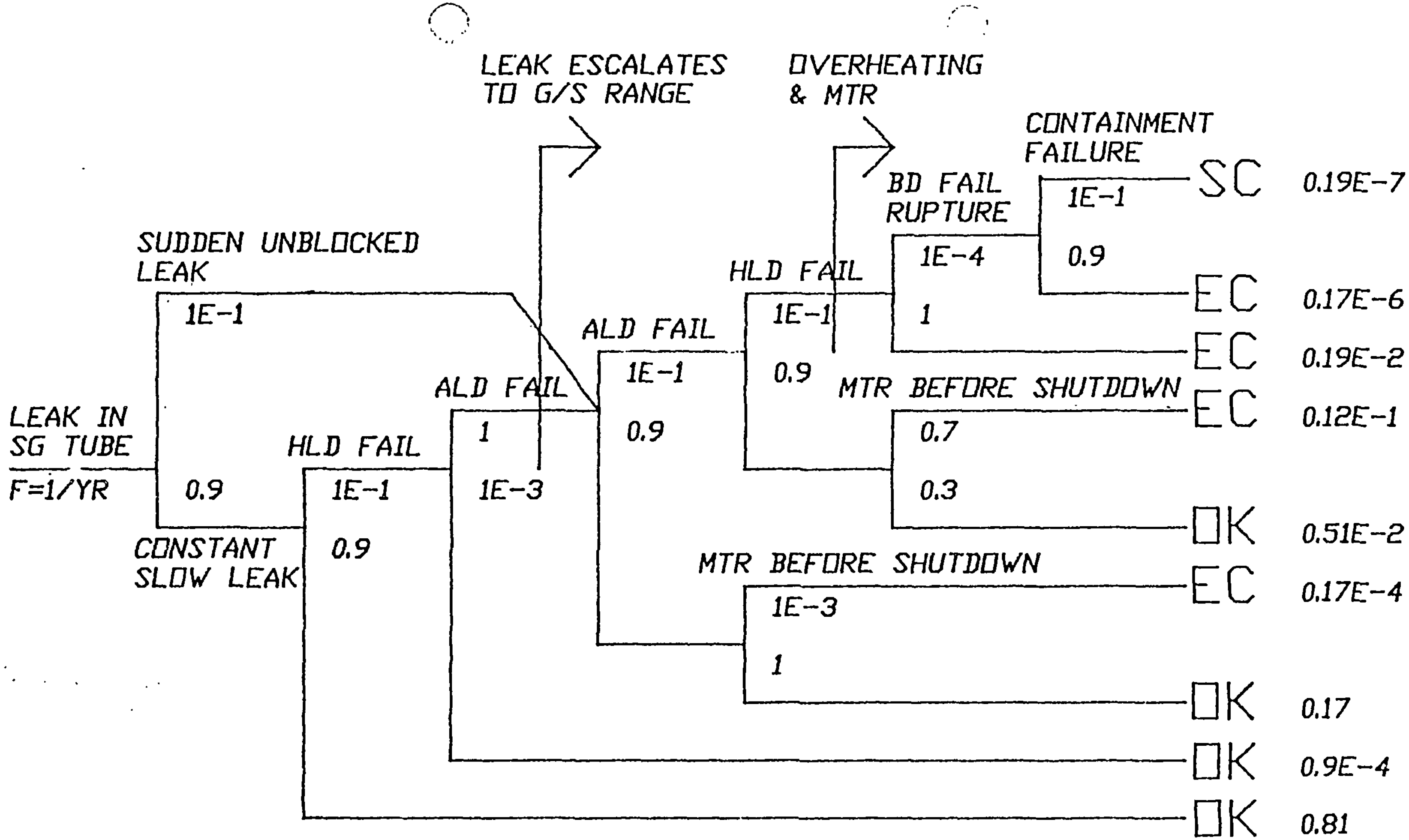


NUCLEAR RELEASE	Σ SC	0.19E-7
SGU WRITE-OFF	Σ EC	0.14E-1
SAFE TRIP	Σ OK	0.985

EVENT TREE ANALYSIS

FIGURE 1

Symbols

A - Background at 123 W/cm²

C - Background at 185 W/cm²

B - Boiling at 185 W/cm²

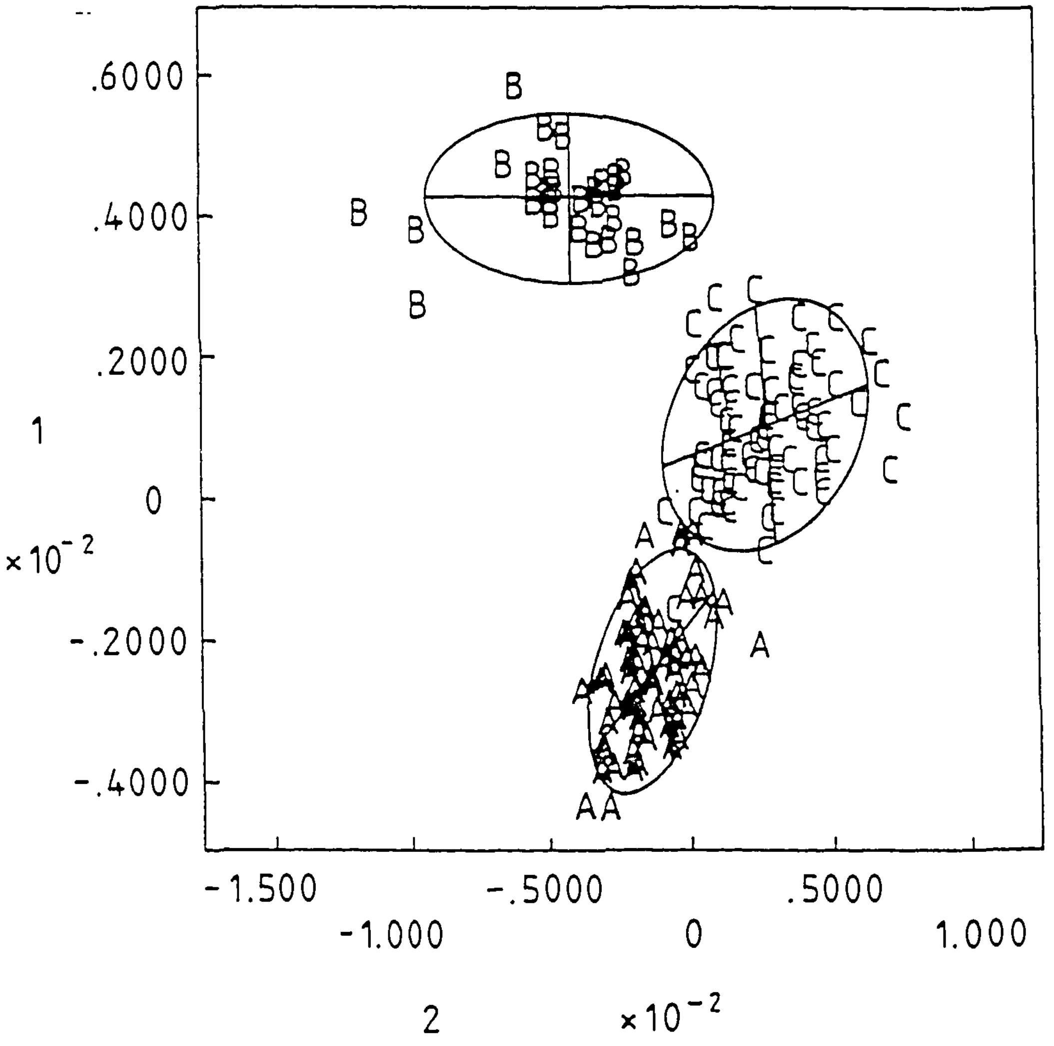


FIG. 3 SCATTER PLOT OF 1st AND 2nd PRINCIPAL COMPONENTS FOR 12 FEATURE ANALYSIS

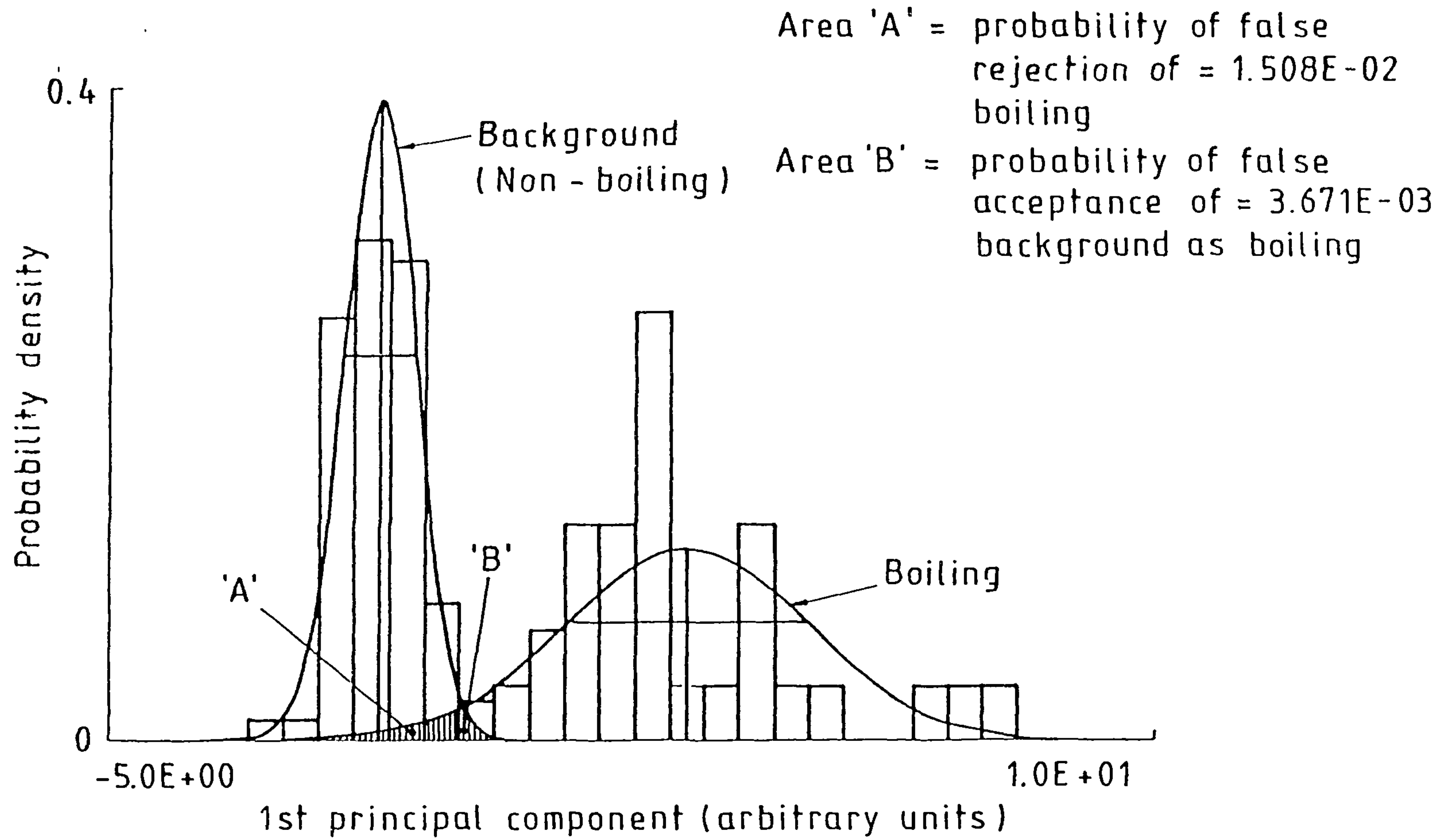


FIG. 4 PROBABILITY DISTRIBUTION OF 1st PRINCIPAL COMPONENT FOR 12 FEATURE ANALYSIS

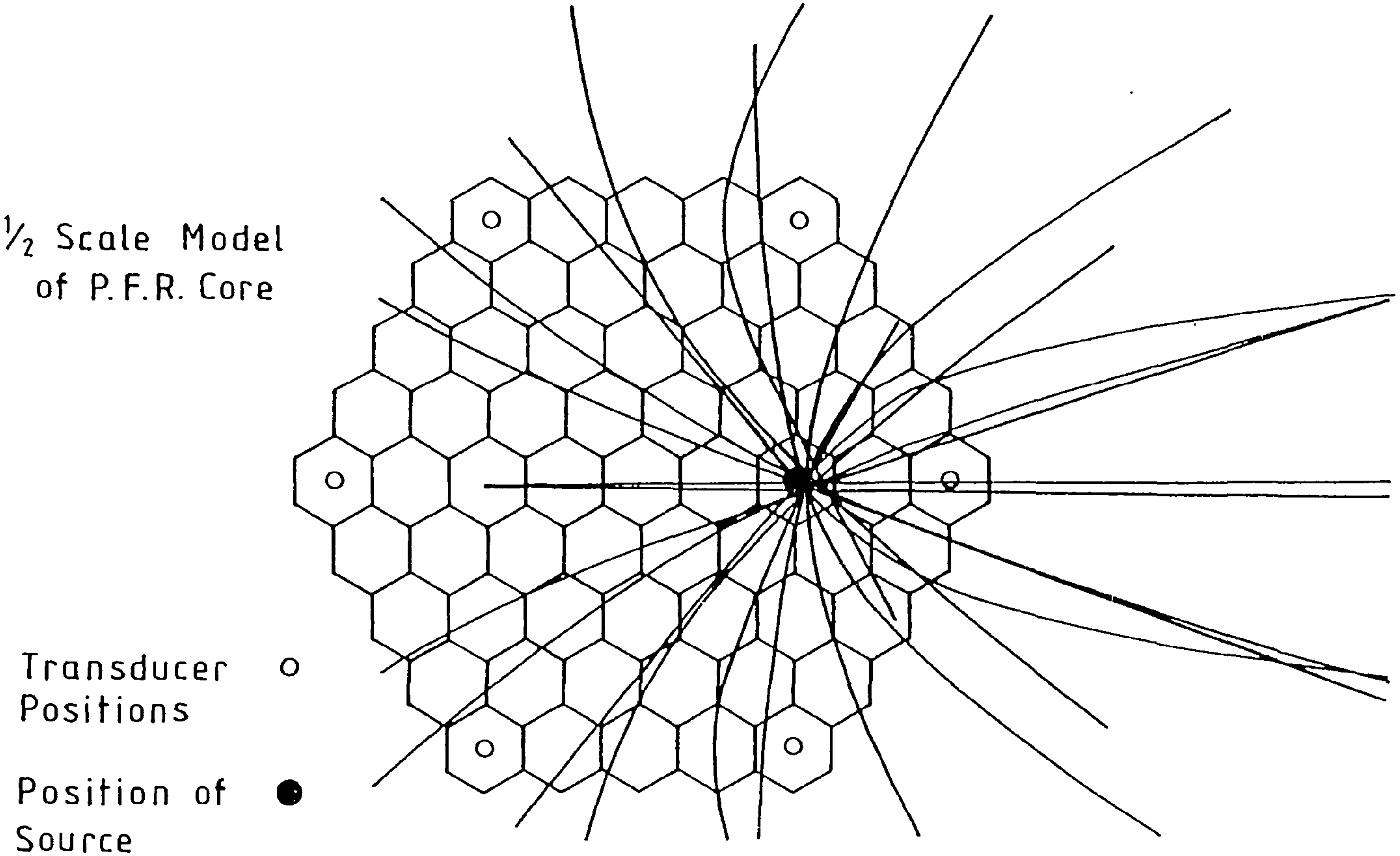
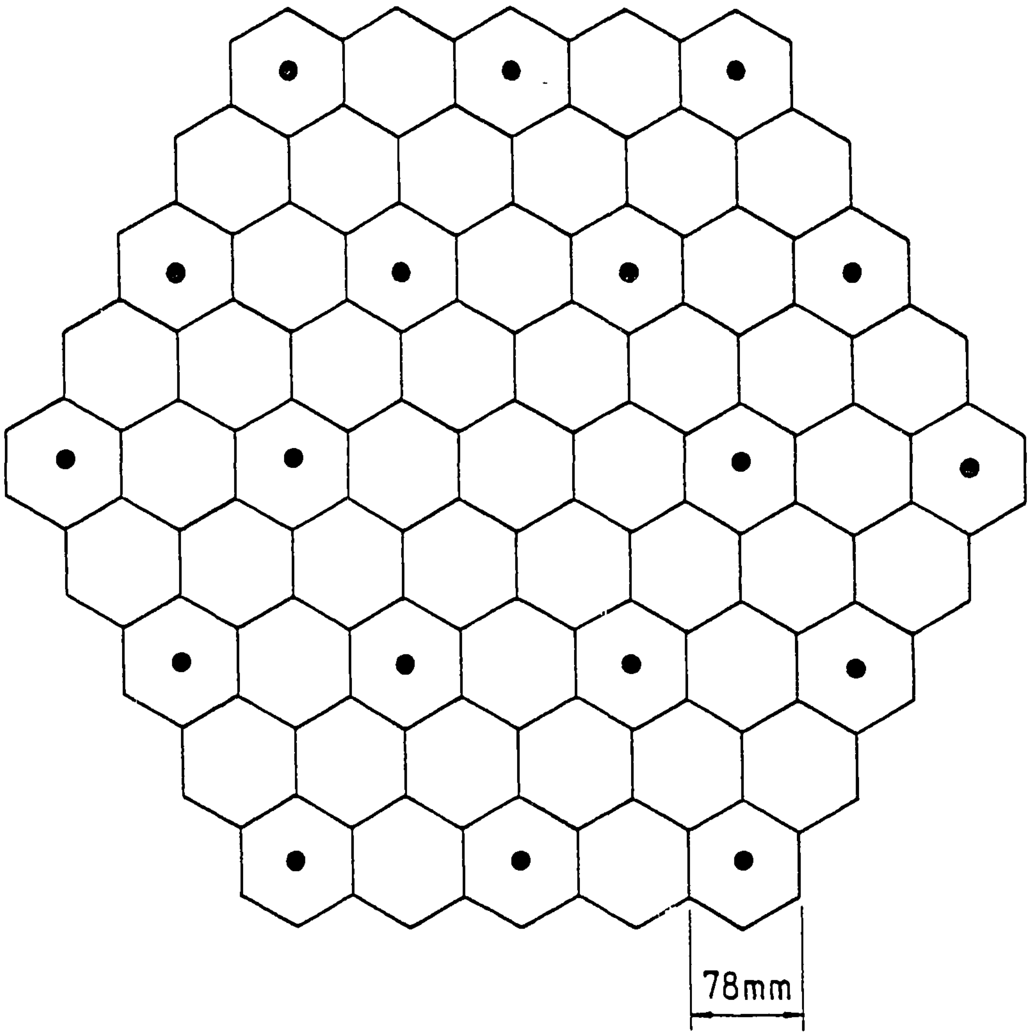


FIG. 5 LOCATION BY DRAWING HYPERBOLAE



• HYDROPHONE POSITIONS

FIG.6 HYDROPHONE ARRAY FOR SOURCE LOCATION

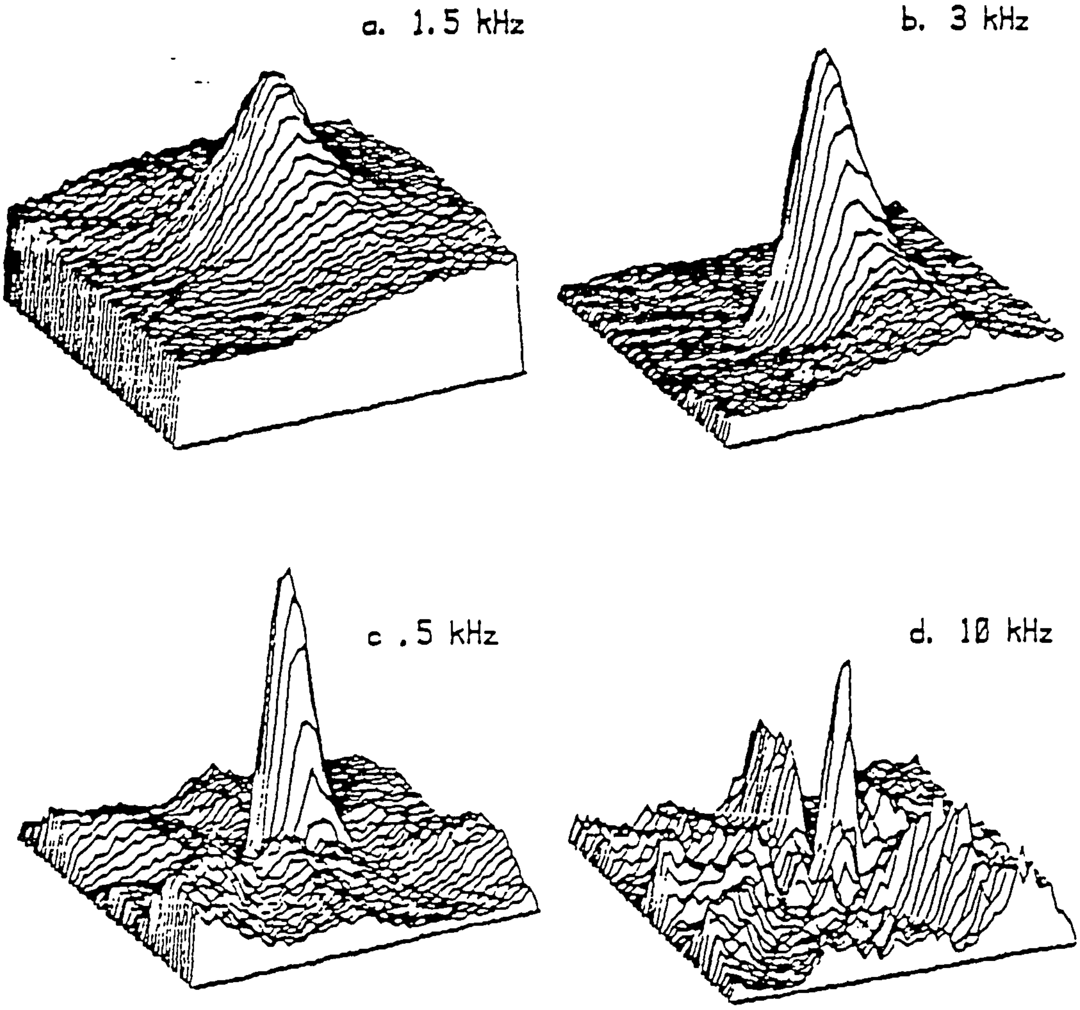
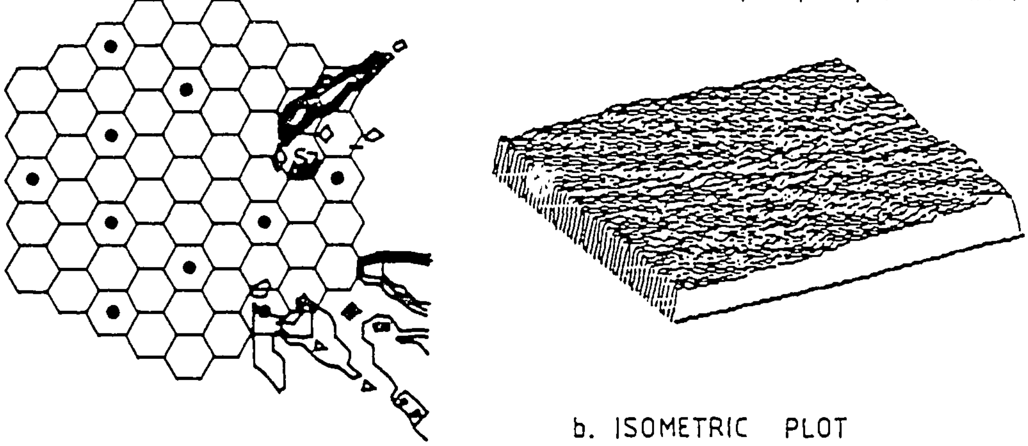


FIGURE 7 : ISOMETRIC PLOTS OF THE OUTPUT FROM THE DELAY AND SUM BEAMFORMER FOR SIGNAL OF VARIOUS FREQUENCIES

MAXIMUM CORRELATION = 0.147
CONTOUR HEIGHTS = 0.98, 0.96, 0.94, 0.92 OF MAX.

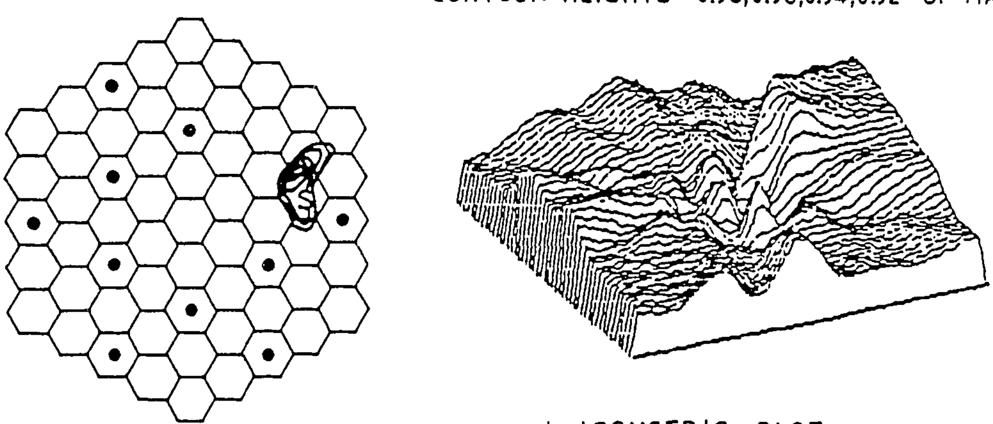


a. CONTOUR PLOT

b. ISOMETRIC PLOT

FIG. 8 PLOTS SHOWING THE OUTPUT FROM THE TIME DOMAIN BEAMFORMER FOR A BROADBAND SIGNAL IN THE PRESENCE OF BROADBAND BACKGROUND NOISE.

MAXIMUM CORRELATION = 0.441
CONTOUR HEIGHTS = 0.98, 0.96, 0.94, 0.92 OF MAX.



a. CONTOUR PLOT

b. ISOMETRIC PLOT

FIG. 9 PLOTS SHOWING THE OUTPUT FROM THE ORTHOGONAL BEAMFORMER FOR A BROADBAND SIGNAL IN THE PRESENCE OF BROADBAND BACKGROUND NOISE.

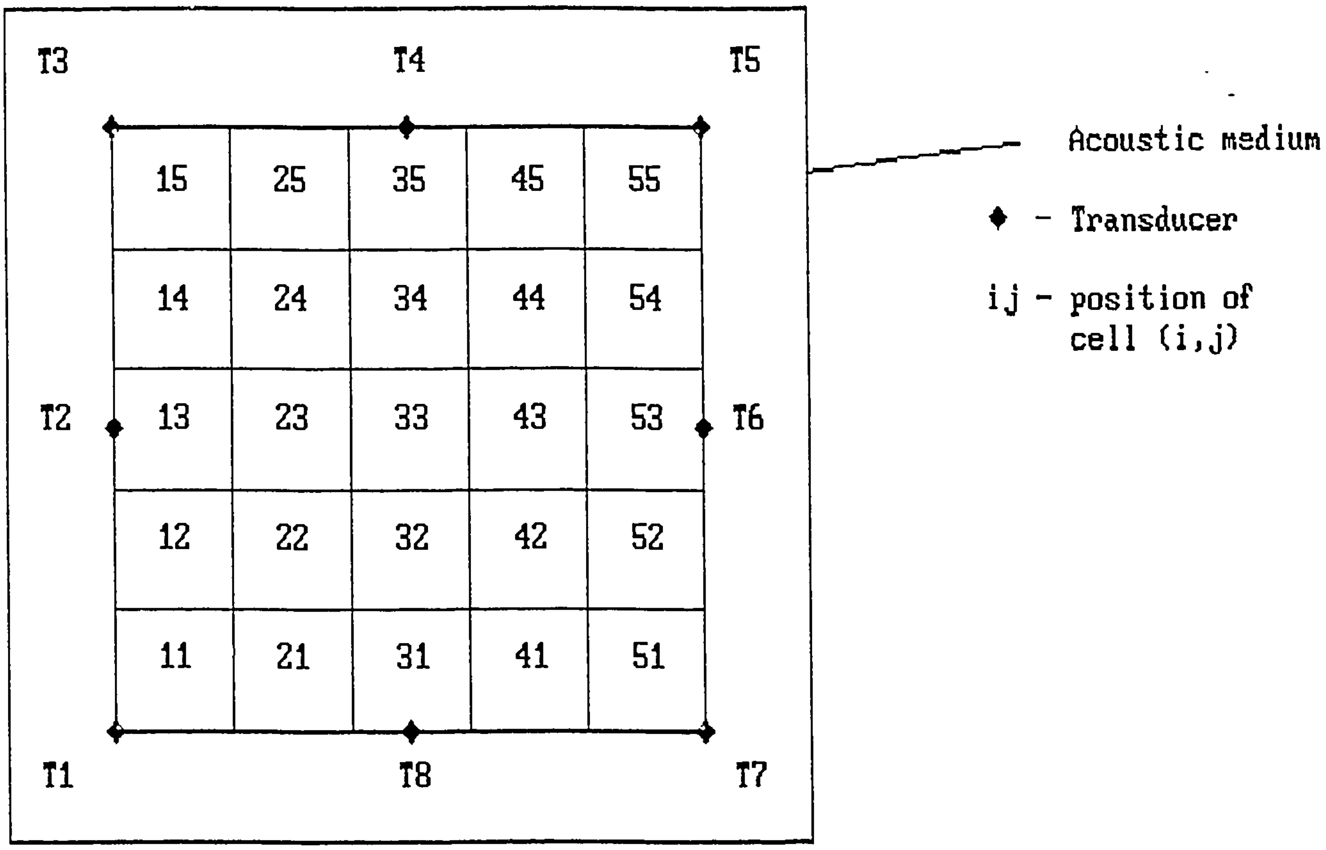


Fig 10 Positions of transducers and cell divisions for system

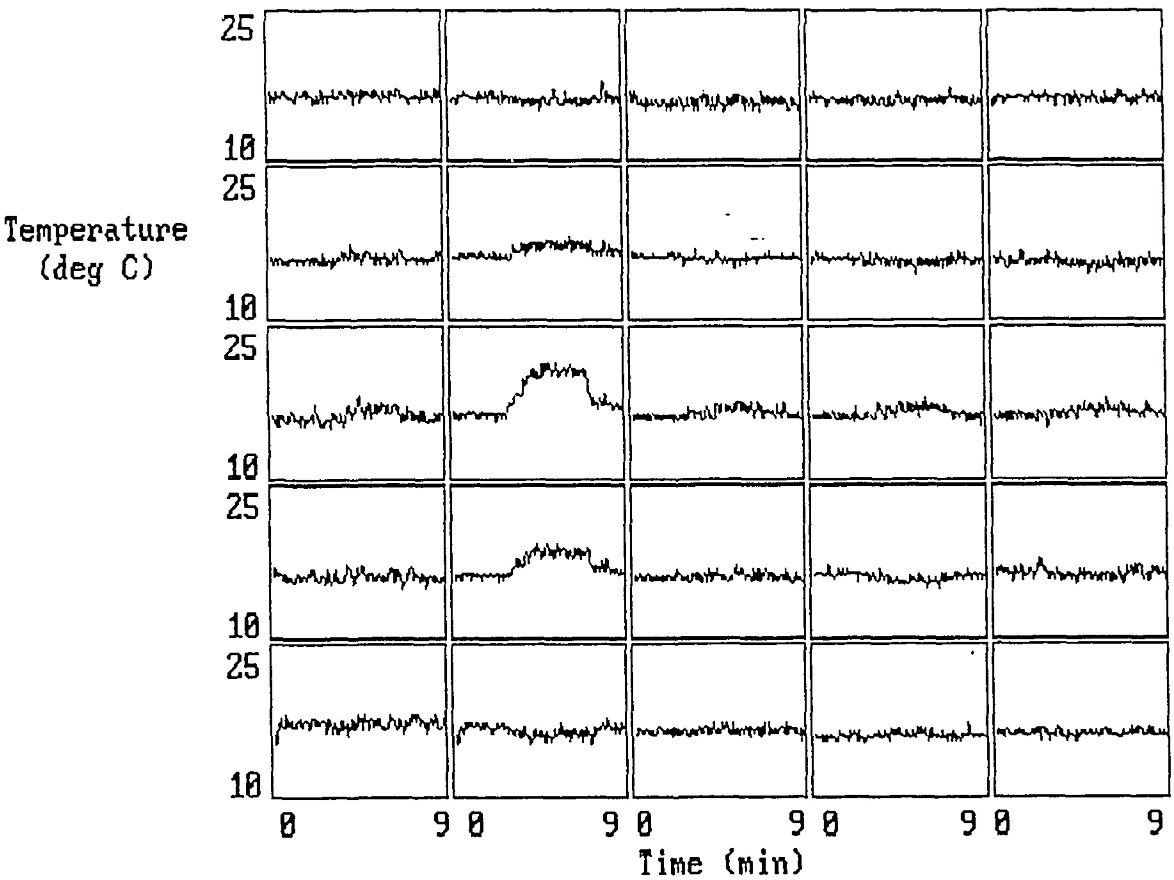


Fig 11 Showing plots of temperature against time for each of the 25 cells in their relative positions.

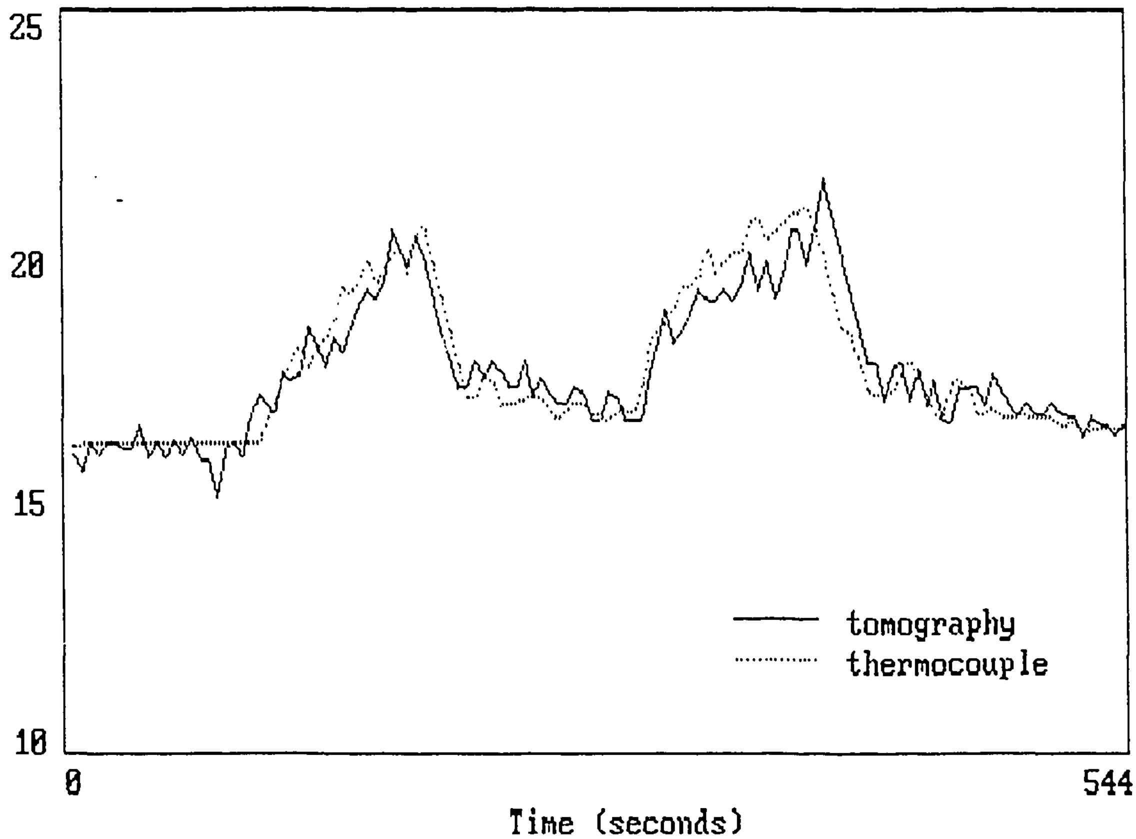


Fig 12 Comparison of tomographical and thermocouple temperature in cell 23 due to switching heat source.