AEA TECHNOLOGY

IAEA IWGFR SM on Steam generators: acoustic/ultrasonic detection of in-sodium water leaks.
Paper for session 3: Experiments with SGUs in service and in experimental loops.

ACOUSTIC TRANSMISSION IN SGUs: PLANT AND LABORATORY MEASUREMENTS

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SUMMARY

In order to assess the performance of an acoustic leak detection system for Fast Reactor steam generator units, it is necessary to have knowledge of the transmission characteristics through the SGU tube bundle, so that the attenuation of sodium/water reaction noise sources can be determined and compared with the plant background noise.

As part of the UK development work an experimental programme is in progress to measure the acoustic transmission through an actual reactor SGU and also through a model tube bundle in the laboratory. This paper gives an outline of the experimental arrangements and examples of the preliminary results. The data from the laboratory measurements in particular is being used for comparison with theoretical studies carried out at the University of Keele which are reported in a separate paper to this Specialist's Meeting.

The plant measurements are being carried out on a Superheater unit of the Prototype Fast Reactor (PFR) at Dounreay. These measurements are primarily aimed at providing information for a loose parts condition monitoring system which is operated on the PFR SGU, but results obtained will make a significant contribution to the acoustic leak detection programme. The Superheater used for the experiment has six blank steam tubes for experimental purposes. An impacting device has been inserted into one of the blank tubes and acoustic signals recorded on waveguides which are attached to the SGU shell. Recordings were made during a reactor shutdown with static sodium in the superheater and with the impacting device at five axial positions in both the inner and outer legs of the 'U' tube. Results are given for signal attenuation and location of the acoustic noise source.

The laboratory measurements are being made using a 721-tube model tube bundle in a water tank. The tube bundle which is approximately 0.75m diameter x 3 metres long is not modelled to a specific design but is of realistic size and construction. A piezo-electric acoustic source is mounted centrally in the tube bundle and the transmitted signal is received by underwater microphones on the periphery of the bundle. Results from the first experiments with water filled tubes are given covering a frequency range of 6KHz to 80KHz.

The preliminary results of the experimental programme are encouraging and indicate that while the transmission is complex the attenuation will not be too severe for an effective acoustic leak detection system.

INTRODUCTION

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As part of the UK development work an experimental programme is in progress to measure the acoustic transmission through an actual reactor SGU and also through a model tube bundle in the laboratory. This paper gives an outline of the experimental arrangements and examples of the preliminary results. The data from the laboratory measurements in particular is being used for comparison with theoretical studies carried out at the University of Keele which are reported in a separate paper[1] to this Specialists Meeting.

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PLANT MEASUREMENTS

Experimental Arrangement

The PFR Superheaters are shown schematically in Fig 1. They are approximately 8 metres high, 1.5 metres in diameter and contain 264 steam 'U' tubes which have an outside diameter of 22mm and a wall thickness of 3mm. The inlet and outlet legs of the 'U' tubes are separated by a concentric baffle. Hot sodium flow enters the base of each superheater shell, passes up a central duct, then flows down past the inner leg of the 'U' tube and up again past the outer leg of the 'U' tube leaving the superheater shell at the top.

One of the Superheaters has six blank steam tubes which have been used for experimental purposes and one of these was selected for the transmission measurements.

The tube chosen for the test has its outer leg in the outermost row of tubes in the outlet side and its inner leg in the innermost row of tubes on the inlet side, thus representing two extremes of tube position relative to the shell. A schematic plan view of Superheater 3 showing the radial position of the tube used is shown in Fig. 2.

An impacting device was designed to simulate loose part rattling and consisted of a steel bobbin which could be suspended by a wire inside the steam tube and excited by a flow of compressed air from the top of the tube. A test arrangement in the laboratory using a 7m length of tube showed that the device produced a series of randomly occurring impulses as illustrated in Fig 3.

Recordings were made during a reactor shutdown with static sodium in the Superheater and with the impacting device at five axial positions in both the outer and inner legs of the tube. The top position corresponded with the centre line of the sodium outlet nozzles and the remaining positions were equally spaced at 1.5m intervals. The bottom position was close to the U-bend region of the steam tubes. Fig 4 shows the relative position of the impacting device excitation points and the waveguides on the superheater shell. Waveguide 3 at Level 1 was not functioning during the measurements.

Detection of Rattling

At all excitation positions in both inner and outer tubes the rattling of the impacting device was detected on all the waveguides.

An example of the acoustic signal seen on each waveguide with the impacting device in the outer tube is shown in Fig. 5. The impacting device was positioned at its lowest position, near to the bottom of the tube, and close to the level 4 waveguides. It should be noted that the amplitude scale on each of the traces in figure 5 is adjusted to give the clearest picture of the pulses at each waveguide. The duration of the sample is about a third of a second. The largest pulses were seen on the level 4 waveguides but can still be seen clearly on the level 1 waveguides at a distance of about 7 metres.

Fig. 6 shows an example of the acoustic signal seen on each waveguide with the impacting device in the inner tube, in this case at the top excitation position (No. 1). As can be seen the acoustic signal amplitudes were smallest on the level 1 waveguides which were closest to the impacting device, while the largest signal was seen on waveguide 10 near the bottom of the unit and close to the U-bend region of the tube bundle. A similar result was obtained at each of the other excitation positions in the inner tube suggesting that the mode of transmission from the inner tube was down the tube to the bend region and then across to the shell. This is considered further below in the section on location analysis.

Measurement of signal amplitudes for up to 16 pulses similar to those shown in Figs 5 and 6 for each waveguide at each excitation position has shown that attenuation of acoustic signal amplitudes in the superheater shell is small, between 2 and 5dB per metre.

Signal Amplitudes

For the impacting device in the outer leg of the tube, Fig 7 shows an amplitude distribution for acoustic pulses measured at a waveguide on the shell close to each excitation position compared with the distribution of pulse amplitudes obtained directly on the tube from the laboratory measurements. The attenuation in signal amplitudes compared with the measurement directly on the tube in the laboratory tests was between 20 and 35dB (a factor of between 10 and 56). These figures exclude any correction for attenuation in transmission through the shell to the various waveguides but since this is small, between 2 and 5dB/metre, it can reasonably be neglected to give a worst case value.

Fig 8 shows an amplitude distribution for acoustic pulses measured at waveguide 10 for each excitation position in the inner leg of the tube, again compared with the laboratory measurements directly on the tube. For excitation positions 1, 2 and 3 the signal attenuation is very similar and about 40dB or a factor of 100 compared with the measured levels on the tube in the laboratory. At excitation position 5 and axially close to waveguide 10 the signal attenuation is only about 24dB (a factor of 16) and very similar to that obtained with the impacting device in the outer tube as given in Fig 7. A comparison of the signal amplitudes from excitation positions 1, 2 and 3 imply an attenuation of acoustic signal amplitudes down the tube of less than 0.2dB per metre. This is an important result and suggests that a significant acoustic path from within a steam generator may be along the steam tubes, the tubes in themselves acting as waveguides. For the EFR, with an overall steam tube length of 33.3m, the maximum attenuation would be less than 4dB from the mid point of the tubes to either end. There will of course be energy losses in coupling from the tubes to the tubeplate, the magnitude of the loss depending on the method of attachment, and also attenuation across the tube plate. However, the indications are that an enhanced acoustic monitor may be possible by including acoustic waveguides on the tube plate in addition to those on the steam generator shell. It is proposed to include measurements of signal attenuation at and across the tube plate in the current experimental programme.

Comparison of Signal Amplitudes with Background Noise During Normal Reactor Operation

It is instructive to compare the signal amplitudes produced by the impacting device with the background noise measured on Superheater 3 during normal reactor operation since this could provide a route for estimating the detection sensitivity of the acoustic monitoring system.

A simplified approach to this is shown in Fig. 9 where a distribution of signal amplitudes from the waveguide which typically measures the largest background noise signal during normal operation is compared with the smallest and largest signals measured on any waveguide at any excitation position. It can be seen that even in the worst case the rattling produced by the impacting device would be detected by a margin of a factor of two and up to an order of magnitude in the most favourable circumstances.

Location Analysis

While detection of noise sources is of primary importance in the SGU in-service condition monitoring, location of the source of the acoustic signals can provide two additional advantages. Firstly, it will provide valuable information which can be used to assess the possible cause of the noise and to assist inspection teams to make the choice of optimum regions of the SGU to monitor during shutdown and secondly it can allow selective monitoring of specific regions of interest on the SGU.

Location of impulsive acoustic signals can be made effectively by measuring the arrival time of pulses at each sensor. Then from the differences in arrival times at different pairs of sensors the location can be computed by, for example, plotting sets of hyperbolae using a known or assumed velocity of sound This is the method used here. An alternative method which would also be applicable to continuous noise signals is to employ beamforming techniques using multiple sensors as described in a companion paper to this Specialists Meeting[2].

Fig. 10 shows an example of a typical acoustic pulse from the impacting device at the bottom excitation position (No.5) in the outer tube as seen on each waveguide. The variation in arrival times at each sensor can be seen clearly, the pulse arriving earliest at waveguides 10 and 12 which were closest to the excitation position. Fig. 11 shows an example of a pulse from the impacting device inserted in the inner tube at the top position (No. 1), and again the different arrival times of the pulse at each waveguide can be seen clearly. However it can be noted that the pulse is seen first on the level 4 waveguides close to the bottom of the SGU and furthest away axially from the excitation position. This confirms the indication given above in the discussion of signal amplitudes that transmission from the inner tube is predominantly down the tube to the bend region and then across to the shell arriving first at the level 4 waveguides and then transmitting through the shell to the other waveguide positions.

The traces in figures 10 and 11 were produced by signal averaging techniques which enhance signal to noise ratio for repetitive events. A similar analysis was made for each of the excitation positions averaging up to 16 pulses. The differences in arrival times were measured and used to compute source locations in each case by plotting the corresponding hyperbolae. An example location plot is shown in Fig. 12 for excitation position no.1 in the inner tube. In an ideal case the various hyperbolae should cross at a single point, the source location. In practice inaccuracies in measurement of time delays and uncertainties in the transmission velocities result in some scatter in the crossing points of pairs of hyperbolae. However examination of figure 12 shows that a region of multiple crossings of the hyperbolae can be identified clearly, as shown in the figure by the circle which is equivalent to an area of 0.3m diameter on the superheater shell.

Figs 13 and 14 show estimated source locations derived by the above method for each excitation position in outer and inner tubes respectively drawn onto a view of the unwrapped superheater shell.

For the outer tube, examination of Fig.13 shows that the estimate of source location circles the actual excitation position in 3 out of the 5 cases with a possible error of less than 0.3m. Maximum error occurred at position 2 where the circle of best estimate of source location gives an error of about 0.5m in the worst case. The good results from this location analysis supports the assumption that has been made in previous work that, for the outer tubes at least, the transmission of acoustic signals is to the shell at the closest point and then around the shell to the waveguides.

Fig. 14 shows the best estimates of source location for the inner excitation positions. The circles of best estimated source location for each excitation position overlap. The location for excitation position 3 fits less well in the cluster of indications from the other four excitation positions but appears to give the best indication of the actual source position. The scatter is assumed to represent the uncertainties in what is a complex transmission path but clearly the primary transmission path from the inner tube is down the tube to the lower part of the unit and across to the shell. As shown in Fig 14 the transmission to the shell is in the region of the thicker grids 20/13 and 18/15 between which is the 'T'-forging which links the inner and outer parts of the central baffle and which could contribute to the acoustic transmission path. While one consequence of the indicated transmission path from the inner tube is that it is unlikely that axial location of acoustic sources in the inner tube will be possible, it does apparently give much larger acoustic signal amplitudes on the shell waveguides than would occur if transmission was radially through the tube bundle only, giving improved capability for detection.

Future Work in Plant Measurements

The measurements described here have provided valuable information to assist in the interpretation of noise signals from the steam generators and in the understanding of acoustic transmission from extremes of tube position within the tube bundle. However no data is yet available on transmission from tubes in intermediate positions in the bundle. Since the impacting device operated successfully, was relatively easy to use on the superheater and has provided good information, it is proposed that a further set of measurements be made at a suitable time during a reactor shutdown to determine the transmission paths from tubes in intermediate positions. One tube of the six blank steam tubes available, has one leg in the innermost row of tubes on the outlet side and the other leg in the outermost row of tubes on the inlet side and would therefore be particularly suitable for further measurements.

LABORATORY MEASUREMENTS

The measurements described above have given practical experience and valuable information on acoustic transmission properties in the complex structure of an operational Fast Reactor SGU. However, in order to provide data for comparison with theoretical modelling work, a more carefully controlled experimental arrangement is required under laboratory conditions.

A programme of measurements is in progress in the UK using arrays of tubes and a 'model' tube bundle in a large water tank facility (HECTR - Heat ExChanger Transmission Rig) at the Risley Laboratories. The tube bundle, shown in Figure 15, does not model a specific SGU design but is large, approximately 3m high x 0.75m diameter and containing 720 tubes, and is of a suitable size to provide a realistic simulation of a steam generator. Data obtained will be used to validate the mathematical models which can then be used to predict transmission characteristics for various engineering designs.

Some preliminary results from the series of experimental measurements with the tube bundle are given below.

Experimental Arrangement

The experimental arrangement is shown schematically in Fig 16. The tube bundle was centrally positioned in a 3m high x 3m diameter water tank. The bottom of the tube bundle can be open or sealed to allow measurements with water or air filled tubes. The measurements described here were made with water filled tubes. With the tank filled to its normal operating level the tube bundle was covered to within 0.32m of the top of the tubes. Before installation of the bundle in the tank a small number of tubes were removed allow insertion of acoustic sources at selected positions in the tube bundle.

For the measurements described here a miniature hydrophone was inserted in the central channel about 1.6m below the top of the tube bundle and used in the transmission mode as an acoustic source. A hydrophone was placed adjacent to the transmitter to record the source amplitude. A third hydrophone was suspended vertically on the periphery of the bundle at the same vertical height as the source and separated from it by a distance of 0.35m and by 15 rows of tubes. In order to provide accurate amplitude measurements, each of the hydrophones used were calibrated against a standard hydrophone.

Measurements and Results

Acoustic excitation was generated in the form of sine wave tone bursts so that the received acoustic signals could be gated and the effects of reflections from the tank wall could be eliminated. The frequency of the source was varied over the range 6KHz to 80KHz in 2KHz steps and at each step the received signal at each hydrophone was amplified and digitised for analysis. Attenuation through the tube bundle was measured by comparing the peak signal amplitude at the hydrophones on the periphery with the amplitude recorded on the reference hydrophone close to the source at the centre.

Figure 16 shows the attenuation of the acoustic signal as received at the hydrophone at the same axial height as the source. Also shown in Figure 16 for comparison is the attenuation obtained with the same hydrophones at the same relative distances but placed outside the tube bundle i.e. in water only. In this case the it can be seen that the results obtained agree well with the predicted inverse square law attenuation and confirm the general validity of the experimental arrangement over the frequency range considered. Considering transmission through the tube bundle, it can be seen in Figure 17 that up to about 50KHz, the attenuation through the tube bundle is within the range 38 to 46dB which is only about 7 to 15dB greater than that predicted by the inverse square law for transmission through water alone. Above 50KHz the attenuation increases steadily up to about 57dB at just over 60KHz and then remains essentially constant at this level up to highest measurement frequency of 80KHz. The frequency range in which this additional attenuation of between 11 and 19dB occurs corresponds to frequencies at which the wavelength of sound in the liquid is less than the pitch of the tubes in the bundle, the wavelength being equal to the tube spacing at between 52 to 59KHz depending on orientation. This is in agreement with theory and is considered in more detail in the companion paper to this Specialists Meeting [1].

Applying these results to the EFR design, with a tube pitch of 33.9mm and in sodium, the cut-off frequency at which the wavelength of sound becomes equal to the tube spacing would be about 68KHz suggesting a useable frequency range for acoustic leak detection system could be expected to be up to about 60KHz.

Future Work in Laboratory Measurements

The results presented above are from preliminary experiments with the model tube bundle. Further work is continuing and is planned. This will include measurements with air-filled tubes, plotting the acoustic path through the bundle, modifying the acoustic source, measuring the transmission to the tube plate and checking the effect of grid plates. In addition measurements will be made with a simpler tube array using a small number of rows of tubes to allow a more carefully controlled comparison with theory.

CONCLUSIONS

The experimental programme to determine acoustic transmission characteristics of steam generator tube bundles is still continuing. However, the information obtained so far from the transmission experiments on both the plant and in the laboratory is very encouraging from the point of view of acoustic leak detection for EFR steam generators.

The measurements on the PFR Superheater while primarily for loose parts monitoring have shown that an acoustic source can be readily detected throughout a plant size unit. For the outer tubes at least the transmission of acoustic signal appears to be to the shell at a point close to the excitation point and then around the shell to the various waveguides. This provides a simple but physically realistic model for determining source positions. The attenuation in the shell is between 2 and 5dB/metre. Transmission from the inner tube was more complex but the dominant transmission path appears to be down the tube to the bend region, across to the shell, and then around the shell to waveguides. This transmission path may be peculiar to the the PFR design with its double central baffle which separates the inner and outer legs of the steam tubes. It is hoped to confirm the effect of this central baffle in a second series of experiments on the superheater in the near future. However, it appears that an important acoustic transmission route is along the steam tubes and that sensors attached to the tubeplate could make a valuable contribution to an acoustic leak detection system. Additionally, sensors fitted to the inlet tubeplate would allow optimum acoustic monitoring for leaks in the possibly critical region around the tube to tubeplate welds which are under sodium.

Preliminary results from the laboratory measurements with a model tube bundle have shown that attenuation through 15 rows of tubes is relatively low, only 7 to 15dB above greater than in open liquid, over a relatively wide range of frequencies up to about 50KHz. Above this frequency where the wavelength of sound becomes equal to or less than the spacing of the tubes an additional attenuation of up to 19dB is observed. Applying these early results to the EFR case would indicate that in the absence of multiple internal baffles as in the case of PFR superheaters, significant transmission of sound through a steam generator tube bundle to the shell could be possible and that a optimum frequency range for acoustic leak detection scheme could be up to 60KHz.

REFERENCES

1. Heckl, M. "Sound propagation in the steam generator - a theoretical approach." IWGFR SM2: Steam generator: acoustic/ultrasonic detection of in-sodium water leaks, session 2. Aix-en-Provence, Oct 1990.

2. McKnight J A, Rowley R and Beesley M J. "Acoustic surveillance techniques for SGU leak monitoring." IWGFR SM2: Steam generator: acoustic/ultrasonic detection of in-sodium water leaks, session 2. Aix-en-Provence, Oct 1990.

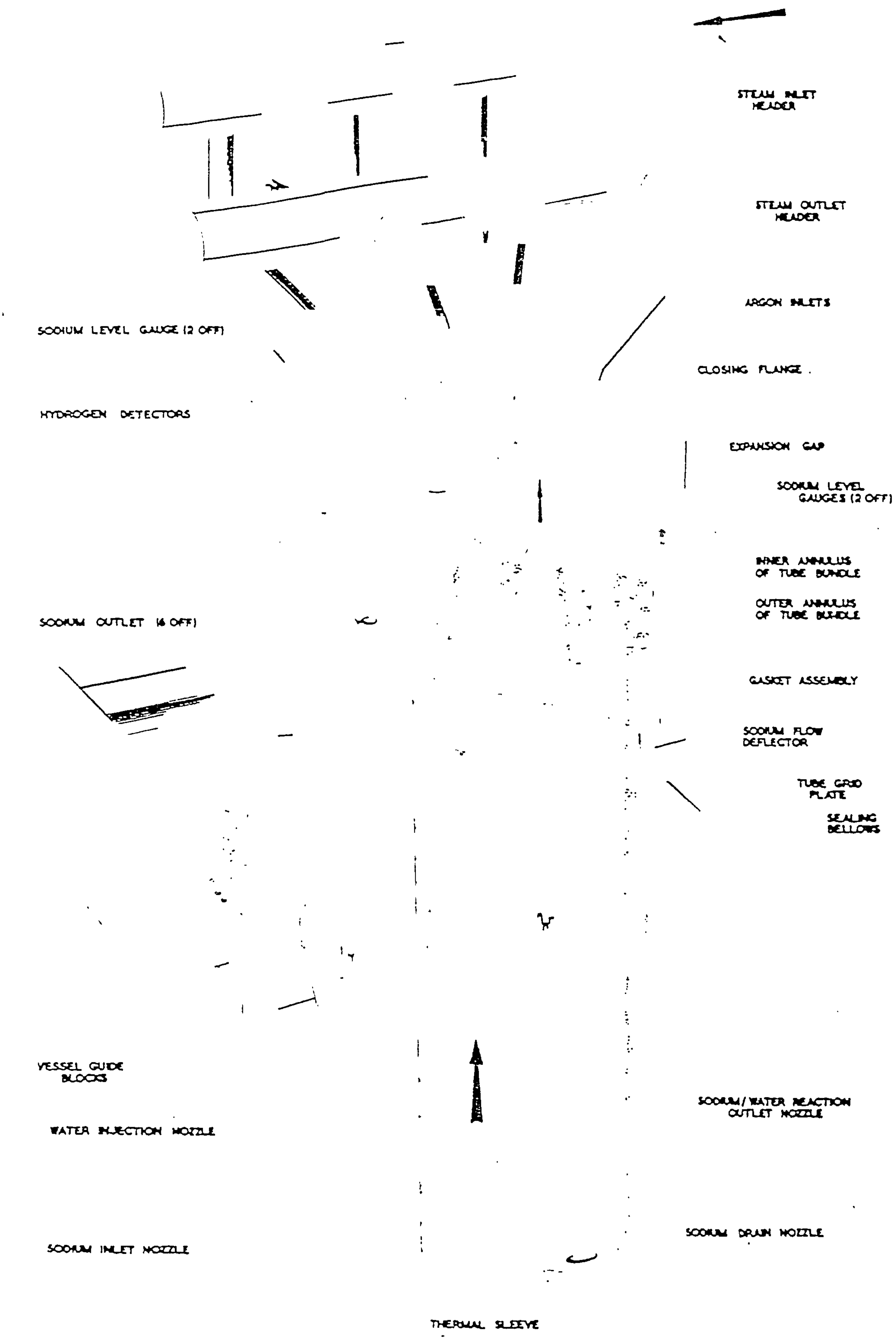


Fig 1 PFR Superheater

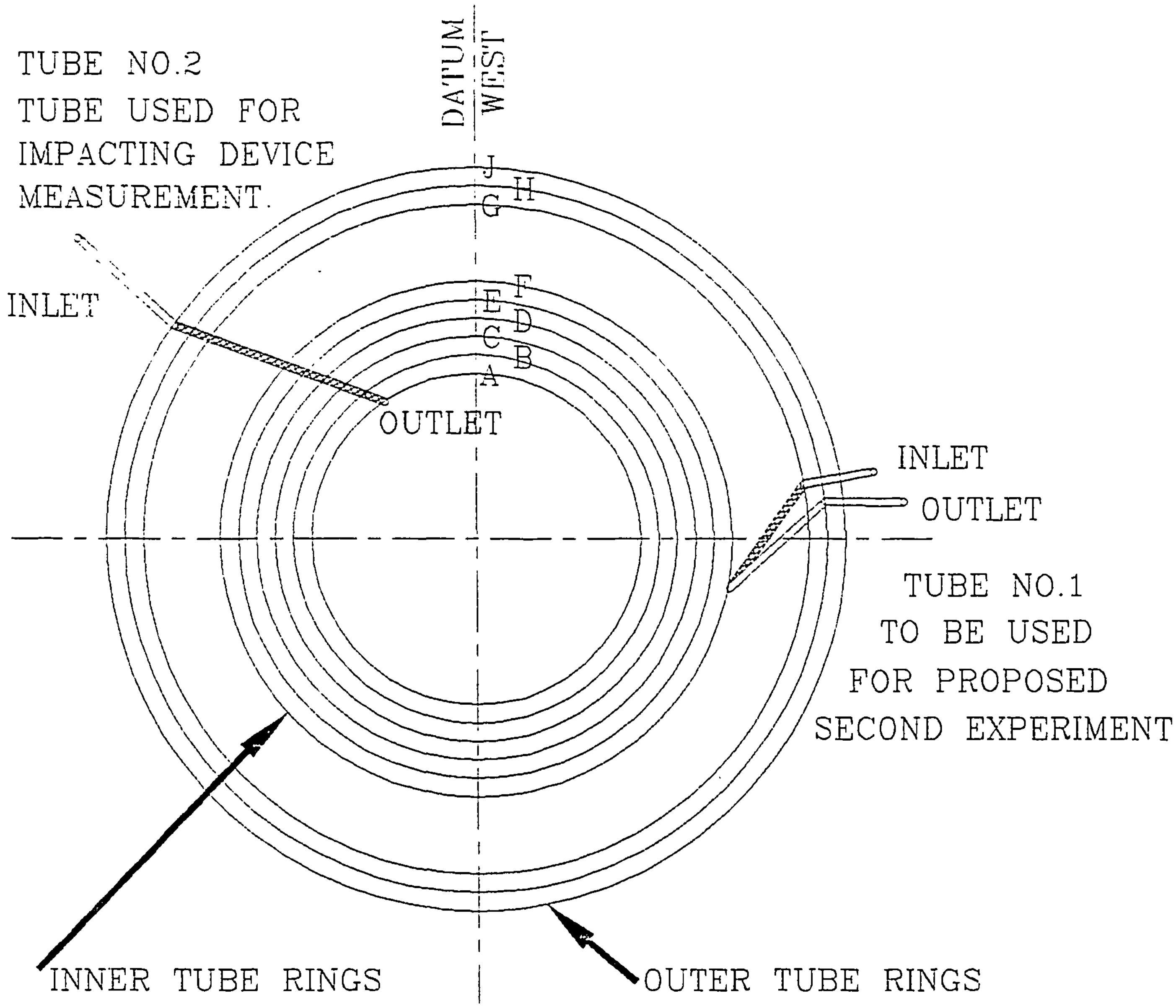


FIGURE 2 SCHEMATIC PLAN VIEW OF SUPERHEATER 3 RTB SHOWING BLANK STEAM TUBE USED FOR ACOUSTIC TRANSMISSION TEST.

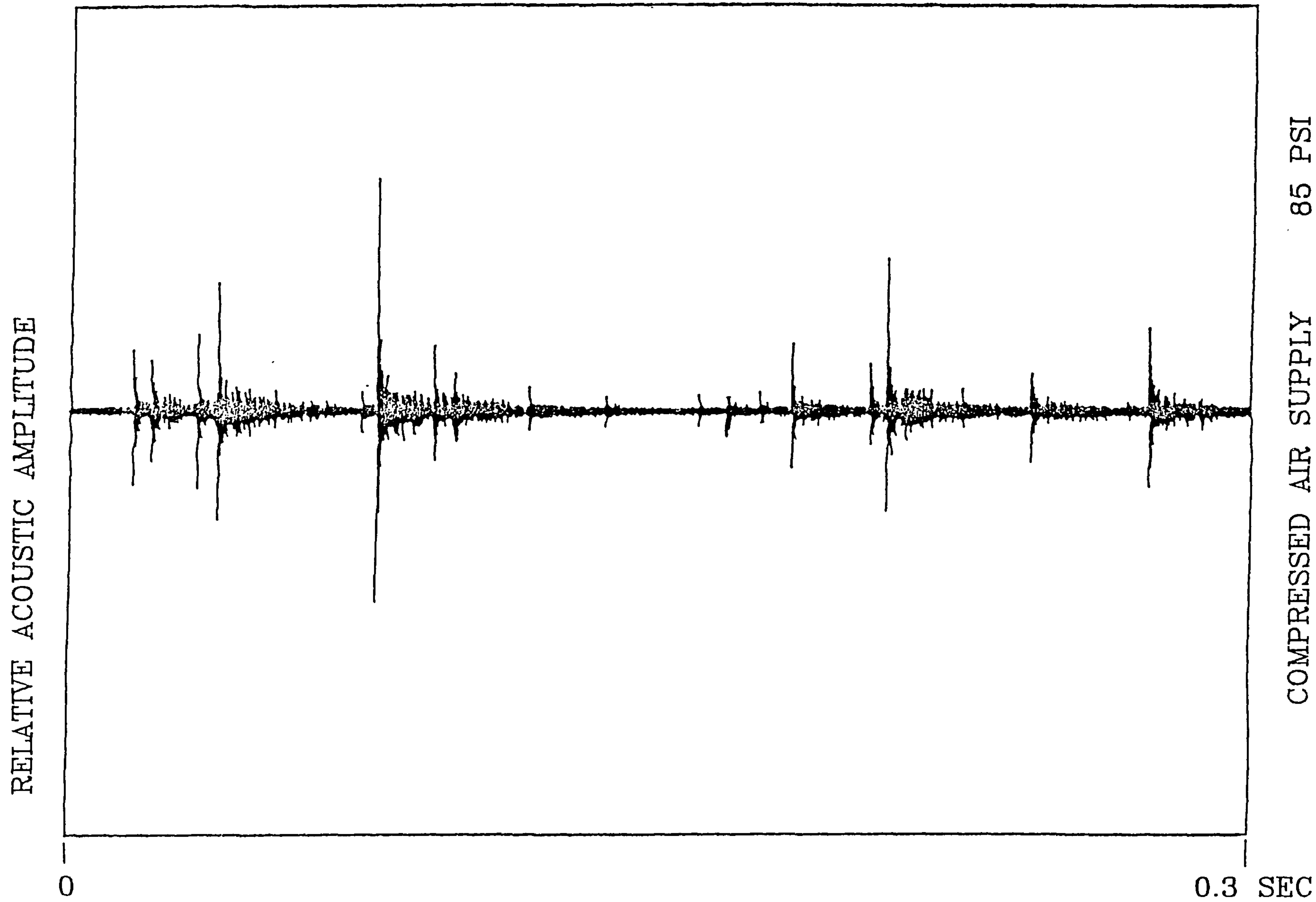


FIGURE 3 TYPICAL SAMPLE OF ACOUSTIC SIGNAL FROM LABORATORY CALIBRATION USING IMPACTING DEVICE.

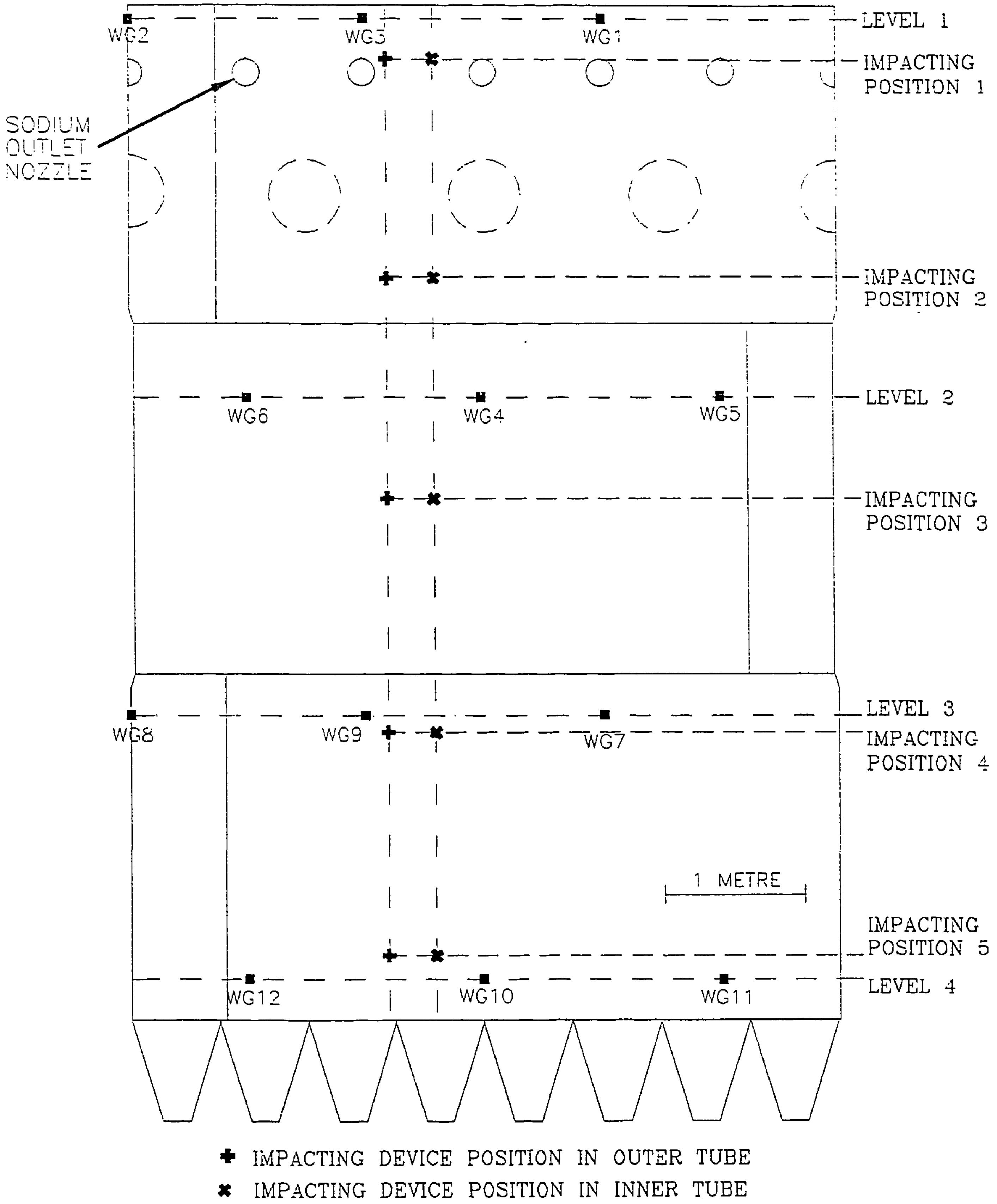
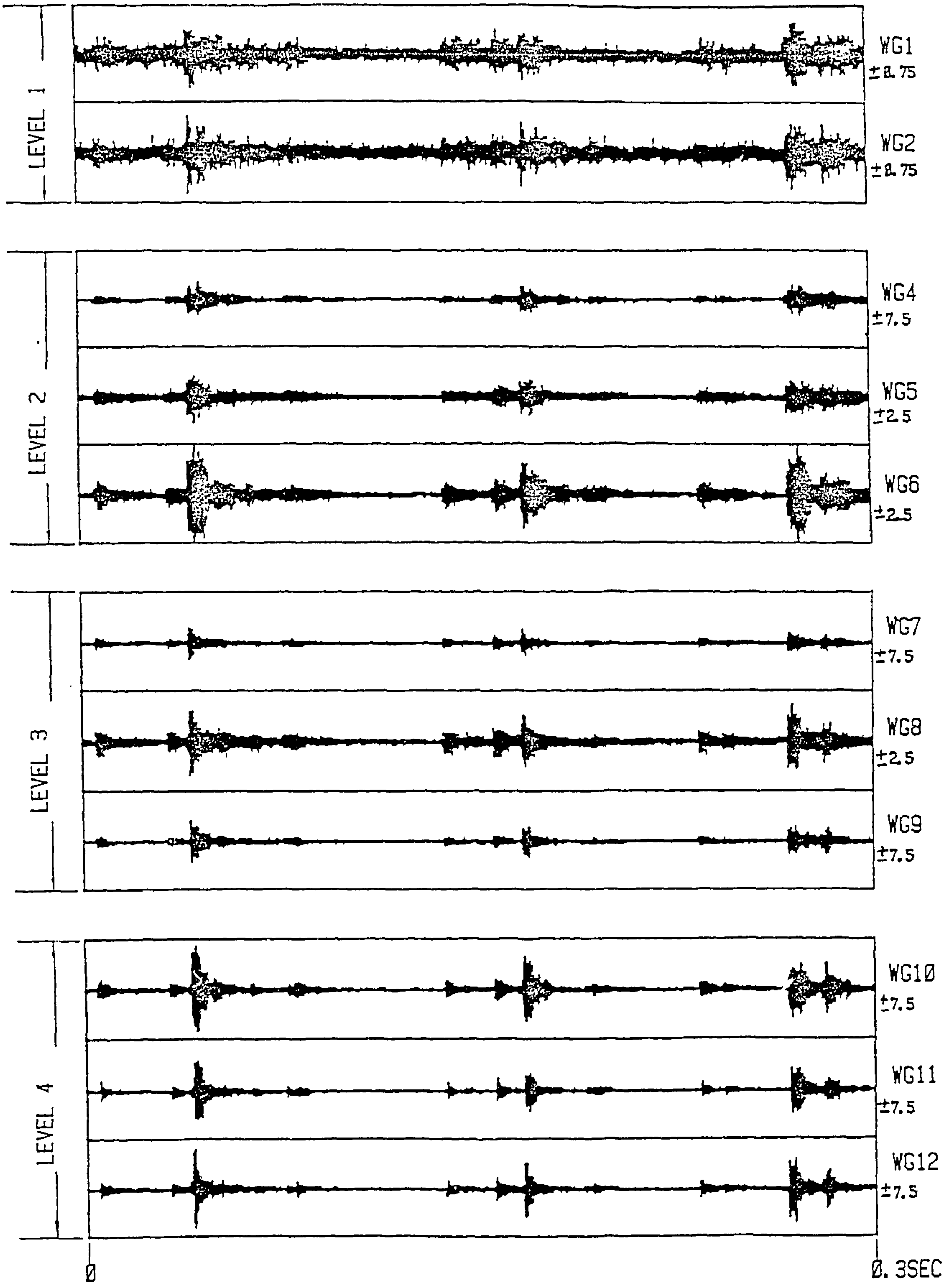


FIGURE 4 TRANSDUCER AND IMPACTING DEVICE POSITIONS ON UNWRAPPED VIEW OF SUPERHEATER SHELL

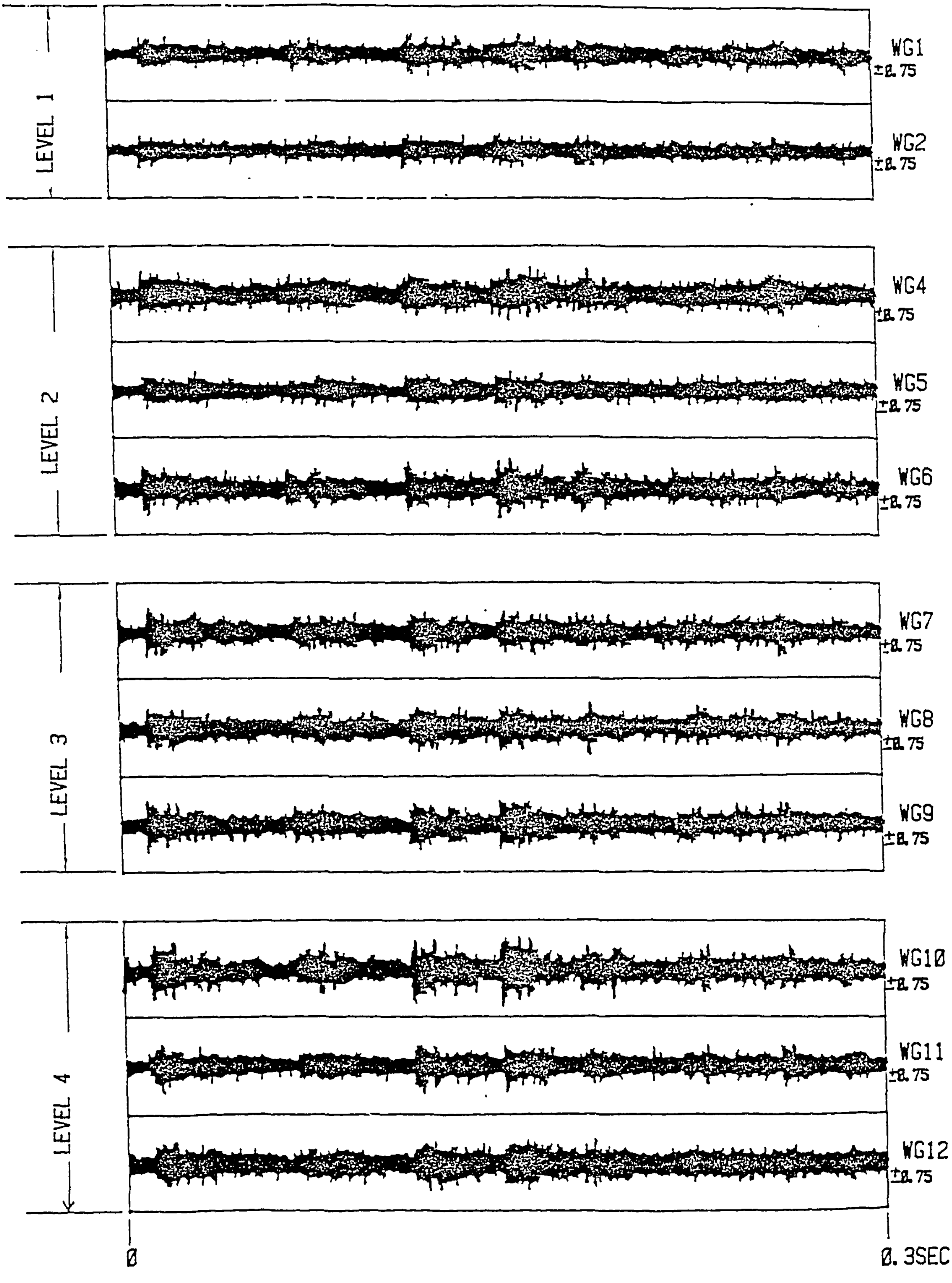
SAMPLES OF ACOUSTIC SIGNALS ON EACH WAVE GUIDE.
IMPACTING DEVICE IN OUTER TUBE - POSITION 5.

FIG. 5



SAMPLES OF ACOUSTIC SIGNALS ON EACH WAVE GUIDE.
IMPACTING DEVICE IN INNER TUBE - POSITION 1.

FIG. 6



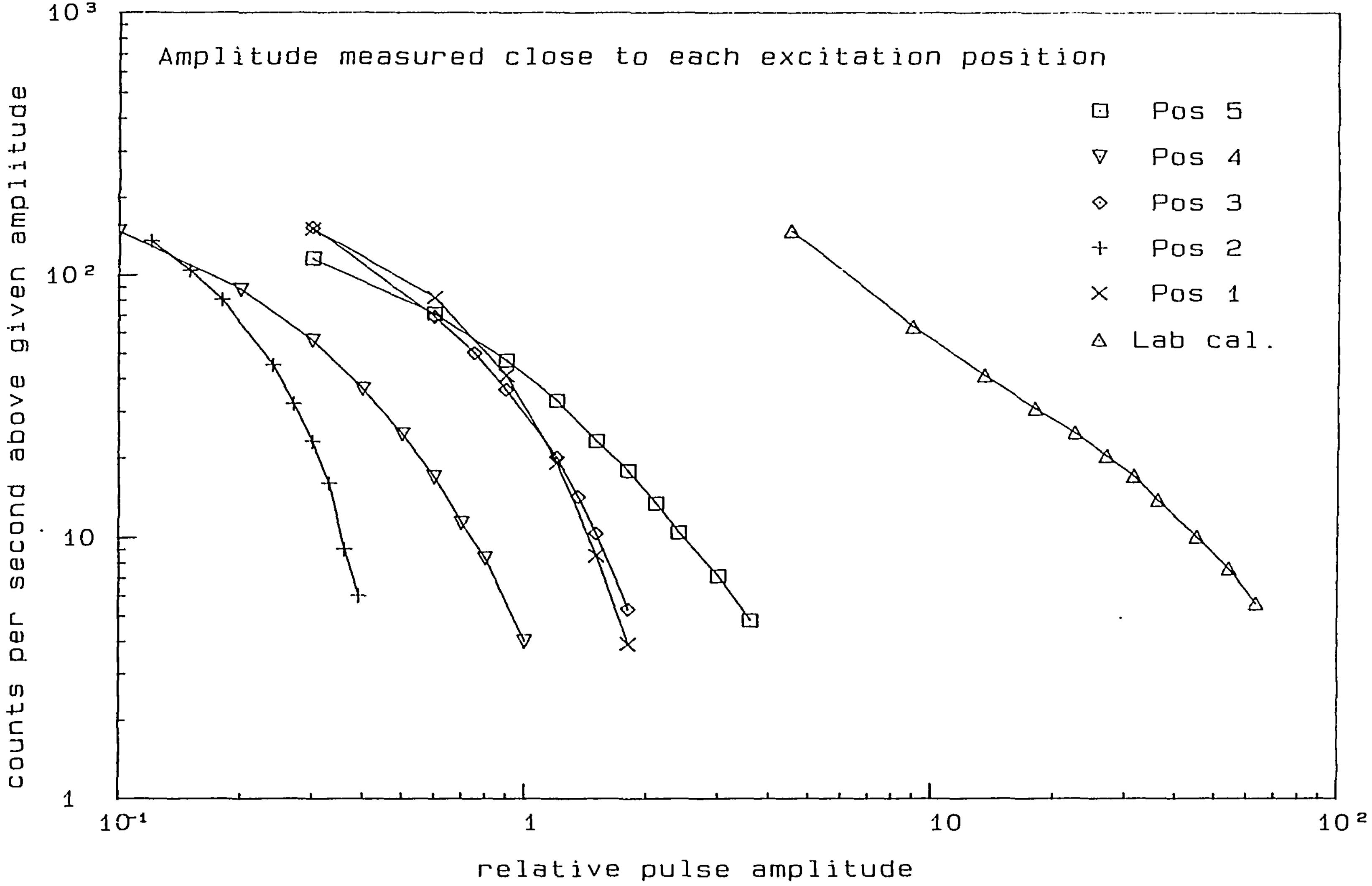


Fig 7 Pulse amplitude distribution with excitation in outer tube

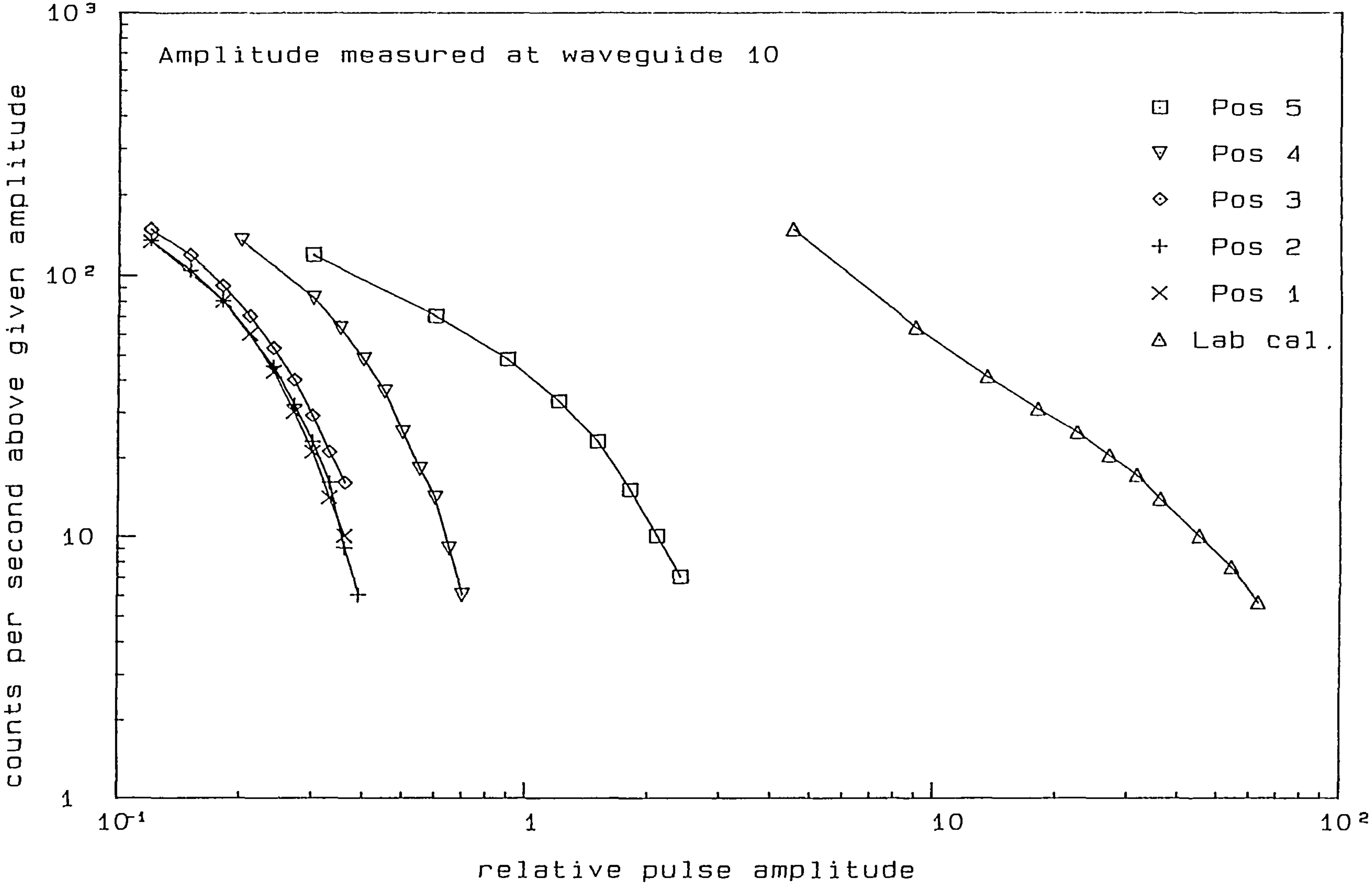


Fig 8 Pulse amplitude distribution with excitation in inner tube

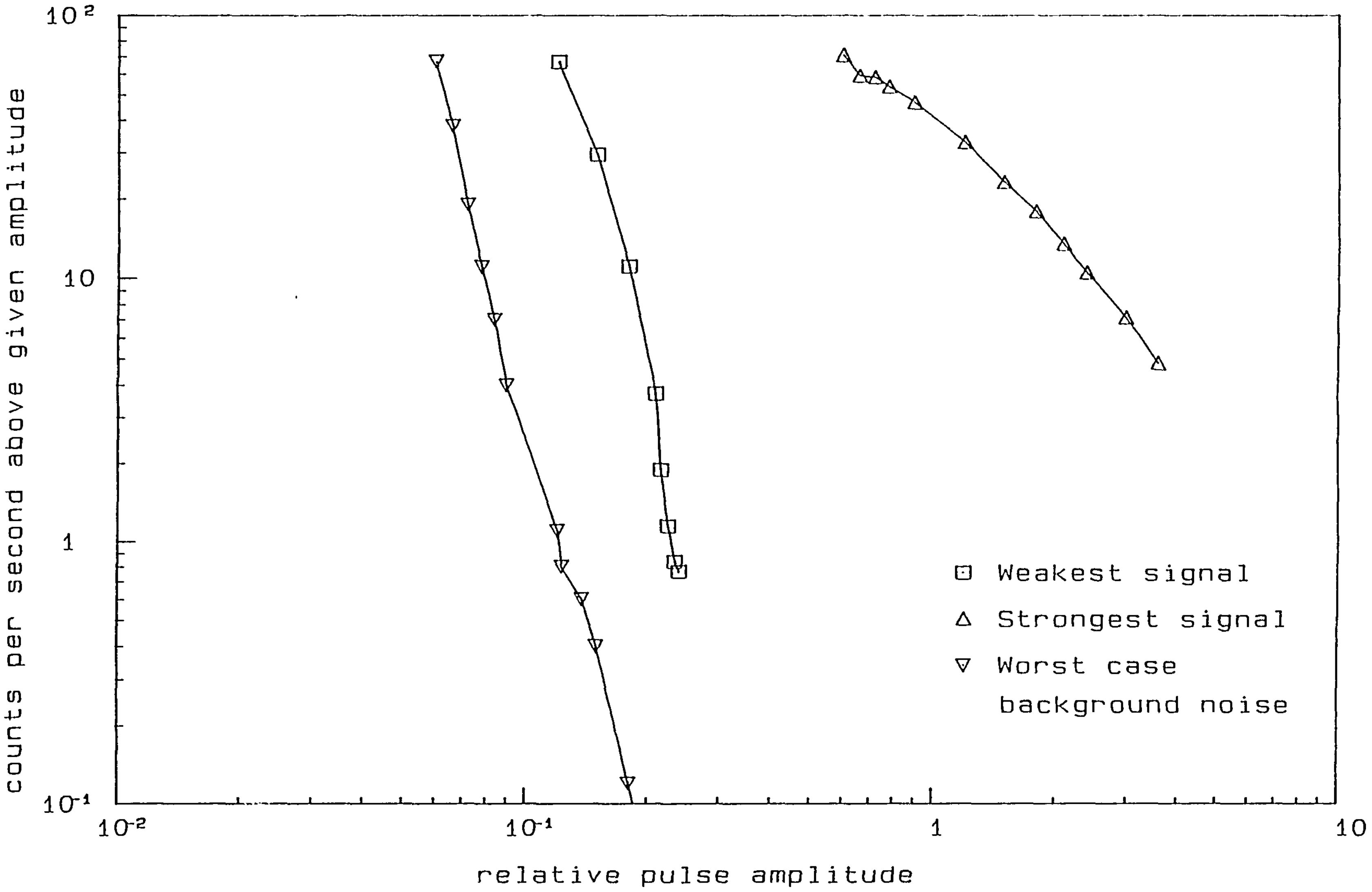
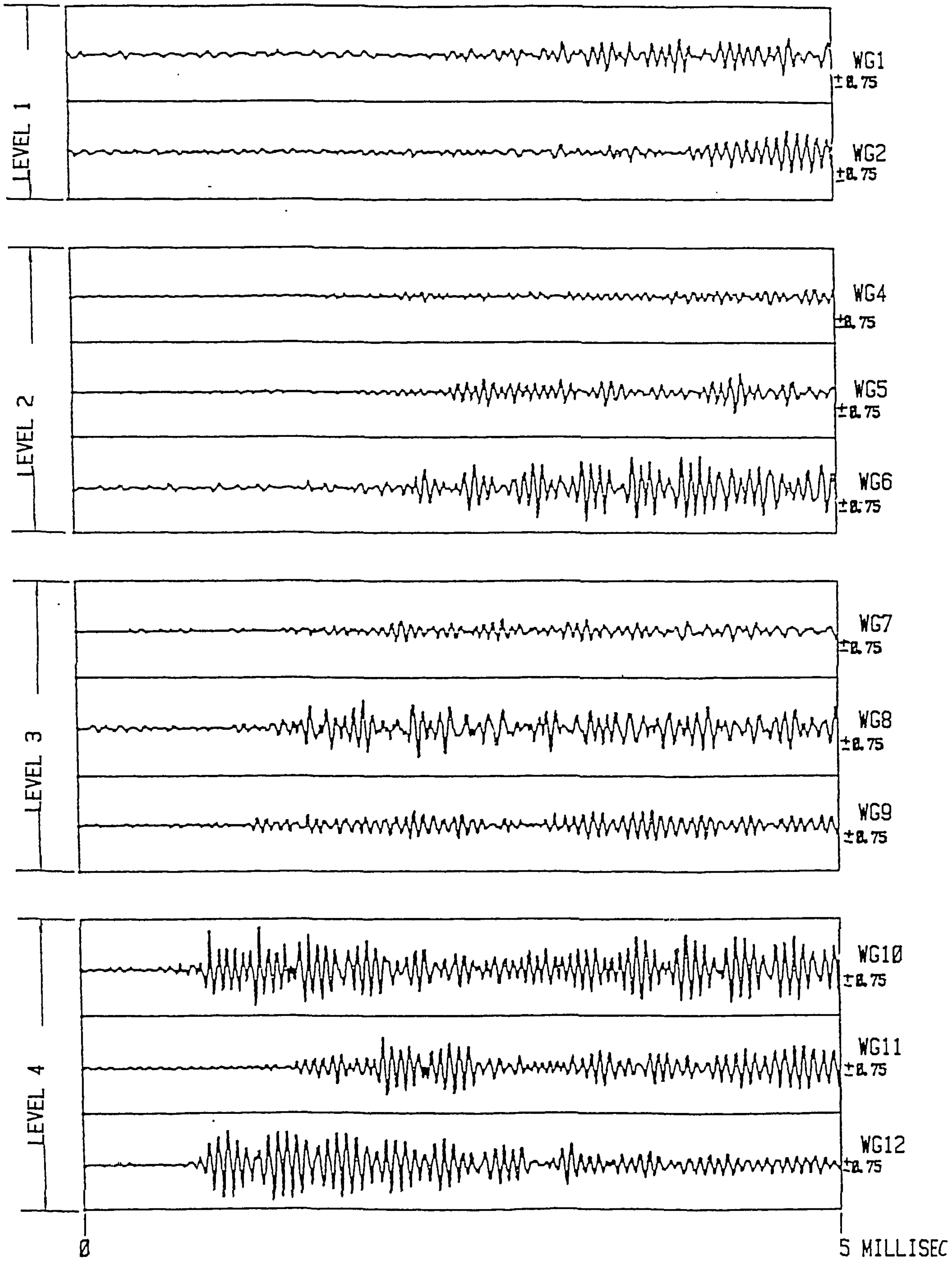


Fig 9 Comparison of impacting signal with reactor background noise

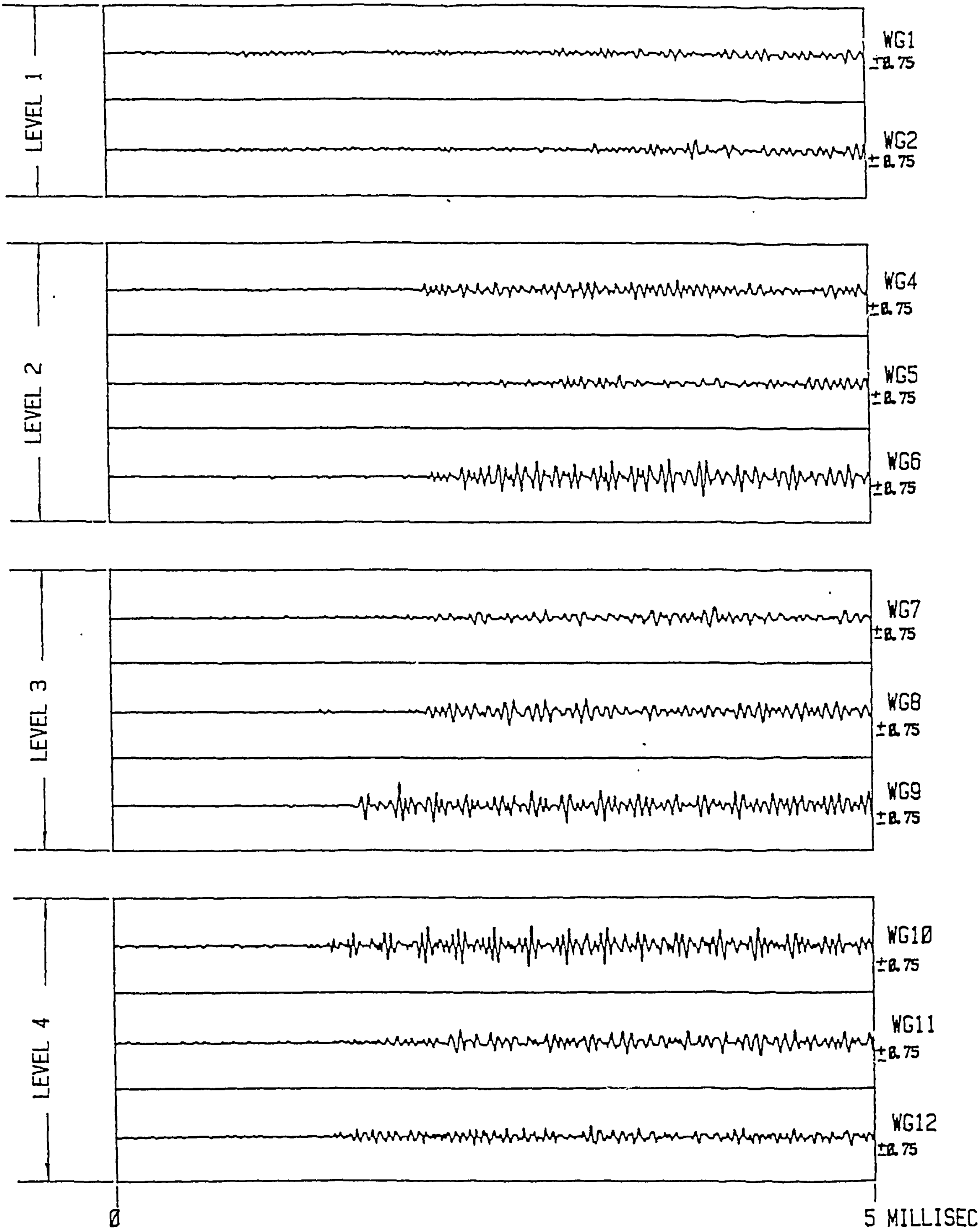
TYPICAL ACOUSTIC PULSE.
IMPACTING DEVICE IN OUTER TUBE - POSITION 5.

FIG. 10



TYPICAL ACOUSTIC PULSE.
IMPACTING DEVICE IN INNER TUBE - POSITION 1.

FIG. 11



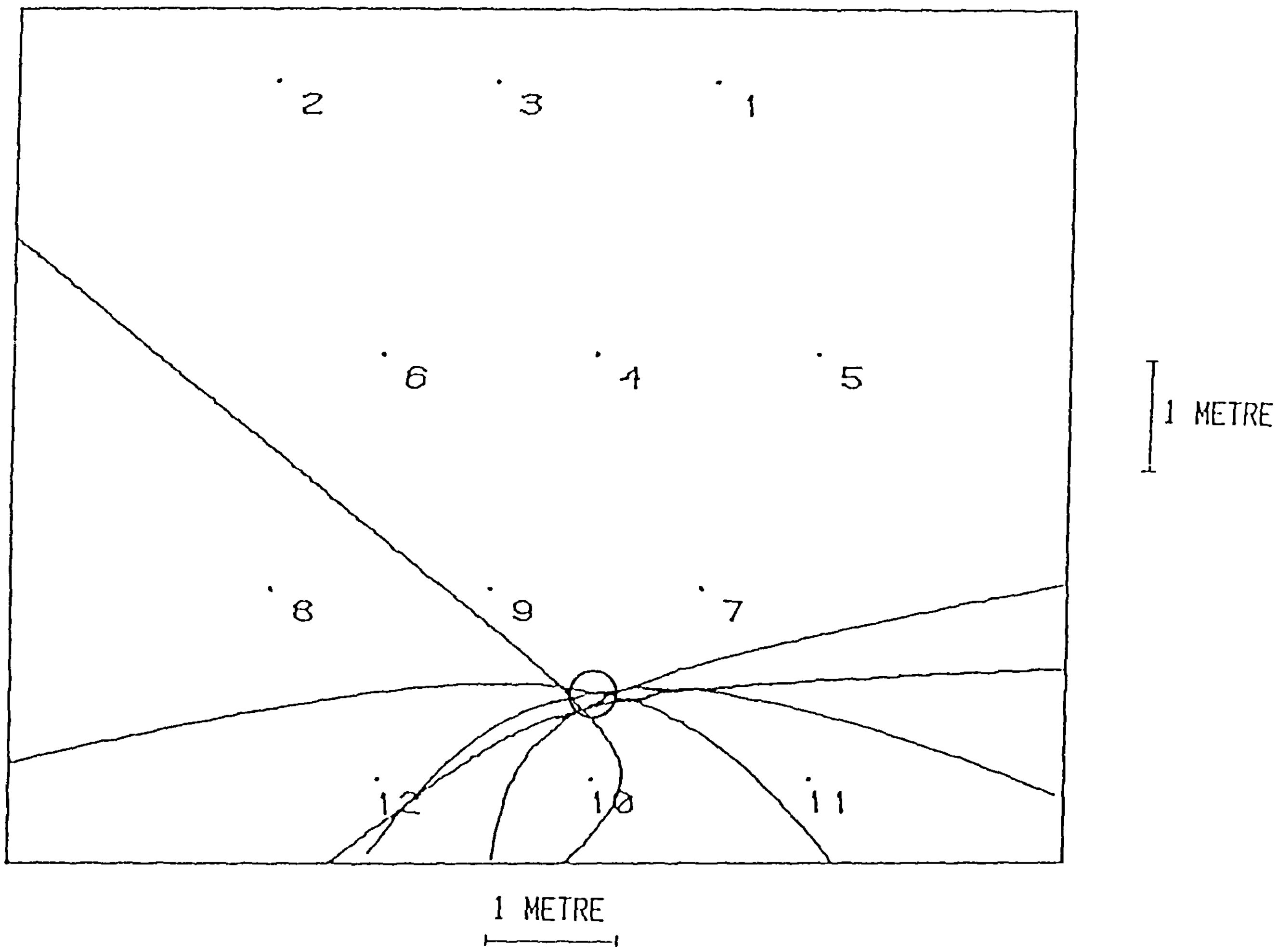


FIGURE 12 LOCATION PLOT OF THE ESTIMATED PATH TO THE SHELL OF ACOUSTIC SIGNALS FROM THE INNER TUBE, NOISE POSITION 1.

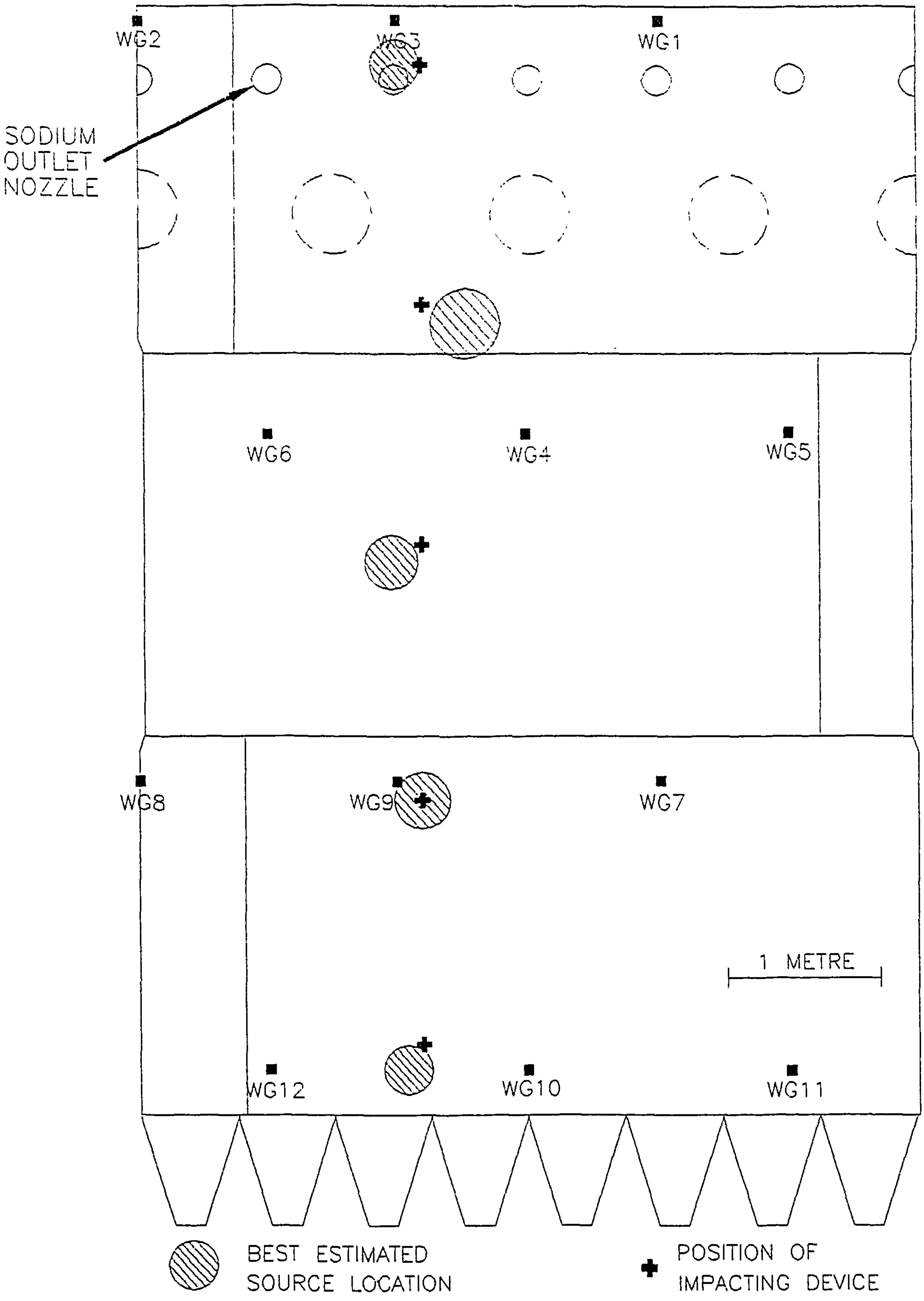


FIGURE 13 ESTIMATED LOCATIONS FOR THE IMPACTING DEVICE IN THE OUTER TUBE.

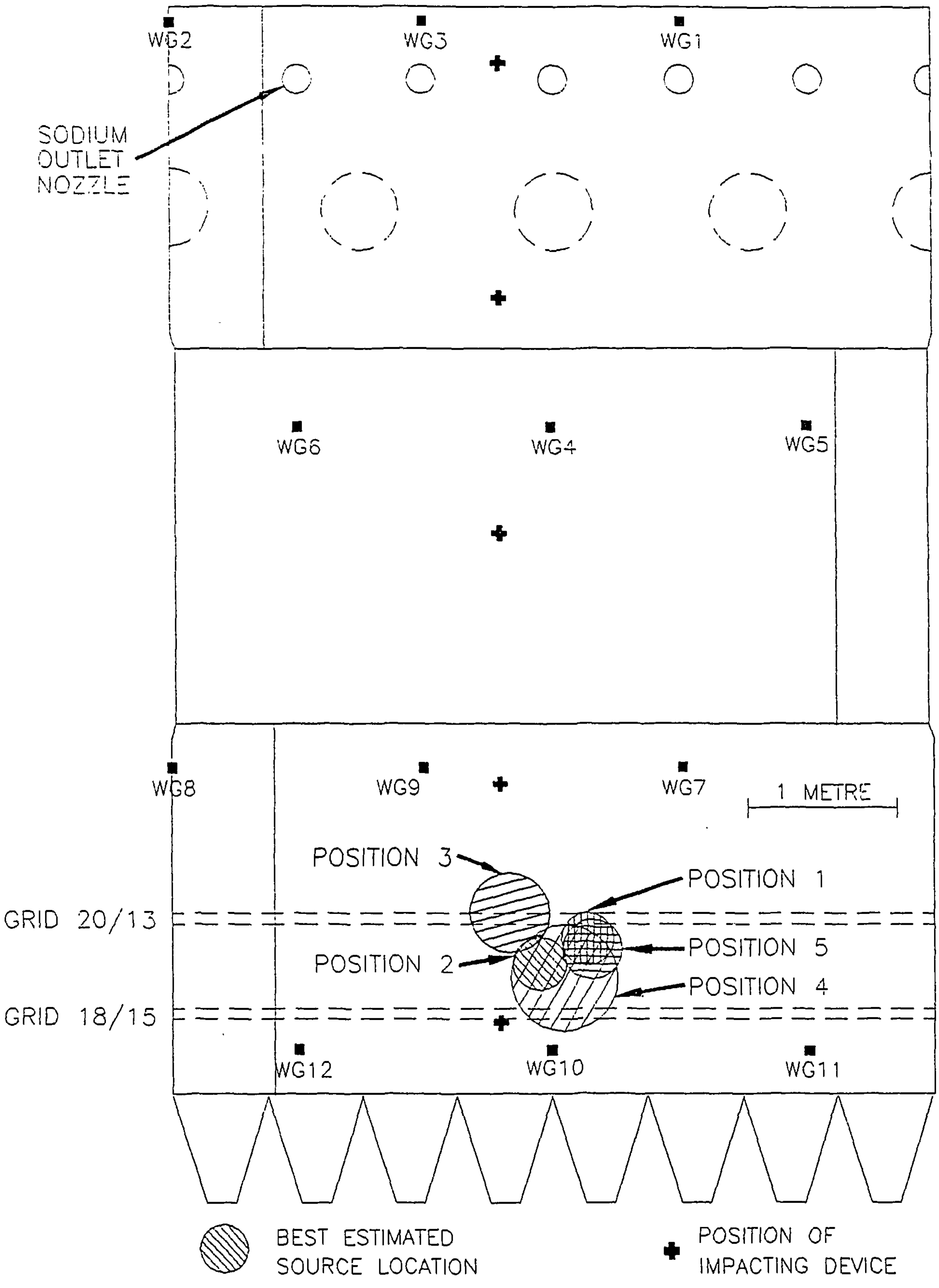


FIGURE 14 ESTIMATED LOCATIONS FOR THE IMPACTING DEVICE IN THE INNER TUBE.

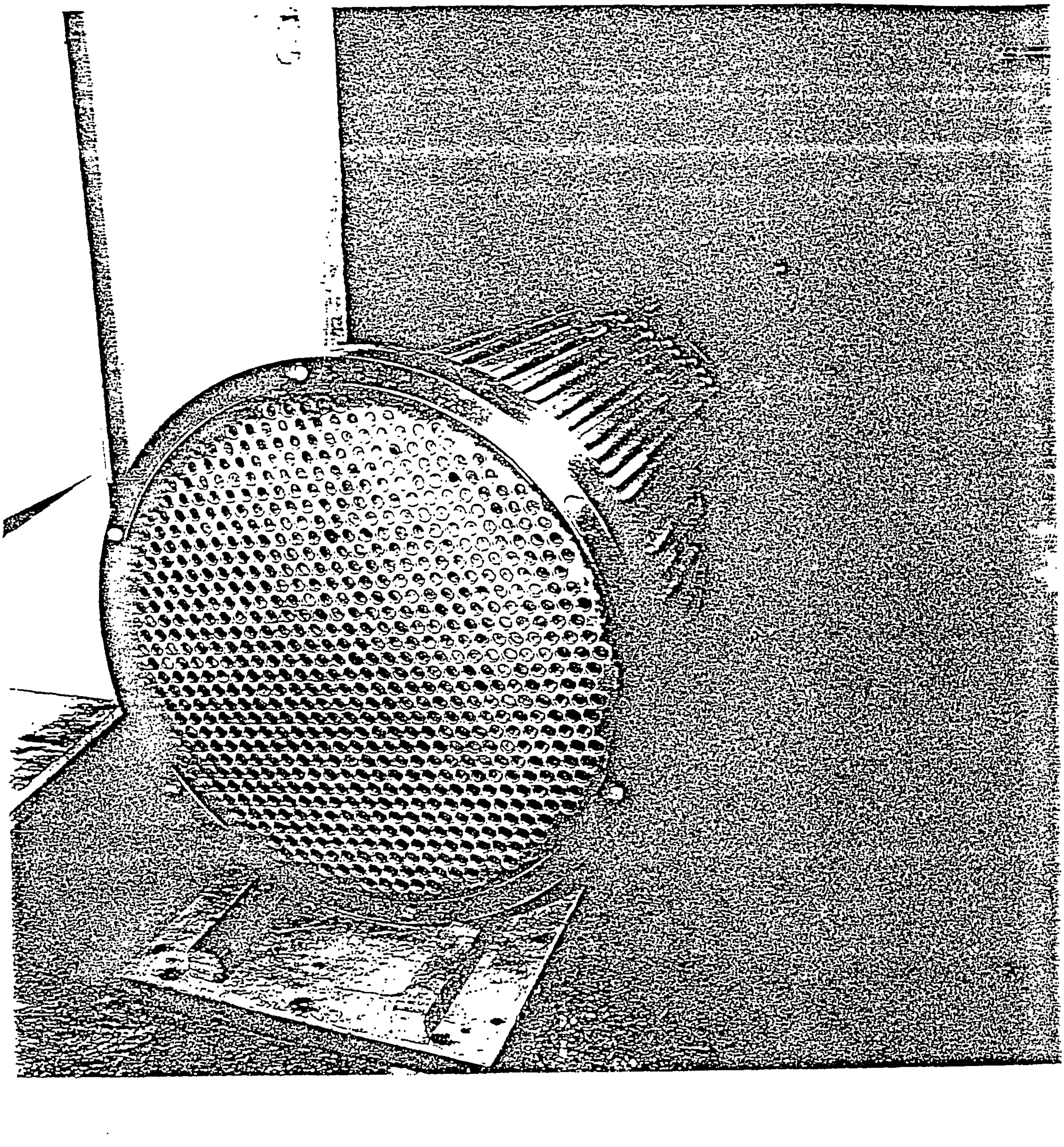


FIGURE 15 MODEL TUBE BUNDLE USED IN WATER EXPERIMENTS

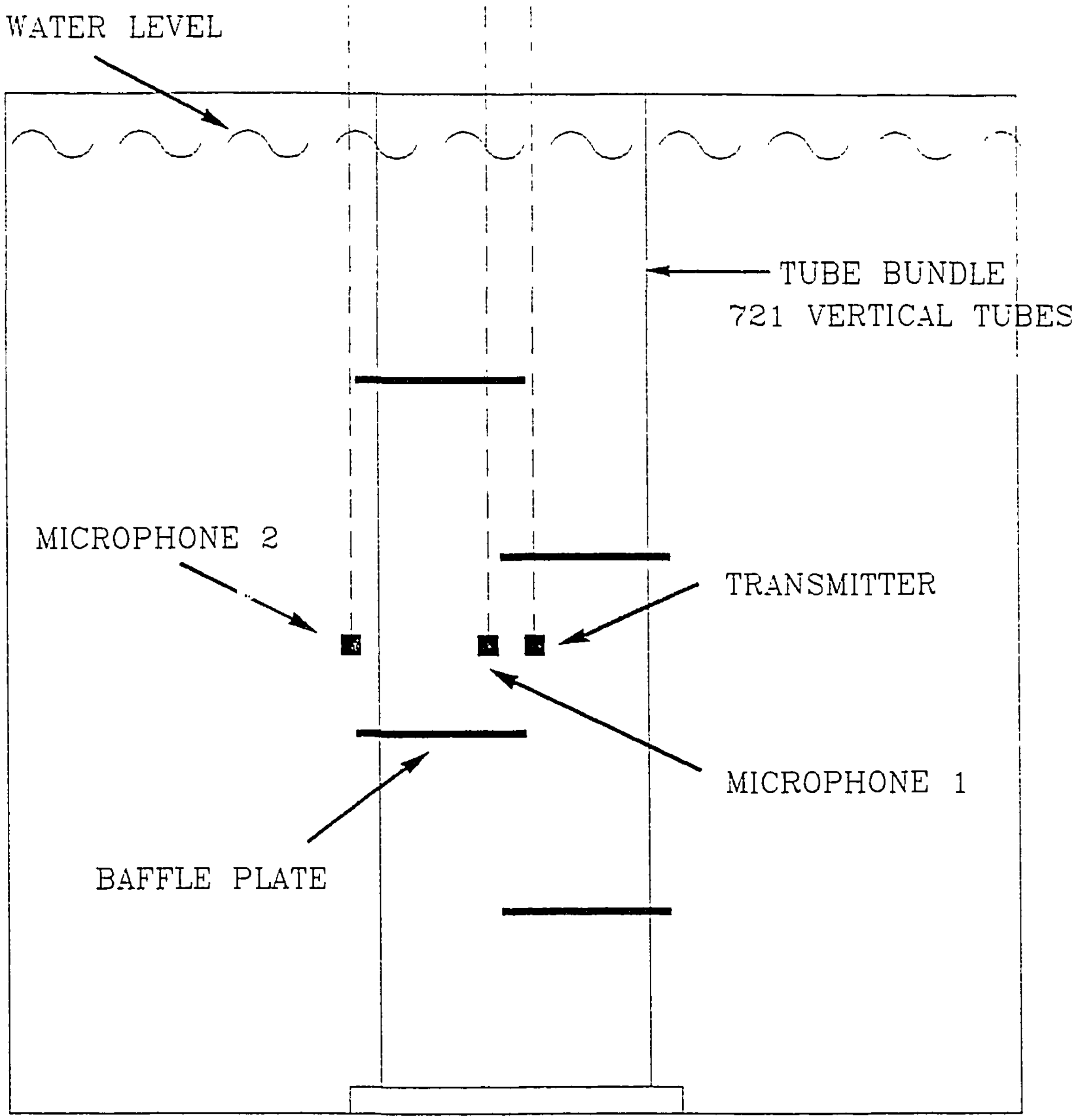


FIGURE 16 STEAM GENERATOR TEST RIG

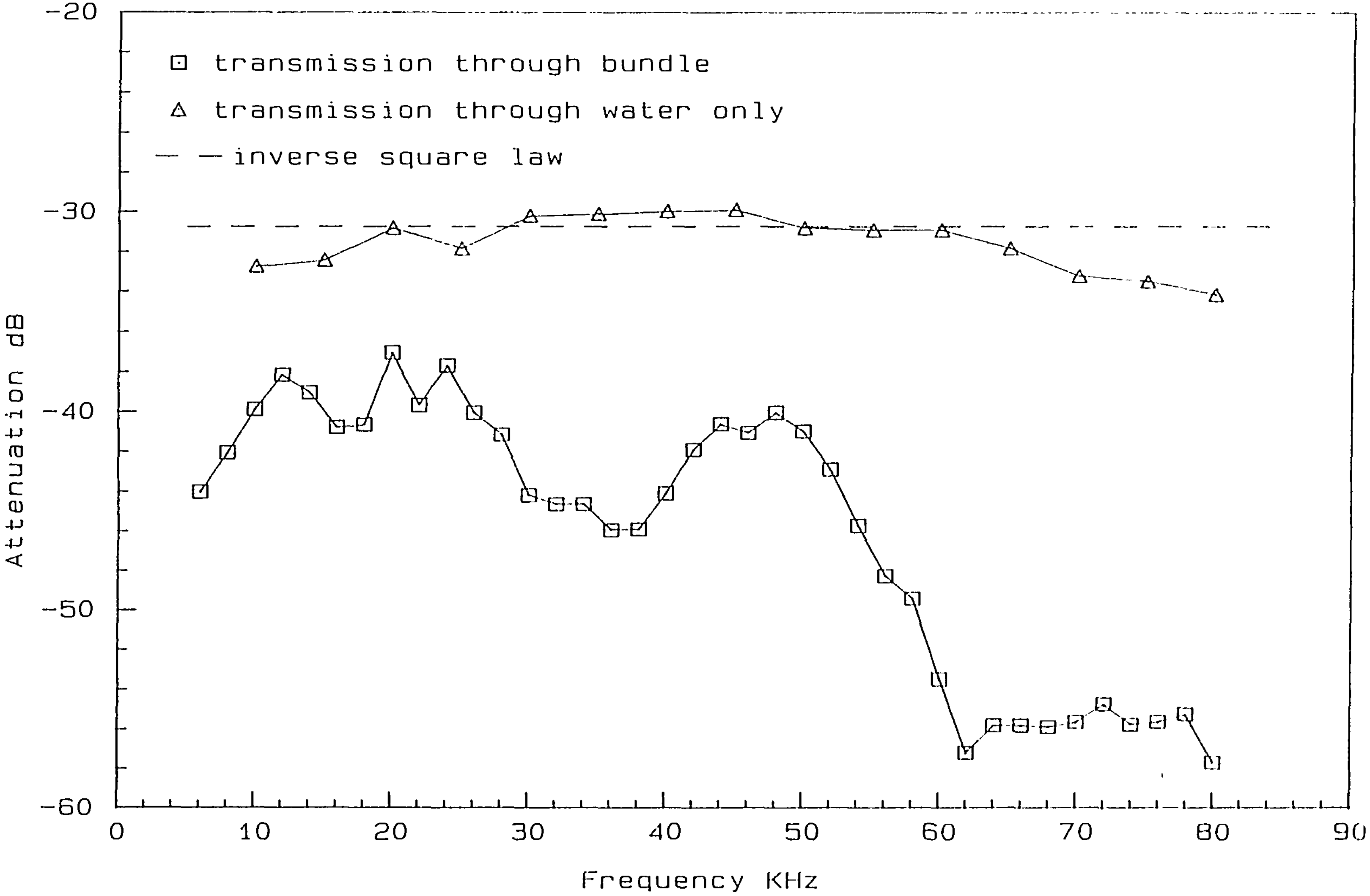


Fig 17 Acoustic transmission through model tube bundle