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DESIGN AND INSTALLATION OF A SOUND SYSTEM TO AID PASSENGER EVACUATION FROM AIRCRAFT

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SUMMARY

During an emergency evacuation an aircraft may be filled with smoke. Passengers may not be able to see their way to the exits and cabin staff may not be able to shout guidance.

An experimental 'audio attraction system' was designed and installed in a Trident aircraft which is regularly used for studying passengers' behaviour during realistically simulated evacuations. Loudspeakers were fitted close to the exits and an 'audio attraction sound' was produced which, when presented through the loudspeakers, was designed to enable passengers to tell the direction of a viable exit and guide them towards it, even if their visibility were highly restricted.

The audio attraction sound was carefully designed to overcome the background noise within the cabin, to be distinctive and recognisable, to be easily localised, and to convey an appropriate sense of urgency while not interfering unduly with any residual speech communication.

An experiment was carried out which showed that passengers seated throughout the cabin were capable of accurately identifying the direction of an audio attraction sound source. Since passengers' abilities to locate a sound source are good the prospects for the success of the audio attraction system should also be good.

The effectiveness of the audio attraction system during simulated evacuations will be independently assessed and reported.

PREFACE

This report, together with related publication CAA Paper 92002 *'Aircraft evacuations: a preliminary series of aircraft evacuations to investigate the influence of acoustic attraction signals located beside the exits'* details research studies carried out for the Civil Aviation Authority to investigate the potential of acoustic signals to aid emergency evacuation of aircraft. The reports indicate that a small reduction in the time taken to evacuate an aircraft may be possible. However it should be noted that such a system has a number of potential disadvantages that have not been fully explored.

CONTENTS

1 INTRODUCTION

The Report by the Air Accidents Investigation Branch (AAIB) on the accident to a Boeing 737 at Manchester in 1985 [1] highlighted the difficulty of evacuating passengers from a cabin filled with dense, black smoke and toxic or irritant gases. In these conditions passengers and cabin staff are unable to see, and the effect of the hot gases on the lungs and throat suppresses the ability to guide people by shouting. The report recommended (Paragraph 4.30) that research be undertaken to assess the potential of 'audio-attraction', distinctive warning sounds designed to attract passengers towards viable exits when speech and vision are impaired.

Following the publication of the AAIB Report, the Civil Aviation Authority (CAA) requested the Institute for Sound and Vibration Research (ISVR), Southampton and the Medical Research Council's Applied Psychology Unit (MRC APU), Cambridge, to design, produce and test a suitable audio attraction sound and to design and install a sound system and loudspeakers in a Trident test aircraft.

The Trident is located at Cranfield, and the Cranfield Institute of Technology use it to carry out research on behalf of the CAA into passenger behaviour during simulated evacuations. The effectiveness of the audio attraction system in assisting passengers to evacuate a smoke filled cabin has been assessed by Cranfield during their continuing trials programme, and is the subject of a separate report [2].

This report describes the design, production and optimisation of the audio attraction sounds, the design of the loudspeakers and sound system, and the installation of the sounds and system in the Trident. This report also describes an experiment in which the ability of passengers to 'localise' the direction of the sound was studied. The experiment, carried out by ISVR and MRC APU in parallel with Cranfield's evacuation trials, provides detailed information to help interpret the results of the evacuation trials.

2 PROJECT OUTLINE, OBJECTIVES AND CONSTRAINTS

The objectives of this project were:–

- to design a sound which would be optimised to attract passengers towards a viable exit
- to design and install an audio system to produce that sound in the Trident cabin used for evacuation trials at Cranfield
- to demonstrate experimentally the ability of passengers to identify the direction of the attraction sound while seated in the Trident.

The evaluation of the sound and sound system as an aid to passenger evacuation was a separate project carried out independently by Cranfield Institute of Technology as part of their continuing research programme.

Designing an audio attraction sound is similar in principle to designing a warning sound. Like a warning sound, the audio attraction sound must be loud enough to attract attention and be recognised above the background noise. It should also be no louder than necessary otherwise it will startle people and disrupt their thoughts and communication, these side effects being counter-productive.

Consequently the first stage in designing the audio attraction sound was to establish the background noise level or range of background noise levels during a passenger evacuation. While we were able to measure the background noise levels during simulated evacuations, we were obviously unable to establish what the likely background noise levels would be in a real emergency. Therefore the audio attraction sound was of necessity designed for use under simulated emergency conditions, to demonstrate the feasibility of the technique.

The second stage of the project was to survey the variation throughout the cabin of the sound levels produced by sound sources located at the exits. The sound level falls as the distance from the exit increases, and it is essential that the attraction sound be loud enough to be heard by passengers furthest from the exit. The effect of smoke in muffling the sound was also considered.

The third stage of the project was to design, produce and record the audio attraction sound. The design of the sound was based on Patterson's [3,4] guidelines for warning sounds and took into account the background noise levels and spectra together with the variation of sound levels within the passenger cabin. Additional guidelines were formulated to ensure that the attraction sound was easily 'localised'. 'Localisation' is the ability of listeners to identify the direction and approximate distance of a sound source. Some types of sound are easily localised while others are notoriously difficult.

The fourth stage was to design, install and test an audio system capable of reproducing the attraction sound at the appropriate predetermined sound levels. The Trident structure imposed constraints on the size and positioning of loudspeakers which will be described below. The system was designed to allow sounds to be produced from more than one loudspeaker (or exit) simultaneously, although for the present trial, the audio attraction sound was constrained to one loudspeaker at a time.

Finally, the fifth stage in this project, was to verify that the audio attraction sound was easily localised when heard from the audio system within the acoustic environment of the Trident passenger cabin. This stage took the form of a carefully designed experiment performed with volunteer listeners after an evacuation trial.

Each of the above stages is described in more detail below. Observations, conclusions and recommendations for further work are collected together in the final section.

3 ANALYSIS OF THE BACKGROUND NOISE IN THE EVACUATION SIMULATOR AND THE SPECIFICATION OF AUDIO ATTRACTION SOUND LEVELS

The first stage in the design or assessment of any set of audible warning or information sounds is an analysis of the background noise above which the sounds must be heard, understood and acted upon. An information sound must be loud enough to be heard reliably, but not so loud that it causes startle reactions, interferes with live or recorded speech communication or disrupts thinking. In practice these conditions are met if the main frequency components of the sound are between 15 and 25 dB above the 'masked threshold' imposed by the background noise [3].

The masked threshold of a signal is the minimum sound level of a signal which can just be heard above the noise by an attentive listener. Because of the inherent variability in noise and in the ear's processing, threshold does not occur at one signal level. Rather the probability of detecting a signal rises from very low to very high as the signal level increases. Because of this masked threshold is specified statistically as the level at which the signal would be audible on a given percentage of occasions, normally 50 percent. When defined in this way the threshold is well defined, accurate and stable across listeners and over time.

A signal just at masked threshold would not be heard on every occasion nor would it necessarily be recognised even if heard. A signal 15 dB above its masked threshold is loud enough to be easily heard and recognised, even if the listener is not expecting a warning or is distracted by other tasks. A signal more than 25 dB above masked threshold becomes increasingly aversive, annoying and disruptive when the background noise is as loud as that normally encountered in an aircraft.

Under quiet conditions however, the signal should not be allowed to fall below about 70 dB(A) even if it is now more than 25 dB above threshold as it may then seem insignificant.

The above guidelines were designed for warning sounds and in principle would also apply to audio attraction sounds. The guidelines are easily applied to warning sounds, where the sound level from a single sounder can be controlled at a single listener's position, or where a number of synchronised sounders can be distributed to give a fairly uniform sound level throughout a large space or building. But the use of multiple distributed sound sources is not an option when presenting an audio attraction sound, because the position of the source is crucial and must act as a single unambiguous target for listeners to move toward. If the sound level from the single audio attraction source falls off with distance by more than 10 dB between the passenger seats closest to the source and the seats furthest from the source, then the guideline that the sound level should be more than 15 dB but less than 25 dB above the masked threshold must be relaxed. This fall off with distance will be addressed in the Section 3, however it is still important to establish the background noise levels throughout the cabin in order to set the level of the audio attraction sound.

3.1 The cabin noise environment during simulated evacuations

The background noise was measured in the Trident cabin during four simulated evacuations. These were part of a series of trials designed to establish whether evacuations were faster when cabin staff shouted guidance to passengers.

Only the rear part of the passenger cabin from Row 8 to Row 19 was used for these trials. Figure 1 is a plan of the rear cabin showing the bulkheads and available exits. About half of the 71 seats were occupied.

The background noise was measured in the cabin at two positions using miniature microphones. These microphones are very small, about 8 mm x 4 mm x 2 mm and were unobtrusive in use. The microphone positions are shown in Figure 1. One microphone was midway between the two exits, above seating Row 10. It protruded 10 cm from the luggage rack and was approximately above the division between seats B and C. The other microphone was close to the overwing exit, above the edge of the aisle, and was placed below a slotted lighting panel. Both microphones were small enough to be supported solely by their small diameter signal leads. The signal leads were routed through and behind lighting panels and luggage racks.

The port side Type I (main) and the port side Type III (overwing) exits shown in Figure 1 were used separately with two evacuations through each. The stewardess was initially near the main Type I exit. All evacuations were carried out with the cabin filled with 'smoke' – a non-toxic theatrical fog which limited visibility to about 25 cm.

3.1.1 *Equipment used*

The miniature microphones used to measure the noise were Knowles Electronics Company type BT 1759. Despite their small size they have a frequency response from 50 Hz to 10 kHz ± 3 dB. They were powered from separate 9 volt battery supplies hidden in the Trident's luggage racks. The microphone signals were routed via cables through the luggage racks to a Control Area behind the rear bulkhead where they were recorded digitally on separate channels using a Sony PCM F1 Digital Audio Processor to digitise the signals and a Sony SL F1UB Video Cassette Recorder to record the digital data. The combination of the Digital Audio Processor and Video Recorder enable recordings to be made and replayed to very high quality.

The two microphones and recording channels were calibrated before and after the series of measurements with a Brüel and Kjær Type 4230 Sound Level Calibrator. This calibrator, unlike a pistonphone, provides a reference acoustic tone at a standard sound level which is virtually independent of the enclosed volume of its cavity, and is suitable for use with the miniature microphones. The calibration tones were recorded on tape. The calibration was found on playback to be stable during the course of the recordings. The sound level calibration is traceable to the National Physical Laboratory via pistonphones and microphones calibrated annually by NPL and held by ISVR Consultancy Services exclusively as laboratory reference standards.

3.1.2 *Measured levels*

The background noise in the passenger cabin was a mixture of tape recorded and real passenger noise. The tape recorded noise, replayed at a moderate sound level through loudspeakers concealed within the luggage racks, was mainly agitated babble and shrieks. Cranfield use the recording to add a sense of realism and urgency to their evacuation trials. The real passenger noise dominated and was mainly the sounds of rushing and moving to the exits with virtually no vocal noise, other than from the stewardess. Both the recorded and the live passenger noise were from sources distributed throughout the length of the cabin and the sound level would be expected to be fairly uniform within the cabin. The actual levels measured are give in Table 1.

The sound levels at the two microphones were broadly similar without the stewardess's shouts and averaged 78 dB(A). When the stewardess was shouting the microphone closer to her showed the higher sound levels, about 91 dB(A). The sound level at the more distant microphone was about 85 dB(A).

The sound levels without the stewardess's shouts are the more relevant to the design of an audio attraction sound. This is firstly because the audio attraction sound is mainly intended for use in conditions which make shouting impossible, and secondly because the audio attraction sound will be designed so that it can be heard between the shouts and so that any shouts can be heard in pauses within the audio attraction sound. In other words the shouting and the audio attraction signal will not be in direct competition.

3.2 Calculation of masked thresholds

A Brüel & Kjær type 2032 Dual Channel Analyzer was used to measure the spectrum of samples of recorded background noise. Typical samples a few seconds long were selected. Some samples included the shouting of the stewardess, others were chosen to avoid this. Spectra were obtained over the frequency span up to 6.4 kHz with a resolution of 8 Hz. Each was transferred to a Hewlett-Packard 216 computer and stored on disc. The masked threshold for tonal signals heard in each noise was calculated from the spectrum of that noise using a computer program written for this purpose. The program works by modelling the filtering processes of the ear and has been shown experimentally to give predicted thresholds in very good agreement with the measured thresholds of groups of listeners in various noisy environments [5].

The spectrum of each noise and the masked threshold predicted for signal components are shown in Appendix A. Note that each spectrum is plotted as a spectral density, ie with the sound pressure level normalised to 1 Hz bandwidth, and the x-axis shows pressure spectrum level in decibels re 400 x 10^{-12} Pa^2/Hz (equivalent to 20 $\mu Pa/Hz^{1/2}$). The threshold curve is a simple sound pressure level with a decibel reference of 20 μPa. Both curves are plotted together with the same numerical scale for compactness.

3.3 Optimum sound levels for audible warnings and audio attraction sounds

Figures A.1 to A.8 in Appendix A apply to the case where no stewardess is shouting. These figures show threshold curves which are generally flat or downward sloping, with minor peaks and dips, over the frequency range from 500 Hz to 4 kHz. In this frequency range, the main range for warning and information sounds, the average masked threshold for a tonal signal is about 58 dB SPL. Applying Patterson's guideline that warning sounds should consist of frequency components, each 15 to 25 dB above the masked threshold, the audio attraction signal would consist of frequency components each having a sound level of between 73 dB and 83 dB.

Assuming eight components, a reasonable number, each at about 73 dB in level, the components combined will have a total sound level of 82 dB, ie about nine decibels above the levels of the individual components. To meet Patterson's criterion for general warning sounds therefore, the audio attraction signal will need to have a level of between 82 and 92 dB (unweighted) throughout the main cabin area. For warning sounds comprising several tonal components between the frequencies of 500 Hz to 4 kHz, the A-weighted sound level is usually similar to the unweighted level. Whether these levels can be achieved will depend on the factors discussed in Section 4.

4 VARIATION IN SIGNAL SOUND LEVELS THROUGHOUT THE EVACUATION SIMULATOR

Potential locations were identified for audio attraction sound sources. A loudspeaker was placed at each position in turn to represent the audio attraction source and the variation in sound level was measured throughout the passenger cabin. Though not difficult, the measurements were time consuming and involved the generation of high sound levels and were therefore made without passengers in the cabin. Most measurements were made without smoke, some measurements were made with the smoke.

4.1 Measurement procedure without smoke

The potential locations of audio attraction sound sources are marked on Figure 2. A single-unit loudspeaker, a KEF B110 in a sealed cabinet, was placed at each of the potential locations in turn. 'Pink noise' – a standard noise containing all the sound frequencies of interest – was played through the loudspeaker. The sound produced by the loudspeaker was recorded through the two miniature microphones connected to a Sony PCM-F1 recording system as described in Section 3 above.

One of the miniature microphones was located at a fixed position about a metre from the loudspeaker. This microphone was used to ensure that the sound level from the loudspeaker was constant throughout the measurements. The second microphone was moved to detect the spatial variation in sound level within the cabin. This second microphone was held at each sampling position for twenty seconds before moving it to the next position.

Sampling positions, shown on Figure 2, were chosen to cover the length and width of the cabin on a regular grid pattern. Measurements were made along the length of the cabin at each seat row, and across the cabin at three positions, above Seat B, above Seat E, and in the centre of the aisle. The measurements above the seats were about 1.55 metres above the floor, directly above the position normally occupied by the centre of a passenger's head. Measurement positions in the aisle were at the same height.

4.2 Spatial variation in sound levels without smoke

The variations in sound level throughout the passenger cabin are shown in Figures 3 to 5. Contours of equal A-weighted sound level have been interpolated between the measurement positions. These contours are at increments of two decibels.

In Figures 3 and 4 the loudspeaker representing the audio attraction source was near the main Type I exit. The contours show an interesting effect whereby the sound level in the aisle is about 2 dB to 3 dB higher than the sound level above the seats to the side. The sound is beamed down the aisle relatively unobstructed whereas off to the sides the sound is obstructed and absorbed by the furnishings and luggage racks. When only the main Type I exit is in use it will be necessary for the audio attraction sound to be heard at the far end of the cabin. With the loudspeaker in the centre of the aisle between the bulkheads near the main Type I exit, an ideal position, the variation in sound level along the length of the aisle from Row 8 to Row 19 is about 12 dB to 13 dB. The range in sound levels throughout the cabin's seating area is 15 dB. This is more than the 10 dB range hoped for.

With the overwing exit (Figure 5) the sound level from the loudspeaker representing the audio attraction source varies by about 14 dB throughout the cabin, excluding the region closer to the speaker than 1 seat row. It might be thought initially, since the furthest seats are no more than half the length of the cabin from this loudspeaker, that the variation in sound level should be less than the variation measured along the full length of the cabin from the loudspeaker near the Type I exit. The reason this is not so is the proximity of the nearest seats to the sound source in each case. The seats nearest to the loudspeaker for the Type I exit were about 3 metres from the loudspeaker. The seats nearest the loudspeaker by the Type III exit were at less than 1 metre. The fall off in sound power from a source follows an inverse square relation with distance in the absence of reflections, consequently sound levels fall off rapidly with distance close to a source and fall off more slowly with distance further from the source. This leads to the observed effect.

4.3 The additional effect of smoke on sound levels

To measure the effect if any of the imitation smoke used in the evacuations one of the miniature microphones was located in the aisle at seating Row 9 (the second row from the bulkhead) and the other microphone at Row 19, the row furthest from the bulkhead. The loudspeaker was set up at the bulkhead to generate pink noise within the cabin.

The cabin was filled with smoke by operating the two smoke generators for thirty seconds, as was the normal practice during trial evacuations at that time. The microphone signals were recorded throughout.

The tape recordings were subsequently analysed using a B&K type 2131 Third octave Analyser to give the spectrum and noise levels at the microphone positions. With the smoke at its densest, just after the generators were switched off, the A-weighted sound level at Row 19 was 16.9 dB below the level at Row 2. Without any smoke the A-weighted level at Row 19 was 7.9 dB below the level at Row 2. Thus the effect of the smoke was to introduce an extra 9 dB attenuation over and above that due to the increased distance from the sound source. Noise attenuation due to absorption and scattering by water vapour and solid particles in the atmosphere is usually a linear function of distance and the reduction can be quoted as an 'attenuation rate' in decibels per metre (dB/m). Thus in the passenger cabin the simulated smoke would be expected to reduce the sound level of the audio attraction signal by about 0.9 dB/m along the length of the aisle.

Although an overall attenuation rate of 0.9 dB/m has been quoted the frequency analyses showed that attenuation was greater for the higher than for the lower sound frequencies. The rate at 3.15 kHz was about 1.3 dB/m; the rate at 500 Hz was about 0.6 dB/m. The reduction in high frequencies relative to the lower frequencies will substantially affect the tonal quality of an audio attraction sound, and will be perceived as a progressive muffling of the sound at increasing distances from the source. This must be accepted as unavoidable, but may not be entirely undesirable. The smoke may have an unquantifiable but beneficial effect in that, as a passenger proceeds toward the sound source the sound will become 'brighter' and clearer and confirm that he or she is getting closer to it.

Furthermore, in future tests two exits may be in use together. For a passenger slightly nearer to one exit than the other, the nearer exit will have a clearer as well as a louder signal and the smoke will enhance the difference.

The rate of attenuation of sound in real smoke as opposed to theatrical fog is not known. It will need to be known if audio attraction sounds are to be designed for real use. It could be measured under controlled conditions if necessary, though with difficulty and almost certain risk of damage to equipment.

4.4 Implications for audio attraction sounds

From the Type III exit to the furthest seats is about half a cabin's length; from the Type I exit to the furthest seats is a full cabin length. The Type I exit is the more critical. It will be more difficult to obtain sufficient sound levels throughout the cabin from the loudspeaker at the Type I exit than from the loudspeaker at the Type III overwing exit.

The sound level of an audio attraction signal close to the Type I exit will fall off along the full length of the main seating area by about 14 dB in the absence of smoke. With the additional effect of simulated smoke the sound level will fall by 25 dB over this distance. Other factors such as the obstruction caused by passengers which have not so far been considered will further increase this 25 dB range but by an unpredictable amount which will vary from moment to moment.

Clearly it will be physically impossible to keep the sound level of the attraction signal within the normally recommended 10 dB range. It must be accepted that signals will need to be too loud closer to the loudspeaker and/or too quiet far from the speaker. The minimum desirable signal level can be relaxed slightly say from 15 to 10 dB above the threshold imposed by the background noise. The sound would then be 'easy to hear' rather than 'difficult to miss'. Any further reduction is undesirable but may be necessary. Higher than desirable sound levels will in any case have to be tolerated closer to the source. Such high levels may be aversive and counter productive, but it is thought that the desire to escape will overcome the aversion.

Assuming that the audio attraction sound will be set so that it is at least 10 dB above threshold, its minimum sound level anywhere in the cabin would be specified as 77 dB. The highest level within the seating area from the Type I exit's loudspeaker would then be about 102 dB. This level will be difficult to generate, and levels may need to be further relaxed.

5 THE DESIGN AND REFINEMENT OF THE AUDIO ATTRACTION SOUND

Guidelines for producing warning sounds for aircraft have been set out in detail [3] and summarised [4] by Patterson. Broadly speaking, once the noise environment has been assessed and the range of appropriate sound levels for the components of the warning sound have been established, it is the spectral characteristics of the sound and the temporal characteristics of the sound that determine its suitability, and it is they that have to be tailored to the environment. Some of the characteristics, such as the procedure for ensuring that the warning sound does not cause a startle reaction, are well established and do not vary from one warning set to another; other characteristics such as the urgency of the sound are affected by the context in which the sound occurs and so have to be tailored to the individual environment. Experience has made it clear to the design team that only the end user can specify the appropriate level of urgency in the warning sound and so the procedure we use is to develop a set of prototype warning sounds which all have the correct characteristics for the environment and which vary in the degree of perceived urgency. The prototype set of sound can then be played to an appropriate set of reviewers to demonstrate the range of sounds that are available, and then they can determine the appropriate level of urgency from within this range.

5.1 Prototype Audio Attraction Sounds

A set of 9 prototype audio attraction sounds were developed at MRC APU in accordance with the warning sound guidelines set out by Patterson [3]. Each sound was composed of a burst of sound pulses with from 2 to 12 pulses in the burst. The pulse of sound is from about 75 to 500 ms in duration and it carries the essential spectral information and gives the warning its sound quality (e.g. harmonium versus calliope). Sounds were made from three different pulses whose spectra appear in Figure 6. The abscissa shows the frequency range that is appropriate for auditory warning sounds and the ordinate specifies the relative level of the spectral components in decibels. The synthesized pulse in Figure 6a is composed of 18 sinusoids with a reasonably regular, but inharmonic spacing which gives the sound a distinctive character. The level of the components decreases slightly as frequency increases to keep the sound from becoming too shrill. The components are spread right the way across the frequency range from 200 to 4,000 Hz to ensure that the sound will not be masked by an unexpected noise occurring in the passenger cabin. That is, only an unexpected sound that completely swamped the entire spectrum would mask this stimulus. The same is true for the other two warnings whose spectra are shown in Figure 6b and 6c.

There is a second reason for spreading the components throughout the spectrum and that is to increase the localisability of the sound. Although the auditory system is most sensitive to weak sounds in the region of 2.0 kHz, this is not the best frequency region for localisation. Indeed, it is close to the worst. The best frequency region for localisation is below 1,500 Hz or above 3,000 Hz. Accordingly, all three sounds contain a wide variety of frequency components to ensure that they will be localisable. We particularly included many low frequency components because they are less attenuated by smoke, and this region of hearing is the least likely to be affected by presbyacusis; that is, the progressive loss of high frequency hearing with age.

Once the spectrum of the sound has been established, it is transformed to the time domain using Fourier techniques to produce a waveform that can be played through a digital to analogue converter. The onset and offset of each pulse is rounded to avoid causing a startle reaction. Provided the sound comes on over the course of 5 ms or more, it is not likely to cause a startle reaction unless it is excessively loud.

Pulses were synthesized for the three sounds in Figure 6 with pitches varying over about half an octave. A sequence of these notes can then be used to produce an attraction sound with a distinctive melody. In the current study a five note sequence of inharmonic pitches was generated.

The most important remaining characteristic is the rhythm of the set of pulses in the burst. Experiments designed to determine whether warning sounds are confusable have shown that distinctive rhythms help prevent confusion [3,5]. Pitch contours for the 9 attraction sounds are set out in Figure 7 which shows the pitch of the sound as a function of time; each small bar shows one note of the melody. Long rising or falling lines indicate frequency glides produced by playing the pulses without gaps.

With regard to temporal pattern, it is perhaps worth pointing out that we considered the temporal pattern set out in the ISO draft standard for an evacuation warning and found it completely unacceptable. The pulses are far too long to convey any sense of urgency whatever.

The sound pulses, whose spectra are shown in Figures 6a, 6b and 6c sound like a badly tuned harmonium note (H), a calliope (C) and a noisy calliope (NC). Three audio attraction sounds with different bursts of pulses were composed from each of the three sound pulses to give a total of nine prototype warnings. The total duration of the burst is 1–2 seconds. The three different audio attraction sounds varied in their perceived urgency from what was labelled low to what was labelled high. In the case of the low-urgency attraction sounds, the pulse rate is slower than in the case of high-urgency attraction sounds and the spacing between the pulses is greater; that is, the low-urgency attraction sounds have a slower melody than the high-urgency ones. In the case of the higher-urgency attraction sounds the pitch reversals in the melody are more abrupt and they occur at points where the rhythmic structure might have led one to expect continuity. With the high-urgency sounds, the rhythms are more syncopated; that is the first few pulses of the burst are used to set up a regular rhythm and then this rhythm is deliberately broken to draw attention to the sound and so make it memorable. The pitches of the sound are similar to the notes in the centre of the musical keyboard.

5.2 Refinement of the Audio Attraction

A meeting between ISVR, the CAA, MRC APU and Cranfield was convened at APU to listen to the prototype sounds and refine the preferred sound. In this particular case, the committee tended to agree with MRC APU on the general levels associated with low, medium and high-urgency. That is, they felt that the low-urgency sounds in Figure 7 were not sufficiently urgent and that the high-urgency sounds in Figure 7 were perhaps a little too urgent. Amongst the melodies and rhythms they tended to prefer that shown in the very centre of the figure for the simple calliope sound. However, with regard to the timbre of the sound, they tended to prefer the noisy calliope. Accordingly, a new attraction sound was constructed with the noisy calliope sound and a slightly modified melody and rhythm from that shown for Sound Five. Specifically, they chose a set of four rising notes rather than the set of five rising notes shown in Figure 7 and they chose to increase the pitch difference between the last two pulses by lowering the pitch of the penultimate pulse by one step. This gives the pattern and rhythm shown for Sound 10 at the bottom of the figure. Finally, the times between the pulses were shortened a little to make the sound somewhat more urgent, and in this form it was considered acceptable.

6 DESIGN AND INSTALLATION OF THE SOUND SYSTEM

The sound system was assembled solely for the purposes of these trials. No account was taken of the availability and voltage of any power supply, power consumption, or constructional regulations which might apply in an airworthy aircraft, or of any automatic switching of signals to serve viable exits. The aim of the trials was to test, as straightforwardly as possible, the principle of audio attraction. The issues involved in a practical installation can be addressed if and when audio attraction is deemed to be worthwhile and practicable.

6.1 Loudspeakers

The main consideration in designing and specifying the sound system was the sounders and their positions. Standard loudspeakers were specified in order to achieve the wide frequency range needed for good localisation of the sounds. These loudspeakers had to be positioned at the point to which passengers needed to be guided. The structure of the Trident imposed restraints on the choice of loudspeaker units and on their positions. The loudspeakers were also designed so that they could be removed after the trials leaving the aircraft trim in its original condition.

The first choice of position for an audio attraction source for the Type I exit was in the ceiling of the cabin between the bulkheads, the position marked as position 2 on Figure 2. A loudspeaker could not be installed here. The door on opening would swing up and over into the space above the ceiling, and we understood that this space contained the door mechanism and counterweight. A second position was considered. This was in the bulkhead beyond the exit. This position would have been clear of the door mechanism but the bulkhead nearer the seating area would have acted as a barrier to the sound, reducing its level by an unacceptable amount.

The final choice of position, judged to be the best practicable, was in the bulkhead between the exit and the passenger cabin. The disadvantage of this position was that it was not as close as the other locations to the exit. Since the bulkhead was not part of the original structure but a mock-up installed by Cranfield for their trials a loudspeaker could be installed with Cranfield's agreement which would not affect the original trim or decor of the aircraft.

There was also a significant constraint in installing a loudspeaker over the Type III overwing exit. For best effect the loudspeaker needed to be mounted in the panels below the luggage rack, and the clearance above these panels was as little as 55 mm in places. Furthermore the back of the loudspeaker had to be enclosed, otherwise its low frequency response would be limited and sound radiated from the back of the loudspeaker could leak out between the panels. The source of the audio attraction would then be less well defined. A further constraint was that any new or existing panel containing a loudspeaker should not protrude below the existing panels to prevent passengers hitting their heads.

Small 75 mm diameter loudspeakers would fit in the available space, but would not provide sufficient sound output. Eventually a larger unit was selected, the KEF B110, the same type that had previously been used as a representative sound source. This was the largest speaker which would fit the space available, and then only by careful construction of its enclosure and by mounting the loudspeaker through the front of a built-up panel. The built up panel protruded below the luggage rack but was flush with the existing white plastic panels which contained the lights and fresh air vents. The same type of loudspeaker was also deemed suitable for the Type I exit.

Constructional details of the loudspeaker enclosure for the Type III exit can be seen in Figure 8. The main built-up panel was chipboard on a hardboard base, and the loudspeaker was let into this from the front. A conveniently sized die-cast box with the lid removed was bolted to the back of the panel as an enclosure. The die-cast box was sufficiently rigid but took up far less space than a traditional wooden or chipboard enclosure. It was just large enough to contain the loudspeaker but not too large to fit below the aircraft luggage rack. The front of the speaker assembly was filled, sanded and painted matt black. Finally a plastic grille was fitted over the loudspeaker to protect it. Care was taken in the appearance of the loudspeaker to make it look like a standard fitting. Figure 9 shows the on-axis frequency response of the finished loudspeaker and enclosure. The response is very good for the intended purpose; the dip in the response at 12 kHz is well above the frequency range of the audio attraction sounds. (This dip occurs at a frequency where the distance from the speaker diaphragm to the back of the die-cast box is a quarter of the sound wavelength.)

The loudspeaker near the main Type I exit was installed directly into the bulkhead in front of Row 8. A die-cast box was bolted to the back of the bulkhead to enclose the rear of the loudspeaker, and a plastic grille was fixed over the front of the loudspeaker to protect it and to conceal the bolt heads.

Figure 10 shows the loudspeaker assemblies in place in the aircraft.

6.2 Signal generation, amplification and switching

Figure 11 shows a block diagram of the sound system as installed. The audio attraction sounds were played from a stereo cassette deck. Two stereo amplifiers gave four channels of amplification, three of which were used with one spare. Independent switches were provided on the output of each channel.

The equipment was designed to be versatile and simple to use. A monophonic recording played on the stereo cassette deck would allow the same signal to be sent simultaneously to whichever of the loudspeakers is switched on for synchronised presentation. A two-channel recording would allow two different sounds to be sent to separate loudspeakers. Alternatively, the same sound could be sent to each of two loudspeakers with a delay introduced in one channel in the recording process, so that sounds from different exits could be interleaved, rather than synchronised. Although initial trials will involve the use of audio attraction when only one exit is used the above flexibility may be needed for future trials with audio attraction signals from two exits.

Three loudspeakers were installed in total. A loudspeaker was installed for both the left and right overwing exits although Cranfield only use the left. There were two reasons for this. The first was to allow use of both the left and the right overwing audio attraction sources in an experiment described below. These loudspeakers were very close together and we wished to test whether passengers could reliably distinguish between them from a distance. The second reason was more pragmatic. The loudspeaker above the left exit was likely to receive very rough treatment as passengers evacuated. If it were damaged the right loudspeaker, which was identical, could be substituted between trials.

The reason why the two stereo amplifiers were not the same model was simply that the supplier, who had promised two NAD 3225PE amplifiers and agreed a delivery date, was able to supply only one. The NAD 3020i was a late substitute.

The mains power for the entire sound system was passed through a separate inline mains filter to suppress interference from the switching of other equipment such as the smoke generators.

6.3 Signal sound levels achieved

Once the loudspeakers and the other equipment had been installed and checked the audio attraction sound was played and the sound level measured. In the aisle between seat Rows 18 and 19 a time-averaged sound level (L_{Aeq}) of 76 dB(A) was achieved from the loudspeaker at the Type I exit. The time averaged level includes the silent pauses between the bursts of the signal. The important level is the level of the signal while present. The dynamics of the signal and its frequency content are such that the A-weighted time averaged level is 9 dB below the unweighted sound level of the signal while present (measured on a sound level meter with time-weighting 'F', ie the 'fast' response with 250 ms averaging time). A sound level of 85 dB was therefore achieved while the signal was present.

The signal level of 85 dB would be reduced, at this distance, by about 11 dB in the simulated smoke to a level of 74 dB. This is 3 dB below the relaxed target level of 77 dB, but is still 7 dB above the predicted masked threshold of hearing and was considered to be acceptable for the trial.

6.4 Anecdotal comments on the sound system installation

Once the loudspeakers were installed and the audio attraction sounds were played through them to test the system, it became obvious that the loudspeaker by the main Type I exit was not ideally situated. It was easy to locate the loudspeaker and move towards it down the aisle from a distant seat. Upon drawing closer to the loudspeaker it was still easy to identify its direction. But, close to the speaker, the direction of the loudspeaker did not correspond to the direction of the exit. When passing through the bulkhead in front of Row 8 the loudspeaker was to one's left, but the direction of travel to the exit was straight ahead, an error of ninety degrees. This was most disconcerting, and unless the direction of the exit was apparent from the direction of the light spilling into the smoke through the open exit, the discrepancy in direction between the loudspeaker and the exit would be highly confusing and might slow down any evacuation. In these circumstances the audio attraction signal might be counterproductive. In any future trials this loudspeaker must be relocated despite the practical difficulties. If future aircraft are to incorporate audio attraction sources their location must not be compromised by the positioning of bulkheads or by the aircraft structure. This means that sources should be designed in from the start rather than being retrofitted as an afterthought.

The loudspeaker positions for the Type III overwing exits were considered to be satisfactory and should not cause any confusion.

7 LOCALISATION EXPERIMENT IN THE EVACUATION SIMULATOR

7.1 Introduction

A brief localisation experiment was carried out after each of three of Cranfield's trial evacuations. The experiment followed the evacuation trials so as not to influence them. The objective was to discover how well the passengers could localise the audio attraction signals and identify sound sources in the acoustic environment of an aircraft.

7.2 Method

After the final evacuation of the day, the passengers reboarded the aircraft and occupied their allocated seats. They were each given a clipboard, pen and a response sheet. The response sheet is shown as Figure 12. The experiment was explained to them, and the instructions, also printed on the response sheet, were read to them. Four loudspeakers, prominently numbered 1 to 4 as in Figure 13 were pointed out. In reality there were three loudspeakers, those installed by the two Type III exits and that in the bulkhead between the Row 8 and the Type I exit. The fourth 'loudspeaker' was a grille matching that of the other speakers, and attached to the rear bulkhead behind Row 19. The dummy fourth loudspeaker was installed following a pilot run with only three loudspeakers. An observer seated towards the back of the aircraft during the pilot experiment commented that some sounds appeared to come from behind him, yet he knew this was not possible as there was no loudspeaker there. The dummy was then installed so that, if subjects thought sound was coming from the rear, they would not be prevented from indicating it by the absence of a visual cue.

Before starting, each passenger wrote the seat number at the top of the response sheet. This was essential for the analysis of the results. The experiment then started.

Two bursts of the audio attraction sound were played through one of the loudspeakers. Each passenger wrote down the number of the loudspeaker from which the sound appeared to come. Two bursts of sound were then played through another, or in some cases the same, loudspeaker and so on until thirty presentations of the sound had been made. The thirty presentations comprised ten presentations through each of the real loudspeakers. To the passengers the order of presentation was random. The order had in fact been preselected so that it was counter-balanced over the three separate runs, ie each of the three loudspeakers came first in one of the three runs, second in one of the runs, etc. so that no one loudspeaker was favoured. On completion of the experiment, which took only a few minutes, passengers were invited to write any comments they wished to make on the backs of their response sheets. The response sheets were collected as they left the aircraft.

7.3 Results and analysis

Data from each response sheet was collated and analysed by computer. Two analyses were made. The first analysis was of all the data from the thirty sound presentations in each run. The second analysis was of the first three presentations in each run. The first analysis gave more statistical reliability because more data had been collected. However, the number of presentations involved in a full run gave each passenger ample opportunity to learn to distinguish between the loudspeakers on the basis of their relative loudness and minor tonal differences. The second analysis was relevant because the subjects' responses were necessarily first impressions without any practice or learning as they might be the case in a real emergency.

The results of the first and second analyses are given in Tables 2 and 3 respectively. In each table the numbers of responses have been converted to percentages, since the total number of passengers seated varied slightly from row to row. Figures 14 and 15 show the percentages of correct responses for each loudspeaker position.

7.4 Discussion

From Table 2 and Figure 14 it can be seen that passengers are able to distinguish very well the direction of an audio attraction source. Loudspeaker number 1 was identified correctly on about 98% of occasions. Loudspeakers 2 and 3 were correctly identified on at least 93–95% of occasions by passengers seated in Rows 11 to 19 inclusive. This is an impressive performance as passengers in Row 19 could reliably tell loudspeakers 2 and 3 apart, even at a distance of about 5 metres, where the angle subtended between the loudspeakers is only about 25°. Passengers seated with these loudspeakers behind them were less certain. Passengers in Row 8 tended to confuse Loudspeakers 2 and 3 with each other, but given that the loudspeakers were about 6 metres behind them and about 20° apart this performance is still good. The confusion between Loudspeakers 2 and 3 from a distance is not a serious error, as evacuating passengers will turn and move in the correct direction, and will be able to distinguish the loudspeakers more accurately as they move closer.

From Table 3 and Figure 14 it can be seen that the results from the initial presentations are very similar to the results from the full experiment. Passengers' initial impressions of the direction of the sound source were excellent with little or no practice or experience. This bodes well for the use of audio attraction sounds.

Since passengers' abilities to discriminate between closely spaced loudspeakers are good, the prospects for success of an audio attraction system are therefore also good. If an audio attraction system does not provide a significant aid to passenger evacuation, the failure will not arise from an inability of passengers to localise the sound.

7.5 Conclusions

Passengers are well able to localise a sound source in the acoustic environment of an aircraft cabin. They can distinguish between two closely spaced loudspeakers. Their first impressions after little or no practice are very reliable.

8 CONCLUSIONS

An audio attraction sound has been designed to assist passengers to locate viable exits when evacuating an aircraft. A sound system has been installed in a Trident aircraft to present the sound, with loudspeakers as close as practicable to the exits. The position of the loudspeaker for the main Type I exit was compromised by the Trident's structure and was not considered to be ideal. The loudspeakers for the overwing Type III exits were satisfactory.

Background noise levels during trial evacuations were measured, in the absence of shouting from the cabin staff, at typically 78 dB(A). Calculations showed that the audio attraction sound would need to have a sound pressure level of about 76 dB for it to be just audible in the background noise – i.e. its masked threshold was 76 dB.

The recommended sound level for warning sounds is within a 10 dB range between 15 and 25 dB above the masked threshold. Measurements in the cabin showed that the sound level of an audio attraction signal would fall off with distance by about 15 dB along the length of the cabin. In simulated smoke the sound level would fall by a further 10 dB at the far end of the cabin making a total reduction along the cabin's length of 25 dB. Thus it is not possible to comply with the recommendation to set sound levels within a 10 dB range.

The sound system as installed was capable of producing audio attraction sound levels which were approximately 7 dB above the masked threshold at the most remote seats. Sound levels elsewhere would be higher. This was considered to be adequate for the audio attraction trials.

The audio attraction signal and sound system were evaluated in a subjective experiment. Passengers were able to correctly identify which sound source was operating on average on better than about 95 % of occasions, even though two of the sources were close together. This accuracy on the part of the passengers suggests that audio attraction should be effective.

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10 ADDENDUM

Our Report No. AC684/1, from which this CAA Paper is reprinted, was prepared before the results of the evacuation trials at Cranfield were available. This Addendum was written following our study of the draft Cranfield report to highlight factors which we consider to be important if further work on audio attraction is to be undertaken.

In Section 6.4 of our report we commented that the positioning of the audio attraction sound source over the Type III overwing exit was satisfactory, but that the positioning of the sound source for the Type I exit was not ideal, and that the audio attraction signal for this exit could be counter-productive under some circumstances. In the event, this proved the case.

Specifically, with the sound source in the bulkhead, before the exit, passengers are initially guided in the right direction. But as they approach the bulkhead, they have to pass the sound source and move away from it to reach the exit. This could cause disorientation or confusion for the first few passengers in the vicinity of the bulkhead. The first few would have no-one to follow and the smoke would then be at its thickest. Hesitation by the initial passengers slowed their evacuation and so the audio attraction sound was initially counter-productive. The position of the sounder became apparent to the passengers on their first evacuation and they would be able to take this into account subsequently. This would explain the learning effect associated with the use of this exit noted in the Cranfield report.

It is important to note that the confusion caused by the poor position of the sounder only occurs because passengers can locate the source of sound very accurately. The position of the source is the problem, not the passengers' abilities to localise. The audio attraction sound improved evacuation speeds through the Type III exit and there was no learning effect noted there. This is consistent with satisfactory location of the sound source, and is what we would expect.

Recommendations

For future trials we suggest removing the loudspeaker in the bulkhead and locating a new source in the ceiling at the position shown in Figure 4 of this paper, even though there are practical difficulties with installation at this point. This main source would be supplemented by an auxiliary, simultaneously sounding, source to the left by the main exit. The main source would guide passengers into the area between the bulkheads. Then as passengers passed into this area the auxiliary source to the left would indicate the direction of the open door. The auxiliary source on its own would not be sufficient, since it is shielded from the passengers by the bulkhead and its sound level would be too low in the cabin.We believe the audio attraction signal shows promise and with careful implementation should be successful. We now know that the *exact* locations of the signal sources are important and that we must be careful because poorly positioned sources can be counter-productive.

August 1991

Table 1 Noise Levels Measured During Evacuations

Evacuation No	*Noise level, dB(A)*			
	Without shouting		*With shouting*	
	Position 1	*Position 2*	*Position 1*	*Position 2*
1	82	76	94	85
2	78	78	91	83
3	77	78	88	83
4	77	–	–	–
column mean	78.5	77.3	91.0	83.7
column s.d.	2.4	1.2	3.0	1.2
condition mean	78.0		not applicable	
condition s.d.	1.9		not applicable	

Note: Values quoted are approximate and will vary slightly depending on which tape extracts are analysed. The extracts were selected as typical. As each recording channel was separately analysed, the extracts sampled for the two microphone positions were not necessarily simultaneous. The stewardess was not standing in the same place for all evacuations.

Table 2 Percentages of Correct Responses from the Full Localisation Equipment

Loudspeaker	*1*				*2*				*3*			
Responses	*1**	*2*	*3*	*4*	*1*	*2**	*3*	*4*	*1*	*2*	*3**	*4*
Row 8	100	0	0	0	0	60	19	21	0	11	69	20
Row 9	100	0	0	0	0	85	0	15	0	1	83	16
Row 10	100	0	0	0	0	85	2	14	0	2	91	7
Row 11	99	1	0	0	1	93	0	6	0	1	96	3
Row 12	100	0	0	0	0	100	0	0	0	0	100	0
Row 13	100	0	0	0	0	97	0	3	0	0	100	0
Row 14	100	0	0	0	0	100	0	0	0	0	100	0
Row 15	98	0	0	2	0	100	0	0	0	0	100	0
Row 16	100	0	0	0	0	100	0	0	0	0	100	0
Row 17	99	0	1	0	0	98	0	3	0	0	100	0
Row 18	96	1	3	0	0	100	0	0	0	0	100	0
Row 19	93	3	4	0	0	100	0	0	0	0	100	0

* Correct responses

Table 3 Percentages of Correct Responses from the Initial Presentations

Loudspeaker	*1*				*2*				*3*			
Responses	*1**	*2*	*3*	*4*	*1*	*2**	*3*	*4*	*1*	*2*	*3**	*4*
Row 8	100	0	0	0	0	56	17	28	0	11	78	11
Row 9	100	0	0	0	0	100	0	0	0	0	89	11
Row 10	100	0	0	0	0	100	0	0	0	0	100	0
Row 11	100	0	0	0	0	100	0	0	0	11	89	0
Row 12	100	0	0	0	0	100	0	0	0	0	100	0
Row 13	100	0	0	0	0	100	0	0	0	0	100	0
Row 14	100	0	0	0	0	100	0	0	0	0	100	0
Row 15	89	0	0	11	0	100	0	0	0	0	100	0
Row 16	100	0	0	0	0	100	0	0	0	0	100	0
Row 17	100	0	0	0	0	92	0	8	0	0	100	0
Row 18	89	0	11	0	0	100	0	0	0	0	100	0
Row 19	100	0	0	0	0	100	0	0	0	0	100	0

* Correct responses

Table 4 Percentages from the full Localisation Trial with responses from Loudspeakers 2 and 3 aggregated

Loudspeaker	*1*			*2*			*3*		
Responses	*1**	*2 or 3*	*4*	*1*	*2* or 3*	*4*	*1*	*2 or 3**	*4*
Row 8	100	0	0	0	79	21	0	80	20
Row 9	100	0	0	0	85	15	0	84	16
Row 10	100	0	0	0	86	14	0	93	7
Row 11	99	1	0	1	93	6	0	97	3
Row 12	100	0	0	0	100	0	0	100	0
Row 13	100	0	0	0	97	3	0	100	0
Row 14	100	0	0	0	100	0	0	100	0
Row 15	98	0	2	0	100	0	0	100	0
Row 16	100	0	0	0	100	0	0	100	0
Row 17	99	1	0	0	98	3	0	100	0
Row 18	96	4	0	0	100	0	0	100	0
Row 19	93	7	0	0	100	0	0	100	0

* Correct or nearly correct responses

Table 5 Percentages from the initial presentations with responses from Loudspeakers 2 and 3 aggregated

Loudspeaker	*1*			*2*			*3*		
Responses	*1**	*2 or 3*	*4*	*1*	*2* or 3*	*4*	*1*	*2 or 3**	*4*
Row 8	100	0	0	0	72	28	0	89	11
Row 9	100	0	0	0	100	0	0	89	11
Row 10	100	0	0	0	100	0	0	100	0
Row 11	100	0	0	0	100	0	0	100	0
Row 12	100	0	0	0	100	0	0	100	0
Row 13	100	0	0	0	100	0	0	100	0
Row 14	100	0	0	0	100	0	0	100	0
Row 15	89	0	11	0	100	0	0	100	0
Row 16	100	0	0	0	100	0	0	100	0
Row 17	100	0	0	0	92	8	0	100	0
Row 18	89	11	0	0	100	0	0	100	0
Row 19	100	0	0	0	100	0	0	100	0

* Correct or nearly correct responses

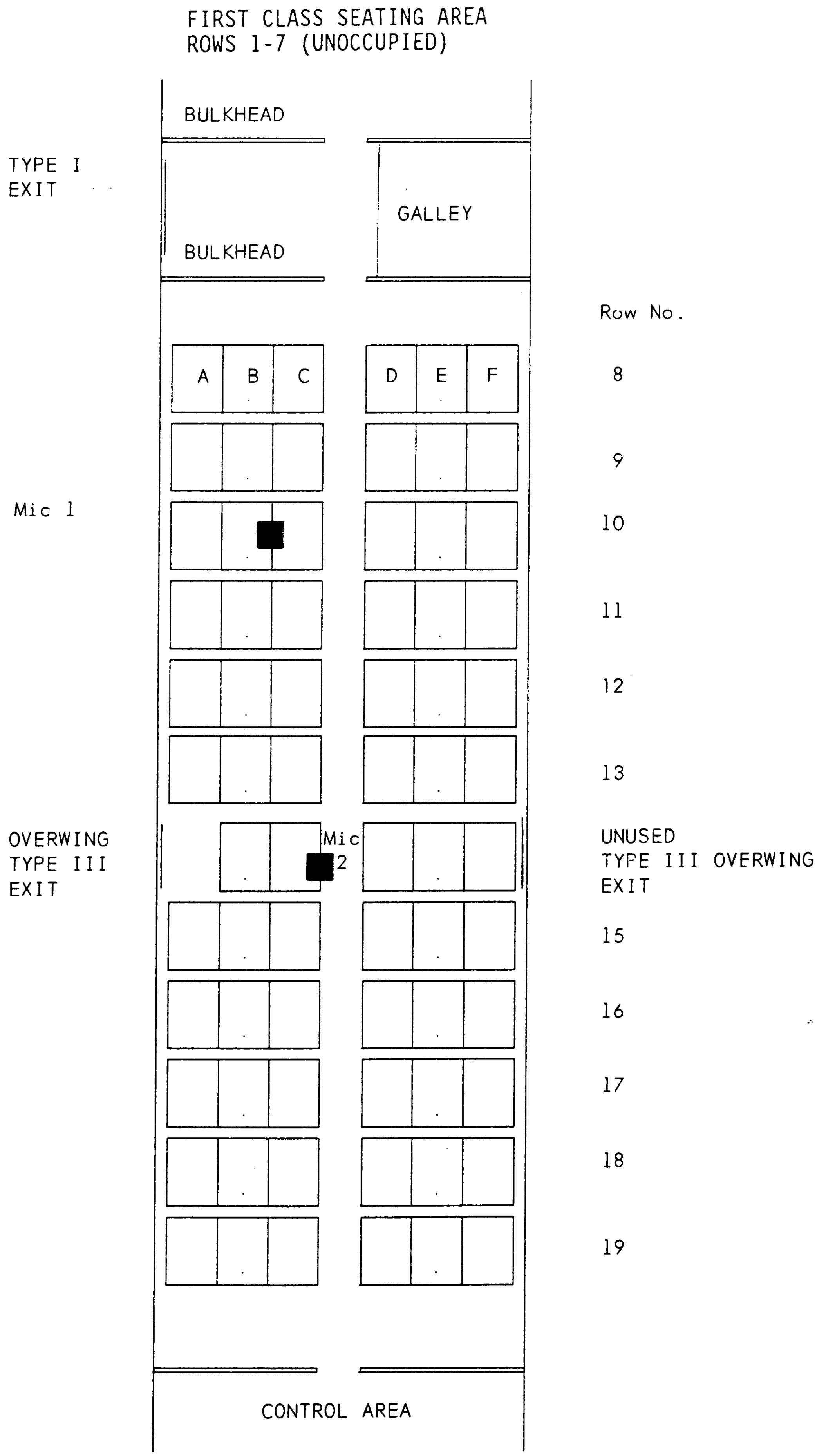


Figure 1 Plan of Trident aircraft used in evacuation trials

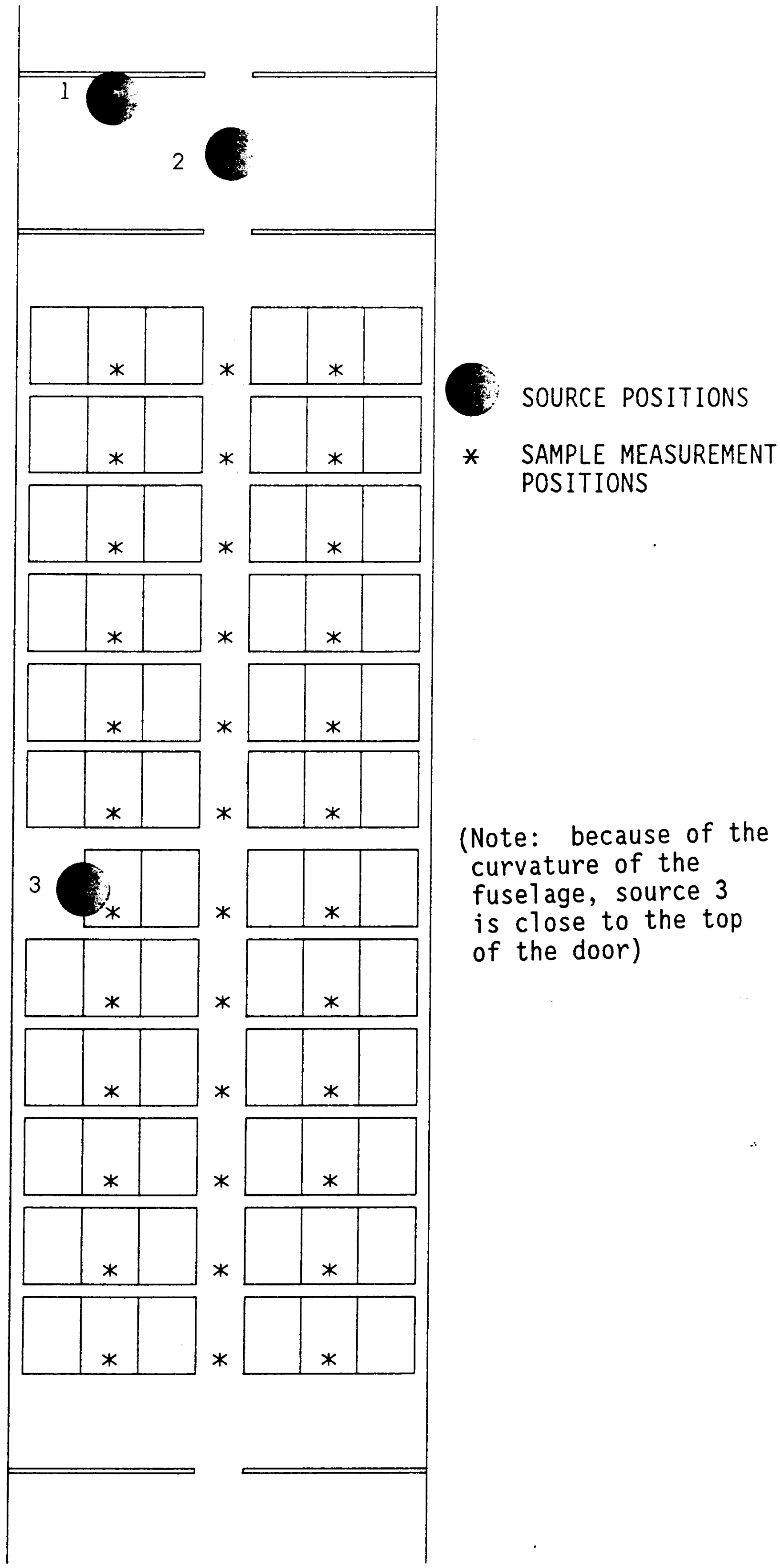


Figure 2 Potential locations of audio attraction sources

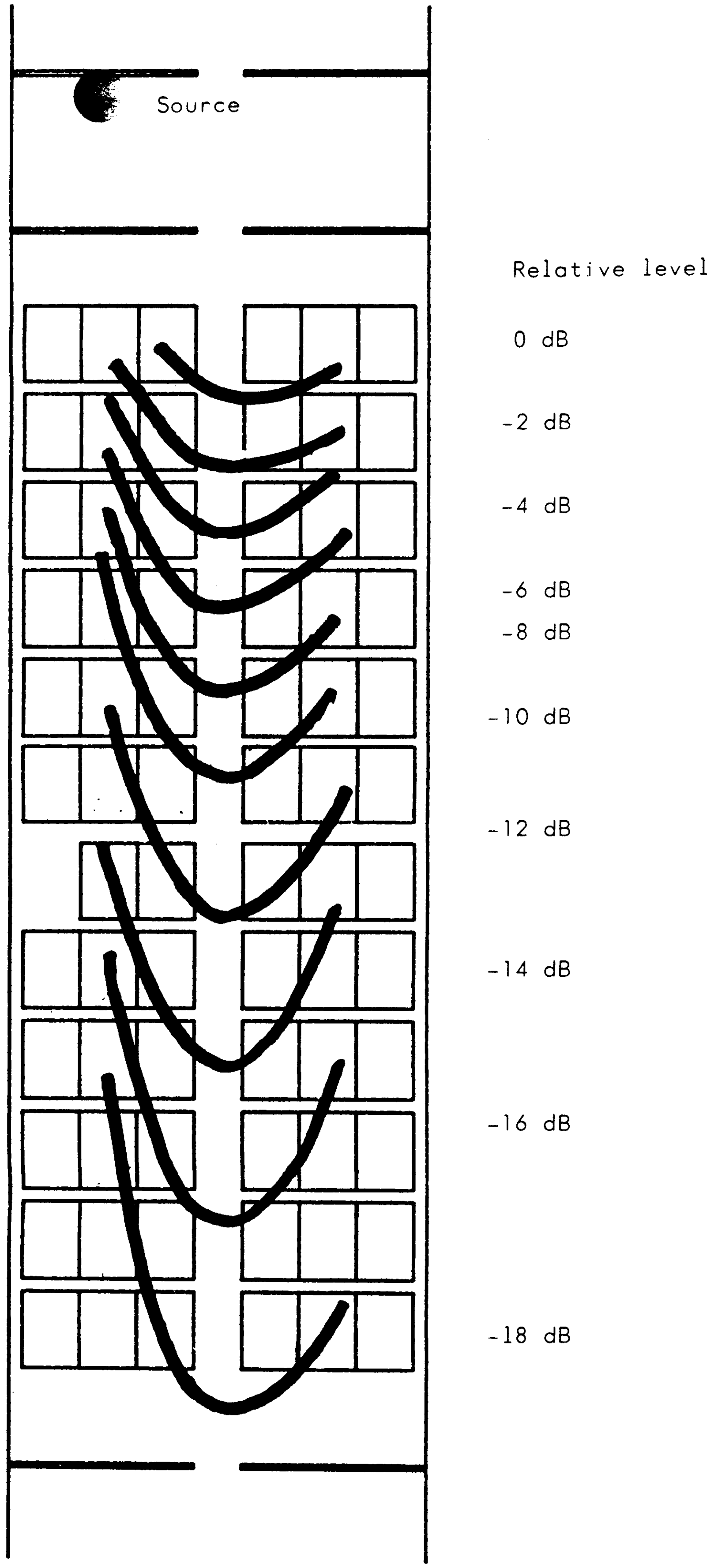


Figure 3 Variation in A-weighted sound level with distance from a sound source near the Type I exit. Contours are 2 dB apart

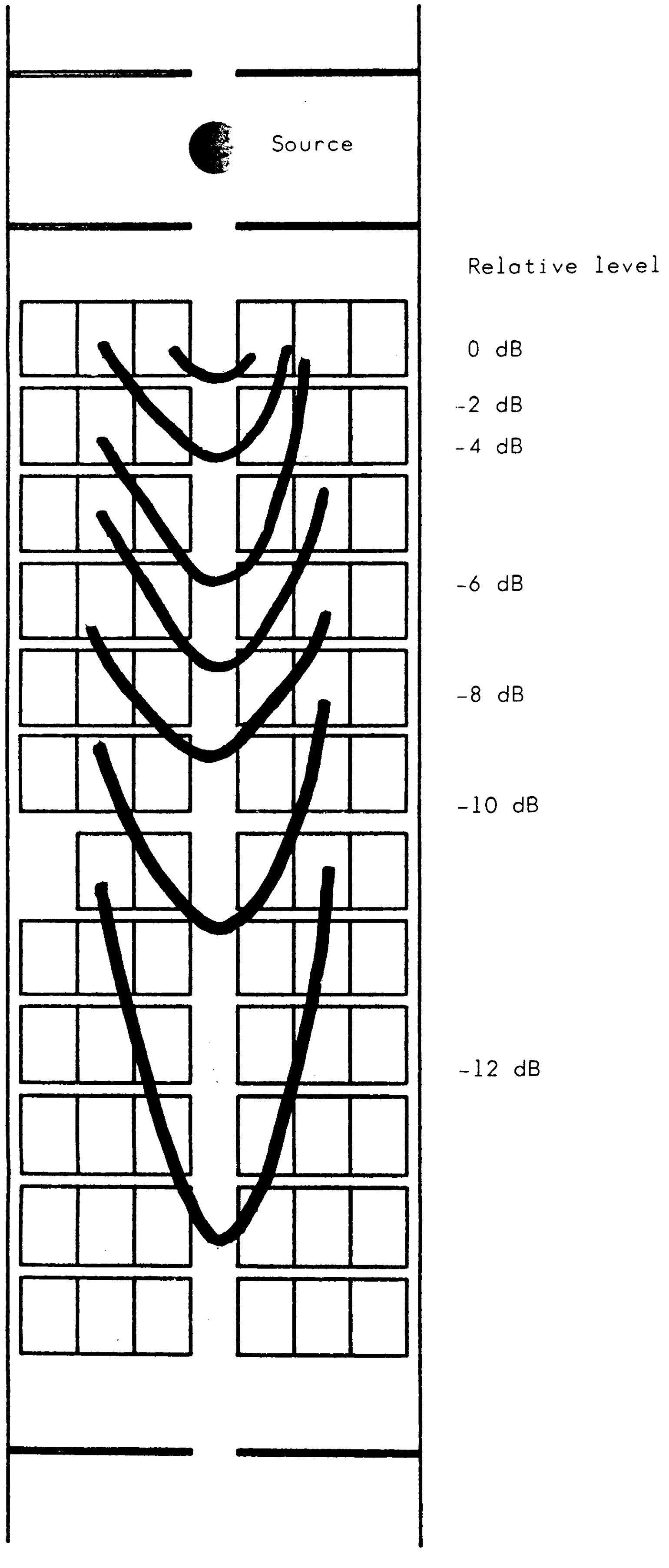


Figure 4 Variation in A-weighted sound level with distance from a sound source between the bulkheads. Contours are 2 dB apart

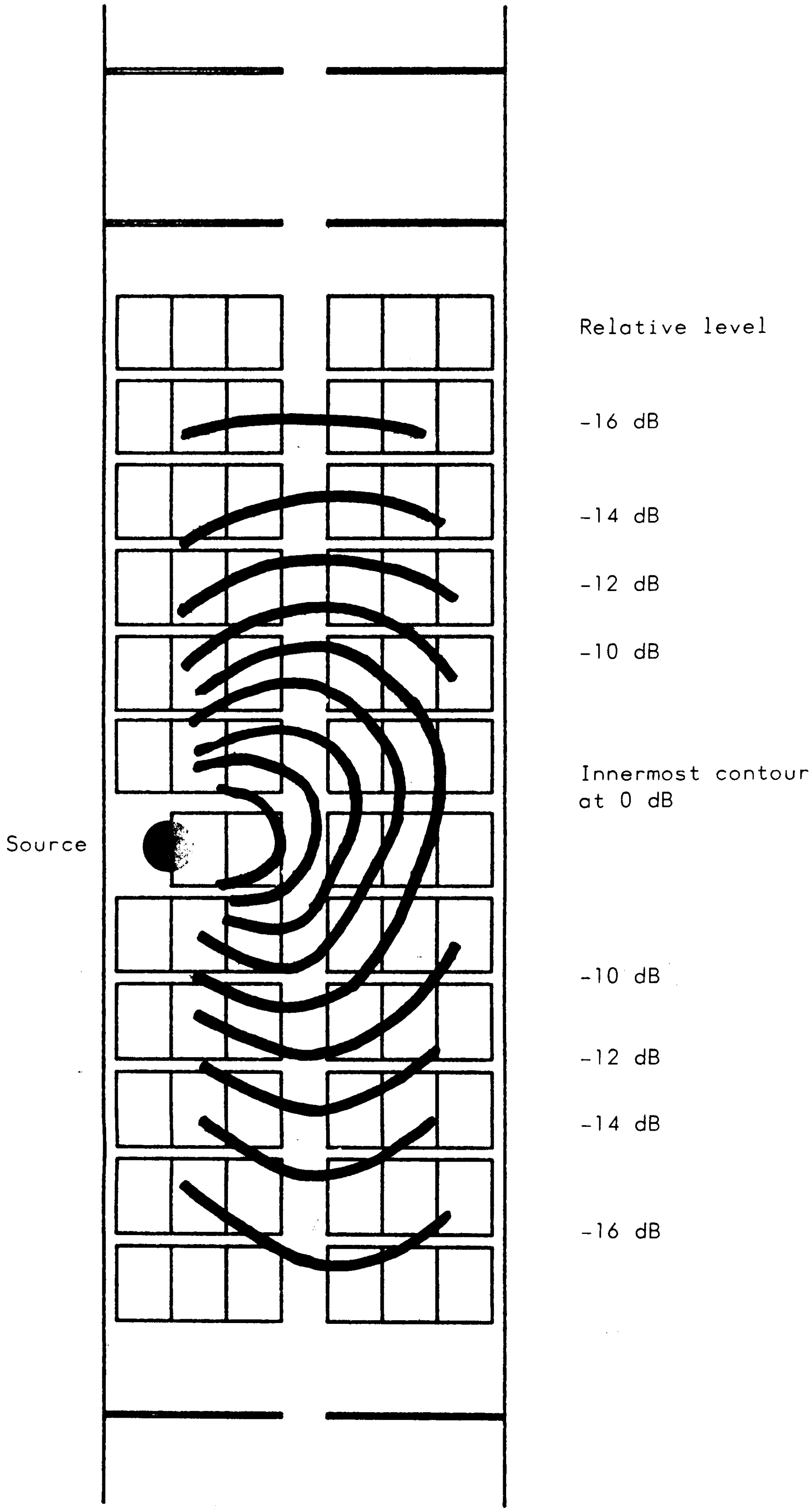


Figure 5 Variation in A-weighted sound level with distance from a sound source near the Type III exit. Contours are 2 dB apart

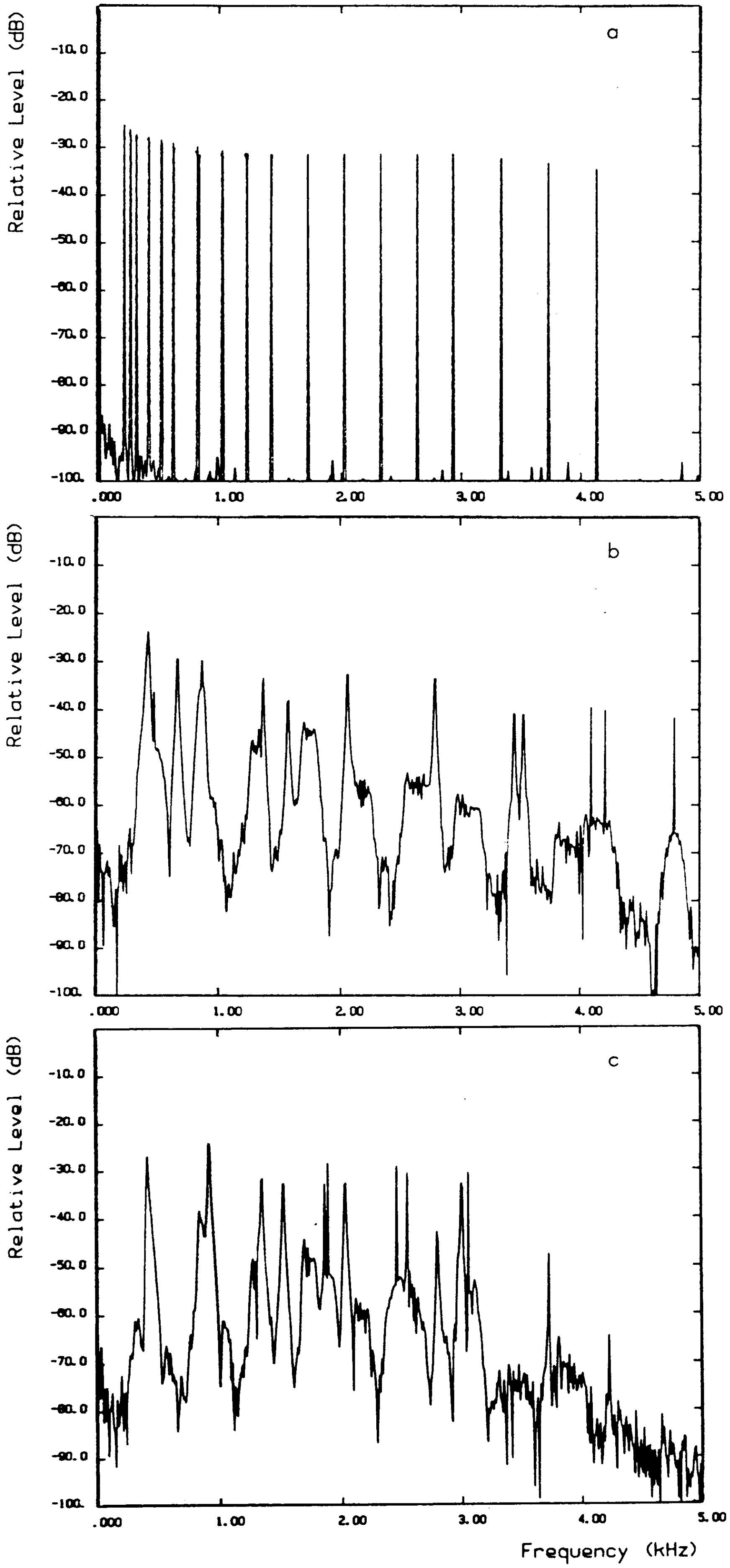


Figure 6 Spectra of basic sound pulses used to make up the audio attraction sound

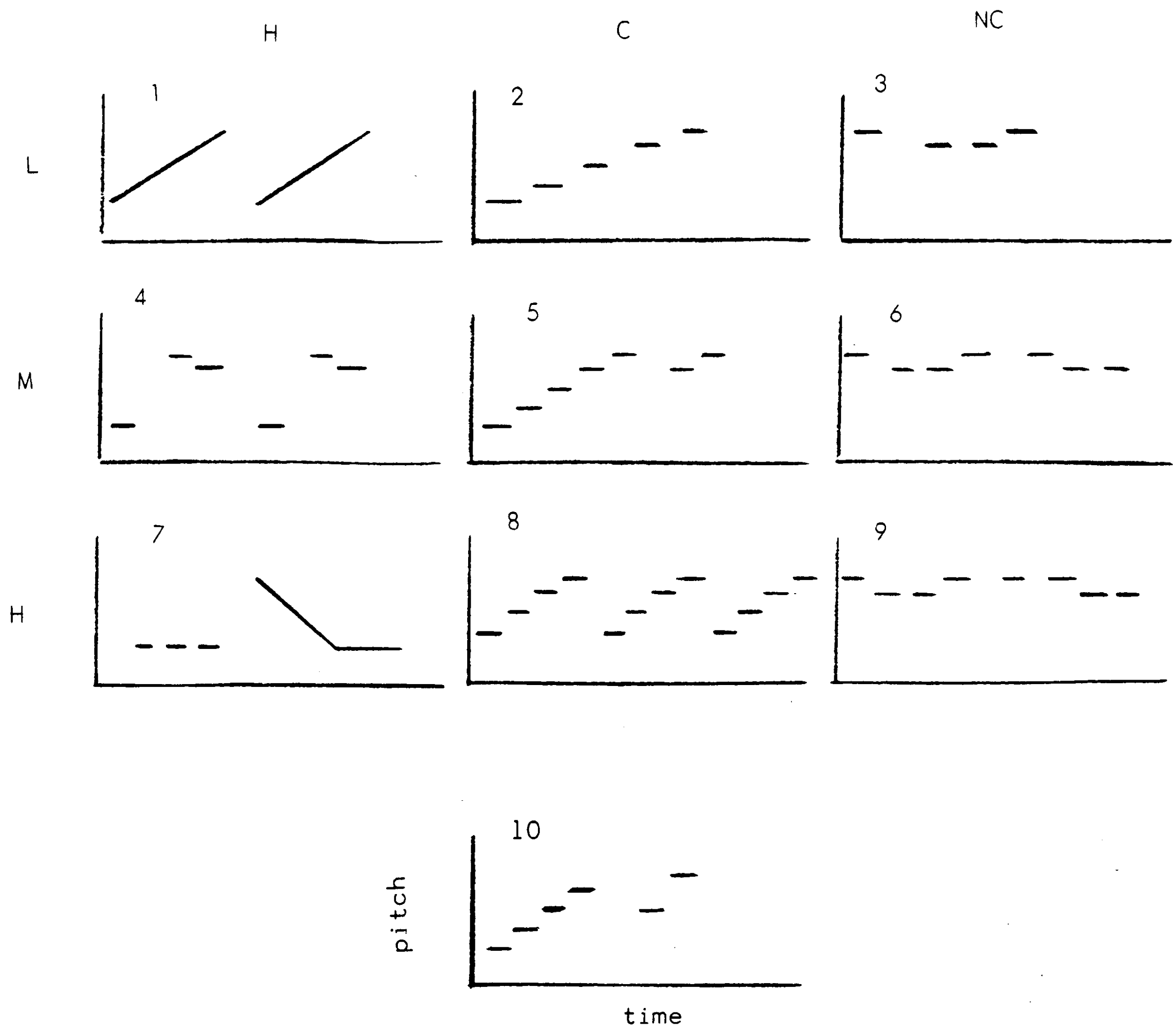
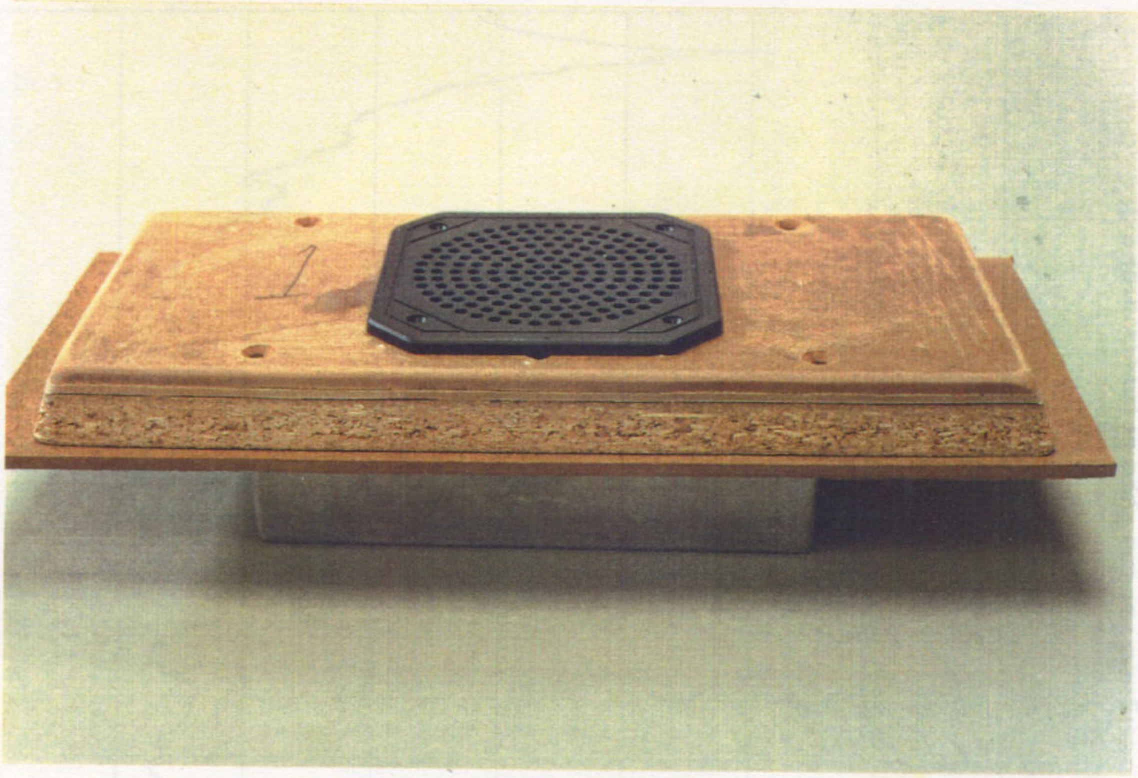


Figure 7 Pitch contour diagrams for the experimental audio attraction sounds. Number 10 was the final choice



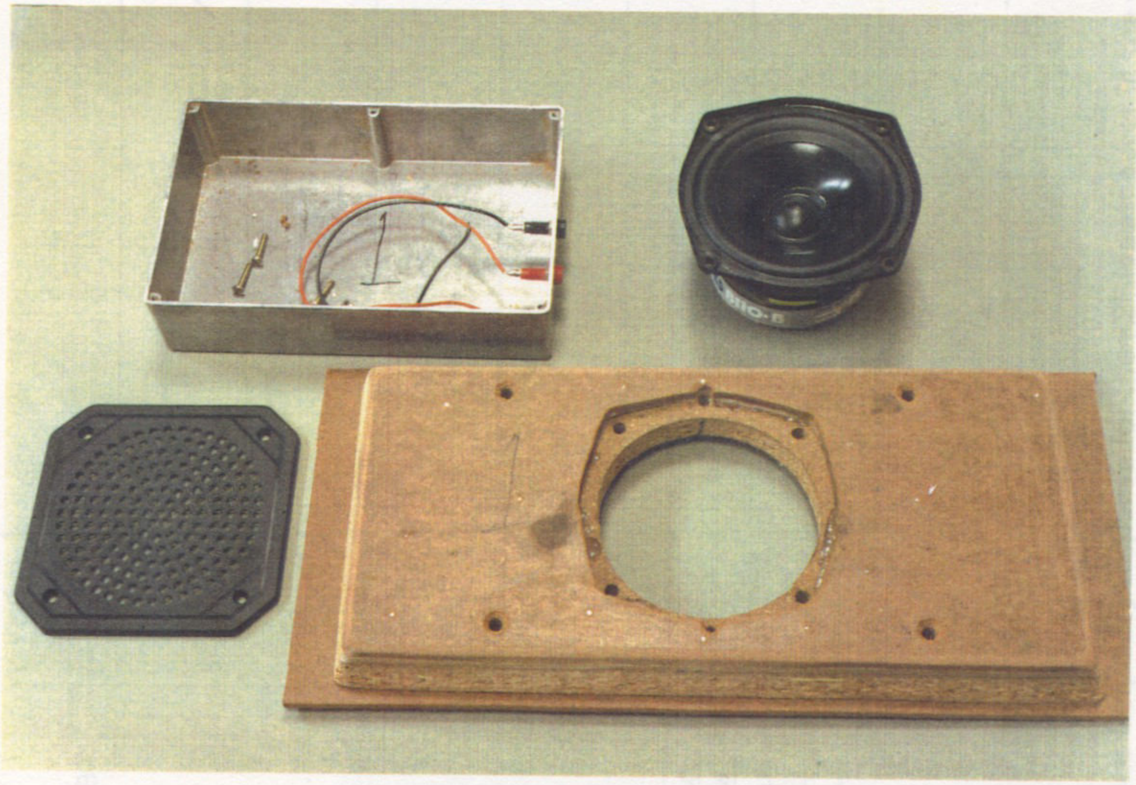


Figure 8 Details of the construction of the loudspeaker enclosure to go above a Type III (overwing) exit

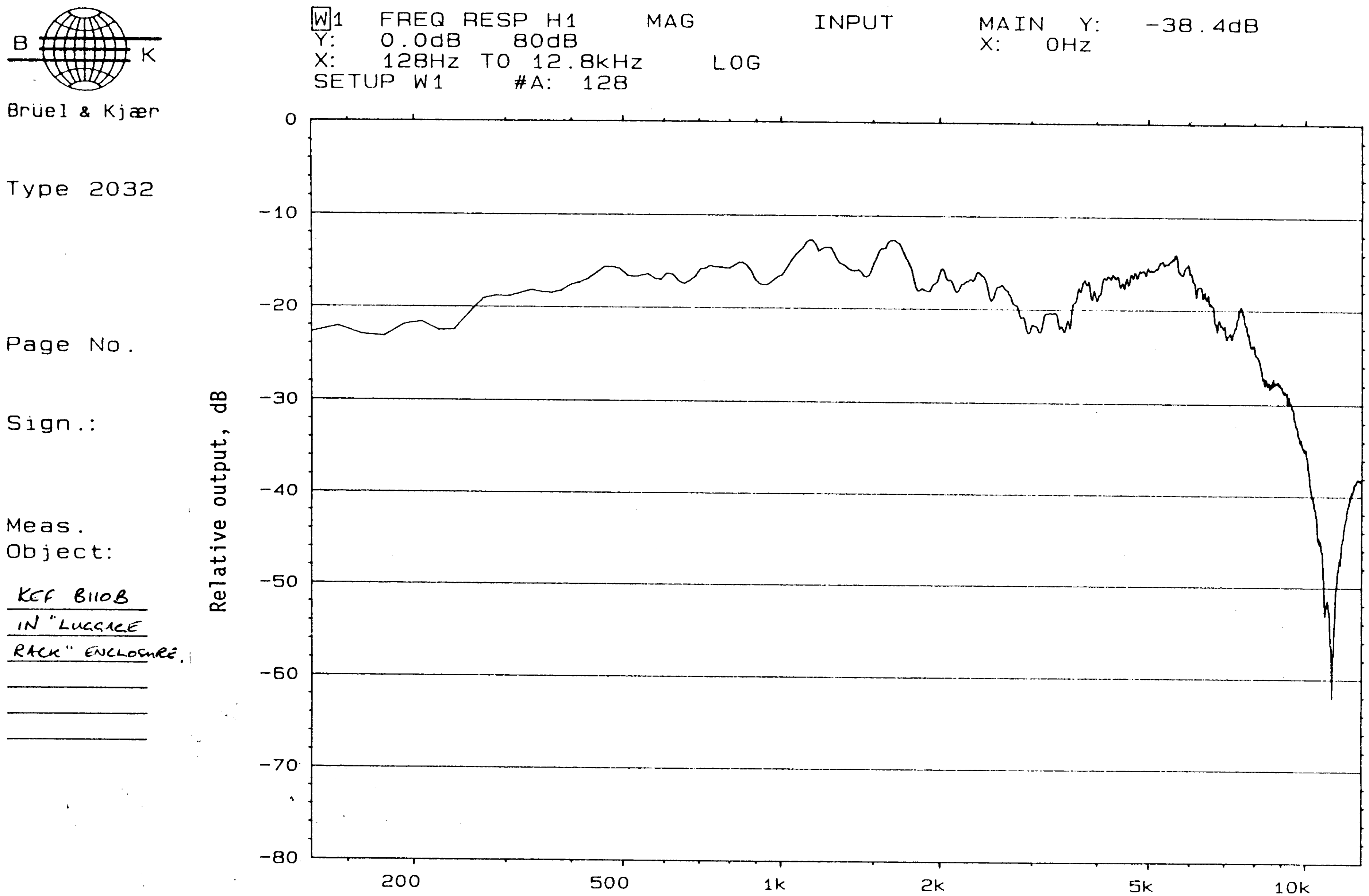


Figure 9 On axis frequency response for the KEF loudspeaker in the enclosure designed for the Type III (overwing) exit

a)

b)

Figure 10 Audio attraction loudspeakers mounted in the Trident (a) In the bulkhead in front of the Type I exit (b) Above a Type III (overwing) exit

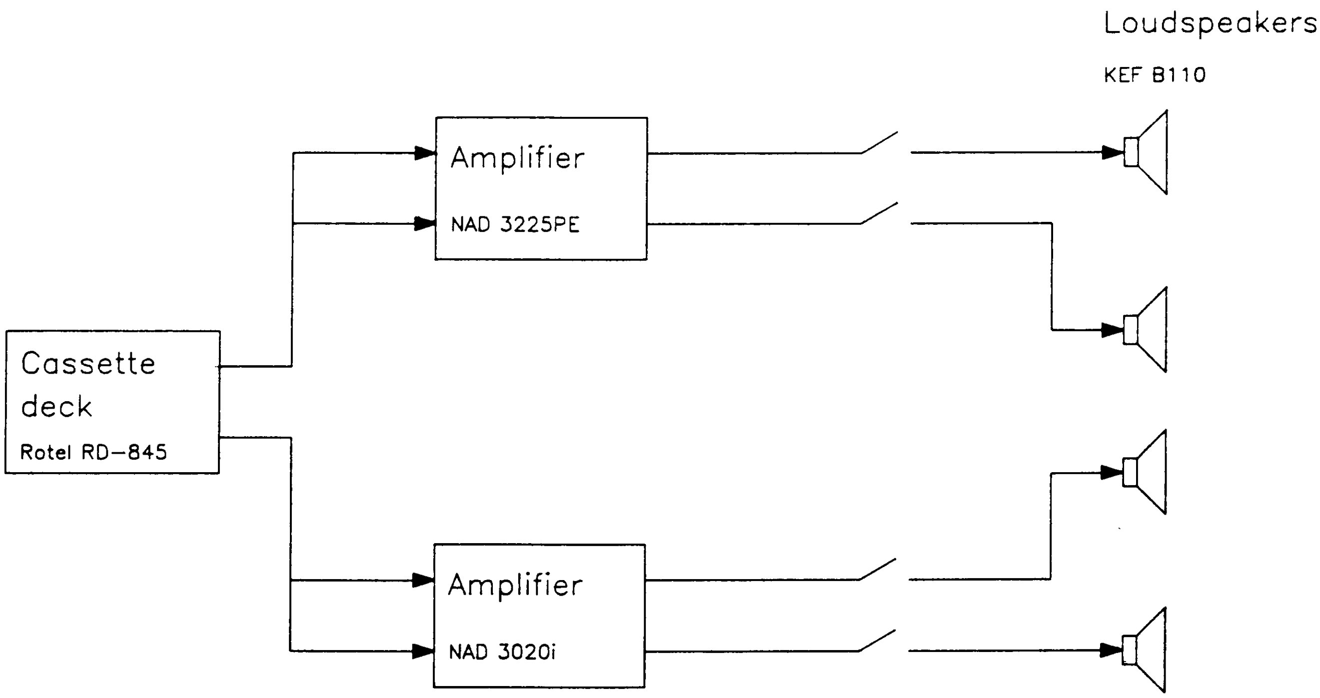


Figure 11 Block diagram of the sound system for replaying the audio attraction sound

LOUDSPEAKER TESTS

PLEASE WRITE YOUR SEAT NUMBER HERE ______

THERE ARE FOUR LOUDSPEAKERS LABELLED 1, 2, 3 AND 4. PLEASE LOOK AROUND TO SEE WHERE THEY ARE.

FOR EACH TEST, WE WILL PLAY A BRIEF SOUND THROUGH ONE OF THE LOUDSPEAKERS AT RANDOM. WE WOULD LIKE YOU TO WRITE DOWN THE NUMBER OF THE LOUDSPEAKER THAT THE SOUND APPEARED TO COME FROM.

THERE WILL BE 30 TESTS IN ALL, EACH TAKING JUST A FEW SECONDS.

TEST NO.	LOUDSPEAKER NO.	TEST NO.	LOUDSPEAKER NO.
1	......	16	......
2	......	17	......
3	......	18	......
4	......	19	......
5	......	20	......
6	......	21	......
7	......	22	......
8	......	23	......
9	......	24	......
10	......	25	......
11	......	26	......
12	......	27	......
13	......	28	......
14	......	29	......
15	......	30	......

THANK YOU FOR YOUR ASSISTANCE

Figure 12 Response sheet for the localisation experiment

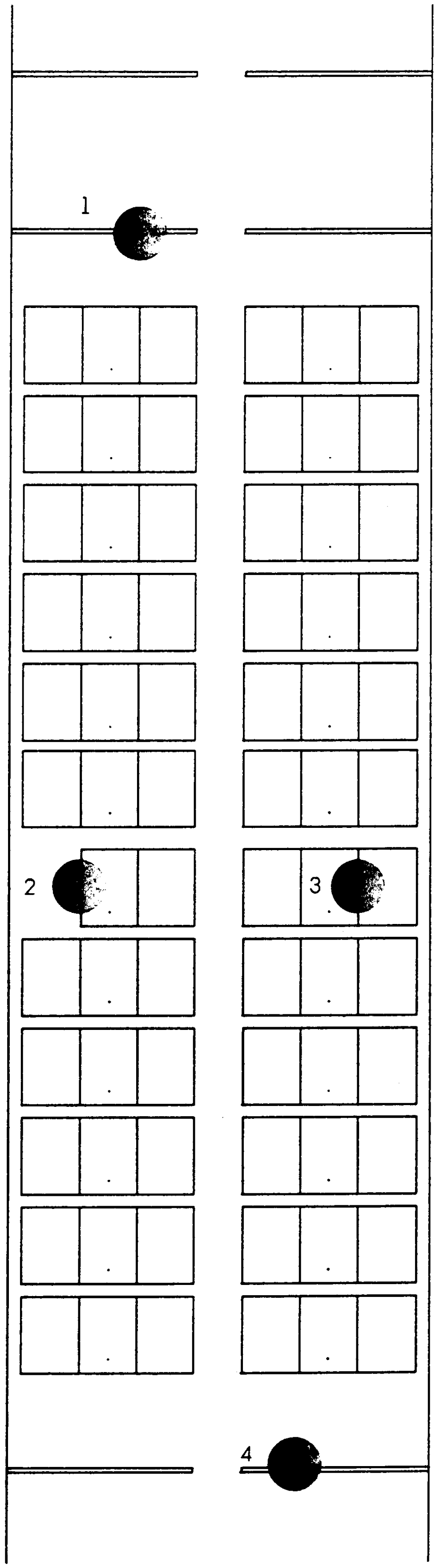


Figure 13 Locations of the three real loudspeakers (1–3) and the dummy loudspeaker (4) for the localisation experiment

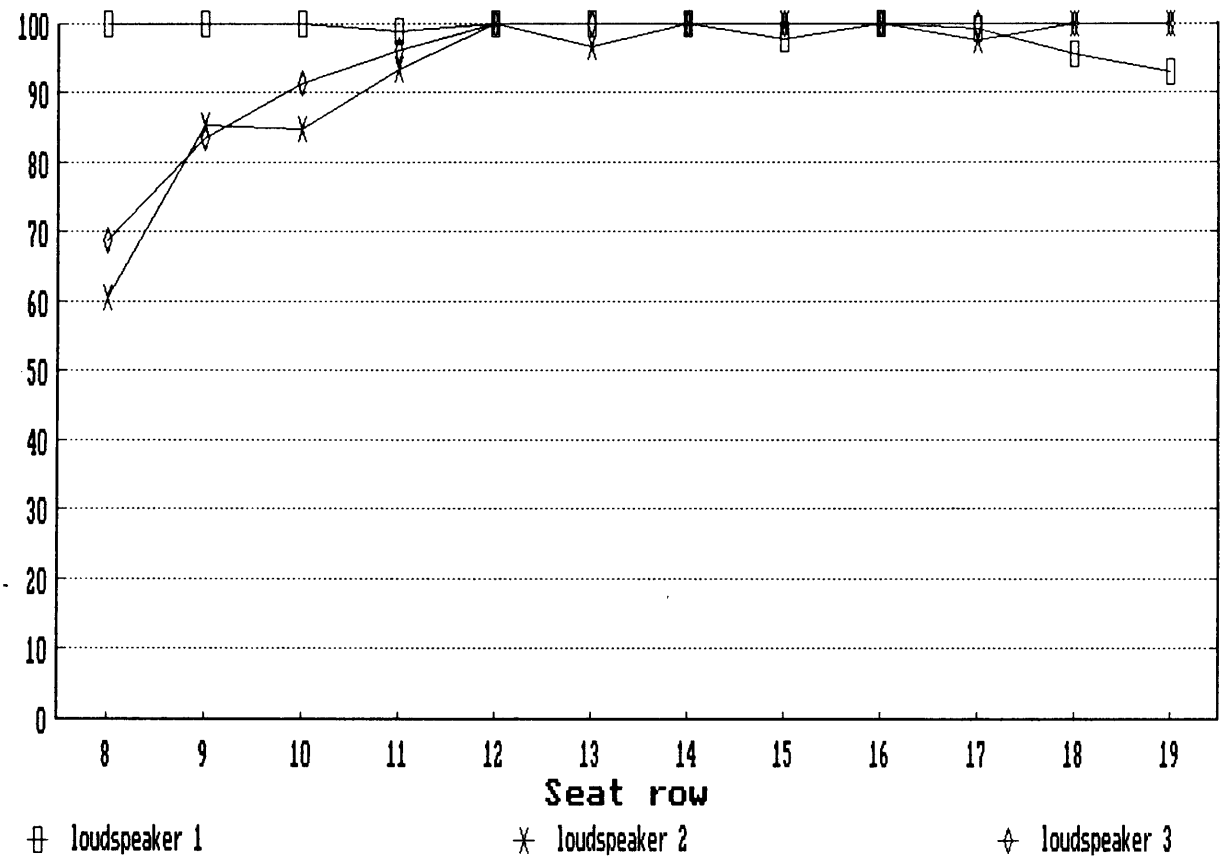


Figure 14 Results from the full localisation experiment. Percentages of loudspeakers correctly identified

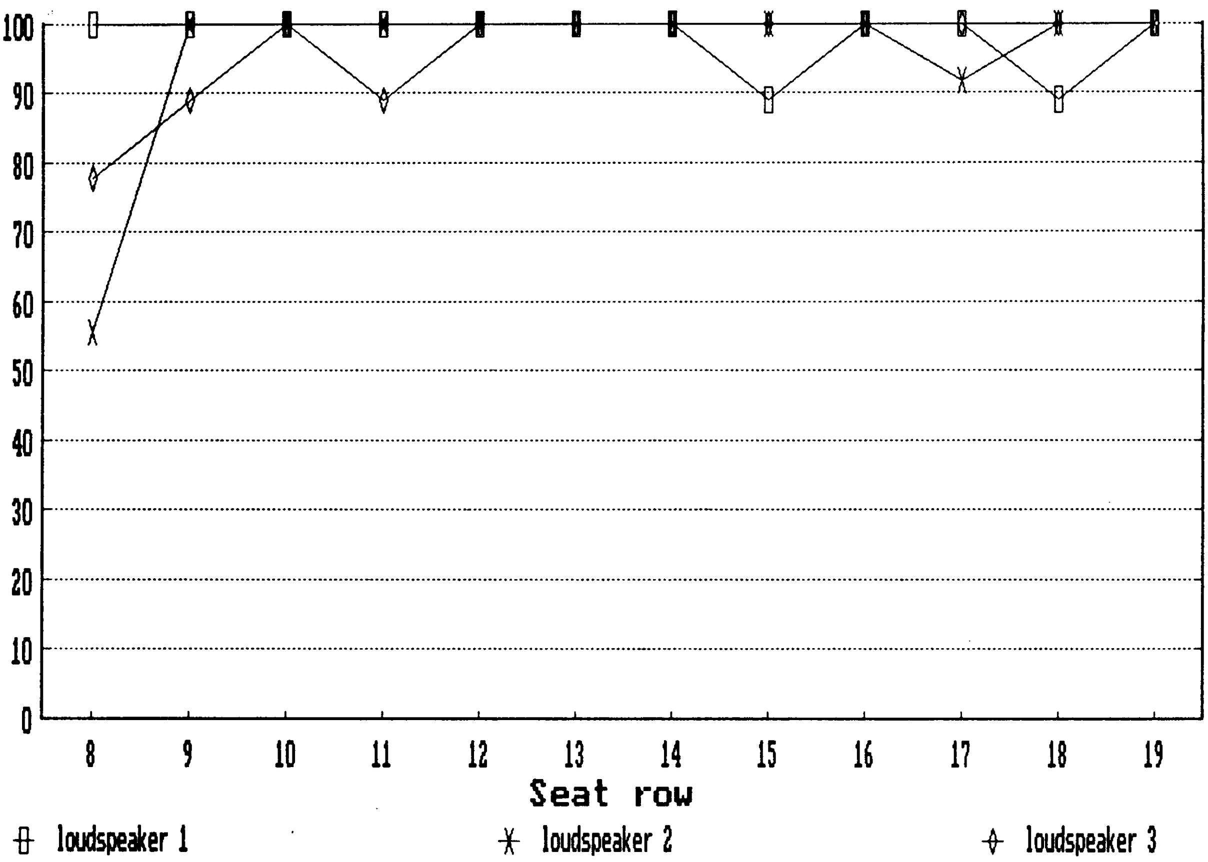


Figure 15 Results from the initial presentation of the localisation experiment

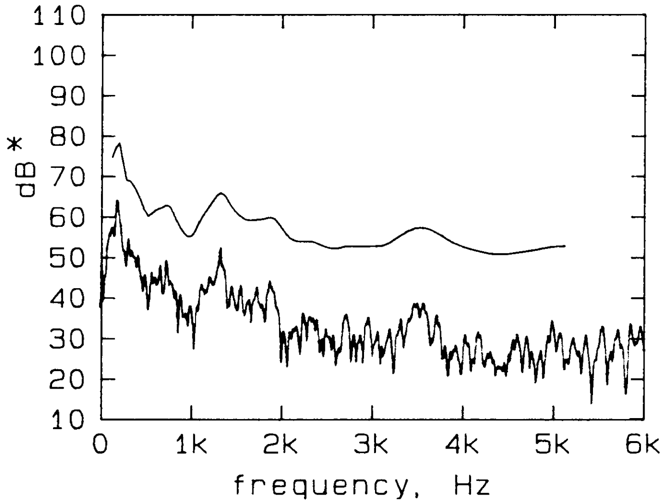
APPENDIX A
BACKGROUND NOISE SPECTRA AND PREDICTED MASKED THRESHOLDS

Technical note:
The lower line in each of the following figures shows the noise spectrum plotted as a pressure spectrum level (sound pressure spectral density) in dB re 400 x 10^{-12} Pa^2/Hz versus frequency in Hz. (This is equivalent to dB re 20 $\mu Pa/Hz^{1/2}$ versus frequency in Hz).

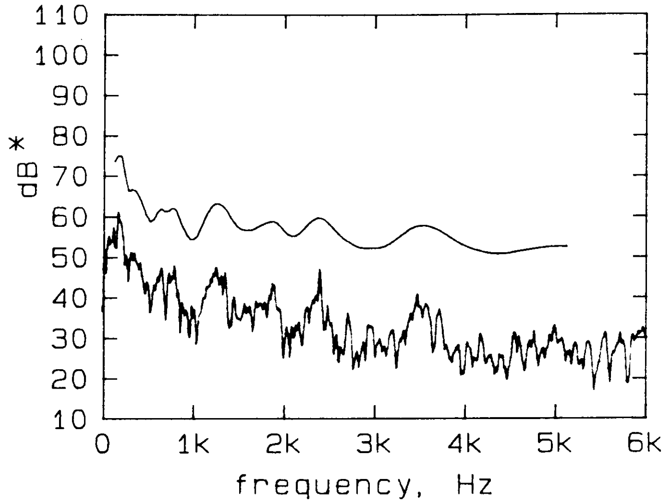
The upper, smoother line shows the predicted masked threshold for tonal components plotted as sound pressure level in dB re 20 μPa versus frequency in Hz.

Both lines are plotted on the same graph for convenience, using the same numerical scale of decibels, although the noise spectrum and the threshold have different dimensions and different reference quantities.

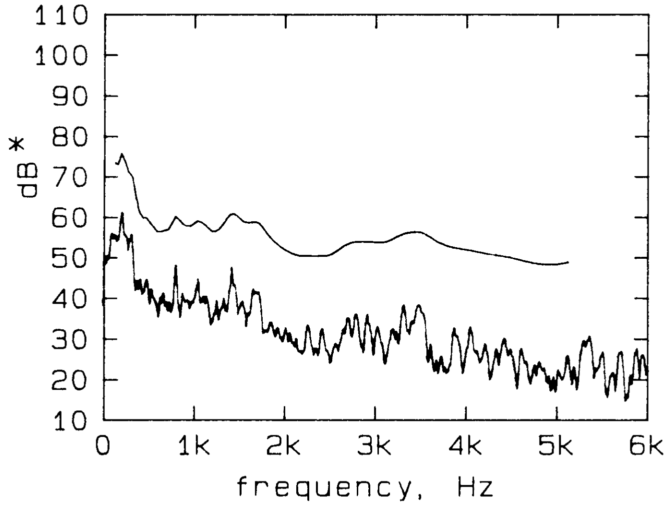
A.1 Evacuation 1,
Position 1, no shouting



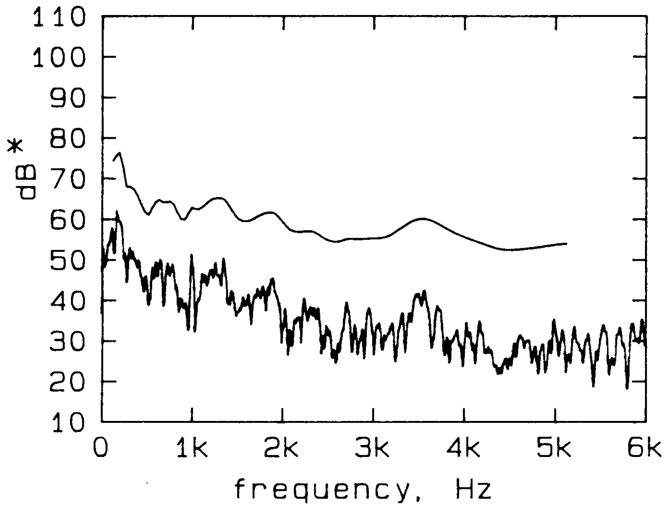
A.2 Evacuation 1,
Position 1, no shouting



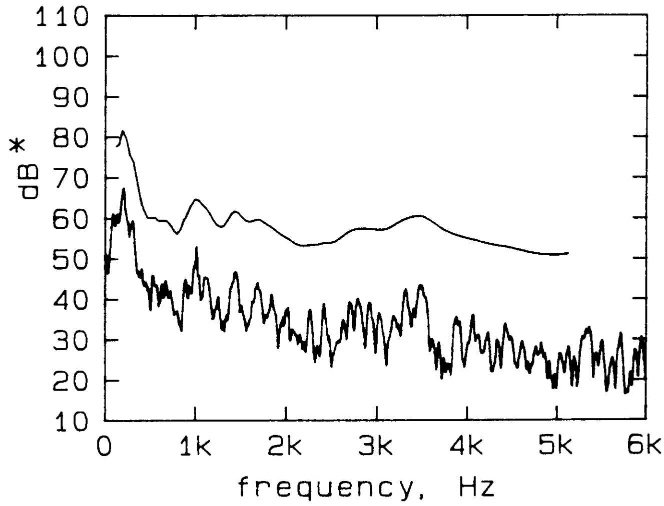
A.3 Evacuation 1,
Position 2, no shouting



A.4 Evacuation 2,
Position 1, no shouting

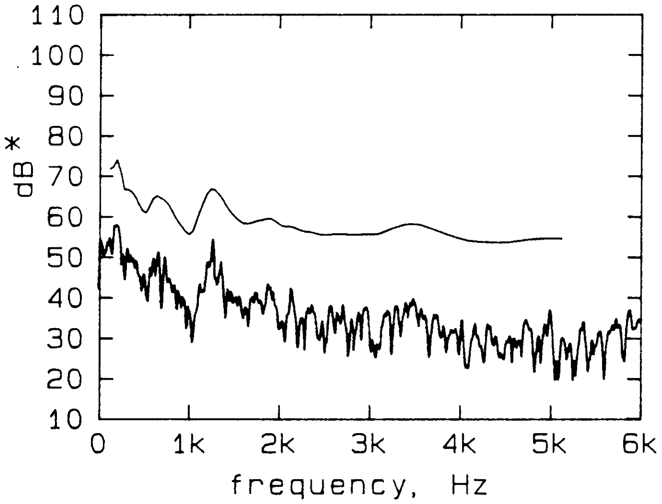


A.5 Evacuation 2,
Position 2, no shouting

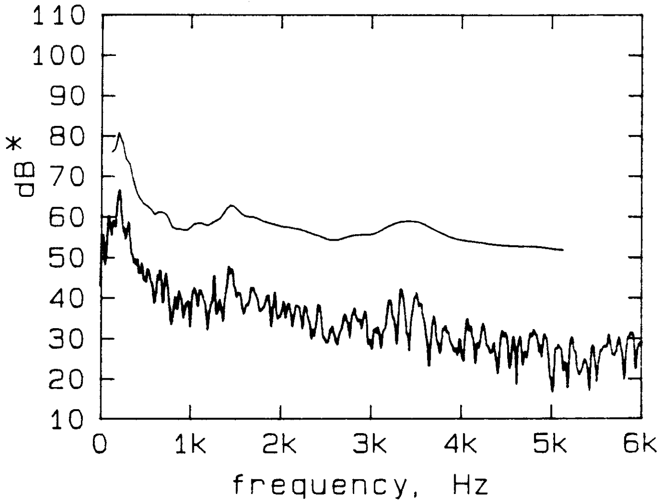


*Note: Spectrum and threshold curve have different units and different decibel reference levels; see Appendix title page for details.

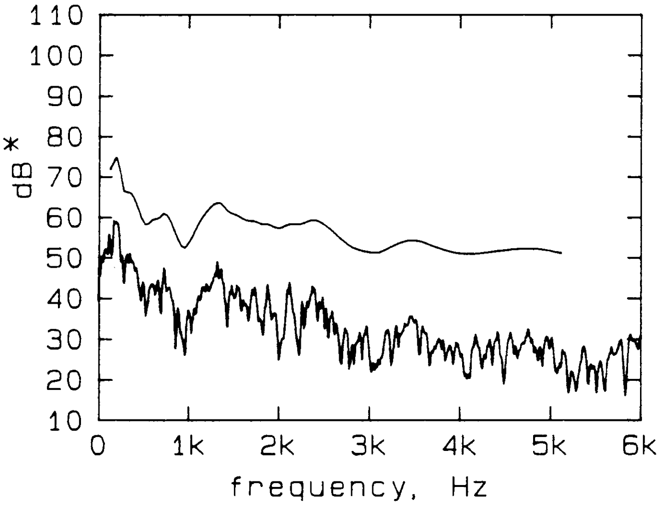
A.6 Evacuation 3,
Position 1, no shouting



A.7 Evacuation 3,
Position 2, no shouting

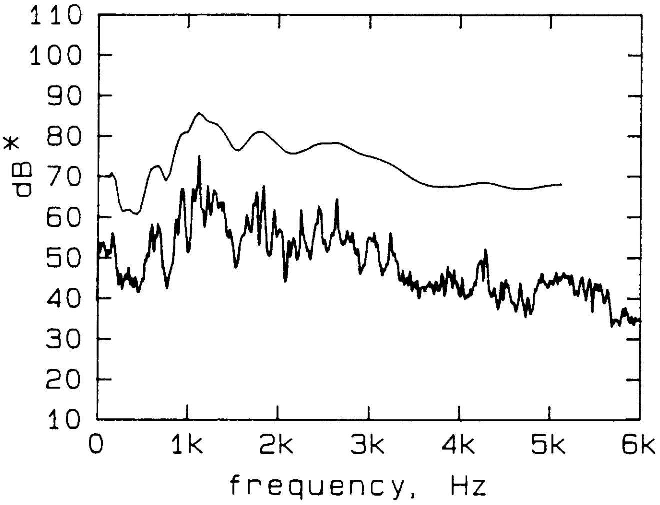


A.8 Evacuation 4,
Position 1, no shouting

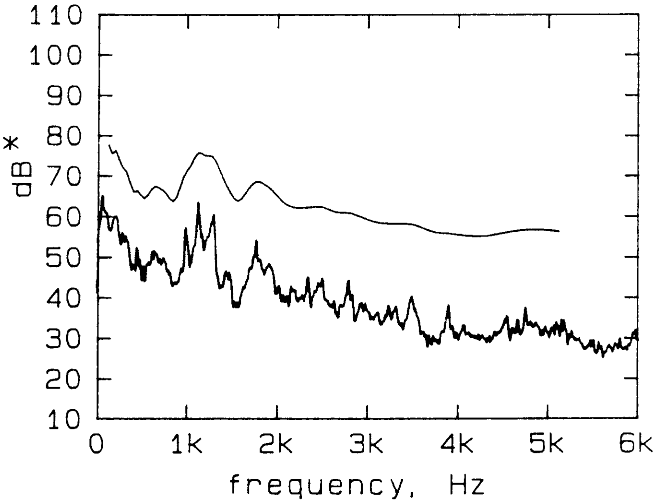


*Note: Spectrum and threshold curve have different units and different decibel reference levels; see Appendix title page for details.

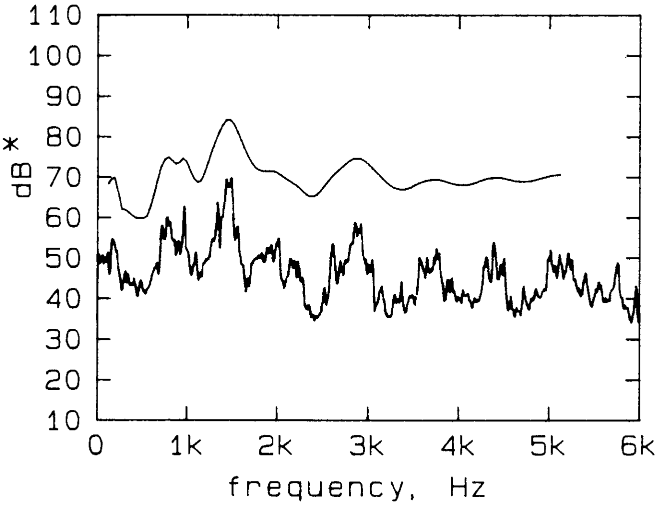
A.9 Evacuation 1,
Position 1, shouting



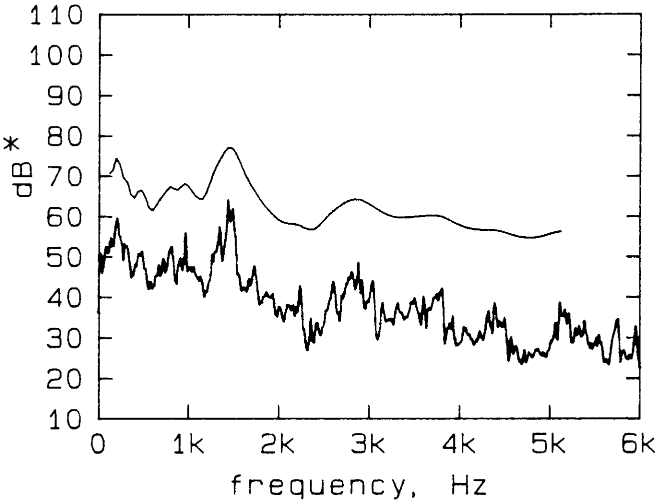
A.10 Evacuation 1,
Position 2, shouting



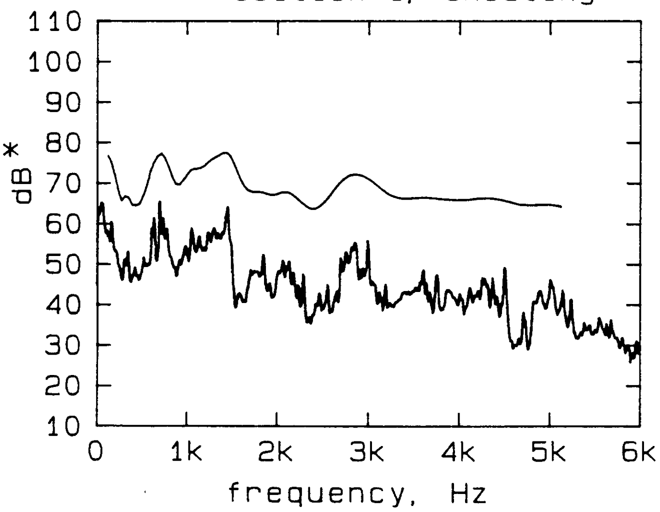
A.11 Evacuation 2,
Position 1, shouting



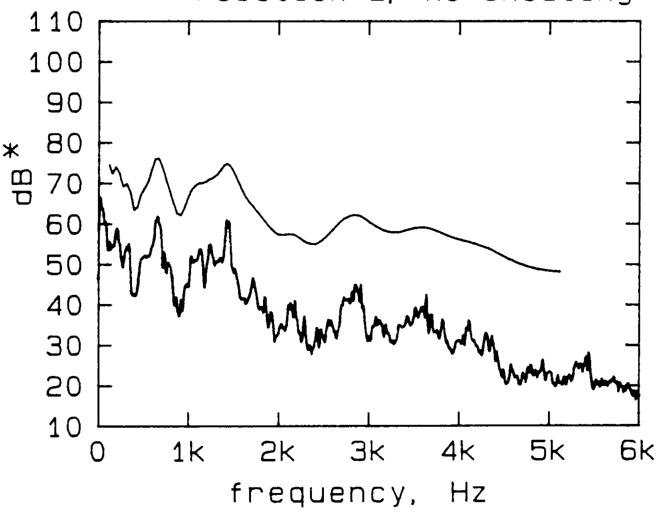
A.12 Evacuation 2,
Position 2, shouting



A.13 Evacuation 3,
Position 1, shouting



A.14 Evacuation 3,
Position 2, no shouting



*Note: Spectrum and threshold curve have different units and different decibel reference levels; see Appendix title page for details.