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INTELLIGIBLE SPEECH COMMUNICATION IN HIGHLY REVERBERANT AND NOISY INDUSTRIAL SPACES

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INTRODUCTION

This paper arises from a project currently in hand for the Central Electricity Generating Board, North Eastern Region. Generally, the brief is concerned with the provision of communication systems at Hartlepool Nuclear Power Station, in part to ensure that proper and adequate means are available to effect an orderly exodus from the site in the event of an emergency incident. Whilst alarms based on conventional mechanical sounder devices provide the backbone of the incident alert system, due to the specific requirements at a nuclear licensed site it is necessary also to provide intelligible speech communication to all building interiors where staff are likely to be at work.

It is not intended here to go into the technical details of the overall scheme - suffice it to say that a highly sophisticated, fully automated, state-of-the-art system has been proposed and it is intended that the systems engineering aspects of the project will be the subject of a further paper in due course.

Instead, this paper is concerned with the one factor, which, after an extensive survey and operational study at the Station emerged as the main technical difficulty:- How to provide intelligible speech in buildings where normal day-to-day ambient noise can be anything up to 96dB(A) and the RT60 typically over 10 seconds?

ENVIRONMENTAL CONSIDERATIONS

A typical power station site comprises virtually all forms of industrial and commercial building, ranging from softly furnished offices, through workshops, switchrooms and boiler houses, to vast operational plant areas. Clearly, due to the many different acoustic environments involved there can be no common approach and each area has to be individually considered.

The Turbine Hall at Hartlepool is 82m long, 72m wide and 35m high, giving a room volume of some 206,000 cu.m, whilst the Reactor Building Pile Cap area measures 92m by 44m and 40m high, giving 162,000 cu.m volume. The general layout is shown in Fig. 1.

Having regard to the low order of absorption co-efficients extant in these areas, the basic Sabine RT60 formula seems appropriate (1), and assuming an absorption co-efficient of 0.12 for the concrete and steel surfaces which make up the majority of these buildings, RT60 in the Turbine Hall works out at 13 seconds, and in the Reactor Pile Cap area, 11 seconds. The ambient noise in the Turbine Hall with both 666MW generator sets running is 96dB(A), whilst in the Reactor Pile Cap area, 60dB(A) is typical.

DESIGN CONSIDERATIONS

Two approaches come immediately to mind - distributed sources and single coherent array. The question of which to use almost answered itself as the existing installation is of the former type and totally ineffective, due partly to inadequate power, but significantly to phase cancellation effects between neighbouring sources. But what sort of array would be likely to effect an improvement?

The Critical Distance is obviously also going to be the critical factor in such reverberant spaces - how far will it be possible to throw before direct energy would be masked by reverberant energy?

Reference to the Turbine Hall plan suggested a throw of 60 meters, as the far end is to some extent screened from the main body of the space by plant and will therefore require separate coverage. But what if someone parked the huge 220 tonne overhead crane right in front of the cluster and masked the entire array? So perhaps we should look at two arrays.

The standard formula for critical distance seems to be:-

$$Dc = 0.14\sqrt{QR}, \text{ where}$$

Q (Directivity Factor of source) = $180^{\circ}/\arcsin(\sin h/2 \times \sin v/2)$ (after Molloy (2))

R (Room Constant) = Sa/1-a (after Hopkins & Stryker (3))

Fig. 2 gives the relationships in a convenient chart form.

The Room Constant, "R" works out at approximately 3000 sq.m for both the Turbine Hall and the Reactor Pile Cap area, as the surface areas are roughly similar. Inputting this into the $0.14\sqrt{QR}$ equation suggests that for a critical distance of 60 meters we need a source Q of 63. That represents a highly directional source - a $40^{\circ} \times 20^{\circ}$ horn for example has a nominal Q of only 53. Also, a source with a 40° coverage angle will not provide uniform coverage of the area we are interested in, so more than one source will be required anyway, irrespective of crane masking considerations.

Reverberant energy however is not the only concern. It is also necessary to get at least 3dB, but preferably 6dB clear of the 96dB plant noise 60 meters out from the source. The inverse square law loss over 60m works out at -36dB, so the target source level should be: 96dB + 6dB +36dB = 138dB at 1m.

So the requirement is now defined - more than one source, each having a Q of at least 60 and capable of generating 138dB SPL at 1 meter. If we can achieve that we can solve the problem - but how?

SPEECH COMMUNICATION IN REVERBERANT & NOISY INDUSTRIAL SPACES

IMPLEMENTATION

As the only concern is speech intelligibility, not fidelity, there is nothing to lose and a great deal to be gained by restricting the bandwidth to the bare minimum, i.e. 400Hz to 4KHz, for which a compression driver and horn must provide the answer. So a number of compression drivers were tested in the anechoic chamber at GEC-Hirst Research Centre at Wembley where amplitude response and sensitivity were measured, each test sample coupled to a standard circular exponential horn with an air column length of 1 meter, a flare rate of 190Hz and a Q of 12. In this way it was established that the best sensitivity available from a standard product at a commercially viable cost is about 112dB for 1 watt at 1 meter - some 3dB better than the nearest rival. The response curve obtained is given in Fig. 3. Also, it is reasonable to expect at least another 3dB on another horn with a Q of 60 or so. That product, the Atlas PD30T, has a continuous programme rating of 30 watts, so its maximum programme level will be 112dB + 3dB + 15dB, = 130dB SPL. It will therefore be necessary to use six PD30Ts in order to achieve the 138dB source SPL target. But how to mount six drivers to a horn, what comb filter effects would result, and where do we get a horn with a Q of 60+ anyway?

THE DARTMOOR CONNECTION

Paul Taylor of Pamphonic Reproducers, in a paper presented to the British Sound Recording Association in January 1963, described a highly directional line source horn array having a throw of several miles, which was used as an emergency warning system to alert villages in the vicinity of Dartmoor prison of a breakout by dangerous criminals. Pamphonic of course were the experts on line source arrays and Taylor's paper, which was subsequently published in the Journal of the BKS(TS) (4), remains to this day the principle work on the design and application of line arrays.

It is not proposed to investigate the theory of line array design here as Taylor's paper renders such a digression superfluous, but refering to Fig. 4, the rule-of-thumb basics are that providing wavelength is not greater than "D", nor smaller than "d", the arrangement will behave as a coherent array and more or less exhibit the classical line source throw characteristics shown. Obviously, the design objective is to provide the highest possible ratio between the energy of the main axial beam and that of the unwanted side lobes. Secondary lobe suppression is dependant upon many factors, but as these are made up of a series of nulls due to phase cancellation effects between the various sources in the array, factors like the number of sources that make up the array, the spacing between them, the contour of the radiating baffle and the excitation curve are all relevant.

So if the Q and SPL capabilities of a single horn are insufficient for the purpose, what about arranging the six drivers in a vertical array, each with its own horn flare? That should provide the required source SPL and the dispersion characteristics. The wavelength at 400Hz is 0.9m and at 4KHz it is 0.09m. In round figures therefore, the array height must not be less than 1 meter, and ideally, the source spacing should not be more than 10cm, but as in effect, the entire array will constitute a single radiating source, this latter dimension is of less importance. So we need a flat, radial type horn, suitable for stacking, having a horizontal dispersion characteristic of something like 40°. The vertical pattern is not important as this will now be dictated by the array parameters rather than by the characteristics of each individual horn. The Vitavox Monoplanar is just such a horn, having a mouth dimension of 0.9m x 0.3m, an air column length of 1.2m and its 190Hz flare rate is sufficiently low to ensure that there will be no possibility of out-of-band energy being fed to the drive units below the horn cut-off frequency.

A prototype array of six Vitavox Monoplanar horns, each fitted with an Atlas PD30T driver was therefore built. The array height was 1.8m, which, being twice the minimum requirement, was expected to provide excellent vertical pattern control at the longest wavelength of interest, and further tests at GEC-Hirst Research confirmed the theory. Fig. 5 shows the horizontal pattern of the array, Fig. 6 the vertical, A) with uniform excitation and B) with linear taper. The Q works out at 59 and Fig. 7 shows the axial amplitude response, giving a 1 watt 1 meter SPL of 112dB. This should provide a maximum SPL of 140dB at one meter at full power.

SITE TRIALS

Having proved the array in the laboratory, the next step was to prove it on site. It was tested in both the Reactor Pile Cap area and the Turbine Hall, hoisting it on the overhead cranes to a suitable working elevation and monitoring speech articulation.

In the Reactor Pile Cap area it generally worked well, but with insufficient vertical angle to cover some of the high level walkways and working platforms. This was remedied by reverting to uniform excitation to broaden the vertical beamwidth, increasing elevation and adjustments to the array declination. Because of the relatively quiet working environment in this part of the site, the power input to the array did not exceed 20 watts, and apart from some masking by large plant, the single array provided intelligible speech over approximately half the building. So two arrays, with some local infill, are expected to provide coverage of this area.

The Turbine Hall was another problem however, for whilst the targeted 60m throw and the SPL was indeed obtained, with good intelligibility, this was found only to obtain over a very narrow coverage angle of about 20°. The reason was twofold. Firstly, because of an unforeseen restriction in available amplifier power, it was not possible to fully drive the array without severe peak clipping. This restricted the SPL at 60 meters to 96dB. On the day of the test, as it happened, one of the generating sets was down, thus reducing the ambient SPL to 93dB(A). But we still had the 3dB minimum headroom available, so something else had been overlooked.

The problem turned out to be the way in which response parameters of loudspeaker components are traditionally specified at their -6dB points. With only 3dB clearance over the noise floor, the horizontal coverage of the horn array was 6dB down at the edges and had therefore disolved into the ambient noise. Also, because polar response is not uniform with frequency the coverage obtained varied over different octave bands, becoming surprisingly narrow above 2KHz. Further, whilst the amplitude response of the array as shown in Fig. 7 is remarkably uniform by normal comparison, it is some 5dB down at 400Hz and 7dB down at 3.5KHz, and in such a critical application we do not have that amount of leeway.

The use of a graphic equaliser to normalise the amplitude response and lift the HF out of the ambient noise floor at the coverage extremities resolved the problem for the academic purpose of proving the point. In practice, we will probably change to a 3 section multicell horn to overcome the directional uniformity problem, normalise the array amplitude response by equalisation, and allow 3dB amplifier headroom - 360 watts to each array.

CONCLUSIONS

We have shown that the array concept will solve the problems and provide intelligible speech in the adverse conditions described. It is an approach that is not widely used these days, although correspondence on the subject has been noted in recent issues of the ASCE Journal, where smaller re-entrant type horns have been arrayed vertically with a similar object in view.

References

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Acknowledgements

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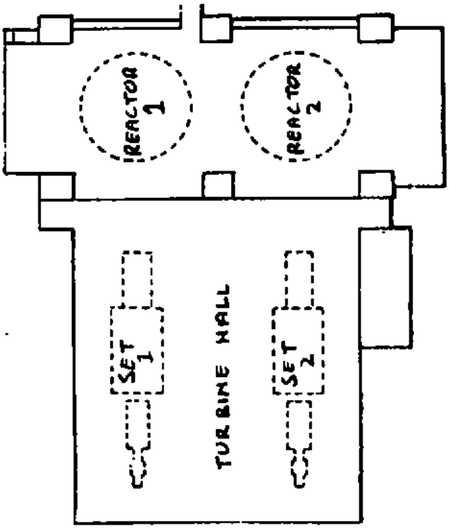


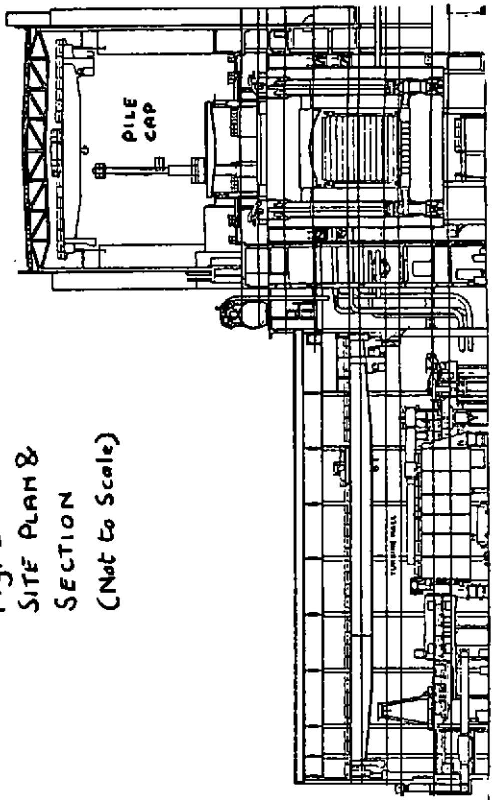


Fig. 1 SITE PLAN & SECTION (Not to Scale)

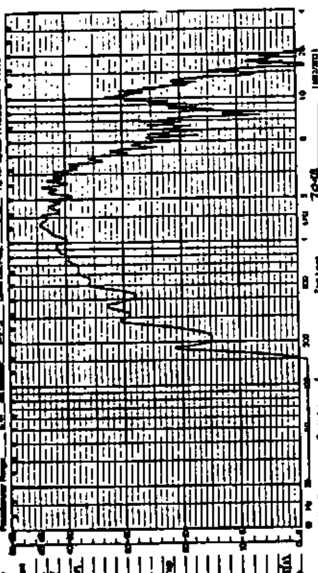
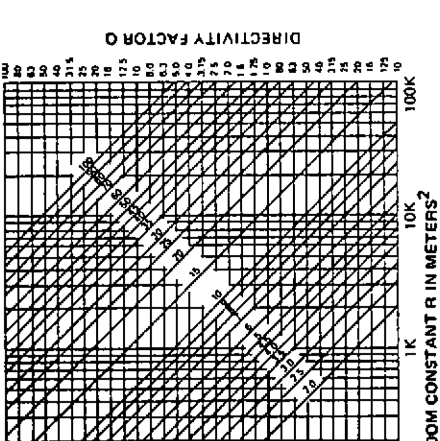


Fig. 3 DRIVE UNIT AMPLITUDE RESPONSE



Critical Distance as a Function of Room Constant and Directivity Factor

Fig. 2

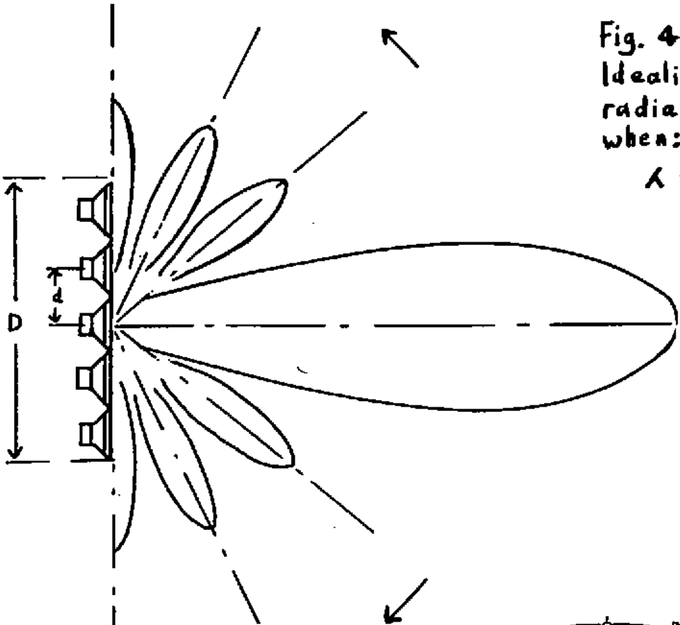
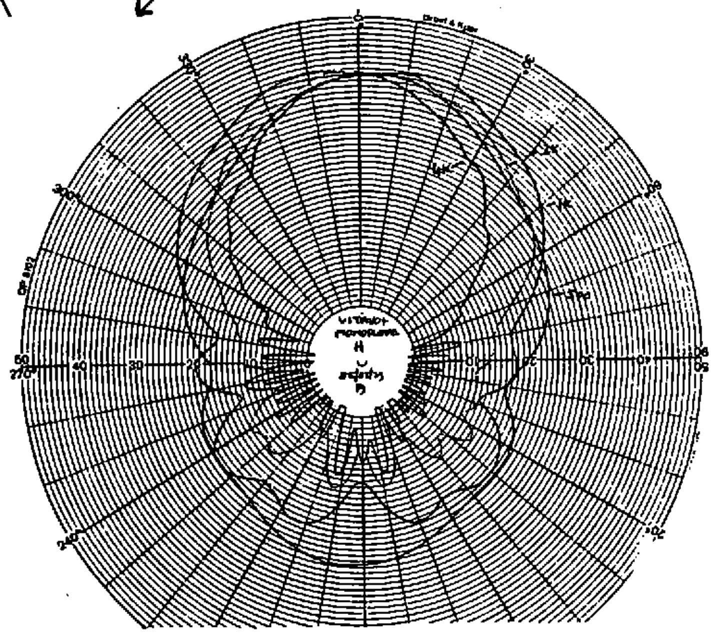


Fig. 4
Idealised linesource radiation characteristic when:-
λ <D, >d

Fig. 5
Horizontal Polar Response same as for single source.



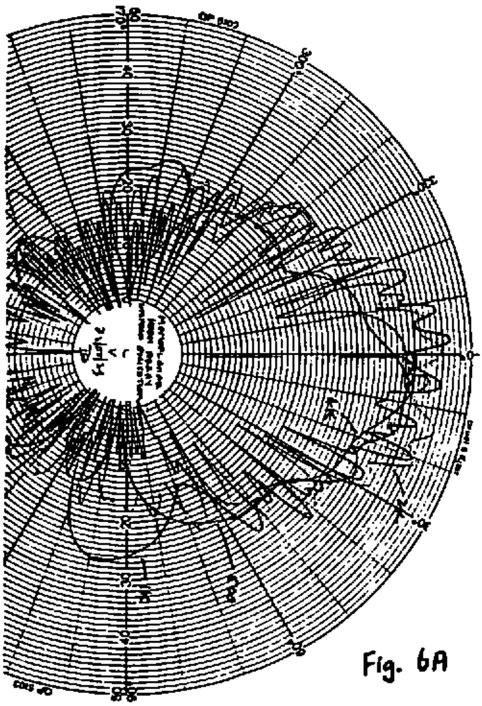


Fig. 6A

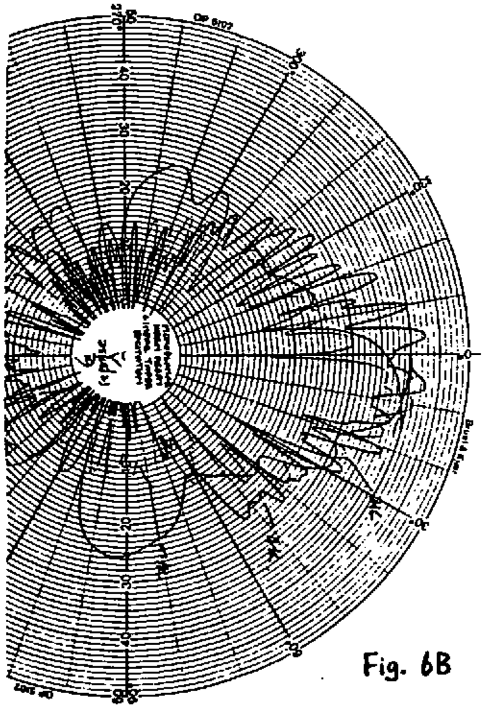


Fig. 6B

ARRAY VERTICAL POLAR RESPONSE:- A - Uniform Excitation
B - Linear Taper Excitation

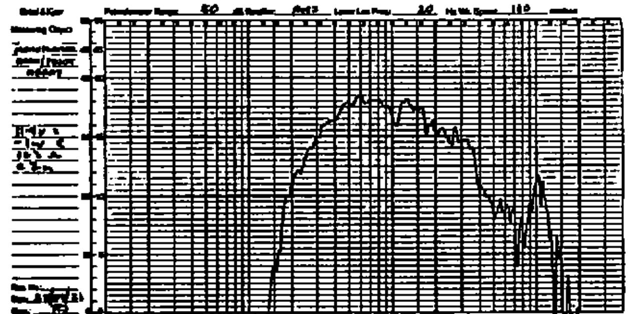


Fig. 7 - ARRAY AMPLITUDE RESPONSE