Sound absorption of an audience on unupholstered seating: and the technique for its measurement

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**Publication Date:**
1970

**DOI:**
https://doi.org/10.26190/unswworks/8612

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SOUND ABSORPTION OF AN AUDIENCE ON UNUPHOLSTERED SEATING: and the technique for its measurement

Laurie William Hegvold

A thesis submitted for the degree of Doctor of Philosophy in the Faculty of Architecture of the University of New South Wales.

May, 1970
ACKNOWLEDGEMENTS

I wish to express my sincere thanks to my supervisor, Mrs. Anita Lawrence for her critical appraisal of this work and her guidance during its preparation.

I wish also to thank Professor E.P. George of the School of Physics, University of New South Wales for the many stimulating discussions we had concerning the work generally and for his advice on some physical aspects of sound fields; Mr Ted Weston for the use of the Reverberation Room facilities at the Commonwealth Experimental Building Station, North Ryde, N.S.W. and for his assistance with the experiments carried out therein; and Mr. Robert Green of the Australian Broadcasting Commission for his constructive criticism of the work and the fresh ideas it stimulated.

Finally I wish to thank those of my students and friends who patiently provided me with an audience for the full size tests carried out at C.E.B.S., North Ryde and particularly those who assisted with the actual production of the thesis.
ABSTRACT

SOUND ABSORPTION OF AN AUDIENCE ON UNUPHOLSTERED SEATING: and the techniques for its measurement

Despite attempts to find more precise criteria for acoustic design, the traditional Sabine reverberation time remains an important practical criteria for assessing acoustic quality. It is readily measured and has an established relationship between subjective impression and objective measurement, provided a diffuse sound field exists.

Three major factors which influence the decay of a sound field are (a) the volume enclosed, (b) the state of diffusion and (c) the rate of sound absorption in the space. As calculated reverberation times have often proved inaccurate, one or more of these factors could be the cause.

As volume can be calculated accurately, the nature of the sound field in both diffuse and 'normal' situations is analysed with particular regard to initial decay rate. On the basis of this work the absorption of an audience, the largest single contribution to absorption of an auditoria, is studied.

There are two basic methods for analysing audience absorption.
ABSTRACT CONT

(a) Statistical averaging of measurements in numerous auditoria. This is considered valid due to the lack of control over variables.

(b) Measurement of individual absorption effects under fully controlled conditions both separately and in combinations.

This method has practical and economic restrictions and a completely controlled full size environment in which all variables can be held constant except the one under test, e.g. floor rake, is economically prohibitive.

This problem is overcome by developing an accurate scale model of a typically dressed Australian auditor. The influence of clothing here is found to be important.

Acoustic model techniques are investigated and five model rooms were constructed to examine audience absorption on unupholstered seating.

The following aspects are examined.

(a) dependence of audience absorption coefficient on seating density.

(b) The existence and magnitude of edge absorption.

(c) The non-linear relationship between audience area and total absorption, attributed to edge diffraction.

(d) The effect of varying seating rake.

(e) Low frequency absorption due to vertical resonance between seating rows.
ABSTRACT CONT

(f) High energy region absorption adjacent to hard surfaces.

The resulting data are tested against existing situations. Over the range of seating densities for which absorption coefficients are constant, data are given for calculating audience absorption on unupholstered seating based on frequency, size of seating bloc and floor rake. It provides for low frequency absorption due to seating rows and correction factors for edge absorption.
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INTRODUCTION

The past fifteen years have witnessed the introduction of several new criteria to the field of architectural acoustics. They have been developed to enable the acoustic consultant to predict the subjective quality of a hall more accurately at the design stage.

The development of many of these criteria began with the analysis of the physical properties of the sound field and the expectation that as the subjective effects were further understood the significance of the physical parameters would become apparent.

These concepts are listed by Kuttruff\(^{(1)}\) in a summary of design criteria and broadly involve (a) the detailed structure of the decaying sound field, (b) the structure of sound transmission curves and (c) directional sound and subjective diffusion.

Of these, group (c) has received the most attention with the detailed analysis of reflections in terms of direction and sequence of arrival and the introduction of the autocorrelation function as a measure of the subjective diffusion of the sound field (Kuttruff\(^{(1)}\), West\(^{(2)}\)). There have also been studies of the build-up and decay of the reverberant field in an effort to establish the relationship between the subjective decay time and that traditionally
These attempts to find more precise criteria for acoustic design have been initiated to supplement reverberation time as the major criterion for acoustic quality and to establish objectively measurable criteria to replace totally subjective judgements.

However it is essential that the relationship between the physical characteristics of the sound field and the subjective impressions of the listener be fully established before any objective measurement can be considered valid for design purposes.

Such correlations have not always been readily apparent with the notable exception of the autocorrelation function which has been successfully used for both objective and subjective measurement of the diffusity of a sound field.

The traditional reverberation time of Sabine, et al., despite the uncertainties expressed by some, continues to play an important role in room acoustics. Providing a fairly diffuse field exists, there remains an established correlation between subjective impression and objective measurement and it is still the first parameter to be calculated for a new design as a test of its general acceptability. Only when this broad parameter has been established are more detailed criteria concerning reflection sequences, geometrical arrangement of surfaces, distribution of sound...
energy, selective absorption problems etc. subjected to investigation. Reverberation time also has the advantages of being measurable without complex and expensive equipment and being theoretically easy to calculate.

Three major factors which influence the decay time of a room in the occupied state are (a) the nature of the sound field, i.e. its state of diffusion, (b) the volume and (c) the total sound absorption within the room, (essentially the room's surfaces), to which the audience area is a major contributor.

Sufficient information regarding these factors should enable fairly accurate prediction of the reverberation time. However calculations using the classical formulae of Sabine, Eyring, etc. which require the existence of a diffuse sound field, have more often than not given values which did not agree with those measured in the completed or test hall.

The volume may be calculated with any degree of accuracy desired using the design drawings. The state of diffusion of the sound field is not so easily predicted. The nature of sound fields will be discussed in Section I but essentially four important points arise from it. (a) The classical formulae require the existence of a sufficiently diffuse field before their predictions can be considered valid. (b) A diffuse field seldom, if ever, exists in a room without diffusing devices when the absorbing materials in the room are not uniformly dispersed. (c) The absorption exhibited in the
vicinity of a material in a non-diffuse field is very similar to that measured on a large sample by the standard reverberation room technique using a diffuse field.

d) There is no other theoretical basis which gives a measure of decay time that correlates as well with the subjective criteria as the reverberation time based on the first 15dB decay, \( T_{15} \), extrapolated to \( T_{60} \).

However the application of the classical formulae requires a detailed knowledge of the absorption of all materials used in the subject room. As the major contributor to total absorption in the occupied state is the audience, it is this factor that must be examined first. Figures published for audience absorption vary greatly and, whether based on unit absorption or on area absorption coefficient, are expressed as a frequency dependent constant. The application of such data will give a family of curves for audience absorption based entirely on total seating area with no allowances for seating rake, configuration of seating, shape of individual seating blocs, edge diffraction etc.

The present measurement and interpretation of audience absorption may be responsible for considerable errors in calculation of reverberation time. Two things are required, (a) a valid means of measurement which permits investigation of all of the variables involved so that their effect and relative importance can be ascertained and (b) a valid means of expressing the results.
This thesis looks at audience absorption by establishing the effect of each variable as it relates to total absorption in any practical situation. It discusses measuring techniques and examines in detail the absorption of an Australian audience on unupholstered seating. Design data is given for use in the Sabine and Eyring formulae.

The study was restricted to an audience on unupholstered seating for the following reasons.

(a) The study aimed at establishing a method of measuring audience absorption and for this purpose it was desirable to have seating which exhibited a known minimal absorption therefore eliminating a variable which would be difficult to control.

(b) With an established method the more absorptive seating could be included in the available data at a later stage as another variable. This however would require considerable work in categorising upholstered seats and to be of practical use chair manufacturers would have to offer data on sound absorption with their product.

(c) There is growing demand for the multi-purpose type of hall which caters for an audience on removable unupholstered seating. Data is needed for the design of this type of hall.
SECTION 1.

1.0 THE NATURE OF SOUND FIELDS

In order for measurements of audience absorption to be carried out correctly and the resulting data to be of use for future predictions it was important that the nature of the sound field in which the measurements were taken be known.

Much has been written about the techniques for measuring sound fields and about the nature of the fields themselves. Particular attention has been given to the influence of sound absorbing materials on the state of diffusion of the field and the methods of and prerequisites for establishing the absorption coefficients of such materials.

The three major aspects of a sound field are (a) the buildup, (b) the steady state and (c) the decaying field. Of these it has been the latter which has received the most attention. The subjective aspects of a sound field have been traditionally associated with decaying fields although the buildup as measured by the rise time has also received considerable attention (3,4&6). However Schroeder(5) has shown the buildup to be complementary to the decay.

To be able to predict the properties of a decaying sound field it is essential to know the rate at which
sound energy is dissipated within the subject space. It is therefore necessary to know the sound absorbing properties of all materials used within the space and the type of sound field that exists when the source is shut off.

The traditional measurement of sound absorption coefficients requires a reverberation chamber which exhibits a homogeneous and isotropic sound field both in the steady-state and the decaying situation when both empty and with the sample in place. Only under these ideal conditions can the classical formulae of Sabine, Eyring etc. be applied.

Many aspects of the classical reverberation theory have been critically examined in recent years. Fitzroy\(^{(7)}\) devised an empirical formula which considered the decay rates along the three axes of rectangular rooms. It was intended to give better prediction of the reverberation time particularly when the surfaces were not uniformly absorbing. Hunt\(^{(8)}\), Batchelder\(^{(9)}\) and Gomperts\(^{(10)}\) among others have questioned the validity of the 'mean free path' and proposals\(^{(11)}\) have been made using 'collision rates' of sound rays with reflecting surfaces. Gomperts\(^{(10)}\) discussed several interpretations of the mean free path (m.f.p.) and, as examples, derived three cases of a reverberation formulae in which the constant varied by as much as 21% from the classical value depending on room proportions. He concluded that the classical
formulae were based on suppositions "none of which was realistic." Kuttruff \cite{12} however disagreed with Gomperts' analysis and concluded in favour of the classical formulae.

1.1 EFFECTS OF ABSORBING MATERIALS

Meyer, Kuttruff and Grushka \cite{13} showed that reverberation obeyed approximately an exponential decay only if the room contained adequate diffusion. Jusofie \cite{14}, Balachandran and Robinson \cite{15}, and Knudsen, Delsasso and Leonard \cite{16} found a diffuse sound field to exist in a rectangular room with surfaces that were of uniform low absorption but the introduction of an area of highly absorptive material resulted in a field which was far from diffuse. These rooms contained no artificial diffusion.

A diffuse sound field has been defined by Balachandran \cite{15} as

....."the superimposition of an infinite set of plane waves of the same average intensity arriving from all directions with equal probability and random phase; thus the time average energy flux is everywhere the same, i.e. the sound field is homogeneous and isotropic."

Knudsen et al. \cite{16}, in experiments carried out in a 13,680 ft$^3$ rectangular room with 24 ft high ceiling, found
that for the empty room, the classical formulae gave sufficiently reliable results for practical purposes when using a white noise or impulse source in a fairly reverberant and diffuse field and for wavelengths small in comparison to the rooms dimensions. However when one surface was entirely covered with an absorbing material, (2" mineral wool), all other surfaces remaining reflective and with no added diffusion, the classical formulae gave errors as great as a factor of 8 for absorption coefficient of the material and a factor of 5 for reverberation time of the room. The extent of variation depended on the relative positions of source, receiver and sample.

The decays were marked by a double slope in which the initial decay rate (first 20 to 25 dB) of approx. 39dB/sec. measured in the vicinity of the sample (2ft from surface) gave an absorption coefficient which generally agreed with that of 43dB/sec. measured for a smaller sample of 72ft² by the standard reverberation room technique. However as the measuring position was systematically removed from the sample, the double sloped decay became more obvious, particularly at low frequencies and for certain source positions. When measured at the maximum distance from the sample (22ft), the initial decay rate (first 10-15dB) dropped to a range of 12.5 to 17.0dB/sec and the secondary decay (remaining 25dB) from 7.5 to 7.8 dB/sec.

These findings were of considerable importance as
Jusofie(14), Kath and Kuhl(19) and Meyer and Kuttruff(16a) have shown that the most reliable determination of the absorption coefficient of a material was obtained when one entire surface of the test room was covered by the material under test.

Schultz and Watters(17), and Sessler and West(18) found a selective low frequency attenuation effect giving a 15 to 20dB decrease in sound pressure level caused by vertical resonances between audience seating rows. This effect was also greater in the vicinity of the absorbing material and was less noticeable with increase in distance from the material (audience) until at approx. 14.0ft it was almost indistinguishable.

1.2 USE OF DIFFUSERS

Kosten(20) in a discussion of the 1960 Round Robin series of comparative measurements of the absorption of Sillan SP100 in a large number of reverberation chambers concluded:

"a) A sample of 10m² (108ft²) is desirable

b) Such a sample requires a room of not less than 180m³ (6350ft³) in which a large number of diffusing elements are installed in order to provide a really diffuse reverberent field.

c) The remaining discrepancies between the various Institutes (measurements) are probably mainly due to various edge effects (i.e. perimeter per unit area)".
I.S.O. Recommendation R354 (1963) gives rules for the dimensions of a reverberation room to promote adequate diffusion. The major dimension of the room should not exceed \(1.9V^{1/3}\) and the total surface area should be of the order of \(6V^{1/3}\). However Kosten\(^{(20)}\) has shown that to achieve diffusion in the presence of a large area of highly absorbing material, it is essential to install a number of diffusers randomly orientated. It is generally considered that the dimension of the panels must be comparable with the lowest frequency of interest and that they should be arranged so that the projected area on each room surface is roughly proportional to its area.

Since the publication of Kosten's conclusions several investigations have been carried out on the effects of diffusing panels and edge effects, Meyer, Kuttruff and Lauterborn\(^{(21)}\), Kolmer and Krnak\(^{(22)}\), and Venske\(^{(23)}\) being some of them. These investigations were summarized by Balachandran\(^{(15)}\) who concluded that:

".....All investigations show that the major cause of difficulties with the measurement of absorption coefficients in reverberation room can be ascribed to a lack of diffuseness of the field."

Knudsen et.al.\(^{(16)}\), however, found the inclusion of randomly disposed plywood diffusers in the room to be "pallative" only and not the perfect answer to obtaining a diffuse condition with the absorbent in place.
1.3 DIFFUSITY OF A SOUND FIELD

Doubts have been expressed as to whether a diffuse sound field can ever exist. Gomperts\(^{(10)}\) felt that

"...At the most one can expect to achieve an approximately isotropic sound field."

Both Gomperts\(^{(10)}\) and Randall and Ward\(^{(23a)}\) had even greater doubts about the existence of a diffuse sound field during the reverberant decay.

The argument for this was that once the source had been shut off only very specific directions of sound ray propagation remained in a rectangular room, the number of directions being related to the band width of the source. The probability of an isotropic field therefore decreased with narrowing of the frequency band.

There have been mathematical solutions put forward based on acoustic wave theory in an attempt to predict the reverberation time of an enclosure without firstly assuming an ideal state of diffusion.

Brue1\(^{(24)}\) stated that while it would be difficult to account for the individual contributions of natural oscillations (room modes) at any particular moment, it could be possible to group them. These groups he based on a rectangular room with six uniformly lined surfaces and they represented groups of oscillations with approx. equal damping. From this he evolved a fairly complex formula for plotting the decay curve.
Kinsler and Frey\(^{24a}\) derived a somewhat simpler formula based on wave theory which allowed for axial, oblique and tangential oscillations.

However, despite the complication to reverberation time calculations caused by either of the above methods, neither is applicable to room shapes other than rectangular. They are also highly dependent on the actual room modes set up as a result of particular source and receiver position.

Kinsler and Frey stated that for a reverberant room, their formula reduced to the classical form.

The complex formula of Bruel gave no greater reliability than the classical formula of Sabine and the more accurate version of Eyring which give reliable prediction for rectangular rooms having uniformly absorbing surfaces.

\[
\begin{align*}
\text{Sabine } T_S &= \frac{KV}{A+4mV} \quad \ldots (1.01) \\
\text{Eyring } T_E &= \frac{KV}{-S \log_e (1-a) +4mV} \quad \ldots (1.02)
\end{align*}
\]

where \( A = S_1a_1 + S_2a_2 + S_3a_3 \ldots \text{etc} \)
\[
\ddot{a} = \frac{a_1S_1 + a_2S_2 + a_3S_3}{S_1 + S_2 + S_3} \ldots \text{etc}
\]
\[
S = S_1 + S_2 + S_3
\]
\( m = \text{attenuation of sound in air} \)
\( K = 0.049 \text{ (F.P.S.)}, 0.163 \text{ (M.K.S.)} \)
Fitzroy\(^{(7)}\) derived an empirical formula based on the Eyring form, which was intended to give more reliable prediction of reverberation time for rectangular rooms with non uniform absorbing surfaces.

\[
RT_F = \frac{x}{S} \left[ \frac{K.V.}{-S \log(1-\bar{a}_x)} \right] + \frac{y}{S} \left[ \frac{K.V.}{-S \log(1-\bar{a}_y)} \right] + \frac{z}{S} \left[ \frac{K.V.}{-S \log(1-\bar{a}_z)} \right] \quad \text{(1.03)}
\]

\(x, y, z\) = areas projected in the direction of each axis.

The results of applying the above formula will be discussed in Section 4.53 but suffice it to say that no reliable correlation between measured results and formula (1.03) could be obtained when surfaces were non-uniformly absorbing.

1.3.1 Conclusion

None of the above approaches therefore offered any more reliable means of calculating the reverberation time other than for simple rectangular rooms and, in the case of Bruel's formula, uniformly absorbing surfaces; the same theoretical restrictions that apply to the classical formulae.
1.4 THE TEST SOURCE

The number of modes existing within a space is at least partially dependent on the modes excited by the source at the moment of cut-off. The nature of the source itself is therefore important. Bands of white noise and a 10% warbel tone are in a state of constant fluctuation and the resulting decay curve will be considerably influenced by their state at the cut-off time.

Fig. (1.01) shows the cross-correlation coefficients for 1/3 octave bands of random noise and ±10% warble tone as measured by Balachandran (15) indicating the far better diffuse conditions given by the former. Knudsen (16) found both white noise and impulse sources to be satisfactory with white noise giving approx. 3% greater decay rates than the impulse source while the latter gave far better reproducibility. In the 250Hz band for instance, white noise decay rates gave a total variation of 7.8dB/sec. whereas the impulse source varied only 3dB/sec. They also found that decays from both sources were essentially independent of source location but that a corner position was preferable for exciting the maximum number of modes. Broch and Jensen (25) also found in favour of the impulse source. The important factors with the impulse source are its reproducibility which permits fewer measurements, and its broad band which excites all possible modes in a room for the particular source position.
Steady state cross correlation coefficients in reverberation room

--- measured values
--- theoretical values

Comparison of steady state cross correlation coefficients for 500Hz octave band with 18m² (194ft²) sample of absorbing material. (after Balachandran (15)). Theoretical values and microphone separation as for 1.01a

--- 1/3 octave random noise
--- ± 10% warble tone
1.5 MEASUREMENT OF DIFFUSION

Balachandran\(^{(15)}\) studied the effects of diffusing panels on the diffusion of the steady state and decaying sound field in both the empty room and when an 18\(m^2\) (194\(ft^2\)) sample of Sillan was in place. To do this he utilised a correlation technique to establish the normalised spatial correlation coefficients as a measure of the three dimensional diffusity of the field. This method was applied separately to the steady state and decaying sound fields with and without diffusing elements in place. He concluded the following:

"...a) In the bare reverberation room the sound field both in the steady and decaying states is diffuse as shown by measured cross-correlation coefficients.

b) On introducing a large area of highly absorbing materials these conditions are upset, but can be restored by installing diffuser panels.

c) No one arrangement of panels will necessarily promote steady state diffusion at the test frequencies when there is appreciable nonuniformity in the distribution of absorbing material.

d) Complete diffusion in the steady state does not always guarantee complete decaying state diffusion in the presence of nonuniform absorption. In contrast it is shown that at higher frequencies a particular arrangement of diffusers creates diffuse conditions in the decaying sound field whilst the corresponding steady state sound field is non-diffuse.

e) Absence of perfect diffusion makes the values of cross-correlation in the decaying state rather erratic and the position of the receiving microphones gains special significance. For a given position of the source and microphone the decaying state diffusion is different on successive decays.
f) The extent of sound diffusion in the decaying state can be directly assessed by employing precise methods for determining correlation coefficients with adequate statistical validation."

Balachandran found the double decay curve exhibited when the diffusers were not installed (and which signified a two dimensionally diffuse field only) disappeared when the diffusers were in position. He also found that since the scatter in decay rate observed in the no-diffuser condition vanished when the diffusers were in position, there appeared to be a direct connection between uniform decay rate as measured by level recorder and sound diffusion as measured by cross-correlation.

1.6 EFFECT OF DIFFUSION ON SUBJECTIVE QUALITIES

Some acoustic designers have expressed the opinion that a sound field which exhibits a double decay is advantageous in an auditorium as the subjective decay rate is established by the primary decay while the lower level and longer secondary decay helps to blend consecutive musical phrases together.

However such a condition also indicates a sound field which is not diffuse or at least has only two dimensional diffusion. Under these conditions a much more reverberant condition may exist than that predicted by the classical formulae.

The reverberation time as predicted by the
classical formulae has a unique significance only when the decay rate within a sound field is constant, at least during the audible or unmasked part of the decay. This requires a condition of diffusion which rarely exists in a 'normal' sound field as the sound absorption is seldom uniformly dispersed, most of it being the audience and therefore confined to the floor. In such a room the decay rate in the vertical direction is greater than in the horizontal directions and the initial decay rate (first 10-20dB) is often considerably greater than the subsequent decay as shown by Knudsen\(^{(16)}\).

In many modern halls the reverberation time \(T_{60}\) as traditionally measured over the -5 to -35 dB range and extrapolated to a 60 dB decay may be close to the optimum time and yet the rate of initial decay may be more than twice that rate. Hence during musical performances the initial decay will provide the subjective reverberation time as the remaining decay will be masked by subsequent musical phrases. The subjective reverberation time may then be only one half of the desired values.

Atal, Schroeder and Sessler\(^{(6)}\) in an attempt to assess the subjective reaction to a non-exponential decay found that the decay rate during the first 160 milli-seconds extrapolated to \(T_{60}\) gave the best results. When, for various reasons, it was impossible to get \(T_{160\text{m.s.}}\) they used \(T_{15}\),
i.e. the decay from 0 to -15 dB extrapolated to $T_{60}$. This decay had the same subjective effect as an exponential $T_{60}$ decay of the same rate.

As it is practically impossible to obtain a 60dB decay and seldom ever a 30dB decay except at the end of a musical phrase, the use of $T_{15}$ is also more practical.

1.7 SUMMARY - The Nature of Sound Fields

a) Both the Sabine and Eyring reverberation formulae require an isotropic and homogeneous sound field and therefore uniformly absorbing surfaces.

b) While there is agreement on the necessity to have information on the sound absorbing properties of materials, there is some disagreement on how this data should be obtained and considerable disagreement on how it should be applied in a working situation.

c) A diffuse state can exist in a rectangular room when all surfaces are uniform and of low sound absorbing ability.

d) The introduction of an irregularly dispersed highly absorbing material to a room will cause large fluctuations within the sound field from point to point, particularly if placed so as to cover one of the six surfaces only. A double decay slope will usually be evident indicating the existence of a diffuse field in two dimensions only.
e) A large area of test material is desirable to ascertain the absorption coefficient of a material so as to eliminate excessive edge effect. It should preferably cover one surface of the reverberation room.

f) A three dimensional diffuse field may be obtained in a reverberation room in both steady state and decaying conditions even in the presence of a non-uniformly distributed highly absorbent material by the use of diffusing devices.

g) An impulse test source gives the best reproducibility and is preferable because being a broad band source it excites all possible room modes for that source position.

h) Even though large variations in decay rate occur with increase in distance from sample for rooms with no added diffusion (i.e. the 'normal' situation), the absorption coefficient calculated from the decay rates measured close to the sample compared well with those measured for that material using the standard reverberation room technique and a large test sample. There was some variation at low frequencies.

i) The position of the source within a room of normal proportions does not appear to influence the decay rate when measurements are made close to the sample.

j) The state of diffusion of the steady state or decaying sound field may be measured using cross-correlation techniques, however consistent linear plots of decay curves from a high speed level recorder was sufficient evidence of a relatively diffuse state in the decaying field.
k) The reverberation time given by $T_{(0 \text{ to } -15)}$ has a far better correlation with subjective impression than the traditional $T_{(-5 \text{ to } -35)}$.

l) The absorption coefficient measured in the vicinity of a material in a non diffuse sound field using $T_{15}$ compared well with that measured by the standard reverberation room technique. The latter required a 'forced' diffuse sound field to ensure an exponential decay and used the traditional reverberation time based on $T_{30}$. However if the decay was truly exponential there would, of course, be no difference between $T_{15}$ and $T_{30}$. In each case, therefore, the use of $T_{15}$ would be the more appropriate.
SECTION 2

2.0 MEASUREMENT OF AUDIENCE ABSORPTION

Measurement of audience absorption requires consideration of four factors,

2.1 Test Environment
2.2 Sampling Techniques
2.3 Measurement Techniques
2.4 Expression of Results

2.1 TEST ENVIRONMENT

2.11 Measurements in existing auditoria

Several attempts have been made to establish the absorption of a seated audience by measuring the reverberation time of halls in the occupied and unoccupied conditions, the absorption then being computed by the classical reverberation formulae of Sabine, Eyring etc.

This method has been used in particular by Beranek\(^{26,27}\) and Kosten\(^{28}\). Both based their results on the average of measurements made in some fifty halls throughout the world by various researchers over a period of thirty years using several different techniques and with no record of measuring positions within the sound field. It is most probable that the measurements were also conducted
in varying seasons although no record of this was given.

Most of the data was collected by Beranek and recorded in his book 'Music, Acoustics and Architecture'\(^{(29)}\), the remainder was reported by Beranek and Schultz\(^{(30)}\) and Cremer\(^{(31)}\).

Kosten\(^{(28)}\) carried out a statistical analysis on 41 halls and expressed this data in terms of a cumulative curve for each octave band giving the percentage of halls that had a \(\alpha_{eq}\) (equivalent absorption coefficient) smaller than a given value (Fig.2.01).

Discussion of this work requires the definition of several terms.

\(\alpha_{eq}\): The total absorption (including air absorption) of a hall expressed as an area coefficient to be applied to the modified seating area \(S_T\) (after Kosten)

In the Sabine equation, \(R_T = \frac{K.V}{A}\),

where \(K = \begin{cases} .049 \text{ (F.P.S.)} \\ .161 \text{ (M.K.S.)} \end{cases}\)

\(A = \alpha_{eq} \cdot S_T\)

\[\therefore \alpha_{eq} = \frac{K.V}{S_T \cdot R_T} \quad ...(2.01)\]
ST: The floor area occupied by the audience, chorus and orchestra including aisles up to 1m. in width (the addition of the aisles in a correction for edge absorption) (after Beranek)

SR: The sum of all surface areas other than those included in ST (after Beranek)

Kosten found that for halls with no added absorption there was a normal distribution of $\alpha_{eq}$ for each octave band. Taking the 500/1000 Hz band as an example (Fig.2.01), $\alpha_{eq}$ had a value of 1.07 with a standard deviation of 0.09. He also found that due to cumulative measuring errors a standard deviation of 0.08 might be expected. He concluded that 1.07 ± 0.07 was a safe figure to use as it was the spread within which 50% of 90% of all halls used were to be found. 10% having been discounted for various reasons as unsuitable for inclusion.

$\alpha_{eq}$ was then expressed for both occupied and unoccupied conditions as a frequency dependent constant with tolerances ranging from ±7% at mid frequencies to ±16% at higher and lower frequencies (Fig.2.02). It was used in the Sabine formula

$$R_T = \frac{K \cdot V}{\alpha_{eq} \cdot S_T}$$  \hspace{1cm} (2.02)

In the latest work by Beranek (27) these halls were divided into three categories based on shape and what
Statistical analysis of 41 halls showing the percentage of halls exhibiting a particular $\alpha_{eq}$. (After Kosten(28)).
<table>
<thead>
<tr>
<th>Centre Frequency of octave band (Hz)</th>
<th>$a_{eq}$ for halls that re occupied</th>
<th>$a_{eq}$ for halls that re unoccupied</th>
<th>New $a_{eq}$ for halls that are occupied</th>
<th>New $a_{eq}$ for halls that are unoccupied</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>0.85 ± 0.14</td>
<td>0.68 ± 0.13</td>
<td>0.77</td>
<td>0.60</td>
</tr>
<tr>
<td>125</td>
<td>0.96 ± 0.11</td>
<td>0.76 ± 0.11</td>
<td>0.87</td>
<td>0.67</td>
</tr>
<tr>
<td>250</td>
<td>1.00 ± 0.09</td>
<td>0.81 ± 0.11</td>
<td>0.91</td>
<td>0.71</td>
</tr>
<tr>
<td>500</td>
<td>1.05 ± 0.06</td>
<td>0.81 ± 0.11</td>
<td>1.03</td>
<td>0.79</td>
</tr>
<tr>
<td>1000</td>
<td>1.09 ± 0.07</td>
<td>0.82 ± 0.11</td>
<td>1.09</td>
<td>0.82</td>
</tr>
<tr>
<td>2000</td>
<td>1.15 ± 0.07</td>
<td>0.86 ± 0.13</td>
<td>1.15</td>
<td>0.87</td>
</tr>
<tr>
<td>4000</td>
<td>1.29 ± 0.08</td>
<td>1.01 ± 0.13</td>
<td>1.29</td>
<td>1.01</td>
</tr>
<tr>
<td>6000</td>
<td>1.51 ± 0.16</td>
<td>1.27 ± 0.18</td>
<td>1.50</td>
<td>1.27</td>
</tr>
<tr>
<td>500/1000</td>
<td>1.07 ± 0.07</td>
<td>0.81 ± 0.11</td>
<td>1.06</td>
<td>0.80</td>
</tr>
</tbody>
</table>

**Fig 2.02**

Comparison of $a_{eq}$ (after Kosten\(^{(28)}\)) and New $a_{eq}$ (after Beranek\(^{(27)}\)).

New $a_{eq}$ falls within the confidence limits of 'old' $a_{eq}$.

27.
was considered to be the consequent degree of diffusion of the sound field.

These were (a) Modern (Generally moderate fan shaped plan with low and non-horizontal ceiling).
(b) rectangular
(c) Wide fan-shaped plan

Groups (a) and (b) were further divided into three sub-groups giving three median reverberation times which characterise the spread in each primary group. From the medians of sub-groups 1 to 3 Beranek calculated values for what he termed New $\alpha_{\text{eq}}$ (after Kosten).

These results for which no confidence limits were given fell within the limits of Kosten's results. He found, however, that a higher degree of accuracy could be obtained by extending this method to determine absorption coefficients for $S_T$ and $S_R$ separately, those for $S_R$ being dependent on construction and surface finish.

These results were also expressed as a frequency dependent constant and used in the Sabine formula

$$R_T = \frac{K.V.}{S_T\alpha_T + S_R\alpha_R + 4mV} \quad \ldots(2.03)$$

$$m = \text{attenuation due to air}$$

The advantages of this method are (a) the space has the required scale and the necessary audience area, and
(b) the availability of the audience during performances. The disadvantages are (a) for the occupied condition usually only a few measurements are possible as they require a high degree of audience cooperation (b) the sound field is of unknown properties (c) the data refers to a group of particular cases often with a variety of seating arrangements, and (d) the unoccupied halls usually exhibit a relatively high degree of absorption which reduces the accuracy of the measurements.

The data on which this work has been based must, in some cases, be of doubtful accuracy as over the period during which the individual measurements were made, measuring techniques and equipment have improved considerably. There were also no records of where the measurements were carried out within the sound field and Jusofie\(^\text{(14)}\), Kuttruff and Carstensen\(^\text{(32)}\), Meyer, Gruschka and Kuttruff\(^\text{(13)}\) and Knudsen\(^\text{(16)}\) have all shown this to be critical when measuring absorption in a field of unknown diffusity.

Kosten found no correlation between \(\alpha_{eq}\) and seating rake or degree of diffusity. He could only have carried out such correlation tests on halls which individually contained a variety of different shaped seating areas and floor rakes which varied from flat stalls to steep balconies. As for diffusity, it is the variation within the sound field of each hall which could lead to inaccuracy and there were no data available on this. Under these circumstances any
correlation between $\alpha_{eq}$ and these functions would have been very difficult to establish.

In their conclusions both Beranek\textsuperscript{(27)} and Kosten\textsuperscript{(28)} stated that their data was intended for use only in the type of hall from which it was derived. Kosten suggested that his data would give the best results when all added absorption was eliminated from the hall. They both stated that other types of halls for public assembly i.e. lecture halls, small auditoriums etc. could be substantially different.

While the data from the above work may be applied successfully when used in accordance with the authors' recommendations, it is at best a generalisation of a number of particular cases and therefore is not universally applicable. The major disadvantage of the technique is that it does not provide any further understanding of how an audience absorbs sound. There is no way in which all variables can be controlled while one only is altered systematically to assess its effect and relative importance, and there is no datum for comparison of results.

2.12 Measurements in the Reverberation Room

The traditional method of measuring the absorption of any material has been to carry out tests in a reverberation room. A properly designed and calibrated room would also provide a datum from which to measure and compare different situations and configurations of an audience.
The advantages of measurements carried out in a reverberation room and the problems associated with it have been fully discussed and summarised in Section 1.

For the measurement of audience absorption the reverberation room must be large enough to accommodate sufficient subjects to obtain a representative sample of a large audience. As discussed in Section 1, I.S.O. Recommendation R354-1963 sets down guidelines for such a room.

The reverberant sound field must be as diffuse as possible and this requires non-parallel surfaces, diffusing devices and a sufficiently high ceiling to ensure that a regenerating diffuse field is maintained over the heads of the test audience. I.S.O. R354 recommends a volume of 6800 cubic feet (200m$^3$) and this provides a floor area of approx. 500ft$^2$ allowing for a test audience of approx. 100 subjects.

2.2 SAMPLING TECHNIQUES

2.2.1 The Sample Audience

A major difficulty experienced in the reverberation room technique has been in obtaining an audience on which to carry out the many measurements required. Whilst this may not appear to be an insurmountable problem, it has proved to be so and consequently most reverberation room
tests have been performed with a relatively small test group (10 to 12 persons). An attempt has then been made to extrapolate the results to an infinite audience area. Few tests have been carried out using larger groups (i.e. 50 to 100 persons).

The chief exponents of this technique in recent times have been Kath and Kuhl(33,34,35), Meyer, Kunstmann and Kuttruff(36), and Day(37). All of these researchers have carried out tests on people seated on unupholstered chairs.

Kath and Kuhl(34) found they had to use a small sample of twelve subjects for detailed tests due to the difficulties in obtaining a larger and therefore more desirable sample. To eliminate the exaggerated effects of side and front row absorption with a small sample, these areas were blocked off with reflective panels so that only the plan area of the seating bloc was effectively absorbing sound.

As a result of placing their sample in one corner of the reverberation room they found a correction was necessary owing to the fact that the sound pressure level near the wall surfaces was higher by 3dB than that found near the centre of the room and consequently the absorption in the vicinity of these surfaces was doubled.

They overcame this by allowing a correction factor to be added to the test area in the form of a strip 1/8th of
a wavelength wide along each of the edges adjacent to one
of the room's surfaces, (Kath and Kuhl (19) Waterhouse (38)).
Thus they used the following expression for the working
test area:
\[ S = S_1 + b \left( l_x + l_y \right) + b^2 \]  ....(2.04)
where
\[ b = \frac{\lambda}{8} \]
\[ \lambda = \text{wavelength} \]
\[ S_1 = \text{actual area} \]
\[ l_x, l_y, l_z = \text{sample dimensions} \]

Waterhouse (38) has shown that the sound pressure
amplitude varies in the vicinity of a hard surface in a
diffuse field in accordance with the expression:
\[ p^2(x) = p_{\infty}^2 \left[ 1 + \frac{\sin 4\pi x/\lambda}{4\pi x/\lambda} \right] \]  ....(2.05)
where \( x = \text{distance from the surface} \)
\[ p_{\infty} = \text{pressure amplitude for a very large } x \]
\[ \lambda = \text{wavelength} \]

A layer of homogeneous absorbent covering one
surface of a reverberation room will then absorb more sound
energy in the vicinity of adjacent wall surfaces than towards
the centre. The relative increase in the sound absorbent
being given by
\[
\frac{\Delta A}{A} = \frac{L \int_0^\infty (p^2(x) - p_\infty^2) \, dx}{\frac{f}{p_\infty^2}} = \frac{L \lambda}{8f} \quad \cdots (2.06)
\]

\( f = \) frequency

\( L = \) total length of edges between absorbent material and adjacent surfaces.

Hence the absorption coefficient of the surface will be overmeasured by a factor of \( 1 + \frac{\Delta A}{A} \).

Meyer et al. \((36)\) found that in their reverberation room with a floor area of approx. 490\( \text{ft}^2 \), the absorption coefficient in the 100Hz band would have been overmeasured by a factor of 1.024 and this would increase with lower frequencies. However they felt that rather than being an area of homogeneous absorbing material, an audience was a geometrically badly defined absorption arrangement. They decided that the justification for this correction was highly questionable and chose to disregard it.

Kath and Kuhl \((33)\) did not study the effects of varying the density of occupancy which was maintained at approx. 185 persons/\( \text{ft}^2 \) (2\( p/\text{m}^2 \)), nor the effects of varying the seating rake etc. Their sample was composed of 50% women and 50% men which was considered representative of a typical audience.

Comparison of reverberation room test results with those obtained from measurements made in a hall seating 353
persons with the same seating density showed that the correlation between the reverberation room absorption coefficient and that for the uncorrected seating area in the hall was good. However the hall seating area corrected for side and front row absorption was found to have a smaller coefficient. This was put down to the less diffuse field in the hall to that of a reverberation room. There was no suggestion that the difference might have resulted from not allowing for absorption due to edge diffraction. (Fig. 2.03) shows the results of these tests.

Meyer, Kunstmann and Kuttruff (36) used a large sample of almost 100 people which covered the entire 527 ft$^2$ (49 m$^2$) floor of their reverberation room. They established an absorption coefficient considerably greater than that of Kath and Kuhl for the same seating density of approx. 185 p/ft$^2$ (2 p/m$^2$) (Fig. 2.04). However 90% of their subjects were male, the significance of which will be discussed shortly.

2.22 Variations in Published Data

From tests carried out with seating densities from .067 to .185 p/ft$^2$ (.72 to 0.2 p/m$^2$) Meyer concluded that the absorption coefficient was always dependent on seating density except in the lower frequencies. This was contrary to the findings of Beranek (27) who concluded that the absorption coefficient was constant for seating densities of
Comparison of audience absorption coefficients (after Kath and Kuhl (33))

- (a) measured for actual test area (.67m$^2$) in normal sound field for a sample of 353 people.
- (b) measured as for (a) and corrected for edge absorption of aisle and front row.
- (c) measured in reverberation room and expressed for an infinite audience area.
Sound absorption coefficients for an audience on unupholstered seats measured in a reverberation room for 2p/m$^2$ (0.186p/ft$^2$)

- $\alpha_{Sab}$
- $\alpha_{Eyr}$

FIG. 2.04 (after Meyer$^{(36)}$)
.125 p/ft², (1.35 p/m²) above although this was based on an audience on upholstered chairs.

Van Raalton⁴⁰ however found the absorption coefficient for an audience on unupholstered chairs to be constant for seating densities over 2p/m² (.186p/ft²). Day⁴⁷, in model experiments of auditors on unupholstered chairs, found that for over 50% occupancy a decreasing amount of absorption was added to the total. Meyer and Jordan⁴⁹ reported similar findings in 1935 for the Berlin Philharmonic Saal.

Meyer⁴⁶ also concluded that there was no edge effect due to aisle or front row absorption. Again this was contrary to the findings of Beranek⁵⁰, Van Raalton⁴⁰ and Kath and Kuhl⁴⁴. Beranek allowed a strip 1m wide for an aisle bounded on both sides by audience and a strip 0.5m wide for an aisle bounded on only one side. Again this was based on an audience on upholstered chairs. However Van Raalton allowed an edge correction of 0.5m for all areas based on the results of reverberation room tests on people on unupholstered chairs.

Kath and Kuhl⁴⁴ expressed the edge corrections in terms of absorption coefficients (Fig. 2.05). They represented approx. a 3.0ft strip correction for side aisles and for the front row the strip breadth varied with frequency from 3.0ft at low and high frequencies to approx. 2.0ft at mid frequencies.
FIG. 2.05 (after Kath & Kuhl\(^{(34)}\))

Degree of sound absorption of the front and side aisle edges for people on unupholstered seats

- front edge
- side edge
Apart from the differences in findings regarding allowances for side and front row absorption, variation in absorption coefficient with seating density and allowance for extra absorption adjacent to hard surfaces, there still remains the question of what constitutes a valid sample of an audience.

2.23 Effect of Clothing

Tests by Kath(35) showed that it was the clothing which was the major factor in the absorption capacity of a single subject. He showed that the human body unclothed (swimsuit) had a very low capacity to absorb sound and the spectrum of the sound absorbed was almost flat. However as the amount of clothing was increased there was an increase in the unit absorption of as much as 600% at 2000Hz for seated males. (Figs. 2.06, 2.07, & 2.08).

This effect might be expected as normal clothing is simply a porous type sound absorber and its absorption capacity is therefore dependent on its flow resistance and its thickness. While the flow resistance would certainly vary, the thickness would be the governing factor. The characteristic spectrum shape of a porous absorber can be seen in the above figures with a peak at approx. 2000Hz, in this case as a result of the clothing.

Unfortunately the thickness of clothing varies
Absorption per person based on measurement of 12 people seated randomly on unupholstered seats in a reverberation room.

- male - bathing trunks
- female - bathing costume
FIG. 2.07 (after Kath\textsuperscript{(35)})

Absorption per person based on measurement of 12 people seated randomly on unupholstered seats in a reverberation room.

\begin{itemize}
  \item \textbf{male} - suit
  \item \textbf{female} - summer dress
\end{itemize}
FIG. 2.08 (after Kath (35)) (as for Fig. 2.06)

\[ A_{(m^2/p)} \]

Frequency Hz

- **Male**
- **Female**, both in winter coat.
considerably with normal dress and the absorption of an audience would therefore be expected to vary with geographic and seasonal differences. The whims of fashion (maxi to mini in just over a year) further complicate the issue.

It is extremely probable that the variations in published audience absorption data are due to researchers having simply taken the standard dress relevant to that particular climate at the time of the test. As all of the tests quoted here were carried out at latitudes greater than $50^\circ$ it might be expected that conditions in Australia, with latitudes less than $40^\circ$, could be different.

Unfortunately the dress worn by subjects in the previously mentioned tests was generally not reported so that comparisons are difficult.

The exception is Kath\textsuperscript{(35)} who listed the clothing worn in each test. It ranged from swimsuit to full dress with heavy winter overcoat but unfortunately the tests were carried out on groups of men and women separately and in a random disposition so that the effects of clothing on what must be considered a typical audience sample (i.e. 50% men and 50% women seated in rows) was still not established.

However the tests do show that men absorb considerably more sound than women. For summer dress at 2000Hz there is a difference of almost 100%. Hence the tests carried out by Meyer\textsuperscript{(36)} in which 90% of the audience were men might be expected to give results greater than for a
This effect becomes less important in a large audience where shadowing of one person by another occurs. This is also put forward by some as the reason why the absorption coefficient of an audience is independent of seating density above approx. 0.125 p/ft$^2$, (1.35 p/m$^2$).

2.24 Variables Not previously Considered

All tests that have been carried out to date have attempted to establish the absorption of a large flat area of audience. However most halls contain a variety of seating configurations combined with narrow balconies, boxes etc., and these with seating rakes varying from flat up to 18" rises between seating rows.

To examine the effect of varying the seating rake alone would require that everything else be held constant, (or as near as possible as volume must change), while the effects of various rakes were examined.

Similar problems are involved with measuring the effects of narrow and deep balconies at all of the various seating rakes and how the effects of edge diffraction cause the absorption of an audience to vary.

The practical and economic difficulties associated with such an experimental room are obvious and hence these tests have never been attempted. Nevertheless to apply
a constant absorption coefficient to all of these conditions may well lead to inaccuracies unless its validity has been first established. Only a complete examination of these situations individually and in combination can lead to a more comprehensive understanding of audience absorption.

2.3 MEASUREMENT TECHNIQUES

The actual reverberation room test procedure used by various researchers previously quoted was the standard one involving the excitation and measurement of the sound field with and without the presence of the test sample. The field was analysed by taking readings of the decay time of the test signal at any desired number of positions and carrying out a statistical analysis to establish the mean.

This measuring procedure is set out in I.S.O. Recommendation No 477 of 1962(4) entitled "Reverberation Room Measuring Procedure."

The most efficient sources were discussed in Section 1.4 and the impulse type source proved to be the best and most reliable.

The criteria for the validity of any test procedure must be that it is reproducible and that it simulates the circumstances in which the results will be used so that reliable predictions are possible.

With an impulse test-source the decay curve is reproducible and this source simulates the type of sounds
made in actual practice by most sources. An orchestra largely creates impulsive sounds as does a speaker so the use of this method would seem more valid than that of measuring the decay from relatively steady state situation.

2.4 EXPRESSION OF RESULTS

It has been indicated in Section 1. that the use of the classical formulae to establish the effective absorption of an audience is valid when measurements are carried out in the near vicinity of the audience.

The forms commonly used are those of Sabine (1.01) and Eyring (1.02). Both forms give similar results in a very reverberant sound field but as the field becomes less reverberant the Sabine formula becomes increasingly inaccurate.

The only uncertainty found in the direct application of these formulae concerns the expressions volume (V) and total surface area (S), i.e. whether they should be varied from the occupied to the unoccupied condition.

Van Raalton\(^{(40)}\) found that a reduction of the empty volume was required to compensate for that occupied by the test subjects. He suggested a new datum for volume calculations of 0.80m above the floor justified by better correlation with measured results.

Meyer\(^{(36)}\) felt that it could not simply be a matter of subtracting the volume occupied by the test subjects but felt the correction would be overestimated if the datum were
to be taken immediately above the heads. He felt the "effective volume decrease" was probably dependent on frequency and diffusion and, while justified, it was difficult to place a numerical value on it. He finally suggested a datum of 0.60m above the floor, felt that a larger correction would give more accurate results but decided against the use of any correction in his results.

It is obvious that some correction for $V$ is required but no clear indication of its value has been suggested. The value of $S$ has always been taken as the total surface area of the room but never adjusted in the occupied condition for the audience surface area.

When it comes to interpretation of the results there are two broad approaches:

(a) in terms of unit absorption (i.e. per person)
(b) as an area coefficient.

Sabine\(^{6a}\) had mentioned both but unit absorption was in popular use despite indications of its probable inaccuracy by Meyer and Jordan\(^{39}\) who had shown in 1935 that the Berlin Philharmonic Saal exhibited almost the same absorption with both 50\% and 100\% occupancy.

It was not until 1960 that Beranek\(^{26}\) put forward absorption coefficients based on his findings that the total absorption of an audience did not vary when the seating density was between 0.222 and 0.118 $p/ft^2$ (2.39-1.27 $p/m^2$).
This has since been supported by others. Day\textsuperscript{(37)} and Van Raalton\textsuperscript{(40)}.

Obviously then the use of unit absorption must lead to considerable inaccuracies. If established for \(0.118\text{ p/ft}^2\) and used in calculations involving \(0.22\text{ p/ft}^2\) the error would be of the order of 80%.

However the idea of an area coefficient is not accepted by all without reservation.

Beranek\textsuperscript{(26)} recommended an absorption coefficient but with an edge correction for exposed sides and wave diffraction of 1m for internal aisles and 0.5m for side aisles; (based on measurements in actual halls with upholstered seating).

Meyer\textsuperscript{(36)} recommended an absorption coefficient but found it to be always dependent on seating density except at low frequencies. He found no correction was necessary for either side or front row absorption, edge effect or area effect; (based on measurements in a reverberation room with unupholstered seating).

Van Raalton\textsuperscript{(40)} recommended an absorption coefficient but found this to be higher for small areas; (edge diffraction effect). He also recommended a correction of 0.5m for edge absorp. (based on measurements in a reverberation room and hall measurements, both using unupholstered seating).
Absorption coefficient for an audience on unupholstered seats given by various authors.

- $\alpha_{Eyr}$ Kath & Kuhl (34), Coeff. for an infinite area
- $\alpha_{Eyr}$ Kath & Kuhl (33), Coeff. for a 167 m$^2$ sample measured in a lecture room and adjusted for front and side edge absorption
- $\alpha_{Sab}$ Van Raalton (40) measured in a lecture room
- $\alpha_{Sab}$ Bruckmayer (42) people in ply backed seat.
Kath and Kuhl\(^{(33)}\) recommended an absorption coefficient with allowances for edge effect (after Waterhouse\(^{(38)}\)) and for side and front row absorption; (based on measurements in a reverberation room and hall measurements both using unupholstered seating).

While the concept of an absorption coefficient is generally accepted, it is obvious that the various corrections recommended require clarification.

Fig.(2.09) shows the various absorption coefficients.

2.5 SUMMARY - The Measurement of Audience Absorption.

2.5.1 Test Environment

Due to the uncertainties and generalisations associated with data from measurements made in different halls and as it represented only a group of particular cases, it was obvious that measurements should be performed in a reverberation room which provided a datum for comparison of results.

Measurements carried out in a reverberation room to establish the absorption coefficient correlated well with those measured near the surface of the material in a normal room (Section 1.1). In the case of an audience then, this measurement of the effective absorption coefficient could be used in the classical formulae to predict the subjective reverberation time at the listener's ear.
2.52 Sampling Techniques

General opinion was that the larger the test audience the better although it was difficult to obtain many subjects for the long periods necessary. There was little agreement regarding the nature and magnitude of corrections to be applied to the results and, as all of these effects decrease with increase in sample size, those researchers using the large sample chose to ignore them.

There was not complete agreement on whether corrections were necessary for:

(a) side and front row absorption
(b) high energy areas adjoining hard surfaces
(c) edge diffraction effect.

Those who felt that they applied either in whole or in part disagreed on their magnitude.

Clothing was found to be of considerable influence when measured for individual males and females in different dress but no indication of how it effected large composite audiences was available. From these results however it might be expected that audience absorption for a typical Australian audience might vary from published data as all previous measurements were carried out at approx. 20° greater latitude than the more populated area of Australia.

No tests have ever been carried out to determine the effects separately and in combination of:-
(a) varying the seating area  
(b) varying the seating rake  
(c) various configuration of seating (i.e. narrow and deep balconies).

The economic and practical problems involved here are great but a way needs to be found to facilitate such tests if the effects of audience absorption are to be understood. Acoustic model testing presents itself as a possible solution to this problem.

2.53 Measurement Techniques

The procedure for testing in a reverberation room is well established but questions still remain about two factors used in the classical formulae.

(a) The correction for volume. Those who felt it was necessary did not agree on a value.  
(b) The correction for surface area.

The impulse test source was shown to have advantages over other types.

2.54 Expression of Results

There is total agreement on the use of an area coefficient but with reservations by some as to whether it reaches a constant value above a particular seating density or not. There are also doubts concerning the corrections to be applied to the coefficient.

Apart from the foregoing all authors established a
frequency dependent constant for the absorption coefficient (which varied from author to author) thus implying that none of the conditions mentioned in 2.52 (p53) lead to any variation in absorption. This assumption must be groundless as no experiments have ever been carried out in this area and Kosten (20) has shown that the absorption of a sample of sound absorbing material is at least partially dependent on the ratio of perimeter to area (E).
SECTION 3.

3.0 ACOUSTIC MODEL ANALYSIS

3.1 Validity of the Model

Section 2.5 showed there to be a need for a more thorough analysis into certain aspects of audience absorption, it also showed that the reason why such tests have never been performed was that a totally versatile environment would be required and this would be practically difficult and economically prohibitive.

Spandöck in 1934 had indicated the possibility of using a scale model technique for investigating the acoustic qualities of a hall. However it was not until some 14 years later that technology had improved sufficiently to provide accurate measuring equipment thus allowing the full potential of the technique to be realised.

The technique has since been used for design purposes by numerous designers and the method has received close investigation by Krauth and Bucklein. However the most notable work in this field has come from Brebeck, Bücklein, Krauth and Spandöck.

The technique required the use of relatively inexpensive models which could be quickly constructed and readily altered to facilitate any test required. Essentially the model allowed the creation of the sound field which would
be found in the full size prototype but with the time scale reduced by the scale of the model.

Brebeck et al. \((47)\) stated that their aim was to raise the efficiency of the technique so that reliable predictions could be made from a model of a hall before its construction.

### 3.11 Model 'Rules'

The basis of the technique was as follows:

(a) The model must be geometrically similar in all respects to the prototype but to the chosen scale (i.e. \(1:n\))

\[
\therefore \frac{L_{FS}}{L_M} = n
\]

\(L = \text{Length}\)

(b) All surfaces within the model must be related to those in the full size prototype by

absorption power of model surface at frequency \(nf\) = absorption power of full size surface at frequency \(f\)

\[
\therefore \alpha_{FS} = \alpha_M
\]

\(\alpha = \text{absorption coefficient}\)

\[
n^2 = \frac{A_{FS}}{A_M}
\]

\(A = \text{area}\)
(c) The frequency of the test source must be related to the full size requirements by a factor of \( n \)

\[
\frac{f_M}{f_{FS}} = n
\]

\[
\frac{\lambda_{FS}}{\lambda_M} = n \quad \lambda = \text{wavelength}
\]

The scale factor of 1:n was achieved by using a multispeed tape recorder so that a recording made in the model at a tape speed of \( n \nu \) could be replayed and analysed at speed \( \nu \).

Acoustic similarity required that attenuation due to air as well as surface absorption comply with the scale factor of 1:n. Air attenuation would therefore have to be reduced to 1/n of that in the full size prototype. To achieve this they had to reduce the relative humidity of the air in the model to 3% where the attenuation was almost 1/10 of its value at 50% RH; 1:10 being the particular scale factor used. Harris\(^{48}\), gives data on air attenuation.

### 3.12 Unavoidable wall absorption

However whilst it was possible to control most factors to achieve acoustic similarity, there was still an unavoidable absorption at the wall surfaces.

Cremer\(^{49}\) showed that even a rigid, impervious,
non vibrating wall had an unavoidable absorption which
developed as a result of the friction of the air particles
and the ability of the air to conduct heat energy. He
gave its value as:

\[ \alpha_{\text{unavoidable}} = 1.8 \times 10^{-4} f \quad \ldots (3.01) \]

\[ f = \text{frequency in Hz} \]

As this value increased with \( f \), a higher unavoidable
absorption resulted in the scale model than in the
prototype and therefore the reverberation time of a geometri-
cally similar model could never quite attain the values
of the prototype.

Brebeck et.al.\(^{(47)}\) found this unavoidable absorption
caused a decrease in reverberation time of less than 1\% when
compared with the prototype. As working conditions in the
prototype involved normal variations in temperature and
humidity, factors which were controlled in the model, the
1\% variation was less than that caused by uncontrolled
factors in the prototype.

### 3.13 Other Model Applications

Apart from being used to test or develop a design,
acoustic models have been used to investigate various
phenomena and to obtain a comparison between different
arrangements within the model.
Both Schultz and Watters\(^{(17)}\) and Sessler and West\(^{(18)}\) used simplified models of the seating of a hall to establish the low frequency absorption effect caused by vertical resonances between seating rows. It was dependent on the height of the cavity rather than the row to row spacing. These tests were carried out in an anechoic chamber.

Day\(^{(37)}\) used a model auditorium of which there was no full size version to establish whether a scale model auditor developed in a scale reverberation room would exhibit the same absorption effects with variation in seating density as those reported by Beranek\(^{(26)}\).

### 3.14 Control of Relative Humidity

In neither of these experiments was any attempt made to control the Relative Humidity of the air and as a result the attenuation due to the air was out of scale. However as the purpose of the tests was to establish the difference in absorption due to changes within the model, the air attenuation could be considered constant as long as the same R.H. was maintained during the experiment.

Hence, while an incorrect R.H. may have caused small errors when a true indication of the full size prototype was required, for direct comparison work within the model the results would be valid provided the R.H. was kept constant throughout the series of experiments and that the sound field
was reasonably diffuse.

The elimination of the need to control the relative humidity for comparison tests was of considerable importance as this involved the use of extra equipment, an air-tight model and considerable delays between consecutive tests when opening of the model was required.

3.2 A MODEL AUDIENCE

A considerable amount of work has been done towards compiling a list of model absorbing materials which simulate actual finishing materials available for full size application. Spandöck\(^{(50)}\) has listed 60 examples.

However in the case of a model audience, Brebeck et.al.\(^{(47)}\) recommended the use of "eggtrays" (material unspecified) placed at head height. Four conditions were given but no mention of which one was preferable. (Fig.3.01) gives details and their respective absorption spectra.

Day\(^{(37)}\) reported that he was in the process of establishing a list of model materials which were being matched with full size materials using a full size and scale model reverberation room.

Day's study was undertaken in the belief that materials exhibited an "effective" absorption in the working situation which differed from that measured in a reverberation room, the difference being due to variations in the diffusivity of the sound field between the ideal and the working state.
Absorption coefficients of a 10:1 scale audience of density 2.0 p/m² F.S. (.186 p/ft²) expressed for F.S. frequencies.

- Eggtrays, smooth side up, every second row removed, placed at head height.
- Eggtrays, holes 10mm in diameter in the top of each unit and underside fitted with cotton (wool and lying on floor.)
Day felt that with the technology available for accurate model analysis and in the light of inaccuracies found when using the classical formulae, the surest method for assessing the effective absorption of a material was in a model situation.

He began by carrying out tests to establish a model person (scale 1:10) which would work in all configurations of an audience. He took the audience as his starting point as this was the biggest single contributor to the total absorption of a hall and data on both full size and model audiences was both conflicting and inadequate.

The criteria laid down by Day for a successful model auditor were as follows

(a) The absorption of an nth scale auditor should be related to that of a real auditor by:

\[
\frac{\text{absorption of model at } nf}{\text{absorption of real auditor at } f} = \frac{1}{n^2}
\]

(b) This relationship should remain true when model and prototype are both moved into other configurations, i.e. the effective absorption powers should vary proportionately.

(c) Areas occupied by the model audience should exhibit absorption coefficients equal to those given by Beranek et.al. for seated areas, but at scale frequencies instead of prototype frequencies (i.e. at nf rather than f).
The resulting model was made to the average dimensions, but in a simplified form, of a full size person, scaled at 1/10. It had a smoothed softwood core covered with a single layer of surgical gauze loosely held by adhesive spots to the 'body'. The 'head' was spherical and of hardwood.

Day found that within experimental error the auditor performed well in various configurations when compared with identical full size tests and also agreed with Beranek's data on seating density as it affected audience absorption.

Unfortunately Day did not give details of the clothing worn by the prototypes on which the model was established. The only indication of this was that they were wearing 'normal' indoor clothing but no mention of the season was given.

A possible source of error in Day's prototype was that they were all men and in the light of Kath's (35) work, as previously discussed, might overemphasise the absorption of a normal audience.

It was not Day's intention to use this model auditor to establish numerical data on audience absorption in various configurations for use in any theoretical approach to design as he believed no such application to be valid in the light of present theory. His aim was to use the model in direct physical comparison tests between model and prototype halls only using the Sabine formula as a means
of establishing a numerical comparison between two identical situations.

However, as shown in Section 1, there was a direct correlation between the effective absorption measured close to a material and that measured in a reverberation room so that this measurement could be used in the classical formulae to establish a subjective reverberation time in the vicinity of the material.

While it must be accepted that there will be some variation in the absorption of a material with variation in diffusivity of the sound field, the above correlation appeared to hold provided a fairly diffuse field existed.

3.3 SUMMARY - Acoustic Model Analysis

It would seem therefore that a successful model auditor could be used in a model situation to establish with a reasonable degree of accuracy the effects on audience absorption of varying the seating rake, the size of seating blocs, and of deep and narrow balconies etc. These tests could be carried out at the prevailing relative humidity provided it was kept constant during the series, the important parameter being the difference in absorption resulting from different conditions within the model.
SECTION 4.

4.0 EXPERIMENTAL ORGANISATION AND PROCEDURE

Section 2.5 indicated that there was far from complete agreement about most aspects of audience absorption and that there still remained areas which were unexplored because of the associated practical and economic difficulties. Section 3.1, however, showed that these difficulties might well be overcome by the use of acoustic model analysis, a technique which has become more reliable due to recent work in the field and to the development of more sophisticated measuring equipment.

4.1 SCALE FACTOR FOR MODEL ANALYSIS

It was necessary to decide on a scale factor which would be most practical for the work as, theoretically, many scale would be possible. However practical and economic aspects strongly influenced the choice.

With a large scale the frequency range required for the tests could be achieved without necessitating the more expensive equipment required for measuring very high frequencies. Also the dynamic range of the source would be greater at lower frequencies in the model situation and excessive air attenuation would be avoided. However the cost becomes progressively unrealistic as the scale is
increased and economics is always a prime factor necessitating the use of the technique.

Conversely a small scale would be extremely economic on materials but more sophisticated equipment would be required to cope with very high frequencies, high air attenuation and loss of dynamic range.

Obviously there had to be an optimum scale which balanced reasonable economy of materials and equipment with acceptable performance.

The scales commonly used have been 1:10 and 1:8. The 1:10 scale has been generally favoured and is slightly more economical to construct and suited to the M.K.S. system of measurement. The 1:8 scale is slightly more expensive to construct but has the advantages which accompany a larger scale and is more convenient when working with construction drawings prepared in the F.P.S. System.

The 1:10 scale would provide a simple conversion factor for time from model to prototype but an inconvenient scale for frequency conversion using the standard 63, 125, 250, 500 1000 Hz etc. octave band centre frequencies. These work on a factor of 2 and suit the 1:8 scale.

The dimensioning system could be easily converted but tape speed and frequency conversion were of greater importance as it was a simple matter to obtain a 1:8 scale with standard tape recorder speeds, (which are also governed
by a factor of 2) and as the scale times were of less importance than the octave band centre frequencies which are unchangeable on standard equipment, the 1:8 scale was chosen.

4.2 TEST PROCEDURE

The measuring procedure used in the model and prototype reverberation rooms followed I.S.O. recommendation No. 477 of 1962 (41).

The measuring equipment and set-up was as follows. Plate (1). The decay of the test signal (impulse source) was received by a B&K 1/2" microphone Type 2029/30 with cathode follower type 2614 fed to a B&K microphone amplifier Type 2603 and 1/3 octave Band Pass filter set Type 1612 and thence to a Rola MK IIIB, Series Model 77 tape recorder converted to operate at a tape speed of 30 i.p.s. The tape was then analysed by playing it in reverse on a Nagra Tape recorder operating at 3 3/4 i.p.s. (1:8 scale factor), feeding the signal through the B&K microphone amplifier and filter set for 1 or 1/3 octave analysis with graphical output from a B&K High Speed Level Recorder Type 2305 with paper speed of 30mm/sec.

For experimental work on the use of a white noise source, a Dawe Type 419E White Noise Generator produced the signal which was filtered to the desired bandwidth using a
Wandel v. Golteemann passive High and Low Pass Filter Type HTP-8078, amplified by a Trio Model TK-400E amplifier and fed to a Celestion High Frequency Unit Type 1300 Mk 2.

For experimental tests using a tone burst source, both white noise and pure tone signals were gated using a G.R. Tone Burst Generator Type 1396 - A.

During analysis the tape was replayed in reverse to obtain a slow build up of the decay signal and so obviate any distortion of the curve by overshooting of the stylus of the H.S.L.R. due to the impulse source.

The characteristic curve of both Rola and Nagra tape recorders was flat for the frequency range involved. However as it was the time scale rather than the intensity of the signal that was important, any colouration would be immaterial to decay rate measurements.

Several impulse sources were tried as well as interrupted white noise. They were miniature balloons, tone bursts, and cap and starting pistols. Of these the most satisfactory and convenient was the use of a starting pistol in the prototype and a toy cap pistol in the model. Ever-New "First" Type KC-7 caps were used in the starting pistol. Both these sources had quite consistent spectra and, with the occasional exception, a sound pressure level variation of only ±1.5dB.

This source gave good reproducibility of results whereas interrupted octave bands of white noise did not.
This agreed with the conclusion of Knudsen et al.\textsuperscript{(16)} and Balachandran\textsuperscript{(15)} as discussed in Section 1.3.

Fig. (4.01) shows a series of decay curves from (a) impulse source (cap) and (b) interrupted octave band of white noise. All other factors were constant for both series.

With the few exceptions in which six measuring positions were used, all results quoted in the following work were averaged from either 16 readings (4 readings at 4 positions) or 9 readings (3 readings at 3 positions) depending on whether they represent the primary or check test.

Finally the absorption of the sample was calculated using the Sabine formula for comparison tests and Eyring formula for final results.

**Sabine form:**

\[
\alpha_S = \frac{kV}{S} \left( \frac{1}{T_1} - \frac{1}{T_0} \right) \quad \ldots(4.01)
\]

**Norris Eyring form:**

\[
\alpha_E = \frac{S}{S} \left( e^{\frac{-kV}{ST_0}} - e^{\frac{-kV}{ST_1}} \right) \quad \ldots(4.02)
\]

where \( \alpha_S = \) absorption coefficient after Sabine

\( \alpha_E = \) absorption coefficient after Eyring

\( V = \) Volume of hall

\( S = \) Total surface area of room

\( s = \) Surface area of sample

\( k = .049 \) (F.P.S.), 0.161 (M.K.S.)
FIG. 4.01

Comparison of decay curves from white noise and impulse source. Model A. position $S_1 M_3$, 2500Hz.

Impulse source gave greater reproducibility.
\[ e = 2.718 \]

\[ T_1 = \text{reverberation time with sample} \]

\[ T_0 = \text{reverberation time without sample} \]

### 4.3 THE EXPERIMENTAL MODELS

During the course of the work five different models were found necessary. While they were not all constructed at the same time, for convenience and to obviate any repetition they will be described in this part of the text along with their purpose.

The models were constructed in accordance with the 'model rules' as discussed in Section 3.0 and in each case the surfaces were chosen to simulate a hard reflecting type surface as commonly found in small halls.

They were constructed of 0.75" thick particle board, stiffened where necessary to avoid panel resonance, sanded and given two coats of clear full gloss plastic (See Spec. Fig. (4.02)). This finish had an absorption coefficient at 1:8 scale frequencies which was comparable with plastered or painted brickwork or concrete Fig. (4.02).

Figs. (4.03-4.07) set out detailed information regarding each model but the general descriptions are as follows.

**Model A:** For the purposes of direct comparison, a 1:8 scale model was constructed of the I.S.O. Standard Reverberation
Chamber at the Commonwealth Experimental Building Station, Ryde, N.S.W. This room has a volume of 6400 ft$^3$ (182 m$^3$), has non parallel walls of concrete, rendered and finished with epoxy paint, and is equipped with 24 diffusing panels of 1½" thick plaster, 6 to each corner, mounted on steel 'trees'.

The model was calibrated by carrying out tests while empty at identical measuring positions to those used in the prototype as recommended by I.S.O. Recommendation No. 477. The results of the calibration of both model and prototype are shown for comparison in Fig. (4.03).

Model B: This was a hypothetical reverberation chamber for which no prototype existed. It was built to I.S.O. recommendations and fitted with panel diffusers at the corners. Its main function was to provide a check on results measured in Model A. Fig. (4.04) shows the calibration curve for this model when empty.

Model C: This model was also built for the purpose of direct comparison. The prototype was the Central Lecture Theatre No. 1 at the University of New South Wales which had a seating capacity of 120. The floor had 6" risers between seating rows and was made of concrete screeded smooth. The walls were of brickwork and the ceiling of plaster except for two small areas of plaster acoustic tiles which were successfully simulated by 1/16" thick matt finished cardboard.
Fig. (4.05) shows the correlation between the model and prototype when empty.

**Model D:** Again this was a hypothetical model of a lecture room so constructed that each seating row was on an adjustable platform which could be varied in height to obtain risers between seating rows varying from 0" to 18". This model was constructed to facilitate tests on varying floor rakes, both separately and in conjunction with varying the depth of seating areas, balconies etc. Fig. (4.06) shows the empty calibration of this model.

**Model E:** This was another hypothetical model of a small hall with flat floor used as a check on the performance of the model auditor in a different situation with respect to (a) seating capacity and (b) total volume as a function of seating capacity. Fig. (4.07) gives the empty calibration of this model.
<table>
<thead>
<tr>
<th>Octave band Centre freq.</th>
<th>125</th>
<th>200</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured in Model reverberation room (Model A)</td>
<td>.02</td>
<td>.02</td>
<td>.02</td>
<td>.03</td>
<td>.05</td>
<td>.09</td>
</tr>
<tr>
<td>Eyr Plaster on solid backing</td>
<td>.03</td>
<td>.03</td>
<td>.02</td>
<td>.03</td>
<td>.04</td>
<td>.05</td>
</tr>
<tr>
<td>Painted brickwork</td>
<td>.05</td>
<td>.04</td>
<td>.02</td>
<td>.04</td>
<td>.05</td>
<td>.05</td>
</tr>
<tr>
<td>Parkin &amp; Humphrey (55)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brick, smooth plastered finish</td>
<td>.02</td>
<td>.02</td>
<td>.03</td>
<td>.04</td>
<td>.04</td>
<td>.03</td>
</tr>
</tbody>
</table>

FIG. 4.02

Comparison of absorption exhibited by Model and Full size surfaces.  
(Model surface corrected for air absorption)

FINISH TO MODEL SURFACES

Two pack full gloss clear plastic coating ("ESTAPOL")
A two pack polyurethane air drying system consisting of
Solution (A). - an unsaturated polyester resin in fairly active solvents
Solution (B). - an aromatic isocyanate in similar solvents to A. Curing results from the chemical reaction between the two resins to form a hard, high gloss finish.
FIG. 4.03 MODEL A Test 4A.

- Empty calibration (f.s.)
- Empty calibration (model)

\[
\begin{align*}
V_M &= 12.5\text{ft}^3, 0.354\text{m}^3 \\
V_{FS} &= 6,400\text{ft}^3, 181.5\text{m}^3 \\
S_M &= 43.8\text{ft}^2, 4.08\text{m}^2 \\
S_{FS} &= 2810\text{ft}^2, 261\text{m}^2 \\
(S &= \text{total surface area})
\end{align*}
\]
FIG. 4.04 MODEL B Test 4B.

Empty calibration (model)

$V_M = 13.3\text{ft}^3$, $0.377\text{m}^3$
$V_{FS} = 6800\text{ft}^3$, $193\text{m}^3$
$S_M = 38.2\text{ft}^2$, $3.55\text{m}^2$
$S_{FS} = 2450\text{ft}^2$, $228\text{m}^2$

SCALE: 1"=20'-0"
FIG. 4.05 MODEL C. Test 4C.

* Empty calibration (F.S.)
● Empty calibration (model).

\[
\begin{align*}
V_M &= 21.5\text{ft}^3, \ 0.61\text{m}^3 \\
V_{FS} &= 11,000\text{ft}^3, \ 312\text{m}^3
\end{align*}
\]
FIG. 4.06 MODEL D. Test 4D.

Empty calibration for 3 floor rakes

- 6" rises between rows
- 12" rises between rows
- 18" rises between rows

Data for 18" rises only

\[ V_M = 19.0\text{ft}^3, \quad 0.537\text{m}^3 \]
\[ V_{FS} = 9730\text{ft}^3, \quad 276\text{m}^3 \]
\[ S_M = 44.4\text{ft}^2, \quad 4.12\text{m}^2 \]
\[ S_{FS} = 2846\text{ft}^2, \quad 265\text{m}^2 \]
FIG. 4.07 MODEL E. Test 4E.

- Empty calibration (model)

$V_M = 26.0\text{ft}^3, \quad .736\text{m}^3$

$V_{FS} = 13320\text{ft}^3, \quad 378\text{m}^3$

$S_M = 56.6\text{ft}^2, \quad 5.27\text{m}^2$

$S_{FS} = 3630\text{ft}^2, \quad 338\text{m}^2$
4.4 MEASURING POSITIONS

In order to check the validity of the measuring procedure a series of tests were conducted on a highly absorbing material to obtain comparison measurements for absorption coefficients between the reverberation room condition with what might be called a 'forced' diffuse field and a 'normal' sound field: the 'normal' sound field being that found in a simple rectangular room with no added diffusing devices and therefore similar to many rooms in practice.

4.4.1 Experimental

Four test series were conducted to examine the sound field in 'normal' and diffuse states with and without the presence of one absorbing surface which was covered with 3" mineral wool. These experiments were carried out in model situations but all data has been converted from 1/8 F.S. to Full Size for the purposes of this discussion.

Two model rooms were used and they were outlined in Section 4.3 as Model A, the 6400ft³ C.E.B.S. Reverberation
Room model and Model B, a 6800ft$^3$ rectangular room with no added diffusion.

**Test 4.1**

This test was carried out in Model A, the reverberation room. This room contained 16 panel diffusers 4' square and had what might be called a 'forced diffuse' field. To this end the walls were non parallel with each other.

The sound field was analysed by the method outlined in Section 4.2 using an impulse source and taking three readings at each of four measuring positions at varying distances from the surface covered by the absorbing material. In this test the floor was made the highly absorbing surface.

Figs. (4.08, 4.09 and 4.10.) show the data derived from Test 4.1.
FIG. 4.08 Test 4.1

Empty room calibration for each measuring position, Model A.
Dist. from absorptive sample
- 2.5'
× 6.0'
* 8.0'
□ 11.0'
FIG. 4.09  Comparison of the decay curves, model A, Test 4.1
Reverberation time measured with 506ft$^2$ sample in place.

MODEL A  Dist. from sample

- 2.5' 
- 6.0' 
- 8.0' 
- 11.0'
Fig (4.08) shows the reverberation time measured for the empty room for each position for each octave band. As can be seen the sound field may be considered to satisfy the condition of diffusity required by the classical formulae. Each plot represents the average of three decay curves and Fig. (4.09) shows sample decay curves.

The same measurements were then made with the floor absorbent. While there was some scatter indicating slight variation between measuring positions, the reverberation time for each measuring point for a particular octave band would be considered the same indicating that a fairly diffuse field had been maintained in the presence of the absorbing surface.

Fig 4.10 shows the reverberation times measured with the sample in place from the initial decay (first 25dB). There was also evidence of a slight secondary decay and this aspect will be discussed later.

**TEST 4.2, 4.3 & 4.4**

Tests 4.2, 4.3 and 4.4 form a series carried out in model B in which the sound field was sampled at 6 positions for each of three source positions both for the empty room and for the room with one end wall covered with mineral wool as in Test 4.1. The mineral wool used was 3" thick which would be equivalent to 2 feet of absorbent when used in a 1:8 scale situation. The six measuring points varied from 5' to 30' from the sample face.
Fig. (4.11) shows two surveys of the room in the empty condition for different source positions to be the same and the reverberation time to be independent of either source or measuring position. Again there existed a diffuse sound field which satisfied the classical formulae.

However when the same measurements of the decaying sound field were taken for the condition in which the end wall \((24\text{ft}^2)\) was absorbent, the results indicated a situation which was far from diffuse.

Fig. (4.12) shows a sample of one decay curve for each measuring position for each octave band for test 4.2. For comparison the decay curve of the empty room is shown and may be considered typical of all decays for the empty room regardless of source or measuring position.

4.42 Discussion

Several trends were immediately apparent:

a) In all cases of the empty room the decay curve was exponential.

b) In all cases of the room containing the sample, a distinct double decay curve was obtained although it was less obvious in the reverberation room results.

c) The variation in the initial decay (first 20 to 25dB) ranged from 11.25dB/sec to 28.5dB/sec at 125Hz (a range of 17.25dB/sec) and from
Empty calibration of Model B for two source positions. Each point averaged from 3 readings at 6 measuring positions. The sound field could be considered diffuse.
DISTANCE FROM SAMPLE (FROM SAMPLE FACE TO MEASURING POSITION)

DECAY RATE 48/SEC. 11.9

<table>
<thead>
<tr>
<th>DISTANCE FROM SAMPLE</th>
<th>ROOM EMPTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 FT.</td>
<td></td>
</tr>
<tr>
<td>10 FT.</td>
<td></td>
</tr>
<tr>
<td>15 FT.</td>
<td></td>
</tr>
<tr>
<td>20 FT.</td>
<td></td>
</tr>
<tr>
<td>25 FT.</td>
<td></td>
</tr>
<tr>
<td>30 FT.</td>
<td></td>
</tr>
</tbody>
</table>
75dB/sec to 59.3dB/sec at 4KHz. (a range of 15.7dB/sec); i.e. the influence of measuring position was greater with low frequencies than for high frequencies. (Data from Test 4.2)

d) The secondary decay (remaining 20dB) varied far less with measuring position having values of approx. 4.28dB/sec at 125Hz and approx. 42.8dB/sec at 4KHz. However these values exceeded the values for the empty hall for all octave bands of 9.05dB/sec. at 125Hz and 41.7dB/sec at 4KHz.

e) The decay rate for low frequencies increased with distance from sample while the decay rate for high frequencies decreased with distance from the sample. At mid frequencies the decay rate was fairly constant regardless of distance from sample.

Fig. (4.13 and 4.14) show the decay rates and their extrapolated reverberation times for each measuring position for Test 4.2. Plots of Tests 4.2 and 4.3 gave a similar spread of results and exhibited approximately the same values for the secondary decays.

Fig. (4.15) gives the total absorption exhibited by the material covering the end wall for Tests 4.2, 4.3 & 4.4 as a function of frequency, measuring position and source position. The source and measuring positions both influenced the value of total absorption except for the measuring
position closest to the sample at which the values were fairly constant.

These results may be compared with those from test 4.1, Fig (4.16) in which a fairly diffuse field was maintained as shown by the relatively consistent values for total absorption. These values could be considered independent of measuring position as they almost fell within the scatter caused by normal experimental error.

The sound field in the model B experiments (Tests 4.2, 4.3 & 4.4) was obviously far from diffuse. However there were fairly consistent initial decay rates displayed for all octave bands for the measuring position closest to the absorptive wall and the scatter of results increased with distance from that wall. Only at this measuring point did the decay rates seem to be relatively independent of source position.

When the absorption coefficients derived from the average of initial decays for the measuring position closest to the sample were compared with those derived from the initial decays of the reverberation room tests they correlated well Fig. (4.17). Even with source position constant this correlation became increasingly worse as the measuring position was removed from the sample. This agreed with the work of Knudsen et.al. (16) as discussed in Section 1.
FIG. 4.13  Test 4.2

Primary decay rate (approx. $T_{15}$) for Model B with absorptive end wall
FIG. 4.14, Secondary Decays as for Fig. 4.13.
FIG. 4.15 - Variation in absorption with source and measuring position.
FIG 4.16  Total absorption of sample in Model A as a function of measuring position.

FIG 4.17, Comparison of absorption coefficients from 'normal' and diffuse field measurement.

Distance from measuring position.
4.43 Conclusion

The immediate conclusion was that when measuring the effective absorption of a material, it should be measured in the close vicinity of that material, only then would there be any correlation between the absorption of the material in a 'normal' sound field and its absorption in a 'forced diffuse' sound field.

With an audience, it is the subjective effect with which the designer must be primarily concerned, i.e. what is the nature of the sound field at the auditor's ear. This information on measuring positions is therefore of considerable importance. In experimental scale model testing involving a model audience, the measurements should be taken just above audience head level, but at a sufficient distance away to avoid any quarter wave effects.

4.5 VERIFICATION OF THEORETICAL BASIS

In order to check the validity of the classical formula for use under the previously discussed conditions, the data for sound absorption coefficients measured in the reverberation room (Model A) in Test 4.1 was used to calculate the reverberation times present in Model B. Actual model dimensions are used throughout this section.

The absorption coefficients measured in the reverberation room for (a) the wall surface and (b) the absorbing material (3" mineral wool) were used to calculate the expected reverberation times in Model B in both the empty condition and with one wall clad in the absorbing material. A
comparison was made between, Eyring and Fitzroy-Eyring formulae and in all cases the values for the Volume \((V)\) and the total surface area \((S)\) were the true values for the particular condition. See APPENDIX 1. for sample calculations.

![Figure 4.18](image)

**FIG. (4.18) COMPARISON OF REVERBERATION TIME CALCULATIONS**

<table>
<thead>
<tr>
<th>Model Statistics</th>
<th>Model</th>
<th>V.ft(^3) empty</th>
<th>V.ft(^3) with sample</th>
<th>S.ft(^2) empty</th>
<th>S.ft(^2) with sample</th>
<th>Sample area Ss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A</td>
<td></td>
<td>12.5</td>
<td>12.0</td>
<td>43.8</td>
<td>41.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Model B</td>
<td></td>
<td>13.3</td>
<td>12.5</td>
<td>37.54</td>
<td>35.94</td>
<td>3.17</td>
</tr>
</tbody>
</table>

Measured absorption Coefficient of Walls (from Model A)
\[
a_{Eyr} = 0.02
\]

Measured absorption Coefficient of Sample (from Model A)
\[
a_{Eyr} = 0.17
\]

**Reverberation Times** (Calculated for 8KHz. band only)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Model A measured</th>
<th>Model B Calculated Eyring F. 1.02</th>
<th>Model B Calculated Fitzroy-Eyr. F.1.03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td>0.485sec</td>
<td>0.53sec. 0.55sec.</td>
<td>0.55sec.</td>
</tr>
<tr>
<td>With Sample in Place</td>
<td>0.243 sec</td>
<td>0.37 sec 0.38 sec</td>
<td>0.61 sec.</td>
</tr>
</tbody>
</table>
4.51 Discussion

Both the Eyring and Fitzroy-Eyring forms gave results which correlated well with the measured reverberation time in the empty model B. The Fitzroy-Eyring form is, of course, identical to the Eyring equation when all surfaces are equally absorbing. However whilst the Eyring form also gave reliable results with the sample in place when compared with measured results close to the sample and using the absorption coefficient calculation from tests in the scale reverberation room, the Fitzroy-Eyring form gave results which varied considerably from the reverberation time measured from the initial slope of the decay curve at all measuring positions.

Hence the Eyring formula gave the most reliable prediction of reverberation time in the vicinity of the material and it agreed well with the reverberation time measured from the initial slope of the decay curve (i.e. first 15 to 20 dB) in a sound field that was shown in Section 4.4 to be not of uniform diffusity. These results also agreed generally with Knudsen(16).

As it is the subjective reverberation time that is of importance from the audience's point of view it was important that the measurement of audience absorption be carried out in the vicinity of the audience for the above reasons. All measurements were therefore carried out just above head level, i.e. approx 3" (2.0'F.S.) above to avoid
the quarter wave effects previously mentioned.

4.6 THE MODEL AUDITOR

It had to be established whether figures published for audience absorption on unupholstered chairs in various configurations, all measured in Europe, were the same for similar situations involving a typical Australian (Sydney) audience.

Experiments were carried out in the prototype of Model A, the C.E.B.S. reverberation chamber. A sample of twelve subjects was used comprising six women and six men and tested in various configurations for four states of dress. A sample of twelve was chosen because:

(a) It enabled direct comparison of results with those of other authors who had used a sample of twelve and thereby eliminated the need for correction factors.

(b) The results were to be used to establish the validity of a model audience under identical model test conditions. Their function therefore was to provide a basis for comparative measurement.

The four states of dress were termed Minimum, Light summer, Mid-Season (typical) and Heavy Winter. The actual clothing which these represent is set out in detail for men and women in Fig. (4.19.)

For each condition of dress, tests were carried out in each of three configurations.
<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>MALE DRESS</th>
<th>FEMALE DRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>Bathing Trunks</td>
<td>Bikini</td>
</tr>
<tr>
<td>Light Summer</td>
<td>.Shorts</td>
<td>Light Summer Dress or light skirt and sleeveless blouse</td>
</tr>
<tr>
<td></td>
<td>.Short sleeved shirt</td>
<td></td>
</tr>
<tr>
<td>Mid-Season (Typical)</td>
<td>2 Piece Suit</td>
<td>Medium Weight Dress (mini)</td>
</tr>
<tr>
<td></td>
<td>Long Sleeved Shirt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and tie</td>
<td></td>
</tr>
<tr>
<td>Heavy Winter</td>
<td>As above plus overcoat &amp;</td>
<td>Heavy winter suit or heavy woolen jumper and slacks.</td>
</tr>
<tr>
<td></td>
<td>scarf or Heavy-weight 3 piece suit</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 4.19

Dress Types used in audience absorption tests.
(a) Randomly dispersed over whole floor area. Plate 2.
(b) 3 rows of 4 occupying $54\text{ft}^2$ ($5\text{m}^2$) in one corner of the reverberation room. Plate 3.
(c) As for (b) but with front and side edges of seating bloc shielded by $4.0\text{ft}$ (1.22m) high reflective surround. Plate 4.

The results of the random test, configurations (a) is set out in Fig. (4.20). It shows a similar increase in absorption with increase in clothing to that found by Kath\textsuperscript{35}. Although Kath treated men and women separately, it can be seen that the correlation between the average of his results and those for a combined audience was good. However as the absorption of men was considerably higher than that of women for each state of dress this would indicate that the work of Meyer\textsuperscript{36} and Day\textsuperscript{37} in which an almost all male sample was used might tend to overestimate the absorption of a typical audience.

Fig. (4.21) sets out the results of configuration (b), 3 rows of 4 in normal theatre seating layout with $0.22\text{p/ft}^2$ ($2.37\text{p/m}^2$). Here the effect of clothing on unit absorption becomes less marked and the effects of shadowing of one person by another are indicated by this reduction in unit absorption. A degree of tolerance would therefore be acceptable in the amount of clothing worn without causing any appreciable change in the total absorption of audience seated in this fashion.
Plate Z.

Unsuccessfully models, random disposition in Model B.
Comparison of specific absorption of F.S. people measured for random seating in reverberation room.

from prototype Model A. from Kath (35)

ave. of men & women

- Minimum
- Mid-season (ave)
- Winter

Swimsuit
Summer dress
Winter coat.
Plate 3.

Unsuccessful models, 3 rows of 4 in Model B.
Specific absorption of F.S. people measured for 12 people seated in 3 rows of 4 seats occupying 54ft$^2$ (5m$^2$) measured in prototype of Model A.

Dress
- light summer
- mid season (ave)
- winter
- from Day$^{(35)}$ (unspecified clothing)
Plate 4.
Successful model
3 rows of 4 with surround
in Model A.
Absorption coefficient of F.S. audience measured in F.S. prototype of Model A for a 54ft² (5m²) area. Edges shielded by 4ft reflective surround.

Dress □ minimum ● from Kath & Kuhl(33)
○ light summer (dress unspecified)
× mid summer (ave) for some conditions.
• Winter
Fig. (4.21) also shows the results of Day\(^{(37)}\) and indicates again the higher value obtained for similar tests.

Fig. (4.22) sets out the results of configuration (c). The results are expressed as an absorption coefficient for the plan area of the sample, the sides being enclosed. The results of Kath and Kuhl\(^{(33)}\) for similar tests are shown for comparison.

In all three situations the data shows that what was considered a typical audience sample in previous test centres gave a higher absorption than a typical Sydney audience. As pointed out in Section 2.2., all previous tests have been carried out in latitudes exceeding 50°N and Sydney has a latitude of 34°S. Hence broad climatic zones have a small but significant effect on audience absorption as they effect the amount of clothing normally worn and which may therefore be expected to be worn indoors.

The foregoing data then provided the basis on which to model a typical Australian audience. If a model auditor in a model situation would give the same performance as the full size subject in those three identical full size test situations, it could reasonably be expected to work in any configuration.

Initially twelve models were constructed to the specification laid down by Day\(^{(37)}\). While it was considered that they must exhibit too much absorption as a result of their prototype and although they were developed for a 1:10
scale situation, it was felt that they might be satisfactory in view of the following.

Let it be assumed that a model material has an absorption coefficient which is flat across the audio spectrum at $X$ sabins/ft$^2$. At a scale of $1:n$ the full size equivalent of the material would have an absorption coefficient at all frequencies of $N^2X$ sabins/ft$^2$. Hence at $1:10$ scale this would be $100X$ & at $1:8$ scale it would be $64X$, the $1:10$ situation being nearly 50% higher. However as the increase in absorption is a factor of area and as the area of a $1:8$ scale model auditor is greater than a $1:10$ version by 56.25% ($\frac{1.25^2}{1^2}$), then the absorption coefficient of the model audience would be approximately the same for both scales.

The absorption spectra of an audience is not flat, however it was thought that if the error was slight, some modification to the gauze covering of the smoothed pine base might correct this.

These tests were carried out in both model reverberation chambers A and B. The results are shown in Figs 4.23 & 4.24. They indicated that some discrepancy existed with the results expected from Day's data.

This could have been due to the difficulty in carrying out a specification which was couched in somewhat vague terms i.e.

"A single layer of surgical gauze, loosely draped and held in place with spots of adhesive" Day(37).
This could be interpreted differently by different researchers and it assumed uniformity in surgical gauze from country to country.

The pine base of this model was then used as a basis and a number of claddings applied in an effort to find one which gave comparable results with measured Australian data but with little success.

In the light of the difficulties experienced in trying to establish a model in this form and having doubts about the successful specification of a composite model, it was decided to attempt the establishment of a model using a homogeneous material which could be described more precisely in terms of the manufacturers specification.

Figs. (4.23 & 4.24) also show the results achieved using a variety of materials and, in some cases, combinations of materials in two test configurations. The required performance curve is shown for comparison.

From these results it can be seen that one model conformed very well to the prototype curve and a $\frac{1}{3}$ octave analysis was carried out for confirmation. For this test configuration (c) was used, Fig. (4.25).

The successful model was constructed of 2.0 lb/ft$^3$ rigid polyurethane foam with a sanded pine 'head'. It was based on the average dimensions of men and women in the 50th percentile group of the anthropometric data published by the Royal Australian Institute of Architects$^{(52)}$ Fig(4.26)
Specific absorption, (expressed for F.S. equivalent), exhibited by various 1:8 scale model auditors compared with required performance curve for mid season (ave) clad auditors.

- Full size (performance curve)
- Successful model
- Gauze clad pine
- Fibreboard, head, plastic coated
- Wood particle board
- Smoothed pine only
Specific absorption (expressed for F.S. equivalent) exhibited by various 1:8 scale model auditors compared with the required performance curve for mid-season (ave) clad auditors. Key as for Fig.4.23.
Plate 5. Various unsuccessful model auditors
Absorption coefficient of successful model compared with F.S. prototype: Measured for 54ft² (5m²) sample with reflective surround

- Full size
- Model (polyurethane foam)
SMOOTHED PINE 'HEAD'

2.0 lb/ft³ RIGID POLYURETHANE FOAM 'BODY'

Fig. 4.26

DETAILS OF SUCCESSFUL MODEL AUDITOR.
The surface texture of the polyurethane foam body resulted from cutting the model to shape with a high speed band saw. A number of other cutting tools were tried with the same results so that any sharp edged cutting device would be satisfactory.

As rigid polyurethane foam is almost impermeable, 90% of the cells being closed, the surface texture is provided by a series of minute cells which have been cut open. It is the cut cells of varying depth that are responsible for the absorption of high frequency sound.

The last stage in the development of the model auditor was to compare its performance with that of the prototype in a 'normal' situation. Model C, the scale version of Central Lecture Theatre 1, was used for this purpose. A small group of 30 people was used in two configurations, (a) random and (b) seated in one group in the centre of the room. Plate 7.

In both model and prototype the measuring position was taken just above audience head level. Fig (4.27) sets out the results of these check tests and again the correlation between the model and prototype was particularly good.

Satisfied that the model auditor met the required performance specification, sufficient numbers were produced to facilitate larger scale experiments on audience absorption effects.
FIG. 4.27

Comparison of model and Full size prototype auditor measured in both model and prototype of Model C, for a group of 30 auditors in a bloc.

X  F.S. prototype
○  Model (Polyurethane foam).
4.61 Accuracy of Results

An analysis of the order of accuracy of results was carried out on a group of experiments from Test 5.10. Although this test series is not discussed until Section 5.0, the confidence limits established are essentially the same as can be expected from all experimental work herein.

With the exception of a few check tests in which 3 readings were taken at 3 measuring positions, the results shown as points throughout this thesis for measured reverberation times represent the mean of the readings for each of 4 measuring positions, each measuring position being represented by the mean of four decay rates.

The following table, Fig. 4.28, sets out the variations that could be expected in absorption coefficients calculated from such measured data.

Both \( V \) and \( S \) for use in the Sabine formula (1.01) or the Eyring formula (1.02) were calculated to a high degree of accuracy from the average of three separate measurements of the models. The model rooms used were of relatively simple shapes and easily measured after construction and it will be assumed that no allowance will be necessary for these factors in the order of accuracy calculations.

The confidence limits for the absorption coefficient of an audience area of 650ft\(^2\) were calculated.

\[
95\% \text{ Confidence limits} = M \pm 1.96 \frac{\bar{X}}{\text{S.E.}} \quad \cdots (4.03)
\]
when \( \bar{X}_{S.E.} = \frac{S.D.}{\sqrt{n-1}} \)

\( \bar{X}_{S.E.} \) = Standard error of the mean

\( M \) = Mean

\( S.D. \) = Standard Deviation of Sample.

\( n \) = Number of readings.

The results in Fig. 4.28 represent the expected spread of results for absorption coefficients measured in Test 5.10 but may be considered typical for all model experiments to determine absorption coefficients.

The average spread of results is approx. \( .02 \text{ft}^2\text{Sab} \) (i.e. \( \pm .01 \)) and all results plotted as single points throughout this thesis should be taken to have the above order of accuracy.
<table>
<thead>
<tr>
<th>Freq (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1K</th>
<th>2K</th>
<th>4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% Confidence limits for Empty Reverberation times (Sec)</td>
<td>±.12</td>
<td>±.06</td>
<td>±.08</td>
<td>±.02</td>
<td>±.04</td>
<td>±.01</td>
</tr>
<tr>
<td>75% Confidence limits for occupied reverberation times (Sec)</td>
<td>±.03</td>
<td>±.07</td>
<td>±.02</td>
<td>±.02</td>
<td>±.03</td>
<td>±.01</td>
</tr>
<tr>
<td>Total spread of results for absorption coefficient of sample (M=mean)</td>
<td>M±.006</td>
<td>M±.011</td>
<td>M±.008</td>
<td>M±.012</td>
<td>M±.011</td>
<td>M±.013</td>
</tr>
</tbody>
</table>
4.7 **SUMMARY** - Experimental Organisation and Procedure.

4.71 **Scale Factor for Model Analysis**

(a) For maximum convenience in the use of standard equipment in which tape recorder speeds and octave band centre frequencies progress by a factor of 2, a 1:8 scale factor was chosen.

4.72 **Test Procedure**

(a) Tests were carried out in accordance with relevant I.S.O. recommendations and with the 'model rules' as discussed in Section 3.1. (b) An impulse source was chosen because it gave better reproducibility of results than interrupted white noise. A starting pistol was used in the prototype and a small cap pistol in the model.

4.73 **The Experimental Models**

(a) Five models were constructed to a scale of 1:8 in accordance with the 'model rules' (Section 3.1). They were used in comparison and check tests from which a model auditor was developed and to provide an economic method by which other audience absorption effect previously unexplored (Section 2.2) could be examined.

4.74 **Measuring Positions**

Tests (appendix 1) confirmed that the absorption
coefficient measured in the reverberation room when a complete surface was covered by the audience correlated fairly well with that measured in a 'normal' sound field when measured just above audience head level.

4.75 Verification of Theoretical Basis

(a) The Eyring formula gave reliable predictions for the initial slope of the decay curve of the sound field in the vicinity of the sample. The initial slope referred to was the first 15 to 20dB approx. Then predictions were made using the absorption coefficients established in the model reverberation room when one of the six surfaces (506ft$^2$) was covered by the sample.

4.76. The Model Auditor

(a) A performance specification for a model auditor which would represent a typical Australian audience was derived from tests in the C.E.B.S. reverberation room prototype of Model A.

(b) This data showed that broad climatic zones, as they influence the amount of clothing normally worn, caused changes in audience absorption.

(c) A successful model was finally developed with dimensions based on the latest anthropometric data available. It had a 'body' of 2 lb/ft$^3$ rigid polyurethane foam and a 'head' of smoothed pine.
SECTION 5.

5.0 AUDIENCE ABSORPTION

Having established a satisfactory model auditor which was valid in any audience configuration, a series of tests were performed to assess the following:

5.1 Whether the absorption coefficient of an audience reached a constant value at which it was independent of seating density.

5.2 The existence and magnitude of the edge absorption due to exposed side, front and rear rows.

5.3 Whether there was any edge diffraction effect, i.e. a non-linear relationship between total absorption and the audience area, apart from any effect caused by 5.2.

5.4 Other Factors affecting audience absorption:

Whether the absorption coefficient was in any way related to the configuration of its seating, i.e. depth of balconies, varying floor rakes and combinations of these, also the cause of the selective low frequency attenuation.

5.1 RELATIONSHIP BETWEEN SEATING DENSITY AND ABSORPTION COEFFICIENT

Two separate tests were carried out to investigate this effect. In both cases the model room had seating in place for a capacity audience and the seating density of
the model auditors was systematically increased.

The model seats used in all experiments were of two types.

(a) An individual chair constructed of 1/8" square balsa wood legs and 1/16" cardboard seat all given one coat of the clear polyurethane finish specified in Fig. (4.02).

(b) A bench seating five models with seat and legs of sanded 3/16" plywood.

Both these forms represented unupholstered seating and the absorption they exhibited is shown in comparison with that of full size prototypes, Fig. (5.01)

As all other factors were constant the results of the tests expressed the effect of audience density on absorption coefficient.

Test 5.1: This series was carried out in Model A, the C.E.B.S. Reverberation Room.

The seating density was varied from .099 p/ft$^2$ (1.03 p/m$^2$) to .173 p/ft$^2$ (1.86 p/m$^2$). Fig. (5.02) shows the variation in absorption coefficient with seating density and above approx. 0.155 p/ft$^2$ (1.52 p/m$^2$) there was no noticeable change in total absorption.

Fig. (5.02) also gives seating density in terms of area per person.
Specific absorption of model chairs compared with F.S. prototype

- Model stool (per person)
- Model chair
- F.S. chair
FIG. 5.02
Variation in $\alpha$ with seating density from Model A

FIG. 5.03
Variation in absorption coefficient with seating density from Model E

• 5KHz, ○ 2KHz, □ 1KHz, ■ 500Hz, ◇ 250Hz, ▲ 125Hz
Plate 8.
Typical measuring positions (Model E)
Test 5.2: This series was carried out in Model C, the Central Lecture Theatre Model.

This model differed from Model A in two respects, (a) it represented a 'normal' rather than an evenly diffuse sound field, and (b) it had a rise of 6" between seating rows whereas Model A had a flat floor. As a result of previous conclusions (section 4.4) all measurements in Model C were taken just above audience head level. Plate 8.

Fig (5.03) shows the results of this series in which the seating density was varied from .085 p/ft$^2$ (.93 p/m$^2$) to .196 p/ft$^2$ (2.08 p/m$^2$). Again the absorption coefficient reached a constant value at approx. .155 p/ft$^2$.

5.11 Discussion

These two tests series, together representing the spectrum analysis of over one hundred test signal decays, showed that for all practical purposes the absorption coefficient of an audience on unupholstered seats remained constant for seating densities greater than .155 p/ft$^2$ (1.67 p/m$^2$) or (i.e. 6.5 ft$^2$/person).

As the maximum seating density normally found is of the order of .205 p/ft$^2$ (2.2 p/m$^2$) the above finding was in general agreement with previous work by others, (Section 2.4).

Van Raalton$^{(40)}$ found that the absorption coefficient for an audience on unupholstered seats increased with the number of persons in a non-linear manner until the density
reached .186 p/ft$^2$ (2 p/m$^2$) at which he stated: "the absorption seems to become rather constant". However his graph of this condition does not clearly indicate a constant value above this figure.

Day$^{(37)}$ found that an occupancy of greater than 50% added a decreasing amount to the effective absorption. He did not give a value at which the absorption coefficient reached a constant, nor did he suggest that it did, but his results show a fairly constant value for densities greater than approx. .14 p/ft$^2$ (1.51 p/m$^2$).

Beranek$^{(26)}$ gave the density above which absorption coefficient was constant as .125 p/ft$^2$ (1.42 p/m$^2$) but this was for an audience on upholstered seats.

These findings are, however, contrary to those of Meyer et.al$^{(36)}$ who concluded that the absorption coefficient of an audience on unupholstered seats was always dependent on seating density except in the lower frequencies.

Whilst this effect and its magnitude might be difficult to compute theoretically, it was one which might well be predicted.

It is entirely reasonable to assume this effect to be due to shadowing of one person by another. The degree of shadowing would then become progressively greater with increase in seating density.

With a small density the sound energy would be incident on all parts of the auditorium as they would be
sufficiently distant from one another not to cause interference. With increase in density, the total absorbing surface provided by the audience would also be increased but the relationship between effective absorption and total surface area (and therefore floor area) would become progressively non-linear due to the shadowing of some of these surfaces, in particular the sides by the adjacent auditor; (source at normal speaker position assumed).

Above a particular seating density the effect of adding more absorbent to the system would be nulified by the increased shadowing caused and hence a constant value of absorption coefficient would be maintained.

5.12 Conclusion

Tests 5.1 and 5.2 have established a constant value of absorption coefficient for the normal range of audience seating densities (i.e. greater than .155 p/ft² or 1.67 p/m²). Fig. (5.03) gives the coefficient for smaller densities down to .083 p/ft.

At this stage, without having examined the effect of varying the area of the sample, these absorption coefficients can only be attributed to the particular tests areas used i.e. 506 ft² (47m²) for Test 1 and 465 ft² (43.2m²) for Test 5.2. However they do give a working value for audience absorption within these limits.
5.2 EDGE ABSORPTION

From the foregoing it was obvious that an audience must be considered as an absorbing device as each unit within it is influenced by those around it. It was therefore reasonable to expect that the bounding edges of an audience bloc might behave differently to the body of the bloc.

Three tests were carried out to ascertain the value of extra absorption added to the system by the front, rear and side edges of an audience bloc and the influence of the proximity of walls and other seating blocs. The intention was to determine the extra absorption to be added to the relevant area coefficient.

5.2.1 Side and Centre Aisle Absorption

Test 5.3: Single Aisle Absorption (Model check)

This series was carried out in Model A by comparing the total absorption of a seating bloc with all sides masked and its total absorption with the side masking removed. The difference in absorption was due to the influence of the side only.

Masking was achieved using 4'-0" high reflective screens of perspex.

Fig. (5.04) shows the results of two such tests on different sized audience blocs. They are shown in comparison to similar tests carried out in the full size prototype of Model A with people in the three states of dress previously
FIG 5.04
Side Edge Absorption of Model audience compared with F.S. prototype

- F.S. prototype, winter dress
- F.S. prototype, average dress
- F.S. prototype, light summer dress
- Model auditor
described.

With the exception of the low frequency band the agreement with 'average' dress was good. The model could therefore be used in more detailed tests to ascertain edge absorption.

**Test 5.4: Single Aisle Absorption Adjacent to a Wall**

In this series Model D was used. The whole floor area was covered with audience at a density of 0.17 p/ft$^2$ (2 p/m$^2$), the total absorption measured, then sufficient auditors removed to provide an aisle of 3'-0" wide adjacent to one side wall and the absorption measured again. The total absorption measured in each case was found to be the same within experimental error.

The extra absorption due to the aisle is shown in Fig. (5.05) expressed over a strip 4'-0" (1.22m) high, i.e. the height of an audience bloc, and compares favourably with the results of test 5.3, Fig (5.04).

However the results show that there was no difference in total absorption with or without the aisle. As it has already been established that the absorption coefficient for the body of the seating bloc is constant for the seating density used, the aisle side must exhibit the same absorption as a 3'-0" wide strip of audience. When the aisle absorption was plotted for a 3'-0" strip Fig. (5.05), the absorption coefficient was almost the same as that for a
FIG. 5.05 Test 5.4

1/3 octave analysis of extra absorption exhibited by the side edge of an audience on unupholstered seating.

- from Model audience expressed for 4'.0" edge height
- as above but expressed for a 3'.0" strip width
- for F.S. audience from Kath & Kuhl (34)

from Test 5.5
- Combined absorption of both edges of 4'.0" wide centre aisle expressed for a 4'.0" strip for comparison with Test 5.4.
large area of audience.

Test 5.5: Aisle Absorption when Bounded on Both Sides by Audience Blocs

The test set up was the same as for Test 5.4 except that a 4'-0" aisle was provided in the centre of the room.

The results obtained were almost identical to those for Test 5.4 indicating that the effective absorption of each side of a 4'-0" aisle was only one half that of the test 5.4 condition.

This effect might have been anticipated as the hard wall surface in Test 5.4 would reflect sound energy back onto the aisle side whereas in Test 5.5 each side of the centre aisle would be partially masked by the other.

It is fortunate from the point of view of simplified calculations that both side aisles of 3'-0" in width (.92m) and centre aisles of 4'-0" in width (1.22m) are equally sound absorbent and can each be allowed for by adding a strip 3'-0" wide to the total audience area.

5.22 Front and Rear Row Absorption

A similar series of tests to those in Section 5.21 were carried out to establish the effect of front and rear row absorption.
Test 5.6: Front Row Absorption (Model Check)

The same two seating blocs as used in 5.21 Test 5.3 were used but with the front reflective screens removed for comparison.

Fig. (5.06) shows the results together with the front row absorption measured for three states of dress in the F.S. prototype. Except for the 125Hz. band the correlation was quite good.

Test 5.7: Front Row Absorption

In this series Model D was used. Two rows of auditors were placed in front of the rear wall of the room for its full width and the total absorption measured with and without a front reflective screen 4'-0" in height (1.22m).

The results, Fig. (5.07) show the extra absorption due to the front edge of the bloc.

Test 5.8 Rear Row Absorption

Model E was used for this series. A bloc consisting of 3 rows of auditors extending the full width of the room was tested in two locations, (a) with the rear row hard against the back wall, (b) with the rear row of the bloc ten feet from the back wall. Fig. (5.07) also shows the results of this test expressed as the extra absorption caused by the rear of an audience bloc.

The extra absorption exhibited by both front and
FIG. 5.06
Extra absorption exhibited by the front edge of an audience bloc compared with F.S. prototype

- F.S. prototype, winter dress
- F.S. prototype, average dress
- F.S. prototype, light summer dress
- Model auditor.
FIG. 5.07

1/3 octave analysis of extra absorption exhibited by front and rear edges of an audience bloc on unupholstered seating

- rear edge from model audience expressed for 4'0" edge height
- front edge from model audience expressed for 4'0" edge height
- front edge expressed for a strip width of 1.75ft.

for F.S. audience from Kath & Kuhl(34)
rear rows was almost identical and for all practical purposes may be considered so. It should be noted that for Tests 5.7 and 5.8 the bench type seats were used with no backrests.

5.23 Discussion

It was not possible to express the above absorption in terms of a single area correction for all frequencies as with side and centre aisles. For preliminary calculations the addition of a strip 1.75ft. (.54m) wide would give accurate results for frequencies above 1KHz but for accuracy at all frequencies the area corrections set out in Fig. 5.08 would be required and these are frequency dependent.

A great deal of time could be spent examining the aisle absorption with various row to row spacing of seats. All such tests mentioned here-in were carried out with a row to row spacing of 35" (0.9m) which is fairly typical of modern theatre seating. The variation in aisle absorption due to small differences in this spacing would be slight and in calculations of total audience absorption, negligible. It was not so much the actual area of absorbent material exposed at the aisle that caused this extra absorption but rather the highly absorbent troughs formed between seating rows in which the sound energy was dissipated. Similarly the work involved in testing varying aisle widths would not be warranted.
Again these results agreed in principle with previous work by others.

Beranek\(^{(27)}\) allowed a strip 1m (3.28ft) wide for an aisle bounded on both sides by audience blocs and 0.5m (1.64ft) for an aisle bounded on one side only. These corrections are for an audience on upholstered seats.

Kath and Kuhl\(^{(27 \& 28)}\) found similar absorption exhibited by the front and side rows of an audience bloc, Fig. (2.05). These tests were carried out under similar conditions to, and with the same sample area as, Test 5.1 in Section 5.21 and 5.22 so they can readily be compared with Figs. (5.05) and (5.07) on which they are also plotted. Such comparison shows that Kath and Kuhl's figures are greater, the difference probably being due to the clothing worn in each test as previously discussed.

5.24 Conclusion

Figs. (5.05) and (5.07) show the extra absorption to be added to a seating bloc as a result of edge absorption.

For purposes of simplifying calculations the corrections can be allowed for in the form of area corrections added to the plan area of the seating bloc and the relevant absorption coefficient extended to the total area. (Fig. (5.09).
**FIG. 5.08 Strip Widths for Detailed Area Corrections**

For Front and Rear Edges

<table>
<thead>
<tr>
<th>Freq. (Hz)</th>
<th>Strip Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
</tr>
<tr>
<td>125</td>
<td>0.25</td>
</tr>
<tr>
<td>250</td>
<td>0.6</td>
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<tr>
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<td>1.25</td>
</tr>
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<td>1000</td>
<td>1.75</td>
</tr>
<tr>
<td>2000</td>
<td>1.75</td>
</tr>
<tr>
<td>4000</td>
<td>1.75</td>
</tr>
</tbody>
</table>

**FIG. 5.09 Corrections for Edge Absorption**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Strip Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Aisle approx 3.0' wide adjacent to wall</td>
<td>3.0ft 0.92m</td>
</tr>
<tr>
<td>Centre aisle edge for aisles approx. 4.0' wide</td>
<td>1.5ft .46m</td>
</tr>
<tr>
<td>Total correction for centre aisles approx. 4.0' wide</td>
<td>3.0ft .92m</td>
</tr>
<tr>
<td>Front edge</td>
<td>1.75ft .54m</td>
</tr>
<tr>
<td>Rear edge</td>
<td>1.75ft .54m</td>
</tr>
</tbody>
</table>
No correction would be made for a front edge where a solid balcony rail existed nor for a rear edge when solid seat backs existed.

For greater accuracy with front and rear edge correction, the correction factors in Fig. (5.08) should be used.

5.3 EDGE DIFFRACTION EFFECT

Despite the corrections added to the total audience area as a result of edge absorption, there was consistent evidence of higher absorption coefficients being exhibited by smaller areas.

A series of tests was carried out to examine this effect.

Test 5.9: The absorption of a series of rectangular audience blocks was measured in Model A. In each case the seating density was kept constant at .2 p/ft$^2$ (2.16 p/m$^2$) and the edges were shielded by 4.0ft (1.22m) high reflective screens. The blocs were placed asymmetrically near the centre of the room to avoid the higher energy region near the walls referred to by Kath and Kuhl$^{(33)}$ and discussed in Section 2.2.

The sample size was increased in five steps from 60ft$^2$ (5.7m$^2$), to 506ft$^2$ (47. m$^2$) (the total floor area of the room).

Because of the elimination of edge absorption, the
results could be expressed as an absorption coefficient based on plan area only.

These results Fig. (5.10), clearly show an increase in absorption coefficient with reduction in sample area. They are not corrected for edge absorption.

Fig. (5.11) shows the variation in absorption coefficient as a function of the ratio of perimeter to area of the sample after correction for edge absorption. The theory behind this is discussed in Section 5.13.

These tests were carried out in the scale reverberation room, hence for the purpose of comparison with a 'normal' sound field a second series of tests were performed in Model E.

Test 5.10: Carried out in Model E. The audience blocs were formed by complete rows of auditors with no aisles so that they stretched from wall to wall. There was no shielding of the front row but the allowances for front row absorption as given in Fig. (5.09) were subtracted from the total absorption so that the results could again be expressed as an absorption coefficient based on the plan area of the sample.

The results, Fig. (5.12 & 5.13), again show an increase in absorption coefficient as the sample area was decreased and the relationship between this and the perimeter
per unit area (E).

Both the foregoing tests were carried out for an audience on a flat floor. In order to obtain additional data on the problem of absorption coefficient varying with sample area and to determine the effect of varying the floor rake, a third series of tests was performed in Model D. The variation of absorption coefficient with floor rake will be discussed later.
FIG. 5.10
Increase in $\alpha$ with reduction in $S$ measured in Model A

FIG. 5.11
Increase in $\alpha$ as a function of $P/S = (E)$, Data from Fig. 5.10
FIG. 5.12
Increase in $\alpha$ with reduction in sample area,
Flat floor, measured in Model E

- $\times$ 69ft$^2$
- $\circ$ 192ft$^2$
- $\bullet$ 515ft$^2$
- $\blacksquare$ 650ft$^2$
FIG. 5.13
Increase in $\infty$ as a function of $E$ for a flat floor measured in Model E
Test 5.11: The procedure for these tests was as for Test 5.10. Three separate tests were performed for which all factors remained constant except the floor rake which was set at 6", 12", 18" between seating rows. Consequently there was a slight reduction in room volume with increased floor rake.

The results, Figs. (5.14 to 5.19) show two trends, (a) the now characteristic increase in absorption coefficient with smaller areas as a result of the increase in perimeter per unit area and (b) an increase in absorption coefficient with floor rake.
FIG. 5.14  Increase in $\alpha$ with reduction in $S$ measured for 6" risers in Model D

FIG. 5.15  $E (L^{-1})$
Increase in $\alpha$ as a function of $P/S=(E)$, Data from Fig. 5.14
FIG. 5.16  Increase in $\alpha$ with reduction in $S$ measured for 12" risers in Model D

FIG. 5.17  $E (L^{-1})$
Increase in $\alpha$ as a function of $P/S = (E)$, Data from Fig. 5.16
FIG. 5.18 Increase in $\infty$ with reduction in $S$ measured for 18" risers in Model D

FIG. 5.19 Increase in $\infty$ as a function of $P/S = (E)$, Data from Fig. 5.18.
5.31 Discussion

Several people have examined this effect in the reverberation room condition. Kosten\(^\text{(20)}\), and Kolmer and Krnak\(^\text{(53)}\) among others have concluded that with any absorbent material, the total absorption was increased by diffraction of the sound waves at the sample's edges. As the sample size was decreased the ratio of perimeter to area (E) increased, hence a smaller sample would display a higher absorption coefficient.

\[
E = \frac{L}{S} = \frac{\text{Perimeter of Sample}}{\text{Free area of Sample}} \quad \text{...(5.01)}
\]

Kosten\(^\text{(20)}\) suggested the following linear relationship between absorption coefficient for a particular E value (\(\alpha_E\)), the true coefficient for randomly incident sound on an infinitely large sample (\(\alpha_\infty\)), and E.

\[
\alpha_E = \alpha_\infty + \beta E \quad \text{...(5.02)}
\]

where \(\beta\) is a frequency dependent constant for each material.

Gomperts\(^\text{(10)}\) found the same linear relationship to be true for Sillan S.P. 100 (with different values of \(\beta\)) even when the edges of the absorbent material were not shiel-
ded by reflective strips as they had been in previous work.

All of these tests were performed on sheet absorbing materials such as Sillan S.P. 100.

It was suggested, Kosten (20), that as E approached zero, the 'true' absorption coefficient $a_\infty$ would be established for the material.

There was not complete agreement however. Kolmer and Krnak (53) found that although a linear relationship still existed between $a_E$ and E in an insufficiently diffuse sound field in a reverberation room, the extrapolated value of $a_\infty$ was sometimes too low. Gompert (10) on the other hand found the extrapolated value for this condition to be often too high and did not produce the tube method $a$ at E=0.

The complete theoretical solution to the effect of edge diffraction would involve a long and complex analysis. However a highly simplified approach might be sufficient to lend weight to the results obtained.

The measurement of effective absorption of a planar area of highly absorbent material in a room with otherwise uniform and relatively reflective surfaces would be complicated by two factors.

(A) The highly absorbing sample would introduce anisotropy into an originally isotropic sound field (see section 4.4).
(b) Diffraction effects need to be allowed for.

Take for example a small sample of a homogeneous sound absorbing material placed on one surface of a room in which a diffuse sound field existed.

If, for the sake of simplicity, the sound field impinging on the sample was divided or resolved into two main groups, i.e.

(a) approx. normal incidence and (b) approx. tangential incidence, the analysis would be as follows.

(a) The normal incidence sound would be absorbed proportionally to the sample area $S$ only:

$$\text{absorption } A_N = \alpha_S \ldots (5.03)$$

i.e. twice the area, twice the total absorption.

(b) The tangentially incident sound would be absorbed at the edge of the sample. It would not travel far into the body of the sample before its energy was dissipated.

Therefore the absorption of this component would be proportional to the perimeter, $P$.

$$A_T = \beta P \ldots (5.04)$$

$\therefore$ Total absorption $= A = A_N + A_T = \alpha_S + \beta P$

$\therefore$ apparent absorption coefficient

$$\alpha_E = \frac{\alpha_S + \beta P}{S}$$
As $\frac{P}{A} = E$, Eq. (5.05) is identical to Eq. (5.02)

This was a crude attempt to explain the results obtained empirically. However the fact that the sound field was approx. isotropic would not invalidate the method and would only results in a different set of values for $\beta$ and these have been established empirically.

The results of Tests 5.09, 5.10 & 5.11 are shown in Figs. (5.11, 5.13, 5.15, 5.17 5.19) with $\alpha_E$ plotted against $E$. The proportions of the sample area in all tests varied from 1:1 to 1:4 and in test 5.10 from 1:1 to 1:7.

In all cases the linear relationship expressed in equation (5.02) appears to hold true.

The validity of Equation (5.02) can be shown by comparing Tests 2D and 2E.

### FIG. 5.20 TEST OF EQUATION 5.02

<table>
<thead>
<tr>
<th></th>
<th>Test 2D</th>
<th>Test 2E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bloc Dimensions (ft)</td>
<td>7'x9'</td>
<td>23'x2.6'</td>
</tr>
<tr>
<td>Area (S) ft$^2$</td>
<td>63</td>
<td>60</td>
</tr>
<tr>
<td>Perimeter (L) ft</td>
<td>32</td>
<td>51.2</td>
</tr>
<tr>
<td>L/S = E</td>
<td>.51</td>
<td>.85</td>
</tr>
<tr>
<td>Sample $\alpha_E$ (4K Hz)</td>
<td>.52</td>
<td>.63</td>
</tr>
</tbody>
</table>
These two samples have approximately the same area but different values of $E$ and $\alpha_E$ and both fit the relationship expressed in Eq. (5.02)

These results indicate that for consideration of edge diffraction, an audience bloc can be treated in the same way as any porous absorbing material within the values of seating density for which a constant $\alpha_E$ pertains. They show the consistent increase in absorption coefficient which accompanies both the increase in floor rake and the increase in perimeter per unit area ($E$).

The results of Test 5.9 in the scale reverberation room show higher values of absorption coefficient for a particular value of ($E$) than those for a 'normal' sound field. This is undoubtedly due to the relative diffusity of the sound fields and is an effect commonly experienced by others.

These results show therefore that to establish the absorption coefficient of any porous material, including an audience bloc, a number of samples must be examined to establish the function $\beta$ and from equation (4.01) and (5.02) we get:

$$\alpha \omega(Sab) = \frac{55.3V}{C.S} \left[ \frac{1}{T2} - \frac{1}{T1} \right] - \beta E \quad \ldots(5.06)$$
FIG. 5.21
Variation in $a_{Eyr}$ with $E$, Flat Floor

FIG. 5.22
Variation in $a_{Eyr}$ with $E$, 6" risers. (15.3 cm)
FIG. 5.23
Variation in $\alpha_{Eyr}$ with $E$, 12" risers (30.6 cm)

FIG. 5.24
Variation in $\alpha_{Eyr}$ with $E$, 18" risers (45.7 cm)
5.32 Conclusion

Figs. (5.13, 5.15, 5.17 & 5.19) set out the values of $\alpha$ as they vary with $E$ for various floor rakes for use in the Sabine formula (2.01) and Figs. (5.21 to 5.24) set out the same data for use in Eyring formula (2.02). These figures are for use in predicting audience absorption on unupholstered chairs.
5.4 OTHER FACTORS AFFECTING AUDIENCE ABSORPTION

5.41 Seating Rake

Figs. (5.15, 5.17 & 5.19) set out the absorption coefficient of an audience on a raked floor. The tests were performed in Model D so that with the exception of the slight volume change which resulted from varying the floor rake, all other factors were kept constant. Hence the results show the effect of change in floor rake only.

The tests covered the range from flat floor to 18" rise between seating rows in 6" steps. Different sized seating blocs were used in each case including blocs consisting of two, three and four rows of seating from wall to wall across the rear of the room to assess the effect, if any, of narrow balconies on absorption coefficient. Plate 9.

The results of these tests show that absorption coefficient did increase significantly with increase in seating rake. Again this effect was to be expected as with increase in floor rake more absorbent material is exposed to direct sound. However, no noticeable variation from the theoretical basis laid down in Section 5.3 could be
Test audience in Model D.
detected for any individual test indicating that narrow blocs of seating, shallow balconies etc. do not constitute special cases, the area, proportion \((E)\), and floor rake being the dependent variables for absorption coefficient (all other factors equal).

5.42 Selective Low Frequency Absorption

Both Schultz and Watters\(^{(17)}\) and Sessler and West\(^{(18)}\) in full size and model experiments on a seated audience showed that the excessive low frequency attenuation which was often measured in concert halls at audience level was due to selective absorption of sound energy at grazing incidence by the vertical cavities between seating rows.

This effect was found to reach a maximum attenuation after 15 rows of 15dB, after which there was no increase. It was also a local effect as it was less noticeable with increase in height above the measuring position of 3.66ft (1.12m) until at 16.75ft (5.5m) it was indistinguishable.

In their discussion, Sessler and West explained the attenuation which operates in the region of 80 to 400 Hz as follows:

"..(1) The rows of seats act as an energy-storage mechanism for certain low frequencies.
(2) The frequency of maximum attenuation depends on the height of the rows rather than on their spacing.
(3) Introducing gaps between floor and rows of seats leads to an increase of the frequency of maximum attenuation.
(4) There is considerable attenuation even at frequencies much higher than the frequency of maximum attenuation."
The results indicate that the observed seat attenuation is caused by a combination of at least two effects: namely a vertical resonance between the rows causing the attenuation maximum, and a diffraction effect responsible for attenuation in a broad frequency band.

Sessler and West gave the following formulae for calculating the resonant frequencies approximately:

(A) For a closed floor (i.e. space between seating rows closed off under seats)

\[ f_{1,n} = \frac{nc}{4(h+x_1)} \]  

...(5.07)

(B) For an open floor

\[ f_{2,n} = \frac{nc}{2(h+x_2)} \]  

...(5.08)

where  
\( n \): an integer  
\( c \): velocity of sound in air  
\( h \): height of seats  
\( x_1 \) and \( x_2 \) are end corrections related to the distance between rows.

They suggest that the end corrections can be neglected and reasonable accuracy still obtained.

Calculation of the maximum frequency at which selective low frequency absorption occurred for the four conditions of audience rake using a row height of 3.5ft (1.07m) (shoulder height of model) gives the following results. Fig. (5.25). The rows were essentially the 'closed floor' condition:
These results agree generally with those measured, Figs (5.14, 5.16 & 5.18). Although no measurements were made below 125Hz, the trends can be clearly observed. These figures clearly show the increase in this absorption as the number of rows of seated audience was increased. This absorption was significant when the number of rows exceeded four.

5.43 Absorption Due to High Energy Region in the Vicinity of Hard Surfaces

Regarding the edge correction applied by Kath and Kuhl (33) based on the work of Waterhouse (38) as discussed in Section 2.2, no evidence could be found in the measured data to indicate the need for such a correction.

Fig. (5.26) shows the absorption coefficient measured for a bloc of twelve auditors in Model A. Two measuring positions were used, (a) the bloc in an assymetrical
FIG. 5.26

Effect of proximity of hard surfaces on sound absorption of an audience

× 54ft² sample (5m²) placed in corner of reverberation room (Model A)

○ 54ft² sample (5m²) placed assymetrically in centre of reverberation room (Model A)
position in the centre of the room with a reflective surround and (b) the bloc in one corner with the two walls forming a screen for two sides, the other two being protected by a reflective surround.

There was no noticeable difference in the absorption exhibited by the two conditions.

Fig. (5.11) shows the absorption coefficient measured for Model A completely full of auditors in comparison with smaller seating blocs which were free of the walls on all four sides. Again there was nothing to indicate an increase in absorption as a result of the higher energy region known to be associated with the wall surfaces.

Waterhouse's theory applied in particular to a homogeneous material and the preceding chapters have shown that in many respects an audience does not satisfy that condition. Whilst a degree of added absorption may occur when surfaces of individual auditors are in close proximity to a hard surface, this amount of surface would only represent a small fraction of the edge length of an audience bloc. The resulting absorption would be difficult to separate from normal experimental error.

As a result the findings of Meyer et.al. (36) must be agreed with, i.e. that rather than being an area of homogeneous absorbing material, an audience is a geometrically badly defined absorbing arrangement.

It was therefore considered that any correction
resulting from this effect be ignored.

5.5 GENERAL SUMMARY - Audience Absorption

5.5.1 Relationship Between Seating Density and Absorption Coefficient:

Within the normal range of seating densities found in auditoria, i.e. greater than 0.155p/ft² (1.52p/m²), the absorption coefficient displayed was a frequency dependent constant for a constant area. Fig. (5.02 & 5.03)

5.5.2 Edge Absorption

Extra absorption must be added to that calculated for the plan area of seating blocs to allow for edge absorption. This resulted from the absorption caused by the front, rear and sides of audience blocs.

For simplified calculation, area corrections can be allowed in the form of strips added to the total plan area as per Fig. (5.09). The relevant absorption coefficient would then be extended to the total area.

For more precise calculations below 1 KHz, the corrections in Fig. (5.08) should be allowed for front and rear row corrections, however the difference made to the total absorption of a seating bloc would be negligible.

As the tests used to establish these edge corrections had a sample area of approx. 500ft² and an E value of
approx. .15, they were in the relatively constant zone for audience absorption coefficients. However the corrections listed in Fig. (5.09) could not be considered entirely accurate for audience areas other than those for which they were measured as the absorption would vary with plan area of the seating bloc.

However the difference made to the total absorption of a seating bloc would be negligible so that the corrections in Fig. (5.09) would give sufficient accuracy for all practical purposes.

No correction should be made for the front row when protected by a solid balcony front nor for the rear edge when solid seat backs are used.

5.53 Edge Diffraction Effect

The results clearly show the validity of Eq. (5.02) as a means of predicting the absorption coefficient of a material. However there appears to be no theoretical way of assessing the effect of the degree of diffusity of the sound field on the absorption of a material.

The most accurate way of establishing this within the present state of knowledge is to simulate the degree of diffusion (approx.) that is 'normally' found in auditoria and measuring the resulting absorption. This can only be carried out successfully in a model test.

The results given in Figs. (5.13,15,17,19) and (5.21-24)
allow the prediction of audience absorption for a 'typical' Australian audience on unupholstered seating in terms of the perimeter per unit area and seating rake of individual seating blocs.

5.541 Seating Rake

The absorption coefficient of an audience bloc, all else being equal, varies directly with the seating rake. The results for four conditions of floor rake are given i.e. steps of 0', 0.5', 1.0' and 1.5'.

5.542 Selective Low Frequency Absorption

Extra low frequency absorption was caused by vertical resonances between seating rows. Equations (5.07 and 5.08) gave the theoretical basis for such absorption which was significant when the number of rows exceeded four.

5.443 Absorption Due to High Energy Region in the Vicinity of Hard Surfaces:

Corrections for this phenomena were considered unnecessary. An audience for this purpose could not be considered as a homogeneous absorbing material but rather as a geometrically complex absorbing arrangement.
SECTION 6.

6.0 PRACTICAL APPLICATION OF RESULTS

The foregoing chapters have shown that provision for audience absorption in a design is not simply a matter of applying a frequency dependent constant to the entire seating area with corrections for edges only. Although this may be satisfactory in the initial design stages, a more detailed knowledge of the seating layout is required for greater accuracy.

6.1 Method of Calculating Audience Absorption

The variables involved in the calculation of audience absorption are

(a) Frequency

(b) Dress of Auditors

(c) Type of Seating

(d) Seating Density

(e) Perimeter per unit area of Seating Blocs (E)

(f) Seating Rake

(g) Edge Absorption Corrections

(h) Selective low frequency absorption.

(a) Frequency

Sound Absorption is frequency dependent for all porous
type absorbing materials of which an audience is one. Hence the whole of the relevant spectrum must be examined. From 125Hz to 4KHz is generally considered sufficient for all practical purposes.

(b) Dress of Auditors

Section 4.6 discussed the dependence of audience absorption on the amount of clothing worn. All results expressed in this work were derived from a model of a 'typical' Australian auditor as defined in Section 4.6.

(c) Type of Seating

All results here-in are for an audience on unupholstered seating. The use of upholstered seating is often desirable and/or necessary to lessen the difference between the empty auditorium and the various conditions of occupancy which may arise.

However this work was restricted to unupholstered seating to obtain data for the design of multi-purpose auditoria so often encountered where hard, removable type seating is commonly used.

(d) Seating Density

Section 5.1 discussed the effect of seating density on absorption coefficient and showed this to be constant for seating densities normally found in auditoria, churches, lecture halls etc. Lower densities should be considered special cases and the required absorption coefficient proportionally altered in accordance with Fig. (5.03) which
gives the reduction in coefficient from the constant value of approx. \(0.155\text{p/ft}^2\) (\(1.66\text{p/m}^2\)) or \(6.5\text{ft}^2/\text{p}\), down to \(0.09\text{p/ft}^2\) (\(0.95\text{p/m}^2\)) or \(11.1\text{ft}^2/\text{p}\) for audience blocs having an \(E\) of 0.19.

All results for design purposes lie within the constant range (i.e. audience density greater than \(0.155\text{p/ft}^2\)).

Having eliminated Dress, Seating Type and Seating Density as variables, there remain the most common variables of, (e) Size of seating bloc, expressed in terms of perimeter per unit area (\(E\)), and (f) Seating Rake.

Figs. (5.21-5.24) express absorption coefficient as a function of frequency, \(E\), and seating rake for design purposes. The selective low frequency attenuation was included in these graphs with a levelling off at \(E=1.1\). This figure was only approximate and attempted to allow for this phenomena which became evident with 3 or 4 rows of audience and increased until approx. 15 rows at which it became fairly constant. An audience bloc 60ft (19m) wide by 15 rows deep has an \(E\) of approx. 1.1 and for all practical purposes should provide sufficient accuracy in calculations. It is this allowance which caused the inverse slope of the 125Hz regression line. For design purposes the size of seating blocs can be determined from the seating layout and, depending on the type of seating, are often controlled in width by access requirements laid down by local By-Laws. Similarly the relevant seating rake can be determined from the design drawings.
Section 5.2 showed that area corrections can be made to each seating bloc for edge absorption. The strip widths to be added were set out in Section 5.24, Fig. (5.09).

Seating blocs which are separated only by aisles of approx 3.0ft, (1.92m) in width should, after edge correction, be considered as one area for the purpose of determining E and consequently the absorption coefficient.

For all practical purposes aisles, either side or centre, of approx 3.0' to 4.0' (0.92 to 1.22m) in width may simply be assumed to be part of the audience area except for the calculation of E for which the side, rear and front aisles are omitted. However the extreme front and rear aisles of an audience bloc, providing they are not shielded by balcony fronts or solid seat backs, require an area correction of only 1.75' (0.54m) strip width. For greater accuracy, 4.0ft wide aisles should be reduced in area by 25%.

For design purposes, \[ E = \frac{\text{actual perimeter of bloc}}{\text{plan area of bloc}} \] \hspace{1cm} \ldots(6.01)

where an Audience Bloc is defined as a continuous area of audience separated only by internal aisles of approx. 3.0' in width. The Bloc area includes the internal aisles but not the perimeter aisles.

Total absorption of an audience Bloc is then equal to

\[ A_T = \alpha_E \times S \] \hspace{1cm} \ldots(6.02)
when \( \alpha \) is the absorption coefficient relevant to the particular combination of \( \alpha \) and floor rake, and \( S \) is the block area plus the area corrections for perimeter aisles.

6.2 COMPARISON BETWEEN MEASURED AND CALCULATED RESULTS

The Eyring equation Eq. (1.02) was used to compare the calculated audience absorption with that actually measured in six auditoria. The data for three of the auditoria were obtained from Greenslade (54) and represent typical Australian conditions. Data for the remaining three was obtained from Beranek (29). In all six cases the seating were unupholstered.

Before the Eyring formula could be utilised, a decision had to be made regarding the factors \( V \) = Volume and \( S \) = Total Surface Area.

Van Raalton (40) suggested that for better correlation between calculated and measured results concerning audiences, a datum of 0.8m (2.7') above the floor should be taken when calculating volume.

Meyer et.al. (36) suggested a datum of 0.6m (2.02') but did not use it in his own calculations.

As the term \( V \) implies the enclosed air volume of the room in which the sound energy is propagated and in the absence of any theoretical basis for the above corrections, the volumes used in the following calculation were the actual volumes of the hall in the empty and occupied conditions, i.e. the actual volume of the audience was removed based on
an average value of $3.2\text{ft}^3$ ($0.088\text{m}^3$) per person and $1.0\text{ft}^3$ ($0.035\text{m}^3$) for the seat. Similarly the value of $S$ for the empty condition included the surface area of the seat at $10\text{ft}^2$ ($0.93\text{m}^2$) and for the occupied condition on area of $15\text{ft}^2$ ($1.35\text{m}^2$) for a seated person.

Hence the terms:

\begin{align*}
V_e &= \text{Volume Empty} \\
V_o &= \text{Volume Occupied} \\
S_e &= \text{Total Surface Area Empty} \\
S_o &= \text{Total Surface Area Occupied}
\end{align*}

Whilst the Eyring formula requires an adjustment for volume for occupied and empty conditions it need not necessarily be simply a matter of calculating actual volume. However it seems more reasonable to relate the change in volume to something which is physically measureable than to an arbitrary datum.

Comparison of results from calculations in which the above allowances were made for both $V$ and $S$ against results from those in which only the uncorrected values of $V$ and $S$ were used showed that the former condition gave better correlation between the data measured in the subject hall and that predicted from tables $5.21$ to $5.24$. Hence the method using these corrections was adopted for the following comparative calculations.
The following Figs. set out the calculations of audience absorption used to assess the accuracy of the data resulting from the model analysis.

Fig. 6.02a Castelmaine Town Hall, Victoria
Fig. 6.03a Swan Hill Town Hall, Victoria
Fig. 6.04a Maryborough Town Hall, Victoria
Fig. 6.05 Boston Symphony Hall
Fig. 6.06 Baltimore Lyric Theatre
Fig. 6.07 Vienna, Grosser Musikvereinssaal.

The absorption coefficients for an audience on unupholstered seating as published by Kath and Kuhl\(^{(33)}\) were also plotted for comparison with the 3 Australian examples.

With minor exceptions the measured audience absorption and that calculated by the proposed method correlated well. The most noticeable deviations occurred in the low frequency bands of 125 and 250 Hz. These discrepancies could be due to (a) Inaccuracies in the field measurements which would be more prevalent with low frequencies. The number of readings taken in the occupied condition was usually limited as audience co-operation could not be obtained for sufficiently long periods to obtain a detailed survey.

(b) Incorrect field measuring positions. The ideal measuring position is just above audience head level. If the measuring position is higher the selective low frequency attenuation will have
decreased until at 15 feet it no longer registers.

See Section (5.5).

As these discrepancies are only obvious in the three halls taken from Beranek\(^{(29)}\) in which there was no record of measuring positions, either of the above reasons are possible.

The first three halls were however surveyed at the correct measuring heights and in those the correlation was also good at low frequencies.

It was of interest to compare the prediction of audience absorption using Kath and Kuhl's data which were based on a frequency dependent constant (with corrections) to be applied to the audience area regardless of its configuration, slope etc. In using this data, the same allowances were made for absorption due to seating in the unoccupied room as were made in the proposed method. These are set out in Fig. (6.01).

Comparison of Swan Hill Town Hall Fig. (6.02) and Castlemaine Town Hall Fig. (6.01) show the inaccuracy which can result from the application of a frequency dependent constant to all audience areas.

Both Halls exhibited approx. the same audience absorption at mid frequencies and this correlated well with the data from the proposed method. The prediction from Kath and Kuhl's data gave the audience absorption at 2KHz as being 37\% too high for Castlemaine and 60\% for Swan Hill.
Even though it is probable that Kath and Kuhl's data was too high for Australian conditions for the reasons discussed in Section 2.5, this does not account for the 23% difference between the two predictions. This can only be due to not taking all of the variables into account.

A variation of 23% at 2KHz for Castlemaine Town Hall would cause an error of approx. 0.14sec. in the audience absorption apart from any expected error in such calculations.

However it was difficult to ascertain the extent to which Kath and Kuhl's data may have been too high for Australian conditions because the application of the proposed method to situations outside of Australia i.e. Vienna, Baltimore and Boston, also gave acceptable accuracy of prediction when compared with data taken from Beranek\(^{29}\).

The data for orchestra absorption used in the following calculations was based on that given in Fig 6 of the paper by Kath and Kuhl\(^{33}\) measured for 58 musicians in unupholstered chairs in a 'non-diffuse' sound field. These figures are expressed as area coefficients in Fig. 6.01.
### Absorption Coefficient $\alpha_{Eyr}$

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>125</th>
<th>160</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
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</thead>
<tbody>
<tr>
<td>Audience on unupholstered seats Fig. 5. of Kath &amp; Kuhl(33)</td>
<td>.13</td>
<td>.19</td>
<td>.27</td>
<td>.36</td>
<td>.48</td>
<td>.50</td>
<td>.48</td>
</tr>
<tr>
<td>Contribution to audience absorption by unupholstered chairs when occupied</td>
<td>.01</td>
<td>.02</td>
<td>.02</td>
<td>.03</td>
<td>.04</td>
<td>.05</td>
<td>.06</td>
</tr>
<tr>
<td>Absorption of an orchestra on unupholstered chairs based on 12ft$^2$/person (1.1m$^2$/p) from Kath &amp; Kuhl(33) Fig. 6. (Expressed as $\alpha_{Eyr}$)</td>
<td>.14</td>
<td>.22</td>
<td>.43</td>
<td>.79</td>
<td>.86</td>
<td>.78</td>
<td>.70</td>
</tr>
</tbody>
</table>

**FIG. 6.01**

Data on chair and orchestra absorption
Fig. 6.01a. Castlemaine Town Hall.

Fig. 6.01b. Maryborough Town Hall.
SECTION

PLAN
SCALE: 1" = 32 1/2" 0"

SWAN HILL TOWN HALL
FIG. 6.01C.
Comparison of measured and calculated audience absorption

- $V_e = 90800\text{ft}^3$  
  Measured in auditoria ($\geq 200$)

- $V_o = 88020\text{ft}^3$  
  Calculated from new data ($t45$)

- $S_e = 24000\text{ft}^2$  
  Calculated from Kath & Kuhl ($33$)

- $S_o = 28770\text{ft}^2$
<table>
<thead>
<tr>
<th>Bloc Location</th>
<th>Data on individual audience blocs</th>
<th>Centre of frequency band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{ft^2}$</td>
<td>$P_{ft}$</td>
</tr>
<tr>
<td>Stalls (flat)</td>
<td>3740</td>
<td>258</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balcony (12&quot; risers)</td>
<td>750</td>
<td>122</td>
</tr>
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<td></td>
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<tr>
<td>Orchestra</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total absorption calculated</td>
<td>$\sum A$</td>
<td>1012</td>
</tr>
<tr>
<td>Total absorption measured in hall</td>
<td>$\sum A$</td>
<td>979</td>
</tr>
</tbody>
</table>

FIG. 6.02b
Castlemaine Town Hall—audience absorption calculations

N.B. Absorption coefficients corrected for seat absorption per Fig. 6.01.
Comparison of measured and calculated audience absorption

V 149000 ft$^3$  Measured in auditoria
V$^e$ 145850 ft$^3$  calculated from new data(257) (33)
S$^o$ 37920 ft$^2$  calculated from Kath & Kuhl
S$^e$ 43350 ft$^2$  

FIG. 6.03a. Swan Hill Town Hall
<table>
<thead>
<tr>
<th>Bloc Location</th>
<th>Data on individual audience blocs</th>
<th>Centre of frequency band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( S_{ft^2} )</td>
<td>( P_{ft} )</td>
</tr>
<tr>
<td>Stalls (flat)</td>
<td>2972</td>
<td>252</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balcony (18&quot; risers)</td>
<td>2739</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orchestra</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total absorption calculated</td>
<td>( \Sigma A_T )</td>
<td>1437</td>
</tr>
<tr>
<td>Total absorption measured in hall</td>
<td>( \Sigma A )</td>
<td>1418</td>
</tr>
</tbody>
</table>

**FIG. 6.03b**

Swan Hill Town Hall- audience absorption calculations  
N.B. Absorption coefficients corrected for seat absorption per Fig. 6.01
FIG 6.04a. Maryborough Town Hall
Comparison of measured and calculated audience absorption

- $V_e = 63980ft^3$  \(\times\) Measured in auditoria (± 5% ± 15%)
- $V_o = 61320ft^3$  \(\circ\) calculated from new data (33)
- $S_o = 18800ft^2$  \(\triangle\) calculated from Kath & Kuhl (33)
- $S_e = 21400ft^2$

Frequency (Hz)
<table>
<thead>
<tr>
<th>Bloc Location</th>
<th>Data on individual audience blocs</th>
<th>Centre of frequency band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{ft^2}$</td>
<td>$P_{ft}$</td>
</tr>
<tr>
<td>Stalls (flat)</td>
<td>1965</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balcony A (12&quot; risers)</td>
<td>760</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balcony B 12&quot; risers(2off)</td>
<td>270</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orchestra</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total absorption calculated</td>
<td>$\sum A_{\text{tot.}}$</td>
<td>726</td>
</tr>
<tr>
<td>Total absorption measured in hall</td>
<td>$\sum A_{\text{tot.}}$</td>
<td>646</td>
</tr>
</tbody>
</table>

FIG. 6.04b
Maryborough Town Hall-audience absorption calculations

N.B. Absorption coefficients corrected for seat absorption per Fig. 6.01
FIG. 6.05 Boston Symphony Hall
Comparison of measured and calculated audience absorption

\[ V_e = 662000 \text{ft}^3 \]  
\[ V_o = 651000 \text{ft}^3 \]  
\[ S = 78000 \text{ft}^2 \]  
\[ S_o = 118000 \text{ft}^2 \]

- Measured in auditoria
- Calculated from new data (±15%)
FIG. 6.06  Baltimore Lyric Theatre.

Comparison of measured and calculated audience absorption.

$V_e = 744000 \text{ft}^3$  x Measured in auditoria
$V_e = 732000 \text{ft}^3$  o Calculated from new data (+160)
$S_e = 88000 \text{ft}^2$
$S_e = 129000 \text{ft}^2$
FIG. 6.07 Vienna Grosser Musikvereinssaal

$V_e = 530000 \text{ft}^3$  × Measured in auditoria
$V_o = 522300 \text{ft}^3$  ○ calculated from new data (±90)
$S_e = 66000 \text{ft}^2$
$S_o = 92000 \text{ft}^2$
6.3 CONCLUSION

The foregoing comparison between audience absorption actually measured in the respective auditoria and that calculated from data given in Figs. 5.21 to 5.24 show that a fairly accurate prediction of audience absorption is possible when all variables are taken into account.

The variations, particularly at mid and high frequencies, resulting from the use of a frequency dependent constant can cause considerable inaccuracies as shown in Section 6.2. The resulting slight complication to calculations made at the design stage is apparently necessary if an acceptable order of accuracy is to be obtained.
In acoustics as in many other fields, there is a convincing case for the application of scale model techniques. Whilst they have been generally used for the empirical checking of auditoria designs before committing them to construction, their greatest potential lies in the ability to provide a ready and inexpensive tool for the analysis of aspects of a sound field hitherto not undertaken largely for economic reasons. Such an example is the work reported in this thesis on the effects of varying the floor rake. A full size test environment for such controlled tests would have been economically prohibitive not to mention the practical difficulty in securing the necessary test audience for the considerable time required.

Having derived the design data set out in Figs. 5.21 to 5.24 and established that it offers a reasonable degree of accuracy, the techniques used in this experimental work should now be applied to establishing similar data for an audience on upholstered seating. This has inherent difficulties in that chairs used in such tests would have to be categorised into a pre-determined number of groups denoting the degree of absorption each type exhibited. Data on audience absorption on each type of chair could then be obtained. However for this method to work effectively,
chair manufacturers would have to categorise their chairs accordingly.

A note of caution is required however when using techniques specified by others. An example was the model auditor used in this work. Had the specification for such a model been taken from work by others, the results obtained would not have been those for a typical Australian audience. There proved to be sufficient difference between measurements made on a typical Australian audience and those quoted by other sources to require the development of the new model. This model may, however, be used for experimental work in acoustics where the normal dress is the same as that outlined for an 'average' clad Australian.

Finally, a factor which continually arose throughout this work was just how should one measure a non-diffuse sound field. This is not a new problem and much has been written about it, but it remains unresolved and a problem basic to acoustics.

There is still no valid theoretical basis for predicting the detailed properties of a ground field under all possible conditions of excitation and at any position within it. If there was one it might well be too complex to have any practical value.
There is, therefore, considerable scope for work to be carried out in this field which was only touched upon in this thesis. Again model techniques offer a convenient and accurate way of carrying out controlled tests on this basic aspect of acoustics.
APPENDIX 1

SAMPLE CALCULATIONS RELATING TO SECTION 4.5:
Comparison of Reverberation Times

(a) Model B empty using the Eyring Formula

\[
RT = \frac{K \cdot V \cdot \cdot (1 - \alpha)}{-S \log_{10}(1 - \alpha) + 4mV} \quad \ldots (1.2)
\]

\[
(m \ (8KHz) = 0.0034, \ from \ ref. \ 51)
\]

\[
RT = \frac{0.0212 \times 13.3}{-37.54 \log_{10}(1 - 0.02) + 4 \times 0.0034 \times 13.3}
\]

\[
\frac{0.282}{-(37.54 \times 0.0088) + 0.18}
\]

\[
RT_E = 0.55 \text{ Sec}
\]

(b) Model B, with sample in place using Eyring formula

\[
\bar{d} = \frac{(32.77 \times 0.02) + (3.17 \times 1.6)}{35.94}
\]

\[
= 0.0324 \text{ Sab}
\]

\[
RT = \frac{0.0212 \times 12.5}{-35.94 \log(1 - 0.0324) + 0.17}
\]

\[
RT_E = 0.382 \text{ Sec}
\]
(c) Model B, condition as for calculation (b) but

Using Fitzroy Eyring formula

\[
RT = \frac{X}{S} \left( \frac{C.V.}{-S \log(1-\bar{a}_x)+4mV} \right) + \frac{Y}{S} \left( \frac{C.V.}{-S \log(1-\bar{a}_y)+4mV} \right) + \frac{Z}{S} \left( \frac{C.V.}{-S \log(1-\bar{a}_z)+4mV} \right) \quad \ldots(1.3)
\]

\[
= \frac{10.6}{35.94} \left( \frac{.0212 \times 12.5}{-35.94 \log(1-.02)+.18} \right)
\]

\[
+ \frac{6.34}{35.94} \left( \frac{.0212 \times 12.5}{-35.94 \log(1-.09)+.18} \right)
\]

\[
+ \frac{19.0}{35.94} \left( \frac{.0212 \times 12.5}{-35.94 \log(1-.02)+.18} \right)
\]

\[
= \frac{.816}{(35.94 \times .0088)+ .18}
\]

\[
+ .176 \left( \frac{.265}{(35.94 \times .041)+ .18} \right)
\]

\[
= (816 \times .534) + (.176 \times .16)
\]

\[
= .435 + .176
\]

\[
RT_F = 0.611 \text{ Sec.}
\]
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