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# Variation of the Reverberation Time of Places of Public Assembly with Audience Size

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ABSTRACT

This paper addresses an issue relevant in the first stage of design, namely, the mathematical relationship between the volume of a hall, the size of the audience and the reverberation time required to conform with the hall's acoustical needs. The practical formulae derived from the theory, which is based on the earlier findings of Beranek and Kosten, are very useful for the prediction of the mid frequency reverberation time when the volume and the audience size are known. In addition, these practical formulae may be used in the early design phase to find the optimum hall volume given the audience size and the reverberation time required to conform with the hall's acoustic needs. If the hall under study is not a concert hall but an opera hall, it is necessary to adjust the hall's volume for the absorptive capacity of the audience seated in boxes.

## 1. INTRODUCTION

Current practitioners in the first stage of hall acoustical design continue using, as in olden times, the rule-of-thumb numbers that relate the hall's volume to the total number of seats in the hall.

This practice suggests that the important findings of Beranek[1,2,3] and Kosten[4] regarding the relationship between a hall's volume, the audience size and the reverberation time required to meet the hall's acoustical needs either have not been adequately understood or have not been adequately put into practice. Therefore, further research is needed to make the findings of Beranek and Kosten more usable. In this paper a theoretical construct is proposed which tries to complement the studies of the above acoustical pioneers and offers experimental findings based on acoustical practice.

In addition, there has been no answer as yet to the question asked by Kosten[5] regarding the relation between the reverberation time and the audience size in opera halls, "what to do with the volume and seated area of balconies such as in La Scala of Milan and the Royal Albert Hall?".

It is proposed that the results described in this paper, obtained by experimental approximation, be accepted as heuristic formulae as is the case with most practical engineering expressions. These results should answer the relationship between volume, audience size and reverberation time, for halls with no other absorption than the seated audience at average frequencies of 500 to 1000 Hz.

However, as Kosten[6] has indicated, there are two types of distribution of seated audiences. One type of distribution (as found in concert halls) has most of the audience seated on the main floor and, at times, has a very small audience seated in shallow balconies situated a substantial distance from the ceiling. There are no box seats. This is the "normal" case as depicted in Figure 1.

The second type of distribution (as found in opera houses) has part of the audience seated on the main floor but a large part of the audience sits in balconies that occupy several levels in the back of the hall. This is the "general" case depicted in Figure 2. In this case, the hall walls consist of absorbing surfaces (audience openings) and sound reflecting surfaces (such as the front of balconies and remaining walls).

To switch from the "general" case to the "normal" case it is only necessary to cover the audience openings with walls.

Regardless of the type of distributions of seated audiences, it is necessary to study the effect produced by occupied seats on reverberation.

To this effect, the optimal reverberation time required for various hall functions is reviewed before a general case (opera house) theory is developed. The normal case (concert hall) theory can easily be derived from the general case theory.

## 2. OPTIMUM REVERBERATION TIME

Many acoustic engineers and consultants[7–12] have established and used the criterion of optimum reverberation time as a function of the hall's volume and the hall's function. This criterion is generally referred to as the medium value reverberation time, described as $\mathbf{T}_{MID}$, for frequencies of 500 and 1000 Hz for halls occupied by an audience.

Following are formulae that express $\mathbf{T}_{MID}$ as a function of volume and use. They have been obtained by a power curve fit from the graphs developed by Cremer.[7]

**Concert Halls**

$\mathbf{T}_{MID}$ **optimum** maximum $= 0.60 \,.\, V^{0.1325}$
$\mathbf{T}_{MID}$ **optimum** minimum $= 0.4245 \,.\, V^{0.1331}$

**Opera Halls**

$\mathbf{T}_{MID}$ **optimum** maximum $= 0.509 \,.\, V^{0.1335}$
$\mathbf{T}_{MID}$ **optimum** minimum $= 0.396 \,.\, V^{0.1273}$

**Speech Halls**

$\mathbf{T}_{MID}$ **optimum** maximum $= 0.368 \,.\, V^{0.1505}$
$\mathbf{T}_{MID}$ **optimum** minimum $= 0.264 \,.\, V^{0.1394}$

The specification of the optimum reverberation time for each hall according to its use is essential during the design phase in order to obtain, besides the appropriate volume, the desirable acoustic qualities of a hall such as: clarity, definition and intelligibility, etc.

Therefore, in the first phase of the design, when aesthetic motives and acoustic imperatives are considered it is essential to specify the hall's volume as a function of the designed optimum $\mathbf{T}_{MID}$ and the desired audience size.

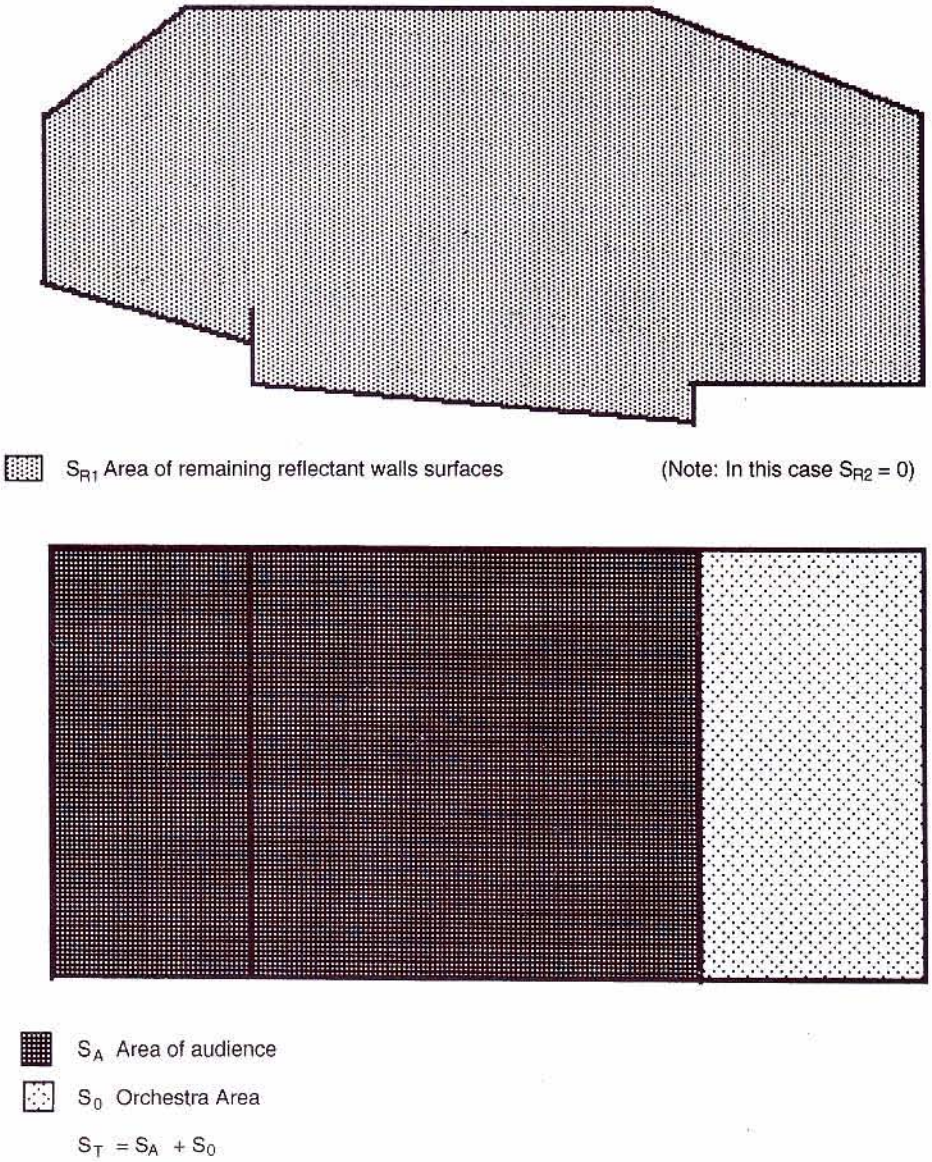


**Figure 1.** Representation of the normal case.

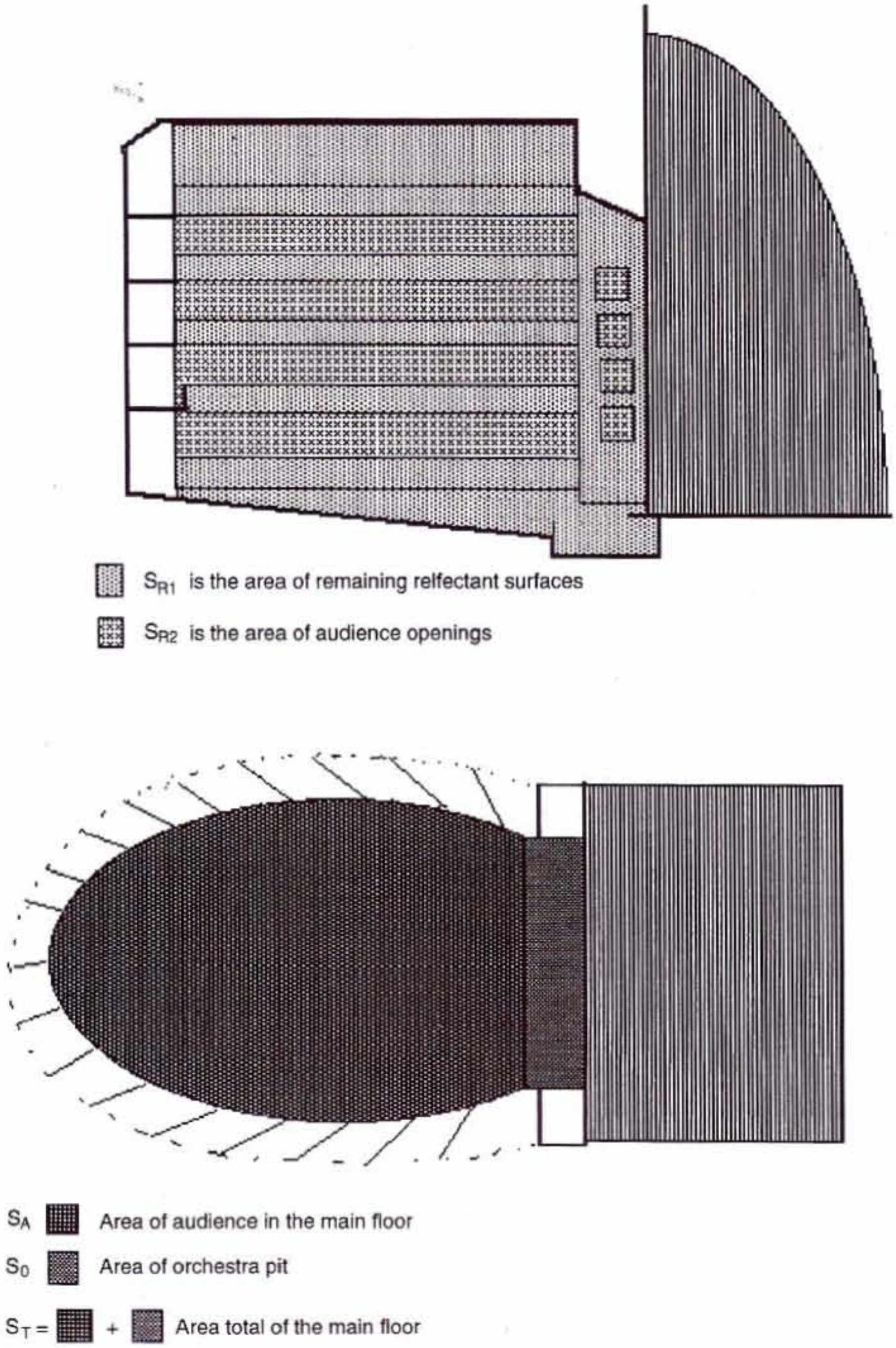


**Figure 2.** Representation of the general case.

## 3. APPROACH TO THE THEORY

Let us imagine a hall similar to the description of the general case (opera halls). Looking at the hall from the inside, the boxes are part of the walls. Thus, the wall area consists of the audience openings $S_{R2}$ and the remaining area $S_{R1}$, the front of the boxes, the sides of the hall and the ceiling. In the normal case $S_{R2} = 0$.

Let us suppose now that the medium reverberation time $\mathbf{T_{MID}}$ for an occupied hall, according to Kosten[4], is:

$$T_{MID} = 0.162\ V/S_T\ \alpha_{eqMID} \tag{1}$$

where:

$$\alpha_{eqMID} = \alpha_T + (S_{R1}/S_T)\ \alpha_{R1} + (S_{R2}/S_T)\ \alpha_{R2} \tag{2}$$

which is the average equivalent absorption coefficient of the seated area for the 500 and 1000 Hz frequencies.

V is the hall's total air volume, including the balconies (per Knudsen[12], the stage box is not included);

$S_T$ is the total floor area, that includes the audience area of the stall seats (main floor) $S_A$, and the orchestra pit $S_o$ (per Beranek and Kosten, the main floor seats area include aisles no wider than 1.5 metres);

$\alpha_T$ is the absorption coefficient of the seated area*;

$\alpha_{R1}$ is the absorption coefficient of the remaining surface areas (walls and ceiling), which are opaque and reflective*;

$\alpha_{R2}$ is the absorption coefficient of the opening area of the boxes, whose area will coincide practically with the area occupied by the seated audience in the balconies*.

Denoting the ratio between the sum of the audience openings $S_{R2}$ and the total area $S_T$ as $\beta$ ($\beta = (S_{R2}/S_T)$):

For the normal case (concert halls), as the audience openings are eliminated, $\beta = 0$. Then V will be the air volume of the enclosure (including the orchestra area), $S_{R1}$ will be the total remaining surface areas, $S_T$ will be the sum of audience area $S_A$ (audience area on main floor and audience area on balconies) and orchestra area, $S_o$.

For the general case, assuming that the audience seating absorbs most of the sound that enters into the balconies, or that $\alpha_{R2} \cong \alpha_T$, the following expression can be derived from (2):

$$\alpha_{eqMID} = \alpha_T\ (1 + \beta) + (S_{R1}/S_T)\ \alpha_{R1} \tag{3}$$

For the normal case, $\beta = 0$ and therefore:

$$\alpha_{eqMID} = \alpha_T + (S_{R1}/S_T)\ \alpha_{R1} \tag{3b}$$

*Average value of 500 and 1000 Hz frequencies.

If $\alpha_T$ is written as a function of the number of people n which occupy seats (with values of n = 0 for a hall without audience, and n = N for a completely full hall) and if the fact is taken into account that the audience introduces an absorption increment $\alpha_s$ over empty seats, and that this absorption increment is increased 10% through the "edge effect" (Beranek[3]), then:

$$\alpha_T = \alpha_{T0} + n\,(S_A/N)\,(1/S_T)\,.\,1.1\,\alpha_s \tag{4}$$

where $\alpha_{T0}$ is the absorption coefficient of the unoccupied seating area.

If Equation (3) is expressed as function of this new $\alpha_T$, then:

$$\alpha_{eqMID} = \alpha_{T0}\,(1 + \beta) + (1 + B)\,n\,(S_A/N)\,(1/S_T)\,.\,1.1\,\alpha_s + (S_{R1}/S_T)\,\alpha_{R1} \tag{5}$$

Therefore, from (1) and (5) the following expression can be obtained for reverberation time as a function of the number of people n occupying seats:

$$T(n) = k/(k_1 + k_2\,n) \tag{6}$$

where:

$k = 0.162\ V/S_T$

$k_1 = \alpha_{T0}\,(1 + \beta) + (S_{R1}/S_T)\,\alpha_{R1}$

$k_2 = (1 + \beta)\,(S_A/N)\,(1/S_T)\,.\,1.1\,\alpha_s$

Thus, T(0) is the reverberation time of a hall with unoccupied seats and T(N) is the reverberation time of a hall with fully occupied seats.

Through a first order Taylor expansion of the variation of T(n) with respect to n (number of occupied seats) between a hall with unoccupied seats and a hall with fully occupied seats, the following expression can be obtained:

$$T(0) = T(N) + \left[\frac{\delta T(n)}{\delta n}\right]_{n = N}\,.\,(-N) \tag{7}$$

This approximation is justified on the basis that the absorption increment produced by occupied seats over unoccupied seats results in only a slight variation in the reverberation time.

Thus, from expression (6) applied to (7):

$$\Delta T = N\,(k_2/k)\,[T(N)]^2 \tag{8}$$

where

$$\Delta T = T(0) - T(N)$$

If the relative variation of reverberation time produced between an unoccupied hall and a fully occupied one is denoted by $\varepsilon = \Delta T/T(N)$, substituting the values k and $k_2$, given in (6), and by taking into account that $T_{MID} = T(N)$ when all the seats are occupied, then:

$$V/S_A = 6.75 \cdot (\alpha_s/\varepsilon) \cdot (1 + \beta) \cdot \mathbf{T}_{MID} \tag{9}$$

This is the general case (opera house) expression, which relates the hall's volume, the audience size and the reverberation time.

The following expression defines the hall's volume for the normal case, when $\beta = 0$:

$$V/S_A = 6.75\,(\alpha_s/\varepsilon)\mathbf{T}_{MID} \tag{10}$$

The author has found as an experimental value that $(\alpha_s/\varepsilon) \equiv 1.09$, which is justified, in Appendix A, as an average value of twenty two halls described by Beranek[1,3], and also confirmed from long years of practice and research on acoustical design of many types of hall.

Substituting this value, expressions (9) and (10) can be rewritten in a more simplified and useful form as follows:

$$V/S_A = 7.361 \cdot (1 + \beta) \cdot \mathbf{T}_{MID} \tag{11}$$

$$V/S_A = 7.361.\mathbf{T}_{MID} \tag{12}$$

## 4. EXAMPLES OF APPLICATION AND VALIDATION OF THE THEORY

Following are examples of well-known halls and halls designed by the author that show how these relationships may be applied.

### 4.1 Special Case

4.1.1 If it is desired to design a concert hall where the audience occupies an area $S_A$ = 1390 $m^2$ and a reverberation time $T_{MID}$ = 1.8 seconds is required, then applying the expression (12), yields V = 18416.9 $m^3$. This would be a case similar to the acoustically renowned Boston Symphony Hall[1].

4.1.2 The author has designed, as acoustical consultant, with R. Artigues and R. Sanabria, architects, a new Symphony Hall called Auditorium Enric Granados in Lleida, Spain. The volume of this hall is 8000 $m^3$ and the area of audience is $S_A$ = 599 $m^2$. Applying expression (12) a theoretical $T_{MID}$ = 1.81 seconds was obtained. This compares closely with the experimental value of $T_{MID}$ = 1.87 seconds obtained by using Schroeder's impulse method (average of $T_{MID}$ at nine points in the hall). A schematic of the hall is shown in Figure 3.

4.1.3 The Vienna Musikverein Saal has V = 15000 $m^3$ and $S_A$ = 985 $m^2$. From expression (12) the calculated $T_{MID}$ = 2.07 seconds which is very close to the measured value quoted by Beranek[1], $T_{MID}$ = 2.05 seconds.

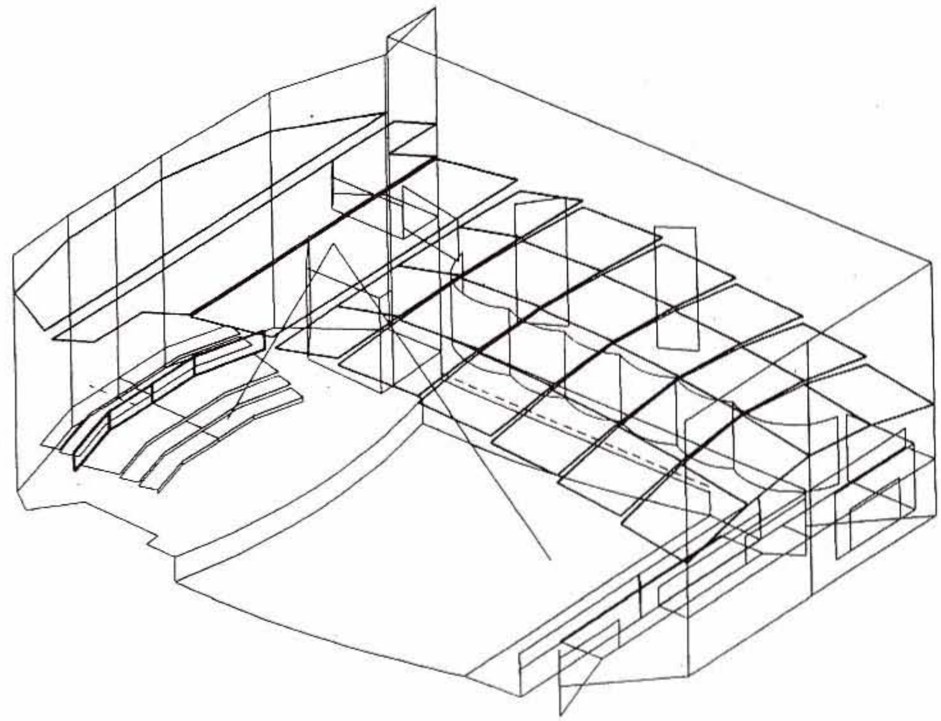

**Figure 3.** The auditorium of Lleida.

4.1.4 The hall La Chaux-de-Fonds in Switzerland has $V = 7870\ m^3$ and $S_A = 650\ m^2$. From expression (12) the calculated $T_{MID} = 1.64$ seconds which is very close to the measured value quoted by Beranek[1], $T_{MID} = 1.71$ seconds.

4.1.5 The author has designed, as acoustical consultant, with Artigues and Sanabria, a multifunctional hall in Sant Cugat, Barcelona (see Figure 4) which is dedicated to symphonic music, opera and theatre. In its symphonic version (with acoustical shell in place), $V = 9386\ m^3$ and $S_A = 558\ m^2$. Thus, the theoretical $T_{MID}$ calculated by (12), in the first stage of design was 2.29. As a result it was decided to put additional absorption on the perimeter area of the ceiling, because there was a slight excess of volume in relation to the audience size, thus a value of $T_{MID} = 1.89$ s was obtained. In the opera version (without the acoustical shell), $V = 7660\ m^3$ and the experimental $T_{MID}$ is 1.43 s.

4.1.6 The Henry and Edsel Ford Auditorium has $V = 17800\ m^3$ and $S_A = 1850\ m^2$. The theoretical $T_{MID} = 1.31$ seconds and the measured value[1] is 1.45 seconds.

4.1.7 The author has designed with P. Riera and J.M. Gutierrez, architects, the Auditorium Lauretià in Sant Julià de Lòria, Andorra (see Figure 5). The volume is $V = 3095\ m^3$

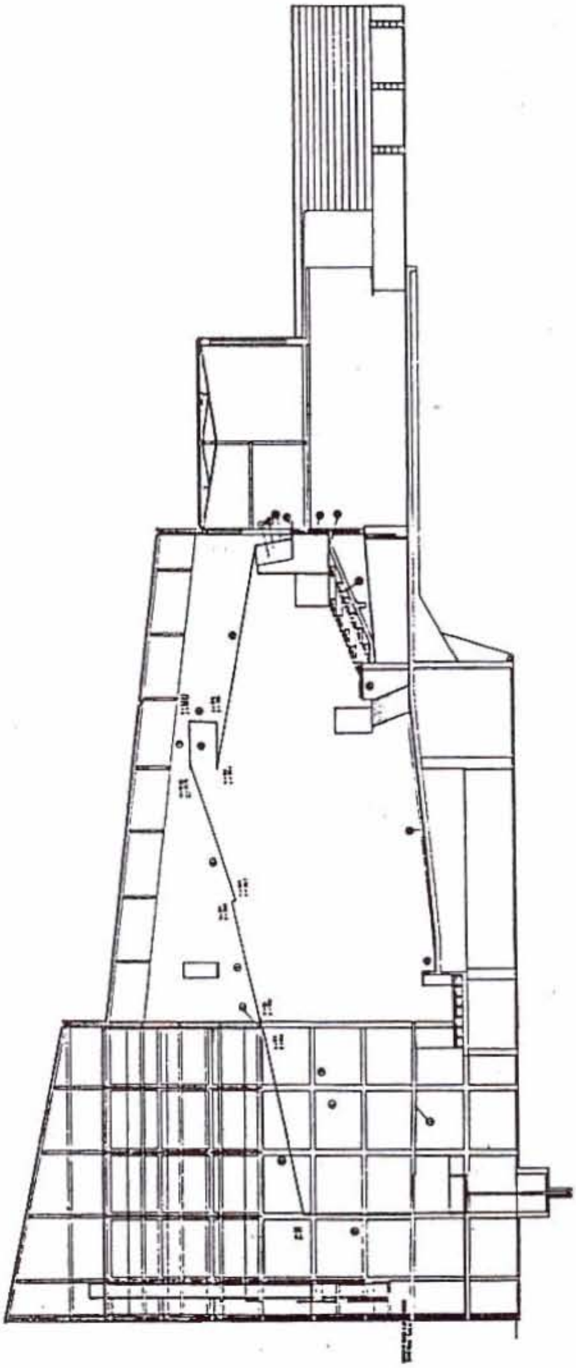

**Figure 4.** The auditorium of Sant Cugat del Valles.

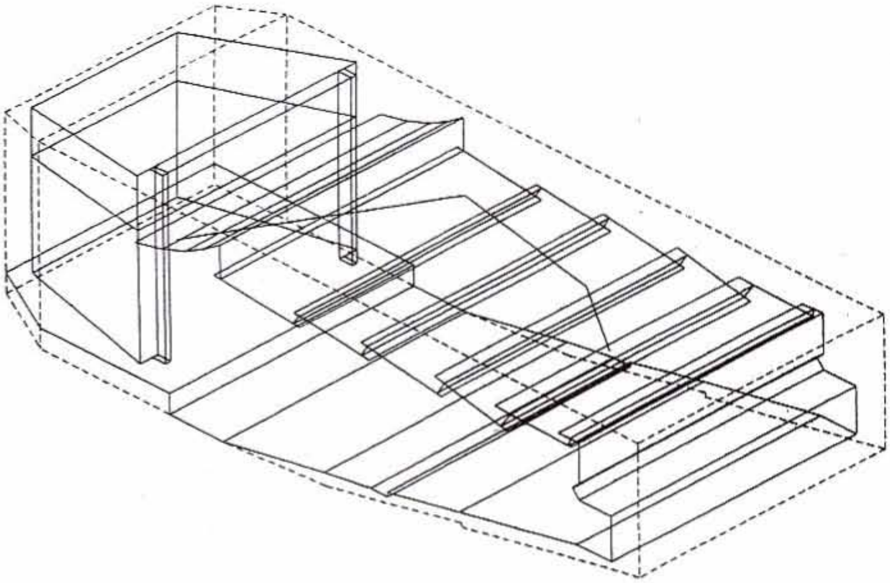

**Figure 5.** Auditorium Lauretià of Sant Julià de Lòria.

and $S_A$ = 300 m$^2$. From expression (13) the theoretical $T_{MID}$ = 1.40 seconds while the experimental $T_{MID}$ = 1.44 seconds.

4.1.8 The Theater, Rochester, New York, has V = 23950 m$^3$ and $S_A$ = 1905 m$^2$, the theoretical $T_{MID}$ calculated by (12) is $T_{MID}$ = 1.71 seconds while the experimental[1] value is $T_{MID}$ = 1.65 seconds.

4.2 The General Case

4.2.1 The Scala of Milan has a volume V = 11245 m$^3$ and $S_A$ = 715 m$^2$, $S_T$ = 1050 m$^2$ and $\beta$ = 0.73, therefore the theoretical $T_{MID}$, calculated by (11), is $T_{MID}$ = 1.23 seconds which compares with the experimental[1] $T_{MID}$ = 1.2 seconds.

4.2.2 The Liceu of Barcelona (now destroyed) had a volume V = 13423 m$^3$ and $S_A$ = 639.64 m$^2$, $S_T$ = 739.6 m$^2$ and $\beta$ = 1.16, therefore the theoretical $T_{MID}$, calculated by (11), is $T_{MID}$ = 1.32 seconds and the experimental value determined was $T_{MID}$ = 1.3 seconds.

5. CONCLUSIONS

The practical formulae derived from the theory expounded above, which is based on the earlier findings of Beranek and Kosten, are most useful for the prediction of the $T_{MID}$ when the volume and the audience size are known. In addition, these practical formulae may be used in the early design phase to find the optimum hall volume given the audience size and the reverberation time required to conform with the hall's acoustic needs. If the hall under study is not a concert hall but an opera hall, it is necessary to adjust the hall's volume for the absorptive capacity of the audience seated in boxes.

After many years of research and professional use, it is the author's view that these formulae are very valuable for determining the necessary volume of a hall at the initial design stage. The simplicity of formulae (11) and (12) does not reflect their value in practical applications. However, their use is better justified from a theoretical point of view than the use of rules of thumb that relate volume with the number of seats. Moreover, these formulae are consistent with Beranek's finding that the relationship between volume and audience size has to be made not through the number of seats but through the area occupied by the seats.

The proposed expressions also provide an answer to Kosten's question: "How do we handle the volume and the box seats area of opera halls such as the Scala of Milan and Royal Albert Hall?".

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## APPENDIX A

In this section, in Table 1, we write the value of $(\alpha_s/\varepsilon)$ calculated from the expression (12) taking the data of twenty two halls analyzed per Beranek[1,3].

**Table 1**
**Data for twenty-two halls (modern shaped, rectangular, wide fan-plan types)**

| Case | $V/S_A$ | $T_{MID}$ | $\alpha_s/\varepsilon$ |
|---|---|---|---|
| Chicago Arie | 11.805 | 1.70 | 1.028 |
| Berlin MHS | 12.973 | 1.65 | 1.164 |
| Stuttgart | 12.308 | 1.62 | 1.125 |
| Cleveland | 12.975 | 1.7 | 1.130 |
| Turku | 12.886 | 1.6 | 1.193 |
| Liverpool | 10.465 | 1.5 | 1.033 |
| London RFH | 11.167 | 1.5 | 1.103 |
| Brussells | 9.615 | 1.4 | 1.017 |
| Buffalo | 9.343 | 1.3 | 1.064 |
| Vienna MVS | 15.22 | 2.05 | 1.099 |
| Cambridge | 11.65 | 1.5 | 1.150 |
| Glasgow | 12.828 | 1.9 | 1.000 |
| Boston | 13.482 | 1.8 | 1.109 |
| Bristol | 11.746 | 1.7 | 1.023 |
| La Chaux de Fonds | 12.107 | 1.7 | 1.055 |
| Basel | 14.189 | 1.7 | 1.236 |
| Zurich | 13.028 | 1.6 | 1.206 |
| Leipzig | 11.712 | 1.55 | 1.119 |
| Lenox | 14.842 | 2.05 | 1.072 |
| Jerusalem | 11.542 | 1.75 | 0.977 |
| Tel Aviv | 12.470 | 1.55 | 1.191 |
| Detroit | 10.340 | 1.55 | 0.988 |
| Average value | | | 1.09 |

This average value of $(\alpha_s/\varepsilon)^{\sim}$ 1.09, is almost equal to the value obtained from the author's experience in practice. Also for these twenty two halls, the average value of So/SA = 0.136, which implies that $\alpha_{eqMID}$ = 1.06, this value being almost identical with that obtained by Kosten.[4]