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by

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General Theory of the Energy Relations in Halls with Asymmetrical Absorption

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SUMMARY
In this paper we describe a method of calculation of the energy relations in halls where the existence of a non-uniform distribution of absorptive material in the room results in a non-diffuse sound field. The cases of halls used for concerts and speech have both been treated in order to derive new energy relations that yield known expressions when applied to a diffuse sound field. The importance of the initial reverberation time corresponding to the first portion of the decay has been verified showing that the main subjective parameters relating to the sound energy are influenced strongly by this portion, which is called the Early Decay Time if it is measured in the first 10 dB of the decay.

1.INTRODUCTION

The classical expression for the total sound-pressure level in a diffuse sound field is given by:

$$L = 10 \log \left[\frac{\rho c}{P_{ref}^2} \left(\frac{W}{4\pi r^2} + \frac{4W}{A} \right) \right] \tag{1}$$

It is obtained adding the pressure of the direct sound to that of the reverberant field, without taking into account the law of the sound growth, or sound buildup, produced in a room when the sound is first established within the hall.

The revised Barron and Lee theory [1] analyzes this topic taking into account this growth phenomena but on the assumption that there is a diffuse sound field, or that the absorption in the hall has a uniform distribution and that this disposition in the hall produces a Sabine space.

In the next sections it is shown how the energy relations of Barron and Lee can be obtained from the analysis of the growth of sound in a room as the complement of the sound decay and new relationships are introduced in an attempt to show the effect of a non-diffuse sound field produced by an asymmetrical distribution of absorption in a room.

2. GROWTH AND DECAY OF THE SOUND FIELD

The relationship between the sound source power W and the average sound energy density, ϵ_o in a steady state is:

$$\epsilon_o = 4\ W/c\ A \qquad (2)$$

Where A is the total absorption of the room: A = S a
a is the average absorption coefficient of the room
S is the total area of the surfaces,
c is the velocity of sound,
T is the reverberation time.

The sound decay, within a certain definite time, after the source has been switched off, is given by:

$$\epsilon(t) = \epsilon_o e^{-Nat} \qquad (3)$$

where:
N is the number of reflections per second:
V the volume of the enclosure

And N is given by N = cS /4V,

The average absorption coefficient of the room **a** is related to the average sound decay rate **D** by the following expression [2,3]:

$$\mathbf{D} = N\ \mathbf{a}\ 10 \log e; \text{ or } \quad \mathbf{a} = \mathbf{D}/N\ 10 \log e \qquad (3bis)$$

Therefore **a** is a false absorption, related to decay rate, called Sabine absorption, that may violate the principle of the conservation of energy, and because of this we call this coefficient an absorption decay coefficient.

In a diffuse sound field we observe only a single slope of the sound level decay which is linear with time or an exponential decay of sound energy.

The concept of a diffuse sound field is a common assumption in room acoustics, but in order to achieve it uniform absorption is required and perhaps also the uniform distribution of the sound energy from the source to the receiver point.

After a time $t > t_d$, where t_d is the time of arrival of the direct sound to a receiver point, after the source has been switched on the energy density of sound at the receiver grows exponentially and is given by:

$$\epsilon(t) = \epsilon_o(1 - e^{-Nat}) \qquad (4)$$

Thus the energy density of the sound field, assumed to be equally distributed, grows exponentially. When the source ceases the sound energy decays exponentially, the growth and the decay being complementary forms of behaviour.

Taking as reference the sound energy density produced at a point in a free-field placed 10 m from the source $\epsilon_{10} = W / c\ 400\pi$, the total sound energy density $\epsilon(t)$ relative to the direct sound at 10 m, is given by:

$$\frac{\epsilon(t)}{\epsilon_{10}} = \frac{\epsilon_d}{\epsilon_{10}} + \frac{\epsilon_i}{\epsilon_{10}} + \frac{\epsilon_f}{\epsilon_{10}} \tag{5}$$

The total sound energy is the sum of the three components:

1) The direct sound: $\epsilon d / \epsilon 10$
2) The early reflections <80 ms: $\epsilon i/\epsilon 10$
3) The late reflections >80 ms: $\epsilon f/\epsilon 10$

We know that $\epsilon d/\epsilon 10$, the direct sound energy, is: $100/r^2$ (6)

Evaluating the early sound energy $\epsilon i/\epsilon_{10}$ from (4) yields:

$$\epsilon i/\epsilon_{10} = \left[\epsilon(t_d + 0.08) - \epsilon(t_d)\right]/\epsilon_{10}$$

$$= \left[\ \epsilon\ (\infty) - \epsilon(t_d) - (\epsilon(\infty) - \epsilon(t_d+0.08))\right]/\epsilon_{10} \tag{7}$$

$$\epsilon i/\epsilon_{10} = 31200\ (T/V)\ e^{-0.04r/T}\ (1 - e^{-1.11/T}) \tag{8}$$

Evaluating the late sound energy from (4) by the same procedure yields:

$$\epsilon f/\epsilon 10 = \left[\epsilon(\infty) - \epsilon(t_d+0.08)\right]/\epsilon 10 \tag{9}$$

$$\epsilon i/\epsilon_{10} = 31200\ (T/V)\ e^{-0.04r/T}\ e^{-1.11/T} \tag{10}$$

Thus the total sound level as derived by Barron and Lee from (5), using (6),(8) and (10), is:

$$Lt(10) = 10 \log\left[\epsilon(t)/\epsilon 10\right] = 10 \log\left[100/r^2 + 31200\ (T/V)e^{-0.04r/T}\right] \tag{11}$$

Therefore it is clear that the classical expression of the total sound, as also the expres-

sion derived by Barron and Lee and also the other energy relations derived by them, may only be true in rooms with diffuse sound fields although the Barron and Lee expressions consider the effect of distance in the reverberant sound components.
Thus we have the situation that the classical theory is inadequate, while the revised theory of Barron and Lee is a reasonable approximation to the actual values, except in halls where the sound field deviates significantly from the diffuse condition.

Rettinger [4] used a similar treatment to that of Barron and Lee for determining the energy relations, but employed a time interval of 62 ms, however he did not consider the effect distance on the reverberant components.

3. ANALYSIS OF THE PROBLEM IN NON-DIFFUSE SOUND HALLS: SOUND DECAY AND GROWTH LAWS

The normal procedure in reverberation measurements is to aim at obtaining a reasonably linear decay throughout a 60 dB fall and relate this slope D to the reverberation time: T=60/D.This situation is realized when there is uniform distribution of absorption, but when the absorption is non-uniform the sound field is not diffuse In this situation it is natural to expect a two-dimensional, or three-dimensional diffuse state, if a large area of high absorption is concentrated on on y one of the surfaces of the room.

Thus in a non-diffuse sound hall, Cremer et al [5], have proposed that the sound energy density ofthe reverberation decay will be composed of a sum of dissimilar exponential functions A plot of the sound level over time no longer leads to a straight line, but instead to a sagging reverberation curve.

Arau [2], has developed, as an approximate method for the calculation of the reverberation time for an asymmetircal distribution of absorption, assuming that the reverberation decay is a curved process This decay is a superposition of a three-contributions as described below.

The first slope is the initial decay A steep gradient is observed at the beginning of the decay, corresponding to a strong direct-sound component. Other steep descents discernible in the first portion are caused by early reflections produced by surfaces near to the receiver point.

This first linear portion of the decay Di is strongly related to the area of maximum absorption of the room (seating area), (see Yegnanarayana & Balachamdran [6]) There is increasing evidence that the initial sound decay rate of the reverberation process is at least as important as the later portions of the reverberation for determining the human perception of the reverberancy of the space.

The second linear portion of the decay **D** of the reverberation curve expresses the average value of the sound decay which is related to the Reverberation Time of the room.

The third linear portion Df is related to the areas of a room with little absorption, however this third portion is frequently not observed because of its low energy and also it is masked by the background noise of the room. However it has been experimentally determined by several researchers such as Meyer and Thiele[7], Meyer, Kuttruff and Lauterborn [8] and Knudsen, Delsasso and Leonard [9].

The curved nature of the reverberation decay plots, in where Di, **D** and Df, are the decay rates of each of the slopes and the absorption coefficients ai, a and af, which are related to the decay rates by the formula (3bis), are shown in figure 1.

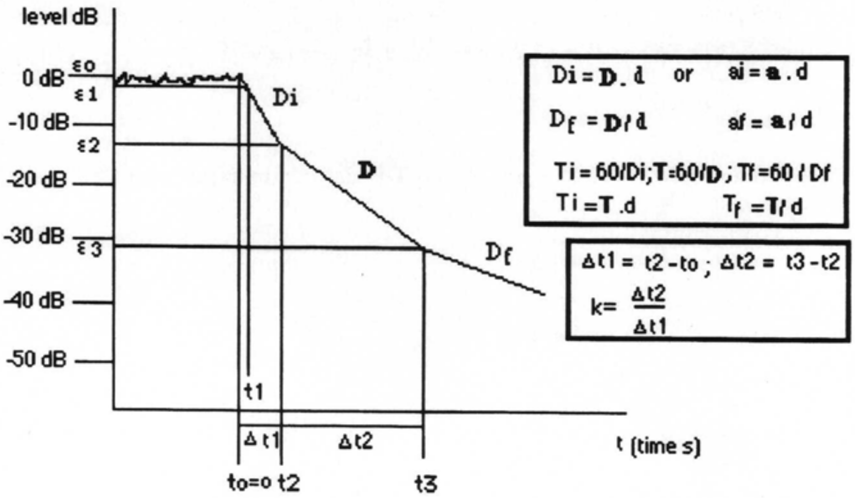

Figure 1: Sound decay with asymmetrical distribution of absorption in the room Di, **D**, and Df, are the decay rates of each slope.

In this curved reverberation process the duration of each individual slope is never known "a priori", because this phenomena is dependent on the relative positions of the source and the microphone and their position relative to the different surfaces of the room, as observed by Knudsen, Delsasso and Leonard [9]. Therefore it is not possible to calculate the values of $\epsilon 0$, $\epsilon 1$, $\epsilon 2$, $\epsilon 3$, although they can be determined experimentally by measurements in a hall.

Therefore the standard procedures for measurements of the RT, measured over the range –5 dB to –35 dB, and the early decay time EDT, measured over the first 10 dB of the decay, which are then both expressed as an equivalent 60 dB reverberation time, may lead to distortion of the reality of the situation as indicated by such clearly different slopes. If one tries to evaluate the reverberation time from such a decay curve, a plot of level over time, according to the standard procedures by fitting a straight line to the decay curve where there is an inflection, the result always depends on the portion of the decay to which one chooses to fit the straight line.

The existence of two or three linear slopes in the sound decay process can generally be observed and first slope corresponds to the early decay time, the second slope corresponds to the reverberation time and the third slope, always negligible, corresponds to the late reverberation.

The sound decay for a non-diffuse sound field resulting from the asymmetrical distribution of absorption disposition, from Arau [2], is given by:

$$\epsilon(t)=\epsilon 1\ \epsilon^{-D_i\, t/10 \log e} + \epsilon 2\ e^{-\mathbf{D}\, t/10 \log e} + \epsilon 3\ e^{-D_f\, t/10 \log e} \tag{12}$$

or

$$\epsilon(t) = \epsilon 1\ e^{-Na_i t} + \epsilon 2\ e^{-Nat} + \epsilon 3\ e^{-Na_f t} \tag{13}$$

where

Di = **D**.d and Df= **D** / d; **D** = 60 / **T** and **T** is defined in expression (26)

a_i= **a**.d and af=**a**/d

and

$$\mathbf{a} = \mathbf{a}_x^{Sx/S}\ \mathbf{a}_x^{Sy/S}\ \mathbf{a}_z^{Sz/S} \tag{14}$$

$$d=\text{antilog}\Big[\Big(\frac{1}{6+\beta}\Big)\ \{(Sx/S)(\log \mathbf{a}_x)^2 + (Sy/S)\ (\log a_y) + (Sz/S)(\log a_z)^2 -$$

$$\big[\ (Sx/S)\ (\log \mathbf{a}_x) + (Sy/S)\ (\log \mathbf{a}_y) + (Sz/S)\ (\log \mathbf{a}_z)]\ \}^2\Big]^{1/2} \tag{15}$$

The absorption coefficients used in this formulae are described in Appendix I
Where d is the dispersion factor of the logarithm-normal distribution modified by a correction term β which can be obtained from experimental observation: $\beta = -5$ to -4 for a non diffusion halls, $\beta = 3$ to -2 for regular diffusion, $\beta = -1$ to 0 for good diffusion and $\beta = -1$ for very good diffusion

With this diffusion coefficient β, introduced here in this article, we consider, by inspection, how the sound energy is distributed from the source to the receiver point taking into account the qualitative nature of the surfaces that define the sound path between these points.

Thus, if for example, a hall with audience in the floor plane, has side walls and ceiling which are reflective and diffuse and is shaped to emphasize the transverse, vertical and longitudinal, reverberant sound, the resulting sound field can be considered diffuse and then $\beta = 0$ or $\beta = 1$. This should be the normal case for a concert hall.

In a similar hall but one having an absorptive ceiling with side walls reflective, then in such enclosure, the rate of decay of sound in the vertical direction is much greater than in the horizontal direction with the coefficient $\beta = -1$ to -3.

If all the boundaries of a hall are absorptive then $\beta = -5$

Therefore the sound growth law is governed by the following expression:

$$\epsilon\ (t)=\epsilon_0 - \left\{\epsilon_1 e^{-D_i t/10 \log e} + \epsilon_2\ e^{-\mathbf{D}t/10\log e} + \epsilon_3\ e^{-D_f t/10\log e}\right\} \tag{16a}$$

$$\epsilon\,(t)=\epsilon_0 \left\{1-(\epsilon_1/\epsilon_0)\, e^{-D_i t/10 \log e} -(\epsilon_2/\epsilon_0)\, e^{-Dt/10\log e} -(\epsilon_3/\epsilon_0) e^{-D_f t/10 \log e}\right\} \quad (16b)$$

or

$$\epsilon(t) = \epsilon 0\left\{1-(\epsilon_1/\epsilon_0)\, e^{-Na_i t} -(\epsilon 2/\epsilon 0)\, e^{-Nat} -(\epsilon_3/\epsilon_0)\, e^{-Na_f t}\right\} \quad (16c)$$

where ϵ_o is sound energy density in steady-state excitation.

In the case of a uniform distribution of absorption, in expressions (16 b) and (16 c):

d = 1
ai = **a** =af
D_i = D = Df
this implies:

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = \epsilon_0 \quad (17)$$

which yields the well-known relationship for a diffuse sound field:

$$\epsilon(t) = e_0\,(1- e^{-Dt/10 \log e})$$

or

$$e(t)=e_0\,(1-e^{-Nat})$$

The following relationships are derived in Appendix 2:

$$(\epsilon_1/\epsilon_0) = 1-(\epsilon_2/\epsilon_0)\left[1+(\epsilon_2/\epsilon_0)^{(k/d)}\right]$$

$$(\epsilon_2/\epsilon_0) = 10^{-Di\Delta t1/10}$$

$$(\epsilon_3/\epsilon_0) = (\epsilon_2/\epsilon_0)^{1+k/d} \quad (18)$$

Thus the level difference between ϵo and ϵ1 is possibly produced by a steep descent at the beginning of the decay, corresponding to a strong direct-sound component

Therefore we can write:

$$\epsilon 0 = \left[1 - \epsilon_1/\epsilon_0\, e^{-D_i t/\log e} - \epsilon_2/\epsilon_0\, e^{-Dt/10 \log e} - \epsilon_3/\epsilon_0\, e^{-D_f t/10\log e}\right] \quad (19)$$

Neglecting the third term as it will be relatively small we have:

≈ 0.98, (l-n) = ϵ_2/ϵ_o=0.02 (implies 20 dB of level difference), ϵ_3/ϵ_o=5 624089.10^{-10}, under this assumption the first term almost 100 % dominant. However in the text we continue on the basis of the first assumption.

In both expressions when T_i = **T** then we obtain the expressions derived by Barron and Lee[1].

In the theoretical analysis the Reverberation Time must be calculated according to the method proposed by Arau [2], taking into account that the absorption must be arranged as the architects draw their plans. Thus it is possible to observe the absorption, for example that of the audience, in two or more sections of the architectural plans when the audience is occupying an inclined surface. In this case the different areas must be added in their respective directions of projection.

$$T=\left[\frac{0.162\ V}{-S.1n(1-\alpha_x)+4mV}\right]^{\frac{S_x}{S}}\left[\frac{0.162\ V}{-S.1n(1-ay)+4mV}\right]^{\frac{S_y}{S}}\left[\frac{0.162\ V}{-S.1n(1-ay)+4mV}\right]^{\frac{S_z}{S}} \quad (26)$$

where is: T_i = **T**/d and T_f = **T.** d; d has been written before in (15) and the operator ln means the natural logarithm on the base e; and a_x, a_y, a_z, are the average absorptivities of each pair of opposite walls. The absorption coefficient are discussed in Appendix 1.

It means that the Reverberation Time of a room is equal to the area-weighted geometric mean of the reverberation periods in each one of the rectangular directions considered. This is as Hope Bagenal suggested [10]. The reverberation consists of three sets of inter-reflections set up between the three pairs of opposite surfaces.

And when the room is analyzed experimentally it is best to introduce the measured values of the Ti (first slope) and **T**(second slope),and the measured values of $\epsilon i/\epsilon o$,i= 1, 2,in expressions (22) and (23), and this must be made in all the formulae that will be found in the remainder of this article.

In the following sections we build upon the simplifying assumptions made for the development of the theory.

Thus from this analysis we will have the following results for the C_{80}, Clarity Index:

$$C_{80} = 10\log\left[\left(\frac{\epsilon d}{\epsilon_{10}}+\frac{\epsilon i}{\epsilon_{10}}\right)/\left(\frac{\epsilon f}{\epsilon_{10}}\right)\right] \quad (27)$$

And for the total sound level Lt(10) relative to the direct sound at 10 m, we have:

$$Lt(10)=10\log\left[100/r^2+31200(\mathbf{T}/V)(n\ e^{-0.04r/Ti}+(1-n)\ e^{-0.04r/\mathbf{T}})\right] \quad (28)$$

From these equations we observe that when the initial Reverberation Time T_i is noticeable lower than the mean Reverberation Time T, then the value of C_{80} is higher and also that the value of $L_t(10)$ is lower, at the same distance r, to that predicted by the revised theory of Barron and Lee. If the value of Ti is greater than **T** then the opposite is observed. The Barron and Lee case is obtained when Ti = T and n=1.

5. DERIVATION OF EXTENDED ENERGY RELATIONS FOR SPEECH ROOMS

In rooms where speech performance is to be considered, two main parameters are important:

1. The Definition
2. The Intelligibility.

Thiele(1953), has proposed the following expression for Definition:

$$D= \frac{\int_{0}^{50\,ms} p^2 dt}{\int_{0\,ms}^{\infty} p^2 d\,t} \,.\, 100\ (\%) \tag{29}$$

For this case the lower limit of integration t = 0, coincides with the arrival of the direct sound at the point of reception.

Thus for a diffuse case, corresponding to a symmetrical distribution of absorption, we have:

$$D(\%) = (\epsilon i/\epsilon_{10})\ .\ 100/(\epsilon f/\epsilon_{10}) \tag{30}$$

We began to analyze the phenomena after the sound has arrived at the point of observation, and so from expression (4) we have:

$$\epsilon i/\epsilon 10 = \left[\epsilon\ (t_d+0.05) - \epsilon(t_d)\right]/\epsilon_{10}$$

$$= \left[\epsilon(\infty) - \epsilon(t_d) - (\epsilon(\infty) - \epsilon(t_d+0.05))\right]/\epsilon_{10}$$

$$\epsilon f/\epsilon_{10} = \left[\epsilon(\infty) - \epsilon(t_d))\right]/\epsilon_{10}$$

Where:

$$\epsilon i/\epsilon_{10} = 31200(T/V)e^{-0.04r/T}(1-e^{-0.069/T}) \tag{31}$$

$$\epsilon f/\epsilon_{10} = 31200(T/V)e^{-0.04r//T}\, e^{-0.069/T} \tag{32}$$

Therefore the result obtained from (30) is:

$$D = \left[e^{0.69/T} - 1\right].100 \tag{33}$$

An analogous expression to (33) was obtained by Rettinger [4] for an interval of 62 ms.

For a non-diffuse case, resulting from an asymmetrical distribution of absorption we have:

$$\epsilon i/\epsilon_{10} = 31200\,(\mathbf{T}/\mathrm{V})\Big(n\, e^{-0.04r/Ti}(1-e^{-0.69/Ti}) + (1\text{-}n)\, e^{-0.04\, r/T}(1-e^{-0.69)/\mathbf{T}})\Big) \tag{34}$$

$$\epsilon f/\epsilon_{10} = 31200\,(\mathbf{T}/\mathrm{V})\,(n\, e^{-0.04r/Ti}\, e^{-0.069/Ti} + (1-n)\, e^{-0.04r/\mathbf{T}}\, e^{-0.69/\mathbf{T}}) \tag{35}$$

Thus the result calculated is:

$$D = \left[\frac{ne^{-0.04\, r/Ti}(1-e^{-0.69/Ti}) + (1-n)\, e^{-0.04\, r/\mathbf{T}}(1-e^{-0.69/\mathbf{T}})}{n\, e^{-0.04\, r/Ti}\, e^{-0.69/Ti}) + (1-n)\, e^{-0.04\, r/\mathbf{T}}\, e^{-0.69/\mathbf{T}}}\right].100 \tag{36}$$

On the other hand the relation C_{50} produced by the reverberation can be interpreted through this expression, using (6), (31),and (32) for the diffuse case and (6), (34) and (35) for the non-diffuse case:

$$E/L = (\epsilon_d/\epsilon_{10} + \epsilon i/e_{10})/\epsilon_f/\epsilon_{10} \tag{37}$$

and

$$C_{50} = 10 \log (E/L) \tag{38}$$

TABLE 1 First example : Q=1

Ti = EDT (s)	Reverberation radius r_c (m) for **T** = 2.65 s, **Q=1**, V=18740 m^3, n= 0.9		
	Classical formula	Diffuse case(41) Ti = T	Non-diffuse case(42)
1.5	—	—	5.08
2.0	—	—	4.99
2.2	—	—	4.97
2.4	—	—	4.96
2.65 (Barron case)	4.79	4.94	4.94
2.85	—	—	4.93

TABLE 2 Second example : Q=30

Ti = EDT (s)	Reverberation radius r_c (m) for **T** = 2.65 s, **Q=30**, V=18740 m^3, n=0.9		
	Classical formula	Diffuse case(41) Ti = T	Non-diffuse case(42)
1.5	—	—	47.30
2.0	—	—	37.60
2.2	—	—	35.94
2.4	—		34.73
2.65 (Barron case)	26.1	33.60	33.60
2.85	—	33.07	33.07

3 The difference of r_c among all the cases analyzed is small if Q=1 ,but it is greater for sources with high Q values.

However we must to analyze the case in where the both curves, direct and reverberant sound fields, do not intersects in a point r_c.

We must obtain the r_{cmin} value which corresponds to the two curves being closest. For it we write the following function f(r) for a diffuse case obtained from (41):

$$f(r) = e^{-0.04\, r/T} / r^2 = (312/Q)\,(T/V) \tag{43}$$

Finding the minimum of the function f(r): df(r)/ dr =0,we obtain:

$$r_{cmin} = 2T/0.04 = 50\, T \tag{44}$$

This is the distance where both curves are nearest. Substituting (44) in (43) we find the minimum Q value for which, for any real state of reverberation of the room, even a very a live room, we get a behaviour similar to that of an anechoic room, i.e. as if no reflections were produced in the walls, this Q value is:

$$Q\text{minimum} = 105561.5\, (T^3/V) \tag{45}$$

For a non-diffuse case we obtain using expression (42), by the same procedure, the following results:

$$r_{cmin} = 2T_i/0.04 = 50\, T_i \tag{46}$$

$$Q\text{minimum} = 105561.5\, (T.Ti^2/V).\left[n+(1-n)e^{-Ti/T}\right] \tag{47}$$

7. COMPARATIVE ANALYSIS OF THE EXTENDED THEORY VERSUS THE REVISED THEORY AND EXPERIMENTAL DATA

In order to a validate this work it is necessary to make a comparison between measured experimental data and values calculated from the main theories. We will now present a comparative analysis using the results obtained by Bradley [16, 17].

In 1991 Bradley [16] produced the answers to many important questions such as:

1. The RT values virtually exhibit no variation with source-receiver distance.

2. The EDT values increase with increasing source-receiver distance. (See figure 14 of Bradley[16]).

3. The variations in C80 values with the source-receiver distance are similar to those for EDT.

In a later publication Bradley [17] presented more experimental data for C_{80} and

$L_t(10)$. We consider here the case of the Boston Symphony Hall (BSH).

We have for this case that RT = 2.65 s for 1000 Hz and we realize a comparison with the experimental data in relation calculated for EDT = 1.5, 2, 2.2, 2.4, 2.65, 2.85 s and also for the variation of EDT with distance according to his fig.14.

In figure 2 we show the comparison of C_{80} values measured by Bradley and those calculated versus distance. Similarly, in figure 3 we show a comparison of experimental and calculated values of $L_t(10)$ versus distance.

Looking figures 2 and 3 it can be seen that there is a great differences for both C_{80} and $L_t(10)$ between the values calculated through our theory and the revised theory of Barron and Lee depending on the EDT value considered.

The influence of the EDT on several energy relations can be understood from consideration of our theory.

Comparing the values of the three cases, for the same Reverberation Time RT, we see:

1. That the early energy is increased with a lower EDT
2. The late energy is decreased with a lower EDT
3. The Clarity Index C80 increases with lower EDT values, as Bradley found experimentally
4. The value of $L_t(10)$ decrease with a lower EDT.

A comparative analysis of the results obtained from application of this General theory in relation to those obtained from the revised Barron and Lee theory for the Boston Symphony Hall (V=18740 m^3, **T**=2.65s, Q=l and n = 0.9) are shown in Table 3.

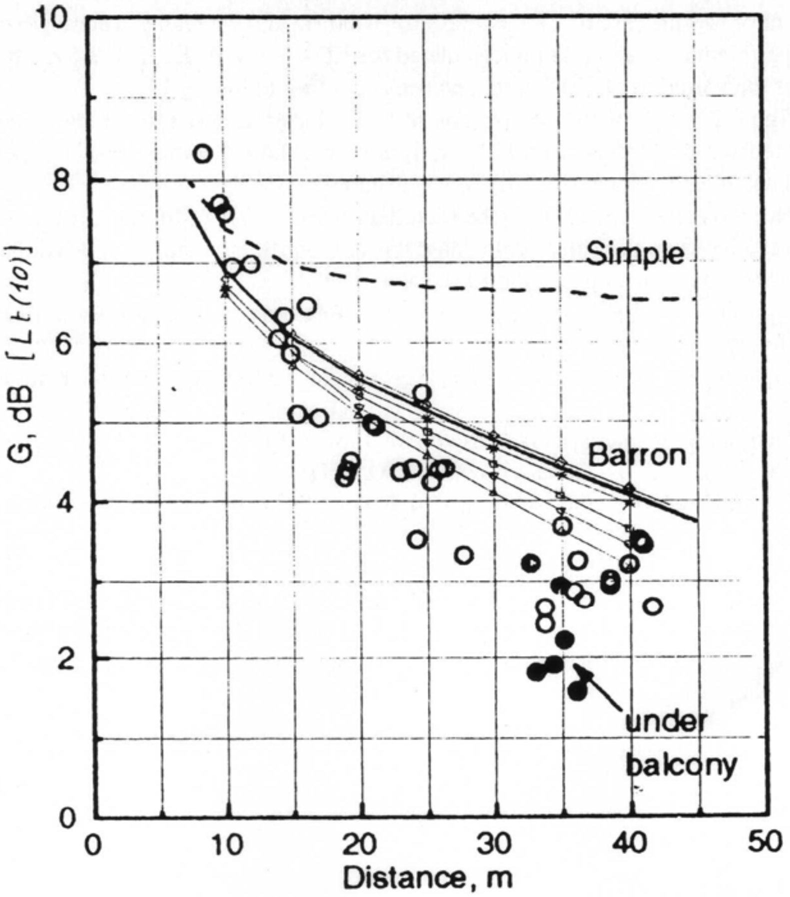

Figure 2: Comparison of C80 values measured by Bradley and calculated using the generalised theory presented in this work versus source-receiver distance

◊	EDT = 2.85s
–	EDT = 2.65s (Barron and Lee case)
□	EDT = 2.40s
▽	EDT = 2.20s
Δ	EDT = 2.0s
+	EDT 1.5s
*	EDT variable with distance according fig. 14 Bradley (1994)
0	Experimental data

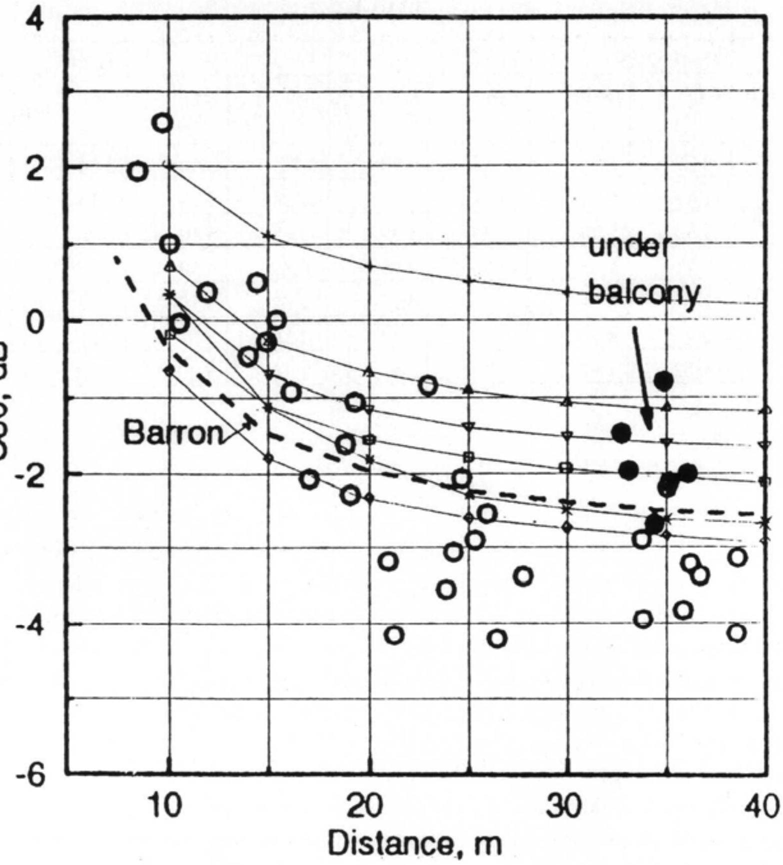

Figure 3: Comparison of Lt (10) values measured by Bradley and calculated using the generalised theory presented in this work versus source-receiver distance

◊ EDT = 2.85s
– EDT = 2.65s (Barron and Lee case)
□ EDT = 2.40s
▽ EDT = 2.20s
Δ EDT = 2.0s
\+ EDT 1.5s
* EDT variable with distance according fig. 14 Bradley (1994)
0 Experimental data

TABLE 3

	Ti =T=2.65		$T_i = 2.5$		$T_i = 2$		$T_i = 1.5$	
Distance (m)	C80	Lt (10)	C80	Lt (10)	C80	Lt (10)	C80	Lt (10)
10	-0.36	6.8	-0.14	6.78	0.75	6.66	2.04	6.46
15	-1.47	5.98	-1.23	5.93	-0.24	5.73	1.15	5.39
20	-1.96	5.46	-1.70	5.39	-0.67	5.10	0.76	4.63
25	-2.21	5.03	-0.95	4.95	-0.89	4.58	0.55	3.98
30	-2.36	4.65	-2.09	4.55	-1.02	4.10	0.42	3.38
35	-2.46	4.29	-2.18	4.17	-1.10	3.64	0.32	2.80
40	-2.52	3.93	-2.24	3.80	-1.16	3.20	0.25	2.23

8. CONCLUSIONS

We have developed a new theoretical treatment of the energy relations taking in account the asymmetrical placement of absorption in the hall. When the absorption is uniformly placed in the room the theory yields the same expressions as the revised theory of Barron and Lee for concert halls.

Also we have developed new relationships concerning the reverberation radius and the energy relations for speech halls In this approach, by means our theory, we have found that the initial reverberation time T_i associated with the first portion of the sound decay, has a strong influence over the energy relations by which is confirmed that subjective human perception depends on this parameter as generally believed.

The theoretical problem has been treated approximately to arrive at a solution, but more work remains to be done in this area because in completing this work we have had to make certain hypothesis, relating to situations that are frequently encountered, but perhaps not always in all cases. However from the perspective of this new analysis that, independently of the accuracy of values calculated from the new formulation, we can draw the following conclusions:

1. That the early sound energy increases and the late sound energy decreases with a lower EDT.

2. That the Clarity Index C80 increases and the Lt (10) value decreases with a lower EDT.

APPENDIX 1

The absorption coefficients used in the section 3 and 4 are:

$$a_i = \mathbf{a} \,.\, d \text{ and } a_f = \mathbf{a}/d$$

being:

TABLE 3

	$T_i = T = 2.65$		$T_i = 2.5$		$T_i = 2$		$T_i = 1.5$	
Distance (m)	C80	Lt (10)	C80	Lt (10)	C80	Lt (10)	C80	Lt (10)
10	-0.36	6.8	-0.14	6.78	0.75	6.66	2.04	6.46
15	-1.47	5.98	-1.23	5.93	-0.24	5.73	1.15	5.39
20	-1.96	5.46	-1.70	5.39	-0.67	5.10	0.76	4.63
25	-2.21	5.03	-0.95	4.95	-0.89	4.58	0.55	3.98
30	-2.36	4.65	-2.09	4.55	-1.02	4.10	0.42	3.38
35	-2.46	4.29	-2.18	4.17	-1.10	3.64	0.32	2.80
40	-2.52	3.93	-2.24	3.80	-1.16	3.20	0.25	2.23

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APPENDIX 1

The absorption coefficients used in the section 3 and 4 are:

$$a_i = \mathbf{a} \cdot d \text{ and } a_f = \mathbf{a}/d$$

being:

$$\mathbf{a} = \mathbf{a}_x^{S_x/S} \cdot \mathbf{a}_y^{S_y/S} \cdot \mathbf{a}_z^{S_z/S} \tag{A1}$$

$$\mathbf{a}_x = -\ln(1-\alpha_x) + 4mV/S$$

$$\mathbf{a}_y = -\ln(1-\alpha_y) + 4mV/S$$

$$\mathbf{a}_z = -\ln(1-\alpha_z) + 4mV/S$$

α_x is the area-weighted arithmetical mean of the energetic absorption coefficients of the floor S_{x1} and ceiling S_{x2} surfaces;

$$S_x = S_{x1} + S_{x2}$$
$$ax = (\alpha_{x1} S_{x1} + \alpha_{x2} S_{x2})/S_x$$

α_y is the area-weighted arithmetical mean of the energetic absorption coefficients of the side surfaces:

$$S_y = S_{y1} + S_{y2}$$
$$\alpha y = (\alpha_{y1} S_{y1} + \alpha_{y2} S_{y2})/S_y$$

α_z is the area-weighted arithmetical mean of the energetic absorption coefficients of the frontal S_{z1} and of bottom S_{z2} surfaces;

$$S_z = S_{z1} + S_{z2}$$
$$\alpha_z = (\alpha_{z1} S_{z1} + a_{z2} S_{z2}) S_z$$
$$S = S_x + S_y + S_z$$

m is the molecular absorption coefficient of air.

APPENDIX 2

From the first portion of the sound decay, see figure A2, we have:

$$(\epsilon_2/\epsilon_0) = 10^{-Di\Delta t1/10}$$

$$(\epsilon_1/\epsilon_0) = 1 - (\epsilon_2/\epsilon_0)\left[1 +)\epsilon_2/\epsilon_0)^{(k/d)}\right]$$

$$(\epsilon_2/\epsilon_0) = 10^{-Di\Delta t1/10}$$

$$(\epsilon_3/e_0) = (e_2/e_0)^{1+k/d} \tag{A2}$$

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