Reverberation Slope Ratio Thesis

T60 vs Frequency Guidelines for Modern Architectural Acoustic Environments

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ABSTRACT

The Reverberation Slope Ratio (symbolically $T_{60}SR_6$) is a proposed standard for condensing six octaves (63 Hz – 2 kHz) of reverberant decay data into a singular-quotient, qualitative score, for indoor performance, worship and entertainment facilities.

It's a defining metric for scoring and grading the proportional relationship (i.e. ratio) between the longest and shortest of six reverberation (T_{60}) values, measured or predicted, and applied to fully-enclosed venues employing sound reinforcement systems.

In practice, Bass Ratio (BR) and Slope Ratio (SR) goals are conflicting concepts. BR goals and calculations were developed to support the idea that acoustic instruments need a little extra assistance, via longer reverberation time, in the low-frequency range. SR goals and calculations support the notion that those same low frequencies do not require extra reverberation time, but rather need to be well contained. Longer low and very low-frequency reverberation is not needed, nor desirable, when an extended-range sound reinforcement system is used.

The $T_{60}SR_6$ thesis is offered to advance and define a room's acoustic design objectives, and provide a simple numeric scoring scale and grading vocabulary, from which acoustical design specifications can be initiated and/or evaluated.

1.0 THE $T_{60}SR_6$ ENIGMA

Modern loudspeakers are designed and optimized to perform as flat, or nearly flat, audio output devices. Therefore, shouldn't acousticians be designing the same, nearly-flat timbre into the rooms in which these loudspeakers operate?

Put another way: We have standards and performance goals for speech clarity and intelligibility, but there are currently no "music clarity" standards or performance goals for amplified music. Both can and should coexist.

2.0 BACKGROUND

Even before Sabine, and the subsequent developments in the field of architectural acoustics, it was believed a concert hall's ability to support and sustain low-frequency reverberation was desirable, yet at times difficult to achieve. In addition, low- (LF) and very low-frequency (VLF) sounds from acoustic instruments and voices are weak, and difficult to propagate into a large room.

In the context of this backdrop much of the existing body of acoustic design literature focuses, almost exclusively, on classical music, and the need to properly support acoustic instruments and voices. Yet today, there are many more performances of popular music, including rock and pop [1]. Classical music, opera and ballet are no longer the mass-market entertainment draw they once were.

Fast forward to the 21st-century. Like it or not - live music, supported by powerful, full-bandwidth sound reinforcement systems, sells tickets.

The quantitative expectations of today's audiences are higher than ever, and easily met with the right equipment. However, one key reason the qualitative expectations aren't easily accommodated is poor room acoustics; specifically, excessive LF and VLF reverberation.

In place of traditional concert halls, we now have multi-purpose performing arts theaters, strip mall and warehouse sanctuaries, casino showrooms, sports arenas, and gymnatoria. Introduce thousands, if not tens of thousands of Watts of subwoofer amplification, and you can easily find yourself in a thunderous cacophony.

If we're lucky, such venues have variable acoustics or some form of installed, mid- and high-frequency sound absorption. The obvious examples are carpet, padded chairs or pews, fiberglass wall or ceiling panels, drapes, and maybe a little architectural shape for diffusion and/or modal complexity. Still, it's rare that any attention is paid, or treatment specifically assigned, to absorb modal and reverberant energy below 125 Hz.

Consequently, the problem is often compounded because mid-high absorption, whether it comes in the form of soft finish materials and/or people, causes a dramatic imbalance in the reverberant character of a room. It's not uncommon to encounter an "acoustically treated" facility that has a T_{60} that's two or three times longer at 63 Hz than at 2 kHz.

To further complicate things, ISO 11654, which defines absorption classes, actually does not reference the 125 Hz octave band. This is possibly part of the fundamental problem, as many manufacturers don't feel the need to test for, or show absorption coefficients at or below this band.

In a recent study, Margriet Lautenbach et al., of Peutz BV concluded, "At least as important as the actual reverberation time is a flat reverberation spectrum, from at least 63 up to 4,000 Hz. Special attention has to be paid to absorbing efficiency at low frequencies, i.e. the 63 and 125 Hz octave bands.

If the reverberation level at low frequencies is high, a soup of sound 'swallows' all higher frequencies and kills the definition. In order to achieve a clear and perceivable bass rhythm, in balance with the mid- and higher-frequencies, the reverberation time in the 63 and 125 Hz may not exceed the average RT by more than 10%." [2]

While this thesis was developed independently, and without any prior knowledge of the works of Peutz, Niels W. Adelman-Larsen, and others, the $T_{60}SR_6$ guidelines correlate well with their findings.

3.0 THE CHALLENGE

As Leland Roth points out in his book, *Understanding Architecture*, “Reverberation is frequency dependent: The length of the decay, or reverberation time, receives special consideration in the architectural design of spaces which need to have specific reverberation times to achieve optimum performance for their intended activity.” [3]

Our present-day challenge is that many, if not most contemporary performance, worship, and entertainment venues cannot dissipate the massive amounts VLF energy as quickly as it’s being produced, nor as quickly as the mid- and high-frequencies are produced and absorbed.

Niels W. Adelman-Larsen of Flex Acoustics in Denmark summarizes the problem this way: "Surveys among professional musicians and sound engineers reveal that a long reverberation time, at low frequencies, in halls featuring reinforced music such as pop and rock, is a common cause for an unacceptable-sounding event. Mid- and high-frequency sound is seldom the reason for lack of clarity and definition.

Calculations indicated a standing audience in a rock or pop concert venue will absorb five to six times the sound energy in mid-high frequency bands, compared to low-frequency bands. This indicates, if a venue has a disproportionately long reverberation time in low (bass) frequencies when empty, the difference between reverberation times will be even greater when it is filled with an audience.

Lower frequency sounds are, within the genre of popular music, rhythmically very active and loud, and a long reverberation leads to a situation where the various notes and sounds cannot be clearly distinguished." [4]

4.0 $T_{60}SR_6$ DEFINED

Submitted for consideration is the T_{60} Slope Ratio - represented symbolically as $T_{60}SR_6$. It is a new metric for scoring and grading the reverberant timbre of a room.

- T_{60} - is the acronym for reverberation time, in seconds.
- SR_6 - is the calculated Slope Ratio, using the two extreme time values - from the six, octave centers - between 63 Hz and 2 kHz.

Frequencies above 2 kHz are intentionally excluded. Because of air absorption, naturally short T_{60} values - above 2 kHz - disproportionately skew the ratio. Similarly, while T_{60} measurements below 63 Hz are possible with modern dual FFT technology, implementing effective treatment in the 31.5 Hz octave band, and below, is currently an unreasonable expectation for most.

5.0 T60SR6 TARGET GOALS

The focus of this thesis is the decay time ratio of naturally occurring reverberation, found in fully enclosed, unoccupied buildings. Again, the primary application is directed toward live performance venues, using sound reinforcement systems.

It is suggested here that to achieve an ‘Optimal’ $T_{60}SR_6$ grade, the SR score must fall between 1.11 and 1.20. See Table 1 below for a complete listing of scores and grades.

$T_{60}SR_6$ Scoring & Grading Matrix	
1.00 - 1.10	Good
1.11 - 1.20	Optimal
1.21 - 1.30	Good
1.31 - 1.50	Fair
1.51 - 1.70	Poor
Above 1.70	Bad

Table 1: Proposed Scoring & Grading Metrics

And, regardless of a venue's mid-band requirement, it is implied that the SR guidelines remain a consistently viable metric. For example: In some traditional house of worship settings a mid-band T_{60} of 1.50 seconds might be desired. Given that, or most other mid-band prerequisites, the SR objectives do not change.

6.0 $T_{60}SR_6$ SCORING & GRADING

Much like the subjective MOS (mean opinion score) scoring that is applied to %Alcons or STI grading scales for speech intelligibility, the proposed $T_{60}SR_6$ scoring and grading scale is defined by six numeric scoring tiers, and five grading adjectives, which most people can easily understand.

Until more exhaustive testing is done to update this table, these values are proposed to describe the measured or predicted $T_{60}SR_6$ scoring.

Critics may say the goals are too aggressive. The author suggests they are not. Consider outdoor concerts and festivals. When these rock, pop, blues, rap and country events operate in free field conditions, no one seems to have a problem with the flat, near zero T_{60}s. In many cases, these are the best conditions for high SPL sound reinforcement.

Why not strive for an optimal objective between outdoor free-field acoustics, and tight, well defined indoor acoustics?

7.0 APPLICATION LIMITS

While the Slope Ratio metric can be applied to almost any size room, there are some practical limitations - guided by the true nature of reverberation. The following, defining limitations should be factored into the SR applications and calculations:

A. Room Size – Not too big or small for true reverberation

For best results, it is necessary to consider the room volume. Anything less than about 1,020 m^3 (≈ 36,000 f^3) is approaching a volume that’s too small, for reasons related to the Schroeder frequency, which is outlined below. Reference: A room with the dimensions of 17 m x 10 m x 6 m is 1,020 m^3.

The primary reason for this small-room guideline is to allow for the development of a true reverberant field at or near 63 Hz.

Likewise, a room may be too big for meaningful analysis. Prescribing a specific threshold for what's too large is nearly impossible. The author suggests anything nearing 42,475 m^3 (≈ 1,500,000 f^3) might be. This approaches a volume that may not support a true reverberant field because the mean free path is becoming too long for a homogenous field to develop.

Expressed another way, rooms with seating for 8,000 or more may be approaching the size limit for true reverberation.

It's also important to note: Rooms that are larger or smaller than those described above will still have resonant LF and VLF energy that needs to be managed.

B. Sound Pressure Level – Not too loud or soft

The focus of this thesis leans toward powerful, extended-range sound reinforcement systems. When deployed, these systems are often capable of delivering levels much greater than 100 dBc to the audience.

When sound levels increase, our ear's sensitivity at different frequencies changes dynamically [5]. The $T_{60}SR_6$ scoring calculations are based on mean sound pressure levels between 85 and 105 dBc. As levels get louder, the need for a low $T_{60}SR_6$ score becomes even more important. Levels below 80 dBc are generally less and less problematic, and can be given a little more latitude in scoring and grading.

C. Schroeder Frequency

The Schroeder frequency ($f_{s)}$ marks the approximate boundary between reverberant (ray) and resonant (wave) room behaviour.

In order for a room to have a measureable T_{60} at 63 Hz it must have enough volume (size) to support reverberant behaviour at that frequency. The Schroeder frequency defines the point at which there is enough modal density to support true reverberation at any given frequency.

Per Schroeder's 1954 paper: Within the half-power (-3 dB) bandwidth of 63 Hz, a minimum of 10 Eigenfrequencies should surround the target frequency. See more on Modal Density below.

Also, the Schroeder frequency is influenced by reverberation time. Example: If the 1,020 m^3 room referenced earlier has a mid-band T_{60} average of 1.25 seconds, the Schroeder frequency is 70 Hz. If the same room has a 1.8 second T_{60}, the Schroeder frequency moves up to 84 Hz. [6]

D. Modal Density

The Bonello factor considers how many modes exist in any third-octave band. According to the "Bonello-criteria", this function should be strictly increasing, per each 1/3-octave band, to reach a good distribution of modes. [7]

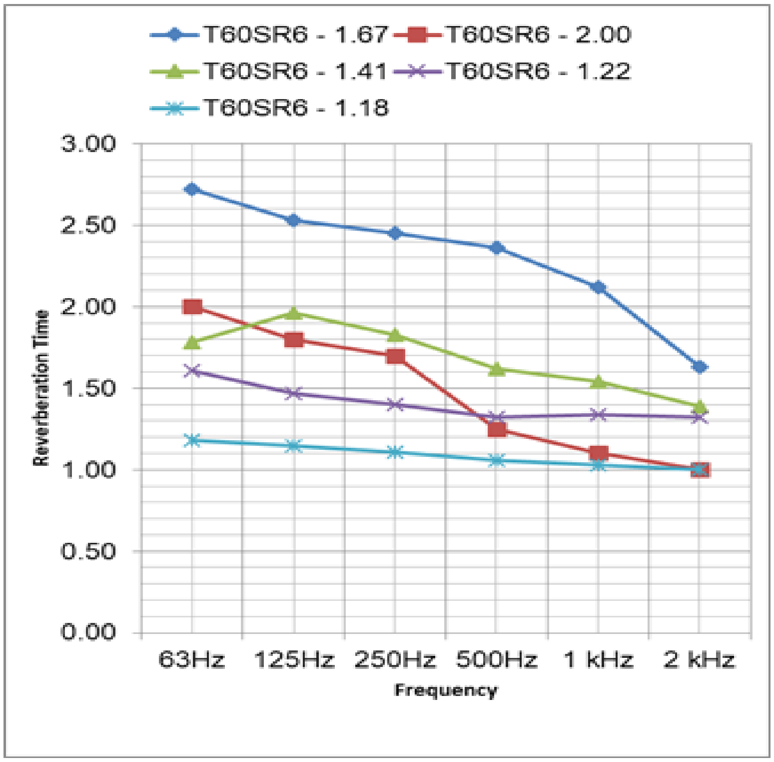
The 1,020 m^3 room cited above has 30 modes (Eigenfrequencies) in the third-octave band centered at 63 Hz. 30 is good density.

8.0 SLOPE ASYMMETRY

It is common for T_{60} times to gradually descend from longest to shortest, starting with the longest at or below 63 Hz. See Graph 1 below. But, this isn't always the case. Slope asymmetry means the longest or shortest times may occur at any of the four, middle-octave centers, not just the lowest and highest frequencies.

As an example, a room may have a 1.78 second T_{60} at 63 Hz and a 1.39 second T_{60} at 2 kHz, but a 1.96 second T_{60} at 250 Hz. See examples in Graph 1 and Table 2 below.

Applying the math (defined below) to the two bookend frequencies in this example would result in a SR score of 1.28. This would appear to be 'Good'. However, if we calculate for the longest and shortest times, regardless of frequency, the result is 1.41. This ratio gets a 'Fair' grade, so specific "parametric" room treatments should be applied to address the asymmetry.



Graph 1: A Graphic Representation of Various T60s

Summarizing: The formula for calculating the SR should be factored from the longest and shortest times, not simply the lowest and highest octave centers. It is also proposed that the time deviation between any two adjacent octave centers be limited to +/- one tenth (0.10) of one second.

	Frequency						$T_{60}SR_6$ Score
	63 Hz	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	
Seconds	2.72	2.53	2.45	2.36	2.12	1.63	**1.67**
	2.00	1.80	1.70	1.25	1.10	1.00	**2.00**
	1.78	1.96	1.83	1.62	1.54	1.39	**1.41**
	1.61	1.47	1.40	1.32	1.34	1.32	**1.22**
	1.18	1.15	1.11	1.06	1.03	1.00	**1.18**

Table 2: Values from Graph 1

9.0 THE MATH

The math is very simple. To find the ratio, divide the longest T_{60} by the shortest T_{60}. Use the two time-value extremes, regardless of frequency. Note: Third-octave resolution can also be used if necessary.

Example: If a 63 Hz T_{60} of 1.90 is divided by the 2 kHz T_{60} of 1.20, the resulting ratio is 1.58:1. The $T_{60}SR_6$ score is the ratio quotient, without the ":1" constant.

To put this into further perspective: In the previous example, the 63 Hz T_{60} lasts 1.58 times longer than the 2 kHz T_{60}.

$T_{60}SR_6$ Score	Comments	Grade
1.67	Recently Measured RIR	Poor
2.00	From Graph 1 BR Chart	Bad
1.41	Asymetrical Slope	Fair
1.22	Recently Measured RIR	Good
1.18	Targeted Goal	Optimal

Table 3: Slope Ratio scores from Graph 1 - Showing All 5 Grades

10.0 CASE STUDY

Because this thesis posits very new thinking, there is only one documented case study; a 3,000 seat, Southern California mega church - offering a very contemporary worship experience. [8]

During the planning phase, the client and author agreed to target goals of reducing the 63 Hz band T_{60} by approximately 1 second, while also reducing the mid-band average to be as close to 1.25 seconds as budget, aesthetics, and logistics would allow.

By specifically targeting the 63 Hz band for custom treatment, along with generic broadband treatment to lower the mid-band T_{60}, a $T_{60}SR_6$ score of 1.22 was achieved.

Graph 1 and Tables 2 & 3 above show this venue's before and after T_{60} testing results. The "before" $T_{60}SR_6$ score was 1.67, which was considered subjectively 'Poor' to the client. After treatment, the room achieved a score of 1.22, which gets a 'Good' grade.

We only have the anecdotal evidence of the professional audio staff, the facility manager, some regularly-booked musicians, and various congregants - all of whom indicated the room was greatly improved. Their collective opinions (MOS), clearly moved from Fair to Good.

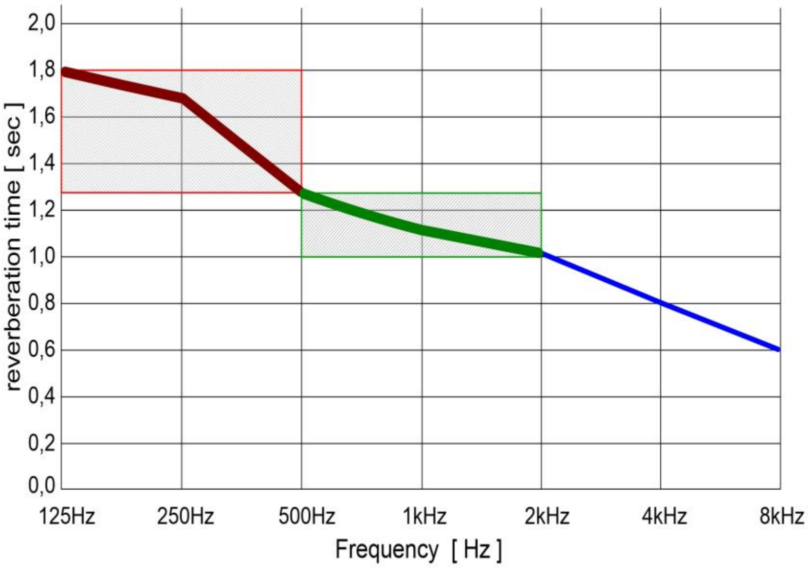
While the author has pursued similar goals and treatment plans for many years prior to this case study, this project was the immediate precursor to the development of the T60 Slope Ratio thesis.

11.0 ARE THERE OTHER SIMILAR STANDARDS?

Do current standards exist that define and quantify appropriate T_{60} times - with at least 1-octave resolution? It is suggested here that they do not.

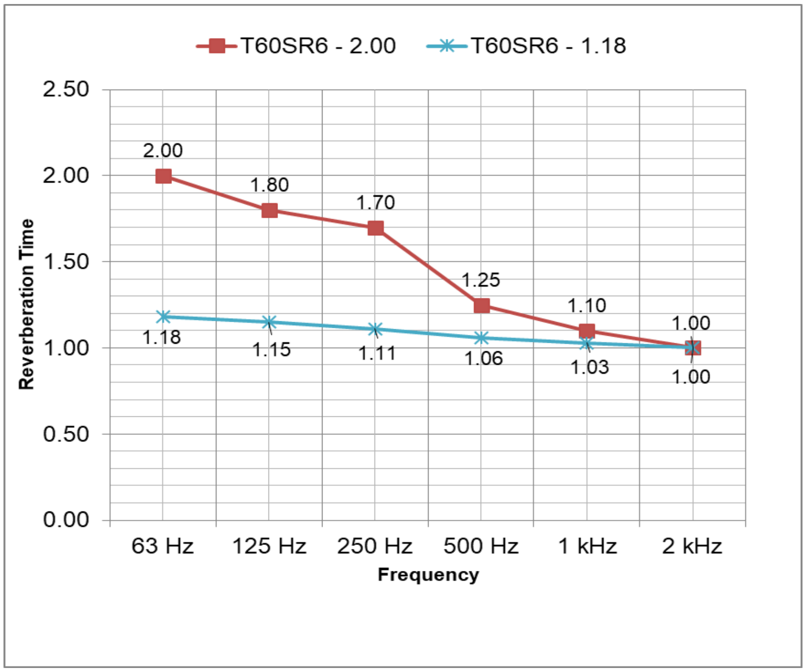
A. Bass Ratio: Leo Beranek developed the concept of the Bass Ratio [9], and recommended it be applied to classical concert halls. BR is the proportional relationship between the summed T60s of the 125 Hz and 250 Hz octave bands, divided by the summed T60s of the 500 Hz and 1 kHz octave bands.

In practice, Bass Ratio and Slope Ratio objectives are conflicting concepts. Further, the BR calculations only factor four octaves of data. It is suggested here that four octaves is insufficient given modern musical styles and technologies.



Graph 2: Sample BR Chart [10]

Using Graph 2, the BR works out to be 1.49:1. Using the same chart, the SR could easily be 2.00:1, if we presume a 2.0 second T_{60} at 63 Hz. A $T_{60}SR_6$ score of 2.00 is considered ‘Bad’.



Graph 3: A sample BR histogram compared to an Optimal SR histogram.

Notice the substantial time disparity in the bottom three octaves when the BR chart above is laid over an Optimal SR chart, and matched at 2 kHz.

B. ICA DIN 18041: This standard falls short for multiple reasons, but primarily because it states, “… that the standard should not cover concert halls, churches, studios and other rooms of high acoustic quality.”

C. The Norwegian Standard 8178: This standard recommends specific acoustic conditions for music rehearsal and performance rooms. But again falls short because the standard is not intended to be applied to “large specialized concert halls, opera venues, and similar spaces designed for concerts and performances.”

D. ISO 3382: This is mainly a procedural reference for measuring reverberation. It addresses nothing below 125 Hz, nor does it provide any qualitative guidance related to acceptable, temporal tolerances - across a broad range of frequencies.

E. Variable Acoustics (VA): Not a standard, but if you’re using VA, are you able to shorten/adjust the T60 in the octave or two below 125 Hz?

F. Or, maybe nothing at all, because no one has asked for anything other than a general, mid-band goal?

Conclusion: None of the standards above adequately define T_{60} guidelines at either 63 Hz and/or are applicable for modern, high-quality, performance venues.

12.0 MODERN APPLICATIONS

The following are some obvious applications for the Slope Ratio metrics:

A. Performing Arts Venues – These facilities need to accommodate many disparate, artistic productions. An ‘Optimal’ Slope Ratio will benefit most, if not all musical productions using amplified sound.

B. Contemporary Worship Facilities – From the perspective of their audio, video and acoustic requirements - These are essentially performing arts venues.

C. Recording Studios and Sound Stages – Most would benefit from an Optimal Slope Ratio.

D. Rooms with Electro-acoustical Enhancement Systems. See more on this in Section 14 below.

E. Large Rehearsal Rooms – Recent European studies, such as those used to support the Norwegian Standard, have shown that rehearsal rooms should closely match performance space acoustics.

F. Also consider most other indoor settings that features both amplified music & speech.

13.0 VLF ACOUSTIC TREATMENT OPTIONS

Retrofitting VLF absorption treatment can be quite challenging. It is usually more cost effective if such treatment is factored into a structure during the initial design and construction phases.

Treatment techniques such as perforated panels with deep mineral wool-filled cavities, limp mass diaphragmatic absorbers, and Helmholtz resonators can be built into the architectural plan, but these will almost always be custom solutions.

Commercially-available VLF treatment methods and materials are not easily found at this time. Flex Acoustics [11] in Denmark is perhaps the leaders in today's market, with no other companies (known to the author) engaging in mid- and large-venue solutions.

There appears to be at least three reasons for the scarcity of VLF acoustic products. First is the lack of standards and testing criteria below 125 Hz. Second - there are very few testing facilities large enough to do reverb testing in the 63 Hz range and below. Third – until the late 20th century there was little need or demand for such products.

The author suggests those deterrents are no longer acceptable reasons to ignore the obvious problems that exist in venues with Fair, Poor or Bad slope ratios.

14.0 ELECTRO-ACOUSTIC ENHANCEMENT

It is well known and understood there are no electronic systems capable of removing reverberation; it can only be added. Modern electro-acoustical systems such as Meyer’s Constellation, LARES from E-coustic Systems, Yamaha’s AFC, Muller-BBM’s Vivace, and others, rely on implementation in a building with a very well-controlled acoustic profile.

A mid-band T_{60} of one second is generally considered a good starting point. When this technology is properly integrated, adding “synthetic” reverberation at various frequencies, and in varying amounts, becomes relatively easy.

However, targeting a mid-band T_{60} of one second does not reveal the whole story. The author suggests that the SR must be evaluated, and the room be properly treated to achieve an 'Optimal' grade, or as close as possible. If any other frequencies have moderately-longer T_{60}s than the mid-band average, an electro-acoustic system can do nothing to compensate.

Also, consider this: In some situations, a venue with a good reverberation profile may now be viewed to be just as limiting as one with too much or too little reverb. Ideal, classical music T_{60}s only compliment a narrow range of 21st century music, entertainment and production. Like it or not, modern economics requires venues that are built to support the widest possible range of offerings.

15.0 TESTING STANDARDS AND NEW TREATMENTS

There are a glut of companies selling absorption products for treating mid-, and high-frequency reverb. But, even today, LF and VLF testing standards and pre-made treatment options are in short supply. Therefore, the author believes the next major phase of acoustic invention and development should be focused on two fronts: Standards and Manufacturing.

The author calls on the ANSI and ISO organizations to develop new guidelines and standards for testing VLF absorption products and integration (mounting) options.

It is further suggested that manufacturers make the development of new, high Q (narrow bandwidth) absorption products a priority.

To this end, the author is currently developing a new acoustic thesis titled: *Parametric Acoustics.* It makes the case for using high Q absorption materials that perform much of their work at various 1- to 2-octave centers.

16.0 SUMMARY

In his paper, *Reverberation and the Art of Architectural Acoustics,* [12] Robert Sekuler notes what Wallace Sabine had to say about concert hall acoustics. Sabine realized that the total acoustic disturbance produced by any ensemble's instruments must be intense enough to overcome the concert hall's tendency to absorb sound. Otherwise, the hall will soak up much of the available sound, leaving little for the audience to hear, and causing the audience to complain that the music lacks body.

Sabine's comment was made more than one hundred years ago. Since then musical styles, venues, technology, and consumer tastes and expectations have advanced far beyond anything relevant to Sabine's concern.

It is offered here that reverberation decay times, in the six octaves of sound outlined above, are fundamentally critical when evaluating a room that has or may require a powerful, extended-range sound system. Therefore, given today's audio technology, and acoustic analysis and modelling options, striving for Good or Optimal music clarity should be every bit as important as striving for good or excellent speech clarity.

The T_{60} Slope Ratio thesis is offered to help quantify a room's current conditions - or proposed reverberation objectives - and provide a simple scoring metric and grading vocabulary from which new treatment objectives can be initiated and/or evaluated.

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