Measuring Sound Absorption: The Hundred-Year Debate on the Reverberation Chamber Method

Jamilla Balint, Marco Berzborn, Mélanie Nolan, and Michael Vorländer

A Seemingly Simple Question

When we enter a concert hall, we enjoy the music that resonates through the space; when we enter a classroom, we want to understand what the teacher explains; and in an office, we need a quiet environment to focus on work. For these and all other spaces, the acoustic design of the room is critical. Sound waves travel through the space and are reflected many times at the surfaces where a fraction of the wave's energy is absorbed. Accordingly, when designing a concert hall or any other space, we have to ask how much energy is absorbed or how much absorptive material should be installed in a room to achieve adequate acoustics. If the classroom sounds like a church, we will not understand the teacher; if the office space is too loud, we cannot concentrate; and if a concert hall is not designed properly, we will not enjoy the music.

On the face of it, this question may seem easy to answer. More than 100 years ago, W. Sabine (1922) (for a short biography, see t.ly/1tw4) derived the well-known reverberation formula and showed that provided the sound field is diffuse, the reverberation time of a room is inversely proportional to the amount of absorption. Based on this theory, the acoustics of a room can be predicted if one knew how much sound energy can be absorbed by a given material, something referred to as the absorption coefficient. It is a seemingly simple quantity, but its measurement has caused perhaps the most controversial and long-lasting debate in the history of acoustics. This article gives an overview of the many discussions and difficulties related to sound absorption measurements and presents some of the ensuing research findings.

The Beginnings of Absorption Measurements

The simple question of "How much sound can be absorbed by a certain material?" can also be answered using W. Sabine's (1922) theory of reverberation, with measurements conducted in a reverberation chamber. Reverberation chambers are typically large rooms with hard exposed surfaces, and they are designed to create a diffuse sound field, something that is required for Sabine's theory to apply. In a diffuse sound field, sound energy is independent of the receiver position in the room and the energy strikes the test material equally from all directions. Despite the method being fairly simple, proving that the underlying theoretical assumptions are fulfilled has been an elusive task.

In 1913, the Riverbank Laboratories for Acoustics (Geneva, Illinois) initiated the construction of the first reverberation room for the measurement of sound absorption (**Figure 1**, *right*). The room was designed by Wallace (Clement) Sabine but was only finished after his death in 1919. His cousin, Paul Sabine, continued the work and the experiments in the reverberation room. The measurement procedure, which was called the ear-and-stopwatch method, was conducted as follows. The trained observer sat inside a wooden box placed in the reverberation room (**Figure 1**, *left*). The box was used to mitigate the influence of the observer on the overall absorption in the room because a wooden box absorbs much less energy than a human body. A rotating vane (the object that looks like a flag in **Figure 1**, *left*) was installed in the middle of the room to guarantee a uniform distribution of sound intensity in the chamber.

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Figure 1. ***Left:*** *ear-and-stopwatch method to measure the absorption coefficient of a material at the Riverbank Laboratories in the 1920s. The experimenter is sitting in a wooden box listening to the sound decay emitted by organ pipes. Reproduced from Kopec (1997), with permission of the Acoustical Society of America, Copyright 1997, John Kopec.* ***Right:*** *drawing of the Riverbank Laboratories with a detailed view of the reverberation chamber. First published in Lescarboura (1923). Courtesy of JSTOR and Eric Wolfram, Riverbank Acoustical Laboratories*

Organ pipes in the room emitted a single tone. When the room was filled with sound, the tone was stopped and the time was recorded. The experimenter listened to the sound decay in the room and, once the sound was inaudible, again recorded the time. The interval between the two recorded times gave the reverberation time that could be measured with a precision of up to 0.01 seconds. An internal report by the Riverbank Laboratories for Acoustics (1919, p. 2) mentioned the exhaustive training needed: "Trials by a number of observers showed that considerable practice is required before the observations of a novice are reliable." The observer had to listen to the sound decay 1,100 times to obtain a reliable result for a single reverberation time at a given frequency (Riverbank Laboratories for Acoustics, 1919).

The procedure was repeated with and without the material under test (most likely some kind of porous fiber such as mineral wool) in the room, and the difference in reverberation times used to calculate the amount of absorbed sound energy, also known as the *random-incidence absorption coefficient,* via W. Sabine's (1922) formula. A value of 1 meant complete absorption, whereas a value of 0 meant that no energy was absorbed by the material.

Technological Advancements and Round-Robin Tests

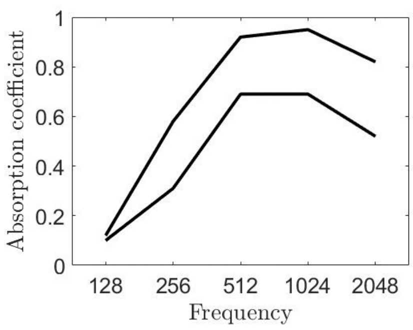
In the following years, technological advances in measurement techniques paved the way for simplification and improvement of the chamber method. In 1928, the US National Bureau of Standards (now the National Institute of Standards and Technology [NIST]) completed the construction of their 15,000-ft^3 (427-m^3) reverberation room that has contributed to knowledge in this field (Chrisler and Snyder, 1930).

By 1928, the interrupted-noise method replaced the ear-and-stopwatch method for measuring the reverberation time. In this method, noise was emitted by a loudspeaker instead of an organ pipe and the sound decay process was recorded by a microphone instead of an ear. Although the measurement procedure was much quicker than the ear-and-stopwatch method, it had to be repeated many times because of the stochastic nature of the excitation signal. However, it is one of the methods that is still in use today for measuring reverberation time.

The novel technologies allowed for more precise reverberation time measurement. Unfortunately, large discrepancies between the values of absorption coefficients assigned to the same material by different laboratories were found to exist and rapidly became concerning, to the point where this period (1925–1933) is known as the *battle of coefficients* (Hunt, 1939). As a matter of fact, this so-called *absorption coefficient problem* was among the motivating influences that led to the formation of the Acoustical Society of America (ASA) in 1929 (Hunt, 1939).

Soon, the first systematic investigation followed. To do this, a round-robin test was conducted in 1933 among seven laboratories to quantify the discrepancies in the measurement results from different laboratories on presumably identical materials (although the authors of this article could not find detailed documentation as to the precise nature of the round-robin tests). For these tests, samples of identical test material were sent to different testing laboratories to measure the absorption coefficient, and the results were reported back to the chairman of the round-robin committee. The results of the round-robin test were later presented by P. Sabine (1939), indicating large variations (see **Figure 2**). It turned out that despite using the same material, there were substantial discrepancies in the findings. For example, at 512 Hz, 1 laboratory reported an absorption coefficient of 0.69 and another laboratory a value of 0.92, results that would make the room acoustic design process very challenging. Many round-robin tests followed in the course of history, verifying the poor reproducibility of absorption coefficient measurements.

Figure 2. *Results from the first round-robin test conducted in the United States. Absorption coefficients at different frequencies are shown for the highest and lowest values obtained by seven testing laboratories. Data taken from P. Sabine (1939).*



The Lack of Sound Field Diffuseness

At the 10-year anniversary of the ASA in 1939, where an entire session was dedicated to the absorption coefficient problem, Hunt (1939, p. 39) noted that something was "gravely wrong, either with the language, with the theory, or with the experiments." He suggested avoiding the term absorption coefficient as a unique measurable property of a material. Instead, he introduced the term *chamber coefficient*, which would be obtained "when certain numbers are placed in a certain formula, the numbers being obtained by means of certain specified operations performed under specific conditions" Hunt (1939, p. 40). It became clear that the condition of sound field diffusion had to be strictly satisfied to be able to use the term absorption coefficient for which it was intended.

Although many attempts were undertaken to increase the diffuseness in a reverberation room by adding diffusing elements like panel or volume diffusers, the absorption coefficients of the same material measured in different laboratories remained in disagreement. Hunt, even then, intuited that it would not be possible to achieve a satisfactory state of diffusion for reverberation theories to hold true.

Diffusion however, proved to be elusive to define. Schultz (1971, p. 17) described the problem of sound field diffusion in the following way: "Almost any man would feel insulted if told he lacks a sense of humor; but "humor" and "sense of humor" have stubbornly resisted definition for years. Similarly, to tell an acoustical laboratory operator that he hasn't adequate diffusion is likely to offend him, although acousticians have not settled on a practical, meaningful definition of diffusion." Cremer (1961, p. 22), on the other hand, was convinced that "the construction of a reverberation room is comparable with building a violin, such that the reverberation room too requires the subtle work of a violin maker who has to build an instrument that responds to all notes in the same manner."

Across the sciences, there is no unique definition of "diffusion." In physics and chemistry, it is the process of equalizing concentration differences in mixtures of substances. The particles in the substances can be atoms, molecules, charge carriers, photons, or even free neutrons. Transferring this concept to a sound field in a reverberation chamber, one imagines that the diffusion (mixing) effect is achieved by the superposition of waves arriving from all directions so that no specific direction of sound incidence can be determined anymore. This is thought to be achieved by numerous reflections off the walls. The term diffuse is used when referring to the type of sound field, whereas the term diffuseness is used when it comes to the quantification of the sound field diffusion.

Direct Quantification of Diffuseness

Closely related to sound field diffusion is *isotropy,* a concept that relates to the directional uniformity of the sound field. In a diffuse sound field, sound waves arrive at the receiver with equal intensities from all directions (aka isotropically) and with random phases. Hence, a diffuse sound field is also always required to be isotropic.

To quantify sound field isotropy, considerable experimental effort has been spent during the last century and different methods have been developed. These methods try to quantify sound field isotropy based on the spatial characteristics of the sound field directly.

A particularly interesting and well-accepted approach consists of measuring the directional distribution of sound energy. The core idea behind this approach is that, in a perfectly isotropic sound field, an equal amount of energy is observed for every direction. The idea goes back to the early 1950s when Thiele (1953) and Meyer and Thiele (1956) captured the angular distribution of arriving acoustic energy using a concave mirror coupled with a single directional microphone. They presented the data in the form of directional "sound hedgehogs (hedgehogs are small spiny animals; when they feel threatened, they roll up into a tight ball and their pointy spines stand erect"; see t.ly/Az1o), showing the directions of sound incidence and corresponding energy in a room (see **Figure 3**). Every spine represents incident sound energy for the given direction where the length of the spine is proportional to the squared amplitude. Based on such directional energy distributions, a measure for the isotropy of the sound field was derived. In a fully isotropic sound field, the hedgehog would possess full spherical symmetry where all the spines would be equal in length and uniformly distributed. Contrastingly, a hedgehog with varying spine length or patches without spines results in reduced isotropy. A hedgehog with only a single spine would indicate full anisotropy. In **Figure 3**, waves with a higher amplitude arrive in the right hemisphere compared with the top or the bottom. The method by Meyer and Thiele (1956) is highly impressive given the simple equipment they had available (one microphone combined with a concave mirror).

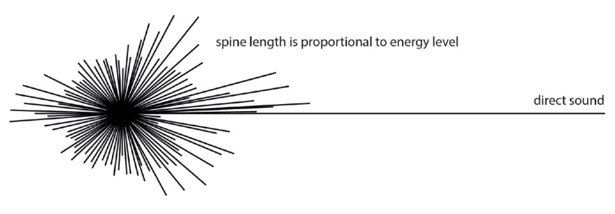


Figure 3. *Hedgehog representation of the directional distribution of sound energy in a room. Schematic drawing after Meyer and Thiele (1956). Spines indicate the direction of incident energy (length is proportional to energy level). The sound field is not fully isotropic because the hedgehog is not fully spherically symmetrical but shows distinct maxima in incident energy for some directions (spines of greater length).*

Over the past few decades, technical developments in sensing methods have facilitated the three-dimensional analysis of sound fields. Different methods have been proposed for the estimation of sound field isotropy from measurements with arrays of microphones. Gover et al. (2002) adapted the method proposed by Meyer and Thiele (1956) to do measurements with a spherical array of microphones. They could deduce the energy arriving at the receiving position as a function of direction and time as well as the rate of the energy decay. An analogous approach was suggested by Berzborn et al. (2019) who calculated the sound field isotropy on directionally dependent decay curves. An alternative criterion for quantifying sound field isotropy in reverberant sound fields was proposed by Nolan et al. (2018) by analyzing the symmetry of the angular distribution of arriving sound energy in the spherical Fourier domain.

Recent studies by Nolan et al. (2020) and Berzborn et al. (2019) applied the aforementioned microphone array-based methods to quantify sound field isotropy in reverberation chambers. These experimental studies showed qualitatively comparable results and confirmed that the sound field in standardized reverberation chambers is not isotropic (maximum 80% isotropy recorded). They also showed that the addition of an absorbing sample drastically influences the isotropy of the wave field (which drops to approximately 50%). In a different study, the distribution of incident acoustic energy on the measuring sample was also recorded, confirming that the sample was not exposed to isotropic sound incidence (Nolan et al., 2019).

Altogether, these findings demonstrate the shortcomings of the *averaging* implicitly contained in W. Sabine's (1922) absorption coefficient. Because sound does not strike the sample equally from all directions, the absorption coefficient measured according to W. Sabine's equation does not properly account for the distribution of sound energy at the sample's surface. Furthermore, the incident directions are highly specific to the respective chambers, which partly explains the fundamental problem of interlaboratory reproducibility associated with the measurement of sound absorption, and only produces new evidence that the measured sound absorption is inseparable from the laboratory room in which the measurements are performed.

A Matter of Standardization

Many attempts were made to standardize the procedure of absorption measurements to guarantee a controlled laboratory environment and improve the interlaboratory reproducibility. The standards have specific requirements on the measurement procedure, the room volume, the sample size, and the procedure to ensure a diffuse sound field. As an example, an International Organization for Standardization (ISO)-certified chamber is shown in **Figure 4**, where a certain number of diffusing elements (e.g., hanging panels and built-in boundary diffusers on the walls and ceiling) are included with the aim of increasing the sound field diffuseness (Kosten, 1960). An indirect measurement procedure for evaluating the state of diffusion depending on the absorption coefficient is also included in ISO 354-2003 (2003). However, this procedure requires a diffuse sound field for the absorption coefficient to be correctly determined: a vicious cycle.

Figure 4. *Reverberation chamber at the Technical University of Denmark, Kongens Lyngby. The chamber is equipped with hanging panel diffusers (**left**) and built-in boundary diffusers (**right**) to create a diffuse (mixed) sound field. Photo by Torben Nielsen.*

Indeed, this method was deemed inadequate to ensure diffusion because the maximal achievable absorption is still a relative quantity, specific to the laboratory (Bradley et al., 2014). In ISO 354-2003 (2003), the measurement procedure to determine the reverberation time is carried out either with the interrupted-noise method or with the integrated room impulse response method developed by Schroeder (1965). The latter has the advantage that it allows for a fast measurement method and reduces uncertainties inherent to the excitation signal.

More recently, the possibility of using a so-called well-characterized reference absorber to calibrate the reverberation room was discussed. However, additional research and round-robin measurements showed that the calibration method only improves the results in a limited number of cases (Scrosati et al., 2020). Unfortunately, all these specifications on room volume, sample size, or measurement procedures could not improve the interlaboratory reproducibility. Even in the latest round-robin test, the issues remain unchanged (Scrosati et al., 2020).

In North America, the ASTM C423 (2023) standard serves as a guideline to measure absorption coefficients in a reverberation room. Although the challenges are the same, the standard acknowledges the difficulties and added a section "Precision and Bias" where the latest round-robin results are shown, and uncertainties are reported in the form of repeatability and reproducibility values. A revision is on the way, where it is suggested to extend the measurement procedure and include the integrated room impulse response method suggested by Schroeder (1965) instead of only allowing the interrupted-noise method. This would greatly improve the

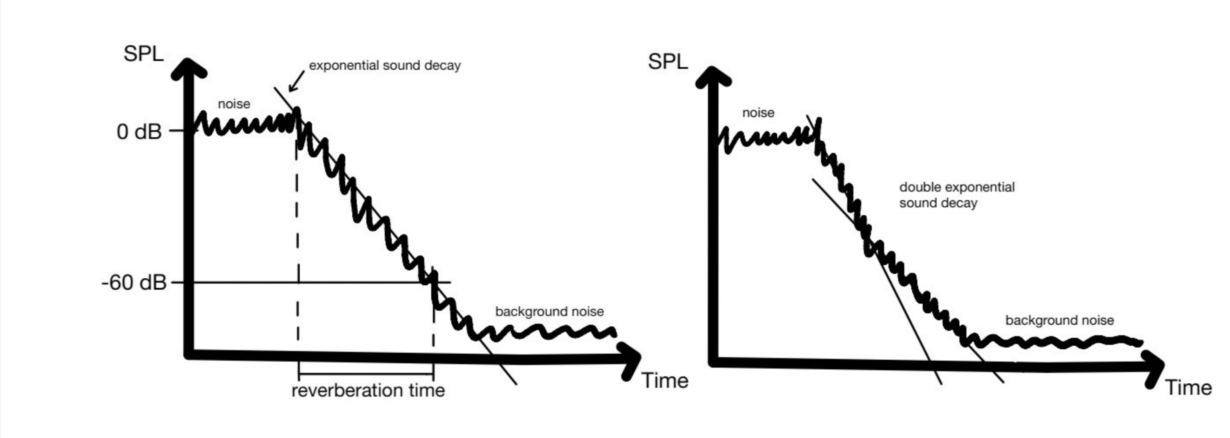


Figure 5. ***Left:*** *estimating the reverberation time from a single exponential sound decay by measuring the time for the sound level to drop 60 dB.* ***Right:*** *when the sound decay is of multi-exponential nature, estimating a single reverberation time is not possible anymore. Here, two simultaneous decay processes are present. SPL, sound pressure level.*

repeatability of measurements by removing the stochastic nature of the excitation signal.

Further Challenges

To determine the absorption coefficient in the reverberation chamber, the measurement of the reverberation time is based on the diffuse field theory. In the case of a perfectly diffuse sound field and even distribution of absorption, the energy decay is linear when plotted on a logarithmic scale and the unique determination of a single reverberation time is possible (see **Figure 5**, *left*). The time for a sound energy level drop of 60 dB corresponds to the reverberation time.

Sadly, in most cases, we deviate from this assumption. As an example, if the absorption in the room is distributed unevenly (e.g., only the ceiling is absorptive), modes in the vertical direction will be attenuated fast, whereas modes in the horizontal plane will be reflected by the sound hard surfaces. Consequently, the assumption of a uniform damping of modes is not valid anymore. The resulting sound field decay will not be a single exponential function anymore but rather a sum of the latter (see **Figure 5**, *right*). In that case, calculating a single reverberation time is not sufficient anymore and multiple decay times must be estimated.

Hunt et al. (1939) suggested using a decay function with at least two to seven decay terms when measuring the absorption coefficient in the reverberation room . They argued that introducing an absorptive sample on the floor will always result in a sound field where at least two groups of decaying modes are present. Experimental results by Berzborn et al. (2021) confirmed the theory by Hunt et al. (1939). Different damping rates were detected for waves traveling almost parallel to the absorbing surface (slow-decaying grazing waves) and waves having oblique incidence (fast-decaying nongrazing waves). This experimental result confirmed the presence of at least two simultaneous but spatially separate decay processes during the absorption measurements theoretically considered in the past (Hunt et al., 1939; Kuttruff, 1958). The results directly contradict the assumption of a uniform damping of all modes required for application of Sabine's (1922) equation.

Schroeder (1965) noted that the integrated impulse-response method (he called it the integrated tone-burst method) to measure the reverberation time would be suitable for detecting multiple sloped-decay curves. He concluded that in most cases, we will not encounter a sound field where the decay is exponential in time. For example, his method revealed the double-sloped nature of the sound decay in the Boston Symphony Hall (see **Figure 6**). He estimated the two reverberation times (T_1 and T_2) by straight-line fits to the first 10 dB and the remainder of the decay. The results mean that an initial short decay is followed by a longer late decay, resulting in two simultaneous decay processes.

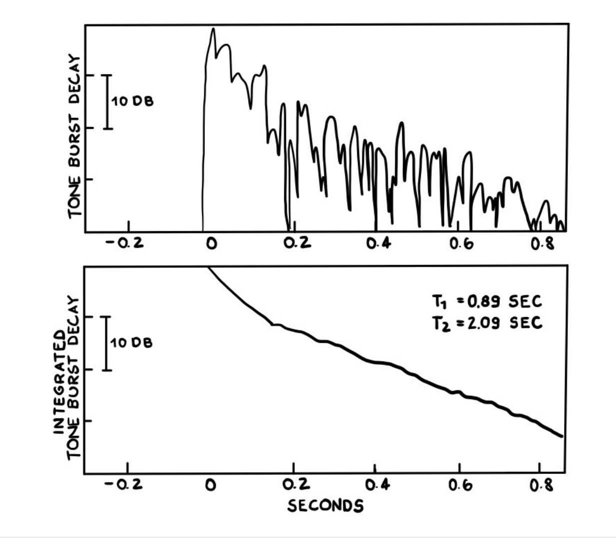


Figure 6. *Energy decay curves obtained at Boston Symphony Hall using the tone-burst method (**top**) and the integrated tone-burst method (**bottom**) suggested by Schroeder (1965). The latter method reveals the double-sloped nature of the decay curve, which results in two reverberation times,* T_1 *and* T_2*. Reproduced from Schroeder (1965), with permission of the Acoustical Society of the America, Copyright 1965.*

Unfortunately, calculating multiple decay times from one decay function is a very challenging task because it results in an inverse problem with infinitely many solutions. Luckily, Bayesian analysis provides the right framework to analyze experimental data that are subject to uncertainties and randomness (Xiang and Fackler, 2015). Xiang et al. (2011) developed a procedure where they introduced Bayesian statistics to calculate multiple decay times to characterize the decay process.

Yet, the question remains as to which of the decay times is physically meaningful to be used for calculating the absorption coefficient. Kuttruff (1958) derived theoretically that the reverberation time can be calculated from the sound decay curve by applying the inverse Laplace transform and that the beginning of the decay function contains the weighted mean of all modes. Based on Kuttruff's theory, Balint et al. (2019) used Bayesian statistics to estimate the initial decay time for calculating the absorption coefficient in a reverberation chamber. Good agreement could be achieved when comparing values of the measured absorption coefficient with theoretically calculated values.

In addition to the systematic issues associated with the lack of sound field diffusion and the nonuniform damping of modes, the reverberation chamber method is known to cause artifacts related to diffraction at the edges of the test specimen, also referred to as the *edge effect*. Absorption values exceeding unity have repeatedly been reported throughout the history of absorption measurements, indicating that the test specimen absorbs more energy than contained in the sound field present in the laboratory. Thomasson (1980) derived a model for the prediction of the *Sabine absorption coefficient* for finite-sized samples and suggested a correction term for rectangular test samples. Nonetheless, a correction term is not yet considered in measurements according to the current standards (ISO 354-2003, 2003; ASTM C423, 2023). Instead, ISO 11654-1997 (1997) suggests using the *practical absorption coefficient*, which is simply truncated to unity, a solution which is of practical nature rather than physically meaningful, especially because systematic measurement errors of materials with low absorption go unnoticed.

The implications of the edge effect are especially problematic for test specimens such as framed materials, slabs of mineral wool, or similar things that are measured in mounting conditions different from their typical applications. Having said that, the reverberation chamber method would still appear to be the most suitable method for measuring the absorption of bulky objects, such as furniture or people.

Final Remarks

Accurately measuring the properties of sound-absorbing materials in reverberation chambers has been a recognized problem in acoustics since the 1920s. Nevertheless, the reverberation chamber method remains in widespread use for measuring sound absorption coefficients and is arguably the most frequently used. There is no doubt, however, that our acoustics community would benefit from the development of novel methods that measure sound absorption more accurately. In computer simulations for room acoustics, for example, experience has shown that absorption coefficients measured in reverberation chambers yield uncertainties that are insufficient for high-precision simulation results because they produce larger systematic deviations than would be allowed by the just-noticeable differences of human hearing (Vorländer, 2013). In computational acoustics, this is even more relevant because the complex boundary impedances determine the sound pressure field. Depending on the application, uncertainties in the boundary conditions may lead to errors in the local sound pressure by orders of magnitudes. For this reason, more accurate methods for determining limiting impedances and absorption coefficients are urgently needed.

Recent developments in array technology and statistical analysis have helped us gain more insights into the physical processes in reverberant sound fields. Yet, many open questions remain. How much diffusion is enough diffusion? Can existing reverberation chambers be improved? The idea of deriving calibration or compensation methods, similar to the approaches in the currently standardized method (ISO 354-2003, 2003; ASTM C423, 2023), based on direct quantifications of sound field diffusion is also widespread. However, there are no investigations on such methods yet.

It may be necessary to clarify the different terms and their usability. Because the conditions for obtaining a *random-incidence absorption coefficient* are not verified in our reverberation chambers, one could use the term Sabine absorption coefficient to emphasize that the calculation was carried out with W. Sabine's reverberation formula and its intrinsic limitations. Another possibility, as Hunt (1939) suggested, is to the use the term *chamber coefficient*, which would describe a material measured in a given chamber.

Regardless, one may question the use of a random-incidence absorption coefficient in rooms where specific angles of incidence dominate the losses (that is, in most ordinary rooms like classrooms, office spaces, and restaurants). Shouldn't the effective use of sound-absorbing materials in room acoustical design require the use of angle-dependent coefficients as opposed to random-incidence coefficients to properly account for the dissipation of sound energy at the room's boundaries? Most likely! Unfortunately, very few data of this kind are available. Would the surface impedance be a more suitable measure of a material's absorption properties? When it comes to computational acoustics, certainly, as the absorption coefficient does not contain information on angle or phase dependency.

In 2029, the ASA will celebrate its 100th anniversary. Will the absorption coefficient problem be solved? Probably not. We are, however, at the forefront of providing some answers and some alternative solutions, to help create good sound environments with even more precision.

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Contact Information

Jamilla Balint
jba@akustik.rwth-aachen.de

Institute for Hearing Technology
and Acoustics
RWTH Aachen University
52074 Aachen, Germany

Marco Berzborn
mbe@akustik.rwth-aachen.de

Institute for Hearing Technology
and Acoustics
RWTH Aachen University
52074 Aachen, Germany

Mélanie Nolan melnola@dtu.dk

Acoustic Technology
Department of Electrical and
Photonics Engineering
Technical University of Denmark
2800 Kongens Lyngby, Denmark

Michael Vorländer
mvo@akustik.rwth-aachen.de

Institute for Hearing Technology
and Acoustics
RWTH Aachen University
52074 Aachen, Germany

For author bio, please go to
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