USING UNCERTAINTIES TO QUALIFY A SMALL REVERBERATION CHAMBER FOR ACOUSTIC ABSORPTION COEFFICIENT MEASUREMENTS

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SUMMARY

In accordance to the European standard ISO 354, the absorption coefficient measurements are performed in a large reverberation room to provide diffuse field conditions above 100Hz but they require large material surface. For the needs of the automotive industry, small reverberation rooms have been developed (so-called Alpha Cabin) to perform faster and cheaper measurements, but there is no information about the reliability and the uncertainties of the results. A few years ago, the CTTM developed its own small chamber and validated it estimating the confidence intervals (based on the GUM) of the absorption coefficients of a large panel of materials measured both in the large and the small chambers of the CTTM.

INTRODUCTION

The acoustic absorption coefficient measurements, defined by the European standard ISO 354[1] and the US standard ASTM C423[2] mainly concern building acoustics. These standards methods require large reverberation room (greater than 200 m^3) in order to provide a diffuse field above 100 Hz and require large test sample area (about 12 m² for the European standard and 7 m² for the US one). These recommendations are not suitable to the needs of the Automotive Industry : smaller components, fast testing procedures, lower cost of the equipments, etc. Due to these needs, the development of small size rooms began several years ago in Europe and in the United States (Chappuis[3], Kolano[4], Rieter[5]) and specially with a small reverberant room (Chappuis[3]), called Alpha Cabin, which volume is 6.44 m^3 and with the feasibility to test sample of area 1.2 m². This cabin is a small scale reduction of 1:3 of the reverberation room at the Swiss Federal Laboratory of Material Testing and Research Institute in Dübendorf. This test device is commercialized by Rieter[5] and is commonly used by the car manufacturers and subcontractors. Renault and PSA have jointly developed their own testing procedure[6] to measure the absorption coefficient with the Alpha Cabin. The procedure imposes a minimum and a maximum reverberation time for the empty cabin (Figure 2). This template is presented as a validity criterion for measurements done in this device.

THE CTTM CABIN

In order to perform absorption and insulation measurements, the CTTM developed its own small chamber (Figure 1) with the recommended volume (6.44m^3) and expanded area (22.2m²) as the Alpha Cabin but with a geometry based on a small scale reduction of approximately 1:4 of the large reverberation room of the CTTM.

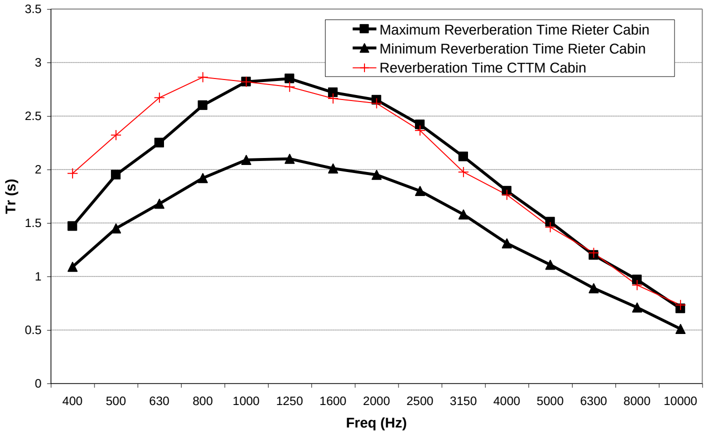


Figure 1 CTTM Small reverberation room

Figure 2 CTTM Cabin Reverberation Time (without material)

After the use of wall mounted diffusers to improve the diffusivity in accordance with the European standard ISO 354[1], the reverberation times of the CTTM cabin are greater than those imposed by the Renault testing method[6], particularly in lower frequencies (Figure 2). This behaviour is assumed to be due to its geometry which is strongly different from the Rieter cabins which are more elongated. Hence, the CTTM cabin does not match with the Renault testing method[6].

However, the atypical acoustic behaviour of the CTTM cabin in comparison with the Rieter Cabin does not qualify its no-usage for absorption measurements.

For this reason, this article presents the validation of the CTTM cabin by a statistical approach and an evaluation of the confidence intervals of the absorption coefficients compared with those obtained in the large reverberation room of the CTTM in accordance with the European standard ISO 354[1].

BIBLIOGRAPHY STUDY

Comparisons between reverberation chambers

These last decades, several measurement campaigns have been conducted to measure absorption in different reverberation installations, in order to compare the results and evaluate the scattering between laboratories[2], [7], [8]. The US standard[2] uses the results of some tests done in 1980 to estimate the reproducibility and the repeatability allowable for the sound absorption coefficients. Recently, a test study was conducted (Veen[8]) to evaluate the feasibility of an US standard for measuring absorption coefficients in small reverberation rooms. This study compares the results obtained in 4 large volume rooms (more than 170m^3), 4 medium volume rooms (25m^3) and 11 cabin of 6,4m^3. Overall, these results underline strong variance on the absorption coefficients, about 0,2 for high coefficients (near 1). Moreover, in low frequencies, the small reverberation rooms present higher scattering of the results due to the sound diffraction at the edges of the absorbent area being important and due to the modal behavior of the volume.

Parameters influencing the absorption measurement

The absorption coefficient measurement in small reverberation room is mainly influenced by the edge effects of the sample in two ways :

- the diffraction phenomena at the upper edges around the sample
- the increase of the absorbing area by the edges surface

Concerning the diffraction effect, Chappuis[3] and Bartel[9] show that the absorption coefficient can be linked to the ratio of the sample perimeter to sample area by an experimental relationship :

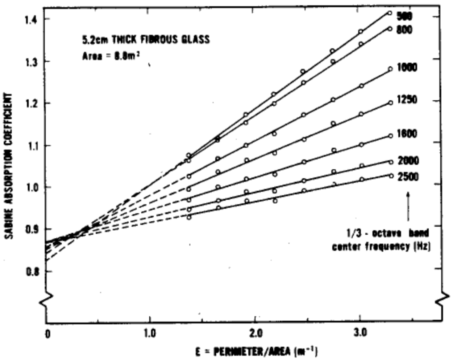
$$\alpha = \alpha_0 + \beta E \qquad (1)$$

with :

- α, the "apparent" absorption coefficient, i.e. measured in reverberant room,
- α_0, the absorption coefficient for a sample of infinite dimensions,
- E, the ratio of the perimeter to area,
- β, a constant depending on the intrinsic properties of the material and on the frequency.

With measurements done in large devices, in accordance with standards, the ratio E equals approximately to 1,2 m^{-1}, whereas E equals approximately 3,7 m^{-1} for samples tested in small reverberation room. An example of the diffraction effect is shown on Figure 3 on a thick fibrous glass (from Bartel[9]). Using a constant surface of material, the absorption coefficients are measured with different arrangements (several perimeters) of the sample, and with edges covered with non absorbent material. Therefore, the effect of diffraction can be important for high values of E, i.e. in a small reverberation room whereas it can be negligible in a large reverberation device. Consequently, a strong overestimation of the absorption coefficient can occur in Alpha cabin.

Figure 3 Absorption coefficient of a very absorbent material as a function of the perimeter to area ratio



Chappuis[3] uses this property to measure the absorption coefficient in an Alpha cabin. Indeed, with measurements done with several values of E in small room, it is possible to estimate what the absorption coefficient would be if measured in a large room (by a linear extrapolation to E=1,2 m^{-1}). The author specifies that this method can be accurate beyond the 500 Hz band frequencies.

However, according to him, if very accurate results are not required, the edge effects due to diffraction can be compensated by applying a weighted factor of 0.92 to the classical Sabine coefficient. This value has been determined by matching measurements performed in a large reverberation room and an Alpha Cabin. This formulation is used by the Renault testing method[6] with a slightly larger correction factor.

Concerning the additional absorption due to the edges areas, Bartel[9] shows that if the edges are not covered, this effect can be important if the material is non isotropic over the thickness. Strong relative errors (5 to 10 %) occur as a function of the thickness (1,5 to 5 cm) even if the edge area is included in the calculation of the coefficient.

Finally, other parameters can influence the absorption measurements, but in a lesser extent as the dimensions and the geometry of the cabin (Kosten[7]), the temperature and the air humidity at higher frequencies, the shape of tested sample (Bartel[9]) and the quarter wavelength effect that overestimate the absorption when thickness is comparable to the one-fourth of the sound wavelength (Nwankwo[10]).

Test facilities

Classical configurations, such as those described by the European standard ISO354, use either a simple rotating microphone or several microphones scattered within the test volume. However, in a small reverberation room, Kolano[4] and Jackson[11] use boundary microphones placed in the room corners. In this configuration, the scattering of the measurements decreases notably compared to the results obtained with classical arrangements of the microphones, specially in low frequencies where a modal behavior appears (Kolano[4]). Indeed, close to the wall, the microphone diaphragm is exposed to a pressure maximum as opposed to a microphone placed in the volume, which can be exposed to a pressure node due to the weak modal density in low frequencies. Therefore, due to the low pressure gradient near to wall, the measurement is less sensitive to the microphone position.

Usually to obtain diffuse field, the room excitation is performed with one or several loudspeakers that present an omnidirectionnal directivity. Jackson[11] uses a large vibrating panel to optimize the spacially and temporally diffuseness.

Finally, in the objective of limiting the edges effects, i.e. diffraction and additional absorption, Wentzel[12] developed a special apparatus where the sample is mounted in a cavity with an adjustable depth that allows the surface to be flush with the floor of the chamber. However this solution requires a complex system, and the comparisons with measurements done in large reverberation rooms still show variance of about 0,2 on the absorption coefficients at low frequencies.

CUT-OFF FREQUENCIES

According to the ISO354[1] standard, the measurement of the absorption coefficient is based on the fundamental assumption that the acoustic field is diffuse. Unfortunately, this condition is hardly feasible in low frequencies and strongly deteriorated when the material is placed in the room.

However, it is widely acknowledged that the acoustic field is considered diffuse when the modal density is sufficient, i.e. when all the modes overlap each other.

Depending on the authors and on the assumptions done to establish the diffuse field frequency limit, several formulations exist. The most admitted is the well-known "Schroeder" frequency (Bruneau[13]) :

$$f_c = 2000\sqrt{\frac{T}{V}} \qquad (2)$$

where T is the longest reverberation time measured. For the CTTM cabin (Figure 2), $T \cong 3$s and $V=6{,}44\text{m}^3$, given a cut-off frequency in the order of 1360 Hz.

Nélisse et al.[14] suggest a formulation based on the concept of modal overlap :

$$f_c \approx \sqrt[3]{\frac{\alpha c^3}{4\pi\eta V}} \qquad (3)$$

where α and η represent respectively the modal overlap and the damping. With $\alpha=3$ and $\eta=0{,}005$ (Nélisse and al.[14]) this last relation gives approximately 660Hz for the cabin. At last Kolano[4] introduces the next formulation coming from an US Standard :

$$V = 4\lambda_{\min}^3 \qquad (4)$$

with λ_{min}, the cut-off wavelength, that gives 290 Hz for the cabin.
Hence, the validity criterion for the low frequencies is not well established.
Finally, in the literature, the use of small measurements volumes as the alpha cabin often imposes a cut-off frequency of about 400 Hz.

SABINE FORMULATION

According to the European standard ISO354[1], the absorption coefficient in third octave bands is computed from the well-known Sabine relationship :

$$\alpha = \frac{0{,}16V}{S_m}\left(\frac{1}{T_m} - \frac{1}{T_e}\right) = f(T_m, T_e) \qquad (5)$$

where V is the volume of the test chamber, S_m is the sample area tested, T_e and T_m are respectively the reverberation times by frequency bands measured without and with material inside the room.

UNCERTAINTIES ON THE ABSORPTION COEFFICIENT MEASUREMENTS

The uncertainties on the absorption coefficient measurements are evaluated according to ISO "Guide to the expression of uncertainty in measurement"[17] called "GUM". The Acoustical technical committee of ISO considers this standard as a reference (Bessac et al.[19]).
This approach uses a model of the measurand by a function linking the input quantitities. In our case the absorption coefficient α is the measurand, the model is the explicit analytical function f of relation 5 and the input quantities are V, S_m, T_m and T_e. The estimated standard deviation of α is represented by the combined standard uncertainty $u_c(\alpha)$ and is then expressed by the *law of propagation of uncertainty* combining the individual standard uncertainties of the input values.
Considering as negligible the error due to the evaluation of the volume V of the test chamber and the area S_m of the sample and considering the input quantities T_m and T_e not correlated, the law of propagation of uncertainty for α can be expressed as :

$$u_c^2(\alpha) = \left(\frac{\partial f}{\partial T_m}\right)^2 u^2(T_m) + \left(\frac{\partial f}{\partial T_e}\right)^2 u^2(T_e) \qquad (6)$$

For i = (m, e), $\partial f / \partial T_i$ represents the sensibility coefficient that weights the standard uncertainty $u(T_i)$ of T_i :

$$\frac{\partial f}{\partial T_i} = \left(\frac{0{,}16V}{S_m}\right)\frac{1}{T_i^2} \qquad (7)$$

The evaluation of the individual standard uncertainty are based on a statistical approach using the standard deviation of the mean (type A approach) :

$$u^2(T_i) = \frac{\sigma^2(T_i)}{n} = \frac{1}{n(n-1)}\sum_{k=1}^{n}\left(T_{i,k} - \overline{T}_i\right)^2 \qquad (8)$$

where n is the number of measurements.
Combining the relations 6 to 8, one estimates the combined standard uncertainty for α as :

$$u_c^2(\alpha) = \left(\frac{0{,}16V}{S_m}\right)^2 \left(\frac{\sigma_m^2}{n_m T_m^4} + \frac{\sigma_e^2}{n_e T_e^4}\right) \quad (9)$$

In this relation the suffixes "m" and "e" appear due to different number of measurements in each situation.
This formulation is identical to the one proposed by Shing[20].
Finally, the absorption coefficient is given in the following form :

$$\alpha \pm k.u_c(\alpha) \quad (10)$$

where k.u$_c$(α) is called the expanded uncertainty and k the coverage factor.
If we consider a normal distribution of the measurements of T$_m$ and T$_e$, k is usually equal to 2, which corresponds to an interval with a level of confidence close to 95 percent.

WEIGHTING MEASUREMENTS IN CABIN

The Sabine formulation (relation 5) is applied for measurements done in large reverberation chambers. For tests done in the cabin, the strong effect of diffraction requires to adjust the values obtained by the Sabine relation. The Renault testing method[6] uses a weighting scalar coefficient W (about 0,9) to correct this effect :

$$\alpha = \frac{0{,}16V}{S_m}\left(\frac{1}{T_m} - \frac{1}{T_e}\right).W \quad (11)$$

The validation approach in this paper is based on a similar formulation, but with a weighting factor depending on frequency on each third octave frequency band. Hence, the weighted absorption coefficient measured in small room is written as follows :

$$\alpha_w(f) = W(f).\alpha(f) \quad (12)$$

where α(f) if the absorption coefficient evaluated by the Sabine theory (relation 5) and W(f) is the mean of the ratios of the absorption coefficients obtained both in the large and the small reverberation room of the CTTM on N different materials :

$$W(f) = \frac{1}{N}\sum_i \frac{\alpha_i^{reverb}(f)}{\alpha_i^{cab}(f)} \quad (13)$$

UNCERTAINTIES ON THE WEIGHTED COEFFICIENT

The weighted absorption coefficient is function of three parameters T$_m$, T$_e$ and W. Considering the weighting factors obtained independently and using the previous approach, the combined standard uncertainty of the weighted absorption coefficient can be expressed as:

$$u_c^2(\alpha_w) = W^2.u_c^2(\alpha) + \alpha^2.u^2(W) = W^2\left(\frac{0{,}16V}{S_m T_m^2}\right)^2 u^2(T_m) + W^2\left(\frac{0{,}16V}{S_m T_e^2}\right)^2 u^2(T_e) + \alpha^2.u^2(W) \quad (14)$$

The term u$_c$(α) is computed from relation 9 and u(W) is the standard uncertainty of the weighting coefficient that can be evaluated using the standard deviation of the mean of the ratios (N is the number of materials) :

$$u^2(W) = \frac{\sigma^2(W)}{N} \quad (15)$$

Considering a coverage factor of 2 corresponding to an interval of confidence of 95%, the weighted absorption coefficient tested in cabin is finally :

$$\alpha_w \pm 2.u_c(\alpha_w) \tag{16}$$

EXPERIMENTAL VALIDATION

Frequency range

The bibliography study shows that the low frequency limit above which one considers the acoustic field to be diffuse is not well established. Thus, this experimental validation has been voluntarily done in a large frequency range outwards the conventional limits : from 100 Hz to 10000 Hz.

Experimental devices

Concerning the acoustical excitation in the large reverberation room, two high level speakers are used, functioning separately during the measurement in accordance with the ISO354[1]. In the cabin, the acoustical source is composed of three loudspeakers connected in series and scattered in the volume near the corners. They are functioning simultaneously during the test in the objective of optimize the diffuseness of the acoustic field.

Concerning the acquisition, four ½" diffuse field microphones are used in both chambers. They are distributed in the measurement volume in the large reverberation room, but placed near the corners in the cabin. Indeed preliminary tests have confirmed the interest of this technique in order to decrease the scattering of the measurements (Kolano[4]).

Concerning the decay rates analysis, the data are treated by the dB4+ acquisition board and the dBBati2 software by 01dB using Schroeder integration routines.

Measurements methods

The measurements in the large reverberation room are done in accordance with the European standard ISO354[1]. Thus for each sample, an area of approximately 12 m² of material is used, and the borders are covered with a non absorbent material. Furthermore, both with and without material, 48 decay rates measurements are performed between 100 and 800 Hz and 24 decay rates between 1 and 10 kHz.

In the cabin, as in the Renault testing method[6], the tested samples all have an area of 1,2m². In order to minimize the additional absorption due to the edges areas, which becomes important in a small device, metal frameworks of adjustable height are placed on the ground. The measurement without material is done with the framework.

Furthermore, in case the samples are not homogeneous (small area tested), three samples of the same material are measured successively with 16 decay rates each. Finally, 48 decay rates are acquired with material and 16 for the empty cabin.

Tested materials

The comparative measurements have been performed on 19 materials that differ in nature (felts, mineral wools, foams), thickness (from 10 to 80 mm) and shape (flat or corrugated surfaces). These materials have been supplied by three manufacturers.

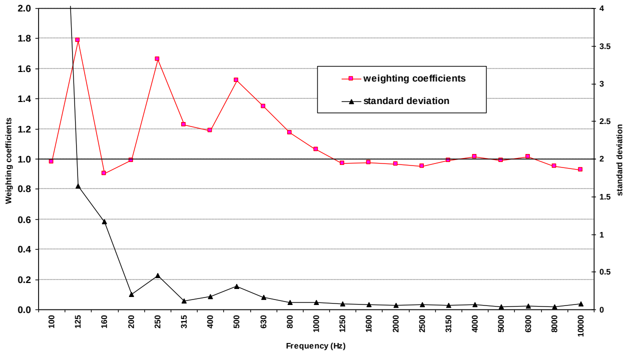
RESULTS

The weighting law

Figure 4 shows the weighting curve, i.e. the correction factors computed from relation 13 and the corresponding standard deviation obtained with the 19 different materials.

Above 1 kHz, the correction factors are close to unity which means that measurements done in cabin are very similar to those done in the large room. On the other hand, the weighting is essential for the frequency bands below 1 kHz, range in which the correction factors are widely different from unity and especially in the 125, 250 and 500 Hz bands. These irregularities are certainly due to the presence of standing waves at theses frequencies. In this frequency range, the measurements done in the cabin under estimate the absorption coefficient.

Figure 4 Weighting curve



Furthermore, this curve shows that above 1 kHz, the diffusivity seems to be correct in the cabin whereas below this frequency the diffuse field assumption is not respected.

The evolution of the correction factor with respect to frequency is rather different from the scalar usually used in the Alpha Cabin, proposed for example by Chappuis[3]. Indeed the main interest of this correction factor is to compensate the effects of diffraction in the medium and high frequencies, whereas our weighting correction takes into account the modal behaviour of the cabin at low frequencies.

Concerning the standard deviation on the mean of the correction factor, it is very small above 1 kHz (<0,1) and acceptable from 200 Hz (<0,4). In contrast, for the lower frequencies, it becomes very high and the comparisons done between the large reverberation room and the cabin are not possible. This behaviour is certainly due to the very weak values of the absorption coefficients in addition with a rough diffusivity.

Absorption coefficients

As illustrated below, the weighting law is applied to two usual absorbent material : a foam of flat surface and 20 mm thickness (Figure 5) and a corrugated foam with a variable thickness ranging between 25 and 45 mm (Figure 6).

Each of these figures shows the benchmark measurement done in the large reverberant room of the CTTM, and the measurements done in the cabin with and without the weighting correction.

Figure 5 Absorption coefficient for a 20 mm foam

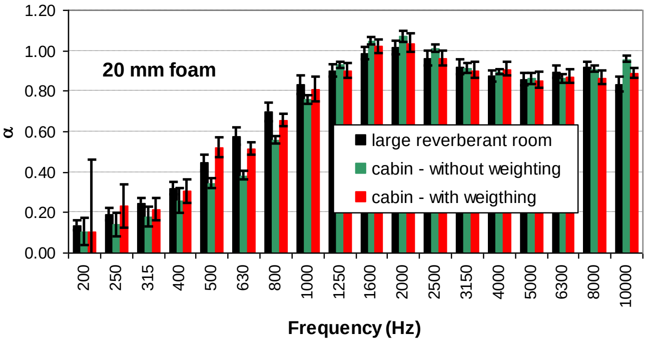
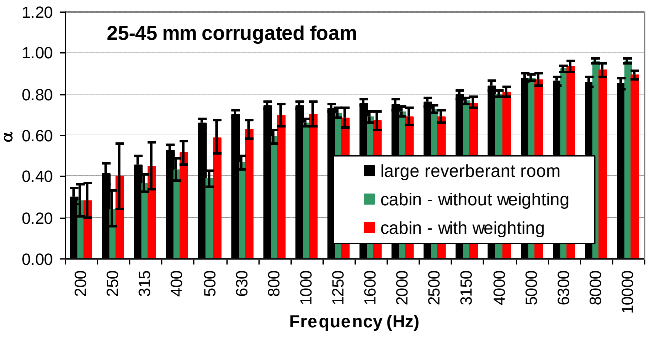


Figure 6 Absorption coefficient for a 25 - 45 mm corrugated foam

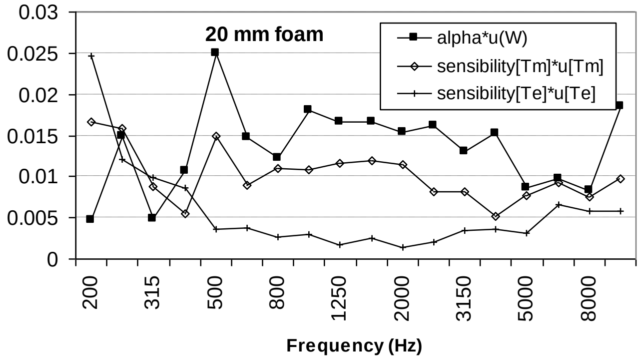


Hence, the application of the weighting law permits the correction of the raw values obtained in the cabin, specially below 1 kHz, range where the correction factors are widely different from unity (see Figure 4).

Concerning the uncertainties, the weighting correction allows again the overlap of the absorption coefficients in most frequency bands. In particular, the uncertainties of the weighted absorption coefficient become important at low frequencies specially in the 200 and 250 Hz frequency bands.

Figure 7 illustrates an example of the weighted standard uncertainties of each parameters measured (see equation 14) : the weighting coefficient W, the mean reverberation times T_e and T_m.

Figure 7 Weighted standard uncertainties of the corrected absorption coefficient



The most important term is the uncertainty due to the application of the weighting coefficient and then the uncertainty of the mean reverberation time T_m, i.e. obtained with material. It should be important to underline that this last term becomes important with material very absorbent in relation with its sensitivity factor proportional to $1/T_m^2$ (equation 7). Finally, in the objective of reducing the composed uncertainty of the weighted absorption coefficient, an effort should undertook on the uncertainty of the weighting law W.

CONCLUSION

Thanks to the automotive industry, the use of Alpha cabins is widely spread in the industrial laboratories. However, the measurements performed in these devices permit relative comparisons between absorption materials. Only benchmark results can be obtained in large reverberant room according to the ISO and ASTM standards. Furthermore, there is no information about the results reliability, mainly below the cut-off frequency and no information about the uncertainties.

The statistical study presented in this paper and the evaluation of the absorption coefficient uncertainties has permitted the validation of the small reverberation chamber of the CTTM. The use of a weighting correction to the cabin results allows for reliable measurements from 200 Hz, far below the conventional limits.

Currently, the small reverberation chamber of the CTTM is being validated to perform other application such as insulation measurements of small samples.

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