Editor's Note: The following paper was orginally published in the March 2011 issue, but it was laid out improperly. We apologize for this oversight and the full paper is reproduced below.

REVERBERATION MEASUREMENT AND PREDICTION IN GYMNASIA WITH NON-UNIFORMLY DISTRIBUTED ABSORPTION; THE IMPORTANCE OF DIFFUSION

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ABSTRACT

As part of a performance verification exercise reverberation times (RT) were measured in several newly constructed school gymnasia, rectangular in plan with two variations in room size, all with similar finishes and constructions. Due to architectural constraints, the rooms have acoustically hard finishes below a height of 3 m. The room finishes are primarily acoustically reflective with the exception of continuous bands of absorptive upper wall paneling around the full perimeter of the rooms (exposed unpainted Tectum over mineral fibre insulation) and painted acoustic metal deck ceilings (fiberglass insulation in the perforated deck flutes). The initial RT measurements exceeded the design targets. Modeling using ODEON room acoustics prediction software was conducted to determine the quantity and placement of additional absorption required to bring the RT into compliance. After installation of an additional continuous band of absorptive paneling in the rooms at a height below the existing panels, the RT were re-measured. The mid-band average RT increased, with a 0.5 sec RT increase at 1000 Hz in one room and a 1 sec RT increase at 1000 Hz in another. Further investigation lead to the hypothesis of an insufficiently diffuse sound field and uninterrupted standing wave modes in the lower untreated portion of the room contributing to the unexpected results. RT were subsequently re-measured under 5 different conditions; an empty gym, addition of 5 people, and 3 levels of diffusion. Diffusion was varied by adding sheets of plywood (5, 10, 15 sheets) leaned against posts or each other. The addition of as few as 5 people or 5 plywood sheets was found to significantly reduce the measured RT, closer to the modeled predictions, with between a 0.6 sec and 1 sec reduction observed in the mid-band average RT from the empty condition.

RÉSUMÉ

Dans le cadre d'un exercice de vérification des performances, les temps de réverbération (RT) ont été mesurés dans plusieurs gymnases d'école nouvellement construits d'un plan rectangulaire, avec deux variations de taille de pièce, mais tous avec des finitions et de construction semblables. En raison de contraintes architecturales, les salles n'ont aucune finition acoustiquement absorbante au-dessous d'une taille de 3 M. Les finitions de pièce sont principalement acoustiquement réfléchissantes, à l'exception des bandes continues du panneautage absorbant de mur supérieur autour du périmètre complet des salles (Tectum exposé non peint sur l'isolation de fibre minérale) et des plafonds peints de plate-forme en métal acoustique (isolation de fibre de verre dans les cannelures perforées de plate-forme). Les mesures RT initiales ont excédé les exigences de performance. La modélisation en utilisant le logiciel de prévision d'acoustique des locaux d'ODEON a été fait afin de déterminer la quantité et le placement d'absorption supplémentaire exigés pour introduire le RT dans la conformité. Après l'installation d'une autre bande continue du panneautage absorbant au-dessous des panneaux existants, les RT ont été remesurés et se sont trouvés plus hauts de 0.5 sec à la bande 1000 Hz dans une salle et 1 sec plus haute dans l'autre. Plus de recherche a mené à l'hypothèse qu'un champ acoustique insuffisamment diffus et des modes d'onde stationnaire non interrompus dans la partie non traitée au bas de la salle ont contribué aux résultats inattendus. Les RT ont été remesurés dans 5 conditions différentes; un gymnase vide, avec l'addition de 5 personnes et avec 3 niveaux de diffusion. La diffusion a été variée en ajoutant des feuilles de contreplaqué (5, 10 et 15 feuilles) appuyé contre les poteaux ou l'un à l'autre. L'addition de seulement 5 personnes ou de 5 feuilles de contreplaqué a réduit les RT mesurés, entre 0.6 sec et 1 sec dans la moyenne des mi-fréquences en comparaison de la salle vide, un résultat plus près des predictions modélisées.

1. INTRODUCTION

School gymnasia present several acoustical challenges as the rooms must support variety of uses, mainly athletic instruction, practice and competition, school and community gatherings, as well as both drama and music performances. Excess noise levels and reverberation are common concerns for these facilities. However considerations such as user safety, surface durability and impact resistance, ease of maintenance and clean-ability often dictate the application of acoustically reflective finishes in the occupied portion of the room. Further, the room contain parallel and acoustically reflective floors, ceilings, and lower wall surfaces.

Previous research [1] has indicated that reverberation times (RT) between 1.5 and 2 seconds across the speech frequency range are favourable for gymnasia in order to preserve a sense of excitement for sporting activities and liveliness for musical performances while not significantly compromising speech intelligibility which is strongly dependent on reverberation time and background noise levels.

This paper documents the results of RT measurements conducted in several newly constructed school gymnasia as part of a performance verification exercise for the builder. These gymnasia are located in Alberta where current government design standards [2] stipulate that RT in a typical unoccupied gym not exceed 2.0 sec averaged over the frequency range of 500 to 2000 Hz.

The gymnasia were built with acoustical finishes described as acceptable in the Alberta Infrastructure design guidelines [2], however the initial RT measurements did not meet the design target. Furthermore, the mid-band average RT measured after the installation of additional acoustically absorptive treatment were found to be higher, with a 0.5 sec RT increase at 1000 Hz in one room and a 1 sec RT increase at 1000 Hz in another, contrary to intuition and the predictions from geometric room acoustical modeling.

It was noted that the presence of a minimal amount of solid objects on the floor during some of the measurement sessions appeared to significantly influence the measured RT, with a 1.2 sec RT decrease at 1000 Hz in one room and a 1.4 sec RT decrease at 1000 Hz in another. This led to the hypothesis of an insufficiently diffuse sound field and uninterrupted standing wave modes in the lower untreated portion of the room contributing to the unexpected results.

RT were subsequently re-measured under 5 different conditions; an empty gym, addition of 5 people, and 3 levels of diffusion. Diffusion was varied in a simple manner by adding sheets of plywood (5, 10, 15 sheets) leaned against posts or each other. The addition of as few as 5 people or 5 plywood sheets was found to significantly reduce the measured RT, closer to the modeled predictions. The results of the above investigations are presented in this paper.

2. ROOM DESCRIPTIONS

Eighteen new elementary schools, nine in Calgary and nine in Edmonton, were constructed for the Alberta Government in a Public Private Partnership P3 arrangement. Two of the seven basic school designs were chosen by the builder for acoustical testing. Two of the schools were in Calgary and the other two were in Edmonton.

The measured gymnasia were rectangular in plan with two different room sizes: Type A, 27.8 m x 18.5 m, slightly sloped ceilings 9.3 m to 9.6 m above finished floor (AFF); Type B 24.0 m x 18.0 m, ceilings 9.1 to 9.5 m AFF. The finishes were painted concrete block walls to 3 m above a cushioned wood floor and painted 2-layer 16 mm thick abuse-resistant gypsum board walls to the underside of a painted acoustic metal deck ceiling. According to an acoustical lab test report provided by the metal roof deck manufacturer, the acoustic deck has a Noise Reduction Coefficient (NRC) of 0.75 with a pronounced peak in the mid-band absorption.

Initially, two 1.2 m high continuous bands of exposed unpainted Tectum/mineral fibre paneling (38 mm mineral fibre behind 25 mm Tectum, edges concealed with wood trim) extended around the full perimeter of the rooms on the upper walls, approximately 222 m^2 and 202 m^2 in the Type A and B gymnasia respectively, providing roughly 25% wall coverage. The bottoms of the panels were approximately 4.5 m AFF in the Type B gyms and approximately 5.5 m AFF in the Type A gyms. According to the panel supplier the tectum/mineral fibre panels have an NRC rating of 0.85 with significant mid-frequency absorption.

3. METHODOLOGY AND LIMITATIONS

A tripod-mounted Brüel & Kjaer 2270 Precision Real Time Sound Level Analyzer equipped with a Brüel & Kjaer 4189 microphone and Brüel & Kjaer UA 1650 windscreen and version 3.2 of the BZ7227 Reverberation Time software was used to record, archive and evaluate the RT measurements. Microphone height was approximately 1.8 m AFF.

Sound decays were measured at a minimum of 5 locations in the rooms with the exception of the first set of measurements in Gym A-1 and Gym B-1. During these initial survey measurements decays were measured at 3 positions in Gym A-1 and at 4 positions in Gym B-2. Measurement positions were consistent (within ~0.5 m) between repeated measurement sessions in the same gymnasium. Standard deviation in RT between measurement positions did not generally exceed 0.1 sec in the 250 Hz to 4000 Hz range. However the standard deviation in RT between measurement positions was as high as 0.14 sec at 125 Hz and 0.12 sec at 1000 Hz in some instances.

Sound impulses were generated from large diameter balloon bursts and the decays measured. In some instances the measurements were repeated with decays generated with interrupted pink noise played over a JBL Eon Power 15 amplified speaker. Good agreement was found between the two methods with the measured mid-band average RT generally within 0.1 sec for the same room using the two methods. During the final measurement session with added diffusion only large diameter balloon burst impulses were used. Reported RT are those measured with large diameter balloon burst impulses.

Background noise measurements were taken during each measurement session and found to not exceed RC 35 (N) with the exception of the initial measurements in Gym A-1 which were taken before the HVAC system air-balancing was completed and met an RC 46 (HF). In all cases sufficient sound energy was generated in the frequencies of concern for the decays that the background sound levels were not a factor in the RT measurements.

4. RESULTS & MODELLING

The initial RT measurements (see Figure 1) did not meet the design target and were surprising in that the mid-band average RT in the slightly smaller Type B gym were 1.2 sec higher than those measured in the Type A gym. These measured times were higher than expected considering the extent of and the manufacturer-claimed mid-band sound absorption of the acoustic deck and acoustic panels.

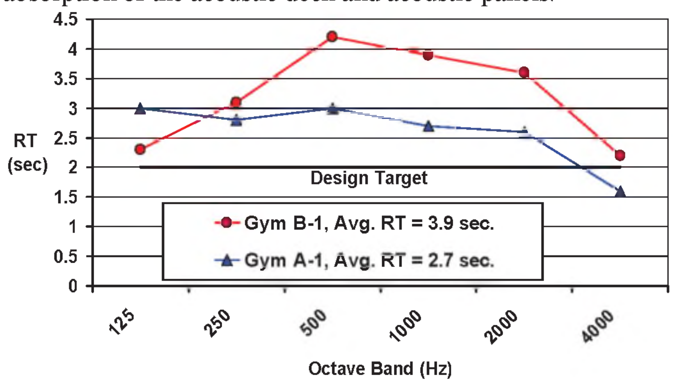

Figure 1. Initial measured gymnasia RT with ~25% wall panel coverage.

The acoustical treatments in this Type B gym were inspected and no problems or defects were apparent. The acoustic deck perforations were not sealed with paint and the flutes had fibrous batt insulation in them. The Tectum appeared to be installed as per the manufacturer's recommendations; the Tectum was porous and mineral fibre was present behind the Tectum.

The RT were re-measured in this room. With the room empty (except for the scissor lift used for the acoustic treatment inspection) the re-measured RT were lower than the initial measurements yet still above the performance requirement (see Figure 2).

A lack of adequate absorption was presumed and the two basic variations of gymnasia (Type A & B) were modelled using ODEON room acoustics prediction software to determine the quantity and placement of additional absorption required to bring the RT into compliance. ODEON is based on prediction algorithms (image-source method, ray-tracing and ray-radiosity) that account for scattering due to surface roughness and diffraction. A reflection-based scattering method is used that accounts for frequency-dependent scattering [3]. Scattering coefficients were chosen according to ODEON guidelines [4].

Air temperature and humidity readings recorded during the gymnasia RT measurements were used in the modelling (Type A Gym: 20 °C, 37% RH, Type B Gym: 20 °C, 38% RH).

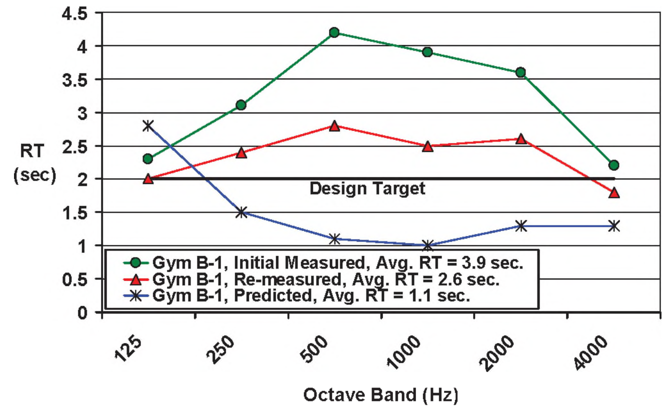

Figure 2. Initial (circles) and re-measured (triangles) RT in Gym B-1 with ~25% wall panel coverage. Predicted RT (asterisks) also shown.

As explained by Cox and D'Antonio [5], the accuracy of geometric room acoustic modelling software is limited by the validity of the input data, namely the accuracy of the modelled room geometry, surface sound absorption and scattering coefficients. In this case the geometry for the gymnasia is not complex. Furthermore, with the exception of the acoustic deck and Tectum panels the absorption coefficients for the various room materials are fairly well established in literature. This does not mean these values are infallible.

Recent literature by Cox and D'Antonio [5] and Sauro and Mange [6] describe how there can be significant uncertainty in absorption coefficients even for common materials due to factors such as sample size, edge effect (sound diffraction at sample edges), and variations in diffusion and sample mounting conditions between various testing labs. Cox and D'Antonio recognize that with practice experienced acoustical modellers gain an understanding of how absorption coefficients vary between lab test data and real rooms. Uncertainties in absorption coefficients are dealt with by adjusting absorption coefficients used in the modelling based on measured RT with repeated use of surface treatments on various projects over time. This is relevant to this study in that both acoustic deck and Tectum panels have been used in enough projects to establish that they provide at least some absorption in the critical mid frequency bands.

As the predicted RT with the acoustic treatment manufacturers' absorption data were significantly below the measured values, the absorption coefficients in the models were 'calibrated' so that the predictions better matched the measured RT. The calculations indicated that an additional 148 m^2 of panels were required in the Type A gyms and an additional 96 m^2 of panels were required in Type B gyms.
A third continuous 1.2 m high band of panels approximately 111 m^2 in area was installed in the Type A gymnasia at a height below the existing panels (bottom of panels constrained to a height approximately 3.4 m AFF). The resulting wall panel coverage in the Type A gymnasia was approximately 40%. In the Type B gymnasia a third

continuous band of panels approximately 76 m^2 to 101 m^2 in area (depending on interference with existing perimeter radiation cabinets) was installed at a height below the existing panels (bottom of panels approximately 3 m AFF). The resulting wall panel coverage in the Type B gymnasia was in the 35% to 40% range.

The RT were re-measured and the mid-band average RT were found to be higher due to primarily to the higher RT at 1000 Hz, contrary to intuition and the predictions (see Figures 3, 4 & 5). The measurement results seemed to indicate a greater difference from the predicted RT than could be explained by invalid absorption and/or scattering coefficients. Subsequent adjustments to these model inputs confirmed this.

The commissioning agents for the project had their independent acoustical consultant conduct RT measurements in Gym B-2 [7]. As can be seen in Figure 5 the results of these measurements were significantly higher, a mid-band average RT of 2.8 sec vs. 2.1 sec.

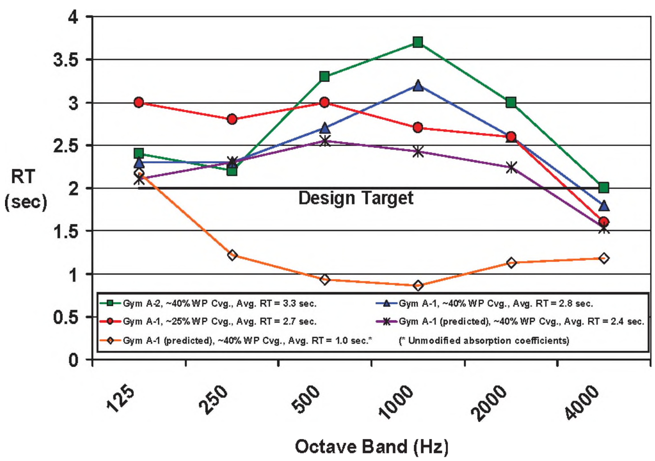

Figure 3. Comparison of initial, re-measured and predicted RT in two Type A gymnasia with varying wall panel coverage. Squares: Gym A-2, ~40% wall panel coverage. Circles: Gym A-1, ~25% wall panel coverage. Triangles: Gym A-1, ~40% wall panel coverage. Asterisks: predicted RT with modified acoustic treatment absorption coefficients. Diamonds: predicted RT with unmodified acoustic treatment absorption coefficients.

5. DIFFUSION AND REVERBERATION

A diffuse sound field is described by Cox and D'Antonio to have uniform reflected energy density throughout the room and where all directions of sound propagation are equally probable [5]. Extensive research has been done by Cox and D'Antonio and others exploring the effects of diffusion on reverberation. In an online paper [8], Dalenbäck states that by redirecting the reflected sound in many directions, diffuse reflection allows room surfaces to be hit by sound in a more uniform manner so that absorbing surfaces are better utilized. He also discusses the example of a rectangular, predominantly concrete gymnasium with absorption only on the ceiling where the measured RT at 1 kHz was 5.7 sec compared to the predicted RT at 1 kHz which varied from 1.9 sec to 13 sec using a variety of statistical and geometric computerized prediction methods that did not account for diffuse reflections. With geometric computer prediction models that accounted for surface scattering the predicted RT at 1 kHz were between 5.1 and 5.9 sec.

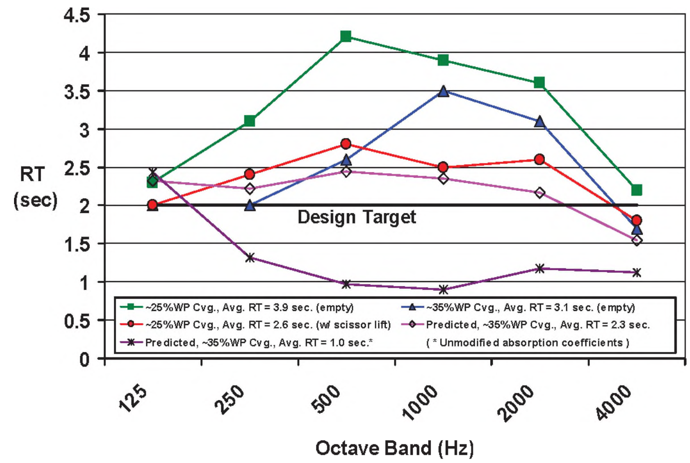

Figure 4. Comparison of initial, re-measured and predicted RT in Gym B-1. Squares: ~25% wall panel coverage. Circles: ~25% wall panel coverage (with scissor lift present). Triangles: ~35% wall panel coverage. Diamonds: predicted RT with modified acoustic treatment absorption coefficients. Asterisks: predicted RT with unmodified acoustic treatment absorption coefficients.

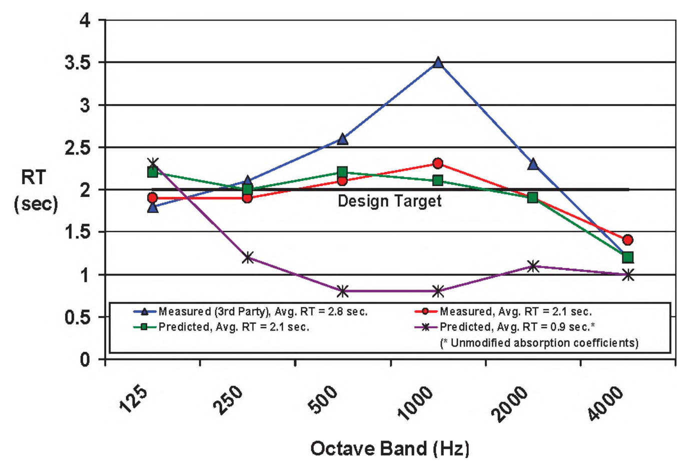

Figure 5. Comparison of initial, re-measured and predicted RT in Gym B-2 with ~40% wall panel coverage. Triangles: independent 3rd party measurements [7] with the room empty. Circles: initial measurements with construction materials present (see Figures 7, 8 & 9). Squares: predicted RT with modified acoustic treatment absorption coefficients. Asterisks: predicted RT with unmodified acoustic treatment absorption coefficients.

In their July 2000 paper [9] Bistafa and Bradley give an overview of various RT prediction formulae and their limitations with regards to non-uniform distribution of absorption and refer to the extensive work by Hodgson [10][11] in this field. In their study of RT in an unoccupied simulated classroom they found it necessary to add gypsum board diffuser panels to the room to increase diffuseness and that increasing the number of panels resulted in lower reverberation times.

The requirement for a sufficiently diffuse sound field is established for laboratory measurements in ASTM C423 - 09a [12]. This is typically achieved with fixed and/or rotating sound-reflective panels hung or distributed with random orientations about the volume of the reverberation room to interrupt standing wave modes. ASTM C423 states that it has been found that in rectangular rooms the area (both sides) of diffusers required to achieve satisfactory diffusion is 15 to 25% of the total surface area of the room.

In this study all of the gymnasia except for the two following cases were measured completely empty (neglecting the measurement equipment and operator): As mentioned previously, for one measurement session in Gym B-1, a scissor lift was located at one end of the room and a 1.2 m by 2.4 m Tectum board was leaning against a wall (see Figure 6). During a measurement session in Gym B-2, a few boxes of construction materials were present on the floor (see Figures 7, 8 & 9).

Figure 6. Scissor lift and Tectum panel in Gym B-1.

In both cases, these objects were judged at the time not to be large enough in area or volume to make a significant difference in the RT. However, the diffusion that they may have provided was not considered. In both cases lower RT were measured with the most dramatic difference in the later case: a mid-frequency average RT of 2.1 seconds, reasonably close to the ODEON predictions and significantly lower than measurements in the same room conducted roughly one week later by an independent 3rd party with the room empty (see Figure 5).

The third band of wall panels appeared to be having some effect in the Type B gymnasia measured with the additional objects but not in the other (empty) gyms. Further investigation finally lead to the hypothesis of an insufficiently diffuse sound field and uninterrupted standing wave modes in the lower untreated portion of the room contributing to the unexpected results. It was suggested that providing some diffusive objects to break up these reflections might provide results closer to a minimally occupied condition and to the predictions. This hypothesis was tested and the RT re-measured in Gym B-1 with some plywood panels and also with a few people.

Figure 7. Construction materials in Gym B-2 (view 1).

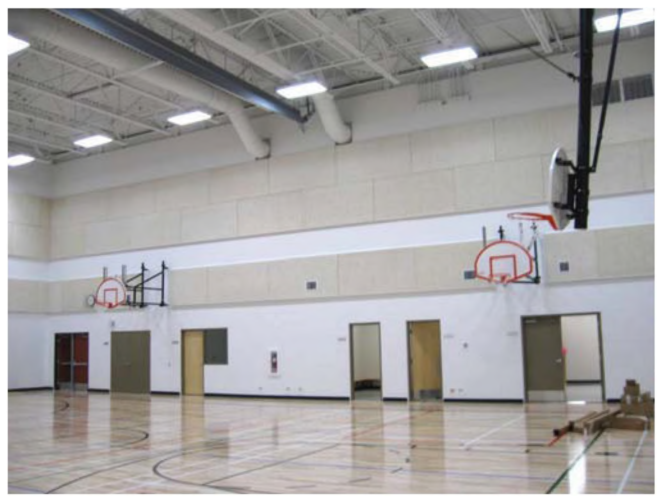

Figure 8. Construction materials in Gym B-2 (view 2).

Five different conditions were measured; an empty gym, addition of people, and three levels of diffusion. Diffusion was varied with plywood sheets, 1.2 m x 2.4 m x 12.7 mm thick, stood on end at various locations throughout the gym. Ten of these plywood sheets were fastened together at one end to form five self-supporting A-frame units. The remaining five plywood sheets were leaned against the volleyball net and supporting end poles at the mid point of the gym (see Figure 10). Sheets were removed and the measurements repeated. The measurements were also repeated with the room empty and again with the equipment operator plus four other adults.

Figure 9. Construction materials in Gym B-2 (view 3).

Figure 10. Plywood sheets in Gym B-1

6. RESULTS WITH ADDED DIFFUSION

The results for the re-measured Gym B-1 with approximately 35% wall panel coverage and with and without the plywood panels (totalling between 2% and 5% of the room surface area) to increase sound diffusion in the room are presented in Figure 11. All plotted measurements were conducted with the room empty except for the noted fittings or occupants plus the measurement equipment and operator. For the RT measurements with plywood sheets two stepladders were also present. The predicted RT are for the empty room (i.e. no people or plywood panels).

The addition of as few as four people or five plywood sheets was found to significantly reduce the measured RT, closer to the modeled predictions, with between a 0.6 sec and 1 sec reduction observed in the mid-band average RT from the empty condition. This decrease in the measured reverberation times is more than can be accounted for by the sound absorption provided by four additional adult bodies alone.

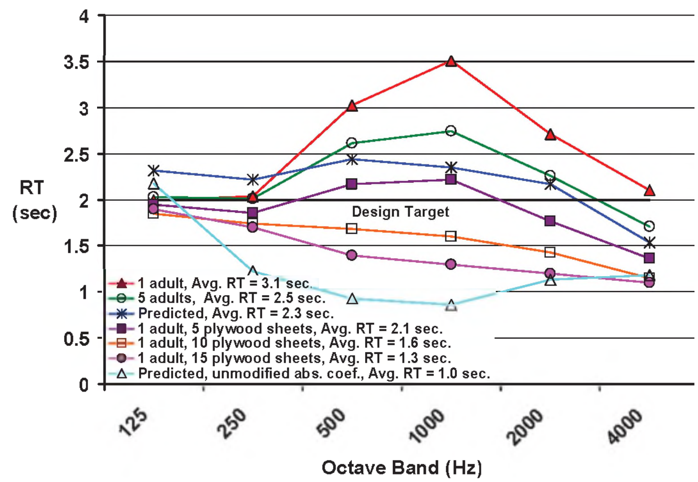

Figure 11. Comparison of measured and predicted RT in Gym B-1 with ~35% wall panel coverage showing the effect of the addition of people and plywood sheets. Triangles: room empty (except for 1 adult). Open circles: 5 adults. Asterisks: predicted RT with modified acoustic treatment absorption coefficients. Solid squares: 1 adult, 5 plywood sheets. Open squares: 1 adult, 10 plywood sheets. Solid circles: 1 adult, 15 plywood sheets. Open triangles: predicted RT with unmodified acoustic treatment absorption coefficients.

The low frequency RT did not appear to be particularly sensitive to the addition of the plywood however the times in the 500 to 4000 Hz bands were significantly reduced. With the addition of the plywood panels, between a 1.3 sec and 2.2 sec reduction in the RT at 1000 Hz from the empty condition was observed resulting in a mid-band average RT of between 1.3 sec and 2.1 sec compared to 3.1 sec for the empty room.

Similar measurements were repeated by Alberta Infrastructure in Gym A-2 and Gym B-2. Their findings (not yet published) were similar with regards to the effect of diffusive elements on the measured RT (see Figure 12).

During their measurements the importance of plywood placement was not extensively evaluated, however some variations were deliberately introduced to help evaluate any effect this may have. Generally it appeared that the RT were not particularly sensitive to the location of the plywood.

They also reported that the physical variations between the two types of gymnasia did not result in any major differences in RT. Eight (8) and 18 adults were also randomly distributed throughout the gymnasia while reverberation testing took place. Using body surface areas calculated with the DuBois formula as suggested by ASHRAE and height and weight determined using Standard Pediatric Data from the National Centre for Health Statistics, they deduced that the equivalent of 15 (K-6) students (9 year old males) results in the same reverberant characteristics as approximately four sheets of plywood and that increasing the number of student equivalents to 34, lowers the reverberation to the same degree as approximately ten sheets of plywood.

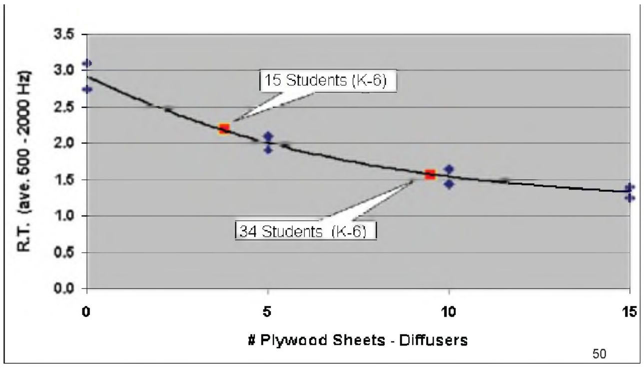

Figure 12. Alberta Infrastructure measured RT in Gym A-2 (upper diamonds) and Gym B-2 (lower diamonds) with ~40% wall panel coverage.

As a result of these measurements Alberta Infrastructure decided that to more fairly and accurately assess the RT criterion applicable to the project, it was important to add diffusion in an appropriate amount to emulate the diffusion that would be provided by a typical class size of 25 (K-6) students and one teacher.

They prescribed that this could be accomplished by adding seven, 1.2 m x 2.4 m sheets of 16 mm to 19 mm thick plywood distributed throughout the gym as described above.

7. ADDITIONAL COMMENTS

It could be argued that plywood sheets are not 'diffusers' per say as they are generally flat and smooth and reflections from them would be predominantly specular. Sound reflectors or re-directors may be a more accurate description of these panels although they were found to increase the level of diffusion or sound mixing in the room.

It has been suggested that the plywood panels change the propagation and reflection of the sound waves in the lower portion of the room and thus of the reflected sound incident on the acoustically absorptive wall panels and acoustic deck, resulting in more effective absorption by the acoustic treatments.

RT measurements in the upper (treated) portion of the room were not conducted during this study but may have yielded some interesting results. One possible explanation for the increase in measured mid-band average RT in the empty rooms with the addition of additional absorptive wall panels could be that by adding absorption in the upper portion of the room while leaving the lower portion of the room (where the measurements were conducted) acoustically reflective actually made the sound field in the room less diffuse. This hypothesis requires further study.

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