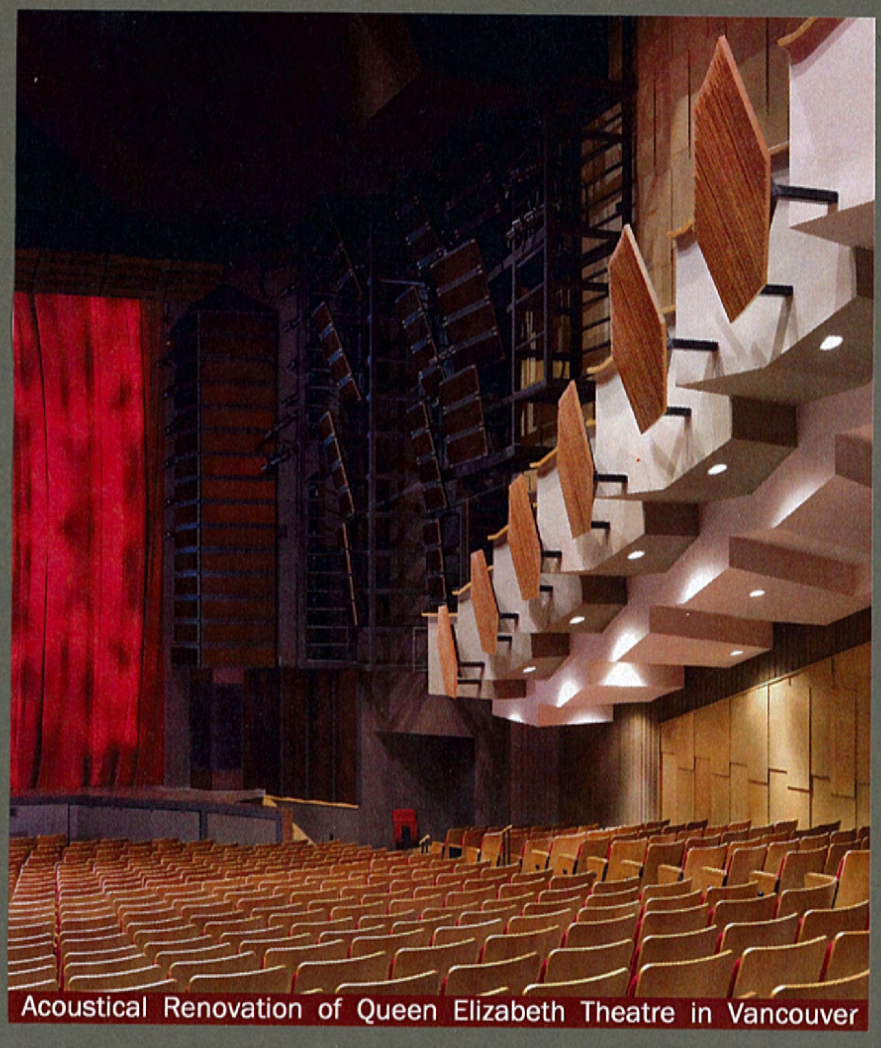

Acoustical Renovation of Queen Elizabeth Theatre in Vancouver

Acoustical Renovation of Queen Elizabeth Theatre, Vancouver BC

ACOUSTICAL RENOVATION OF QUEEN ELIZABETH THEATRE IN VANCOUVER BC

CONTENTS

Project Highlights

QUEEN ELIZABETH THEATRE ACOUSTICAL RENOVATION, VANCOUVER B.C.

Introduction

Like so many other performing arts centres, the renovation of Vancouver's Queen Elizabeth Theatre took a very long time to complete. The acoustical assessment and design started in 1994 and the completed building didn't open until November 2009. That period saw three complete designs of the renovation, each fraught with financial challenges requiring innovative engineering response.

Schedule & Finance Challenges

Much of the project was driven by acoustical design requirements. Working in the prevailing Canadian environment – one that has chronically underfunded performing arts infrastructure – the acoustical recommendations and their architectural implementation had to be far more cost effective than anything our colleagues overseas might face. To put this into perspective, Seattle renovated a similar sized building for their opera company in 2003 at a cost of US$127M. In 2009, the Queen Elizabeth Theatre was renovated for only C$45M. Toronto and Oslo opened opera houses within two years of each other; Toronto's cost C$103M, Oslo's C$800M. Compounding these challenges was a scheduling disaster halfway through construction. Hazardous materials on the site, in the form of lead dust, had to be removed, forcing a major redesign so that the project could be finished before the 2010 Vancouver Olympics.

Acoustical Challenges

Much of the focus of the acoustic design was on the needs of the Vancouver Opera. To ensure good acoustics, modern opera house design typically limits the number of seats in the room. In the Toronto and Olso examples, the seat counts were 2,000 and 1,450 respectively. This was simply not an option for the Queen Elizabeth Theatre renovation. Opera only occupies the room 30% of the time. For the rest of the year, popular music acts are booked and they can fill a lot more than 2,000 seats. In short, the leading acoustical engineers of the world would never set out to build an opera house this big. We did, because we had no other choice.

When the original room was built, the nascent science of acoustics had identified only one aspect of sound they thought to be critical to the appreciation of sound in a room. We now know that there are at least six components of acoustical appreciation, all of which can be influenced by the shape and size of a building. Only one of these components came close to the required levels in the existing building.

The acoustics of the Queen Elizabeth Theatre have long been lamented. It was typical of its post-war era. It had a very dry acoustic – it wasn't reverberant enough. It had a poor or non-existent spatial sound. It wasn't loud enough, that is to say, it didn't have enough impact. It lacked warmth. The ventilation system was very noisy. And there was a lot of sound transfer between it and the adjacent Playhouse Theatre. The only thing it had going for it was acoustical Clarity, if anything, too much of it.

Reverberance

The first renovation design, completed in the late 1990s, attempted to fix the building without removing the ceiling. The Queen Elizabeth Theatre simply didn't sound as reverberant as the traditional Reverberation Time measurements would suggest. We noticed that the room, in its original state, was very wide and not very tall. Could this be the reason for the poor Reveberance? Abandoning our building design tasks for a while, we developed a series of experiments. Computer and scale model studies on a number of simple six sided boxes (representing a theatre or concert hall) revealed that perceived Reverberance can indeed be related to the Height to Width Ratio of a room. This concept has since been published several times and is becoming a recognised component of acoustical design.

Then, the first renovation design fell victim to financial shortages and was put on hold for more than six years.

Spaciousness

In the second design, the existing ceiling was removed, a decision that was informed by our discoveries about Height to Width Ratios. The design also included two new balconies (for a total of three) and incorporated some of the more modern concepts of the so-called "Directed Energy" halls. In a room that is too big acoustically (typically over 2,000 seats) it is possible to compensate with strategically located reflecting surfaces. In addition, if those reflectors direct sound to arrive at listeners from the sides, an overly wide room can be made to sound more like the well-loved narrow

shoe-box shaped rooms of the 19th century, i.e. the sound will have a better Spatial quality – a single violin can appear to fill the whole room. Two design precedents were employed; large lateral reflectors in the ceiling space (similar to the Christchurch Town Hall in New Zealand) and a terraced seating level in the orchestra level (inspired by the Berlin Philharmonie). These are both concert halls, which are fundamentally different from a proscenium arch theatre such as the Queen Elizabeth. The only documented success of Directed Energy in a proscenium arch room of this size is the Segerstrom Hall in Costa Mesa, USA. There was risk involved to be sure.

Construction work on the building began in the summer of 2006. The plan was to do the work in phases during the summer months when the theatre was less frequently in use. In that first summer, the building was literally cut in two. This was done to prevent structure-borne noise between the two theatres housed in the building, the second being the smaller Playhouse Theatre. The next summer the ceiling was removed and a new ventilation system installed.

Ventilation Noise

Performers on stage need a quiet room in the same way that painters need a white canvas. Most of the background noise in a concert hall or opera house comes from the ventilation system. Many new venues now use a displacement system to provide air slowly and very quietly. Air is blown into a plenum below the seats and is allowed to drift up through holes in the floor. At the Queen Elizabeth Theatre this option was precluded by an existing parking lot underneath the audience. The solution, first developed by Aercoustics, was to turn the concept upside down. Air is now blown into a series of plena in between the roof joists. The plena act as a noise control mechanism and take up a lot less of the room's precious acoustic volume than a normally ducted system would.

Half way through the summer of 2007 the lead dust disaster struck. The room had to be redesigned, and rather quickly as construction was going to re-commence in May 2008. The two new balconies had to be deleted from the design, as did the terraced seating levels that were providing the critical lateral reflections for Spaciousness. Quite fortunately, it was at this point that we discovered a new software tool, originally intended to optimise lighting in green buildings.

It is extremely difficult to design a reflector to its optimum location and orientation in 3-Dimensional space. This software, for the first time, allowed us to calculate reflection direction and coverage in real time. The reflectors needed to compensate for what we lost in the lead dust crisis are astonishingly small. The tilt on many of them has been optimised to within less than a degree. We have conferred with our colleagues overseas and we believe that we are the first to optimise reflectors on this scale and this accurately.

Loudness

Some rooms are naturally louder than others. The Queen Elizabeth Theatre was not loud enough. Loudness was a very big design challenge. One of the concerns with a Directed Energy hall is that the first few reflections are sent to the acoustically absorbent seats, which presumably precludes the opportunity for further reflections that would eventually embellish the later part of the decay and, of course, the overall Loudness of the room.

It seems a legitimate concern, at least at first glance. But during the design, a scientific paper was published suggesting that the opposite might be true. It turns out there was also a previous paper suggesting the same in 1988. Two papers, however, are rather thin evidence on which to base critical engineering decisions. The veracity of the science in these papers was hard to challenge but, once again, the risk is clearly evident. In the end the newly renovated Directed Energy Queen Elizabeth Theatre performed exactly as predicted in the two papers.

Results

The new sound in the room has been widely acclaimed by the client, users, press and public.

> *What has transpired as a result of Aercoustics Engineering's work is, in my estimation, a minor miracle. We are delighted and – more importantly – the audience is thrilled.*
>
> ***James W. Wright***
> ***General Director, Vancouver Opera***

The renovated acoustics have also been quantified extensively with objective scientific measurements. In the cases of Reverberance, Spaciousness, Loudness and Warmth, measurements in the renovated room exceed Just Noticeable Differences (JND), proving the audible improvement. In the latter case (Warmth) a comparison was made between eight of the world's favourite opera houses. The original Queen Elizabeth Theatre came last out of the eight. The renovated room came first.

Owner:	Vancouver Civic Theatres Rae Ackerman, Natalka Lubiw
Acoustician:	Aercoustics Engineering Ltd. John O'Keefe, Kiyoshi Kuroiwa, Daniel Ruvalcaba
Architect:	Proscenium Architects + Interiors Thom Weeks, Jennifer Stanley, Hugh Cochlin, Greg Piccini, Kerri Shinkewski, Ron Clay, Pablo Yuste, Tanya Southcott, Alex Vizvary, Matthew Kurnicki, Richard Leong, Ben Nielsen, Eli Niakan, Yumi Cross, Kim Dodge, Tony Vaccarino, Elena Vilis,
Sound System:	Engineering Harmonics Phil Giddings, Paul Alegado, Martin VanDijk
Theatre Consultant:	Douglas Welch Design Associates Douglas Welch, Paul Hodson, Scott Miller
Mechanical Engineer:	Stantec Ken Junck, Barry Taylor
Structural Engineer:	RJC Engineering Renato Camporese, Colin Macmillan
Electrical Engineer:	Schenke Bawol Engineering Wolf Schenke, Rick Arikado
Heritage Consultant	Commonwealth Historic Resource Management Limited Hal Kalman, Jonathan Yardley
Contractor:	Heatherbrae Construction Project Manager Michael Keenan
Cost:	James Bush and Associates James Bush
Code:	LMDG Alan Jung
Photography:	Ed White
Budget:	$45M
Completion:	November 2009

Project Description

The following six sections form the Project Description for this submission. The first five sections address the acoustical properties of good sound in a performing art centre and how these properties were achieved in the Queen Elizabeth Theatre renovation. The sixth section discusses the environmental and social benefits of the project.

The final section of this submission is supplemental information including; letters of reference, a glossary, formulae for the acoustical measurements and published scientific papers dealing with the Queen Elizabeth Theatre acoustical design.

Reverberance
Height to Width Ratios

REVERBERANCE – HEIGHT TO WIDTH RATIOS

History

Wallace Clement Sabine is the father of modern acoustical science. At the turn of the 20th century, using nothing more than organ pipes and a stop watch, he was able to identify one of the most fundamental concepts of a new branch of science now known as architectural acoustics. He called this new concept Reverberation Time (RT). RT is proportional to the enclosed volume of a room and inversely proportional to the amount of acoustic absorption in it. Thus, a small room with a lot of soft acoustically absorbent material in it will have a short RT, for example your living room. A cathedral, on the other hand has a very large volume and very few soft material in it. Accordingly, cathedrals have long Reverberation Times.

For a good part of the 20th century, buildings were designed to supposedly ideal Reverberation Times. Many of the designs actually satisfied their required Reverberation Time only to be panned by critics, patrons and musicians. This nascent understanding of acoustics held sway during the post-war theatre building boom, when the Queen Elizabeth Theatre was built. Indeed, it was this era that gave acoustics the reputation it still holds today in some quarters; pseudo-science.

At around the same time, fortunately, scientists around the world were beginning to learn a lot more about our perception of sound in a room. It turns out that peoples' perception of sound is a multi-dimensional experience. We now know that Clarity, Spatial Impression, Loudness, Intimacy, Warmth and, yes, Reverberance are all critical components of a room's sound. We shall speak to each of these as the narrative progresses and a glossary has been provided at the end of this submission. For now we will concentrate on Reverberance.

In the 1960s it became apparent that Sabine's turn of the century definition of Reverberation Time might not be an entirely appropriate description for the subjective perception of Reverberance. Sabine defined RT as the time is takes sound in a room to decay by 60 decibels (dB). In a typical concert hall the RT should be about 2 seconds or slightly more, in an opera house it should be about 1.5 seconds, as indeed it was in the original Queen Elizabeth Theatre. But for fifty years, people had complained that the Queen Elizabeth Theatre didn't sound reverberant enough. Why not?

The answer is obvious; but only in hindsight. Musical notes in a typical passage are not separated by two seconds. Melodies, slow or fast, have note separations in the range of tens or the low hundredths of milliseconds (ms). The only time that a listener might hear a full 2 seconds of reverberation is at the end of a piece of music or, perhaps occasionally, at a stop chord. In the early 1970s a refinement to Reverberation Time was introduced, the so-called Early Decay Time (EDT). An EDT measures the decay over the first 10 dB and, in so doing, correlates much better with the actual perception of reverberance.

The Original Room

A perfect example of the difference between Reverberations Times (which are easy to calculate and easy to measure) and Early Decay Times (which correlate much better with human perception) is seen with the measurements in the original Queen Elizabeth Theatre. Please see Figure 1. Except at the very front of the room (the first two seats in Row 15), the Early Decay Times are always lower than the Reverberation Times. The vertical error bars on the Early Decay Time data points indicate the Just Noticeable Differences (JND) for Reverberance. A JND is the point where a listener can discern the difference between two data points. Thus, the differences between Reverberation Times and Early Decay Times shown in Figure 1 are surely significant. These measurements,

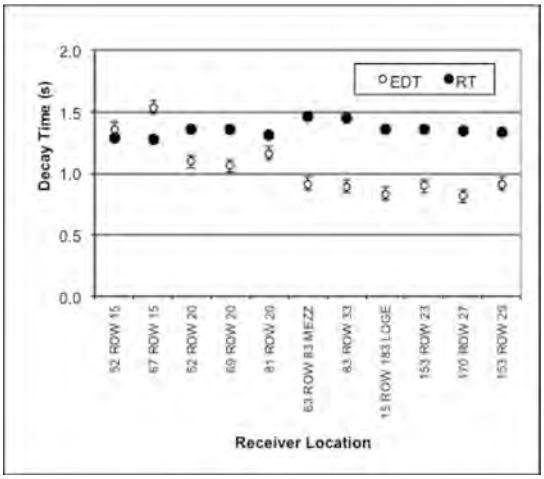

Figure 1. A comparison of Reverberation Times (RT) and Early Decay Times (EDT) in the original Queen Elizabeth Theatre. The latter correlates much better with the subjective perception of Reverberance.

performed in 1994 were the first scientific corroboration of what patrons of the Queen Elizabeth Theatre had been saying for decades; “the room isn’t Reverberant enough”.

The First Design

There are at least six ingredients that must be addressed if one is to provide good acoustics in a performing arts venue: Reverberance, Loudness, Clarity, Spatial Impression, Warmth and Intimacy. The great lesson of the 20th century is that not one of these, on its own, can guarantee good acoustics. Rather, each ingredient must be present and in its right proportion. That said, one of the really big challenges with the Queen Elizabeth Theatre was to improve the long lamented Reverberance.

The first of the three renovation designs spent a lot of effort trying to get the Reverberance right. One of the iterations is shown in Figure 2. It seemed no matter how hard we tried, we just couldn’t get the Early Decay Times to match the Reverberation Times. We were dealing with an inefficient temporal distribution of sound but we didn’t know why. A chance observation sparked a flurry of experiments that have helped, we hope, improve the understanding of how geometry affects sound in a room.

The original Queen Elizabeth Theatre was very wide with a proportionally low ceiling. It had a very low Height to Width ratio. Could that explain the poor Reverberance?

A series of experiments, using both computer and physical scale models, set out to answer this question. (Two of the resulting papers are included in an appendix to this submission.) The study was a classical exercise in reductive science. Two room geometries were studied: the much appreciated shoe-box shaped rooms of the 19th century and the much maligned fan shaped rooms of the mid 20th century. Both geometries were reduced to their bare essentials – six sided boxes. Then, as shown in Figure 3, the height of the boxes was raised from 1/8 of the width to twice the width. Several acoustical parameters were measured during the process but perhaps the most interesting was the parameter that quantifies Reverberance, the Early Decay Time. If we compare it to the classical definition of Reverberation Time we find some very informative results, as shown in Figure 4.

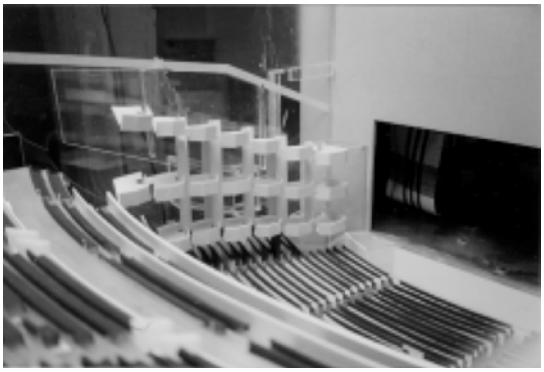

Figure 2 1:48 scale model of an early renovation design, ca. 1998.

Parenthetically, a ratio of an EDT to an RT is an interesting concept. RT expresses the physical world and assumes a perfectly diffuse sound field, making it easy to calculate. The Early Decay Time is very difficult to calculate but expresses the subjective requirements of listeners. One is easy to

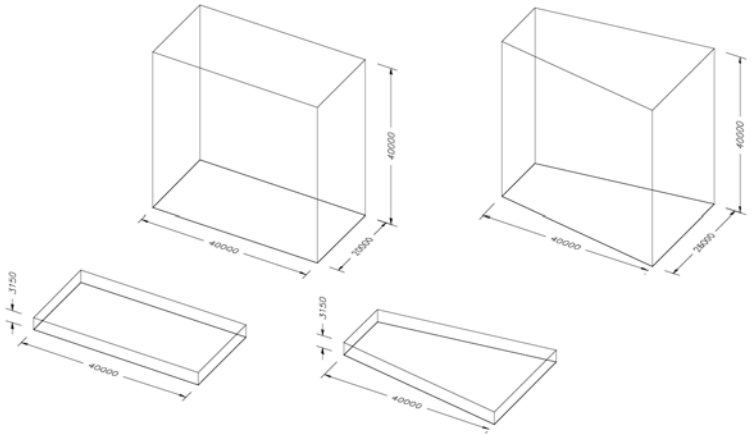

Figure 3 Schematics of the fan and shoebox shape room varying in height from 1/8 of the width to twice the width.

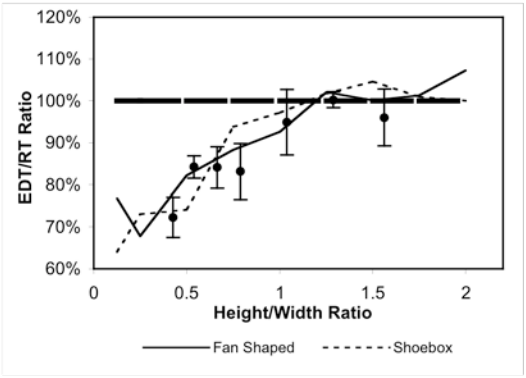

Figure 4. Results of computer model (lines) and scale model (dots) Height/Width studies.

calculate and the other is what our ears listen to. Combined together as an EDT/RT ratio we get an expression of Reverberation Efficiency, i.e. how efficient a room is at using the sound energy to provide good Reverberance.

The results in Figure 4 are interesting on at least two levels. It is clear that a tall narrow room has a better reverberation efficiency than a low wide room. What is also notable however is that there seems to be little difference between the shoebox and fan shaped geometries. Fan shaped rooms are notorious for having poor EDT/RT ratios, so how could this be? The answer is simple, fan shaped rooms invariably have very small Height/Width ratios. At the back of Toronto's Sony Centre (formerly the O'Keefe Centre) the Height to Width Ratio is only 9%.

The first renovation design in the late 1990s included side wall boxes, as can be seen in the scale model shown Figure 2. In an effort to improve the Height to Width ratio of the room, large floor to ceiling fin-like reflectors were introduced, as seen in Figure 5. Scale model measurements of this new arrangement demonstrated an improvement in EDT/RT ratios from 51% to 75%.

This first renovation design scheme however was never built. It fell victim to budget restraints and lay on the shelf for more than six years.

2nd and 3rd Designs

When the renovation was revisited, starting in 2004, it was decided to remove the existing ceiling. This decision was informed, in part, by the Height/Width experiments described above. By that time, also, commercial computer model software could generate "auralizations" of a room. (An auralization is to sound what a visualization is to sight.) Listening tests compared the sound generated in the Design 1 model to a model of the original room. Upon hearing the differences between the two it was decided that, among other things, the ceiling must be removed.

As mentioned elsewhere in this document, the 2nd Design also fell victim to cost and schedule restraints. Over the winter of 2007-2008 a third and final design was developed. Plans and sections of that design are shown in Figure 6.

The new designs incorporated some of the more modern concepts of the so-called "Directed Energy" and "Vineyard Step" halls. In a room that is too big acoustically (typically over 2,000 seats) it is possible to compensate with strategically located reflecting surfaces. Two design precedents were employed; large lateral reflectors in the ceiling space (similar to the Christchurch Town Hall in New Zealand, a Directed Energy hall) and a terraced seating level in the orchestra level (inspired by the Berlin Philharmonie, a Vineyard Step hall). The was a risk in this approach however; Directed Energy and Vineyard Step halls are known to have poor EDT/RT ratios.

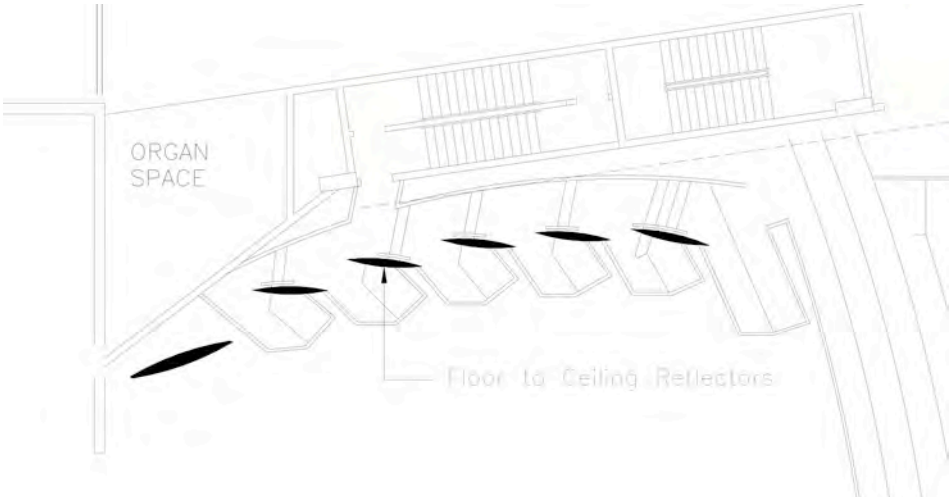

Figure 5 Plan of the side wall boxes showing the floor to ceiling fin shaped reflectors.

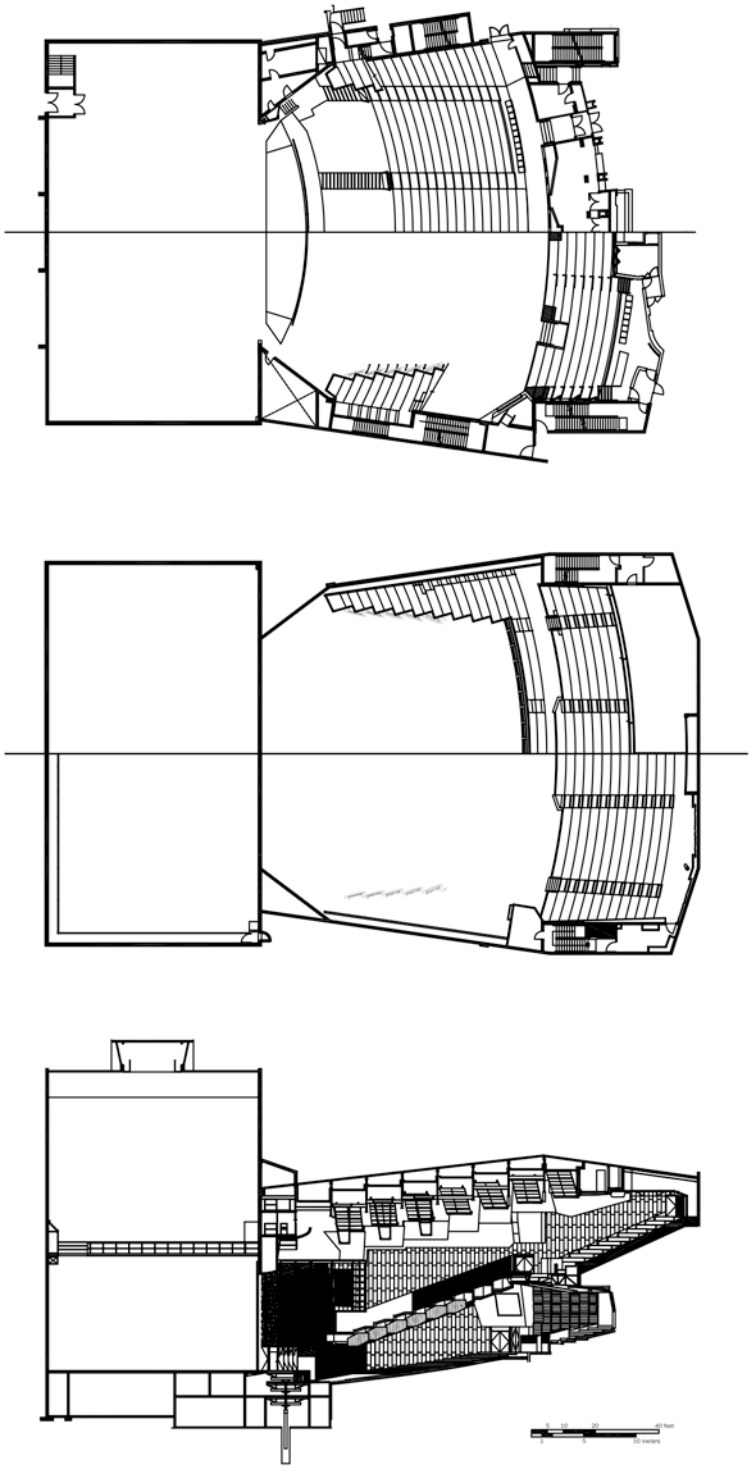

Figure 6. Composite Plans and Longitudinal Section of the 3rd and final renovation scheme.

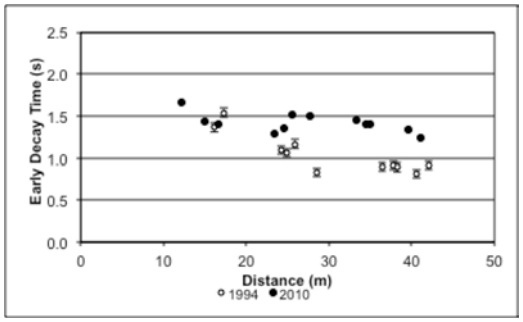

Figure 7. Early Decay Times quantify perceived reverberance. The vertical error bars indicate the Just Noticeable Difference (JND) for reverberance. This before (1994) and after (2010) comparison clearly indicates that the improvements are audible and significant.

Measurements

A complete range of acoustical measurements was performed on the original building in 1994 and the finished room in 2010. These included all of the salient properties of sound in a performing arts venue: Reverberance, Clarity, Loudness, Spatial Impression, Warmth and an experimental measurement of Intimacy. In this section we will only discuss Reverberance, the others will be reviewed in the following chapters. Reverberance in a good opera house should be in the range of 1.4 to 1.6 seconds. In the original building the Early Decay Times, which quantify reverberance, were often 1.0 second or less. Figure 7 shows that the renovated Queen Elizabeth Theatre now has Early Decay Times in the range of 1.5 seconds. Note also the vertical error bars in Figure 7. These indicate the Just Noticeable Differences (JND) for reverberance. The Early Decay Times in the renovated room far exceed the JNDs, indicating that the improvements in the space are clearly audible.

Analysis

As noted above, the renovation design followed the so-called Directed Energy format. One of the concerns with a Directed Energy hall is that the first few reflections are sent to the acoustically absorbent seats, which presumably precludes the opportunity for further reflections that would eventually embellish the later part of the decay. Even in a shoebox shaped room, some have discouraged raked seating for this very reason. The concern is legitimate on an intuitive level but not very far beyond that. The real story is, as always, more nuanced.

Sometimes a Directed Energy room (or a steeply raked room) doesn't sound as reverberant as it should. That is, the Early Decay Times (EDT) are shorter than the Reverberation Times (RTs) in a Directed Energy hall, resulting in a poor EDT/RT ratio.

Our Height/Width experiments however suggested that we might be able to overcome the Directed Energy reverberance risk if we could make the room taller and narrower. The measurements in the finished room agree with the hypothesis put forward in the experiments. We shall explain.

First, it should acknowledged that real rooms, of course, are not simple six-sided boxes. However, the experiment, deliberatively reductive as it is, does indicate a pattern worth considering. One could describe the original room as having a poor Height/Width ratio. The new building definitely falls into the category of a Directed Energy hall. It does not have a Height/Width ratio per se; its geometry is too complicated to fit within the confines of the experiment described above. But, with the ceiling removed, the room is taller and, with all the lateral reflectors, it is acoustically "narrower". Figure 8 shows a comparison of EDT/RT ratios for the new and original rooms. The new room has consistently higher EDT/RT ratios, even though it is a Directed Energy hall, where one would expect lower EDTs. The original room, with its poor Height/Width ratio, has lower EDT/RT ratios. It appears that the Height/Width ratios influence EDTs more than the well-known deleterious effects of Directed Energy and, in this case, for the better.

The risk we took in employing the new Height/Width ratio concept has paid of.

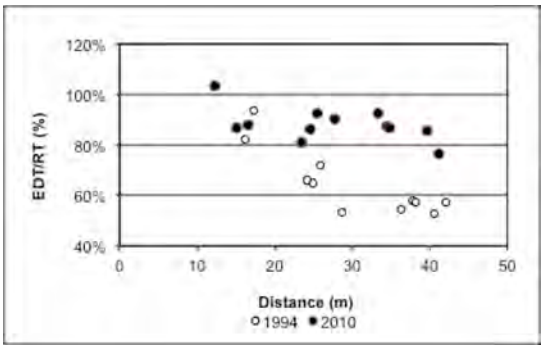

Figure 8. A comparison of EDT/RT ratios before and after the renovation.

Loudness
The Direct Energy Dilemma

LOUDNESS – THE DIRECTED ENERGY DILEMMA

History

Some rooms are louder than others. That is, a calibrated and consistent source of sound power can sound louder in one room than it might in another. Wallace Clement Sabine, the previously mentioned father of modern acoustical science, pointed to the importance of Loudness at the beginning of the 20th century. Few, however, considered it of any importance until the late 1970s. Around that time, three independent surveys of German and British halls all pointed to the importance of Loudness. This came as a surprise to many because the difference in Loudness from one hall to the next is not often large. Sometimes the differences in Loudness measured at difference points inside a hall are larger than the average differences between halls.

In our normal day to day life, in an office or classroom for example, people typically only begin to notice a difference in Loudness when levels increase by 5 to 7 dB. But, consider the physical fact that if an orchestra was halved in size, the sound level would only go down by 3 dB. As a result, our sensitivities are much more acute in a performance space. It turns out that the Just Noticeable Difference (JND) for Loudness in a concert hall or opera house is 1 dB.

Shortly after the importance of Loudness was discovered, the existing formula to predict it was found wanting. A British researcher named Mike Barron developed a new concept that has taken on the name of Revised Theory. Briefly stated: a room's Loudness is governed by three components: Volume, Reverberation Time and Distance. This suggests that it is very difficult to achieve adequate Loudness in a large room like the Queen Elizabeth Theatre where the volume is too big, the distances too long and, compared to a concert hall, the Reverberation Times too short.

Predictions of Loudness based on Revised Theory have proved accurate for the most part, although some studies have suggested that can predict values higher than actually measured. In the Height/Width ratio experiments mentioned in the previous chapter, it was found that Revised Theory tended to over-predict levels in wide, flat rooms (i.e. rooms with a poor Height/Width ratio) and was more accurate for taller, narrower rooms.

The Loudness Challenge

Despite these few exceptions, Revised Theory has been widely accepted as a benchmark indicator at the beginning of acoustic design, long before computer or scale models can be employed. Indeed, it is often used to confirm the veracity of computer model predictions.

Revised Theory tells us that:

(i) Loudness is proportional to Reverberation Time. Unfortunately, for its use as an opera venue, the Queen Elizabeth Theatre must have a shorter than normal Reverberation Time.
(ii) Loudness is inversely proportional to the room's enclosed Volume. The Queen Elizabeth Theatre is very big indeed, with a volume in excess of 30,000 m^3.
(iii) Loudness is inversely proportional to distance and, because the renovated Queen Elizabeth Theatre had to seat so many, the average distance from a listener to the stage was longer than normal.

Thus, all three parameters that control Loudness are pointing in the wrong direction.

In 2002, Aercoustics published a paper on the acoustical shortcomings of five large Canadian post-war auditoria. Most of them, of course, were found wanting when it came to room Loudness, especially the Queen Elizabeth Theatre. It is generally accepted that the average Loudness levels in a concert hall should be 0 dB or higher. If we use Revised Theory to calculate Loudness based on the high Volumes and the short Reverberation Times in these rooms and if we assume a source-

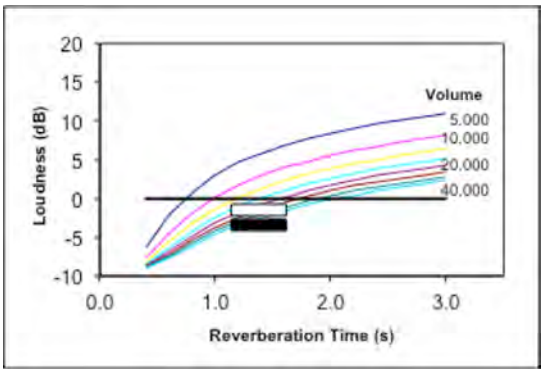

Figure 1. Revised Theory predictions of Loudness in large rooms with short Reverberation Times, r=30 m. The white box indicates the levels expected in the five halls considered in this study. The black box demonstrates the levels expected when the effects of height to width ratio are taken into account.

receiver distance of 30 m (which is reasonable in large rooms such as these) the white box in Figure 1 suggests that the Loudness criteria of 0 dB will never be satisfied. (The 0 dB criterion is indicated by the solid black line in Figure 1.) To compound the problem, our Height to Width studies suggested that in rooms that were low and flat, like the Queen Elizabeth Theatre, the predictions would be even lower, in the range of the black box shown in Figure 1.

The power of Revised Theory is its simplicity. It is based on diffuse field theory in a simple box-like room. That's why it's used as a benchmark; without the benefit of special reflectors or perhaps the deleterious effects of a long balcony overhang, it predicts the sound levels that would naturally occur in a room. And, unfortunately, what Revised Theory tells us about the Queen Elizabeth Theatre is that, somehow, we had to improve on the natural order of things.

Directed Energy

It was for this reason, and a related concern with the need for lateral reflections, that we decided to employ the Direct Energy format into the second design scheme and, eventually, the third. Recall from the previous chapter that a Directed Energy hall is one in which strategically located reflectors are designed and installed in a room that is otherwise too big or too wide or both. Remember also the commonly held concern about Directed Energy halls, is that the first few reflections are sent to the acoustically absorbent seats, which presumably precludes the opportunity for further reflections that would eventually embellish the later part of the decay. Without these reflections, one might expect lower Loudness levels.

Of the five or six salient acoustical properties that have been identified not one, on its own, can guarantee good acoustics. Rather it's the blend of the six parameters that must be carefully crafted. Still, there are some parameters that are more important than others and Loudness is one of them. (There is a reason why the largest knob on a home stereo controls Loudness!) Throughout the design there was a lot of concern and worry about Loudness. The existing Loudness in the room was low. Revised Theory and our Height/Width studies predicted low Loudness levels and the received wisdom about Directed Energy halls suggested low levels as well.

Then in 1999, just as the first design scheme was about to be put on the shelf, a single paper was published that contradicted the received wisdom about Directed Energy halls, at least insofar as Loudness was concerned. Critically, the paper, unlike the received wisdom, was based on measurements in real halls. One of the rooms, in fact, was the Segerstrom Hall in Costa Mesa, USA, the only documented proscenium arch room of the Queen Elizabeth Theatre's size to successfully employ the Directed Energy format.

The paper was written by the American acoustical physicist Jerry Hyde. Hyde, coincidently, worked on the acoustical design of Segerstrom Hall. He cited a little known work by Japanese acoustician Yasuhisa Toyota which was presented to the Acoustical Society of America in 1988 but, except for a short abstract, was never published.

Toyota noted that the rank ordering of Loudness levels was established by about 80 to 100 ms into the decay. (In an opera house it takes 1500 ms, or 1.5 seconds for the sound to completely decay) Toyota's was a powerful observation because it meant that if one can improve early sound levels, as one would do with the spatially optimised reflectors in a Directed Energy hall, those improvements will still be there in the late field.

Hyde expanded on this idea in his 1999 paper. He found strong correlations between early sound levels (quantified as G80[1]) and the total sound level (G). The correlation between early (G80) and total (G) sound levels was 0.91.

These ideas, developed by Toyota and Hyde, strongly influenced the acoustic design decisions for this building. They gave the designers the confidence to move forward with the Directed Energy concept. But, it should be noted that, at the time, most acoustical consultants, especially in North America, were not paying attention to this work. Many still don't. Two papers, even though their findings were hard to challenge, are not much to go on when the quality of a renovation costing tens of millions of dollars counts on them.

Measurements

The risk is clearly evident but, in the end, the renovated room performed as Toyota and Hyde suggested. Hyde found a correlation of 0.91 between

[1] Acoustical engineers often split reflected sound into its early and late components. This mimics some of the neural processing in the brain. For music, the threshold between early and late is 80 ms. Thus, the term called G80 quantifies the sound level in the first 80 ms. In a room the size of the Queen Elizabeth Theatre that usually means the first one of two reflections.

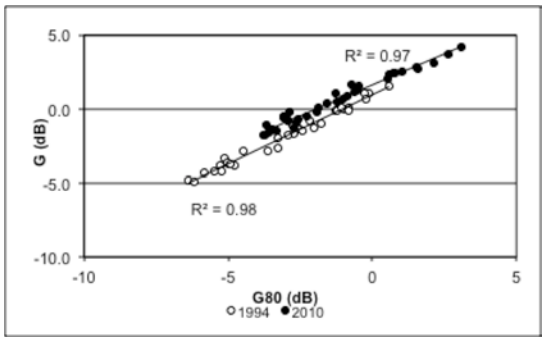

Figure 2 As suggested by Hyde, there is a strong correlation between early reflected sound (G80) and the total Strength (G). In the renovated QET, a 1.8 dB increase in G80 has generated a 2.5 dB in G. Popular wisdom would suggest the opposite.

G80 and G. In the renovated Queen Elizabeth Theatre the correlation is 0.97, as seen in Figure 2. This figure may not look like much but the physical behaviour it expresses is key to the success of the renovated room. The need for laterally reflected sound, which will be described in the following chapter, pushed the design towards the Directed Energy concept. But we also had to improve Loudness. What Figure 2 tells us is that all the reflectors that we very carefully designed to direct sound to the listeners did just that and, in so doing increased the first few reflections (G80) by 1.8 dB. Because of the strong correlation between G80 and G (i.e. between early and total Loudness) this translates into an overall increase of 2.5 dB. Again, this may not sound that much but it was very hard to achieve and, over the years, generated considerable worry. Remember, the Just Noticeable Difference (JND) for Loudness is 1 dB. The renovated room delivered Loudness 2.5 JNDs louder than before!

Finally, Figure 3 shows a before and after comparison of Loudness. In all but one or possibly two cases, Loudness in the various seating locations is audibly louder than before, i.e. the new data points are higher than the JNDs for the old measurements.

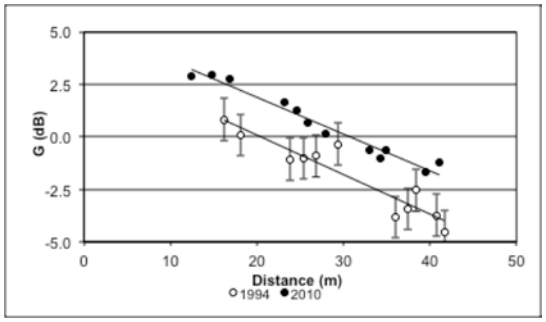

Figure 3. Before and after comparison of Loudness as quantified by the acoustical parameter called G. The vertical error bars indicate the Just Noticeable Differences for Loudness.

Spaciousness Reflector Optimisation

SPACIOUSNESS – REFLECTOR OPTIMISATION

History

If one had to choose the most exciting and influential acoustical discovery of the 20th century it would have to be the Lateral Energy thesis. It came, apparently, out of nowhere. It explained why the classic shoebox shaped rooms of the 19th century worked so well and it opened up new opportunities for the larger Directed Energy halls of the future.

In 1967, a young New Zealander named Harold Marshall had just finished his Ph.D. at Southampton University, UK. He published a short, 2 page note to the editor of the Journal of Sound and Vibration. It was just a hypothesis at the time but, a few years later, another Southampton student, Mike Barron, would publish the findings of his Ph.D., this time with hard data to back up Marshall's postulate.

Marshall had noticed that the narrow shoebox shaped concert halls that everybody loved so much had a good spatial component to the sound. Up until then, nobody had noticed that sound had a spatial component. It turns out it does and Marshall suggested that what the narrow halls had that others didn't was strong reflected sound arriving at the listeners for the sides. Narrow means in the range of 25 m. The original Queen Elizabeth Theatre, designed and built 10 years before these findings, was very wide; 32.2 m.

In laboratory tests, Barron found that if reflected sound in the first 80 ms (essentially the first 1 or 2 reflections) arrives at the listener from the side it will promote a sense of Spatial Impression, as it was called at the time. In the 1990s, this idea was refined by John Bradley and Gilbert Soulodre at Canada's National Research Council. It turns out that there are two components to Spatial Impression, which can be explained as follows:

Imagine a single violinist on stage and you are sitting in the audience of a concert hall. Close you eyes and imagine how big the sound is in front of you. If you get strong early lateral reflections, as you would in a narrow shoebox shaped room, the sound will appear to fill the whole stage in front of you. If you only get frontal reflections, as you would in a fan shaped room, the spatial sound will be very small, probably constricted to a small area around the performer. That's the first part of Spatial Impression and it's called Source Broadening.

If the late reflected sound, i.e. sound arriving after 80 ms, is still arriving from the sides, it will generated a sensation called Envelopment. The sound fills the entire space of the room. It's as if you're immersed in a cloud of music and you could almost reach out and touch it. This is a characteristic displayed by all the worlds' favourite concert halls and, once heard, is a truly unforgettable experience.

After his 1967 note to the editor, Harold Marshall did not rest on his laurels in Southampton. He returned to his home in New Zealand and immediately put his ideas into practice, a bold move that probably couldn't be repeated today. The resulting Christchurch Town Hall opened in 1972. It was the first of what became known as the Directed Energy Halls.

Ironically, the Lateral Energy thesis, having shown the way of the future, led to a return to the past. The shoebox shaped concert hall format was resurrected and dominated acoustical design for the last 20 years of the 20th century. It is only recently, in the last five years or so, that the potential of the Lateral Energy thesis is being unlocked, in the new Paris Concert Hall, currently under construction and, of course, in the renovated Queen Elizabeth Theatre.

Design Influences

The 2nd renovation design for the Queen Elizabeth Theatre was a combination of the Directed Energy and the Vineyard Step concert hall formats. (The glossary at the end of this submission explains these further.) Specifically, we were using Christchurch Town Hall and its immediate descendant The Michael Fowler Centre in Wellington NZ as our Directed Energy examples and the Berlin Philharmonie as the Vineyard Step example. Note that both of these are concert halls and we were trying to make the concepts work in a very different building, a proscenium arch theatre.

The rendering in Figure 2 shows the combination of the two influences. The intension of the design is to encourage as much early lateral energy as possible. Images of both the Christchurch and Berlin halls are available in the Glossary at the end of this submission and may help the explanation that follows.

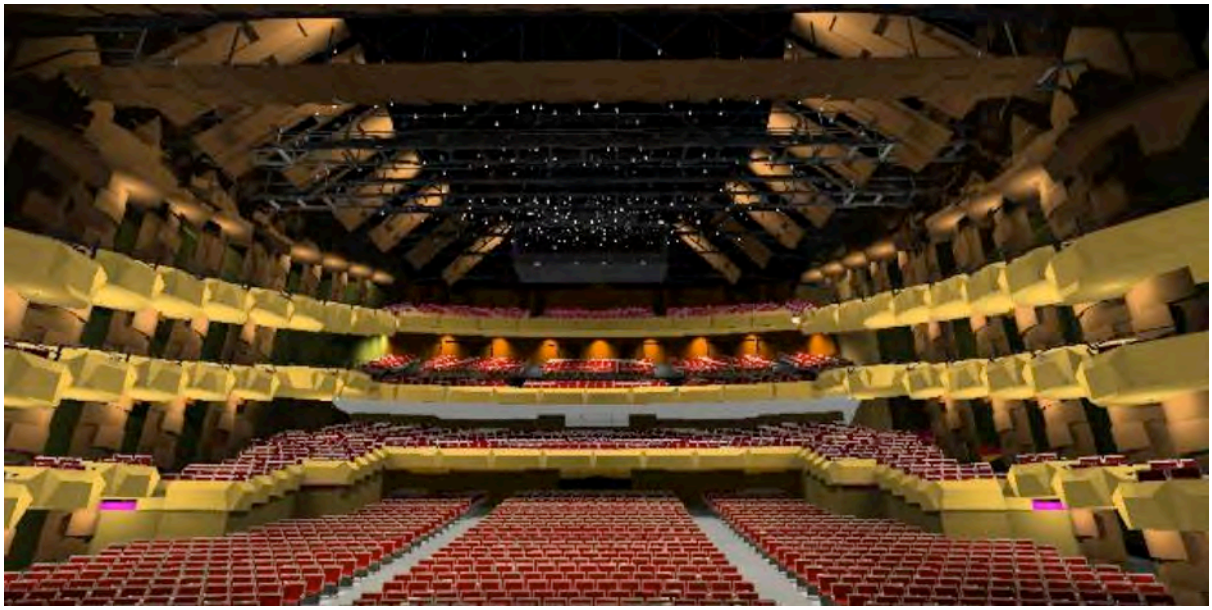

Figure 2. Computer rendering of the 2nd renovation design. Note the ceiling reflectors, inspired by Christchurch Town Hall and the narrowing of the orchestra level at the back, inspired by the Vineyard Step layout of Berlin Philharmonie.

The Christchurch influences are obvious in the ceiling. The large array of reflectors directs sound towards the orchestra and balcony levels to arrive at the listeners from the sides. Less obvious is the Berlin influence but it is there at the back of the orchestra level. Note how the next level up (the mezzanine) is used to narrow the back of the orchestra level. This was done to provide a lateral reflecting surface for the benefit of listeners in the back. A plan view of the reflection pattern is shown in Figure 3. Unfortunately, the Berlin inspired balconies fell victim to the budgeting and scheduling crisis caused by the lead dust problem.

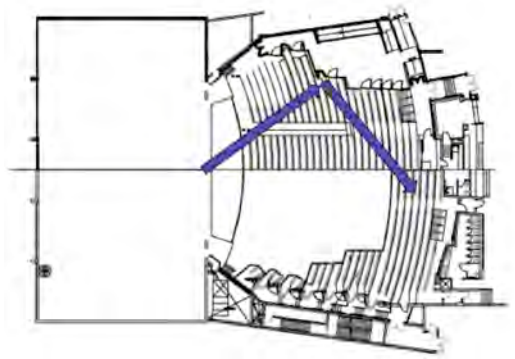

Figure 3. Plan view showing how the walls of the Mezzanine level were strategically located to provide lateral reflected sound to listeners in the orchestra level below.

The Final Design

As mentioned above, the lead dust problem forced a 3rd re-design of the renovation in response to a 30% reduction of the budget. The re-design was a rather frantic affair, carried out over the winter of 2007-2008. A view of the finished room is shown in Figure 1. Ceiling and side balcony front reflectors are clearly expressed. But there is more here than meets the eye. The room is very wide. By the time the design was complete, virtually every available surface that might improve early lateral reflections had been employed – all of it cleverly disguised by the architects, Proscenium Architects + Interiors.

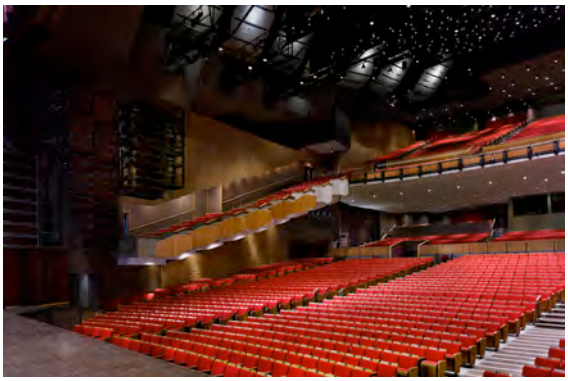

Figure 1 View of the renovated Queen Elizabeth Theatre from the stage. Lateral reflectors can be seen in the ceiling and on the face of the side balcony

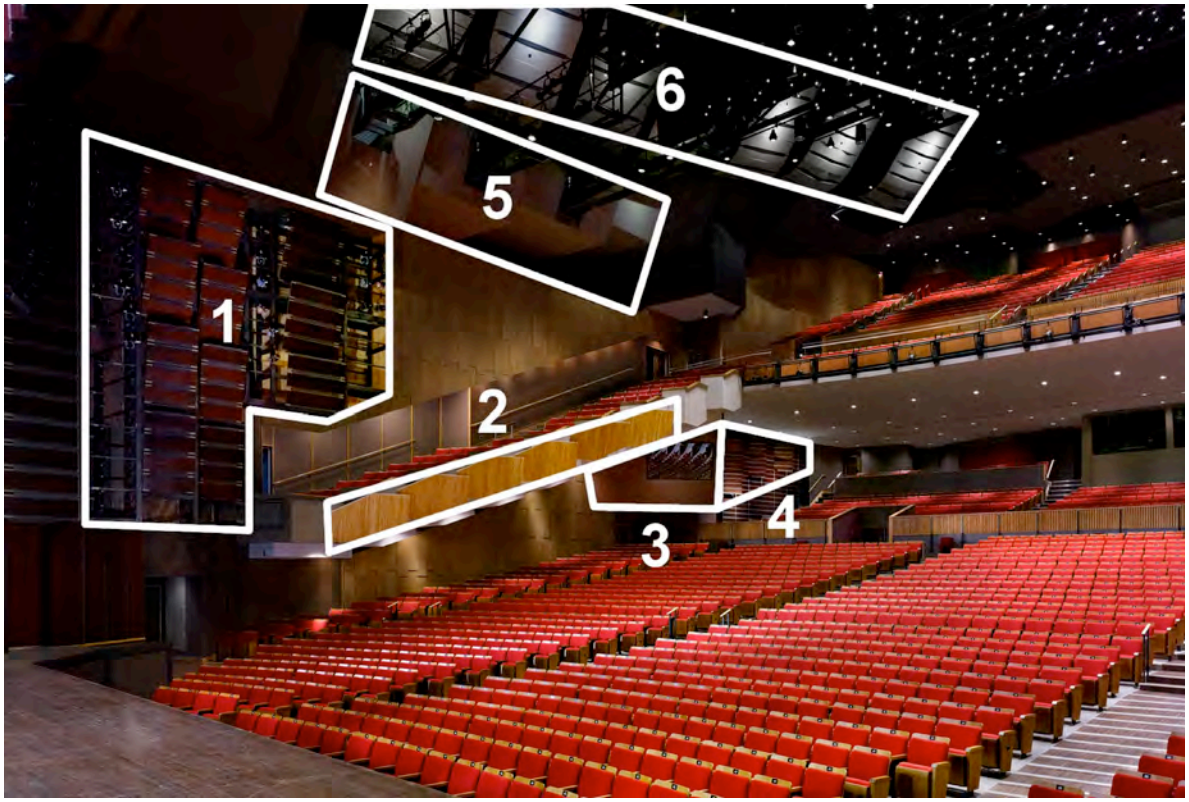

Figure 4. Same as Figure 1 with the lateral reflector zones identified and, in some cases, enhanced for a better view.

Figure 4 is larger version of Figure 1. Please see Figure 5 as well. Lateral reflector zones have been identified and will be discussed below. An attempt has been made to lighten those zones buried in darkness. (Please note these lightened zones will be easier to see in the electronic version than on printed paper.) Not shown in these images are further lateral reflecting surfaces in the ceiling above the balcony.

Optimizing the size and, especially, the location of so many lateral reflectors was a very arduous task, made infinitely easier by modern 3D computer modelling techniques. Reflectors in zones 5 and 6 come from the 2007 design. They were aimed by manipulating text files in an acoustic modelling program. The software package was not intended to be used in this way, i.e. to shape and orientate reflectors in 3D space. The interface is through a very clumsy ASCII text files. Evidence of the problem can be seen in Figure 5; note how the ceiling reflectors in Zone 6 do not line up with each other.

Late in 2007, just after the budget crisis, and just in time for the major re-design, we discovered a

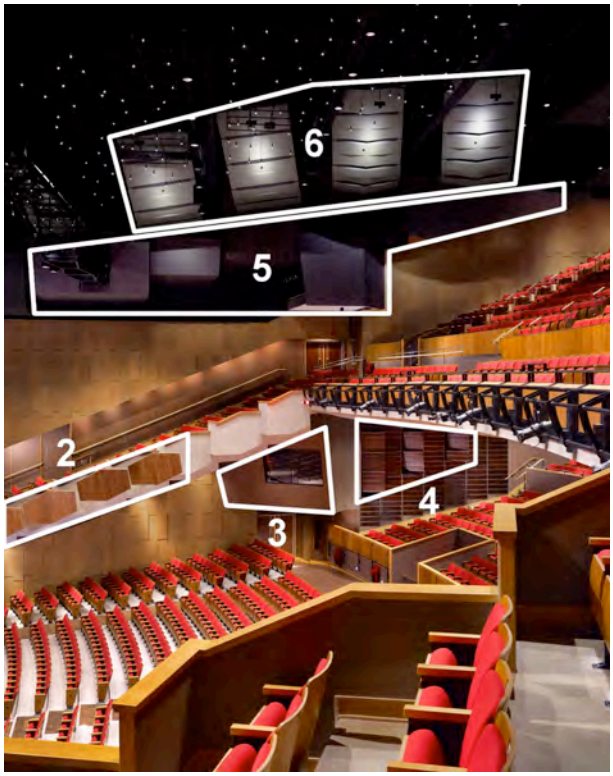

Figure 5 A view from the side box, with reflector zones identified and enhanced.

new software tool, originally intended to optimise lighting in green buildings.

The dexterity of design that this software affords us cannot be overestimated. For the first time, it allowed us to calculate reflection direction and coverage in real time. The reflectors needed to compensate for what we lost in the re-design crisis are astonishingly small. The reflectors are shown in Zones 1, 2 and 4 in Figure 4 and Figure 5 and the reflection coverage of the audience that they generate is shown in Figure 7. The tilt on many of these has been optimised to within less than a degree – optimising the crucial lateral energy in this very wide, high volume room. We have conferred with our colleagues overseas and we believe that we are the first to optimise reflectors on this scale and this accurately.

Lateral Reflector Design

Let us now discuss the lateral reflector zones:

1. This array of reflectors is shared with technical space usually dedicated to production lighting. These small reflectors, in concert with the even smaller and fewer Zone 4 reflectors, cast lateral reflections to almost all of the stalls and all of the mezzanine. (The mezzanine is the area of seating immediately adjacent to the Zone 4 reflectors.) An animation of this particular reflector coverage is currently available online http://aercoustics.com/files/2009/11/QET_Final.gif

2. This zone of balcony facia reflectors really demonstrates how far computer aided acoustical design has evolved in the last few years. Six years ago, prior to the final design, the first author had written this zone off, but not before a very long exercise attempting to make it work. In 2008, with the crucial advantage of new software capable of aiming reflectors in real time, the facia reflectors became a critical component of the acoustical design solution. The location of each reflector has been optimised so that it is not in the shadow of the reflector in front of it. As the array of reflectors moves towards the back of the room, this forces each successive reflector further into the house, towards the centre-line; as can be seen in Figure 6. Note that the array appears to be missing its last two reflectors, seen in the middle of Figure 5, just above Zone 3. For lateral reflectors to work in this location, they would have to be positioned so far towards the middle of the room as to block sight lines for patrons in the back corners of the balcony. Compensation for this was provided by Zone 3.

3. This is a booth for the physically challenged. While there are plenty of wheelchair locations inside the auditorium, a location was required for those who might have problems with involuntary vocalisations or physical tics that would disturb other patrons. Indeed, one of the Vancouver Opera's longstanding subscribers already fits this description. The acoustic design took advantage of this room and its symmetric partner on the opposite side, rotating the front face in plan and tilting it down in section to direct lateral energy to the back of the stalls, just in front of the cross-aisle.

4. These few reflectors are perhaps the most strategically important in the building. Although small in size and number, they cover a good part of the mezzanine level, an area underneath the balcony overhang and thus not visible to many of the other overhead reflectors in the room.

5. This is a bulkhead for return air ductwork. Exposed ductwork would have acted as a low frequency absorber so it was covered with 3 layers of 16 mm gypsum board. These large surfaces were put to further acoustical advantage and, after proper aiming, cover a good part of the balcony that the Zone 6 reflectors could not. Note also the catwalk at the top left hand corner of Figure 5.

Figure 6. Zone 2 balcony facia reflectors are seen in the foreground. Note how they progressively move toward the centre-line of the room.

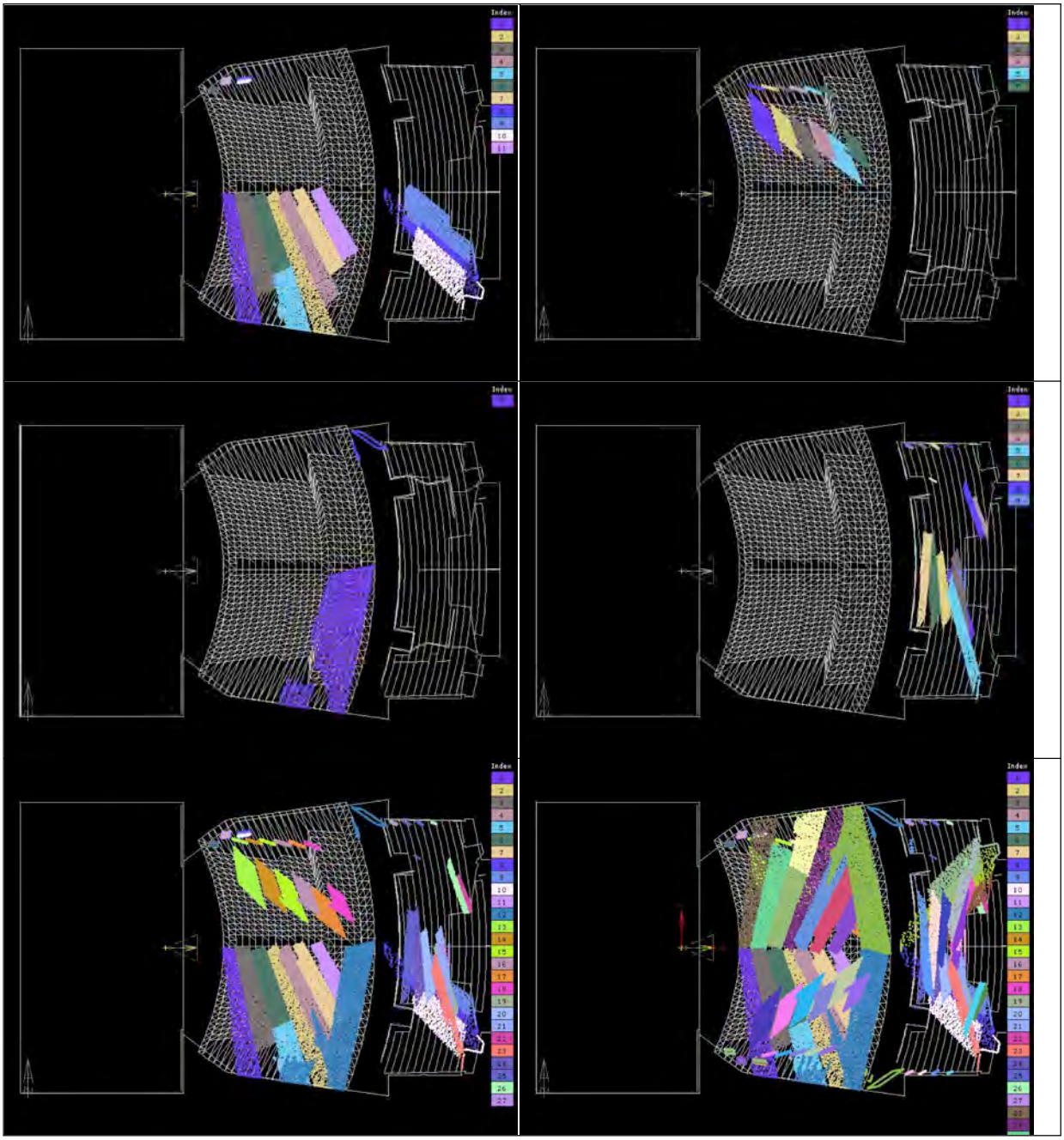

Figure 7. A number of small reflectors have been optimised to provide almost the entire orchestra and mezzanine levels with the required early lateral reflections. Starting at the top from left to right, we see the coverage from Zones 1 and 2 respectively for a single side of the room. In the middle row we see the same for Zones 3 and 4. In the bottom row on the left we see the combination of Zones 1 to 4 from reflectors on one side of the room and on the right we see the total coverage from the Zone 1 to 4 reflectors on both sides of the room.

Having spent a lot of money removing the ceiling, we didn't want to lose that volume to a tangle of ductwork, catwalks and the like. The floor of all three catwalks is actually a wire cable tension grid and, as such, is much more acoustically transparent than a traditional catwalk.

6. These are the overhead reflectors inspired by the Christchurch and Wellington halls. Conceptually they were the first part of the Directed Energy solution and, aesthetically, remain the most visible. These reflectors went through several generations of design prior the final version shown here. They started out as four large, flat and rather awkward looking reflectors located towards the back of the room, providing lateral energy mostly to the balconies. Later on they developed into the elliptical plan now seen in the building, but the individual panels still remained flat. Concerns about image shift generated by the flat panels (where the sound appears to be coming from the panel rather than the stage) suggested a need for diffusion. The size of the reflectors was dictated partly by truss spacing and partly by headroom constraints above the balcony. Providing lateral energy coverage to the orchestra level was rather easy, primarily because the reflectors were so far away. Above the balcony, the reflectors were closer to the seats and the zone of coverage was correspondingly smaller. The elliptical plan compounded the problem, limiting the reflection zone to the centre of the balcony. The problem was solved with two more design improvements. The side walls of the lighting gondola were sloped to direct sound to the back corners of the balcony. Then, in an eleventh hour optimisation, the bottoms of the reflectors were curved into the "J" shape shown in Figures 4 and 5. This will scatter some of the incident sound to directions behind the reflector. Having developed this for the balcony, we realised that it could also be used on the other reflectors to scatter sound to the side wall boxes.

Measurements

Measurements performed in the finished room are shown in Figure 8 and Figure 9. The former show the data at individual seating locations, the latter show the data averaged over all the seating locations, showing how the data varies across the salient audible spectrum. (Note – the data in Figure 8 is from the 1000 Hz octave band, as are other similar graphs seen elsewhere in this submission.)

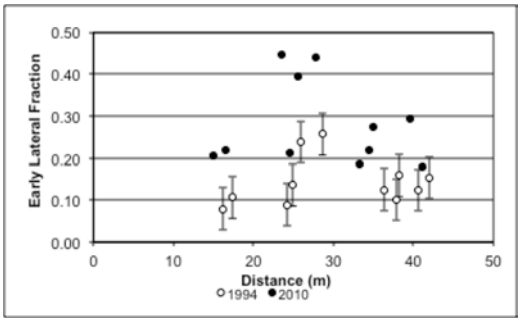

Figure 8. The Early Lateral Fraction quantifies the spatial aspect known as Source Broadening. The renovated room shows a significant improvement.

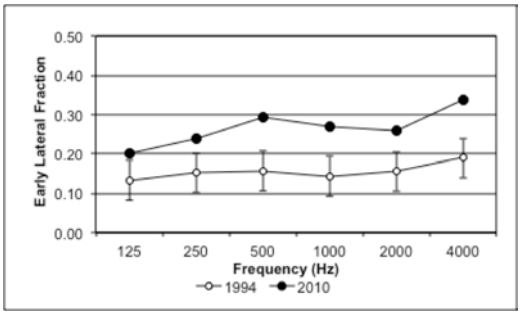

Figure 9. Early Lateral Fractions measured across the salient audible spectrum.

A significant improvement in the Lateral Energy Fraction is seen in both Figures. This would suggest improved Source Broadening which, indeed, is the case. Again, the vertical error bars indicate the Just Noticeable Differences (JND) for the subjective percept Source Broadening. In Figure 8, it's difficult to discern if the JNDs have been exceeded at each seat location. That's because, with a new seating layout, direct seat to seat comparisons cannot be made. But if we look at the average performance, for example the 1,000 Hz octave band in Figure 9, (or any other octave band, for that matter) we see that JNDs indeed have been exceeded, in some cases by twice as much.

As of this writing, late lateral measurements quantifying Envelopment have yet to be processed. Based on the strong correlations we have found between early and late energy in the room (discussed in the previous chapter) we anticipate improvements similar to the early lateral energy seen in Figure 8 and Figure 9.

Clarity, Warmth, & Intimacy

CLARITY WARMTH and INTIMACY

Clarity

Of the five or six properties required for good sound, the only one that the original Queen Elizabeth Theatre had was Clarity. If fact, one of the complaints of the original room was that it had a bit too much Clarity. Like many large post-war venues, it was described as "too clinical". That was because is lacked Reverberance and all the other properties we have been discussing. (Clarity and Reverberance are often inversely related.)

Of the five or six properties of sound that our renovation design had to deliver, Clarity was probably the one we worried about least. The room already had too much Clarity, we were adding Reverberance, which would reduce it, and so long as we didn't reduce it too far we would be okay. In the end that proved to be the case, as seen in Figure 1. In a concert hall, the acceptable range for Clarity is between -4 and +1 dB. In an opera house it's slightly higher, -3 dB to +2 dB. So, although the Clarity ratios have decreased in the renovated room, which in this case is a good thing, they are still within the acceptable range for an opera house.

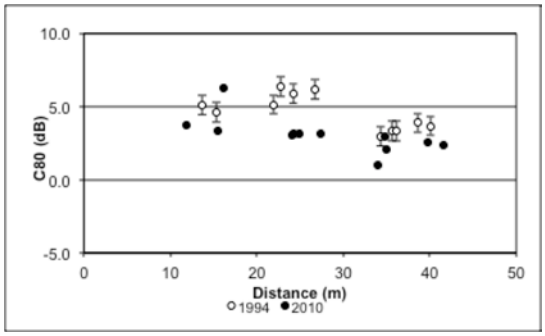

Figure 1. The 80 ms Clarity ratio (C80) quantifies perceived Clarity. The original room had too much Clarity. The vertical error bar indicate the Just Noticeable Difference (JND) for Clarity. In most cases, C80 has been reduced beyond a JND but not so far as to be below the acceptable range.

Warmth

Unlike the Clarity question, we did spend a lot of time worrying about Warmth. A room is said to be acoustically warm when the bass frequencies are strong. The worlds' favourite venues from the 18th and 19th century are known for their warmth. The reason for that is well known. Those buildings were made out heavy materials, much heavier than used in construction today. Light weight materials such as gypsum board (which is ubiquitous in modern construction) or thin wood panels, absorb low frequency sound. The latter belies the popular held belief that "wood is good" in a concert hall. Most wood finishes in a room, whether it be a performance venue or not, are fairly thin. This, of course is done to save money. Concert halls and opera houses, however, require much heavier materials. If it has to be wood, it has to be very thick, in the range of 150 mm to 200 mm (5" to 6"). This was not practical in Queen Elizabeth Theatre, given its financial challenges, but two recent buildings, both of which wanted to express a lot of wood, have worked to these dimensions; the Roy Thompson Hall renovation in Toronto and the new Oslo Opera House have wood finishes that are 150 mm thick or more.

Achieving good Warmth in a building these days relies more on the powers of persuasion than on the nuance of science and engineering. Building designers are used to modern lightweight materials and convincing them to step back into the past isn't always easy.

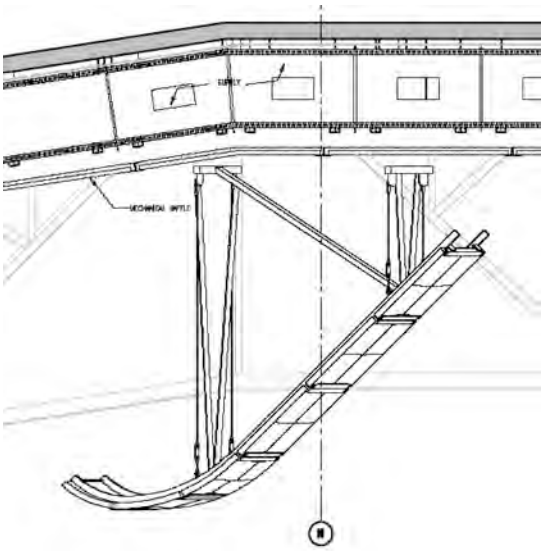

Figure 2. Section detail showing, from the bottom up, the J-shaped ceiling reflector, the concrete ceiling, the Supply Air ductwork and plenum and, finally, the existing concrete roof structure.

One of the biggest single surfaces in a room like the Queen Elizabeth Theatre is the ceiling. And, because it's such a large surface, it had to be heavy if we were going to improve the Warmth. Likewise, the ceiling reflectors providing lateral reflections are large exposed surfaces that need to be heavy. A detail of the reflectors and the ceiling is shown in Figure 2. The J-shaped reflector (referred to by the design team as hockey sticks!) is fabricated from a fibre re-enforced gypsum (FRG) mould filled with a 50 mm thick layer of cementatious plaster. These were fabricated off site, lifted into place, then very carefully positioned to direct sound to the right part of the audience.

Above the structure supporting the reflector (and not shown very well in this detail) is the new ceiling. It forms the underside of the new Supply Air plena and consists of a 38 mm corrugated steel deck (for diffusion) filled with a 38 mm topping of concrete (to maintain warmth). It was very difficult to pour the concrete at that height and there wasn't much room in which to manoeuvre, the ductwork having already been installed the previous summer – but it had to be done.

Both of these components had been designed and were being installed when the lead dust crisis of 2007 occurred. After that the use of costly heavy materials had to be carefully thought out. It was decided that if a surface was small enough, it didn't have to be heavy because its small size would reduce its deleterious influence. For that reason, all the small Zone 1, 2 and 4 reflectors described in the previous chapter are light weight. Likewise, some of the thin wood panels lining the side walls could be removed and some could not, notably in the area just about the side wall balcony seats. Please see Figure 3. Aercoustics could, perhaps, have insisted on their removal but there was more lead dust behind them and the cost to the budget and the all-important schedule would have been formidable. By that time, we were receiving positive feed-back about the Warmth from the Vancouver Opera – information that was puzzling at the time because the new concrete ceiling had yet to be installed. At that point the ceiling space was filled with very lightweight ductwork which would have been a very good low frequency absorber indeed. (This story will be explained in the following section.) With the positive feedback from the Vancouver Op, and other considerations, we decided to take the risk and leave the lead dust laden lightweight panels in place. Once again, the measurements performed after the opening proved that the risk was worth it.

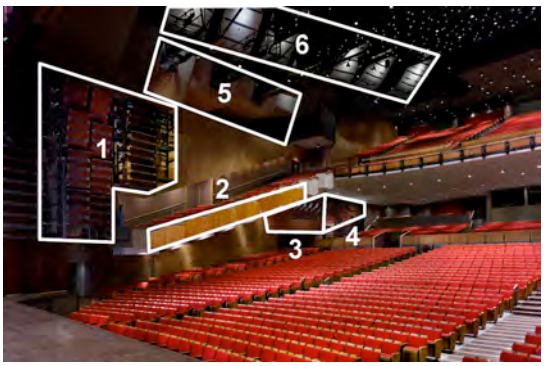

Figure 3. Thin wood panelling on the side wall, just above Zone 2 could not be removed because of the lead dust hazard.

The quantification of acoustic Warmth has been a subject of conjecture since the 1930s. It wasn't until 1997 that John Bradley and his colleagues at the National Research Council performed controlled laboratory tests that firmly established a (very strong) correlation between objective measurements and the subjective perception of Warmth. Up until that point most, if not all, thought that warmth was linked to low frequency Reverberations Times or, more recently, Early Decay Times. Bradley et al. found the Loudness was the best way to predict Warmth, in particular the low frequency content of the Loudness. They developed a parameter that is called weighted Loudness (Gw) and is slowly but surely gaining acceptance.

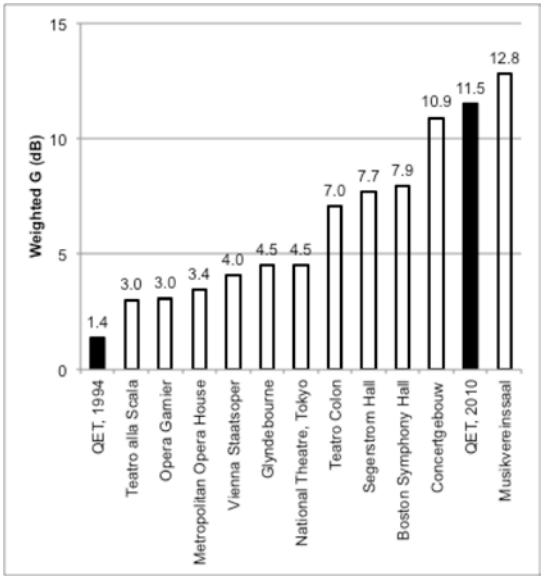

Figure 4. Weighted Loudness (Gw) has been shown to have a very strong correlation with the perception of Warmth. Measurements before and after the renovation suggest that the QET has gone from one of the worst to one of the best.

Measurements of Gw from a number of opera houses and three of the world's favourite concerts halls place the improvement in the QET's Gw into context. Please see Figure 4. Before the renovation, Gw for the QET is lower than all of the opera houses and concert halls. After the renovation it is better than all the opera houses and only one of the three concert halls, Vienna's Musikvereinssaal, exceeds it.

Truth be told, the inclusion of the worlds' three favourite concert halls is a slightly unfair comparison as concert halls typically have better warmth than opera houses. If we limit the comparison to just opera houses – and these include the best in the world – the original Queen Elizabeth Theatre comes in last and the renovated room leads them all.

Intimacy

Acoustic Intimacy is an extremely difficult parameter to quantify with objective measurements. It is, perhaps, the only important subjective parameter left that cannot be measured objectively. Some have linked it to Loudness or, sometimes a combination of Loundness, Reverberance and Clarity. None of the correlations in these studies however were conclusive. There is, however, an encouraging prospect on the horizon. Many now think of Intimacy as a so-called multi-modal percept. That is, the neural process that decides whether a room is Intimate or not, involves both visual and aural stimuli. The postulate is that visual stimuli leads to a certain expectation as to how loud the room might be. If the sound turns out to be louder than that, we get the impression of being closer to the sound; i.e. more Intimate.

The Intimacy of the renovated QET came as a pleasant surprise to the design team. One explanation for the Intimacy might be found in Figure 5. Revised Theory, discussed in the previous chapter on Loudness, has proved to be an accurate predictor of sound levels in a room. As such, it's a good predictor of what people might expect in a room of a given size at a given distance from the sound source, i.e. a good predictor of the visual stimuli that may be part of Intimacy judgment. Figure 5 shows that measured Loudness (G) in the renovated room is consistently higher than the Revised Theory prediction, suggesting that the aural experience is louder than the visual stimuli might lead a listener to expect. This would, in turn, suggest good Intimacy.

This, of course, is fodder for new research and is not really the purview of our task to improve the acoustics of the Queen Elizabeth Theatre. But it's still exciting, nonetheless!

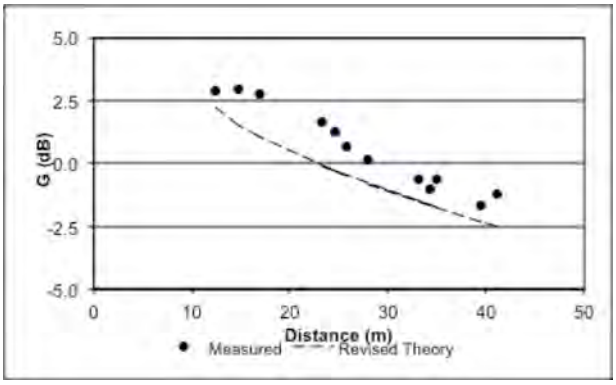

Figure 5 Measured Strength (G) compared to a Revised Theory prediction might explain the better than expected Intimacy.

Noise Control

NOISE CONTROL

Introduction

The Queen Elizabeth Theatre renovation work started out, oddly enough, with the noise control. It might sound mundane but it's one of the more important things in concert hall or opera house design. Musicians and singers need a quiet room in the same way that painter needs a clean canvas. A quiet room gives the performer a wider dynamic range and allows the rest of us to hear the acoustical nuance that would otherwise be covered up by noise.

There are two kinds of noise; intermittent noise that might intrude from the outside and the steady state noise created inside the room, invariably by the Heating Ventilation and Air Conditioning (HVAC) system.

Intrusion Noise

The facility known as the Queen Elizabeth Theatre actually holds two venues, the main theatre after which the building is named and the adjacent 668 seat Playhouse Theatre.

The main auditorium opened as a stand-alone building in 1959. The Playhouse Theatre was added in 1962. It was rigidly connected to the existing building and, in so doing, formed a structure borne sound path that would plague the combined buildings for decades to come. That was fine in the early 1960s when amplification was carried in the back of a van and might amount to 100 watts, perhaps even 200 watts. These days the amplification arrives in tractor-trailers and is measured in 100s of thousands of watts. In short, the two rooms could no longer operate properly when a modern Rock 'n Roll act came to town. The loud music from one room could be clearly heard in the other, forcing staggered starting times, scheduling restrictions, etc. Despite double walls and well-sealed doors, the sound was so loud it travelled through the common concrete structure, i.e. the structure borne path. The solution was simple but quite radical. The building was cut in two.

Large saws cut through walls and floors. For concrete footings, sometimes several feet deep, core drills, such as the one shown here, were brought in. The engineering challenge in this work of course belonged to the structural engineer (RJC Vancouver, Renato Camporese – Partner-in-Charge). The risk however was Aercoustics' because we were the ones who made the radical recommendation and we were the ones who had to make sure it worked.

The two venues now operate quite independently of each other without any sound transmission between the two. And the strategy of doing what became known as "The Cut" as the first phase of the work paid off. Construction noise generated in the Queen Elizabeth Theatre over the following three summers could not be heard in the Playhouse Theatre.

This concept of structural separation is actually fairly typical for the very best venues these days. The new opera house in Toronto, Koerner Hall, The Esplanade in Medicine Hat; all these rooms are structurally independent parts of the building.

Ventilation noise

Most of the background noise in a concert hall or opera house comes from the ventilation system. This kind of noise is like the dirt on a Renaissance painting: you don't notice it until it's gone. And we had a perfect demonstration of that point on this project. As mentioned, the construction work was carried out over four summers when the room was dark. We dealt with the ventilation noise in the second summer. And, interestingly enough, when we were finished, Vancouver Opera were very excited about the warmth of the room, telling us how much better the bass was. The problem was, we hadn't done anything yet to improve the warmth! That was going to happen the next summer with, among other things, the installation of the new concrete ceiling mentioned in the previous chapter. Indeed, we had not improved Warmth, but we had removed the ventilation noise that had been covering it up for the last 50 years. The warmth was always there, they just couldn't hear it.

Many new venues now use a displacement system to provide air slowly and very quietly. Air is blown into a plenum below the seats and is allowed to drift up through holes in the floor. At the Queen Elizabeth Theatre this option was precluded by an existing parking lot underneath the audience. The solution, first developed by Aercoustics, was to turn the concept upside down. Air is now blown into a series of plena in between the roof joists. The plena act as a noise control mechanism and take up a lot less of the room's precious acoustic volume than a normally ducted system would.

The new room is now very quiet indeed.

Environmental and Social Benefits

ENVIRONMENTAL AND SOCIAL BENEFITS

Reduce Re-use Recycle

Acoustic design of performing arts centres is not often associated with environmental impact. Indeed there are no LEED points granted for green acoustic design on any type of building. There are, however, two aspects of the Queen Elizabeth Theatre design and construction that responded to environmental concerns – both of which were assisted by the creative response of the acoustical engineering design.

First and foremost, this was a renovation. Estimates are that construction waste occupies 15% to 30% of landfill sites, depending on the amount of local construction activity. A renovated building is a recycled building. Even better, one could argue that it is a re-used building. The Queen Elizabeth Theatre covers an entire city block. If it was demolished, as many suggested it should be, the impact on the environment would have been formidable. Renovating a building imparts restrictions on all aspects of the design, be it architectural, mechanical, structural, etc. In this building the impact was particularly acute on the acoustic design. This was an overly large, overly wide venue from an era considered to be the nadir of acoustic design. Through a very creative collaboration with the architects Aercoustics was able to rescue a notoriously poor sounding room and turn it into a space hailed by musicians and audience alike.

Workplace Environment

When the Queen Elizabeth Theatre was built it was painted with lead based paint, as was every other building of its age. In 2007, when steel work required removal of the paint in different areas, lead dust began to accumulate on the site, creating an unsafe working environment. WorkSafeBC monitored the situation closely. As the summer construction of 2007 progressed, it was becoming clear that something had to be done. A good part of the next summer, the summer of 2008 when the project was supposed to be completed, was spent cleaning up all the potential sources of lead paint; "bagging it" as the expression goes. Given the implications this had on the construction schedule, this meant that the existing design (the 2nd Design) couldn't be finished until 2011, a year after the critical deadline imposed by the 2010 Vancouver Olympics.

Providing a safe work environment forced a major redesign of the theatre: one that, in the end, still proved successful.

Social Benefits

The Queen Elizabeth Theatre is the largest multi-purpose auditorium in one of Canada's largest cities. Like any auditorium in any city, it is a place for the community to gather and celebrate their common heritage – and, on some very special occasions – embellish that heritage.

Much of this submission has focused the acoustical needs of Vancouver Opera but, as already pointed out, 70% of the time the room is booked for popular music acts, rock and roll and, being in Vancouver, is host to a wide range of ethnic celebrations. The renovated room is not a palace for the elite. It's a facility for the entire community and the acoustical success of the renovation has rejuvenated it in the public's mind. Here's a quote from a popular radio host, reviewing a Jann Arden concert soon after the building opened:

> *... it's the sound! Crystal clear, all the instruments coming through. The vocals right in your face. Fantastic. The patrons feel totally engulfed in sound. ... run, don't walk to the Queen Elizabeth Theatre. You're going to have a great night.*
>
> ***Bruce Allan***
> ***Music Critic, CKNW Radio***

The social benefits of this project are clear. Vancouver's largest (and long lamented) multi-purpose theatre is now a place the city can be proud of.

Testimonials, Glossary, Formulae & Publications

CITY OF VANCOUVER

VANCOUVER Host City

Queen Elizabeth Theatre • Orpheum • Vancouver Playhouse

May 1, 2011

John O'Keefe
Aercoustics Engineering Ltd.
50 Ronson Dr., Suite 165
Toronto, ON
M9W 1B3

Dear John;:

RE: Canadian Engineering Awards

It is my great pleasure to write in support of recognition for the work you did on the Queen Elizabeth Theatre, not for a moment forgetting the stellar work you also did on our Orpheum.

Thinking back over the history of these projects is a bit like reviewing a long military campaign with you and Thom Weeks of Proscenium Architecture + Interiors as the campaign strategists. I remember the phase when we built the 1:25 scale models of the theatres and you brought in the small-scale microphones and sound generator to empirically test the rooms and to test acoustic solutions - a brand-new technology.

Then the various attempts to retain original building characteristics, like the QET ceiling, while still getting opera house acoustics. All the manipulation of side wall reflectors, box-seat faces, balcony fronts etc. We even discussed and rejected electronic enhancement systems. And the day of reckoning when you told us that the only way to get what we wanted would require removing the ceiling, and demonstrated the results we could expect.

Unanticipated were the headaches with lead removal that followed that decision and that required last minute revisions to the design and the building program. All of which we survived.

But what I recall most is that once the decision was made, how much freer the whole project became. And then the delight of us all when you came in with that new software to demonstrate how you would be able to design all the myriad reflectors and focus them for maximum benefit.

The first success came in the fall of 2008. We had installed the "eyebrow" above the Proscenium that summer. At the end of the first opera rehearsal in

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CITY OF VANCOUVER

November, the musicians came out of the orchestra pit cheering - for the first time in 50 years they could hear the singers and hear themselves. For the first time they would be able to play as an ensemble.

And when we went into opera rehearsals after the final phase of work, in November 2009, the new room was so live and responsive without audience, we actually had to reintroduce the sound absorption designed for amplified concerts. Opening night was quite thrilling, if only for the acoustics. Everyone from performers on stage and in the pit to the audience and the severest of critics were thrilled with the sound in Vancouver's "new opera house".

And the other big win that you and Thom, with the involvement of Engineering Harmonics, delivered to us: it is very rare to get excellent acoustics for both natural sound and amplified sound in the same room. Where it is successful for amplified sound, there are "acres" of heavy, mechanised acoustic absorbing drapes deployed into the room to kill all of the reflections that make for good natural sound. In the QET, we have 4 little drapes that are manually drawn across rear-wall flat surfaces, and I mean these are each the size of a living room window, plus 3 shallow roll-drops in the ceiling. After the Jann Arden concert, her manager, Bruce Allen, also a famously outspoken radio personality, raved about the QET as the best sounding room in the country - for rock concerts!!

The Queen Elizabeth Theatre, and Vancouver, is the proud and grateful beneficiary of the innovation you and Thom Weeks brought to the table, that gave us a great "new" theatre in the skin of the old one, in the year of her 50th anniversary.

Thank you John.

Yours truly,

Director

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VANCOUVER OPERA

April 29, 2011

John O'Keefe, M.Sc., P.Eng., MIOA
Aercoustics Engineering Ltd.
50 Ronson Dr., Suite 165
Toronto, ON M9W 1B3

Dear John,

I am happy to send this letter to state how pleased Vancouver Opera is with the acoustical work you did for the Queen Elizabeth Theatre.

Just last evening, one of our principal singers in *La Traviata*, who sings in houses around the world, including the Met, mentioned how great it is to sing in the renovated Queen Elizabeth Theatre. Audience members respond on a regular basis to the improvements and our conductors are so pleased with the balance they can achieve between pit and stage.

What has transpired as a result of Aercoustics Engineering's work is, in my estimation, a minor miracle! We are delighted and – more importantly – the audience is thrilled.

Best regards,

James W. Wright
General Director

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May 3, 2011

To Whom it May Concern,

We are writing in support of Aercoustics Engineering Limited's application for the 2011 Canadian Consulting Engineering Awards for their work on the acoustical renovation of the Queen Elizabeth Theatre, here in Vancouver. Proscenium Architects + Interiors were the architects on the project and Aercoustics Engineering were the acoustical consultants.

For more than 16 years, we have worked successfully with John O'Keefe and Aercoustics Engineering on many acoustically sensitive projects. The Queen Elizabeth Theatre renovation was perhaps the most sensitive and was definitely the most challenging insofar as construction costs and scheduling were concerned.

Most of the auditorium design was dictated by the need to improve the very poor acoustics of the space that have plagued the theatre since its construction in 1959. Aercoustics was instrumental in developing design solutions and played a vital role in pointing the team in the right direction. Their approach is a collegial one, trying to remain sensitive to the architectural issues and, after so many years of working closely together, trusting that we at Proscenium would remain sensitive to the acoustical issues. We hope we have.

On the Queen Elizabeth Theatre Renovation design, as with so many of our previous projects together, Aercoustics never shied away from tackling the type of technically challenging problems that others might choose to avoid. They take a refreshingly scientific approach to acoustical consulting. There are no "smoke and mirrors". Aercousitcs enjoy teaching us and rest of the team the scientific fundamentals of acoustics which, in turn, allows all of us to design more intelligently. At the beginning of construction Aercousitcs' took the time to explain the basic fundamentals of the acoustical separation of spaces to the contractors in order to ensure the success of the project.

Throughout the project, we could rely on Aercoustics' creative response to the many challenges that we faced. The most challenging period was the winter of 2007 – 2008 when a site problem with lead dust forced a complete re-design of the theatre. Facing a spring deadline, when construction had to recommence, the work had to be done quickly and intelligently. After a long day's work, it wasn't unusual to sit down after dinner (or sometimes during dinner), scratch out new ideas on a napkin, and then bring those ideas into the office the next day to be fleshed out with the design team.

Everyone, it seems, is happy with the new sound in the Queen Elizabeth Theatre. We are proud of that achievement and share our pride with Aercoustics. We enjoyed working together on this project and are more than happy to recommend them for the Canadian Consulting Engineers Award.

If you have any questions, please feel to call us.

Yours truly,
PROSCENIUM Architecture + Interiors Inc.

Hugh Cochlin, MAIBC, AAA, MRIAC, LEED™ AP
Principal

KahleAcoustics

John O'Keefe
Aercoustics Engineering Ltd.
50 Ronson Dr., Suite 165,
Toronto, ON M9W 1B3, Canada

Brussels, 1st May 2011

To whom it may concern

I have been asked to comment on the acoustic aspects of the renovation of the Queen Elizabeth Theatre in Vancouver, a project carried out by Aercoustics Engineering Ltd. of Toronto, Canada. I have been informed about the project – and the difficulties of the project, especially due to financial constraints – through irregular discussions and meetings with John O'Keefe of Aercoustics, and have now read with interest and enthusiasm the recent publication about the renovation process and the acoustic results obtained.

The renovation project of this room, plagued by acoustic shortcomings from the date of the opening of the original building, is a showcase of how acoustic design and research can be put to the benefit of a project and a room. It starts with the analysis of the shortcomings of the original buildings, not only from the point of view of objective measurements but equally from the point of view of subjective listening and perception of the space. Having done my own PhD at Ircam in Paris on the correlation of objective measurements and subjective evaluations, I can confirm that both the analysis of the shortcomings and the proposed improvement measures from Aercoustics show a deep understanding of the room and the science of room acoustics and room acoustics perception. Perhaps even more impressive is the acoustic optimization process used by Aercoustics, optimizing all available architectural and acoustic elements, first one by one and then in combination. Some of the optimization procedures have been developed specifically by Aercoustics, for others available software was used and adapted in novel and interesting ways. It can be stated without exaggeration that some of these optimization processes would not have been possible some decades ago – and possibly not even some years ago – and they are clearly at the forefront of computer aided design and computer aided development. As a consequence, the measurement results show truly impressive improvements of room acoustic quality, for all areas in the room. This is extremely comforting for a professional room acoustician with a scientific background: room acoustics is not just "black science"! When the analysis of the problems is correct and the improvement measures are adapted and properly optimized, then a significant improvement can and will be achieved – and in the case of the Queen Elizabeth Theatre this improvement is very significant indeed.

The logic of the acoustic improvements designed, the acoustic optimization procedure(s) and the magnitude of the acoustic improvements obtained as shown by the comparison of the objective measurements before and after the renovation, are all extremely impressive. From an acoustic design perspective, one can only summarize: a perfect project!

My sincere professional congratulations go to John O'Keefe and his team having worked on the project of the renovation of the Queen Elizabeth Theatre in Vancouver, and I can very strongly recommend this project for the Canadian Engineering Award.

If you have any further questions, please do not hesitate to get back to me.

Yours sincerely,

(Eckhard Kahle, PhD)
Director, Kahle Acoustics

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As a recording Engineer for CBC Radio, I have worked in Vancouver's Queen Elizabeth Theatre for over twenty years. Generally we would record one or two opera productions each year. I would often attend other opera productions as an audience member.

My sense of the room's acoustics while listening through the microphones was much the same as my experience in the hall. I was always dismayed that the orchestra sounded like it was playing in a concrete box. The sound was way too dry, also hard and cold. The sound from the stage was always disappointing, not very powerful, and certainly not supportive of the various vocal types. Very good singers could carry nicely into the hall, but lesser singers were very exposed.

The first stage of acoustic renovations removed the ceiling, and right away the orchestra sounded much better. There was warmth to the sound and considerable bloom out in the hall. At this point I could hang microphones further back in the hall, and get a pleasant blended sound. The stage sound for the singers was still not very well focused or flattering.

After the completion of the renovations, the whole room now sounds integrated. The orchestra has a good warm tone out in the hall, and the singers are well blended with the pit. There is very good support for the singers, they are well localized on the stage, yet there is a pleasant reverb bloom in the hall.

Don Harder
Recording Engineer

straight.com
Vancouver's Online Source

Queen Elizabeth Theatre gets an A for acoustics

By Matthew Burrows, November 19, 2009

Vancouver Civic Theatres director Rae Ackerman says it's "easy" to grade the acoustic leaps and bounds heard in the Queen Elizabeth Theatre following long-awaited recent improvements. "It used to be a D and now it's an A," he said.

In a guided tour on November 12, Ackerman explained that the extensive acoustic work formed the core of the $48.5-million renovation. Approximately $23 million of the work occurred in the past six months. An additional $6 million was spent on sound separation between the Q.E. and the Vancouver Playhouse.

"Without final testing, I would say right now that we have acoustics here in this whole theatre that rival those of the…Four Seasons [Centre for the Performing Arts] opera hall in Toronto," Ackerman said.

To be more acoustically sound and to improve access for people with disabilities, Ackerman said, the total seating capacity has dropped to 2,760 from 2,929.

THE GLOBE AND MAIL

November 14, 2009

SHOW TIME

By MARSHA LEDERMAN
From Saturday's Globe and Mail

For 50 years, everyone's been a critic. Now, as Marsha Lederman reports, the old theatre is getting its act together

REFIT FOR A QUEEN

Since the Queen herself opened Vancouver's Queen Elizabeth Theatre in 1959, everyone, it seems, has been a critic: audiences complained about the sightlines, the acoustics, the legroom; women complained about the washrooms as lineups stretched out the door and up the stairs; technicians fretted over how difficult it was to light a show and deal with the muddy amplified sound. Patrons called the entryway unexciting, boring, even shabby. Audiences seeing serious theatre next door at the Playhouse Theatre walked out, demanding their money back because the sound from rock concerts at the QE was leaking through the walls. And municipal officials worried that "the big shake" would occur during a performance, because the almost 3,000-seat theatre wasn't seismically prepared. Today marks a new act in the theatre's life as it reopens to the public after a $48.5-million four-phase renovation carried out by some 170 people working around the clock for the past five months.

LOBBY FOR CHANGE

The experience of going to the theatre changes the moment you walk in. The lobby, once a retro (not in a good way), closed-in space, has been opened up into a three-storey atrium. The floors and control rooms were ripped out and moved to create the airy space. New marble-covered concrete walls support the building on each side of the lobby - part of a massive seismic upgrade. The wall of glass facing south overlooks the new first nations Olympic pavilion, and chandeliers made from sustainably harvested seashells from the Strait of Georgia dangle from above. The theatre has new bars and concession stands, slick, new furniture and, yes, more women's washrooms on every level - about 12 additional stalls altogether.

SOME SOUND DECISIONS

Improving the notoriously flawed acoustics drove this project. To quell the sound absorption, the redesign team raised the roof - or at least the auditorium ceiling - by six to 12 metres. The carpet was ripped up and replaced with engineered hardwood; the metal seats were replaced with wood. The wooden floors of the catwalks above were replaced with woven wire (think tennis rackets), allowing sound to move through. About 100 sound reflectors (some nicknamed "hockey sticks" and "Shreddies" because of their shape) direct sound to the audience. Thick, red

curtains can be pulled into action to prevent the sound at amplified events from rocketing all over the place. Meanwhile, the QE and Playhouse were structurally separated so sound no longer leaks through. Rae Ackerman, Director of Vancouver Civic Theatres, predicts the sound at the QE will rival that of Toronto's Four Seasons Centre for the Performing Arts. We won't really know until Nov. 28, when the first non-amplified event is staged at the theatre, Vancouver Opera's production of *Norma*.

ARE YOU SITTING DOWN?

The theatre has gone to 2,760 seats from 2,929. About 150 seats in the old configuration were virtually unsellable (with rare exceptions - such as *Mamma Mia*) due to poor sightlines. The new seats are upholstered wood, made in Quebec, and offer more legroom.The seating in the centre block is staggered - so you don't have someone's head directly in front of you any more. Some wider seats were placed along the aisles for larger patrons, and some aisle seats on the orchestra level have swing arms for people with mobility issues. The auditorium is far more accessible, with 20 wheelchair spaces plus companion seats (there were only 14 spaces before). The wheelchair spaces at the back of the mezzanine level are raised so those patrons can see over the heads of people standing, say for an ovation or a rock concert. And no more cold drafts - the ventilation system has been redesigned.

ROOMS WITH A VIEW

Wolf Blitzer may never make it to the new theatre, but a situation room is part of the new design. The glassed-in room overlooks the stage from the mezzanine level and serves as a refuge for parents with crying babies, people with noisy respirators or a director having a nervous breakdown. They've become fairly common in newer theatres, but this is a completely new undertaking for the QE. Two large chorus dressing rooms have been built at stage level, each accommodating about 24 performers. The old chorus dressing rooms in the sub-basements will be used for overflow. A new wig room and wardrobe rooms are near the stage. The plans have been in the works since the early 1990s, when the design team first got together. So the skeleton for the dressing rooms was actually created 10 years ago when a salon was built on the side of the theatre. "The gift," says Rae Ackerman, director of Vancouver Civic Theatres, "was that we always knew where we were going to be in the end."

Royal rebirth for Vancouver's Queen Elizabeth Theatre

BY SUSAN LAZARUK, THE PROVINCE NOVEMBER 13, 2009

A worker prepares for opening night inside the newly renovated Queen Elizabeth Theatre in Vancouver.
Photograph by: Arlen Redekop, The Province

Fifty years and four months after a young Queen Elizabeth II christened Vancouver's brand-new $9-million downtown theatre after herself, the theatre celebrated the building's rebirth Friday night with an official re-opening ceremony.

At the original grand opening, the Queen, then 33 and just six years into her reign, attracted 250,000 well-wishers on her one-day visit to Vancouver on July 15, 1959, which was capped by the official christening of the state-of-the-art building at Georgia and Hamilton streets, then one of the largest "soft-seat" theatres in Canada.

If the Queen were to return today, it would be to see, and especially hear, a different theatre, one that's been spruced up to the tune of $48 million, or almost $1 million for each of its years.

Its director and designers say the changes were designed to improve the experience for those who attend musical events from opera to bhangra at the 2,760-seat theatre, beginning with the ceremony Friday night featuring the Vancouver Welsh Men's Choir, the UBC Opera Ensemble and Canadian singer songwriter Judy Ginn Walchuk, named Canada's most promising new singer in 1963, followed by a Broadway musical tribute.

"What we've got is the large auditorium that Vancouver should have had all along," said Vancouver's director of civic theatres, Rae Ackerman.

“All the renovations were done to make a major improvement for every point of view for the audience,” he said.

The most immediately noticeable change is the atrium in the now bright lobby, created by removing the ceiling that separated the floors and relocating the lighting and sound control room into the theatre. A modern crushed-seashell version of the spherical chandeliers, removed during previous renovations, now hang like giant snowflakes over the lobby.

Bars have been added to the upper levels, eliminating a need to stampede down the stairs at intermission, and the washrooms have been updated with square stainless-steel sinks and 12 additional stalls in total in the women’s rooms.

Most importantly, the theatre itself has been transformed from what even in 1959 were considered poor acoustics and bad sightlines. The Queen E has been criticized since its opening for being uninteresting, shabby, lacking legroom and having terrible acoustics, said Ackerman.

The city hired John O’Keefe of Aercoustics Engineering to use the latest in acoustic engineering to remove the low ceiling — once considered state-of-the-art acoustic engineering — and add sound reflectors along the walls and ceilings, all designed to direct music back to the audience.

Even the catwalks for technical crews above the stage were designed with mesh walking surfaces that allow sound to pass through it to the proper reflectors, unlike the old solid-bottomed ones that blocked the sound but didn’t properly direct it.

Aercoustics used computer-generated and scale models to tweak its designs sometimes by as little as a half-degree to achieve optimum sound, said O’Keefe.

The Queen E’s carpet has been replaced with engineered dark wood flooring and the old metal seats and their perforated bottoms — which “soaked up sound,” said O’Keefe — with cushioned wooden ones, both features designed to reflect sound instead of absorb it. Even the glass in the control room at the back had to be positioned to reflect the sound back to the audience.

The seats in the centre section are now staggered (where before people sat directly behind the people in front of them) and there’s more leg room — a six-foot-one Ackerman said he used to have to splay his knees and now has a five-centimetre clearance.

The centre has are more spaces for disabled seating and a “situation room,” where mothers with fussing babies or patrons with noisy respirators can watch a show; there are about 100 wider seats on certain aisles, which will eventually be identified for people wanting roomier seats; some end rows in the orchestra section swivel to allow people to pass and the ventilation system is quieter.

There are 169 fewer seats, largely because of the relocation of the control room, but Ackerman said 150 of the original 2,929 seats weren’t normally sold because of poor sightlines.

The renovations, which were done over four years during the annual summer shutdown, also included “acoustic separation” to eliminate sound bleed from the adjoining Vancouver Playhouse, which was built in 1962, before the high-decibel rock shows of the 1970s and later.

The Playhouse received many walkouts and requests for refunds over the years, even though rock shows at the Queen E were scheduled to start at 9 p.m. to mitigate any overlap, said Ackerman.

Although the first show is the Warren Miller’s annual ski film, on Saturday and Sunday, the first musical concert is Jann Arden next week, and O’Keefe said the big test for the acoustics will be Vancouver Opera’s *Norma*, opening on Nov. 28.

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RENDERINGS COURTESY CITY OF VANCOUVER

Queen Elizabeth Theatre Renewal

by Tiffany Sloan

"From the day you make the commitment to the day it opens, it takes 20 years on average to build a theatre from scratch," says Rae Ackerman, director of theatres for the City of Vancouver. But for such a high-use facility like the Queen Elizabeth Theatre, starting anew wasn't an option. "So we decided to fix it instead."

Not that fixing it was any faster, but it was one-quarter the cost. The project began in 1992 with a wish list of upgrades from users. This became the framework of what Ackerman calls the "Lego-block plan" – the team would pick tasks as funding came available, and as they started a project, they built infrastructure for future ones.

After hearing from other Canadian theatres that closing for renovations had drastically hurt user groups, Ackerman and Thom Weeks, principal architect with Proscenium Architecture + Interiors Inc., developed a compromise: Minor upgrades would be completed during the three-month off-season, and for the major upgrades from 2006 to 2009, the operating season was reduced from nine months to six.

The first major project was to acoustically isolate the Queen Elizabeth from the Vancouver Playhouse next door, cutting a gap several inches wide between the buildings. New expansion joints, shear walls and support elements were added to the Playhouse to prevent vibration travel. "It was built when acoustics weren't well understood, and they made several errors," says Weeks. "But to be fair to the original architects, the sound systems in 1956 were tiny, so the level of sound now generated could not have been anticipated."

Once the sound was isolated, the next step was to improve its quality, which included raising the ceiling. But when crews opened it up they saw red: "It was common to prime steel with lead primer in the '50s," says Michael Knight, president of general contractor Heatherbrae Builders. "But the nature of it and the amount of it no one anticipated."

Removal of the lead paint required extensive precautions and removal specialists – as well as a significant amount of time and money. Knight estimates it would have pushed the opening by two or three months – an unacceptable delay as the theatre had already committed to various productions. "We had crews working from six in the morning to midnight to gain back the time that was lost."

Ackerman and company studied the dispersion patterns of sounds from the speakers (suspended from the ceiling) and live voices (generally originating about five feet above the stage). Acoustics from live performances are best when echoing off hard surfaces, and sound reflectors were mounted strategically throughout the chamber to accommodate the echo patterns. Meanwhile, five hideaway curtains function as the absorptive surfaces needed to accommodate amplified events.

"Yes, it has better acoustics, but it's also a better technical facility for the productions," says Douglas Welch, principal of theatre consultant Douglas Welch Design, referencing extensive technical infrastructure improvements. While the original theatre had few theatrical lighting positions, raising the ceiling allowed for new catwalks. Fibre-optic LED lights are suspended from the ceiling, creating the illusion of a starry night sky and hiding the ceiling infrastructure from view.

This is especially true of the HVAC upgrades, notes Ken Junck, principal of mechanical consultant Stantec Consulting. From re-plumbing and re-ventilating the washrooms and expanding the sprinkler system to installing supplementary cooling in the lobby and adding mechanical for the new control booths and projection room, the 50-year-old building required extensive mechanical upgrades. The most significant change to the HVAC systems was the replacement of all of the supply and return ducts with much larger ducts enabling larger volumes of air to be moved at slower speeds eliminating one whole strata of noise.

The theatre's lighting capacities were significantly increased. "Theatre systems are described in terms of the number of dimmers, or the number of circuits, they provide to shows for operating stage lights," explains Wolf Schenke of electrical consultant Schenke Bawol Engineering. With the replacement and addition of new dimmer racks, the theatre nearly doubled capacity from 570 circuits to almost 1,100. But dimmer racks are heavy power users and the increased power draw meant adding a new service transformer, by carving a new room for it out of a boiler room. A challenging task, says Schenke, but necessary. "This is how a modern theatre operates. With the increased number of circuits, the Queen Elizabeth has stepped into the modern world in terms of technical capabilities."

Bringing the theatre up to seismic safety standards was integral. "It was built in the 1950s and I don't think there was much understanding of earthquakes or of Vancouver as a seismic region," says Colin Macmillan, design engineer with structural consultant Read Jones Christoffersen Ltd. "We added soil anchors that go about 50 feet into the ground to support the foundations for some walls. We did a lot of horizontal drilling within walls, which was challenging work because of the precision involved."

Macmillan notes that while most of the structural work is hidden, removing a portion of the second floor in the lobby to create a three-storey atrium makes a noticeable difference. "It was challenging to remove a portion of the slab while ensuring everything else was still supported properly, but the visual impact is quite dramatic."

Unlike renovations done in the '80s that aimed to modernize the theatre, the goal now was to restore it to its former glory – albeit in a more functional, technically proficient manner. "We actually brought the building back to its original design in some ways, and I think the interventions we've made have been respectful of the original intent of the building and of the original mid-century architecture," says Weeks. ■

LOCATION
649 Cambie Street
Vancouver, B.C.

OWNER/DEVELOPER
City of Vancouver

ARCHITECT
Proscenium Architecture + Interiors Inc.

GENERAL CONTRACTOR
Heatherbrae Builders

STRUCTURAL CONSULTANT
Read Jones Christoffersen Ltd.

MECHANICAL CONSULTANT
Stantec Consulting Ltd.

ELECTRICAL CONSULTANT
Schenke Bawol Engineering Ltd.

THEATRE CONSULTANT
Douglas Welch Design Associates Ltd.

ACOUSTICAL CONSULTANT
Aercoustics Engineering Ltd.

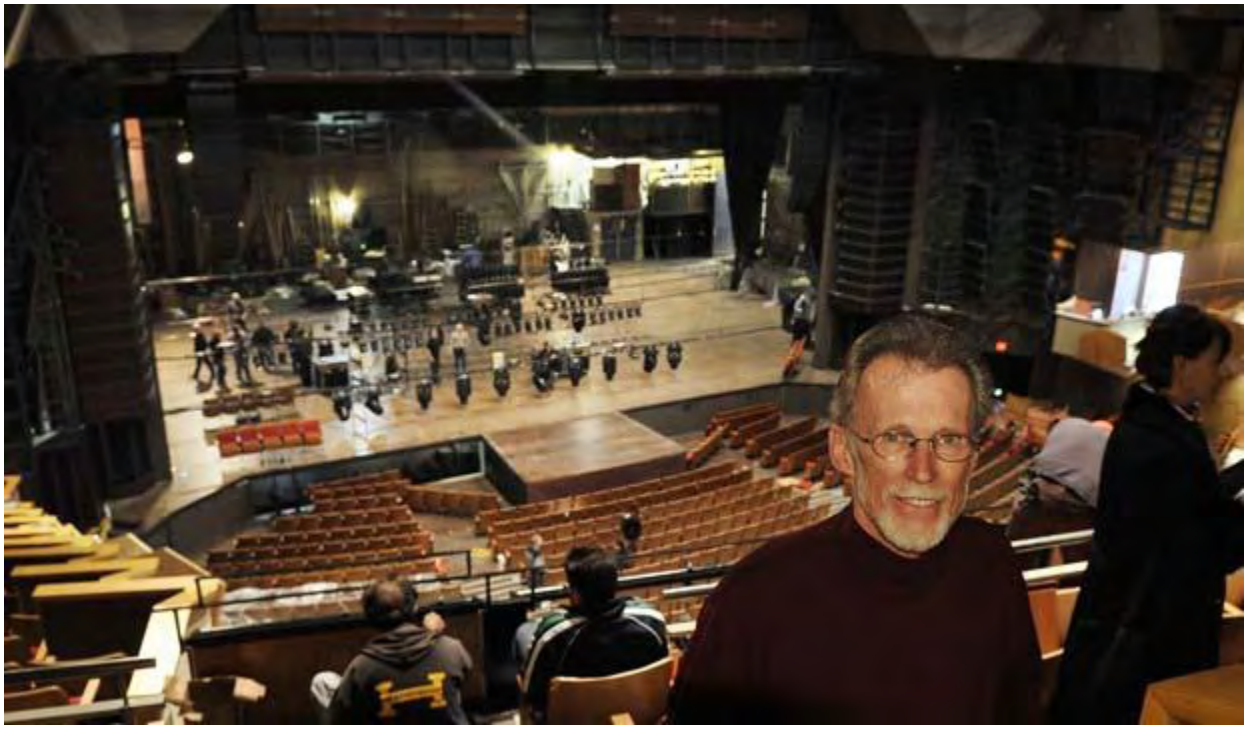
TOTAL AREA
95,000 square feet

TOTAL PROJECT COST
$54.5 million

THE VANCOUVER SUN

Vancouver is all ears for renovated Queen Elizabeth Theatre

BY JOHN MACKIE, VANCOUVER SUN NOVEMBER 13, 2009



Vancouver Civic Theatres Manager Rae Ackerman inside the freshly renovated Queen Elizabeth Theatre.

Photograph by: Ian Lindsay, Vancouver Sun

VANCOUVER — The Queen Elizabeth Theatre was regarded as a textbook example of theatre design when it opened in 1959. In fact, it was actually in a textbook on theatre design.

But the bloom was soon off the rose.

The exterior was cool, in a Mad Men-modern way, but the sound inside the 2,929-seat hall seemed kind of dead and lifeless. Soon the late-50s theatre style — a low ceiling in a deep, wide auditorium — went out of vogue, replaced by a new wave of theatres like the National Arts Centre in Ottawa.

“It was narrower, higher, [and] shallower,” relates Rae Ackerman, the director of Vancouver Civic Theatres. “It’s all about acoustics.”

Ackerman first approached Vancouver council with the idea of renovating the Queen E to improve the sound back in 1994. But it took more than a decade to get approval, and several years of closing the theatre in the summer to do the work.

Almost $60 million later, the work is finally finished. Tonight the Queen Elizabeth Theatre reopens with a Warren Miller ski film, Warren Miller’s Dynasty.

It’s probably not the type of cultural event civic leaders envisioned back in July 1959, when internationally renowned conductors like Herbert von Karajan, Sir Ernest MacMillan and Nicholas Goldschmidt came to town to conduct the Vancouver Symphony. But hey, Warren Miller movies put bums in seats. The Miller movie is also booked for Sunday.

In any event, Ackerman thinks theatre-goers will be pleased with the upgrades.

The most dramatic visual change is in the main-floor lobby, which used to have a relatively low ceiling. The two floors above it have been blown out, opening up the space to the full height of the building. What had seemed kind of cramped and dated now soars three storeys high. The open feel is enhanced because the Queen E’s glass exterior walls are now exposed all the way up.

The lobby also sports chic new chandeliers made out of white seashells, improved bar and washroom facilities and marble and walnut columns. You’d never know that behind the marble and walnut columns is a “shear wall” that runs from the basement parkade all the way up to the roof, providing seismic protection in case of an earthquake.

There are some visible changes inside the auditorium, as well. All new seats, with wood backs and bases rather than metal. (The capacity has been slightly reduced, to 2,760.) Polished cement floors, rather than carpet. Banks of wooden “reflective panels” alongside the loges on either side of the auditorium.

The masses probably won’t notice, but the ceiling is also higher, and the mezzanine isn’t as deep. But Ackerman thinks they will notice one change: the sound is way better.

“The biggest thing everybody will notice is the acoustics,” Ackerman said. “The natural acoustics in here are now going to be equivalent to the new opera house in Toronto.”

The Queen E upgrades are the finale to several years of renos at the three civic theatres owned and operated by the city of Vancouver: the Queen Elizabeth, the Orpheum, and the Playhouse. (The city also owns the Vancouver East Cultural Centre and the Firehall Theatre, but they’re run by non-profit societies.)

The Orpheum had sound problems too, but they were fixed with the addition of some sound baffles in 1996. This summer, the former movie and vaudeville palace also received new seats, 2,720 to be precise. The same ones as the Queen E, with birch backs and bottoms; wood reflects sound much better than metal.

"The first time the orchestra came in to rehearse this summer [people went] 'Whoa! It sounds better,'" Ackerman said.

What happened to the old Orpheum seats? Many were pitched, but 1,100 went to theatres in Powell River and Wells, some wound up at the Vogue, and some went to a movie art director.

"They had to turn up with a truck and a crew on one of two days and take them," Ackerman relates. "We got a dollar credit from the contractor for every seat he didn't have to remove."

The major change to the Playhouse came in 2006, when the 668-seat theatre was separated from the Queen E. This was done to stop amplified sound bleeding over from the bigger venue.

"This past year we had Marilyn Manson in here," Ackerman recounted.

"It was reaaally loud, and in the Playhouse, you couldn't hear anything from Marilyn Manson. It was 100-per-cent successful."

Civic Theaters is also about to pick up a couple of new venues in the Capitol Residences project, on the former Capitol Six theatre site on Seymour street.

"There's a 220-seat theatre that will also be a rehearsal hall big enough for the VSO," Ackerman explained. "There will be a 110-seat recital hall, and three storeys of music practice rooms for the VSO music school."

There is also a big empty room directly behind the Orpheum that will eventually be opened up to enlarge the Orpheum stage, but Ackerman says there is no funding in place yet for the $10-million cost.

The Capitol venues cost $20 million and were paid for by the developer, Wall Financial/McDonald Corp. Developer Bruno Wall says the city allowed the company to build a taller tower (43 storeys) in exchange for the cultural assets.

Wall says the Capitol Residences is a $180 million project, has 372 units and is sold out, with prices ranging from $300,000 to $2 million. It should be ready by fall 2010.

Ackerman also thinks there is still a chance that the long-delayed Coal Harbour arts complex may still be built.

The city still has $20 million it collected in development fees for the Coal Harbour Arts Complex, which had been slated for the site where the Vancouver Convention Centre East was built. Ackerman feels there is a real need for a live theatre that fills the void between the 1,100-seat Vogue and 2,700 seaters like the Queen E and Orpheum.

“A mid-size, 1,500 to 1,800-seat acoustically good hall would make a lot of sense,” he said.

“The only place in Vancouver right now that is of the right size is the bus depot site. That site would hold the Coal Harbour Arts Centre — two theatres, 1,900 and 450 [seats] — and the [Vancouver] Art Gallery, if the Art Gallery would agree to go to three stories instead of two.”

The problem is money. Ackerman says it would cost $200 million to replace the Queen Elizabeth Theatre today, which makes the $59 million spent on renos seem like a bargain.

Also problematic: The Art Gallery is supposed to move to northeast False Creek, not the old bus depot at Georgia and Hamilton. Premier Gordon Campbell announced so himself in May, 2008.

Still, Ackerman says anything is possible.

“Timing is what you’re talking about,” said Ackerman, who turned 65 this summer but plans to keep on working until 2011.

“Put it in perspective. It took me 15 years to get this job done. The average time in Canada from the time you say ‘I want a new arts facility’ to when the door opens is 20 years. So if you’re serious about the Coal Harbour Arts Centre, it’s now been 18 years. ... It should start construction next year.”

He chuckled.

“This is not karate, it’s tai chi. It’s the same moves, it’s just a lot slower.”

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REVERBERANCE: Sometimes referred to by musicians as "Resonance", this lends colour and blend to the sound. Without the appropriate Reverberance, the music will sound dry and lifeless. We provide the appropriate Reverberance by matching the enclosed room volume to the number of seats. The more seats, the higher the required volume. Subjective Reverberance correlates best an Early Decay Time (EDT) measurement.

LOUDNESS: Patrons have been found to be very sensitive to Loudness levels in a concert hall. Small rooms, if not designed properly, can be too loud; large rooms not loud enough. Loudness correlates best the measurement known as Strength (G).

SPATIAL IMPRESSION: This refers to how well the sound appears to fill the room. For example, imagine a single violinist on stage. Close your eyes and try to judge how big the sound is. In a room with poor Spatial Impression, the sound will be restricted to a small area around the instrument. In a good room the sound will appear to fill the whole stage in front of you. In the best rooms the sound fills the whole hall, enveloping the listener in the music. Good Spatial Impression is generated by sound arriving at the listeners from the side and, as such, has a fundamental influence on the geometry of good concert hall design. Spatial Impression correlates with the Early Lateral Fraction (ELF) measurement.

CLARITY: This aspect of sound is self-explanatory. Clarity is often too low in a very reverberant space and too high in a non-reverberant space. One of the goals of good concert hall design is to create a sound that has good Reverberance and good Clarity. Strong early reflections generate good clarity. This means reflecting surfaces need to be close to as many patrons as possible. This is something that is easy to do in a small hall but becomes increasingly difficult as the room gets bigger. Clarity correlates with the 80 ms Clarity ratio (C80) measurement.

WARMTH: The foundation of western music is the bass and with the advent of subwoofers lately, patrons have become more attuned to it. Lightweight materials like gypsum board or thin wood panels absorb bass sound. Thus, in a concert hall, the interior finishes must be heavy, for example plaster, masonry or thick wood. Warmth has recently been shown to correlate best with the Weighted Bass (Bw) measurement.

INTIMACY: This relates to how well the listeners feel connected with the performer, how close they feel acoustically. Intimacy is a multi-modal percept. That is, the brain uses both visual and aural stimuli to judge the sensation. As such, it's one of the trickier aspects of the sound to design for. On the aural side of the equation however, good Intimacy requires strong early reflections, good Loudness and the appropriate Reverberance. Of the six subjectively critical parameters considered important to the description of sound in a room, Intimacy is the only one that has yet to be correlated with an objective measurement parameter. The fact that it is a multi-modal percept probably explains why.

REVERBERANCE

RT_{60} Measured as the time taken for sound to decay 60 dB, extrapolated from the part of the decay curve between -5 and - 25 dB.

EDT Similar to RT_{60} except the calculation is extrapolated from the first 10 dB of decay.

CLARITY

$$C_{80} = \frac{\int_0^{80ms} p^2(t)\,dt}{\int_{80}^{\infty} p^2(t)\,dt}$$

LOUDNESS

$$G = \frac{\int_0^{\infty} p^2(t)\,dt}{\int_0^{\infty} p_A^2(t)\,dt}$$

where: p_A is the free field response of the source at 10 m.

SPATIAL IMPRESSION

$$ELF = \frac{\int_0^{80ms} p_L^2(t)\,dt}{\int_0^{80ms} p^2(t)\,dt}$$

where: p_L is the lateral response of a figure of eight microphone

WARMTH

$$Gw = 10\log\left[E80_{125} + 3Elate_{125} + 0.5\left(E80_{250} + 3Elate_{250}\right)\right]$$

where: $E80 = 10^{(G80/10)}$
$Elate = 10^{(Glate/10)}$

SHOEBOX SHAPED HALLS

It's safe to say that when the average person thinks of a concert hall, they're thinking of the quintessential 19th century shoebox shaped format. Most of the symphonic repertoire we listen to today was written for shoebox shaped rooms. Originally the music was performed in the 18th century ballrooms of the aristocracy. In the 19th century the music was brought to the public in tall narrow concert halls that reflected their 18th century ante-decedents.

Figure 1 The Großer Musikvereinssaal, Vienna.

Acoustically, the shoebox geometry contains within it many advantages and, unfortunately, one very significant limitation. Because these rooms are narrow, they generate strong, early lateral reflections that provide good Clarity and good Spatial Impression. Because they are tall, the provide the appropriate Reverberance. In rooms like Musikvereinssaal, shown here, Clarity and Spatial Impression are further enhanced by reflections off the walls of the loges and by "cue-ball" reflections off the balcony soffits located above the loges. Finally, the building technology of 19th century rooms like Musikvereinssaal was very heavy by modern standards. Interior surfaces are typically heavy plaster or masonry. This prevented the absorption of low frequency sound, so prevalent with the use of modern day light weight materials and gives these rooms the warm tone that they are famous for.

The shoebox has one weakness however – its size. We've already introduced the concept of Clarity and its reliance on nearby reflecting surfaces. The same is true for Spatial Impression: lateral reflecting surfaces need to be close to the audience. A typical shoebox shaped room is around 25 m wide and seats between 1,000 and 2,000 people. Seating capacities for more than 2,000 lead to wider rooms, 29 m and more, and compromise both Clarity and Spatial Impression. Loudness can also suffer if the room is too big. It is hard to name a really good shoebox shaped concert hall with more that 2,000 seats. Indeed, when the new Paris Philharmonie was commissioned five years ago, the shoebox shaped format was specifically ruled out because the program called for more than 2,000 seats.

FAN SHAPED AUDITORIA

Borrowing from Greek and Roman antiquity, Wagner's Bayreuth Festspeilhaus introduced the fan shaped geometry to the modern era. Early 20th century Cinema design relied heavily on the fan shaped format and, it can be said, the geometry worked well for film presentation. The same however cannot be said for live performance, either music or theatre.

One of the great acoustical discoveries of the 20th century was the realisation that listeners benefit from sound that arrives from the side. The fan shaped geometry creates frontal reflections for listeners seated near the side walls and in some cases, reflects no sound at all to listeners seated in the middle of the room. These rooms are inevitably very wide and flat and this does not allow for a resonant build up of sound. Sound coming the stage is directed into the absorbent seating area by the low ceiling.

Fan shaped geometries are acoustically problematic, to say the least, and are not generally considered to be a viable option in modern design.

Figure 2 Toronto's O'Keefe Centre prior to the 1996 renovation.

THE VINEYARD STEP HALL

The period following World Wall II was one of great experimentation in concert hall design. The vineyard step concept is one of only two such experiments that survived into the 21st century. The first example of the format is found in Stuttgart. Architect Hans Sharoun wanted the concert hall to reflect the topography of the local vineyards, hence the name and the geometry.

It was Scharoun's next building however that most recognise as the quintessential vineyard step hall: The Berliner Philharmonie. Blocks of seating layered, as it were, on top of each other are used to provide the requisite early reflections for good Clarity. Fortuitous acoustic design ensured that these reflections arrived at the listener from the sides, thus ensuring good Spatial Impression. (Interestingly, the link between lateral sound and Spatial Impression was identified five years *after* Berlin opened.) The Philharmonie also included a radical departure from traditional concert hall design: the stage was placed not at the end of the room but rather in the middle. This brought the audience closer to the performers, providing an intimate experience in a rather large 2,300 seat hall.

Berlin was an acoustical success as are many of its decedents, notably Suntory Hall in Tokyo and Walt Disney Hall in Los Angeles. Not all vineyard step halls have met with success however. Unlike the rigourous shoebox shaped design format, the relative freedom of design afforded by the vineyard concept can lead to trouble. Careful, informed, well tested acoustic design is the order of the day.

Figure 3 Berliner Philharmonie

DIRECTED ENERGY HALLS

The link between lateral sound and Spatial Impression, mentioned above, was first identified by Harold Marshall in 1967. Marshall quickly put his ideas to work a year later in the design of the Christchurch Town Hall. This led to the only other successful 20th century concert hall format, the so-called Directed Energy Hall.

Christchurch Town Hall is a 2,650 seat arena shaped room. Large overhead reflectors along the side walls of the room provide the required amount of early lateral sound for good Spatial Impression. Ample volume above these reflectors generates the appropriate Reverberation. The room has at least 500 seats more than previously thought practical, layed out in a difficult elliptical plan. Despite this and its remote location, it is renowned for its good acoustics. After Christ Church, most of the rooms designed to promote good lateral reflections have met with success. Like the vineyard step hall, several iterations of the basic design have been

Figure 4. Christchurch Town Hall, New Zealand.

QUEEN ELIZABETH THEATRE, VANCOUVER: ACOUSTIC DESIGN RESPONDING TO FINANCIAL REALITIES

John O'Keefe Aercoustics Engineering Ltd, Toronto, Canada
Daniel Ruvalcaba Aercoustics Engineering Ltd, Toronto, Canada

8th International Conference on Auditorium Acoustics
http://www.ioa.org.uk/events/event.asp?id=91

1 INTRODUCTION

Like so many other performing arts centres, the renovation of Vancouver's Queen Elizabeth Theatre (QET) took a very long time. Two previous versions of the renovation design have been published[1,2,3], in 1999 and 2007, both of which fell victim to budget constraints. The 2007 version included; two new balconies (for a total of three), large lateral reflectors in the ceiling space (similar to the Michael Fowler Centre in Wellington New Zealand[4]), a terraced seating level in the stalls (inspired by the Berlin Philharmonie[5]), and a novel design to control low frequency reverberation. The Sound and Light Locks surrounding the sides of the room would be treated like the coupled volume chambers found in some new concert halls, only in this case they wouldn't be reverberant chambers, they'd be absorbent chambers, and the absorption would extend down to low frequencies. Two weeks before the 2007 design was presented to the Madrid ICA symposium, financial disaster struck. Hazardous materials on the site, in the form of lead dust, and a major source of funding that failed to materialize, combined to reduce the budget by 30%. The two new balconies had to be deleted from the design, as were the terraced seating and coupled volume low frequency absorbing chambers. Another year was added to the construction schedule, the beginning of which involved a rather desperate effort to regain all the lateral reflecting surfaces we had lost. The results, described below, show how relatively small but very carefully positioned reflectors can compensate for the much larger – and much more expensive – reflectors implied by the previous tiered seating levels.

2 GEOMETRIC OPTIMISATION

Acoustician Derek Sugden once claimed that he never liked the look of a room which announced, "acoustician has been here"[6]. The authors fully agree with this sentiment: constrained however by an existing room that had to seat 2,750, could no longer be narrowed with tiered seating and with an enclosed volume in excess of 30,000 m^3, there was little choice but to introduce acoustical intervention into the visual aesthetic. A view of the finished room is shown in Figure 2. Ceiling and side balcony front reflectors are clearly expressed. But there is more here than meets the eye. The room is very wide. By the time the design was complete, virtually every available surface that might improve early lateral reflections had been employed – all of it cleverly disguised by the architects, Proscenium Architects + Interiors. The renovated QET is, most certainly, a Directed Energy hall. Presumably of the ilk that Sugden might not approve – at least not visually. But in the QET, most of the tell tale "acoustician has been here" signs have been hidden.

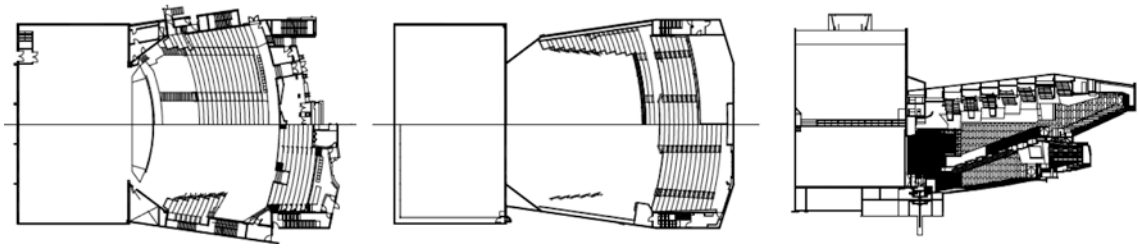

Figure 1 Composite Plans and Longitudinal Section

Figure 3 is larger version of Figure 2. Please see Figure 4 as well. Lateral reflector zones have been identified and will be discussed below. An attempt has been made to lighten those zones buried in darkness. (Please note these lightened zones will be easier to see in the electronic version than on printed paper.) Not shown in these images are further lateral reflecting surfaces in the ceiling above the balcony.

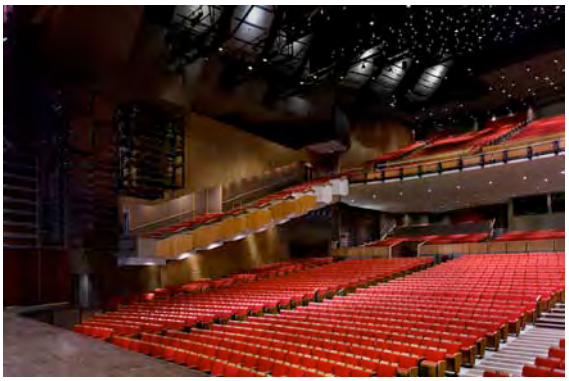

Figure 2 View of the renovated Queen Elizabeth Theatre from the stage. Lateral reflectors can be seen in the ceiling and on the face of the side balcony.

Optimizing the size and, especially, the location of so many lateral reflectors was a very arduous task, made infinitely easier by modern 3D computer modelling techniques. Reflectors in zones 5 and 6 come from the 2007 design. They were aimed by manipulating text files in CATT Acoustic Version 8.0b. Shortly after the 2007 budget crisis, the second author introduced us to a software package that, interestingly enough, is not really intended for acoustics. Its primary purpose is as a design tool to get more natural light into green buildings. But it also allows us to do one crucial thing, align reflectors in 3-D space in real time. The dexterity of design that this affords us cannot be overestimated. Using this software, the myriad of small reflectors in Zones 1, 2 and 4 could be focused – sometimes to within a fraction of a degree – optimising the crucial lateral energy in this very wide, high volume room.

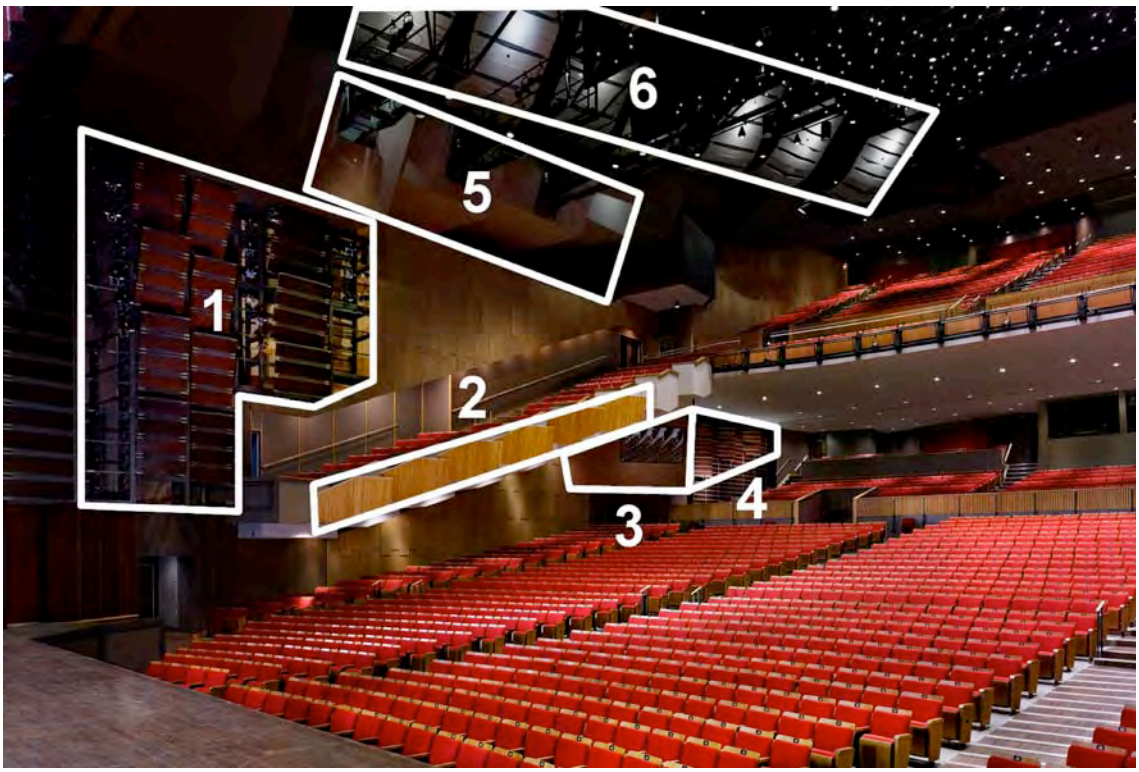

Figure 3 Same as **Figure 2** with the lateral reflector zones identified and, in some cases, enhanced for a better view.

Let us now discuss the lateral reflector zones:

1. This array of reflectors is shared with technical space usually dedicated to production lighting. These small reflectors, in concert with the even smaller and fewer Zone 4 reflectors, cast lateral reflections to almost all of the stalls and all of the mezzanine. (The mezzanine is the area of seating immediately adjacent to the Zone 4 reflectors.) An animation of this particular reflector coverage is currently available online[7].

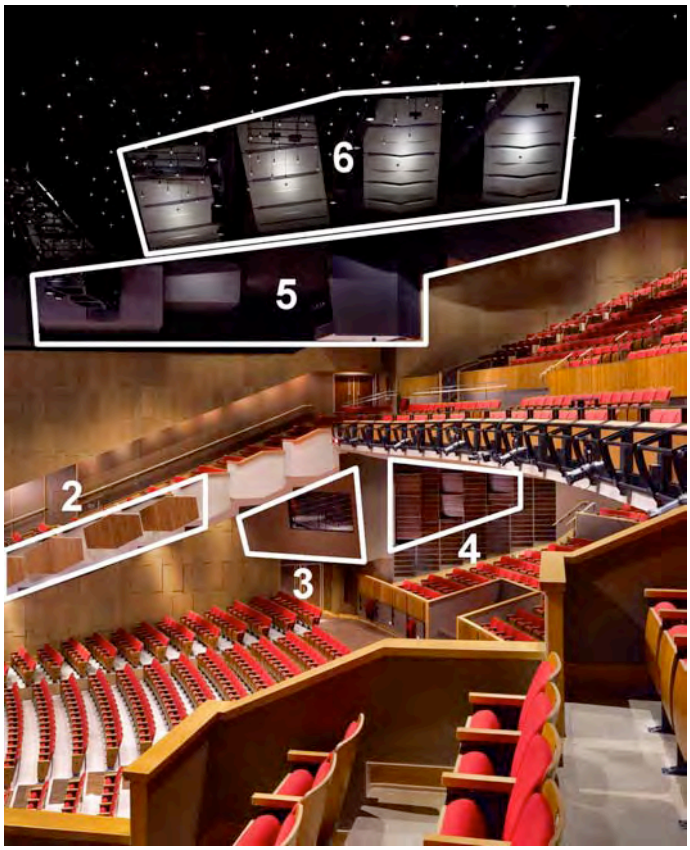

Figure 4 A view from the side box, with reflector zones identified and enhanced.

2. This zone of balcony facia reflectors really demonstrates how far computer aided acoustical design has evolved in the last few years. Six years ago, prior to the final design, the first author had written this zone off, but not before a very long exercise attempting to make it work. In 2008, with the crucial advantage of new software capable of aiming reflectors in real time, the facia reflectors became a critical component of the acoustical design solution. The location of each reflector has been optimised so that it is not in the shadow of the reflector in front of it. As the array of reflectors moves towards the back of the room, this forces each successive reflector further into the house, towards the centre-line; as can be seen in Figure 5. Note that the array appears to be missing its last two reflectors, seen in the middle of Figure 4, just above Zone 3. For lateral reflectors to work in this location, they would have to be positioned so far towards the middle of the room as to block sight lines for patrons in the back corners of the balcony.

Figure 5. Zone 2 balcony facia reflectors are seen in the foreground. Note how they progressively move toward the centre-line of the room. The Zone 1 proscenium reflectors are seen in the background.

3. This is a booth for the handicapped. While there are plenty of wheelchair locations inside the auditorium, a location was required for those who might have problems with involuntary vocalisations or physical ticks that would disturb other patrons. Indeed, one of the Vancouver Opera's longstanding subscribers already fits this description. The acoustic design took advantage of this room and its symmetric partner on the opposite side, rotating the front face in plan and tilting it down in section to direct lateral energy to the back of the stalls, just in front of the cross-aisle.

4. These few reflectors are perhaps the most strategically important in the building. Although small in size and number, they cover a good part of the mezzanine

level, an area underneath the balcony overhang and thus not visible to many of the other overhead reflectors in the room.

5. This is a bulkhead for return air ductwork. Exposed ductwork would have acted as a low frequency absorber so it was covered with 3 layers of 16 mm gypsum board. These large surfaces were put to further acoustical advantage and, after proper aiming, cover a good part of the balcony that the Zone 6 reflectors could not. Note also the catwalk at the top left hand corner of Figure 4. Having spent a lot of money removing the ceiling, the designers didn't want to lose that volume to a tangle of ductwork, catwalks and the like. The floor of all three catwalks is actually a wire cable tension grid and, as such, is much more acoustically transparent than a traditional catwalk.

6. These are the overhead reflectors inspired by the Christchurch and Wellington halls. Conceptually they were the first part of the Directed Energy solution and, aesthetically, remain the most visible. But, although they play a crucial role, the building simply wouldn't have been successful without the other reflectors described above: Many of which, it should be noted, are very well hidden!

3 MEASUREMENTS

Having spent so much time and money removing a ceiling and associated structure, replete with hazardous materials, it would be interesting to see how this improved Reverberation Times. A before and after comparison is shown in Figure 6. The vertical error bars in the graph indicate the subjectively significant Just Noticeable Differences (JND)[8]. The renovated room exceeds the JNDs so one would expect this improvement to be noticeable. The subjectively more salient Early Decay Times (EDT) will be discussed below. Note that the only decrease in Reverberation Time is seen in the 125 Hz octave, a subject that will also be discussed below.

A lot of time and effort was also spent on compensating for a very wide room with the appropriate lateral reflected energy. As can be seen in Figure 7, Lateral Energy Fractions have improved significantly, past the JNDs in all octave bands.

Strength (G), of course, is also a very important component of good sound in a room. It is governed by two components: total absorption and distance. In Revised Theory[9] these are expressed as Volume, Reverberation Time and Distance. This suggests that it is very difficult to achieve adequate Strength in a large room like the QET where the volume is too big, the distances too long and, compared to a concert hall, the Reverberation Times too short, a topic that is discussed further in [2]. Nonetheless, Figure 8 shows that acoustic Strength has been improved significantly in the renovated QET.

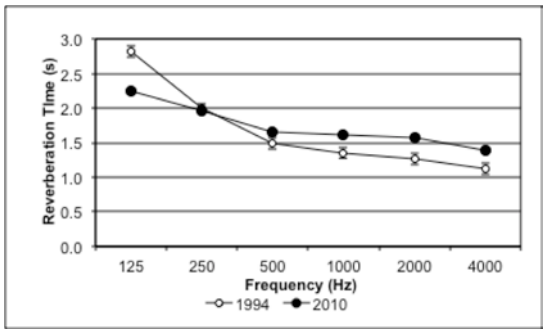

Figure 6 Reverberation Times measured before and after the renovation.

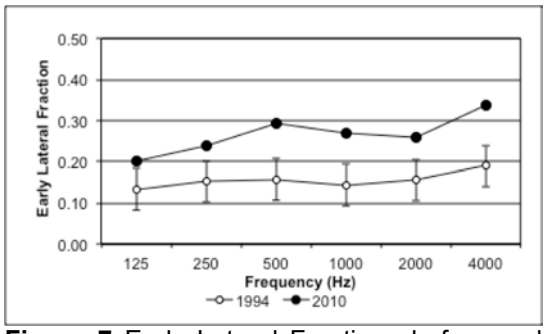

Figure 7 Early Lateral Fractions before and after the renovation. The error bars indicate the Just Noticeable Differences (JND) so the improvements are surely subjectively significant.

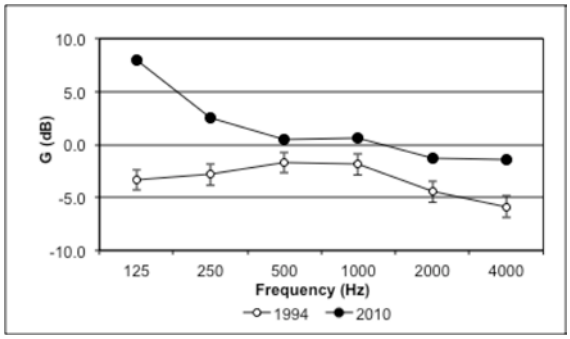

Figure 8 Acoustic Strength (G) measured before and after the renovation. Again, the JND error bars indicate that the improvements are subjectively significant.

4 ANALYSIS

4.1 Reverberance in Directed Energy Halls

One of the concerns with a Directed Energy hall is that the first few reflections are sent to the acoustically absorbent seats, which presumably precludes the opportunity for further reflections that would eventually embellish the later part of the decay. Even in a shoebox shaped room, some have discouraged raked seating for this very reason. The concern is legitimate on an intuitive level but not very far beyond that. The real story is, as always, more nuanced.

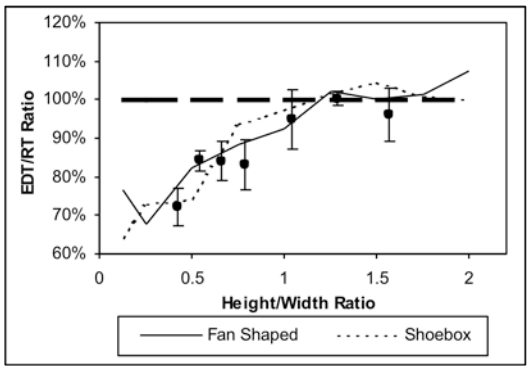

Figure 9 EDT/RT ratios vs. Height/Width ratios measured and calculated by scale and computer models.

Sometimes a Directed Energy room (or a steeply raked room) doesn't sound as reverberant as it should. And, while it is true that Early Decay Times (EDT) are shorter than the Reverberation Times (RTs) in a Directed Energy hall, one must keep in mind that Early Decay Times, by definition, concentrate on early sound. There may be another explanation.

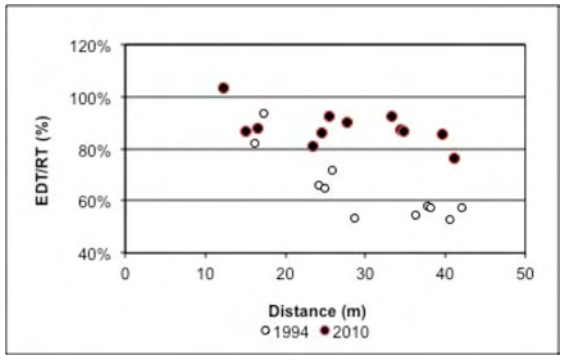

Figure 10 A comparison of EDT/RT ratios before and after the renovation.

In the late 1990s, as we struggled to improve EDTs in the Queen Elizabeth Theatre, we noticed that the room, in its original state, was very wide and not very tall. Could this be the reason for the short EDTs? A series of computer and scale model studies revealed that this, indeed, was the case[1]. Figure 9 shows the relationship between room Height to Width Ratios and Early Decay/Reverberation Time ratios. In these very simplified models there is a clear causal link between the two. Tall narrow rooms have an EDT/RT ratio close to 100%, suggesting that they will sound more reverberant.

Real rooms, of course, are not this simple. However, the experiment, deliberatively reductive as it is, does indicate a pattern worth considering. One could describe the original room as having a poor Height/Width ratio. The new building definitely falls into the category of a Directed Energy hall. It does not have a Height/Width ratio per se; its geometry is too complicated to fit within the confines of the experiment described in reference [1]. But, with the ceiling removed, the room is taller and, with all the lateral reflectors, it is acoustically "narrower". Figure 10 shows a comparison of EDT/RT ratios for the new and original rooms. The new room has consistently higher EDT/RT ratios, even though it is a Directed Energy hall, where one would expect lower EDTs. The original room, with its poor Height/Width ratio, has lower EDT/RT ratios. It appears that the Height/Width ratios influence EDTs more than the well known deleterious effects of Directed Energy.

4.2 Strength in Directed Energy Halls

Let us return to the concern about the absorption of early reflections before they can become late reflections. Is a Directed Energy hall or, indeed a steeply raked shoebox hall, doomed to low late energy levels? The question's answer is informed by Toyota's[10] studies on what he called Reflected Energy Cumulative Curves (RECC). Toyota noted that the rank ordering of acoustic Strength levels was established by about 80 to 100 ms into the impulse response. This is a powerful observation because it means that if one can improve early sound levels (G80), as one would do with the

spatially optimised reflectors in a Directed Energy hall, those improvements will still be there in the late field.

Hyde expanded on this idea in 1999 using measurements from one of the classic Directed Energy rooms, Segerstrom Hall in Costa Mesa, USA.[11] He found strong correlations between early sound levels (G80) and the total sound level (G). Even stronger correlations are found with the QET data, both before and after. Please see Figure 11. Hyde's correlation coefficients were in the range of 0.91. In the new QET they are 0.97. An average increase in G80 of 1.8 dB was achieved with the new optimised lateral reflectors. This translated into an average increase in G of 2.5 dB. Given that the Just Noticeable Difference (JND) for G is about 1.0 dB, this represents a formidable improvement.

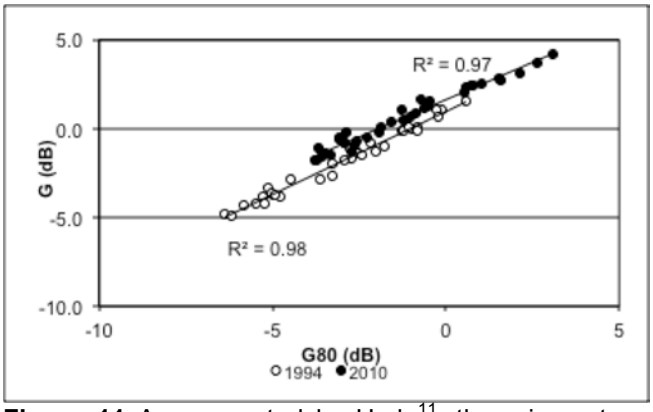

Figure 11 As suggested by Hyde[11], there is a strong correlation between early reflected sound (G80) and the total Strength (G). In the renovated QET, a 1.8 dB increase in G80 has generated a 2.5 dB in G. Popular wisdom would suggest the opposite. (1 kHz octave)

The ideas developed by Toyota and Hyde strongly influenced the acoustic design decisions for this building. It is often thought that a concert hall or opera house won't work if it has to seat more than 2,000. For financial reasons, limiting the number of seats to 2,000 was simply not an option. This was a room being acoustically optimised for opera but it was, and is, a multi-purpose room nonetheless. 70% of the time, the bills are being paid by popular music acts that that can fill a lot more than 2,000 seats. One of the room's biggest challenges was its lack of total acoustic Strength (G). The overly wide room also needed as many lateral reflections as it could get. Received wisdom, at least in North America, suggests the two requirements are at loggerheads. Directing too many early reflections to the seating would, supposedly, rob the room of later reflections and, hence, acoustic Strength (G). Toyota and Hyde's work – based, it should be noted, on measured data – suggests otherwise. This gave the designers the confidence to move forward with the Directed Energy concept. In the end, measurements in the completed hall agree completely with Toyota and Hyde's observations.

4.3 Perception of Bass

McNair[12], in 1930, was probably the first to suggest a link between objective measurements and what later became known as Warmth or the Perception of Bass. He recommended that, for a more natural sounding decay, Reverberation Times in the 125 Hz octave should be 50% higher than those in the 500 Hz octave. Later, Beranek[13] attempted to codify this with a "Bass Ratio" of low to mid-frequency Reverberation Times. The concept – which was never more than a postulate – became one of those acoustical canards so often repeated that, well, it just must be right! Both ideas, although later proved fallacious, can be excused on the grounds that, in their day, Reverberation Times were about the only thing that could be safely measured or, for that matter, easily predicted.

In 1997, Bradley et al.[14] elevated the discussion beyond postulation and found a very good correlation between low frequency Strength (G) and what they called the Perception of Bass. They developed a concept known as Weighted G (Gw):

$$Gw = 10\log\left[E80_{125} + 3Elate_{125} + 0.5\left(E80_{250} + 3Elate_{250}\right)\right] \quad (1)$$

where: $E80 = 10^{(G80/10)}$
$Elate = 10^{(Glate/10)}$

Measurements from a number of opera houses and three of the world's favourite concerts halls place the improvement in the QET's Gw into context. Please see Figure 12. Before the renovation, Gw for the QET is lower than all of the opera houses and concert halls. After the renovation it is better than all the opera houses and only one of the three concert halls, Vienna's Musikvereinssaal, exceeds it.

Interestingly enough, if one were to calculate a Bass Ratio using unoccupied Reverberation Time data from the renovated room, it would suggest a decrease in Warmth: from 1.69 to 1.29. This is contrary to the subjective assessment of the renovated room.

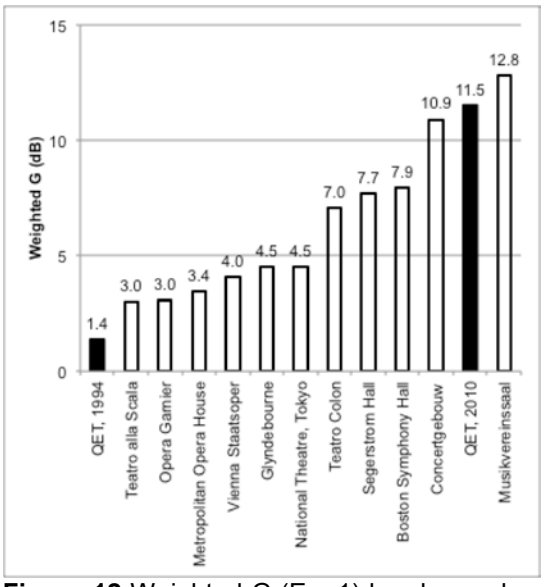

Figure 12 Weighted G (Eq. 1) has been shown to have a very strong correlation with Perception of Bass. Measurements before and after the renovation suggest that the QET has gone from one of the worst to one of the best

5 INTIMACY

Acoustic Intimacy is an extremely difficult parameter to quantify with objective measurements. It is, perhaps, the only important subjective parameter left that cannot be measured objectively. Barron, in his Survey of British Auditoria, found that Intimacy is best correlated with the total sound level (G)[15,16] which, of course, varies with distance. Hyde[17] has shown a connection between Intimacy and visual stimuli, i.e. distance from the sound source. Many now think of Intimacy as a so-called multi-modal percept. That is, the neural process that decides whether a room is Intimate or not, involves both visual and aural stimuli. The postulate is that visual stimuli leads to a certain expectation as to how loud the room might be. If the sound turns out to be louder than that, we get the impression of being closer to the sound; i.e. more Intimate.

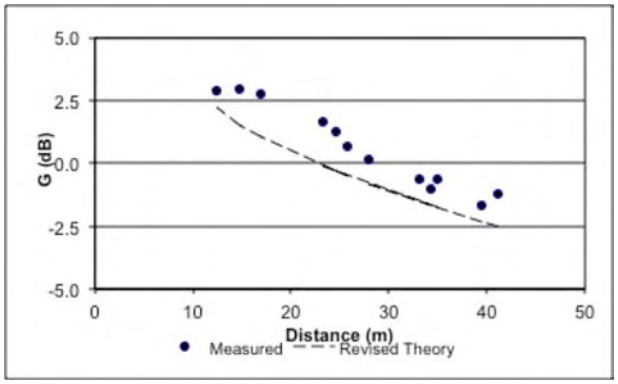

Figure 13 Measured Strength (G) compared to a Revised Theory prediction might explain the better than expected Intimacy. (1kHz octave)

The Intimacy of the renovated QET came as a pleasant surprise to the design team. One explanation for the Intimacy might be found in Figure 13. Revised Theory[9] has proved to be an accurate predictor of sound levels in a room. As such, it's a good predictor of what people might expect in a room of a given size at a given distance from the sound source, i.e. a good predictor of the visual stimuli that may be part of Intimacy judgment. Figure 13 shows that measured Strength (G) in the renovated room is consistently higher than the Revised Theory prediction, suggesting that the aural experience may be louder than the visual stimuli might expect. This would, in turn, suggest good Intimacy.

Another possible explanation for the good Intimacy in the QET comes from Kahle[18], who found a correlation between Intimacy and low frequency perception of loudness. Section 4.3 of the current paper suggests that perception of low frequency loudness is very good in the QET.

6 CONCLUSION

The theme of this meeting of the Institute of Acoustics is how modern acoustic science can respond to increasingly novel design challenges presented by architecture. For the QET the shoe was on the other foot. The architectural team responded to the acoustical design in any and every way that was practical. The design challenges were not architectural, they were financial. The capital costs had been cut by 30% and the operating costs dictated a room that was too wide and had too many seats. The challenges presented by this project were formidable. It is clear to the authors that these challenges could not be resolved without recourse to modern acoustical science and technology.

7 ACKNOWLEDGEMENTS

Many of the key players who participated in the project have been noted in [3]. Their contributions are still appreciated. Thanks also go to Sarah Mackel for her help with the drawings and data analysis. The 1994 measurements were performed by John Bradley and Gilbert Soulodre. Jerry Hyde provided comments on a penultimate version of this paper which are greatly appreciated. Finally, I should like to thank my wife Jacqueline Hayden who, once again, helped make the paper legible.

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INTERNATIONAL CONGRESS ON ACOUSTICS
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ACOUSTICAL RENOVATION OF THE QUEEN ELIZABETH THEATRE, VANCOUVER: SPATIAL SOUND IN A WIDE ROOM

PACS: 43.55.Fw

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ABSTRACT
After a delay of more than a decade, the renovation of Vancouver's Queen Elizabeth Theatre is finally underway. In the summer of 2006 the building, which houses the 2900 seat main auditorium and the 800 seat Playhouse Theatre, was cut in two, leaving a 75 mm wide acoustic joint to control sound transmission between the two venues. The next two phases of the renovation will be carried out in the summers of 2007 and 2008. The work will deal with a number of acoustic and noise control concerns but one of the primary issues is the nature of the spatial sound. The Queen Elizabeth Theatre opened in 1959, long before the importance of spatial sound was identified. It is typical of its age: a very wide room (32.2 m) with a low ceiling. In order to maintain seating capacity, the overall width of the room will be preserved. Designs previously presented by the author have been significantly revised to improve spatial and reverberant sound. Revisions include a terraced seating area in the stalls, removal of the ceiling to increase room volume and overhead lateral reflectors hung in the exposed truss level space above the audience.

HISTORY
The Queen Elizabeth Theatre (QET) is a seminal building in the history of North American theatre design. The 1956 design competition was won by a group of young architects working out of their basement. That team would go on to design most of Canada's large post war auditoria. Eventually taking the name Arcop Architects, its progeny form the senior core of Theatre Projects' North American office and the architects for this renovation: Proscenium Architects + Interiors. The design included seating along the side walls – affectionately known as the "ski slope" – and a rarity at the time. It is seen by some as the first nascent step in the return to the Italian horseshoe shaped plans that were so popular in the 18th and 19th centuries. The acousticians included a young Russell Johnson, making one of his first major contributions to auditorium design. In the Johnson oeuvre, the QET comes in a close second to the Tanglewood Music Shed, which opened only a few weeks before.[1]

A renovation design was developed in 1997-98 and has been reported by the author in References [2] and [3]. The struggle through that process led to a greater appreciation of Height to Width ratios. Scale and computer model studies suggest that rooms with low Height to Width Ratios, i.e. wide and flat, have proportionally shorter Early Decay Times (EDT), i.e. the EDT/RT ratio is significantly less than 1. By narrowing the room with floor to ceiling "fins" at the side wall boxes, EDT/RT ratios were increased from 51% to 75%. The 1998 design also changed the existing single balcony room into a three balcony opera house geometry, replacing the "ski slope" with side wall boxes. The front half of the ceiling was flattened but the rest was left in place. Then the design lay dormant for eight years.

In 2006 the design was re-assessed and found to be wanting. Although EDTs had been improved, there was concern that they would not be long enough. There was also concern about Strength (G) and, of course, spatial impression. Computer models of the existing room and the 1998 design were developed and from these a series A/B auralisations were generated. It became apparent that the 1998 design would either have to be changed or be complemented with an electronic enhancement system.

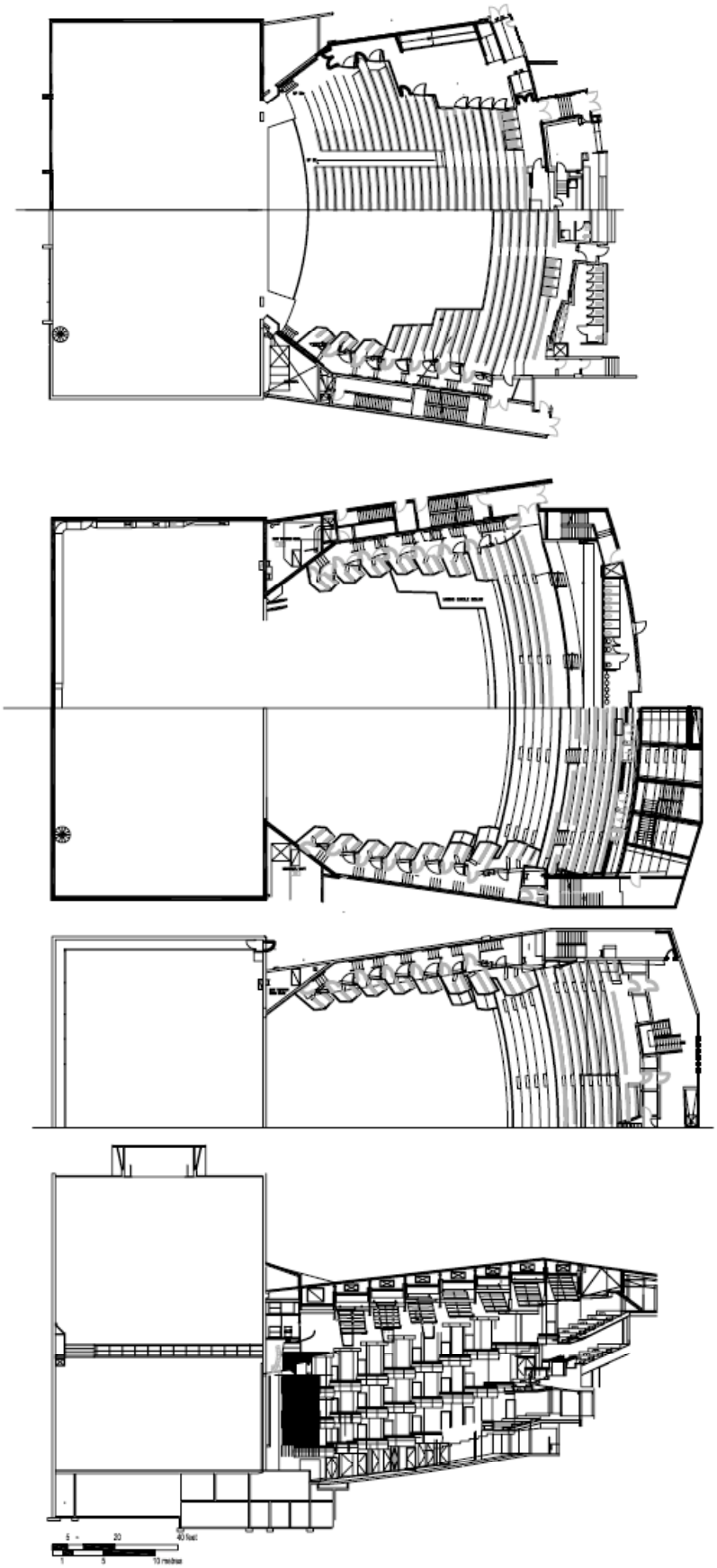

Figure 1 Composite Plans and Longitudinal Section of the Queen Elizabeth Theatre renovation design starting with the Stalls level plan at the top then moving progressively upwards into the balconies.

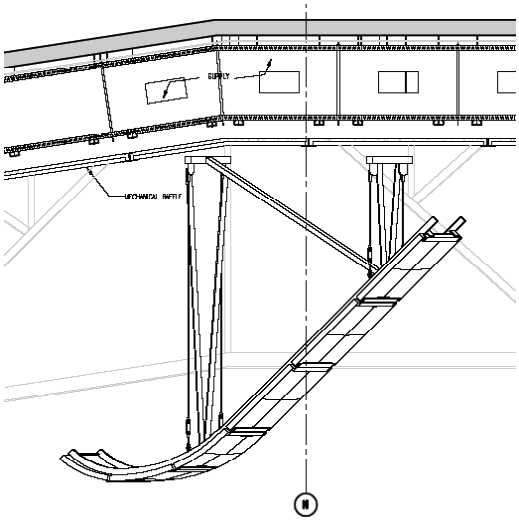

Figure 2 Detail of one of the lateral reflectors in the ceiling truss space. Above the reflector is the ventilation system's Supply Air plenum.

SPATIAL SOUND DESIGN

With a width in excess of 32 m, the need to address spatial sound seems obvious. Two key design elements deal with the issue: lateral reflectors high above the room in the truss space and a terraced, laterally reflecting floor plan. Design precedents for the former come from the Michael Fowler Centre in Wellington, New Zealand[4]. The floor plan makes reference to the recently renovated Jubilee Auditoria in Calgary and Edmonton[5], the Metropolitan Art Space Concert Hall in Tokyo[6] and, of course, the Berliner Philharmonie[7]. Plans and sections are shown in Figure 1. Drawings of the original building can be found in Reference [8]

Where the 1998 design left most of the existing ceiling in place, the new design removes it completely, effectively raising the height of the room by 4.8 m. This part of the construction, and anything else that requires scaffolding, has been carried out over the summer of 2007. The trusses are now exposed. Duct work has been re-designed to slower velocities, air being delivered through plena that are tight to the underside of the roof deck. The design goal for the ventilation system is PNC-15. The undersides of the plena are 38 mm corrugated steel deck (for diffusion) filled with a 38 mm topping of concrete (to maintain warmth). Tucked inside the trusses are seven pairs of lateral reflectors. A detail of one is shown in Figure 2.

These reflectors went through several generations of design prior the final version shown here. They started out as four large, flat and rather awkward looking reflectors located towards the back of the room, providing lateral energy mostly to the balconies. Please see Figure 3. Later on they developed into the elliptical plan shown in Figure 4 but the individual panels still remained flat. Concerns about image shift generated by the flat panels suggested a need for diffusion. Diffusion would also spread the sound out, increasing the zone of coverage. The question was how much diffusion was enough and how much was too much. An early scheme provided diffusion in the form of a three layer fractal, 2-dimensional Quadratic Residue Diffuser (QRD). This was questioned by the architects on aesthetic grounds. Acoustically, there was also concern that the 2-D QRD provided too much diffusion and that lateral energy levels received by listeners would be too low. These concerns were corroborated by Jerry Hyde, who kindly shared some of his experience with the design of the lateral reflectors at the Michael Fowler Centre.[9]

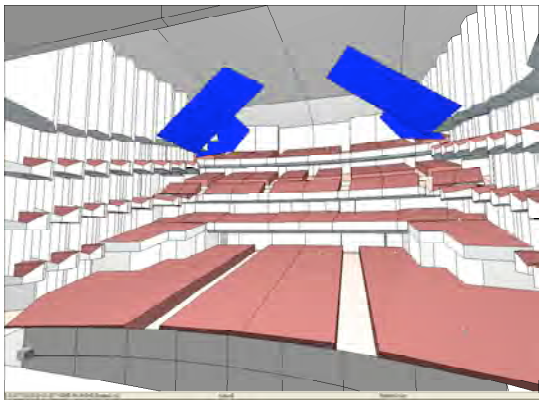

Figure 3 An early version of the overhead reflector design. The colours are for the model, not the room.

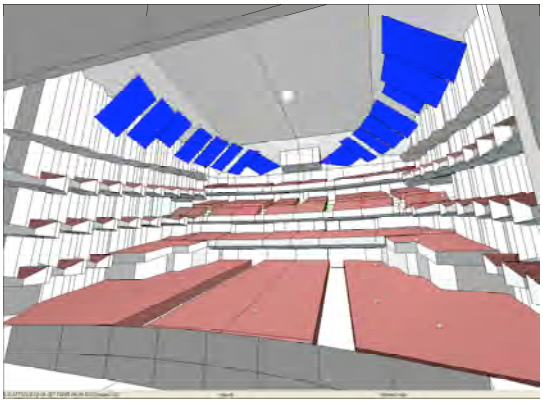

Figure 4 The penultimate design of the lateral reflectors showing the elliptical plan.

The size of the reflectors was dictated partly by truss spacing and partly by headroom constraints on the top balcony. Reflection coverage zones were easily determined using CATT Acoustic 8.0. Aiming the reflectors was easy; determining where to aim them was not. Should a reflector aim for seats on its side of the room or the opposite side? Aiming for the opposite side of the room meant a larger zone of coverage but, because the room is so large, the reflections were arriving rather late; between 60 and 70 ms in the stalls. If a reflector was aimed towards the same side of the room the reflections arrived earlier but the angle of incidence became more vertical than lateral. The decision, once again, was informed by the Michael Fowler design. A quick method of images study of an AutoCAD version of the drawings[10] confirmed that the reflectors should indeed be aimed to the opposite side of the room.

Providing lateral energy coverage to the stalls level was rather easy, primarily because the reflectors were so far away. On the balconies, especially the top balcony, the reflectors were closer and the zone of coverage was correspondingly smaller. The elliptical plan compounded the problem, limiting the reflection zone to the centre of the balcony. The problem was solved with two more design improvements. The side walls of the lighting gondola were sloped to direct sound to the back corners of the balcony. Then, in an eleventh hour optimisation, the bottoms of the reflectors were curved into the "J" shape shown in Figure 2. This will scatter some of the incident sound to directions behind the reflector. Having developed this for the balcony, we realised that it could also be used on the other reflectors to scatter sound to the side wall boxes.

The final question pertaining to the lateral reflectors originated from the multi-purpose nature of the building. Would these lateral reflectors have a deleterious affect on loudspeaker clusters and, if so, should they be rigged to be moved out of the way when required? The sound system designer's experience is that loudspeaker clarity correlates with its spatial image. If the image is small, the loudspeaker will be clear. After much consideration, computer model reflection studies, auralisations and an on-site experiment with a similar reflector configuration at Vancouver's Orpheum Theatre[11], it was decided that the reflectors could remain fixed in place.

MULTI-PURPOSE ACOUSTICS

The Queen Elizabeth Theatre is, above all, a multi-purpose venue. Although much of the acoustic design was centred around the needs of Vancouver Opera, most of the bookings for the room rely on amplified sound. Thus the room has opposing acoustical requirements. The traditional solution, of course, is to provide the appropriate room volume for opera and when amplified productions are on stage, absorb the excess reverberation with adjustable acoustic banners. The client, whose knowledge of the building type was at once formidable and challenging, objected to curtains for two reasons. First – and for him foremost – they collect too much dust and are difficult to clean! Second, they don't absorb low frequency sound. The client wanted something better than curtains. Discussions between the author and the architect led to a simple solution that addresses both of the client's concerns.

Coupled volumes have long been used to modify the acoustics of a room, usually to extend the Reverberation Time. While there are many successful examples, some acousticians remain sceptical. What most agree on, however, is that coupled volumes can be used as very efficient low frequency absorbers. We informed the architect of this and a few days later he came up with a proposal to put a series of doors in the side walls, opening them up to the Sound and Light Lock (SLL) corridors that run down the sides of the auditorium. The SLLs will be lined with 100 mm thick glass fibre mounted in front of thin wood or gypsum board panels. The doors will be 55 mm thick wood. For opera, ballet, etc. these doors will be closed and will provide strong early lateral reflections. For amplified sound, the doors will be open, exposing the absorption material to the room. By eliminating the lateral reflections, this will also address the sound system designer's concerns about the spatial image of loudspeaker clusters. Other absorption will be found on the back walls, in the form of moveable fabric covered panels, and in the ceiling, in the form of vertical roll-up curtains at the catwalks.

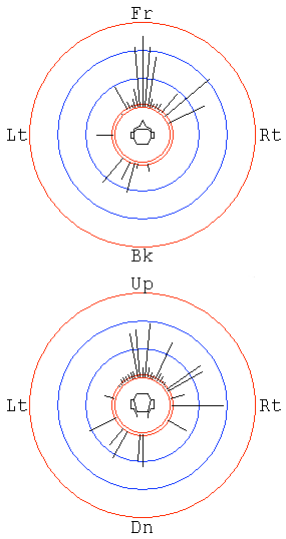

Figure 5 Computer model calculation for a seat in the stalls of the existing room showing the lack of laterally reflected sound.

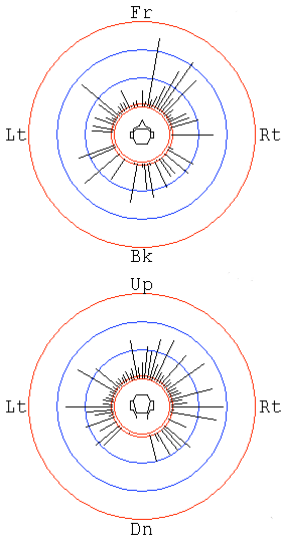

Figure 6 Computer model calculation for the same seat as Figure 5. Laterally reflected sound has been increased by the overhead reflectors and the terraced floor plan.

COMPUTER MODELLING

In the 1998 design, most of the work focussed on a 1:48 scale model study. The current design makes use of computer model studies exclusively. The author's experience is that scale models are more accurate than computer models[12]. For design however, computer models are a much more powerful tool, especially for the design of spatial sound. In an effort to improve the accuracy of the computer predictions, a model of the existing room was developed and calibrated to the full scale measurements. The model of the existing room was then used for comparative studies as the design progressed. There were 36 versions of the model in all and more than 900 auralisations. An example of one of the comparative studies is shown in Figure 5 and Figure 6. Figure 5 shows the level and direction of reflections received in the first 80 ms at a location near the back of the stalls, in the existing room. Figure 6 shows the same calculation in a version of the room similar to Figure 3. Lateral reflections have increased significantly, and it is evident that these are coming both from the side walls and the overhead reflectors.

OTHER ISSUES

If there was one overriding directive from the client it was to keep the room's seat count as high as possible. The resulting design is thus very wide with long balcony overhangs; two design elements that do not lend themselves well to good acoustics! The width of the room was overcome with the terraced floor plan and ceiling reflectors described above. The long balcony overhangs will be compensated for electronically.

A number of other modifications are being made to improve acoustics. The side walls are currently lined with thin wood panels that absorb low frequency sound. These will be removed and used elsewhere in the building. To improve acoustic warmth, all surfaces exposed to the auditorium will be massive, either 50 mm plaster or the equivalent weight.

Perhaps one of the most important improvements is what became known as "The Cut". The building houses two venues: the 2900 seat QET and the 800 seat Playhouse Theatre. In the summer of 2006, the QET – which ironically was a stand alone building up until 1962 – was separated from the Playhouse. Prior to The Cut, structure borne noise limited concurrent use of the two venues.

ACKNOWLEDGEMENTS

I would like to thank Thom Weeks, Jennifer Stanley, Hugh Cochlin and all the staff at proscenium architecture + interiors for their patience, hard work and creative insight. The sound system was designed by Engineering Harmonics. The Director of Civic Theatres for Vancouver, Rae Ackerman, has encouraged our work over these past 15 years and, with his consummate hands-on knowledge of theatre design, has been an inspiration to the team, knowing when to challenge the design and when to praise it. Most of all I should like to thank Kiyoshi Kuroiwa and Alison Norris for all their hard work on the computer models, auralisations and so much more.

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ACOUSTICAL PROBLEMS IN LARGE POST-WAR AUDITORIA

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1 INTRODUCTION

The period following World War II is surely one of the most exciting in the short history of acoustic research. In the space of thirty or more years, the phenomenon of sound in a room was de-mystified through a series of ground breaking discoveries. Academic and institutional research in the UK, Germany, New Zealand, Denmark and Canada, to name but a few, created the foundation of knowledge that acousticians rely on today. It is ironic therefore that the auditoria built during this time should have such lamentable reputations. The people who designed these buildings however were working in the dark, without the benefit of the information we take for granted today. To their credit, they learned along the way, each building being a little bit better than the last. Fifty years on, there is still much to learn from these rooms, using tools and ideas unheard of in their time.

This study will examine the acoustics of five typical multi-purpose rooms built between 1959 and 1972. Although all the halls described here were built in Canada, they are indicative of rooms built throughout the western world in the post-war era.

Figure 1 Queen Elizabeth Theatre, Vancouver, Canada

Almost without exception, these rooms were designed to direct energy to the back of the room with frontal overhead reflections. Rooms had been designed this way since the early part of the 20th century, Salle Pleyel in Paris being the first notable example. This was unfortunate because these frontal overhead reflections had the effect of shortening perceived reverberance, led to comb filtering and resulted in a harsh tone from the violins.

Many of these rooms are very wide with relatively low ceilings. A typical example is the Queen Elizabeth Theatre, opened in Vancouver in 1959[1] shown in Figure 1. As we will see, the height to width ratio of these rooms may explain many of their problems. A summary of the rooms studied here is shown in Table 1. (All data presented in this study is in the 500 Hz octave band.)

Table 1

	Seats	Volume (m3)	RT (s)	G (dB)
Jubilee Auditoria	2,700	30,473	1.35	-1.68
Queen Elizabeth Theatre	2,813	32,452	1.36	-1.86
Saskatoon Centennial*	2,014		1.79	-1.14
National Art Centre*	2,325	20,000 (37,452)	1.8	-0.55
Hummingbird Centre	3,167	36,319	1.2	-3.09

* - orchestra shell installed, volumes without the shell shown in brackets

2 ACOUSTIC MEASUREMENTS

For post war acousticians, the Reverberation Time (RT) was the acoustic parameter of paramount concern. Certainly it was the only one that they could predict with any kind of confidence. Unfortunately, we now know that the Sabine's classical definition of RT does not correlate well with subjective Reverberance. In the early 1960s it was found that the first 160 ms of decay correlate much better with a listener's perception of Reverberance.[2] This led to Jordan's definition of Early Decay Time (EDT), using the first 10 dB of decay as opposed to Sabine's previous definition of 60 dB.

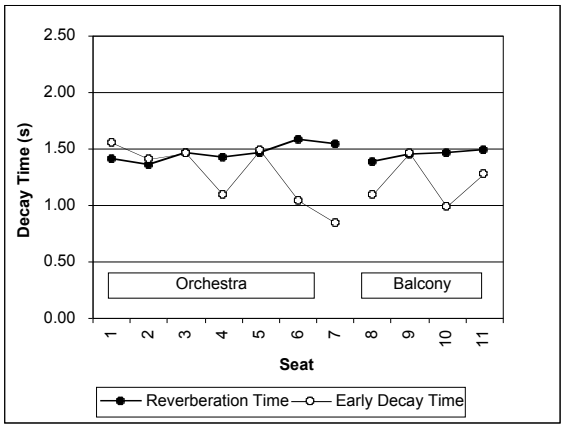

Figure 2 Reverberation and Early Decay Times measured in the Queen Elizabeth Theatre, Vancouver, Canada.

One of the interesting aspects of the post war rooms is that the RT is generally uniform throughout the space and, more often than not, is in the appropriate range. Unfortunately, the EDT, and hence the perception of reverberance, varies quite a bit and, more often than not, is significantly lower than the RT.

A fairly typical example is shown in Figure 2. In Vancouver's Queen Elizabeth Theatre the RT is around 1.5 seconds; which is not too bad if you're trying to reach a compromise between symphony and opera. Unfortunately, the EDT is much lower, in the range of 1.2 seconds and in many seats 1 second or less. In other words, unsuitable for symphony or opera. Toronto's Hummingbird (formerly O'Keefe) Centre has an average RT in the range of 1.2 seconds; EDTs are much lower. One seat on the balcony has an EDT of 0.24 seconds.

The subjective perception of Loudness is quantified by the objective parameter known as Strength (G). The generally accepted criterion for music is 0 dB or higher.[3] The best loved shoebox shaped halls of the 19th century, such as Vienna's Musikvereinssaal and Amsterdam's Concertgebouw have Strength levels in the range of +5 dB or slightly higher.[4] Figure 3 shows a compilation of Strength measurements from four large auditoria. Out of 133 measurement locations, 92 (69%) do not satisfy the 0 dB criterion. If the National Arts Centre data is taken out of the set, 89% of the measurements do not satisfy the criterion. Only a few seats – located again in the National Arts Centre – come close to the 5 dB level found in the preferred halls of the 19th century. In the Hummingbird Centre, not one of the 30 measurement locations satisfies the 0 dB criterion. To put the data in Figure 3 into context, remember that if we doubled the size of the orchestra, levels would only increase by 3 dB.

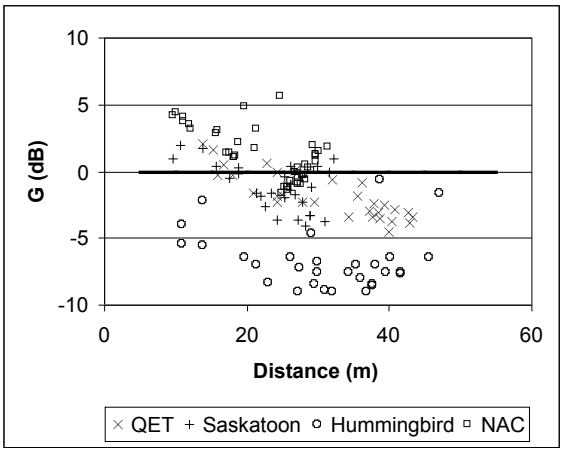

Figure 3 Strength measured in four Canadian post war auditoria. The arbitrary criterion for Strength is 0 dB indicated by the thick solid line. Data from Saskatoon and the National Arts Centre were measured with the orchestra shell in place. The Queen Elizabeth Theatre and Hummingbird Centre do not have orchestra shells.

One of the more fascinating measurement results in this study is shown in Figure 4. This is a comparison of late energy (Glate) in a typical mid 20th century fan shaped room (the Hummingbird Centre) to the three quintessential shoebox shaped rooms of the 19th century (Boston Symphony Hall, Vienna's Musikvereinssaal and Amsterdam's Concertgebouw). The difference between the two building types is enormous, in the range of 15 dB! This explains in part why some of the post-war rooms have problems with echoes. The paucity of late energy means that any reflection that does arrive at the listener after 80 ms will not have any other nearby reflections to mask it and hence will be heard as an echo. The problem is exacerbated by the large sizes of these buildings, which can often lead to strong reflections arriving around 150 to 200 ms.

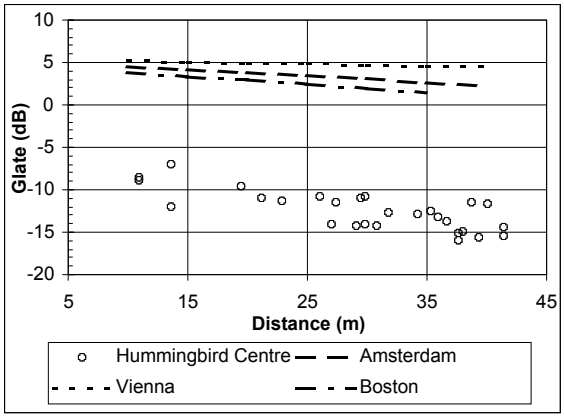

Figure 4 A comparison of late energy (Glate) in a mid 20th century fan shaped room with three of the best 19th shoebox shaped rooms.

Most of these rooms are characterised by higher than normal Clarity, as one might expect from a space with short EDTs and low Glate levels.

The lateral energy thesis is surely one of the most important developments of late 20th century acoustics. Early lateral energy has been associated with the spatial perception known as "source broadening"[5], late lateral has been associated with the effect known as "envelopment".[6] Early Lateral Fractions (ELF) are poor in some rooms examined here and better than one might expect in the others. For example, the 35 m (115') wide Queen Elizabeth Theatre has an ELF of 0.16. Although not measured directly, one should also expect lower than acceptable Late Lateral Energy given the very low (omni-directional) Glate levels. We shall see that the impact of the lateral energy thesis extends beyond the immediate concerns with spatial impression.

3 EXPLANATIONS & SOLUTIONS

3.1 Revised Theory

With the advantage of hindsight, we find a fairly simple explanation for one of the more important deficiencies of these rooms. The low Strength levels can be explained by a concept developed in the 1980s, known to us now as Revised Theory.[7] Like the classical theory of sound in a room, it tells us that Strength is proportional to Reverberation Time and inversely proportional to room volume. The innovation is that it also accounts for the change in reverberant level with distance. In classical theory only the direct sound attenuates with distance. In Revised Theory, both direct and reverberant levels decrease with distance.

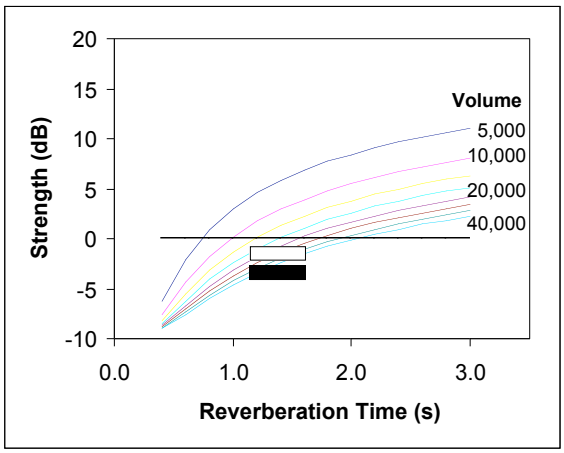

Figure 5 Revised Theory predictions of Strength in large rooms with short Reverberation Times, r=30 m. The white box indicates the levels expected in some of the halls studied here. The black box demonstrates the levels expected when the effects of height to width ratio are taken into account.

Figure 5 shows how Strength varies according to Volume and Reverberation Time for a given source receiver distance. Remember that the criterion for Strength is 0 dB or higher. The white rectangle shows the Strength levels that

Revised Theory predicts for five typical post war auditoria (the Jubilee Auditoria in Edmonton and Calgary[1], Hummingbird, National Arts Centre and Queen Elizabeth Theatre). The calculation parameters are as follows: the rooms all have fairly high seat counts, in the range of 3000, so a source receiver distance of 30 m has been assumed; with the exception of the National Arts Centre, all of the rooms have short Reverberation Times, in the range of 1.3 seconds; all have very large volumes, in excess of 30,000 m^3. (With Reverberation Times in the range of 1.3 seconds it is assumed that these multipurpose rooms are best suited for opera and hence, the volume of the flytower has been included.)

The results, shown in Figure 5 demonstrate the lethal combination of a large room with a short Reverberation Time. It can be seen that near the back of these rooms, even if everything turns out according to expectations, the best one can hope for is Strength below the accepted criterion of 0 dB. In most rooms, unfortunately, measured Strength is lower than predicted by Revised Theory.[8]

3.2 Increasing the Early Decay Time

Most post war auditoria were designed with reflectors near the front of the room. While there was a legitimate concern to direct sound towards the back of the room where it was needed, it led to some unfortunate side effects. One of these, as mentioned above, was a foreshortened Early Decay Time caused by the very early, mostly frontal, reflections.

Figures 6 and 7 show one of the author's first experiments during the renovation design of Vancouver's Queen Elizabeth Theatre. On the left of Figure 6 one can see the existing ceiling configuration, directing sound towards the back of the room. The right hand side of Figure 6 shows the first version of the revised geometry, eliminating the frontal ceiling reflections. The results of the experiment are shown in Figure 7. EDT has been increased in 7 of 10 seats. In some seats EDT increased by as much a 0.5 seconds. The difference limen for Reverberance (i.e. EDT) is 0.1 seconds and is indicated in Figure 7 by the vertical error bars.

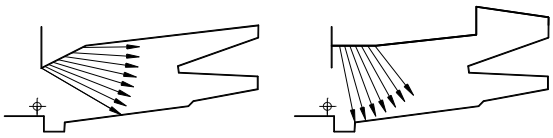

Figure 6 Longitudinal sections showing the existing Queen Elizabeth Theatre (right) and the first iteration of a renovation model experiment (left).

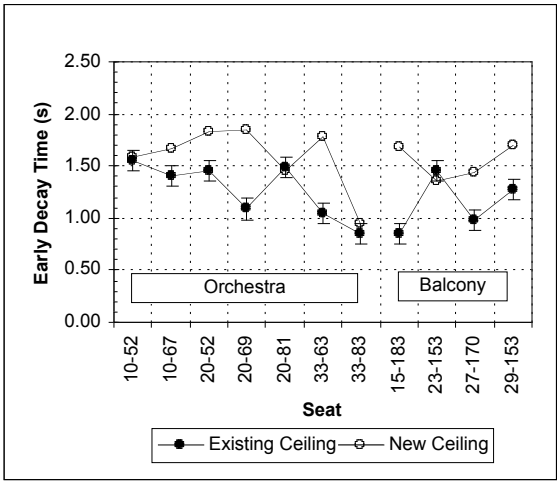

Figure 7 A comparison of Early Decay Times in a 1:48 scale model using the configurations shown in Figure 6.

3.3 The Effect of Height to Width Ratios

Another possible explanation for the post war problems comes from the author's study of height to width ratios.[9] In a series of experiments in both computer and scale models, using both fan and shoebox shaped rooms, it was found that the EDT/RT ratio can be related to the Height/Width ratio of the room. A compilation from computer and physical scale model experiments is shown in Figure 8.

Height to width ratios were also found to influence Strength. In the 1980s it was discovered that, contrary to what one might expect from classic theory, reverberant sound levels are not uniform throughout a room.[7,10] It was this finding, by the way, that led to Revised Theory. Sound levels were found to decrease at a rate of about 0.1 dB/m in a good room and more than 0.2 dB/m in a poorer room. It was thought that a fan shaped geometry might have something to do with this.

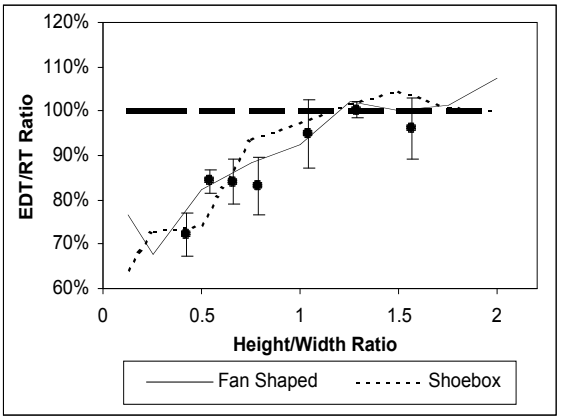

Figure 8 EDT/RT ratio vs. the Height/Width ratio of simple six sided fan and shoebox shaped rooms. Computer model experiments are indicated by lines and the scale model measurement by dots.

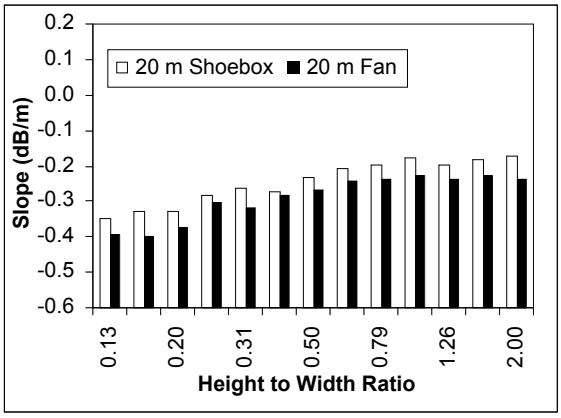

Figure 9 Computer model experiment showing the rate of attenuation of Strength (G) in 20 m wide fan and shoebox shaped rooms of varying Height/Width ratios.

The height to width experiments help to explain this finding. Figure 9 shows the rate of attenuation of Strength (G) in fan and shoebox shaped rooms for a range of height to width ratios. In the fan shape rooms, shown with the dark bars, the rate of attenuation is consistently higher than the shoebox rooms. This leads to lower levels at the back of the fan shaped rooms and corroborates the 1980s postulate. But note how the Height/Width ratio has just as much, if not more of an effect on the rate of attenuation.

The height to width experiments also help to explain the discrepancy between Revised Theory prediction of Strength and *in situ* measurements. Figure 10 demonstrates the difference between Revised Theory predictions and scale model measurements. The difference between the predictions and measurements increases as the Height/Width ratio of the room is decreased. The same results were found in computer model experiments, also shown in Figure 10.

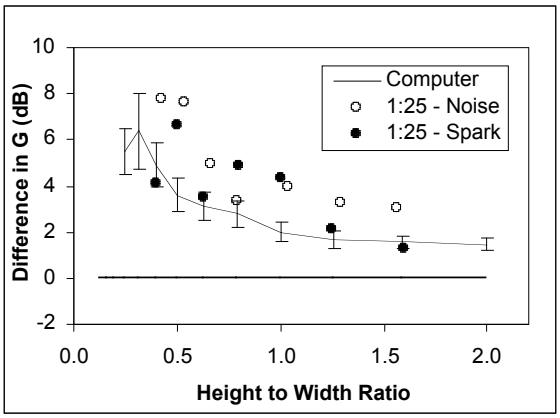

Figure 10 A comparison between Strength (G) predicted by Revised Theory to calculations by a hybrid method of images/ray tracing computer model and measurements in a 1:25 scale model.

To summarise, in a wide, flat room one can expect the EDT to be much shorter than the RT, EDT/RT ratios could be in the range of 70 to 80%. This implies poor Reverberance. The rate of attenuation of Strength will be high, perhaps in the range of 0.25 dB/m or more. At the back of a large hall (e.g. 35 m long) this corresponds to a decrease of 8.75 dB, while a good hall (with an attenuation rate of 0.1 dB/m) might only exhibit a 3.5 dB decrease in level. That means that the Strength at the back of a low wide room will be slightly more than 5 dB lower than a tall narrow room of the same length. Remember again that doubling the size of the entire orchestra will only increase the level by 3 dB. Finally, in the wide, flat room we can expect Revised Theory to over-predict Strength levels. Recall in Figure 5 that Revised Theory suggested less than desirable Strength in the five post war venues under study. The white box in Figure 5 indicates the Strength predicted for these rooms by Revised Theory. Taking the effects of Height/Width ratios into account, Strength will be even lower, as indicated by the black box in Figure 5, i.e. in the range of -3 dB.

Many of the large post auditoria were wide and flat. Height/Width ratios in the range of 40% or lower were not uncommon. The fan shaped geometries are particularly problematic. In these

rooms, Height/Width ratios decrease towards the back of the room. Unfortunately, in a fan shaped room, most of the people sit at the back. That's where the balcony is located and that's where the room is at its widest.

The Hummingbird Centre provides an interesting example. Looking at the photograph in Figure 11, one might be fooled into thinking that the room has a reasonable Height/Width ratio. Figure 12 shows an iconic representation of the actual Height/Width ratios. At the front of the room, where the camera is pointing, the Height/Width ratio is 46%. In Figure 12 this is indicated by the white rectangle. At the back of the room, where the camera is actually located, the ratio is only 9%, indicated by the black rectangle in Figure 12. The experiments described above suggest that a 9% Height/Width ratio should lead to an EDT/RT ratio in the range of 60%. Measurement taken in this location reveal EDT/RT ratios slightly lower than that: 57% near the camera 50% a bit further back.

Figure 11 The Hummingbird (formerly O'Keefe) Centre prior to the 1996 renovation.

Figure 12 Height/Width rectangles at the front and back of the Hummingbird Centre.

3.4 Stage to Pit Balance

The fan shape geometry also proves problematic for Stage to Pit Balance. A simple first order method of images exercise is shown in Figure 13. It shows the comparison of a 30° fan shaped geometry to a rectangular plan of the same size. The hatch marks in the top row indicate the reflections cast off the side wall when the sound source is located in the orchestra pit. The bottom row demonstrates the same for a sound source located slightly upstage of the proscenium arch. Note how the reflection coverage is much more sensitive to source location in the fan shaped room, compared to the rectangular room. From this, one might expect Stage to Pit Balance to be poor in a fan shaped room. At least one set of measurements indicates that this might not always be the case. The reason why proves interesting.

Stage to Pit Balance measurements in the fan shaped Hummingbird Centre are fairly high. Higher than 3 other halls measured in a 1995 survey of Canadian theatres,[11] all of which are rectangular in plan. Of the four halls, the Hummingbird Centre had the lowest G and Glate.

Table 2

Theatre	B (dB)	
	Orchestra	Balcony
McPherson	-0.9	-0.2
Royal	2.0	1.5
Saskatoon	-2.6	-2.1
Hummingbird	2.8	3.7

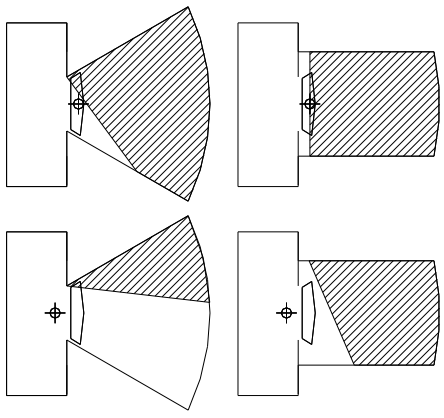

Figure 13 Reflection zones cast off the side wall of a 30° fan shaped room and a rectangular room. In the fan shaped room sound sources in the pit have a larger reflection zone than singers on stage.

It turns out that the Balance between stage and pit sources is strongly influenced by reflected sound energy, both early and late. This was demonstrated by the author in a hemi-anechoic 1:25 model.[12] In the first part of the experiment the walls and ceiling of the model were lined with the full scale equivalent of 1.5 m deep glass fibre. The floor consisted of a hard stage and an upholstered seating area. In the second part of the experiment, the glass fibre was removed from the ceiling and the walls were left absorbent. The purpose of the experiment was to demonstrate the importance of ceiling reflection(s) on Stage to Pit Balance. The results are shown in Figure 14.

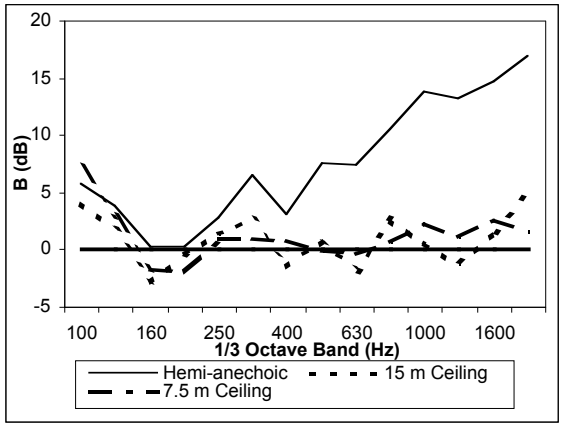

Figure 14 Balance measurements (B) in a 1:25 scale model demonstrate the importance of reflected sound.

The solid line indicates the Balance in the hemi-anechoic space, i.e. the Balance between the direct sound coming from the stage and the pit. The dashed lines indicate the Balance measured with two different hard ceilings, one that is 7.5 m high (full scale) and the other 15 m high. Without the benefit of reflected sound, Balance tips heavily in favour of the stage (solid line). One sees uncharacteristically high Balance levels and clear evidence of barrier effect on the pit source. With the benefit of ceiling reflections (dashed lines), Balance is shown to be in the 0 to 2 dB range that one is more likely to encounter in a theatre or opera house.

Returning to the case of the fan shaped Hummingbird Centre, recall that reflected sound energy (G) is low and that late reflected energy (Glate) is particularly low. The Balance experiment described above suggests that, just like Clarity (C80) measurements in these rooms, good Balance is generated not by strong early reflections but rather as a consequence of weak late reflections.

4 REVIEW

If one accepts the height to width ratio concept presented above, it is hard to over-emphasise the influence of the lateral energy thesis. In the last quarter of the 20th century acoustical design gravitated towards tall, narrow rooms. Many of the designers did this trying to maximise spatial impression, as suggested by the lateral energy thesis. This was fortuitous because the problems with wide, relatively low ceiling geometries spreads far beyond the concerns about spatial impression.

In trying to satisfy the single requirement of early lateral reflections, acousticians got a five fold return:

1. The narrow room provided early lateral reflections which led to source broadening, as intended.
2. It also led to strong late lateral energy which generated envelopment, an effect that wasn't known until the mid 1990s.[6]
3. A tall narrow room meant that the Early Decay Time was much closer to the Reverberation Time. As a result the room sounded more reverberant and the decay of sound was smoother. This the designers could not have known at the time, except perhaps on an intuitive level.
4. The tall narrow room also meant that the rate of attenuation of the reverberant sound level was much lower and, as a result, Strength at the back of the room was higher. Again, it's unlikely the designers knew this at the time.
5. Finally, since the introduction of Revised Theory in the middle 1980s, acousticians may have had over-optimistic expectations of acoustic Strength. If they opted for a wide, low ceiling room design, Revised Theory would have seriously overestimated the Strength. If, on the other hand, they chose a tall narrow building, Revised Theory would provide a much better prediction of Strength, albeit slightly high.

5 SUMMARY

The lamentable reputation of four representative post war auditoria has been confirmed by acoustical measurements. Of the four or five parameters now thought to be important, only one - Reverberation Time (RT) – was found to be in the appropriate range. Coincidentally, it was also the only parameter thought to be important when these rooms were built and the only one that could be easily predicted before the age of computers. Early Decay Times (EDT) were found to be shorter than Reverberation Times in all four halls and, in most cases varied significantly from seat to seat. Strength (G) was found to be consistently low, lower than generally accepted criterion of 0 dB and much lower than the 5 dB levels found in the preferred shoebox shaped rooms of the 19th century. Clarity was high, Early Lateral Fractions were generally low and Late Lateral Energy, although, not measured directly, can be expected to be low based on the low (omni-directional) Late Energy (Glate) measurements.

A simple exercise using Revised Theory explains the low G levels through the unfortunate combination of a large volume, a short Reverberation Time and long distances. Many of the post war rooms had a low Height/Width ratio, which has been correlated with poor EDT/RT ratios and low G. EDTs were also shortened by early reflections generated by reflectors located at front of many of these rooms. A simple ray tracing exercise suggests that the fan shaped geometry typically used in this era favours sound from the pit over sound from the stage. Measurements in at least one room however shows measured Stage to Pit Balance in favour the stage. The reason for the discrepancy is a lack of reflected energy (G and Glate).

The problem with these post war facilities was never really solved. With the notable exception of California's Segerstrom Hall, the building type was simply abandoned. The lateral energy thesis, introduced in the early 1970s proved to be one of the great turning points in modern acoustics. It dictated that rooms should be narrow to encourage strong early lateral reflections. In so doing, it also led to longer Early Decay Times, higher Strength and, most likely, higher Late Lateral Energy. In short, the tall narrow geometry provides a much more efficient use of reflected acoustic energy.

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The influence of height/width ratio and side wall boxes on room acoustics measurements

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1. INTRODUCTION

The Queen Elizabeth Theatre in Vancouver, Canada opened in 1959 with a seating capacity of 2900[1]. The building design was commissioned in 1956 and now, in 1999, is ready for a major renovation. Much of the renovation will be driven by acoustical concerns and, as such, the room presents a good opportunity to compare our mid-century understanding of acoustical design with the formidable revelations of the last forty years.

For most of this century the Reverberation Time (RT) has been the predominant quantifier of sound in a room. One reason for this is that it can be easily calculated. With Sabine's formula, RT can be determined from the two simple pieces of information: the enclosed volume and the amount of acoustical absorption. Of course, it is now clear the subjective significance of RT is not as important as was thought in 1956. In 1965 Atal et al.[2] demonstrated that the Early Decay Time (EDT) correlates much better with the subjective assessment of reverberation. In many rooms, the EDT is shorter than the RT and, in the this sense, the Queen Elizabeth Theatre is no different than any other. It was during an effort to improve EDT in this room that the concept of this paper developed: the influence of simple geometric parameters on modern acoustical measurements. In particular, the Height to Width ratio in a simple six sided box and the presence and geometry of balconies or side wall boxes.

2. HYPOTHESIS

One possible explanation for the difference between EDT and RT was suggested by Hodgson[3] during a series of scale model experiments on the Queen Elizabeth Theatre. The Queen Elizabeth Theatre is typical of its age in that it has a relatively low ceiling. Traditional 18th and 19th century performance venues are high and narrow. The Queen Elizabeth Theatre is flat and wide. When this was pointed out, Hodgson suggested that it might be the reason for its low EDT/RT ratio.

The hypothesis can be explained as follows:

1. A theatre or concert hall, in its simplest form, can be thought of as six sided box with acoustical absorption on only one of the six sides, i.e. the floor.
2. One might expect the early reflected sound (and hence the EDT) to be influenced by the sides of the box that are closest to each other. In a narrow shoe box shaped room, this would be the two non-absorbent side walls.
3. In a flat and wide room like the Queen Elizabeth Theatre, the closest pair of sides is the ceiling and the floor. The latter, of course, is the only acoustically absorbent surface in the "box".

3. PROCEDURE

A number of experiments were performed using computer models of six sided shoe box and fan shaped rooms. In all cases, except one, the acoustical absorption was limited to the floor. The rooms were 40 m in length and the height was varied from 1/8th of the width to twice the width, increasing in a 1/3 octave sequence, i.e. 0.125W, 0.160W, 0.200W, etc. Three room widths were tested:10 m, 20 m and 40 m. For the narrower rooms, source and receiver elevations were higher than 1/8W, which limited the range of ratios, e.g. from ¼W to 2W. The angles of the fan shaped rooms were 8.5 and 16.7 for the 20 m and 40 m rooms respectively. Schematic representations of the six sided boxes are shown in Figure 1.

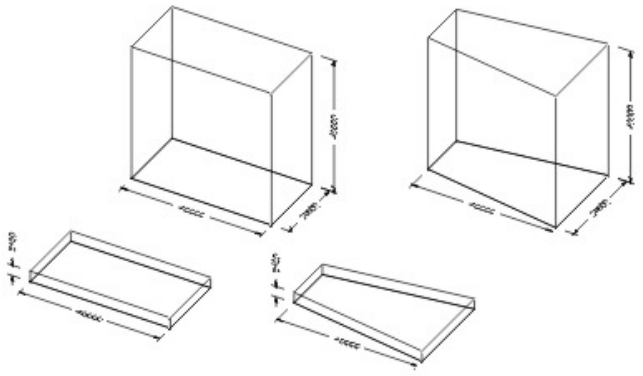

Figure 1 Schematic representations of the six sided boxes used in the initial computer model experiments

Calculations were performed at five receiver locations in each of the four computer models. A single source location was used, situated at the front of the room, stage left of the centre line. The computer program employed for the experiments was CATT Acoustic Version 7. The method of images algorithm was set to 5th order with a truncation time of 300 ms and diffuse reflections commencing after the 1st order. The ray tracing algorithm was set to 12,000 rays and a truncation time of 6000 ms.

Later, in an effort to verify the computer modelling, some of the experiments were repeated in a 1:25 scale model. Two sets of verification tests were performed on a 10 m wide room[4] using the MIDAS system[5] and, more recently, the WinMLS system[6].

The six sided box experiments produced some very interesting results so the concept was extended to include side wall boxes and end wall balconies. Two levels of balconies and side wall boxes were introduced into the 40 x 20 x 20 m (l-w-h) six sided fan and shoebox shaped rooms.

1. In the first experiment, the vertical distances between the two balconies was varied from 3 to 7 m.
2. Next, the importance of the fascia height was examined. For two balconies (separated vertically by 5m) the height of fascia was varied from 0 m (i.e. no fascia) to 4.5 m.
3. In the third set of tests, the depth of the balcony overhang investigated. Experiments were performed in both the 20 m and 40 m wide fan and shoebox shaped rooms. In both cases the rooms were 20 m high and 40 m long. The depth of the overhang ranged from 1 to 8 m in the 20 m wide room and 2 to 16 m in the 40 m wide room.

4. EARLY DECAY TIMES

Results from the initial experiments are shown in Figure 2. EDT/RT ratios are seen to decrease as a function of the Height to Width ratio. For Height to Width ratios greater than 1.0, the EDT/RT ratio is perfectly efficient, i.e. there is no compromise in Early Decay Time for a given Reverberation Time. If the Height to Width ratio is less than 1.0 there is a degradation of the Early Decay Time and hence the perceived reverberance in the room. The effect seems to be independent of the shape in plan, i.e. fan or shoebox. Likewise, the nominal width of the room, 20 or 40 m, was found to have little effect on the EDT/RT ratio.

The ideal RT for a concert hall is in the range of 2.0 s. The Difference limen for Reverberance are thought to be in the range of 0.1 seconds[7]. The results shown in Figure 2 suggest that the EDT can be as much as 0.4 seconds shorter than the RT in a low ceiling concert hall, i.e. four times the difference limen. The difference between RT and EDT, under these circumstances, would be clearly audible to both casual and expert listeners.

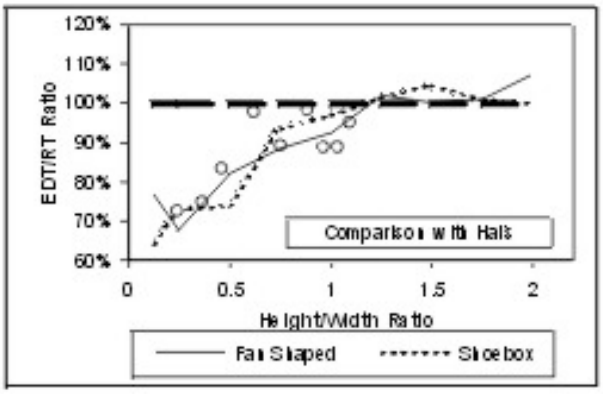

Figure 2 EDT/RT Ratio vs. Height/Width Ratio. Computer models indicated by dashed and solid lines, selected halls by circles.

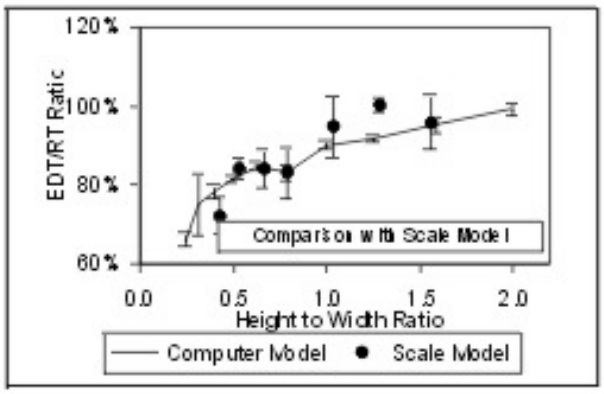

Figure 3 Comparison of a 10 m wide shoe box scale model (dots) with 10 m wide computer model predictions (line).

Recognising that the computer models can be misinterpreted, a number of attempts were made to validate the results. In the first, a comparison was made with measurements taken in a number of existing halls[8]. A random sample of 50 halls produced little or no correlation with the computer model results. When the sample was limited to rooms that matched the very simple geometry of the model, correlation was much better. Please see Figure 2. A second comparison between the computer model and a 1:25 (physical) scale model is shown in Figure 3. Once again the correlation is good. Note however that the seat to seat variation, indicated by the standard deviation bars, is higher in the scale model than in the computer model. Thus it appears that the EDT/RT phenomenon exists in the scale model but, in this experiment at least, the relationship is less consistent than the computer model might suggest.

Other attempts to challenge the hypothesis were made through a series of changes to the computer model parameters. Seat absorption coefficients were varied from 0.5 to 0.99, EDT/RT results did not change appreciably. Seat diffusion coefficients were changed from 30 to 80%, again no difference was found. Changing the absorption coefficient of the entire room did however effect EDT/RT ratios. Absorption coefficients of the seats, floor, walls and ceiling were varied from 0.5 to 0.99, In Figure 4 the EDT/RT ratio is shown to be proportional to H/W ratio and inversely proportional to average room absorption.

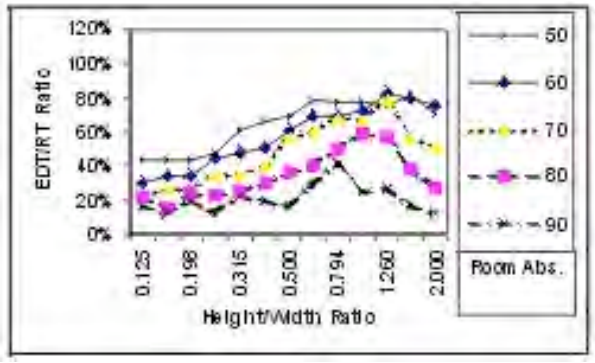

Figure 4 EDT/RT vs. Height/Width Ratios calculated for a range of room absorption coefficients.

Turning to the study of balconies and side wall boxes: as expected, the EDT/RT ratio is reduced significantly as the overhang is increased. Even shallow, 3 m deep balconies reduced the EDT/RT ratio by almost 30%. The effects were evident in both the shoebox and fan shaped models.

Fascia height may have a marginal effect on the EDT/RT ratio. In the 20 m wide shoebox, the EDT/RT ratio is in the range of 65% for fascia heights less than 1.0 m. A larger fascia, for example 2 m or higher, results in a ratio of 70% to 74%, an improvement of almost ten percent. For a 2s RT this is the equivalent of two difference limen. Changing the vertical separation between side wall balconies had no effect on EDT/RT ratios.

5. CLARITY

The balconies and boxes increase Clarity quite a bit. In the 20 m wide shoebox shaped room, Clarity is about 0 dB without the boxes. Introducing boxes on the side walls increases the Clarity by approximately 3 dB. The difference limen for Clarity is 0.67 dB[9]. A change in Clarity of 3 dB - more than four times the minimum noticeable difference - would surely be heard by audience members.

The explanation for the increased clarity proves interesting. Acoustical Clarity is a simple ratio of early to late reflected sound. One might expect that the reason for increased Clarity is because the side wall boxes provide stronger early sound to the listeners. The computer model study suggests otherwise. When balconies are introduced into the 40 m wide shoebox the strength of the early reflected sound (G80) remains essentially the same. In a 20 m wide room, shown in Figure 5, the early energy goes up slightly, about 1.0 dB. However, in both rooms, the late reflected energy (Glate) is reduced by approximately 3 dB when the balconies are added. In other words, contrary to expectations, Clarity is increased not by stronger early reflected sound but by weaker late reflected sound. It is worth noting however that the fascia were perpendicular to the floor, i.e. no effort was made to direct the sound back down towards the seating plane.

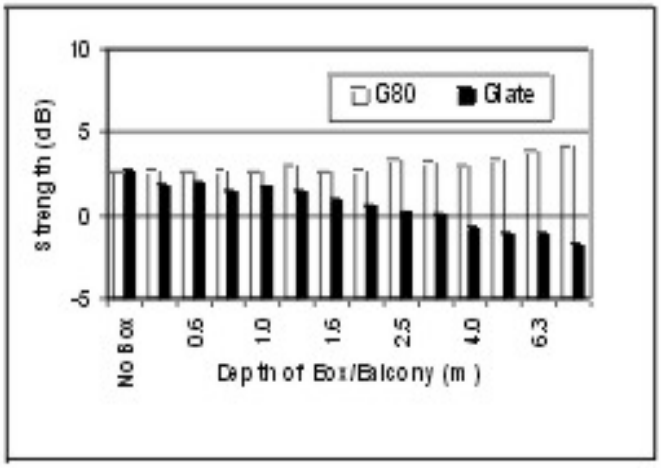

Figure 5 Computer model experiments suggest that C80 increases as the depth of side wall boxes and end wall balconies increase. The reason for this appears to be a reduction in late energy (Glate).

Once again, the vertical distance between balconies does not appear to influence 80 ms Clarity.

6. STRENGTH

Measurements in the 1980s established that acoustic Strength decreases towards the back of a hall and that the rate of decrease is typically in the range of 0.1 to 0.2 dB/m[10,11]. Some room shapes, for example, a fan shape, were found to have higher rates of Strength attenuation

The computer based experiments agree with that finding. Figure 6 shows the slope of Strength versus the Height to Width ratio predicted in the six sided boxes without balconies. The solid bars represent the fan shaped room and they can be seen to be consistently lower than the shoe-box shaped room. Note however that the Height to Width ratio of the room has a greater effect on Strength than its shape in Plan.

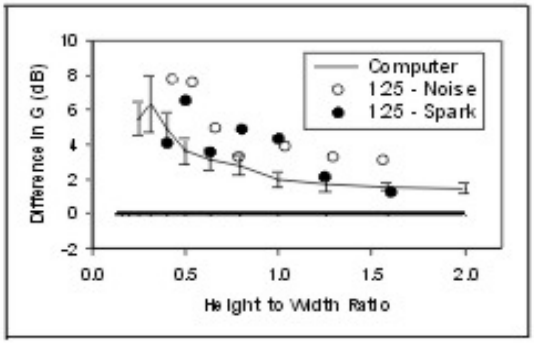

Figure 6 The rate Strength attenuation is found to be a function of shape both in plan and section.

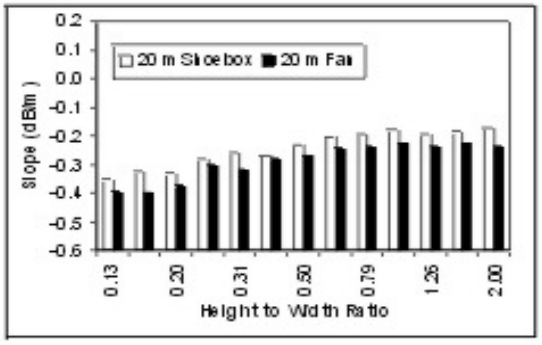

Figure 7 Scale model experiments also indicate a relation between rate of Strength attenuation and Height to Width ratio but the correlation is not as consistent as suggested by the computer model.

Scale model Strength measurements were performed to confirm this finding, at first with at an electronic spark source then with a tweeter radiating steady state noise. Results from the spark source measurements are shown in Figure 7. General agreement is observed but in neither case was the behaviour of Strength as obvious as suggested by the computer model.

Computer experiments with balconies and side wall boxes, also indicate influences on the rate of Strength attenuation. As the depth of the side and end wall balconies are increased, the rate of attenuation increases, from approximately 0.2 to 0.3 dB/m. The effect was noted in both fan and shoebox shaped rooms.

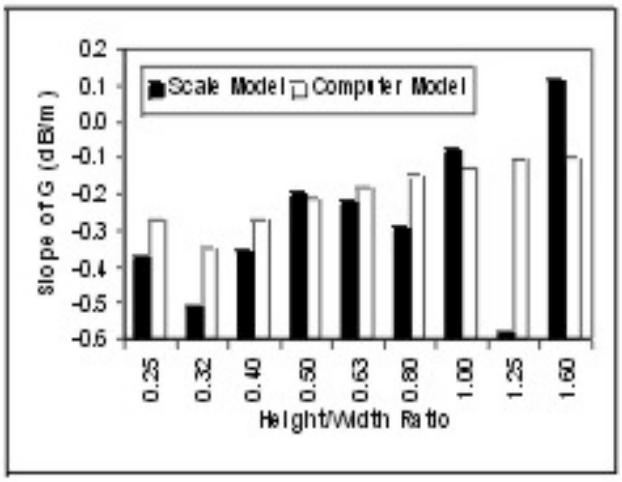

Figure 8 $G_{revised\ theory}$ minus $G_{computer}$ (lines) and $G_{revised\ theory}$ minus $G_{scale\ model}$ (circles and dots)

The six sided box experiments revealed interesting comparisons revised theory[10,12]. Revised theory is perhaps one of the most useful developments in room acoustics in the last few decades. Some have noted however that it often predicts higher levels of Strength than are measured in actual halls[13]. Differences between Revised Theory and measurements are often in the range of 1 or 2 dB. The computer model experiments in a 10 m wide shoebox agree with this observation. Please see Figure 8. All shoebox and fan shaped variations of the computer model experiments displayed similar results. Measurements in the scale model indicate similar behaviour. The discrepancies with revised theory are seen to increase as the Height to Width ratio decreases.

7. DISCUSSION

To summarise, computer and scale model studies suggest that the ratio of Early Decay Time to Reverberation Time is effected by the Height to Width Ratio of the room, the amount of acoustical absorption in the room and by the presence of balconies and side wall boxes. Thus, we can expect a room with Height to Width Ratio significantly less than unity to have short Early Decay Times. The same will be true for rooms with deep balconies and side wall boxes and for rooms with extensive side and back wall absorption, e.g. the acoustic curtains that are often found in multi-purpose performing arts centres.

Many of the same arguments hold for acoustic Strength. As the Height to Width ratio decreases, rates of Strength attenuation increase, as does the discrepancy between measured Strength and Strength predicted by Revised Theory. Adding side and end wall balconies produces similar effects.

Contrary to received wisdom, the height between balconies appear to have little influence on the measured acoustics. Parameters that were investigated included RT, EDT, Strength, 80ms Clarity, Early Lateral Fraction, the EDT/RT ratio and the rate of Strength attenuation. It was not possible to quantify late lateral energy in either the scale or computer models.

One thing that is particularly interesting about this study is the performance of fan shaped auditoria. In many of the effects noted here, the fan shape plan produced results no worse than the shoe box shaped room. Two exceptions were the rate of Strength attenuation and, of course, Early Lateral Fractions. One possible explanation is the difference between the geometry of our computer model and the (deceptive) geometry of real auditoria. The

Figure 9 Cross sections at the front and back of the 3000 seat fan shaped Hummingbird Centre, indicated by white and black rectangles respectively.

highest part of a typical fan shaped auditorium is at the front, the part of the room that everyone is looking at but few are seated in. For the majority of seats in a fan shaped auditorium the ceiling is quite low. An illustration of this is shown in Figure 9. This is an iconic representation of Height to Width Ratios taken near the front and back of the Hummingbird (formerly O'Keefe) Centre in Toronto, Canada. The white and black rectangles indicate the cross-sections taken at the front and back respectively. At the front of the room the Height to Width Ratio is 46%. At the back, were most of the seats are located, the ratio is only 9%. The inference here is that many of the acoustical shortcomings of these rooms is not necessarily the fan shape itself but the unfortunate combination of (i) a fan shaped plan (ii) a sloped floor and (iii) an end balcony. This combination can lead to extremely low Height to Width ratios. The experiments presented here suggest that these are responsible for some of the low EDTs and high rates of Strength attenuation that have been observed in fan shaped auditoria.

8. APPLICATIONS

The impetus for all this work was the Queen Elizabeth Theatre renovation design. Part of the design calls for the introduction of three levels of side wall boxes. With modifications to the ceiling, it was possible to improve the existing EDTs in the Queen Elizabeth Theatre but as soon as the side wall boxes were introduced into the 1:48 scale model, the EDTs dropped back to their original levels. The eventual design of the side wall boxes was informed by this experiments described above. Please see Figure 10. The design, proposed by architect Thom Weeks, uses fin like reflectors to effectively reduce the depth of the boxes by half. These reflectors extend from floor to ceiling. In addition to improving the Early Decay Times they should improve lateral reflected energy and, as a consequence, improve source broadening.[14,15] Scale model measurements have demonstrated improved EDT/RT ratios: from 51% with the first set of side wall boxes to 75% with the revised boxes.

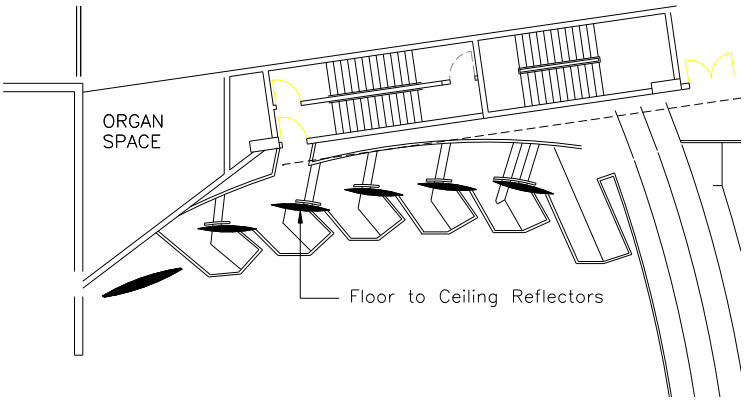

Figure 10 Plan of the proposed Queen Elizabeth Theatre renovation.

Another project that will benefit from this experimental work is the new 800 seat Magna A&E Auditorium, to be built in Aurora, just north of Toronto. The plan and longitudinal section for the room are shown in Figure 11. The width of the room was easily established from the beginning; no more than 22 m. Two more difficult questions remained: (i) should a side wall balcony be included and (ii) how high should the ceiling be. The owner preferred a low ceiling.

Three ceiling heights were considered as indicated at the extreme right of Figure 11. Acoustical tests were performed in a 1:50 scale. The Height to Width study produced mixed results. EDT/RT ratios increased when the ceiling was raised from elevation 1 to 2, but decrease slightly when the ceiling was raised to elevation 3. (The difference between elevations 2 and 3 was less than EDT measurement accuracy.[16])

The two side wall balcony configurations that were considered are indicated by the dashed lines at the left of Figure 11. When the side balconies were introduced into the model acoustic Strength was reduced by about 2 dB. Early (G80) and late (Glate) energy both decrease, Glate more than G80. In all ten seats that were measured the Reverberation Time (RT) decreased, on average by 0.25 s. The biggest change in RT, as with other parameters, happens when the first balcony is introduced. In 6 out of 10 seats C50 and C80 increased but in some cases not beyond difference limen. RT/EDT ratios were the only parameter to show both positive and negative trends, but in most cases the ratio decreased. For these and other reasons, it was decided not to include a side wall balcony.

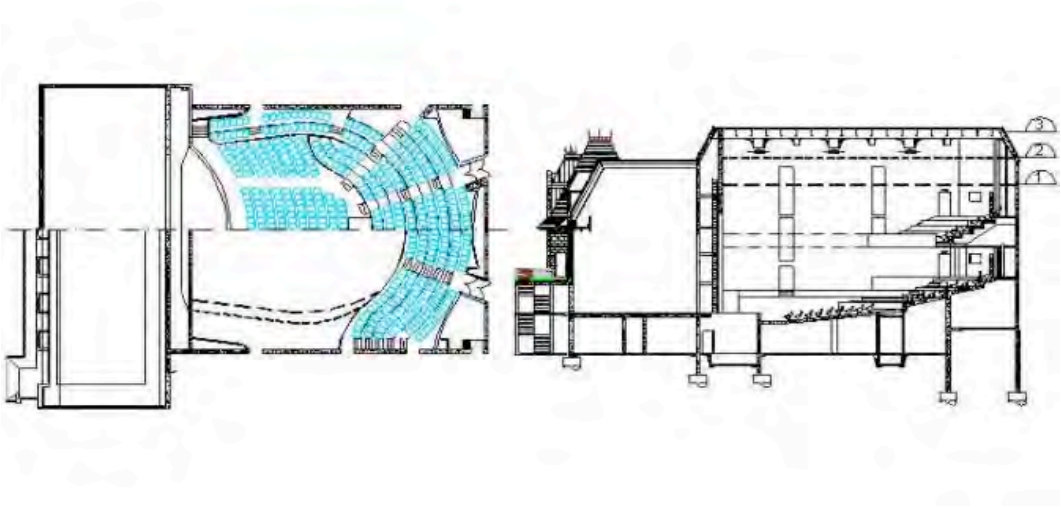

Figure 11 Composite Plan and Longitudinal Section of the proposed Magna A&E Auditorium

9. CONCLUSION

Through the initial computer model experiments, Height to Width ratios were found to have a significant effect on an number of room acoustic parameters, notably the Early Decay Time and acoustic Strength. Later, the computer experiments revealed that side and end wall balconies had similar influences. Scale model experiments have confirmed these findings although the trends are not as obvious or as consistent as the computer model. Nonetheless, the findings have proved useful for acoustic design, two examples of which have been provided above.

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