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ACOUSTICAL DESIGN OF THE ALBERTA JUBILEE AUDITORIA

BY

T. D. NORTHWOOD AND E. J. STEVENS

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ANALYZED

Acoustical Design of the Alberta Jubilee Auditoria

T. D. NORTHWOOD AND E. J. STEVENS
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(Received February 3, 1958)

Two large auditoria have recently been built by the province of Alberta, Canada, in the cities of Edmonton and Calgary. The main auditoria, which seat 2700 persons, are designed for both concert and large-scale stage presentations. This paper reports on the design and on the extensive acoustical testing in the laboratory and in the halls themselves. Impedance tube and reverberation chamber data were obtained for materials and components of the auditoria. Reverberation time, pulse tests, and other objective measurements were made in the halls as they approached completion. The project culminated in a test concert attended by about 1800 people, including 11 expert observers who afterward participated in a discussion of the acoustical properties of the hall.

INTRODUCTION

TO commemorate the Golden Jubilee of the Province of Alberta the provincial government has constructed two large auditoria. The two buildings are located in Edmonton and Calgary and are intended to serve the northern and southern parts of the province as cultural and recreational centers. Planning of the auditoria began in the fall of 1954 and they were officially opened in April, 1957. The design and construction were undertaken by the Alberta Department of Public Works. Acoustical design and testing were done by a special design group of that department in collaboration with the Division of Building Research, National Research Council of Canada.

* In collaboration with the Alberta Department of Public Works, Edmonton, Alberta.

This paper deals with the acoustical design and performance of the auditoria. Extensive testing was done, beginning with laboratory work in Ottawa, on the materials and furnishings of the halls and followed by tests in the halls themselves. Except for a few comparative measurements, the hall tests were done in the Edmonton Auditorium. Since the two buildings are almost identical, reference will generally be made to the single auditorium design.

DESIGN—GENERAL CONSIDERATIONS

The project began with a survey of existing halls and theaters and a consideration of the variety of functions that might reasonably be combined in one building. It was finally decided to design a hall seating about 2700 people and suitable particularly for large-scale theatrical and concert performances. This appeared to be a good size for concert purposes and about the maximum size for successful theatrical presentations.

The theater requirements led to a stage tower and proscenium opening large enough to accommodate full-scale opera. An orchestra pit was provided accommodating about 75 musicians. For concert hall purposes an orchestra shell was planned that would partition off the stage tower and provide suitably shaped reflecting surfaces around the musicians. By covering the orchestra pit with removable panels it was also possible to extend the forestage and thus bring the orchestra forward into the auditorium proper. Several modifications of these two basic conditions were also envisaged: the curtains are designed so that for small stage presentations the proscenium opening can be suitably reduced; similarly the orchestra shell can be varied in size to accommodate anything from full orchestra and chorus to a string quartet. Adjacent to the stage are elaborately equipped dressing rooms, a rehearsal stage, a workshop, scenery storage space, and other facilities.

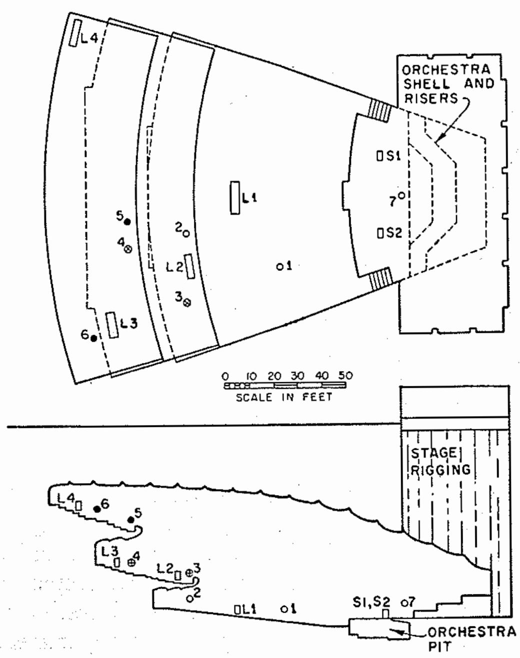

FIG. 1. Plan and longitudinal section of auditorium. (Note: *S*1, *S*2—test sources; 1, 2, 3···7—test microphones; *L*1-*L*4—articulation test listening positions.)

The plan and longitudinal section of the hall are shown in Fig. 1. A fan-shaped hall was chosen because this provides good sight lines for the maximum number of people within a reasonable distance of the stage. Maximum distance from the stage is about 150 ft. Originally a single large balcony was planned but structural problems necessitated splitting it into two balconies.

The side walls are paneled in French walnut plywood, presenting an unbroken surface from floor to ceiling. The absence of boxes or other distractions makes a clean unobtrusive surface, directing the attention of the audience to the stage. This desirable visual effect had to be weighed against the acoustical dangers associated with large unbroken surfaces. The latter problem has been dealt with partially by using wall panels of two types, visually identical but differing in their low-frequency absorption properties. The two types are combined in an irregular pattern so that the walls should be reasonably diffusive for low-frequency sound. The walls are also inclined slightly inward, to improve the coupling between the live ceiling region and the absorptive region at audience level.

The rear walls are moderately absorbent and diffusing to minimize the danger of a rear-wall echo common in fan-shaped halls. Diffusion is obtained by mounting out from the wall a series of inclined elements which direct reflections safely and usefully into the rear seats.

Following a tentative design, the final location and shape of the wall and ceiling surfaces were determined with the aid of ray-tracing techniques, including a consideration of intensities and arrival times of the various reflections. To obtain some indication of transient response the principal reflections of a 20-msec pulse were considered and a plot was made of the complex signal arriving at representative listening points. The relative intensities of the various arrivals were calculated by taking into account distances, curvature (if any) of the reflecting surfaces, and their absorption coefficients. Figure 2 shows two typical transient plots, for test positions 1 and 6 (Fig. 1). Position 1, well forward on the ground floor of the hall, was in the region where the most serious transient problem was expected. The high proscenium arch, necessary for stage purposes, resulted in a rather flat ceiling contour at the front and danger of delay in reflections reaching the front of the seating area. This possibility was examined further by ray analysis, with the result that the front ceiling sections were made convex to reduce the intensity of these reflections to a safe level. The response is further smoothed by additional reflections when the orchestra shell is in place. A smooth transient response seemed desirable for the concert hall property known as "good definition," which should also mean good speech intelligibility. Subjective observations during the test concert have led to a reconsideration of this assumption, insofar as it applies to orchestral music. This will be discussed later.

REVERBERATION TIME

Although much work has been done in auditorium acoustics since W. C. Sabine's day the one criterion still universally accepted is reverberation time. It has the advantage of reducing a complex acoustical problem

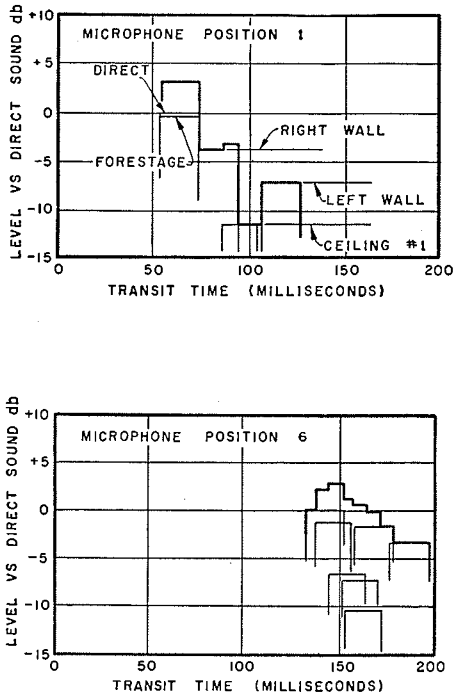

FIG. 2. Calculated transient response for two seating positions. Position 1—middle of ground floor; position 6—rear of top balcony.

to a single number, which thus gives the impression of being a simple quantitative measure. The number one chooses depends on the function for which the hall is to be used. The Alberta Auditoria may be used on successive days for symphony concerts, opera, little theater, fashion shows, or public speeches. After some debate it was decided to design the hall so that when arranged for concert use (with orchestra shell) it would have a reverberation time of 1.7 sec in the middle and high frequencies, increasing to between 2.0 and 2.5 sec at 125 cps. This conforms with the recommendations of Knudsen and Harris,[1] which are somewhat lower than

[1] V. O. Knudsen and C. M. Harris, *Acoustical Designing in Architecture* (John Wiley and Sons, Inc., New York, 1950).

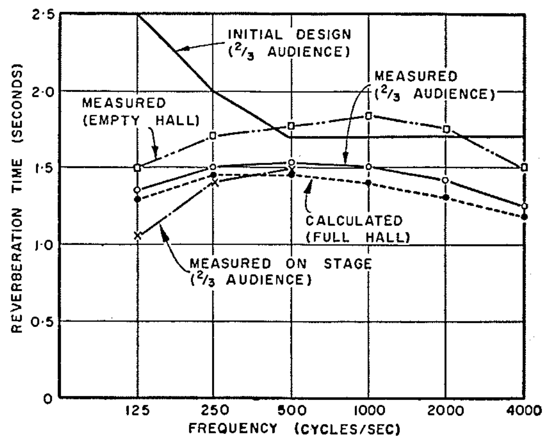

FIG. 3. Reverberation times: initial design and final observations.

other recommendations for concert halls. For speech a still lower value would be preferred, but it was hoped that careful shaping of the hall would result in a transient response smooth enough to provide satisfactory reception of speech.

For the theater condition, without the orchestra shell, it was expected that the absorptive stage tower would reduce the reverberation time to about the optimum value for speech. This would probably not actually improve the acoustical properties, however, since the extra absorption is not added in a very useful place.

There were several compromises between the initial design and final construction, resulting in a slight reduction in anticipated reverberation time at both low and high frequencies. And finally, the actual tests in the hall indicate an unexpected amount of absorption at low frequencies. Average reverberation times are shown in Fig. 3, together with the initial design curve. Also included are the data for the stage microphone position, illustrating the relative deadness of the stage area at low frequencies. This is related to difficulties with the orchestra shell, which will be discussed later.

It is interesting to compare the Alberta results with those obtained by Parkin and others[2] in the Royal Festival Hall, London. The two halls are similar in size and capacity, and the initial reverberation time criteria were identical. In both cases, for rather similar reasons, the actual reverberation time turned out to be slightly shorter than intended.

Sound Absorption: Laboratory and Hall Measurements

The first tentative design was based on published data for the materials selected for the inner surfaces of the hall. This was followed by a revised design based on laboratory tests on the more absorptive components, including carpet, plywood wall panels, chairs, and people. Sound absorption data for a selection of these

[2] Parkin, Allen, Purkis, and Scholes, Acustica 3, 1 (1953).

TABLE I. Absorption of auditorium components.

Material	Test condition	125	250	500	1000	2000	4000
		Frequency (cycles/sec)					
		(Absorption coefficient)					
Carpet							
Short uncut pile wool, on $\frac{1}{4}$ in. sponge	Lab test	0.06	0.13	0.37	0.41	0.46	0.55
Tufted nylon on $\frac{1}{4}$ in. sponge	Lab test	0.06	0.14	0.34	0.36	0.31	0.37
Plywood panels							
With glass fiber backing	Lab test	0.60	0.30	0.10	0.09	0.09	0.09
With back bare	Lab test	0.40	0.18	0.08	...	...	...
Ceiling							
2 in. plaster on metal lath	Hall test	0.08	0.06	0.05	0.04	0.04	0.04
Orchestra shell							
$\frac{1}{16}$ in. glass fiber reinforced plastic	Lab test	0.48	0.25	0.11	0.04	0.04	0.04
As above, with $\frac{1}{32}$ in. undercoating	Lab test	0.27	0.22	...	...	...	...
As above, with $\frac{1}{8}$ in. undercoating	Lab test	0.14	0.17	0.13	...	...	...
$\frac{1}{4}$ in. birch plywood, braced at 16 in.	Lab test	0.11	0.17	0.12	...	...	...
Chairs							
		(Sabines per chair)					
Unoccupied chair	Lab test	2.4	2.8	3.5	3.2	2.7	2.6
	Hall test[a]	2.7	2.5	2.6	2.4	2.2	1.4
Audience increment	Lab test	0.9	0.8	0.9	1.6	1.8	1.8
	Hall test	0.8	0.8	0.9	1.4	1.8	1.6

[a] Not reliable.

are shown in Table I. These will be discussed in the following paragraphs.

Until the recent definitive paper by Harris,[3] the available data for carpets were sketchy and were lower than for typical materials, so that the initial design underestimated carpet absorption. Laboratory tests were therefore made on tufted and short-pile materials in search of a low-absorption substitute for carpet. The data for conventional carpets agreed closely with the values given by Harris.

Measurements were made on a large number of plywood panel designs to obtain the desired low-frequency absorption characteristic. Two types were finally selected and used in about equal quantities distributed in random fashion on the side walls of the auditorium. Each type consisted of a panel of $\frac{1}{4}$-in. walnut plywood, 2 ft by 4 ft, glued to a $1\frac{1}{4}$- by $1\frac{1}{4}$-in. frame and mounted on 2- by 2-in. wood furring, so that a total back space of about 3 in. was formed. One type had glass fiber batts fastened against the back of the plywood, whereas the other type was left with the back space empty.

Important items in the absorption design were chairs and people. The published information for these items is rather incomplete, and there has not been a very satisfactory correlation between laboratory tests and hall performance. The chief difficulty with laboratory tests appears to be extra absorption due to the exposed edges of a small sample. This is not present with a full assembly of chairs and people. In the present study, laboratory tests were done mainly on samples of ten chairs with and without occupants. Subsidiary tests were done with screens around a group of chairs to simulate the screening effect normally provided by adjacent chairs, and from these an estimate was made of the full-scale performance of the chairs with and without occupants. The estimated values together with some rather complicated deductions from auditorium measurements are shown in Table I. The latter are unreliable at both low and high frequencies. Measurements in the unfinished hall presented unexpected problems which will be discussed later. The increment of absorption due to the audience was the one hall measurement uncomplicated by extraneous absorption items. This checked very closely with the values predicted from laboratory data.

Apart from such matters as comfort and appearance, the aim in the chair design was to keep total absorption to a minimum, since the likelihood of an excess of absorption was foreseen. At the same time it is desirable to minimize the difference between occupied and unoccupied chairs, so that the acoustical properties of the hall will not vary too much with the size of audience. Experiments were made with chairs in which most of the absorption was concentrated in areas that would be covered by an occupant. Thus the absorption added by an occupant was partly compensated for by the chair absorption he canceled out. Ultimately, however, this design was greatly modified, resulting in a more durable and less absorptive chair. Despite this compromise the reverberation time in the finished hall changes only

[3] C. M. Harris, J. Acoust. Soc. Am. 27, 1077 (1955).

TABLE II. Absorption in the completed hall (units: Sabines$\times 10^2$).

Item	Area ft²	Frequency (cps) 125	250	500	1000	2000	4000
Hall proper (empty)							
Forestage—maple panels	1150	1	1	1	...	...	...
Aisles and crosswalks—carpet	8000	2	14	27	19	24	29
Floor—plastic tile on concrete	16 400	8	8	8	8	8	8
Rear walls—carpet over plywood	4400	15	12	15	13	13	13
Ceiling—2 in. plaster on metal lath	18 000	14	11	9	7	7	7
Soffits and balustrades—2 in. plaster on lath	8900	7	5	4	4	4	4
Side walls—walnut plywood panels	11 200	56	28	10	10	10	10
Rear wall diffusers (145 units)		3	6	7	6	5	3
Misc. wood paneling	800	2	1	1	...	...	...
Chairs (unoccupied) (2700)		65	76	94	86	73	70
Misc. openings and vents	900	12	9	8	7	7	7
Total to proscenium		185	171	184	160	151	151
Stage—with orchestra shell							
Stage floor—varnished pine	2500	2	1	1	1	1	1
Orchestra shell and stage tower	6700	30	17	7	5	4	4
Misc. openings	100	2	1	1	1	1	1
Risers and other stage furnishings		5	4	3	3	3	3
Total on stage		39	23	12	10	9	9
Total—empty hall		224	194	196	170	160	160
Occupied hall							
100 players (plain chairs)		3	4	5	5	5	5
Increment for 1700 audience		15	14	15	27	31	31
Total—occupied hall		242	212	216	202	196	196
Measured values							
Hall empty		214	191	185	172	164	152
Hall occupied as above		232	211	209	205	205	189

from 1.8 sec when empty to about 1.4 sec when full. The final chair design had the seat, back, and arms upholstered in foam rubber covered with a densely woven repp fabric. Both foam rubber and fabric were relatively impermeable and nonabsorptive, compared to spring-and-pad upholstery and various mohair and frieze fabrics.

Unfortunately, no information was obtainable about the orchestra shell until it was delivered on the eve of the test concert. And in the last-minute rush the design was completed without sufficient consideration of its sound transmission properties. To facilitate supporting it from the stage rigging it was made as light as possible, of $\frac{1}{16}$-in. glass-fiber-reinforced plastic riveted to a light aluminum framework. Laboratory tests were later made with the shell material covering an absorbent cavity (to simulate the absorptive stage tower). The resulting absorption coefficients are shown in Table I. Also shown in the table are various modifications aimed at improving the performance of the material.

Measurements of Reverberation Time

The interpretation of the hall measurements made during construction was complicated by the presence of scaffolding, piles of material, and debris, as well as by the fact that several construction operations always proceeded simultaneously. The procedure in analyzing the results was to make a careful catalog of hall conditions at each test and apportion the absorption among the various items in a consistent way through successive stages of construction. It was hoped that useful absorption data would be obtained to compare with the laboratory measurements.

The first measurements were made as soon as the shell of the auditorium was closed in. At this stage the ceiling was finished, including a prime coat of paint, but the other surfaces were mainly bare concrete. Even at this time there was a low-frequency discrepancy. After making liberal allowances for the other surfaces in the hall, it appeared that the ceiling must be significantly absorptive at low frequencies (0.08 at 125 cps). The ceiling panels are made with expanded-metal lath plastered top and bottom to a total thickness of 2 in. of gypsum plaster. This structure is suspended from the main steel work above. Despite the heavy plaster the ceiling sections evidently act as panel absorbers at low frequencies. (The final data for the ceiling and other components of the finished hall are shown in Tables I and II.) It might be noted that a similar effect was observed in the Royal Festival Hall, although it was attributed to the inadvertent use of a lightweight plaster for the ground coat.

Subsequent reverberation tests were made as the auditorium surfaces were gradually finished. Of particular interest were the plywood wall panels, which constituted a major portion of the low-frequency absorption. The tests showed an unexpectedly small increase in low-frequency absorption as the panels were installed. On the other hand, the installation of chairs and carpets and stage fittings (which occurred simultaneously during the last few weeks of construction) showed an unexpectedly large increase in low-frequency absorption.

A reconsideration of the matter led to the conclusion that the stage tower, which is about two-thirds the volume of the auditorium, must be regarded as a separate space, partially coupled to the auditorium by the proscenium opening. Unfortunately, the sound sources were always placed on stage, so that the tower was as well energized as the hall. If the reverberation times are shorter for the stage tower alone than for the main hall alone, then the times observed in the hall should correlate with hall absorption (making due allowance for energy absorbed by the stage). But if the stage tower is more reverberant than the hall, it will feed energy into the hall during decays and lengthen the hall reverberation times.

Calculations indicate that the two spaces had nearly the same reverberation time at the beginning of the tests, but the stage thereafter remained bare and reverberant until the last few weeks of construction. Thus many of the intermediate test results are of doubtful value. This is particularly true for low frequencies. At high frequencies these early results are in doubt due to uncertainty about air absorption. Temperature and humidity were very low in the unfinished building during the winter, and varied greatly from floor to ceiling.

Reverberation measurements in the completed hall included an extra microphone position on stage, and additional studies were made in this region after the test concert. It was found that with the orchestra shell in place the stage tower was effectively cut off except for low frequencies. At 125 cps the transmission loss of the shell was only 8 db. Consequently a large fraction of low-frequency energy was transmitted into the stage tower and mostly absorbed. As a result the low-frequency reverberation times in the stage area were lower than for the rest of the hall (Fig. 3).

Using the laboratory values for chairs, wall panels, and carpets, hall values for the ceiling, and estimates for the other less important components, the agreement with the final hall results is reasonably good (Table II).

TABLE III. Articulation scores for Edmonton Auditorium.

Test No.	Date	Percent articulation	Reverberation time at 500 cps
1	March 10	56	4.6
2	March 17	68	3.7
3	March 24	75	3.6
4	March 31	77	2.5
5	April 8	84	1.4

SPEECH ARTICULATION TESTS

Since the auditorium will be used for public speech, it was considered worthwhile to make articulation tests with listeners at various areas in the hall. A group of students from the University of Alberta were recruited to act as listeners and talkers. Since both the number of tests and the number of observers were limited, one cannot ascribe very high precision to the tests, but a few interesting points emerged. The word lists and procedure suggested by Knudsen and Harris[1] were used. In the tests reported here no sound reinforcement was used.

Partly for training purposes the tests began in the bare concrete hall and continued until it was completed. Four listening positions were used in the hall; these are indicated as *L*1, *L*2, *L*3, and *L*4 in Fig. 1. Position *L*1 gave articulation indices about 5% higher than the other three positions, which did not differ significantly among themselves.

The articulation scores obtained in a series of five tests are given in Table III. Test No. 5 was an abbreviated one made during the test concert and the results have been adjusted to be consistent with the others in accordance with the observed differences in speakers and listening positions. The progressive improvement in score is about what might be expected, considering the effects of learning and of improved acoustics. Observers present during the final test criticized the talker's delivery because he paused unduly before each test word, thus minimizing the blurring effect of reverberation; allowing for this the average articulation index still appears to be about 80%, which is a very satisfactory value for a large hall.

SPECIAL TESTS

In addition to reverberation time measurements and articulation tests, several other objective studies were made. As soon as the auditorium was closed in, a series of pulse tests was begun, in search of echo problems. Several echoes were observed in the early stages of construction, when most of the surfaces were bare concrete. It was of interest to examine these carefully as the final surface treatments were installed. A pistol source and an oscillograph display were used for a systematic study. The most serious echo, from the rear walls, was observed on stage and in the first few feet of the seating area. This diminished into unimportance when the rear wall treatment was applied and the seats were installed.

Following the diffusion studies of Meyer and Thiele,[4] measurements were made of direct and reflected sound. Meyer has suggested that in a good hall the listener receives the sound from all directions. A pulsed loudspeaker source and a directional microphone array were used to make measurements of peak intensity as a function of angle. This was done at a number of seating

[4] E. Meyer and R. Thiele, Acustica 6, 425 (1956).

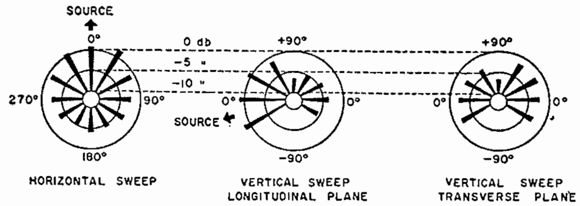

FIG. 4. Variation of sound level with direction. (Position 2, Fig. 1: 2000 cps; 400-msec pulses.)

positions, including those that were found by the observers to be most and least satisfactory. Typical directional patterns are shown in Fig. 4. The results showed a very diffuse field, even on the ground floor under the grand circle, where considerable loss in the vertical and rear directions might be expected.

The same long-pulse source and a nondirectional microphone were used to make a sound level survey from front to back of the seating area. Measurements were made at six frequencies and for three microphone heights: zero, 1 ft, and 2 ft above the chair backs (in the empty hall). Variations with microphone height were rather complicated but showed no consistent trend below 1000 cps. Above this frequency there was generally a diminution when the microphone was level with the chair backs. Maximum diminution was about 5 db, and occurred in the middle of the ground floor area. In the balconies and under the first balcony the effect was small, becoming negligible at the extreme rear. Results at the three microphone heights were averaged to obtain the variation of sound level with distance, from a stage source to the back of the hall. Curves for three frequencies are shown in Fig. 5. All six frequencies gave similar results: a maximum drop of 5 to 7 db and a slight rise near each rear wall.

NOISE PROBLEMS

The possible sources from which noise may reach the hall proper lie mostly within the building itself. The buildings are situated in spacious grounds in quiet surroundings, and the only external noise of any consequence is likely to be from aircraft. Aircraft noise in the vicinity is estimated to be about 75 db, and special attention was therefore given to the roof construction. The auditorium proper forms an inner shell within the building with a double wall and roof. Doorways leading to the auditorium are carefully planned in relation to the various accessory spaces which surround the auditorium, so that the minimum of extraneous noise will be carried into the hall.

The roof structure consists of a lightweight reinforced concrete deck weighing 35 lb/sq ft. This is supported on steelwork which spans the width of the building. From this structure is suspended the auditorium ceiling which weighs about 25 lb/sq ft. In addition the interspace is heavily lagged with mineral wool. The weakest area in the roof design is the main ventilator exhaust louver at the top of the stage tower. In the unfinished building, aircraft and traffic noise were clearly discernible in the stage area, and an unfavorable wind impinging on the louver tended to produce sound effects of its own. The stacks are being modified to take care of these and other problems.

The most serious noise sources were the main mechanical rooms, which had to be located directly under the main auditorium. Judging from measurements on similar equipment, a noise level of about 90 db with peaks at 60 and 135 cps was anticipated. (An over-all level of 96 db was measured.) Structure-borne vibration from the heavy compressors and fans was an additional hazard. The mechanical room was constructed as a completely isolated shell, with its walls and ceiling as free as possible from the rest of the building. The design was complicated by the fact that an array of columns supporting the auditorium floor passes through the mechanical room. The columns were boxed in and the mechanical room ceiling was supported on the outer box structure. It was anticipated that this arrangement, with absorptive lagging in the interspace, would adequately reduce noise transmission. As the mechanical design progressed, however, it was decided to use the interspace as a plenum, and to exhaust air from the auditorium through the floor slab with a large number of small openings under the seats. As a result, the transmission loss of the completed system for air-borne noise is only about 40 db. The over-all sound level in the empty hall is 56 db with all equipment running. With an audience present, the audience noise tends to mask the machinery noise so that it is no longer identifiable.

THE TEST CONCERT

No matter how carefully a concert hall is designed and built, the designer cannot be satisfied with the result until a subjective opinion has been established on the basis of actual use. Ordinarily it might be years before this is achieved. The designers of the Royal Festival Hall sought to accelerate the process by holding a series of test concerts, and by inviting a number of musical and acoustical authorities to examine the hall.

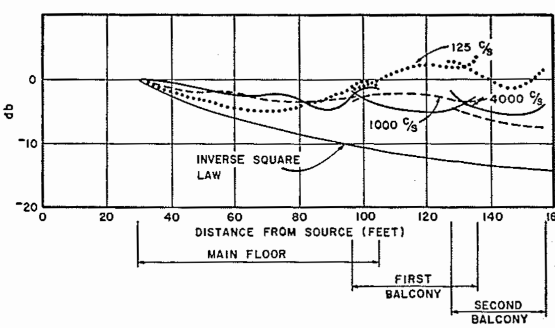

FIG. 5. Variation in sound level with distance from source.

TABLE IV. Program of test concert.

Symphony No. 4 (1st movement)	Tschaikowsky
Symphony No. 40 (1st movement)	Mozart
Demonstration of solo instruments	
Intermission	
Symphony No. 4 (3rd movement)	Tschaikowsky
Demonstration of orchestrated chords on strings, brass, woodwinds	
A Walk to Paradise Garden	Delius
Intermission	
Acoustical measurements	
Sonata No. 4 for violin and piano	Franck
Excerpts from Mass in B Minor	Bach

A similar course was followed at the Edmonton Auditorium.

Only one test concert was possible, and this was carefully planned to make best use of the $2\frac{1}{2}$ hr available. The program is shown in Table IV. Several types of music were played, ranging from solo violin to full symphony orchestra and chorus. Special demonstrations with various orchestral instruments were included to allow a study of the reception of various tone qualities. A commentator instructed the audience in acoustical matters from time to time during the program.

In addition to the concert, permitting subjective assessments of the hall by about 1800 people, a series of objective tests was also done, during which the function of the audience was merely to provide sound adsorption. The tests included measurements of reverberation time, variations of level with position, a few pistol shots for pulse tests, and a brief speech articulation test.

The audience consisted of three categories of people: a specially invited group of 13 authorities in music and acoustics (Table V); a group of 160 persons with special knowledge of music or acoustics; and approximately 1800 ordinary concert goers, of whom about 300 reported an acquaintance with other well-known concert halls.

TABLE V. Special observers at test concert.

Murray Adaskin, Professor of Music, University of Saskatchewan.
Leslie Bell, Leslie Bell Singers, Inc., Toronto.
Leo L. Beranek, Professor of Communications Engineering, Massachusetts Institute of Technology.
R. S. Eaton, Professor of Music, University of Alberta.
Cyril M. Harris, Professor of Electrical Engineering, Columbia University.
Lee Hepner, Conductor, Edmonton Symphony Orchestra.
Vern O. Knudsen, Vice-Chancellor, University of California.
Hugh LeCaine, Electronic Music Group, National Research Council.
Henry Plukker, Conductor, Calgary Philharmonic Society.
Michael Rettinger, Radio Corporation of America, Hollywood.
Arnold M. Small, Convair, San Diego.
Geoffrey Waddington, Director of Music, Canadian Broadcasting Corporation.
Arnold M. Walter, Director, Faculty of Music, University of Toronto.

Each of the three categories and the performers was given a questionnaire to fill out, the questionnaires varying in content with the group concerned. The large audience group was requested to stay in one seat during the performance, and on their questionnaires to compare the reception of the various types of music. (This after a brief lecture defining the terms "sonority," "definition," and "brilliance.") The group of 160 semiqualified persons was assigned to definite seats and moved at each intermission to new locations, so that they could compare seating locations. The dozen experts moved at will throughout the concert, exploring the whole hall including the stage.

After the concert a colloquium was held during which the experts discussed the properties of the hall. A good portion of the discussion was devoted to reconciling the viewpoints and terminologies of musicians and acousticians, but there was reasonable unanimity in the final conclusions. At the outset it was necessary to distinguish between the qualities of the hall and the qualities of the performance. The orchestra included members of both Calgary and Edmonton symphony orchestras, and had only one rehearsal before the concert. As a consequence they were not a well-balanced, disciplined ensemble. The results of several experimental rearrangements of players (with consequent additional practice) indicated that what one heard depended greatly on the players. As far as possible these effects were disregarded in discussion of the hall.

There was considerable discussion about reverberation time. Most of the musicians indicated that they would have preferred a more reverberant hall. Most of the acousticians found that although a slightly more reverberant hall would be preferable for some classes of music (e.g., Tschaikowsky), it was about optimum for a general purpose hall. As the discussion proceeded, it became evident that the impression of deadness was mainly a low-frequency effect, associated particularly with the stage area. It was observed that the orchestra was deficient in low-tone strength despite a very large bass section, and it was surmised that the orchestra shell was not an effective barrier to low-frequency sound. Thus at low frequencies the shell failed in its two functions of partitioning off the stage tower and properly distributing these important first reflections.

The experts were asked to indicate preferred seating areas, if any. It was agreed that reception was very uniform all over the hall. The preferences showed no definite consensus about "best" and "worst" areas, although for symphonic and choral music most of the preferences were for areas remote from boundaries (e.g., positions 1 and 3, Fig. 1), and against areas near the boundaries (e.g., position 2, Fig. 1). The hall was compared favorably with the best concert halls of this continent and Europe. In particular, it was compared with the Royal Festival Hall and the Kleinhans Hall in Buffalo, with which it has some similarities.

Questionnaires were received from about 100 of the musicians and singers who participated in the concert. Generally the musicians were well satisfied with playing conditions and indicated that they could hear both themselves and the other players, although some of the inner strings felt overpowered in the arrangement that placed them adjacent to the brass. Members of the chorus were also satisfied with conditions, feeling well balanced with respect to the other singers and the orchestra. Since the rear wall echo would be prominent on stage if anywhere, the players were specifically asked about echoes. None of the players heard echoes during the performance, and only five noticed them during the pulse tests.

The violin soloist, who was also one of the dozen experts, reported that he found it easy to play in the hall, contrasting it with others of his experience in which he had to work very hard to achieve what he wanted to hear. The one thing he would have liked was a little more prolongation of the sound. It is suspected that for a soloist it is not so much reverberation time that matters as the hall size, and the nearness of first reflecting surfaces. A more effective shell would provide the performer with a higher intensity of reflected energy and a greater sense of prolongation of the sounds of his own instrument. Normally the shell will be considerably smaller for solo work, and this will improve matters.

Of the 160 musically trained members of the audience, 124 returned questionnaires. Asked to judge the performance of the hall under the term "sonority," they gave the hall a better rating for the third section of the concert than the first, indicating perhaps that they confirm the expert's desire for more sonority for Tschaikowsky. No echoes were reported except a few that were traceable to orchestral difficulties rather than to the hall. About 80 of this group had had experience in other known halls, and most of them rated this hall as equal or better. Analysis of seating preferences showed nothing significant.

Of the general audience, 884 returned questionnaires. Although the questionnaires were intended to be simple, it was evident from the small fraction returned and the answers on those received that it was too complicated. However, the following items were gleaned. About 30% made comparisons with other halls, almost all favorable. About 80% approved the solo violin performance. About 30% were aware of noise, but mainly it was audience noise they reported. About 25% reported poor orchestral balance, usually adding that the brass was too loud. Most of these reported an improvement when the orchestra was rearranged with better grouping of strings relative to brass.

In summary, the test concert was very valuable as an opportunity for the designers and the special observers to study the hall during an actual concert. As was anticipated, the general audience was of value chiefly as one of the essential ingredients of a concert and of a concert hall design: they provided the atmosphere of a concert, enjoyed the music, and absorbed sound. The semiqualified group gave opinions that correlated well with those of the special observers, and they provided useful, if negative, information about seating preferences.

Except for the special observers, the questionnaires gave disappointing results. Many of the questions were misunderstood or evoked answers that were interesting but difficult to classify. Perhaps the main thing learned was how to design questionnaires. The first principle, elementary perhaps, is that each question should have a small number of possible answers.

SUBJECTIVE *VS* OBJECTIVE OBSERVATIONS

It may be interesting, finally, to compare the subjective and objective observations. Generally there was a close correspondence between the two. The observers' low opinion of the orchestra shell, for example, is confirmed by laboratory tests and more directly by the hall reverberation measurements, which showed that with the shell present the stage area was appreciably deader at low frequencies than the remainder of the hall.

The subjective impressions of reverberation were influenced by the local deadness at the stage, but the consensus of the observers was that the reverberation time was slightly below the optimum for large-scale music. This agrees with the various reverberation time criteria. The comments about lack of low-frequency power are influenced particularly by the stage condition, but they also agree with the fact that the low-frequency reverberation time is lower than the mid-frequency value, rather than higher as is recommended.

The rather indefinite seating preferences correspond to the very minor differences observed objectively. No significant differences were observed in reverberation time, diffusion or intensity levels (up to 4000 cps). Pulse tests indicate minor differences in the pulse train received at various positions, and these might correspond to slight differences in quality observed subjectively, but no positions were notably bad. Perhaps the most significant subjective difference was between the middle and rear seats on the ground floor. One of the observers who noticed the difference (Beranek) suggested that it was due to a loss of high-frequency sound because of the grazing angle of incidence at which direct sound reached the rear seats. The sound level measurements made with the microphone level with the chair backs indicated that there might be a loss of 5 db at 4000 cps. This seems hardly significant, but the effect might be larger at higher frequencies.

Although both subjective and objective tests indicated that reception was good throughout the hall, there were marked differences that the listener could perceive which did not show up in any of the data. In the middle of the ground floor area, for example, one was strongly aware of being in a large hall, presumably because of recognizable reflections from various surfaces. In striking contrast was the rear of the top balcony, where the sound had brilliance and an incisive quality of attack that would please the "hi-fi" enthusiast, but much less large-hall effect. The difference between the two may be found in a study of the shape of individual transients. Unfortunately, the transient tests made during this project were in search of delayed echoes and other major defects and were not suitable for a study of the initial arrivals. The computed responses shown in Fig. 2 illustrate the differences that might be expected.

Both types of sounds are interesting, but for symphonic music most of the observers evidently preferred the large-hall sound. It was disconcerting to find that the preferred areas are the ones which the designers expected to be least satisfactory, because of the relatively wide spacing of major reflections. Evidently, for symphonic music at least, one can go too far in the direction of a smooth, uncomplicated transient characteristic.

INSTRUMENTATION

The instrumentation was not unusual, but the details are noted here. The laboratory measurements, employing the impedance tube and reverberation chamber, were done in the Ottawa laboratories of the National Research Council. In general the laboratory techniques followed established practice on this continent. Reverberation work in the hall was done with a white noise source passed through a band-pass amplifier and power amplifier to one or two portable speaker units placed on the stage. The receiving system consisted of a dynamic microphone fed through a selective analyzer (Brüel and Kjaer Type 2105) to a high speed level recorder (B and K Type 2304). Up to six microphone locations were used in the hall (Fig. 1) plus a stage position for measurements in the completed hall. Ten decays per frequency per position were standard and most of the records were read independently by the same three observers. For the test concert two sets of equipment were used to speed up the operation.

For pulse tests, a starting pistol was used as a source, and the pickup system consisted of a cardioid microphone whose output appeared on a cathode-ray oscillograph with a triggered sweep. For simplicity, triggering was done by the first arrival at the pickup microphone. This spoils the beginning of the trace but does not interfere unduly with later arrivals. The oscillograph screen was photographed using an ordinary camera with a portrait attachment.

Diffusion experiments were done with 400 msec bursts of white noise. This is too long for echo studies but was considered a reasonable simulation of the transient sounds of speech and music. It was then possible to use the high speed level recorder as an indicating instrument. An array of 4 cardioid microphones was devised to increase the directionality of the system at 2000 cps. The calculated sensitivity of the array was 10 db below the axial value at 30° from the axis of the array with minor lobes below 15 db.

CONCLUSIONS

In summary, it appears that the auditorium performs most satisfactorily for concert purposes and for speech. For concert purposes the reverberation time is slightly below the textbook optimum but it is well within the range of small differences relating to personal taste and the nature of the music. The major deviation from design was an excess of low-frequency absorption, which appears to be due principally to an unexpectedly large absorption in the ceiling panels.

The objective tests showed uniformly good reception throughout the hall, and these results were in general borne out by the subjective impressions of a team of observers. There were marked differences in the subjective impressions received at various points, which appear to be related to the transient response. For symphonic music there was a preference for areas at which the shape of individual transients was recognizably modified by the hall.

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