Acoustical design of the opera house of the New National Theatre, Tokyo, Japan[a)]

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Architect Takahiko Yanagisawa's preface explains his approach to the design. The NNT opera house seats 1810, its volume is 14 500 m^3, and its reverberation time, with audience, is 1.5 s (proscenium curtain open). Measurements on CAD computer and 1:10 wooden models and full-sized materials samples were conducted over a 7-yr. period. The main floor is almost rectangular, the three balconies have modest fan shape in plan, although the balcony facia at each level create a rectangular shape. The unique design has a large curved reflector in front of and above the proscenium and six curved reflecting surfaces at the front ends of the three side balconies to form, in combination, an ''acoustic trumpet.'' These surfaces, along with the balcony faces and the shaped ceiling, distribute the singers' voices uniformly over the seating areas from a large portion of the large stage at sound levels that easily override the orchestra in the pit. [S0001-4966(00)00201-0]

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ARCHITECT'S PREFACE: TAKAHIKO YANAGISAWA, TAK ARCHITECTS, TOKYO

The theater or hall is a place where one is able to experience directly the power of humanity. The live sensory information that is physically transmitted by the people on stage is also perceived physically by the members of the audience. The theater is therefore a place where there is direct, ''heart to heart'' communication among people.

The theater space facilitates the exchange of energy through a multi-faceted network. It goes without saying that this network includes the exchange between those on the stage and the audience. There is also, however, an extremely powerful force which results in the unconscious bonding between the members of the audience as they coexist in space and time. The excitement of the theater is to be found in those moments in which the performers on stage and the audience become a single, unified entity. This mutual exchange of energy and innervation of the five senses creates a place of great intensity. It is therefore necessary, when designing theaters and halls, to create spaces that heighten the whole range of human senses. Of course, in this respect sound is second to none in its importance.

The design of the hall itself must be based upon principles that intensify the exchange of energies described above. We felt that the best way to achieve this was to have the people in the audience positioned so that they surround the stage as much as possible. In particular it was felt that the role of the balconies, both in reflecting the sound and encouraging empathy amongst the members of the audience as they face each other across the hall, was very important.

In the opera house of the New National Theater, multiple balconies are wrapped around the hall on the three sides, while in plan the overlaying of a fan-shaped main floor by a rectangular balcony geometry has resulted in a new kind of opera house. With a quite different approach, the concert hall of the Tokyo Opera City, adjacent to this hall, combines a rectangular plan form for the seating spaces with a dramatic pyramidal ceiling section, which represents a new departure for its genre of performance space.

The architectural team visited many of the world's great halls with the acoustical design team to listen and take measurements, overlaying the latest scientific data with the sensual evaluation made possible by actually listening to the halls' acoustics. I believe that the design of these two halls shows that in order to create original theater spaces it is absolutely vital that the organization of the design team should allow a more organic relationship among the specialist fields.

INTRODUCTION

An international architectural competition was announced in 1985 by the (National) Agency for Cultural Affairs and the Japan Arts Council for the design of the overall New National Theater (NNT) Project which embodies an opera house, a medium-sized (drama) theater, a small (experimental) theater, a sunken garden, and associated spaces for rehearsals, dressing rooms, workshops, training rooms, reading and documents rooms, offices, and a large multilevel garage underneath.

TAK Architects of Tokyo with Takahiko Yanagisawa, president, and architect in charge, won the competition. The characteristics specified before the competition that would bear on the acoustics of the opera house were (1) approximately 1800 seats; (2) adequate visibility of performers' movements and expressions from all seats; (3) to be used

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TABLE I. Acoustical characteristics judged to be important for the design of an opera house in the Italian style (Hidaka *et al.*, 2000a).

(A) Reverberation time RT: Room reverberation gives fullness and singing tone to the music, but must not be so great as to destroy voice intelligibility. In the best opera houses the RT's at mid-frequencies range from 1.3 to 1.6 s. A reverberation time of 1.5 s was the design goal for the NNT opera house. This requires the proper cubic volume in relation to the areas covered by the audience, the top of the pit and the proscenium opening.

(B) Early Decay Time EDT: EDT affects principally the hall's support to the voice and adds definition to the higher tones of the music. If EDT is too high, it reduces the intelligibility of the voice. The magnitude of EDT measured in unoccupied opera houses is usually about 0.1 to 0.2 s higher than RT measured occupied, with the proscenium open. To achieve this result, a satisfactory combination of RT and of surfaces for reflecting early sound to all seats is necessary. A goal of 1.7 s was chosen.

(C) Bass Strength BR: BR, the bass ratio, is a measure of the support the reverberation in the hall gives to the low notes of the music. Many factors, including surface materials and chair design, contribute to BR. Its value should be greater than 1.0.

(D) Intimacy: The music should sound as if heard in a small hall—the listener should feel in intimate contact with the performers. The arrival time of the first reflections after the direct sound must be short, i.e., should be less than 25 ms in an opera house.

(E) Spaciousness: The sound at listeners' seats should include a sizable number of early reflections that arrive from near lateral directions. This is saying that the source of the music should sound broadened. In good concert halls, its measure, $[1-\mathrm{IACC}_{E3}]$, should exceed 0.6. The same criterion was assumed for an opera house.

(F) Diffusion: Every successful hall for music has irregularities, both large and small, on the walls, balcony facia, and ceiling to give the sound a rich patina. The usual measure of adequate diffusion is by observation of the irregularities.

(G) Strength: The strength of the sound, which is related to loudness, is a quantity that must be as uniform as possible throughout the house. It is related to the ratio of the volume of the hall in m^3 divided by the early decay time EDT in s. Early decay time depends on whether the proscenium is open or closed.

(H) Reflecting surfaces: Special reflecting surfaces above the proscenium and at the six fronts of the side balconies were to be specially designed to enhance the strength of the singers' voices in the audience seating areas.

(I) ST1, a measure of the strength of orchestral sound returned by nearby reflecting surfaces to the ears of each player in the orchestra pit: This measure is technical and is described in the companion paper (Hidaka *et al.*, 2000a).

(J) Quiet: The hall must be quiet, both in regard to external and to internal noise and vibration sources. A goal of NCB less than 18 dB was chosen.

(K) Echoes: The room and stage must be free from echoes.

primarily for presentation of opera and ballet in the manner of an Italian opera house; (4) reverberation time in the range of 1.4 to 1.6 s with full occupancy; and (5) orchestra pit to accommodate up to about 120 musicians. In the competition the architect chose a moderate fan-shaped plan for the main floor and three balconies, each rectangular in plan. The architect's desire was to minimize the distance between the front of the stage and the most remote listener while maintaining adequate visibility from all seats. Also, he wished to line the interior of the hall with richly colored wood. Masuda was acoustical consultant during the competition stage.

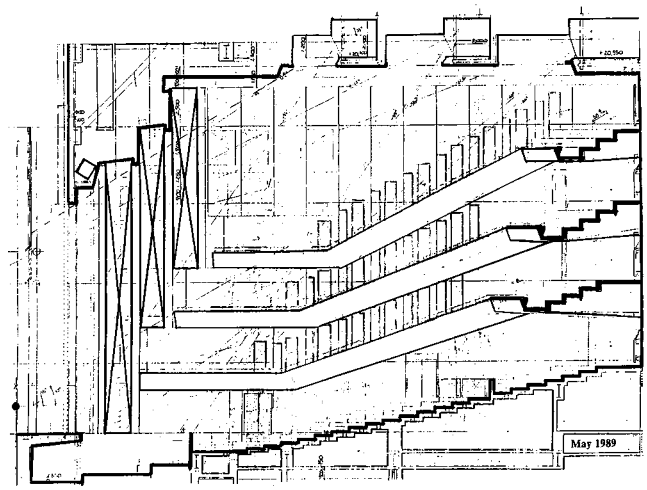


FIG. 1. Architect's suggested design that was presented to the acoustical design consultant in May 1989.

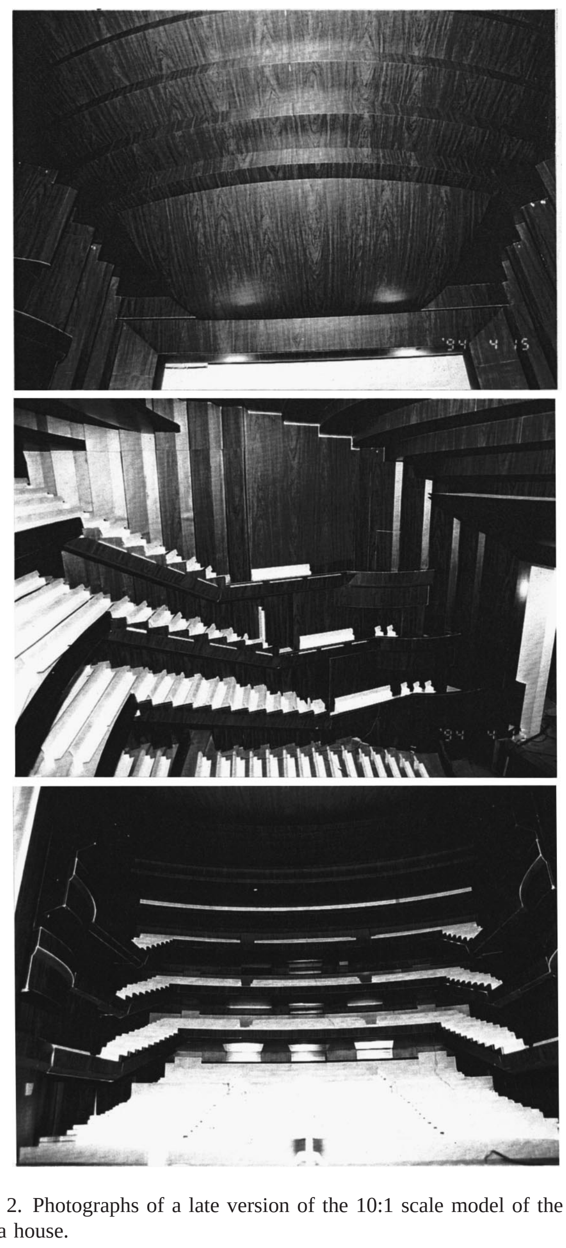


FIG. 2. Photographs of a late version of the 10:1 scale model of the NNT opera house.

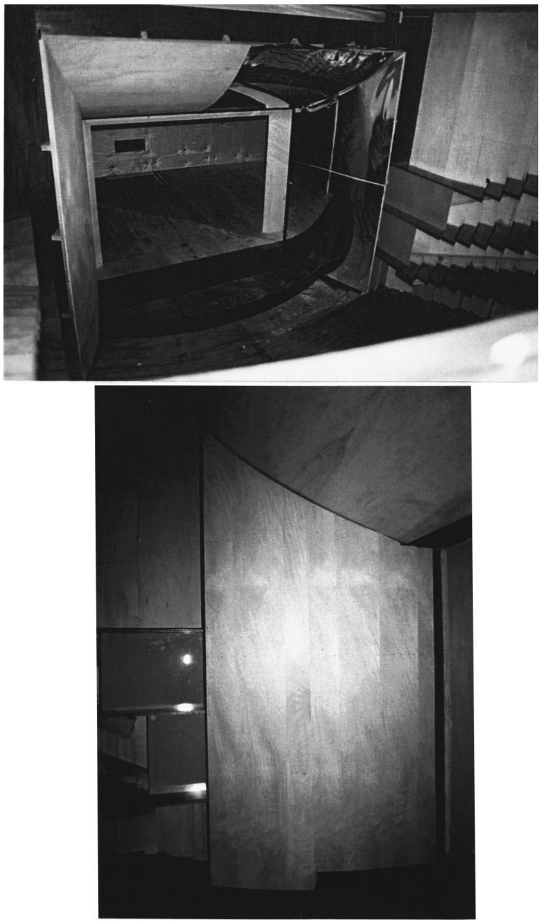


FIG. 3. Early study of the efficacy of an ''acoustical trumpet'' on the three sides of the proscenium.

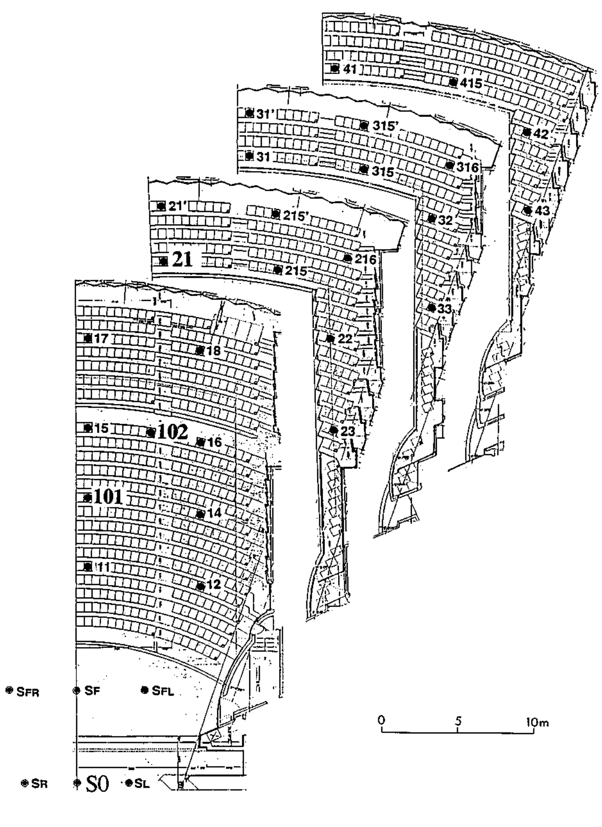


FIG. 4. Source and receiver positions used by Takenaka R & D Institute for the acoustical measurements in the models and the completed opera house.

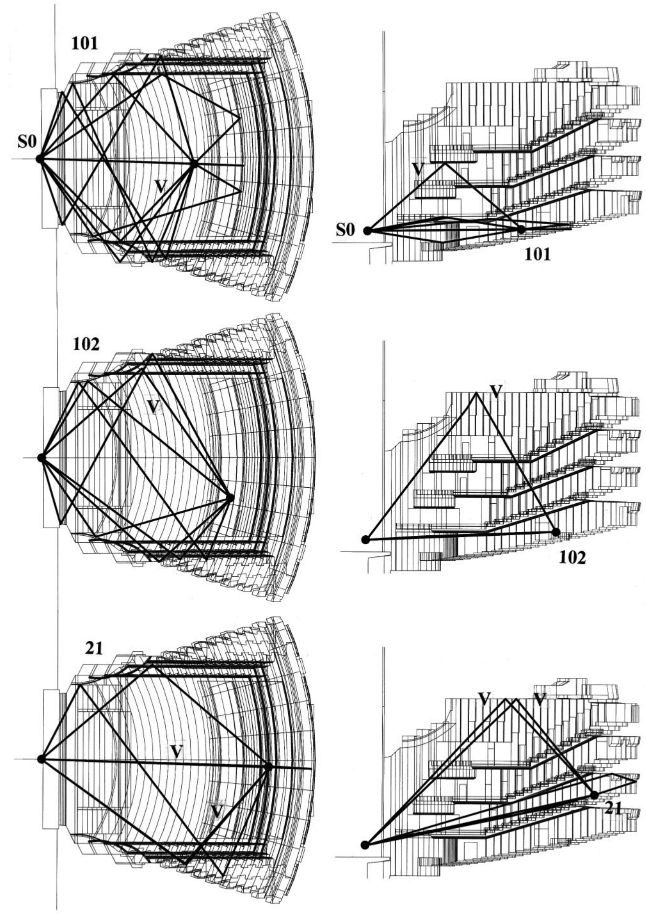


FIG. 5. Drawings showing early reflections obtained in an early computer CAD model of the NNT opera house. The source is at S_0 and the rays to audience seats 101, 102, and 21 are shown. All reflections are lateral except those marked ''V'' for vertical, directly in front and directly from rear.

On receiving the commission of Acoustical Design Consultant for the NNT in April 1989, Beranek reviewed in depth the researches carried out on the acoustics of halls for music by groups in Germany, England, Denmark, New Zealand, Canada, Japan, and USA (Beranek, 1992). Simultaneously, a systematic endeavor was made to bring to a close the assembling of drawings, photographs, and details on materials obtained from architects and the acoustical data measured by acoustical engineers worldwide for 12 opera houses in Salzburg, Vienna, Milan, Paris, New York, Philadelphia, San Francisco, Washington, DC, Buenos Aires, London, Bayreuth, and Tokyo. The architect's technical staff under the direction of Hidaka made new acoustical measurements in 14 European opera houses and theaters for music: Vienna, Milan, Paris, Dresden, Hamburg, Berlin, Amsterdam, Budapest, Prague, and Essen. The results of those efforts were published in Beranek (1996) and in a companion paper in this issue (Hidaka *et al.*, 2000a).

I. BASIC ACOUSTICAL PARAMETERS AND MEASUREMENTS

A list of the acoustical parameters that came from the concert hall studies and that were assumed also to be important in combination for aiding in the successful design of the acoustical environment for Italian opera is compiled in Table

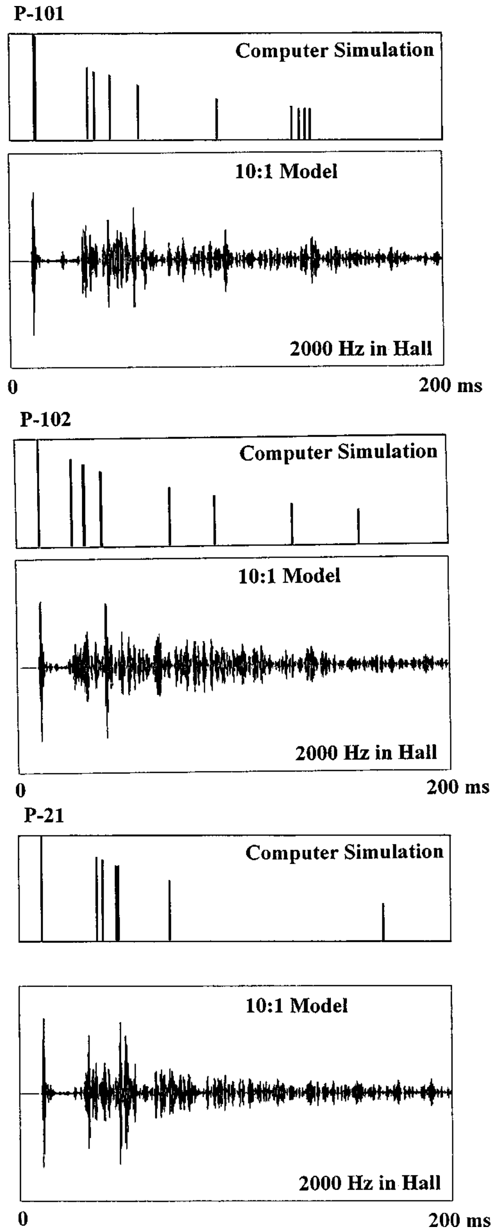


FIG. 6. Comparison of reflectograms at three seat positions obtained in computer CAD model with those obtained in 10:1 wooden model of the NNT opera house. Data from 1993.

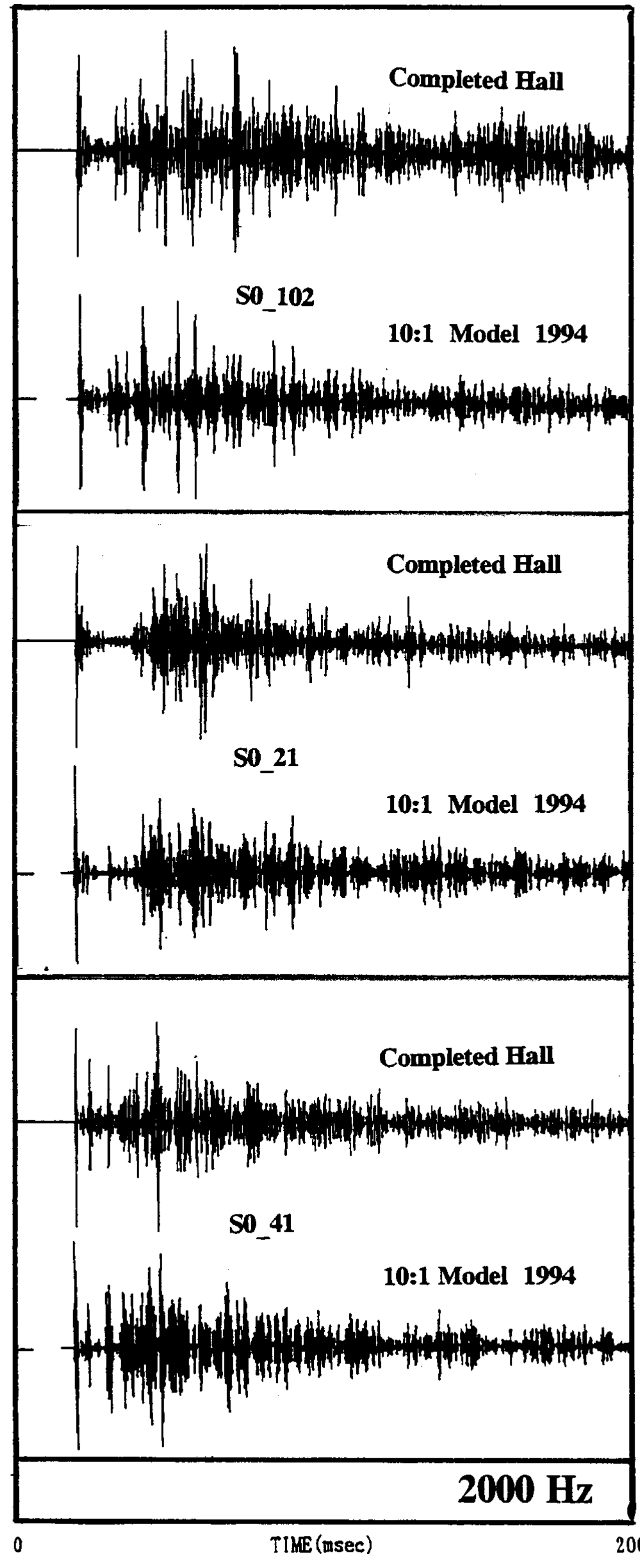


FIG. 7. Comparison of reflectograms measured in 10:1 model (1994) and those measured in the completed (NNT) opera house (1997), both for occupied condition.

I. The definitions of these quantities are given in the companion paper (2000a) in this issue of JASA on the design of the TOC Concert hall, which is located on a contiguous site in Tokyo (Hidaka *et al.*, 2000b). The second companion paper presents recent research on the subjective ratings and objective measurements for 23 opera houses and their correlations and shows that items A–G in Table I are orthogonal to each other except for EDT which is highly correlated with RT. Procedures and precautions for the measurement of these quantities are given in Hidaka *et al.* (1995), Okano *et al.* (1998), and Hidaka *et al.* (1998).

From the outset, the acoustical design consultant emphasized that the most critical problem in almost all opera houses is the difficulty the singers have in attempting to override the music of a 60-piece, or larger, orchestra. The solution to this problem became a major part of the architect/consultant cooperation.

Shown in Fig. 1 is the drawing of the NNT opera house that was presented to the acoustical design consultant at the outset. This design concept greatly resembles the NNT as constructed—in gross shape and dimensions, including three balconies that have front arms that slope downward. But, satisfactory acoustical reinforcement of the singer's voices

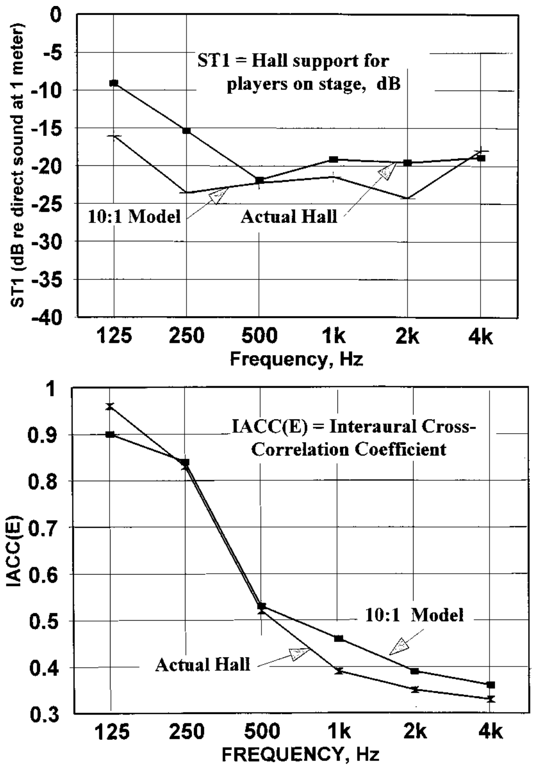


FIG. 8. Comparison of ST1 (average on stage) and $IACC_E$ (average in audience areas) as measured in 10:1 model and the completed NNT opera house.

was inhibited by three lighting bridges in the ceiling and three large lighting coves on either side of the front of the hall and by a loudspeaker bridge above the proscenium. The reverberation time of 1.2 s for this design was too low. Also, sound diffusion was only shown on the balcony faces.

The first acoustical recommendation was a new architectural concept in opera house design, namely, that the six ends of the sidewall balconies nearest the proscenium and the space immediately above the proscenium should, together, resemble the bell of a brass wind instrument, for example a trumpet or French horn. These constructions, if properly shaped, will amplify the voices of the singers without amplifying the orchestral music. The result will be less strain on the voices and will reduce the feeling by the pit orchestra that its music must continually be restrained.

II. THE RESEARCH AND DEVELOPMENT PHASE

A. CAD and 10:1 models

The architect's technical staff, under the direction of Hidaka, constructed a computer CAD model and a 10:1 wooden model. The first tasks were to confirm and to correct the acoustical deficiencies of the original design and to investigate and refine the proposed concept of an acoustic horn structure around the proscenium. The 10:1 model, actually photographed at a later stage, is shown in Fig. 2. An early construction of the horn concept is shown in Fig. 3. Although the arrangement of Fig. 3 tested well acoustically, it was obviously not an acceptable architectural solution.

Figure 4 delineates the source and audience positions that were used for measurements in both models. Very little difference among the results measured at the audience positions were found for the four source positions on stage or the three in the pit. Twenty-seven audience positions were selected in this symmetrical hall.

As Fig. 5 shows, the CAD computer model was used to trace the number and directions of the early reflections and to determine the length of the initial-time-delay gap. On this figure are shown the positions that are primarily used as illustrations in this paper, namely, S_0, the source location, and 101, 102, and 21 (first balcony), audience positions. All reflections shown occur within 150 ms and arrive at the listener's position from lateral directions, except for those marked ''V,'' meaning, arriving from the overhead, directly forward, or directly backward direction.

Typical comparisons of the results from the computer and 10:1 models are illustrated in Fig. 6. The computer data of that era gave both the time of arrival and the angle of each reflected wave, but not much detail. The levels of the components were often greatly different from those of the 10:1 model. The wooden model gives detail, out to 200 ms and beyond, including all reflections generated as a result of dispersion from irregular surfaces.

With the 10:1 model, the measurements could determine the acoustical coverage pattern from the various reflecting surfaces, the spaciousness measure $[1-IACC_{E3}]$; the strength of the sound throughout the hall G; the initial-time-delay gap ITDG; and any echoes.

To show how the data from the 10:1 model relate to

TABLE II. Calculated reverberation times with proscenium curtain open, highly absorbent scenery tower, and no stage set. Volume: $V=14\,500\ m^3$; pit area: $S_0=102\ m^2$; audience area with edge correction: $S_A=1153\ m^2$; proscenium area: $S_p=205\ m^2$; and residual wall and ceiling areas, with unoccupied pit area: $S_R=4308\ m^2$. The residual absorption was measured before the seats were installed. The audience absorption was measured at the tuning concert and the proscenium opening was measured with and without a heavy metal fire curtain with the house unoccupied.

	125	250	500	1000	2000	4000
α_R=residual absorption	0.17	0.16	0.13	0.11	0.11	0.10
$A_R=4308\times\alpha_R$, includes pit	732	689	560	474	474	431
α_A for S_A, occupied,	0.39	0.44	0.60	0.62	0.65	0.54
$A_T=1153\times\alpha_A$, occupied w/o pit	450	507	692	715	738	623
A_R+A_T m^2	1182	1197	1252	1189	1212	1053
Proscenium absorption (approximate)	220	302	302	302	302	378
A_{total}=total absorption	1402	1499	1554	1491	1514	1391
4 mV	0	16	41	76	138	349
RT=0.161*14 500/(A_{total}+4 mV)	1.67	1.54	1.46	1.49	1.41	1.34
Measured RT, occupied, 2/15/97	1.62	1.59	1.49	1.49	1.42	1.32

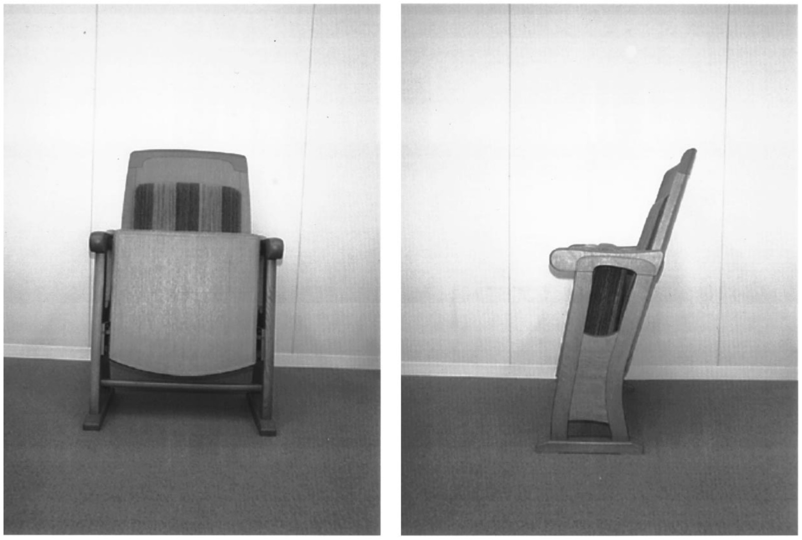
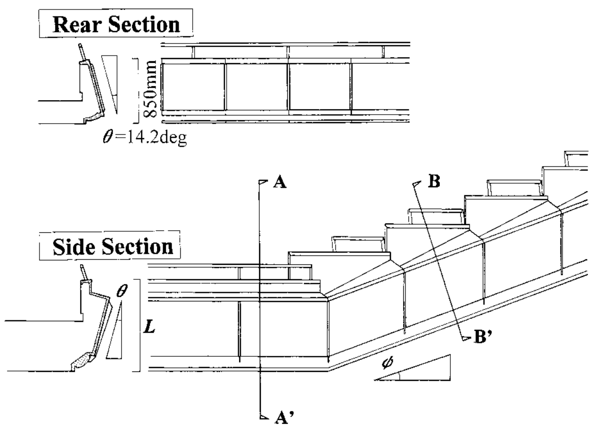


FIG. 9. Photograph of audience seat in the NNT opera house.



	ϕ (deg)	L (mm)	θ (deg)	
			A-A'	B-B'
1st Balcony	17.6	1209	8.5	8.9
2nd Balcony	20.8	1212	15.0	15.9
3rd Balcony	26.2	1163	21.0	23.0

FIG. 10. Details of the three balcony faces, shaped to provide early reflections at all parts of the house and to eliminate possibility of echo from the rear section.

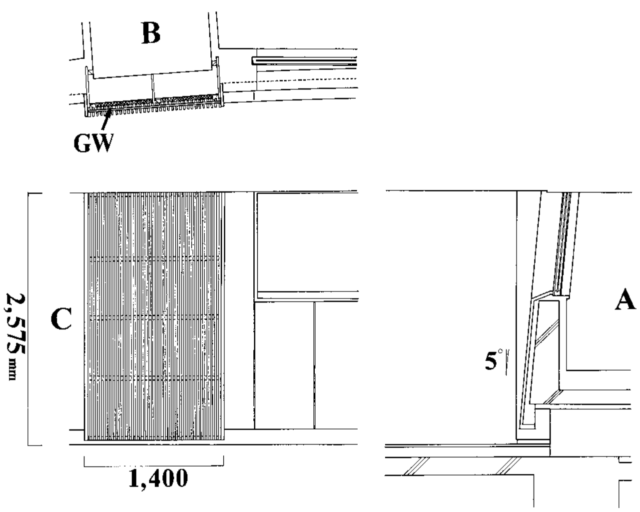


FIG. 11. Design of the curved (in plan) rear walls. The slope is indicated by A. The sound absorbing portion of the rear wall is shown by B and C. The same treatment as C was used under the soffit of the first balcony and at the rear of the ceiling.

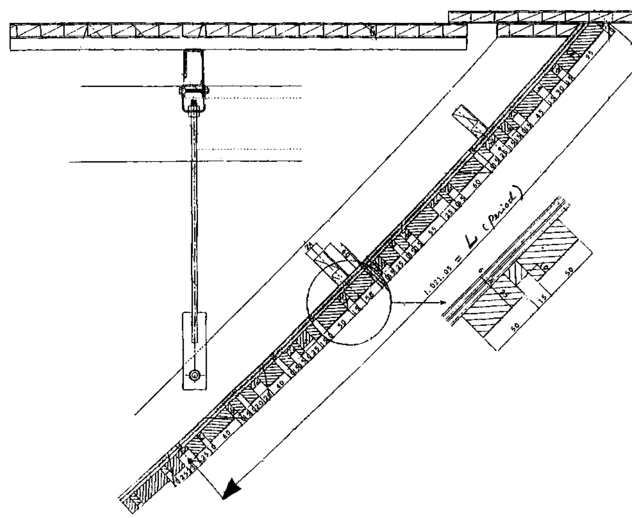


FIG. 12. Detail drawing of the fine-scale diffusion on the sound reflector above the proscenium and the front ends of side-wall balconies.

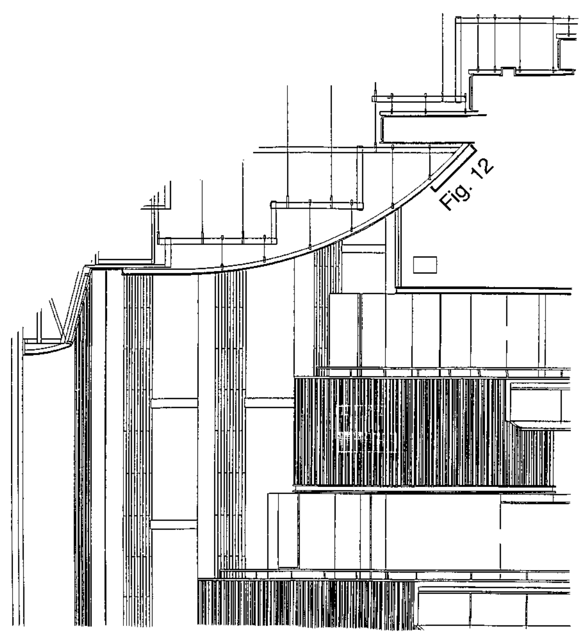


FIG. 13. Drawing showing the shape of the over-proscenium sound reflector. The location of the fine-scale diffusion on the proscenium reflector and the balcony fronts is also indicated.

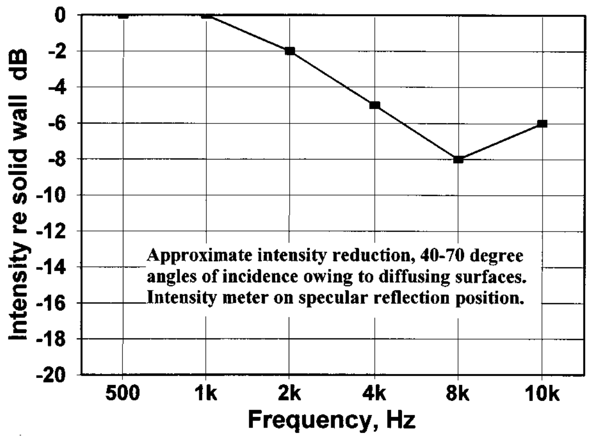


FIG. 14. Approximate intensity reduction in a range of 40- to 70-degree angles of incidence of a sound wave on a sound-diffusing surface like that shown in Fig. 12. The surface was flat during the measurement and the intensity meter was at the optical angle of reflection of the incident wave.

those measured in the actual hall, Fig. 7 presents comparisons of reflectograms measured at 2000 Hz, the approximate center of the spectrum of the singing voice, in the completed hall and in the 10:1 model. The source position was S_0 and the audience positions were seats 102, 21, and 41, i.e., main floor and first and third balconies. Although the reflectograms are not exactly alike, the general nature of the patterns are the same. Desired are a uniformly spaced set of reflections along the time axis, with considerable energy in the first 50 to 80 ms.

In Fig. 8, two of the most important measures of acoustical quality ST1 (on stage) and IACC_E (in audience) are seen to be well predicted from the 10:1 model. We had our least success in determining the reverberation time from the 10:1 model measurements, mostly because of that date, we did not know how to simulate the audience seats that would eventually be used in the hall. Consequently, we relied on calculations like those described in Beranek (1996) and Beranek and Hidaka (1998).

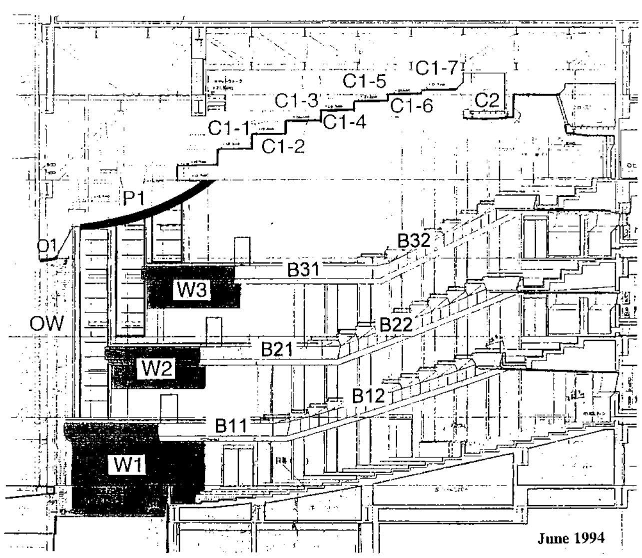


FIG. 15. Reflecting surfaces O1, OW, P1, W1, W2, W3, B11, B12, B21, B22, B31, B32, C1 group, and C2, all designed and adjusted to distribute the sound of orchestra and on-stage singers uniformly to the audience areas.

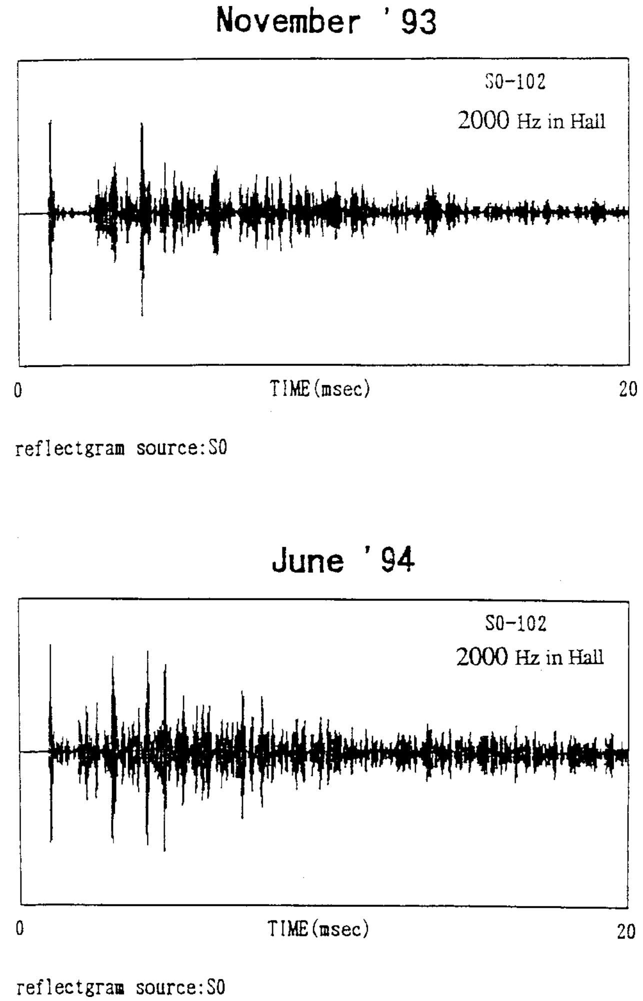


FIG. 16. Reflectograms showing the improvement achieved in the 10:1 model between November 1993 and June 1994 as a result of adjustments in the reflecting surfaces shown in Fig. 15. The source was at S_0 and the receiver at audience seat 102.

B. Seats

The acoustical characteristics of the seats as a function of frequency must be planned along with those of the sidewall and ceiling surfaces. The house has a wooden interior, which absorbs low-frequency sound more than it does the high-frequency sound (see Table II, first line). In order to avoid a deficiency in the strength of the bass and a short reverberation time at low frequencies, the choice of seats becomes very important. When the audience enters the house it adds absorption to that of the empty seats mainly at high frequencies. The absorption at low frequencies is heavily dependent on the thickness of the cushions over which the audience sits. An extensive series of tests of the sound absorption of different chairs, occupied and unoccupied, was made in the reverberation chamber and was preliminarily reported in Hidaka *et al.* (1996). The chair selected, similar to those in Vienna's Grosser Musikvereinssaal, is shown in Fig. 9. The thickness of the seat cushion is 6 cm and 65% of the front of the back rest is covered with a cushion 2 cm in thickness. Thus the sound absorption coefficient by the seated audience in this house at 125 Hz is only about 40% (see third line of Table II) compared to about 70% for an

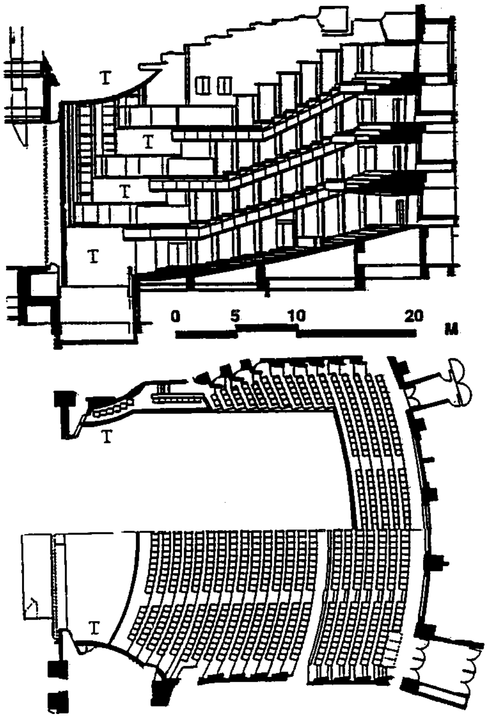


FIG. 17. The NNT opera house as built. (Upper) Longitudinal section drawing. (Lower) Plan drawings of main floor and first balcony. The ''T'''s show the trumpet reflecting surfaces.

occupied seat with thick upholstering. The absorption at higher frequencies is less than that of samples tested in the reverberation chamber because the upholstery cloth of those installed was apparently back-sprayed (Beranek and Hidaka, 1998).

C. Sound-reflecting and -absorbing surfaces

To achieve adequate lateral sound-reflected energy over the entire seating area, the balcony fronts had to be individu-

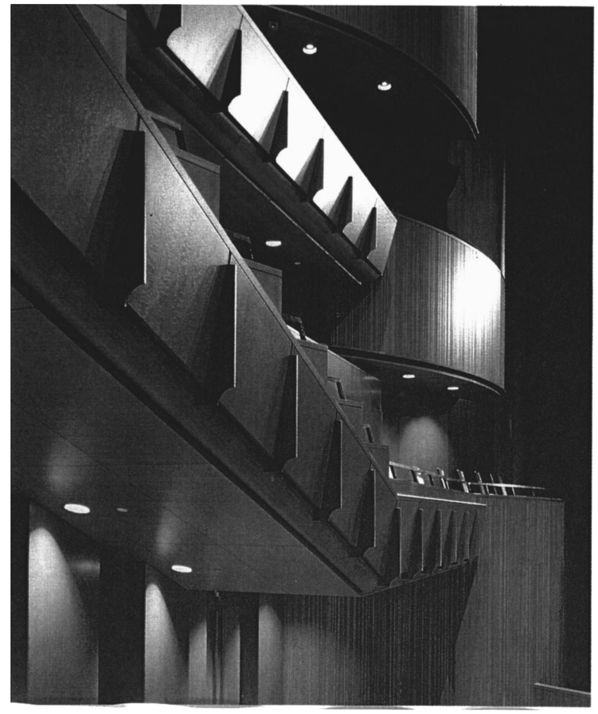


FIG. 18. Photograph showing the three reflecting surfaces W1, W2, and W3 in the completed NNT opera house. The large scale diffusing elements on the fronts of the balconies are also seen.

ally shaped. In Fig. 10 the details for the three different parts of the three balconies are shown, the rear part being the same at all levels and shaped to eliminate the possibility of echo.

Also to prevent echo, all of the back walls of the house were tilted backwards 5 degrees [see Fig. 11(A)], except for six vertical structural columns at each level, so as to throw the sound incident from the stage to the underside of the

FIG. 19. Photograph of the NNT opera house taken from the rear of the hall looking toward the proscenium. (Photo by Murai, Tokyo.)

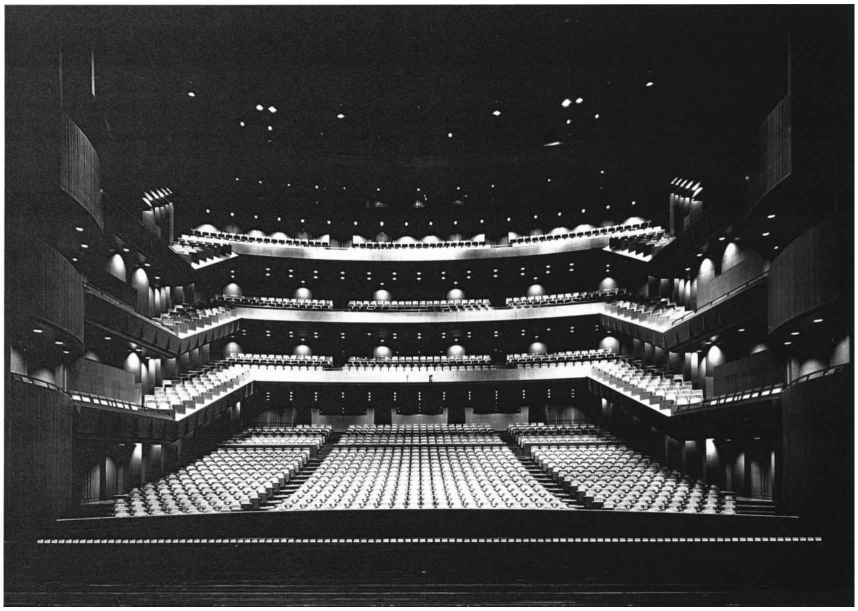


FIG. 20. Photograph of the NNT opera house taken from the stage looking toward the rear of the hall. (Photo by Murai, Tokyo.)

balconies and the rear part of the ceiling and not directly back to the stage. The total area of the back wall on the main floor (most critical acoustically) is 84 m^2. Of this 65% is reflecting, that is, the windows for the booths and the wooden panels beneath, and 35% is sound absorbent. The sound-absorbing portion includes the doors, which have perforated wooden faces, and the columns which are covered with a series of small vertical slats backed by a layer of glass wool (GW) over an airspace as seen in sketches (B) and (C). To absorb the reflections from the lowest and the highest tilted back walls, which were most capable of creating echoes, this same construction was incorporated as follows: (1) the rear 70% of the soffit on the underside of the first balcony with the strips running parallel to the front/rear axis of the hall and made removable so that the amount of sound-absorbing material could be varied to send more or less reflected sound back to the stage, and (2) a sound-absorbing area 1.2 m wide running the full spread of the rear of the ceiling.

Parenthetically, by trial and error after construction, with baritone and soprano singers at various positions on stage, adjustment in the amount of sound absorption by these surfaces was made until the singers expressed approval of the hall support to their voices.

Experience in halls with smooth reflecting surfaces has shown the value of small-scale irregularities, which serve to scatter the reflected sound and give it a warm ''patina.'' This type of irregularity had both to be effective acoustically and to satisfy the architect's desire to avoid visual ''disturbance.'' Extensive research was undertaken to find a solution to satisfy both needs. The result is shown in Fig. 12. This fine-scale sound diffusion (small irregularities) was added to the sound reflector over the proscenium and to the curved surfaces at the fronts of the side balconies (Fig. 13). The width of the dips are 10, 15, 20, 23.6, 25, 30, 40, 45, 50, 55, and 60 mm, and are distributed randomly. Each wooden slat is firmly glued to wooden boards, 25 mm thick. The whole period L is 1021.05 mm, which number was selected as non-integer. The pattern was repeated alternately, making the acoustical period $2L$. The laboratory program that designed these irregularities yielded the approximate reduction in specular reflection shown in Fig. 14.

D. Orchestra pit

The orchestra pit is conventional in shape, except it is normally set up for 60 to 80 musicians. The back wall is removable so that, under the stage, the size is expandable to accommodate 120 musicians. The dividing back wall, when in place, is made of individual reversible panels, one side of which is hard, the other sound absorbent.

III. THE COMPLETED OPERA HOUSE

By June 1994, the acoustical design was near complete (see Fig. 15). The ceiling design, C1s, was stepped to make it acoustically more effective, and W1 was extended down into the pit. The curvatures of W1, W2, W3, and P1 (see also Fig. 13) were finalized. The surface O1 at the top edge of the proscenium was shaped to reflect more sound to the players in the pit.

The improvements in the reflectograms, typically like those at seat 102 for 2000 Hz, are shown in Fig. 16. The coverage pattern, as determined in the 10:1 model, showed that the levels within the front two-thirds of the main floor and the centers of the balconies were within ±1.3 dB. Only in the corners beneath the second and third balconies did the levels drop to -5 to -6 dB below that near the front of the main floor, position 11. Elsewhere the levels were within -2.2 and -4 dB of position 11.

The longitudinal section and plan drawings of the NNT opera house as built are shown in Fig. 17. The ''trumpet'' reflectors are indicated by ''T'''s, —the main reflector overhead and the three reflectors on each side at the fronts of the side balconies. A photograph of the balcony reflectors is shown in Fig. 18, and photographs of the finished house are shown in Figs. 19 and 20.

To illustrate that the primary goal of increasing the strength of the singers' voices as heard in the audience was

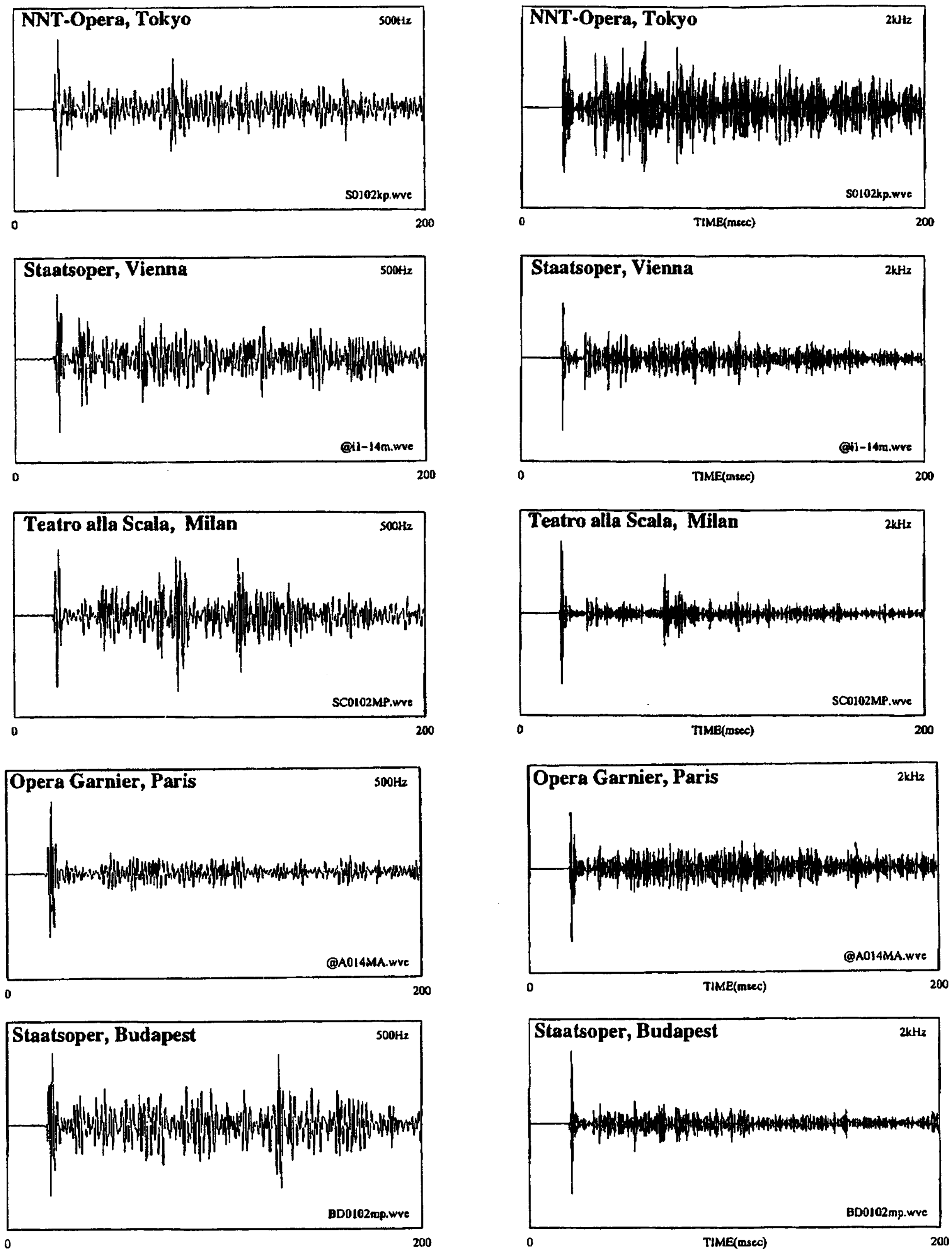


FIG. 21. Comparisons of reflectograms, using the same omnidirectional source on stage at position S_0 and the receiver at audience position 102, for NNT, Vienna, Milan, Paris, and Budapest opera houses. The reflectograms have approximately equal SPLs at 500 Hz, but the SPLs are much greater at 2000 Hz in the NNT opera house than in the others. Note that the center of the intelligibility range of voice frequencies is about 1600 Hz for men and near 2000 Hz for women.

accomplished, comparisons of reflectograms in the audience at seat positions 102 *with the same omnidirectional source at S_0 used in all the halls* are shown in Figs. 21 and 22 where eight well-known opera houses of Europe are represented. The distances of position 102 from the source S_0 are NNT (23 m); Vienna (21 m); Milan (20 m); Garnier (20 m); Budapest (S) (16 m); Berlin (22 m); Dresden (19 m); Amsterdam (22 m); and Budapest (E) (21 m).

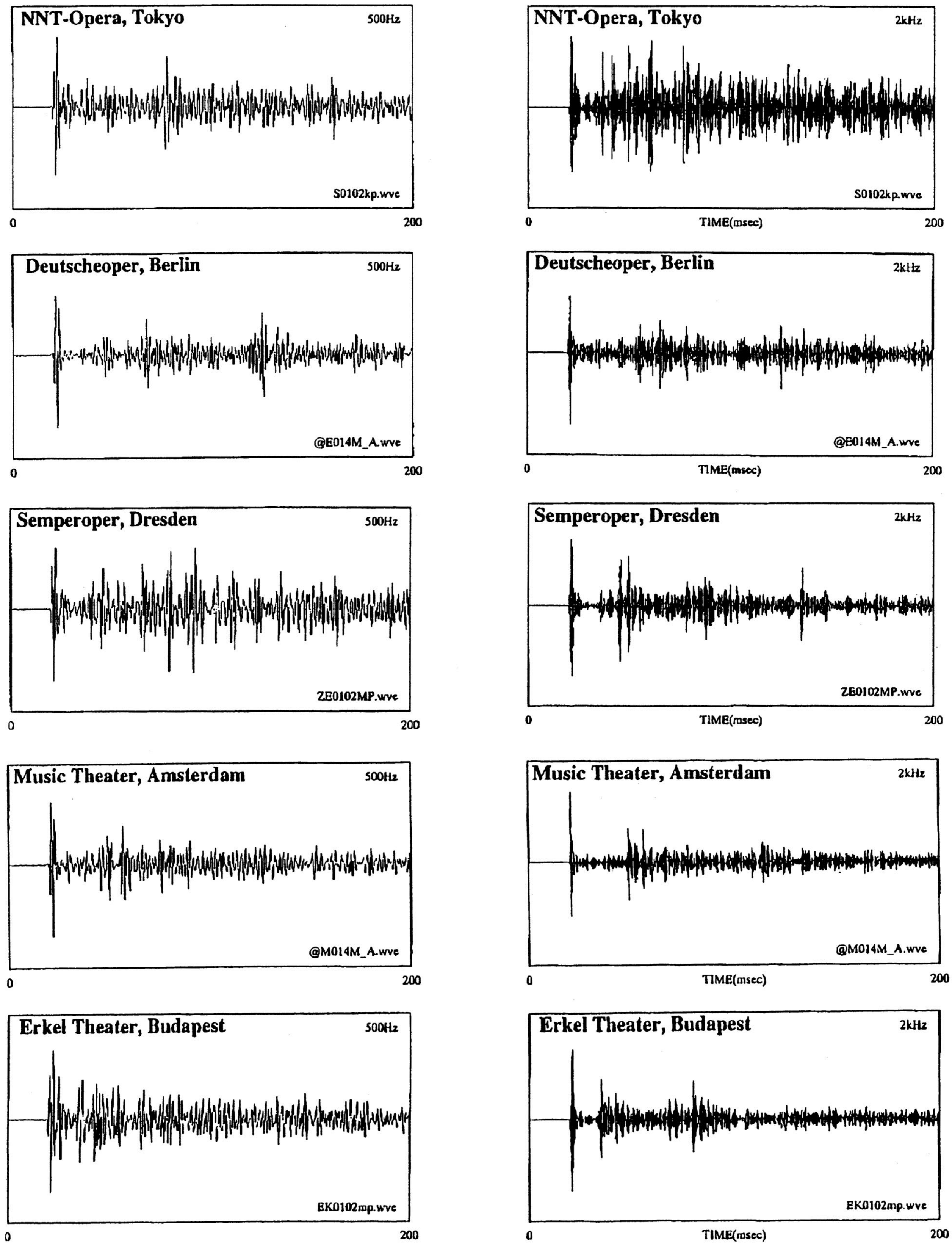


FIG. 22. Same as Fig. 21, except comparison is with NNT, Berlin (Deutscheoper), Dresden, Amsterdam (Music Theater), and Budapest (Erkel).

Reflectograms for the octave band centered on 2000 Hz were chosen as best for this comparison, because it is nearest the center of the frequency range important to the singing voice. It is obvious that the singers voices are substantially augmented in the NNT house.

The reverberation times measured and calculated with audience and open proscenium are shown in Fig. 23 and Table II. Finally, there is no echo and the background noise (NCB-16) with no audience and HVAC in operation is plotted in Fig. 24.

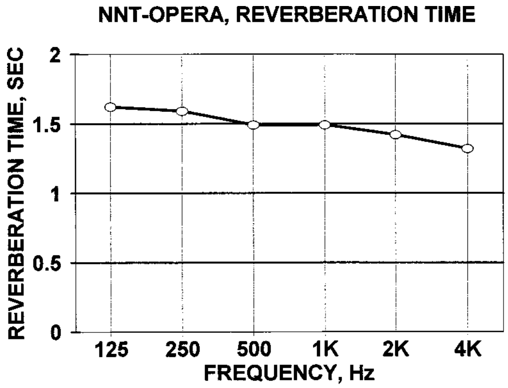


FIG. 23. Reverberation times as a function of frequency for the fully occupied NNT opera house, with orchestra in pit and stage curtain raised and performing set in place on stage.

IV. MEASURED ACOUSTICAL PARAMETERS

The major objective parameters as measured in the finished NNT opera house are listed in Table III. A comparison of these data (which are given first) and those measured in the Buenos Aires Opera Colón, Dresden Semperoper, and Vienna Staatsoper, all world standards (given in parentheses), are $RT_{MID}=1.5$ s (1.4 to 1.6 s); $EDT_{MID}=1.7$ s (1.4 to 1.8 s); ITDG=17 ms (17 to 20 ms); $C_{80}(3)=1.6$ dB (0.8 to 2.7 dB); $[1-IACC_{E3}]=0.65$ (0.60 to 0.72); BR=1.1 (1.2); and $(V/EDT_{MID})\times 10^{-2}=85$ (74 to 119) (see Beranek, 1996, p. 445). Note that RT_{MID} and BR are for the houses when occupied, while all other numbers are for the houses unoccupied. These numbers indicate that the NNT opera house has rich reverberation, clarity, spaciousness, warmth, and strength of sound equal to those in three of the world's highly rated opera houses (see Hidaka and Beranek, 2000a).

V. TUNING CONCERT

The hall was fully completed by January 1997, eight months ahead of its grand opening date, and the tuning concert was held on February 15. The measured reverberation time at mid-frequencies was 1.5 s occupied with orchestra, open stage curtain, and a performance set on stage. Unoccupied it measured 1.8 s. No acoustical problems were detected and no changes were made.

VI. GRAND OPENING AND PROFESSIONAL CRITICISM

The grand opening took place 10 and 11 October 1997. The Emperor and Empress of Japan attended and Prime Minister Ryutaro Hashimoto spoke from the stage, saying that the New National Theater and the adjoining TOC concert hall now make Tokyo a world center for music and ballet. The performance was a success.

Excerpts from reviews and comments for this opera and Bizet's *Carmen* and Wagner's *Lohengrin* that followed were as follows.

Yasutoshi Nakagawa, *Asahi Shimbun* (newspaper), 15 October 1997: ''This house is as grand as any first-rate opera house in the world...Evidence of the excellent acoustics is that one does not feel as if in a strange place even at one's first experience.''

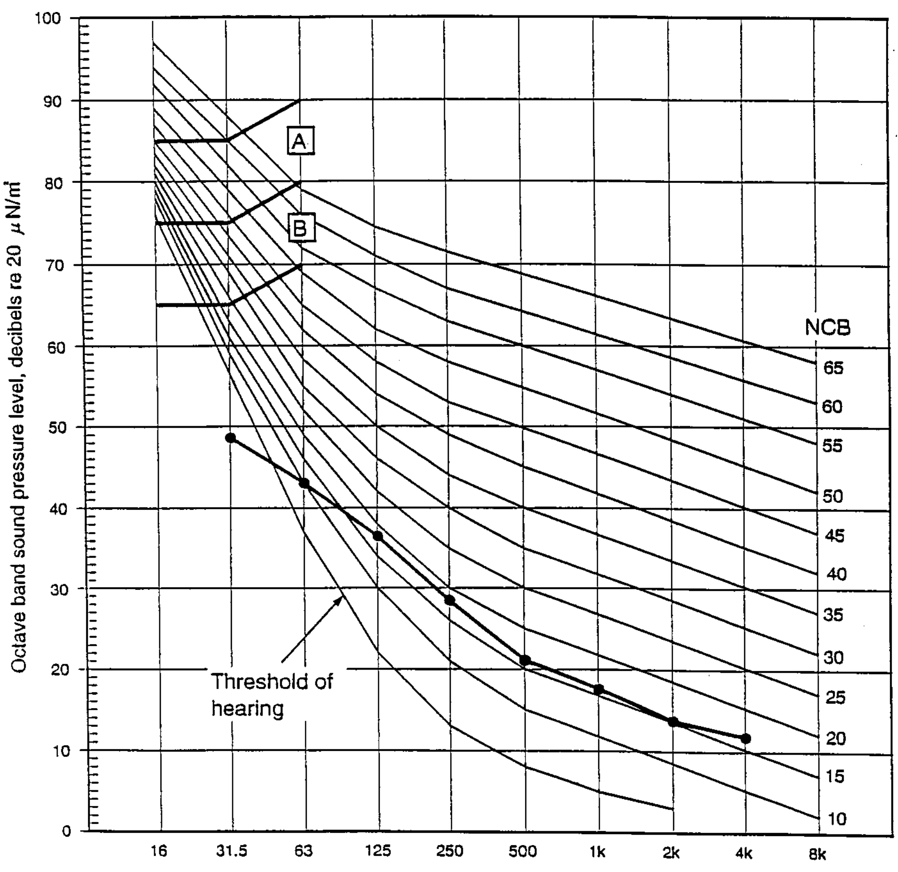


FIG. 24. Average noise level in audience areas of the unoccupied NNT opera house (NCB-16). The HVAC system was in operation.

TABLE III. Measured acoustical parameters for the New National Theater (NNT) opera house (opened 10 October 1997, 1810 seats). The occupied conditions for the IACC's were measured at the tuning concert with full audience, using seven dummy heads fitted with binaural microphones. Four were on the main floor and three in the balconies. The other occupied parameters were measured at the same positions as for the unoccupied measurements with omni-directional microphones. The unoccupied data were taken at 27 audience positions. The data at the various locations were averaged. The source was at position S_0.

	Frequency (Hz)					
	125	250	500	1000	2000	4000
RT, unoccupied	1.65	1.66	1.73	1.85	1.83	1.60
RT, occupied	1.60	1.58	1.48	1.49	1.40	1.31
EDT, unoccupied	1.55	1.59	1.65	1.75	1.73	1.48
EDT, occupied	1.56	1.51	1.38	1.26	1.23	1.09
IACC_A, unoccupied	0.93	0.78	0.29	0.20	0.21	0.24
IACC_A, occupied	0.87	0.78	0.41	0.31	0.27	0.27
IACC_E, unoccupied	0.94	0.82	0.42	0.31	0.31	0.34
IACC_E, occupied	0.90	0.83	0.52	0.39	0.35	0.33
IACC_L, unoccupied	0.92	0.74	0.19	0.13	0.11	0.08
IACC_L, occupied	0.85	0.72	0.22	0.15	0.13	0.10
C_{80} (dB), unoccupied	−0.1	0.9	1.7	1.6	1.4	2.2
C_{80} (dB), occupied	0.90	1.3	2.9	3.7	3.3	3.8
G (dB), unoccupied	−0.4	0.2	1.2	2.2	2.4	−0.3
G (dB), occupied	−0.3	−0.1	−0.1	0.9	0.2	−1.5

Tokihiko Umezu, *Nami* (art magazine), November 1997: ''What surprised me first was the wonderful acoustics of the opera theater...The acoustics are sure to guarantee remarkable joy to listeners.''

Toshiya Inagaki (lead tenor, sang the part of *Takeru*): ''It is very easy to sing in this opera house. The reverberation...is just right. The sound of the large orchestra does not burden the singing at any time even in the loudest passages. I heard that the audience hears the singers easily above the orchestra.''

Ikuma Dan, libretto and composer of the opera, *Takeru*: ''The quality of sound—high tones and low tones—was beautifully balanced. The conductor played full strength. There was no holding back of the orchestra. Yet, every voice and every instrument were clear; everything went together as if one...I have heard operas in many theaters in the world, but this house is my most favorite one...This hall is like a great musical instrument.''

Maestro Gustav Kuhn of Austria wrote, after conducting four performances of *Carmen* in January 1999: ''The National Theatre Opera House is absolutely 'One of the Best' [in the world]. Congratulations on your wonderful work.'' (The only other opera house with this high a rating among the fourteen that Maestro Kuhn ranked was the Teatro di San Carlo in Naples, Italy.)

Other reviews and performers' comments: ''The sound in the pit is excellent. The singing was clearly heard in the pit, even when the orchestra played full strength.'' Another said: ''The acoustics are wonderful. The conductor let the orchestra go full force and the orchestra blended with the singers, not covering their voices.'' Another: ''Perfectly balanced acoustics.'' Another: ''I can say the hall is a success-...The theater gives the voice full reach, while eliminating any masking of the voice by the orchestra. With the Wagner work, the acoustics of this theater reached a high level of perfection.''

VII. CONCLUSION

To summarize, the goal set at the beginning to strengthen the projection of the singers' voices, while preserving the beauty of the music from both the stage and the pit, has been accomplished. The sound is of equal quality and near-equal strength throughout the house. The critical evaluations show that the architectural design of the opera house fully meets the esthetic and sight line requirements desired by the architect. And, highly significant, the acoustical characteristics as measured and appraised equal those of the world's best opera houses, all without resort to the ''horse-shoe'' shape of the conventional Italian opera house.

ACKNOWLEDGMENTS

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