Architectural Acoustics
Part Two: Sound System Design, Noise Control, and Sound Isolation

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In this second and concluding part, the author covers sound system, design, noise control, and sound isolation. Part One covered Room Acoustics (see March, 1968).

DESIGN OF A SOUND AMPLIFICATION SYSTEM is an integral part of the over-all acoustical design of a theater, concert hall, auditorium, or a studio (if a reinforcement system is included in a studio). The three basic considerations in designing systems are:

1. Providing a proper acoustical match to the room acoustics,
2. Insuring correct signal flow, or a proper match to the functional needs of the owner, and
3. Satisfactory appearance.[11]

Basic Purposes

The primary goal of the amplification system in a typical theater, auditorium, or concert hall should be high speech intelligibility. Intelligibility depends upon the orientation and location of the loudspeakers with respect to the live sound sources, together with the shaping and acoustical characteristics of the interior room finishes, as discussed in Part I, and the directional characteristics of the loudspeakers, the operating sound levels, and the background noise within the space, as discussed in this article.

The second goal of any sound system should be naturalness for all reinforced or amplified program material. For music reproduction or reinforcement the system must clearly have a flat response, wide range, low noise and distortion, in other words, *high fidelity*. For speech, sound should appear to come from the person speaking, and the sound system's operation should go unnoticed; the amplified sound should be a clearer and more intelligible version of the speaker's natural voice.[9,11]

Use of Central Systems

By positioning a central loudspeaker system so that the amplified sound arrived slightly after the live sound (10 to 20 milliseconds is best), and by insuring that the amount of amplification is not excessive, it is possible to "fool" even highly experienced listeners into believing the amplified sound is coming from the live sound source.[4,9] The time of arrival and loudness of *both* the amplified and live sound for any particular room design must be studied carefully to achieve this effect.

Our ears are at the sides of our heads; our ability to localize a sound source is more efficient in a horizontal plane than in a vertical plane. Therefore, a loudspeaker location directly above the live sound source can produce sound energy appearing to come from the live sound source, even when the sound level from the system is considerably higher than its natural source or arrives first.[4]

The ratio of live sound to amplified sound can vary somewhat throughout an auditorium, but it is important that live and amplified sound both arrive at the listener's ear at approximately the same time (within 30 milliseconds) if their contributions to speech intelligibility are to be additive rather than cancelling. The central over-the-proscenium loudspeaker location can maintain approximately the same path length between amplified and live sound throughout a typical auditorium or concert hall.

Directional Characteristics

Since loudspeaker and microphone must be close to one another in a central sound system design, their *directional* characteristics are important. Loudspeaker equipment should be chosen to provide the most even coverage possible over the entire audience seating area, while minimizing the sound energy directed at the microphone position and at any wall or ceiling surface that may reflect energy back to the stage. Directional microphones should be chosen to minimize pickup in the direction of the loudspeaker and, in many cases, minimize pick-up of room reverberation.

It is important that the coverage pattern of the loudspeakers (or loudspeaker cluster) be based on a realistic appraisal of the loudspeaker's characteristics. This coverage pattern should assure that all listeners receive the signal with smooth frequency response at a sufficient level to assure an increase in speech intelligibility.[10]

Even though one directional loudspeaker could be chosen to provide coverage for an entire seating area, it may be advisable to divide the seating area into two or three sections and assign two or three loudspeakers in a cluster, (rather than one) to provide a uniform level throughout. The input

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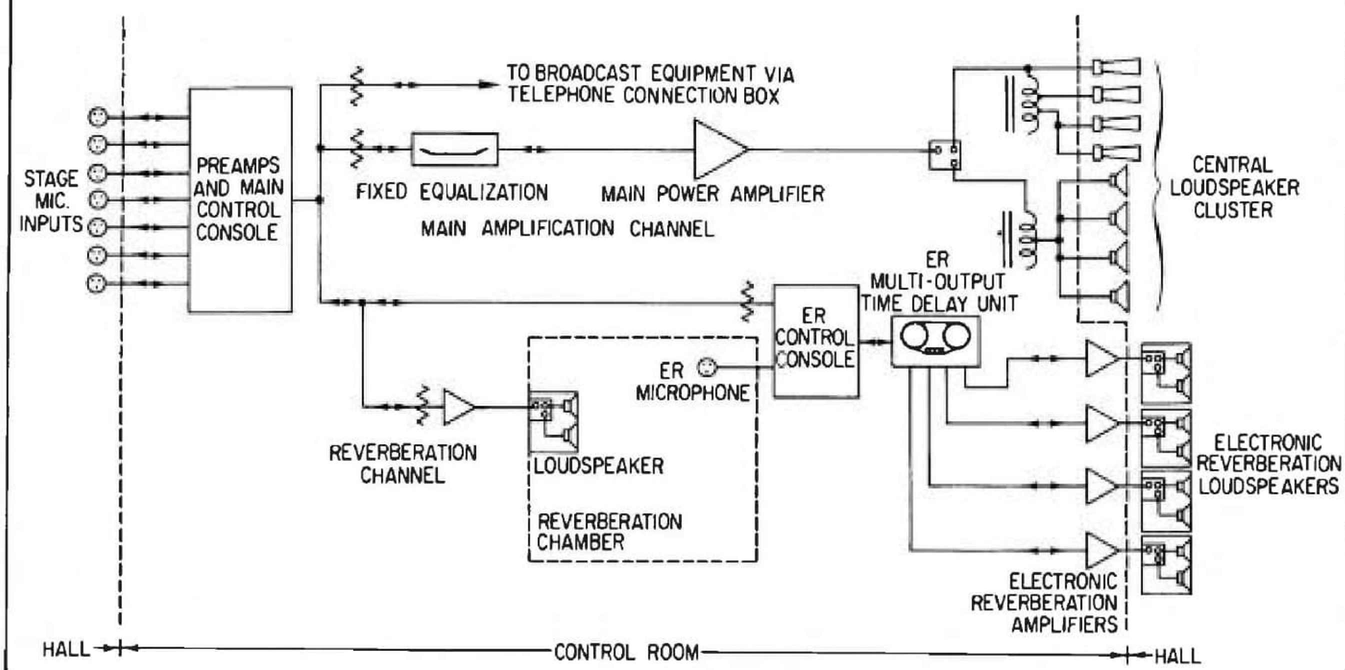

Figure 1. Line diagram for a typical modern straightforward sound reinforcement system for a multipurpose auditorium. Electronic reverberation is included, but the recording and playback facilities, usually included in such systems, are not shown.

signal to the loudspeaker directed to cover the forward seating area may be reduced in level, thus maintaining a more uniform level than possible solely with one loudspeaker.[9,10]

Reducing Reverberation

For spaces with a relatively high reverberation time, including concert halls and those churches where music is an important part of the service, central loudspeaker systems employing loudspeakers with the proper directional characteristics can actually minimize room reverberation by concentrating sound on the sound-absorbing audience. Therefore, such systems can produce high intelligibility by minimizing the masking effects of reverberation on the transient speech sounds and allow satisfactory intelligibility in reverberant environments ideal for music. Large radiating surfaces are required for directional control, and these are most often in the form of line-source or *column* loudspeakers or arrays of direction horns (usually multicellular or radial horns).[10]

Increasing Reverberation

Sound amplification systems designed to increase the reverberation time of an auditorium or concert hall are a separate category — electronic reverberation systems. Generally, such systems and their equipment are separate and in addition to the basic "house" sound systems discussed earlier. ER systems frequently employ many loudspeakers to provide maximum diffusion and minimum ability to localize the source of amplified reverberant sound. The most frequently encountered ER systems use conventional close microphoning and then use magnetic tape delay devices to insure that the sound from any ER loudspeaker reaches the listener after live sound from the stage or after the direct (main system) amplified sound from the stage. Multiple successive delays are usually employed, with the loudspeakers farthest from the stage receiving the longest delayed systems.[5] In some ER systems the time delay tape mechanism is also used as the reverberation generator, with delayed signals from the playback head(s) mixed into the record head via a scrambler circuit signal. One such system, designed and installed by the Aeolian-Skinner Organ Company, has had over ten years of experience in use for increasing the liveness of "dry" churches.

Other systems use supplementary reverberation devices or, better yet, a separate echo chamber or reverberation room where a loudspeaker plays back the sound picked up near the source. A microphone in the reverberant rooms picks up the multiple reflected sound. A mix of the direct sound and the reverberant signal than feeds the record channel of the time-delay system. One such system, together with a fully-developed stereophonic "central" stage reinforcement may be observed in the Purdue University Hall of Music, Lafayette, Indiana.[5]

There are other types of ER systems, such as that installed in London's Royal Festival Hall; these pick-up reverberant or delayed sound at various points within the hall and distribute it via many separate simple amplification channels (perhaps with electrical or acoustical filtering); and it will be interesting to learn which type will find most frequent application in the future for improving the liveness of existing relatively dry halls and smaller than optimum new halls.[5,11]

Noise Control and Sound Isolation

Intruding sounds that require control may be divided into

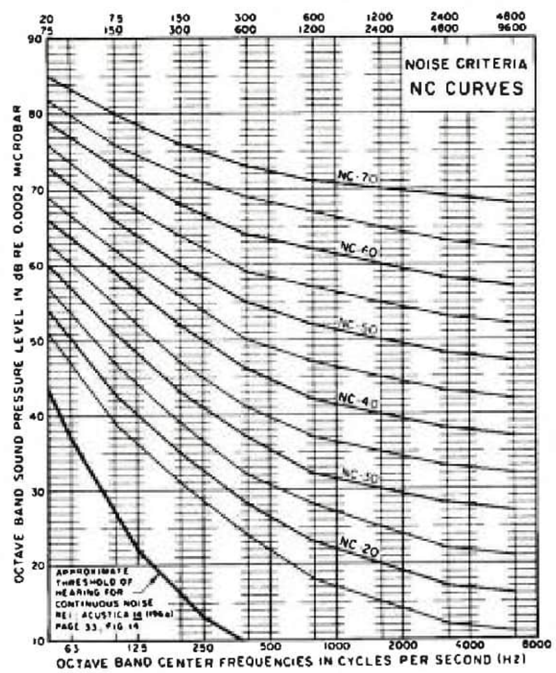

Figure 2. Noise criteria or NC curves show the allowable noise levels in octave bands for different types of spaces. NC-20 has been the commonly accepted curve for theaters, concert halls, studios, and similar spaces; but NC-15 has proven superior, as standards become more critical, and should be used where close to ideal results are desired.

two categories: (a) continuous and relatively innocuous sounds, usually produced by the ventilating system, and (b) intruding discontinuous sounds having programmatic content, such as sounds from adjacent auditoriums or studios. One of the most important concepts of modern noise control engineering is use of the first type of noise to mask the second type.[6]

Naturally, even the steady-state or innocuous ventilating system noises must be held below certain levels or they will be annoying in themselves. Criteria for the allowable background of *all* types of noise have been established for the spaces we are discussing. FIGURE 2 shows a family of noise criteria curves (NC curves) showing the allowable noise levels in octave bands as a function of the octave-band center frequency.[2,3] For critical broadcast and recording studios NC-15 appears the appropriate criteria curve today; although both NC-15 or NC-20 have been considered applicable for the concert halls and theaters.

Mechanical Equipment

Having established the criteria for noise control of air-handling equipment, the responsibility for meeting it rests on the mechanical engineer (with the help of the acoustical consultant) and the contractor installing the equipment specified. All parts of the air-handling system and mechanical equipment design should be studied from the standpoint of noise control.

The noise of air supply and return fans must be estimated properly; then noise control must be incorporated into supply and return ducts by use of lining (lined bends are particularly effective) and/or by use of packaged sound attenuating mufflers.[5,7] For spaces requiring a background noise as low as NC-15, it is good practice to locate the supply and return fans very remotely from the hall or studio, and then lining or mufflers may not be required. The sound attenuation or unlined ductwork, lined ductwork, and mufflers or various configurations is predictable, allowing the engineer to design the required amount of sond attenuation into the air-supply and return system.[1]

Similarly, air supply and return grilles or diffusers should be chosen to meet the requirements imposed by the criteria. Larger grilles, with lower "face velocities" (feet of air-movement per minute or fpm) mean less hiss for a given amount of air moved.[8]

Care must be taken that air velocities in ductwork within or near the hall or studio are not so high as to create turbulence noise* without appropriate sound-attenuating duct construction and lining or mufflers to control sound transmitted to the diffusers or grilles.[8]

Generally, the further all mechanical equipment is from the critical hall or studio, the easier will be the noise control job of the mechanical and acoustical engineers. It is wise to locate mechanical equipment in a basement area under the lobby of a hall, rather than under the hall itself. The practice of mounting fans in attic space directly over hall or studio ceilings should be avoided if at all possible. The equipment will produce a "problem" sound level in the area it is mounted; if this area is directly adjacent to – or above or below – the hall or studio, then special sound-isolating construction may be required.

Equipment mounted near critical spaces also requires careful attention to mounting arrangements; otherwise the equipment can easily introduce vibrations into the building structure, and these vibrations can be radiated as noise inside the studio or hall. Springs, sometimes in combination with concrete inertia blocks, are required for isolation of low-frequency vibrations; ribbed rubber, neoprene, or cork pads are often useful for high-frequency vibration isolation. On occasion, concrete vibration-isolation bases may be supported off the floor on springs – or the entire floor of a mechanical equipment room, located above a studio or hall, many consist of a triple-sandwich of concrete-springs-and-concrete.

Sound Isolation

There are many potential sources of intruding sounds that should be considered in the design of a studio or hall, in addition to those from mechanical equipment. Potential sources from inside a building include performances located in adjacent studios or halls, footfall noise, casual conversation in corridors, lobbies and other circulation areas, and even in control rooms and viewing rooms. Offices can contain problems including office machinery ranging from typewriters to computers. External noise sources include aircraft fly-overs, street and highway traffic, railway lines, and subways.[5]

Any acoustical engineer will urge that as many of these problems as possible be solved in the basic planning of a new hall or studio facility; but inevitably studios and halls will be planned adjacent to each other within the same facility – or a hall or studio facility will be located in the main flight path of an airport. The acoustical enigineer, working with the architect, can still accomplish much in planning the facility even after the basic decisions are made. Adjacent studios or halls can be separated by circulation

*Mixing boxes and dampers are potential producers of turbulence noise, which then requires control by lining or mufflers.

spaces, control rooms, storage rooms, etc; and a concert hall within the main flight path of an airport can be built into, rather than above the earth, with circulation spaces, lobbies, ticket offices, etc., located between the hall and the building roof. The basic technique is to surround and separate the most critical areas (from the standpoint of acoustics) with less critical ones.

Eventually, the basic wall, ceiling, and floor construction for the critical area must be chosen. The sound-pressure level on the *sending* or *source* side of the boundary must be estimated as a function of frequency; the criterion for noise levels in the critical space subtracted, and the difference is the required "noise reduction" for particular boundary surface.

The ability of the particular wall, floor, or ceiling construction (or any other partition) to isolate (stop) sound energy is expressed by the *transmission loss* of that construction. The transmission loss (TL) of a construction is a ratio, expressed in decibels ($10 \log_{10}$) of the acoustic energy incident on the wall to the acoustic energy transmitted through it, and it applies to a unit area. (In the U.S., this is usually one square foot.) Transmission loss curves (as a function of frequency) may be calculated for various types of construction (based on mass, stiffness, distance between elements in sandwich construction, etc.), measured in a laboratory, or calculated from field measurements of noise reduction (NR).

Unlike transmission loss, noise reduction includes the effects of the area of the boundary surface and the room acoustics of the receiving room, so the expression relating the two concepts is:

$$NR = TL - 10 \log_{10} \left(\tfrac{1}{4} + \frac{Sw}{R_2} \right) dB$$

where

NR = noise reduction (reverberant levels on source side of partition minus receiving room levels measured near the partition)

TL = transmission loss of partition construction ($10 \log_{10}$ ratio of incident energy to transmitted energy.)

Sw = Area of partition

R_2 = Room Factor of receiving room

($R = S_2 \alpha_2 / (1 - \alpha_2)$) where S_2 is the total interior surface area of the receiving room, α_2 is the average absorption coefficient, and $S_2 \alpha_2$ is the total absorption in the receiving room.

The quantities S_2 and α_2 will be known or calculated from the room-acoustics design of the receiving room (the hall or studio).

Generally, the more massive a partition construction is, the higher its transmission loss. Really high-TL partitions employ multi-layer construction. For example, a typical wall recommended to separate two music practice and teaching rooms – and matched to a ventilating system noise level of NC-35 – would consist of 8-in. solid masonry or concrete, with a separate ¾-in. plaster wall on each side. Only resilient connections would be employed between the plaster walls and the masonry or concrete core, and glass-fiber may be installed in the two air-spaces of this triple-layer construction.

A somewhat heavier construction technique would be employed to isolate halls or studios requiring a lower background noise level (NC-15 or NC-20). Where one hall is located above another, a vertical slice through the common floor-ceiling construction might show a 3-in. concrete floor slab floated on 2-in. glass fiber, a 12-in. structural concrete slab below and then a resiliently suspended 1-in. plaster

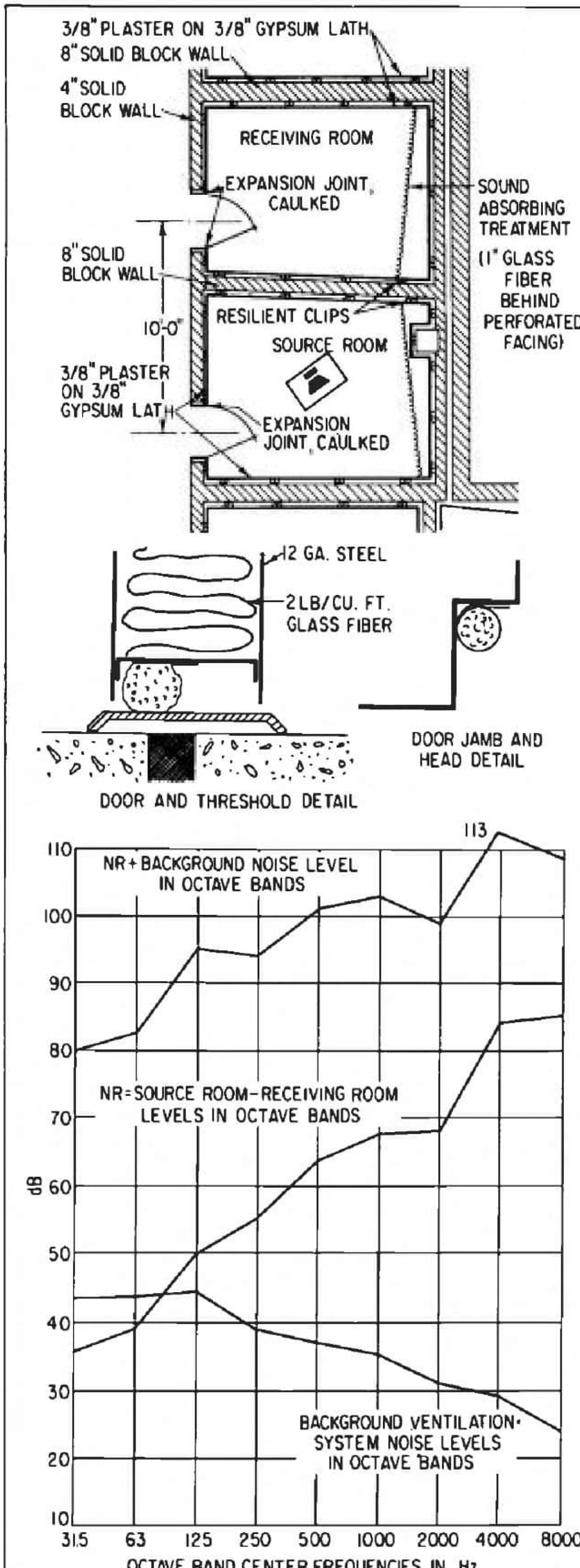

Figure 3. Construction and resulting noise reduction (NR) between two typical music practice rooms In addition to the resilient plaster skin, each room has a resiliently suspended ceiling and isolated floor slab. The doors are glass-fiber-filled hollow-metal doors with polyurethane-filled vinyl-covered gasketing as shown. The noise reduction (NR) plus the background is a measure of the levels that can be tolerated in the source room without interference with use of the receiving room.

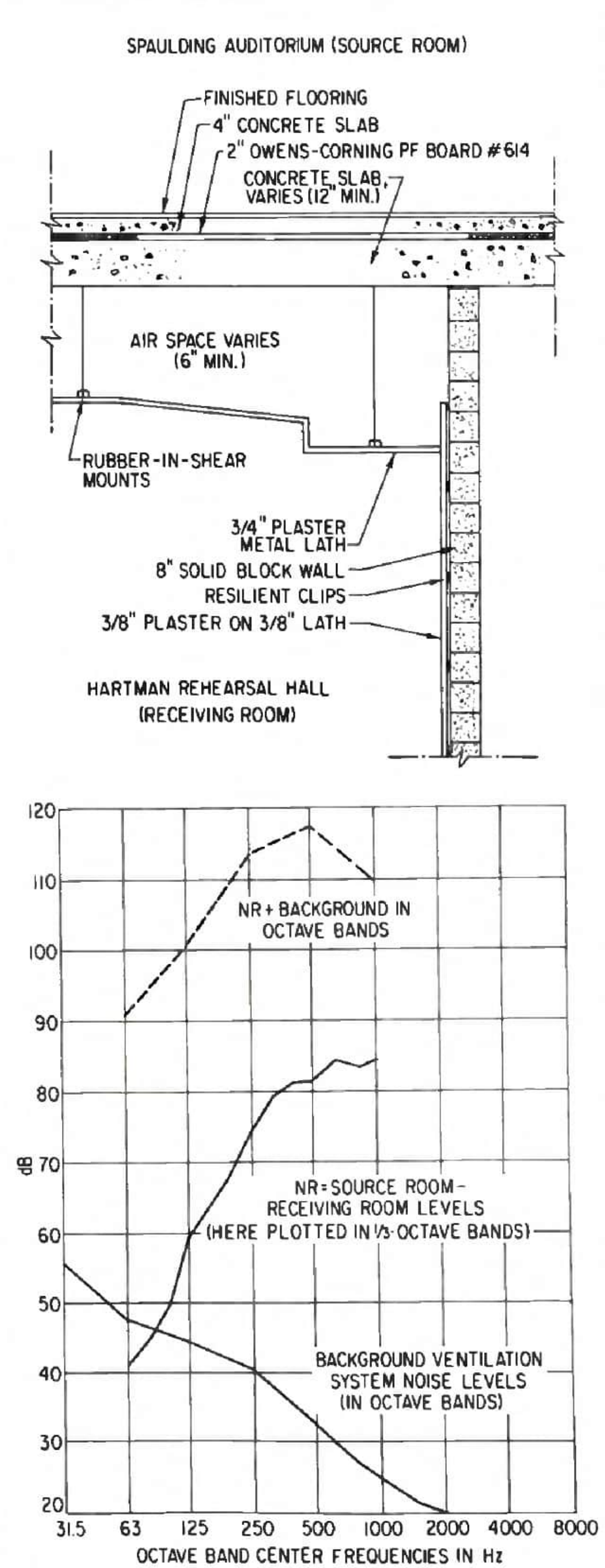

Figure 4. Construction and resulting noise reduction (NR) between a multipurpose auditorium (concert hall — lecture hall) and broadcast studio — rehearsal room below. Values of NR above 1000 Hz are not shown because the test signal source (horn loudspeaker) was not high enough in level to be measured above the ambient in the receiving room, but are known to be above 83 dB. Again, the NR plus background indicates the tolerable levels in the source room.

ceiling below the structural slab. FIGURES 3 and 4 show the noise reduction possible with the construction techniques mentioned.

Doors and windows in high TL-walls must be matched to the construction they interrupt. Details for windows separating control rooms from studios or halls have been refined for many years, and such windows now generally include the following characteristics:

1. Double construction, using two panes of different thicknesses, with one pane sometimes sloped.
2. Resilient airtight mounting for the glass.
3. Sound-absorbing material applied to the frame in the space between the two panes.

High TL doors may now be purchased complete with frames and gasketing (weatherstripping), and careful installation will allow matching the sound isolation of the surrounding constructions.

Details — and airtightness — are very important in all sound isolating construction; light fixtures, grilles, electric outlets, and conduit must all be handled specially to avoid compromise to the basic construction. In this respect, achieving high noise reduction is no different than other areas of acoustical design: details make the difference.

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