Each time a space is enclosed by walls and a ceiling, a new acoustical environment is created. For churches, the acoustical environments that result from design can be critical. Church sanctuaries are complicated by the opposing acoustical demands of speech and music. And, typically, the bigger the space, the more pronounced the acoustical qualities which result from the room’s shape, its finishes, and its furnishings. Since the size and shape of the room and all the interior materials combine to create the resulting acoustical qualities of the room, an acoustical consultant should be a part of this decision-making team. Everything from the client's needs and
basic design concepts through to finish details and their specification must be considered.

**Establishing Acoustical Criteria**

In the early stages of a church project it is important that the acoustical consultant meet with the clients—usually the pastor and minister of music or organist, sometimes the whole building committee. The architect should also be included. This is the time to establish the acoustical design criteria.

One of the major issues that must be discussed is the type of music the church will perform and the relative importance of musical quality versus speech intelligibility. Traditional organ music was developed in the very reverberant, old cathedrals of Europe. Speech intelligibility, however, is poor in those old churches. Today we expect much more clarity in the spoken word.

When there is a strong desire for traditional music, with a fine pipe organ and a large choir, my firm will design the room for the music, and the sound system, with equalization, for the speech. We will establish the criteria for the reverberation time on this concept, usually at about two to two and a quarter seconds at mid-frequencies. Where there is less desire for a cathedral sound, the reverberation time can be established at, or just under, two seconds.

In contrast to this approach, we have consulted on churches in which every sound, both voice and music, is amplified, and the music is more contemporary. In these projects the reverberation time can be much shorter, therefore closer to the optimum reverberation time for speech. Reverberation for music may be introduced electronically.

Whenever a sound reinforcing system is used it must be “equalized.” That is a process of adjusting the electroacoustics to match the particular acoustical qualities of the room. It provides greater clarity and natural equality, and more gain before feedback would occur.

In establishing the criteria for the acoustical requirements in churches, there is another area of concern. It is the control of disturbing noises transmitted into the sanctuary from the mechanical systems, from adjacent activities, and sometimes from exterior sources. Solutions to these problems involve the noise levels of the sources, the allowable levels of “quiet” desired in various rooms, the transmission loss of various constructions, and the methods of controlling the noise transmission along critical paths. In establishing design criteria it is best to decide on the allowable background noise levels in various rooms, so that sources and solutions can be studied during the design development stage of the project.

The human ear cannot hear equally well at all frequencies, and, consequently, we use the Noise Criterion (NC) curves to relate noise levels across the full frequency range. (See Figure 1.) These NC curves are used to establish the allowable levels of background or ambient noise for various spaces and activities. Some of the typical criteria we establish with our client are shown in Table 1 (page 57).

All mechanical engineers are aware of the NC curves and their use as criteria for allowable noise levels. These
are published in the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Handbook's chapter on mechanical noise control. The architect should learn to use this criteria in setting the design goals for the consulting engineer. Another type of acoustical design criteria is a "rule of thumb" that the architect should use in considering how big to make the sanctuary. The usual determinants are the area required for seating, aisles, platform, and choir, as well as the overall form appropriate for a particular client. These two factors include both area and height and, thus, a resulting volume. Our rule of thumb relates the volume and the number of people—a ratio of cubic feet per seat. This ratio is meaningful because in rooms with relatively long reverberation times ("live" rooms) with audiences, the people represent the greatest amount of sound absorption, and the reverberation time depends on volume and total absorption.

A "live" room, then, is appropriate for church music and, by contrast, a short reverberation time, a somewhat "dead" room, is better for speech clarity. Table 2 relates various uses of audience spaces, their seating capacity, and volume relationships. This should be useful to the architect in the early stages of sanctuary design.

When using Table 2, realize that the higher ranges allow more absorptive treatments to control echoes and focus and flutter echoes; lower ranges, however, may not allow much, if any, use of absorptive materials in the room.

As soon as we calculate the reverberation times for the sanctuary, we establish all the finishes and furnishings, and we see the effect that the room's volume has on its desired acoustical qualities. These concepts prove to be significant form determinants.

**Primary Shapes**

The four basic sanctuary plan shapes we see in our consulting work deserve particular acoustical consideration: the basic "shoe box," the cruciform, the fan, and the circular or octagonal.

The shoe box shape is a basic rectangle, and sound usually flows from front to rear without complication and with normal reverberation and sound distribution. Side wall reflections to the whole seating area are more beneficial than in the other three plan shapes. Ceiling forms are usually no problem, except for the barrel vault if it has its focus near ear levels. The rear walls can cause echoes and this must be checked—solutions include diffusive shapes or absorptive treatment. In general, side walls that are made very scattering and diffusive are best, as this controls transverse flutter echoes and provides a sense of surrounding sound in a room of this shape.

The cruciform shape varies from a
Variations in the octagonal shape of Second Baptist Church, Houston, Texas, help overcome focusing problems.

simple cross plan with equal arms to the cathedral plan with a long nave and short transepts. If the “equal arms” are shallow compared to their width, one senses a “one room” quality in the acoustical environment. If the arms are long compared to their width, however, the nave and the transepts tend to have varying reverberances of their own, and this needs special analysis in design. Side wall reflections are still useful in the cruciform plan, but their coverage patterns are interrupted by the deeper transepts.

The ceilings of the cruciform plans usually have a “crossing” that should be analyzed for reflection patterns, especially if the form includes a raised portion or dome which may exaggerate the tendency for vertical flutter echoes.

Fan shape plans are a normal result of designing as many seats as close to the platform and pulpit as possible, with straight side walls and with rear walls following the seating curves. A popular variation of this includes a balcony with seats at each side wall, stepping down to the main floor or platform level.

Analysis of the fan shape plans shows that the side walls tend to reflect useful sound only into the rear side corners of the room. But we usually design for a lot of diffuse side wall reflections to all the seats to achieve a sense of envelopment. In the fan shape plan, if the walls are played strong to reflect sound to the middle of the room, we find that the time delay of these long paths turns these reflections into echoes. It seems, therefore, that the ceiling must provide the sense of “sound surround” as well as strong early reflections. For that reason we have developed highly figured ceiling designs, with strong convex forms for a broad diffusion of sounds throughout the room.

The ceiling in the First Baptist Church of Orlando, Florida, is one of the best examples of this diffusive ceiling concept in application. The triangular- and diamond-shaped “inverted pyramids” are most appropriate acoustically. Their grid layout was based on three strong architectural lines of the roof structure above.

The fan shape plan creates another acoustical concern. Because it is so wide and because rear walls and balcony faces follow circular curves, those surfaces can become the sources of very disturbing focused echoes. The surfaces, therefore, must be made either highly scattering or very sound absorptive.
Some Terms of the Trade

Absorption. A property of materials that reduces the amount of sound energy reflected. Thus, the introduction of an "absorbing" into the surfaces of a room will reduce the sound pressure level in that room by virtue of the fact that sound energy striking the room surfaces will not be totally reflected. This is an entirely different process than transmission loss through a material, which determines how much sound gets into the room via the walls, ceiling, and floor. The effect of absorption reduces the resultant sound level in the room produced by energy that has already entered the room.

Absorption Coefficient. A measure of sound-absorbing ability of a surface. This coefficient is defined as the fraction of incident sound energy absorbed or otherwise not reflected by the surface. Unless otherwise specified, a diffuse sound field is assumed. The values of sound absorption coefficient usually range from about 0.01 for marble slate to almost 1.0 for long absorbing wedges such as are used in anechoic (echoless) chambers.

Flutter Echoes. A rapid succession of noticeable echoes reflecting back and forth between two parallel or concave facing surfaces.

Hertz (Hz). Unit of measurement of frequency, numerically equal to cycles per second.

Noise Reduction Coefficient (NRC). A measure of the acoustical absorption performance of a material, calculated by averaging its sound absorption coefficients at 250, 500, 1000, and 2000 Hz, expressed to the nearest integral multiple of 0.05.

Reverberation. The persistence of sound in an enclosed space, as a result of multiple reflections, after the sound has stopped.

Reverberation Time (RT). The time taken for the sound pressure level (or sound intensity) to decrease to one-millionth (60 dB) of its steady-state value when the source of sound energy is suddenly interrupted. It is a measure of the persistence of an impulsive sound in a room and of the amount of acoustical absorption present.

Transmission Loss (TL). Refers to the number of dB (as a function of frequency) by which sound energy incident upon a material is reduced in transmission through it. Specifically, it is a laboratory measurement of the difference in the sound pressure levels in two adjacent reverberant rooms with a noise source in one and the material under test mounted in an opening between the two rooms. TL has only one variable: a single material or composite under test.

—D.M.

The circular plan is the most acoustically dangerous form that can be considered for an audience space. The curved walls can cause serious focusing and dead spots. Either (1) the walls are made absorptive, which "deadens" the room too much, or (2) the walls are splayed severely and still tend to cause focused echoes. In some plans, when functions and features can be off-centered and when some diffusion and some efficient absorption can be combined in the walls' design, it is possible to handle a circular plan acoustically, but don't count on it until an analysis of reflections is conducted.

The ceiling of a circular room is also critical. It must be designed in relation to what the walls are doing acoustically, and to the way the church functions are located below it. Its design should be based on reflective materials and scattering forms. An absorptive ceiling would undoubtedly make the room too dead. And in no case should the ceiling be a dome shape—that could add more focusing problems to the ones already created.

Octagonal plans can cause variations on the problems of the circular scheme. Sometimes, however, the segments of the octagon can be made shorter or longer (from center) and functional positions can be set off axis, and these variations can overcome some of the inherent focusing problems. In a small octagonal church on which we consulted, the ceiling was made of eight gently sloping sections rising to a high point in the middle. To keep this "dome" from focusing we created a similar inverted form in the center that broke up the focus patterns and also contained the sound reinforcement speakers.

Finishes and Furnishings

One can see that form follows function, acoustically, and so do the choices of finishes and furnishings. There are many materials which can be used in a church's interiors, and, once chosen, finishes and furnishings all become contributors to the resulting acoustical environment. All materials, therefore, are acoustical materials, whether they are basically reflective or absorptive. Some of the typical ones deserve discussion.

Gypsum board is seldom thought of as an acoustical material. For 250 Hz sound, on up to the highest frequencies, it is a good reflector of sound, as are plaster, wood paneling, masonry, and other hard materials. Below 250 Hz, however, gypsum board has a tendency to respond to sound "diaphragmatically," and sound is somewhat absorbed into the structure. This results in a loss of
low frequency sound energy in the desired reflections and reverberation in the auditorium.

This gypsum board condition becomes serious in designs where great areas of it are used on the ceiling and walls, especially in churches where pipe organs are used. It can weaken the sound of the music. The solution is to stiffen the gypsum board by using double layers, laminated. That makes it about as stiff as a good plaster surface. While this may seem expensive, it should be noted that air-borne noise transmission through walls is better prevented by this increased mass than it is, in usual circumstances, by insulation between the studs. This construction may therefore be necessary for mechanical and activity noise control. (It should be noted that plywood, thin wood decking and paneling, glass, and similar “sheet” materials have this same weakness at low frequencies.)

Carpet can have a very dominant effect on the acoustics of a church interior. If the room design causes a short reverberation response, the carpet usually soaks up so much energy that the room will be quite dead unless the carpet is of a low absorption type, used sparingly. If the room is high in the volume per seat ratio, however, you may need carpet throughout to control the reverberation. Carpet should never be used in the choir area; it is best to have a hard, reflective floor in front of the singers. Carpet under the pews can also deaden the seating areas and dampen the enthusiasm of congregational singing.

In specifying carpet, one must understand the differences in carpet materials and types. The least absorptive carpets are of synthetic fibers, in a tight loop pile, thin, and without an under padding. By contrast, the most absorptive carpets are of natural wool fibers, a fuzzy cut pile, thick and plush, with a soft padding. There is a real difference, acoustically, and we usually find we must recommend the least absorptive commercial type of carpet.

Pew cushions, on the sitting surface only, are invariably recommended to provide some absorption where a seat might be vacant. Without it there could be more variance than desired in the reverberation times for full attendance and the nearly empty services. These cushions should be of a breathable fabric over an open cell, porous padding. We usually recommend against more pew cushioning as it can also dampen the congregation’s enthusiasm for singing.

Special absorptive treatments are often necessary in churches, not just for the proper balance of the reverberation response, but specifically for the control of surfaces which would otherwise cause echoes. This can be very serious when the sound source is the loudspeaker cluster. It is, appropriately, a “point source” above the

The First Baptist Church in Carrollton, Texas, top, features a fan-shaped auditorium. Above, the equal arm cruciform plan, with short, wide transepts and nave, at the First United Methodist Church, Waco, Texas.
Church furnishings and interior finishes are all contributors to the resulting acoustical environment.

preacher; balcony faces and rear walls can focus the loudspeaker sound reflections back to the front pews to be heard as echoes. High side walls can also cause echo reflections to distant seats, depending on the geometry of the room.

If those surfaces cannot be reshaped to achieve appropriately scattered reflections, they must be very absorptive. In detailing and specifying this treatment there are two components: the basic absorption material, and the architectural facing over it. Because of the high energy so often involved, the absorptive core must be about four inches thick. The standard core material is a semi-rigid glass fiber insulation board with a density of six pounds per cubic foot. This is often used in one- or two-inch thickness, covered with a breathable fabric, and distributed by several commercial sources of absorptive wall panels. The one-inch-thick panels can have an absorption rating of NRC = 0.95, but that is for calculating the reverberant decay of sound, not for controlling the reflection on "first bounce." That is why we need the thicker four inches of absorption.

The facing can be breathable fabric, a grille cloth material, insect screen, even a finely perforated metal (30 to 50 percent open area). Thin, 3/4-inch wood battens, 50 percent open area, can also be used as an architectural screen over the basic core.

Insulation is a very misused and misunderstood material in solving acoustical problems. It has caused what I often refer to as the "acoustics mystique," a syndrome of improper assumptions, detailing, and specifications. Many products are called insulators because they slow down the flow of heat. Unfortunately, they do not similarly slow down the flow of transmitted noise, as many people assume. Consider the wood stud wall: the majority of the transmission is through the movement of the studs, not through the dead air space. Consider four inches of plain fiberglass insulation: by itself it is a negligible barrier to sound. When various layers of gypsum board are supported resiliently in wall and ceiling details, however, the addition of some insulation in the dead air space can be beneficial. Note that it is the combination of structure and materials, not the insulation alone, that makes the difference.

But insulation exposed to the sounds in a room, and placed close to one of the room's surfaces, can be a very good reverberant sound energy absorber. There are many ways that insulation materials can be used properly for acoustical controls; to avoid the acoustics mystique, one must recognize the difference between, and the proper details for, surface absorption and sound transmission.

"Hearing" the Design

Churches that are designed acoustically do not have to look that way, but designers must balance their client's visual and functional needs. Proper acoustics is one of those functional needs. Quite simply, if the architect can see the design, he should also be able to hear it. The architect who does will automatically and subtly use acoustical needs as form determinants. The architect who doesn't may get some surprises, because the forms in the design will be the acoustical determinants in every case.