THE SHOW HORN

BY BRUCE EDGAR
Contributing Editor

Every speaker project has a stimulus. In this case, *Speaker Builder* and Madisound sponsored a room at the 1988 Stereophile Show in Los Angeles. I saw this as an opportunity to display audiophile horn technology to the public and the audio industry. However, one problem existed: Although I had midrange and tweeter horns ready to use, I didn't have a suitable bass horn. Luckily, I had a paper design for a one-eighth-size 50Hz bass horn. Since the show was two months away, I was forced into a fast paced building program. Several friends helped build and finance the project, and we were able make the show deadline with some cushion. Thus, the Show Horn (*Photo 1*) was built.

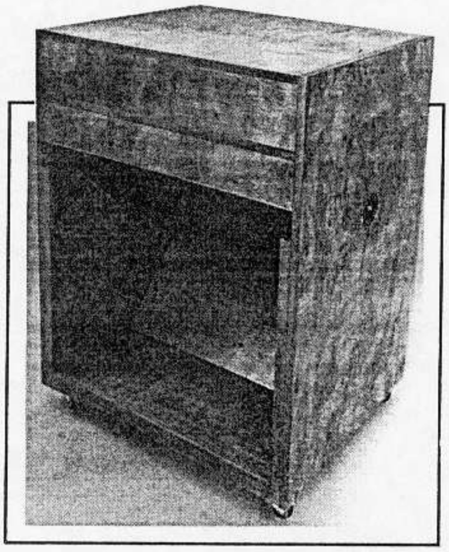

PHOTO 1: The Show Horn.

Reactions to my system varied. I saw many jaws drop as people came into the room. A sample comment was, "I can't believe you would display a horn at the show." But it was gratifying to talk with many audiophiles/speaker builders who, after getting over their initial surprise, began to show interest in the possibility of horns for their own systems. Some people were enthralled by the sound and kept returning. After three days, I was exhausted, but all the feedback from listeners stimulated me to do further research and design work. So for all those enthusiastic builders I met at the 1988 Stereophile Show, I now give you the theory of how the Show Horn was designed and construction details so you can build it.

INTRODUCTION. For a very old design, the horn loudspeaker literature does not give the amateur any clear step-by-step method of how to design a bass horn. In contrast, there have been a good many expositions on designing vented- and closed-box loudspeakers. Keele probably presented the first comprehensive and simplified design methodolgy for bass horns.[1] He showed most horn design parameters could be calculated from the Thiele/Small parameters for the driver. Leach extended Keele's work by introducing losses into the model.[2] However, Leach's math formalism makes the paper very hard to follow.

The principal problem in bass horn design is maximizing the bandwidth response. Most ad-hoc horn designs yield efficiency but not always a smooth response over several octaves. For example, I designed a tractrix corner horn (*SB* 2/83) which, while sounding good, did not achieve the design objective of a good response down to the flare frequency, 70Hz. Instead, the response died below 100Hz. After some thought and experimentation, I have concluded that the prime limitation on bass response is what acoustical designers call throat reactance.

You can think of a horn as a transformer which transforms the low impedance air load into a high impedance that a driver likes to see at the throat. At the flare frequency, the throat reactance peaks, whereas the throat resistance is zero and rises to its maximum value above the flare frequency (*Fig. 1*). Theoretically, a bass horn should give response down to the flare frequency, but the throat reactance will choke off any response near the flare frequency.

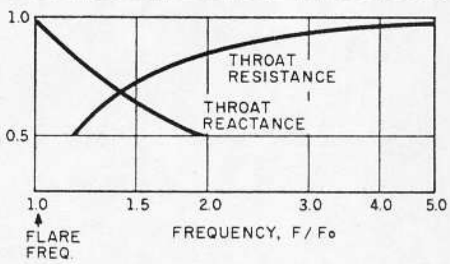

FIGURE 1: Normalized acoustical throat impedance of an exponential horn.

Over the years, Wente and Thuras at Bell Labs and Klipsch[3] independently found you could cancel out the throat reactance by using a sealed back chamber. This technique, which Plach[4] termed "reactance annulling," allows for bass response right down to the flare frequency. Leach showed that, for a number of exponential horn examples, reactance annulling does not occur at the flare but at a higher frequency.[2] In a follow-up letter,[5] Leach concluded that reactance annulling works best with the hyperbolic-exponential horn as discovered by Salmon (US Patent #2,338,262).[6] And it is the difference between a horn with reactance annulling at the flare rate frequency and one without that spells the difference between superb and marginal bass response.

ABOUT THE AUTHOR

Dr. Bruce Edgar is a project engineer/scientist at a Los Angeles aerospace company. His interests include horn design, woodworking, and the history of loudspeakers.

Here, I present a simple comprehensive method of designing a hyperbolic-exponential bass horn, combining the best of the Keele and Leach approaches. I have successfully applied it to a number of driver and horn combinations. This approach, using the hyperbolic-exponential horn contour, supersedes my earlier efforts using exponential and tractrix horn contours. The latter make good midrange and tweeter horns but in my experience suffer near the flare cutoff due to throat reactance problems.

DESIGN. The Edgar design method can be outlined as follows:

1. Select a suitable driver.
2. Measure driver F_S, Q_{ES}, and V_{AS}.
3. Calculate the throat area (S_T) and mass cutoff frequency (F_{HM}).
4. Calculate α (V_{AS}/V_B, V_B = back volume).
5. Determine M (hyperbolic-exponential horn parameter) and flare rate.
6. Decide on wall or corner placement and specify mouth area.
7. Calculate area expansion of the horn with linear distance.
8. Work out folding geometry.
9. Experimentally determine the back volume.
10. Integrate bass horn response and SPL sensitivity with the rest of the loudspeaker system.

SUITABLE DRIVERS. Actually, driver selection is predicated on the lowest desired frequency. With the hyperbolic-exponential horn, the flare rate is usually set close to the driver resonant frequency, F_S, so driver selection and flare rate are somewhat tied together. The old myth that you can take any bass horn design for a 12″ speaker, stick in any good looking 12″ driver, and expect good results is simply not true. I don't mean you shouldn't try other drivers; sometimes through serendipity you find combinations that work unexpectedly well.

For bass horns, we require drivers with relatively high F_S (40–80Hz) and a low Q_{ES} (0.2–0.3). The bandwidth can be specified as being between the flare rate (or F_S) and the mass rolloff frequency, F_{HM}. As derived by Keele,[1] $F_{HM} = 2F_S/Q_{ES}$. For proper mating to a midrange horn, F_{HM} must be above 300Hz, preferably near 500Hz for best results. S_T, the optimum throat area,[1] is defined as:

$$S_T = 2\pi F_S Q_{ES} V_{AS}/c,$$

where c = velocity of sound, or

$$S_T = 0.8 F_S Q_{ES} V_{AS},$$

where S_T is in square inches and V_{AS} is in cubic feet.

In *Table I*, I have listed several 12″ drivers with their given Thiele/Small parameters, SPL sensitivities, throat sizes, and mass rolloff frequencies. The first two Audax *[Polydax in the USA—Ed.]* drivers yield almost the same throat sizes and rolloff frequencies even though their F_S and Q_{ES} vary widely. The throat sizes are comparable to the area of a 12″ driver, but the rolloffs of the Audax drivers are too low to mate to a typical midrange horn. However, you could use them in a subwoofer horn with 1:1 coupling up to 100Hz.

The EVM12L has a throat size a third of that for the Audax drivers, and the rolloff is up in the 400Hz region. The FORCE 12 is a cousin of the EVM12L, but it has a heavier cone and voice coil giving a higher Q_{ES} and consequently a lower rolloff of 250Hz even though both drivers have comparable SPL ratings. The FORCE 12 is marginal for this application.

We can do the same comparison for the JBL 2202H and 2204H drivers. The 2202H has very high rolloff frequency but a very small throat size. The 2204 has a low rolloff but a good throat size. The last driver, the JBL E-120, is similar to the 2202H, with a high rolloff and a small throat. Thus you can observe from these examples, as the mass rolloff frequency goes higher, the throat size be-

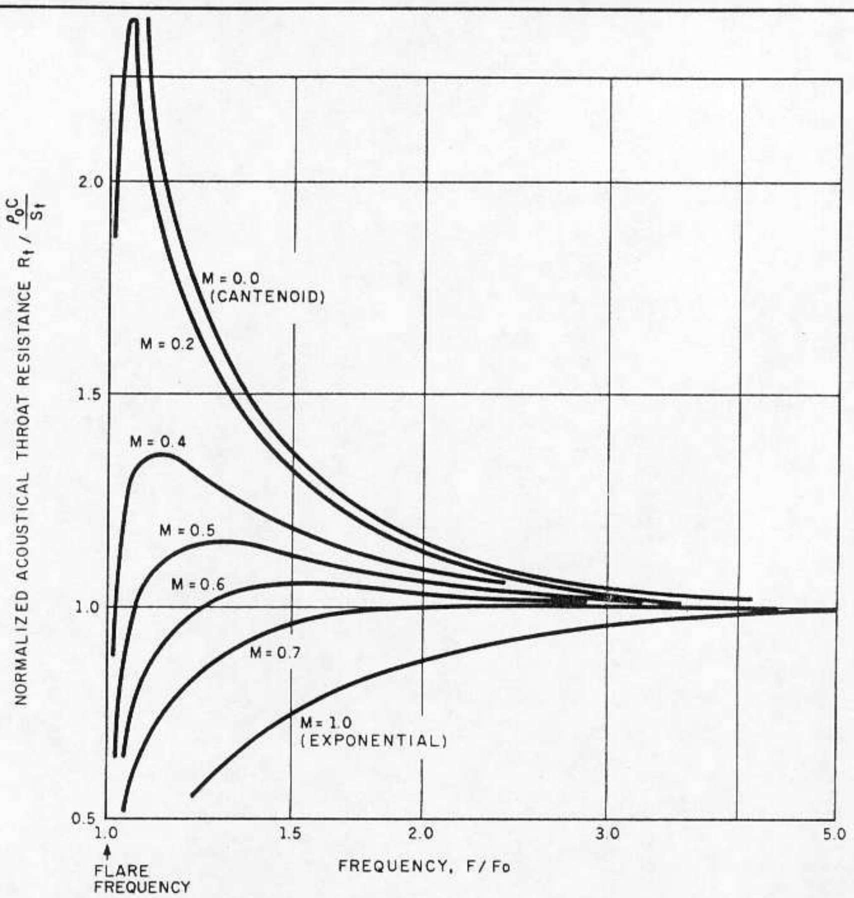

FIGURE 2: Throat resistance for hyperbolic-exponential horns.

TABLE I

PARAMETERS OF CANDIDATE 12″ DRIVERS

DRIVER	F_S	V_{AS} (cu. ft.)	Q_{ES}	EFF (dB)	S_T (sq. in.)	F_{HM}
Audax HD30P	17	25.0	0.27	95	91	126
Audax PR30ST100	40	5.0	0.69	95	110	116
EVM12L	55	3.3	0.25	98	36	440
FORCE 12	55	3.0	0.44	99	58	250
JBL 2202H	50	3.0	0.17	99	20	588
JBL 2204H	45	3.0	0.44	95	48	204
JBL E-120	60	2.8	0.19	103	26	632

comes smaller. The EVM12L seems to be the best compromise between a reasonable throat size and a sufficiently high mass rolloff freqency.

The EV and JBLs in this comparison are professional musical instrument drivers, characterized by very heavy magnets, high (greater than 100dB SPL ratings) sensitivities, moderate resonant frequencies and low Qs. They will produce very high sound levels when mounted in small boxes. However, there will be no response below 100Hz. But when mounted in a properly designed bass horn, you regain the bass response below 100Hz with about 10dB additional sensitivity. Beware of any surplus or other driver advertised as a "musical instrument" driver. While it may be suitable as a direct radiator, using it in a horn may give unsatifactory results. You must still go through the comparison as given in *Table I*.

ALPHA CALCULATION. In Leach's formulation the α parameter (ratio of V_{AS} to the back volume) is calculated from the bandwidth.[2] The bandwidth frequencies are essentially the flare cutoff at the low end and the mass rolloff frequency at the upper end. Leach calls these two frequencies F_L and F_H, respectively. Then alpha is calculated by the formula:

$$\alpha + 1 = F_L F_H / F_S^2$$

Taking the EVM12L parameters from *Table I*, assuming a 50Hz flare frequency, and substituting them into the above formula, we come up with an alpha of 6.2.

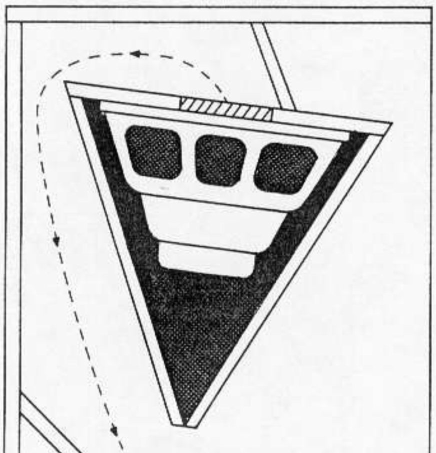

FIGURE 3: University Classic horn folding configuration.

TABLE II

MEASURED EVM12L DRIVER PARAMETERS

DRIVER	F_S	Q_{ES}	V_{AS} (cu. ft.)	F_{HM}	S_T (sq. in.)
1	56.4	0.20	3.30	564	29.9
2	53.2	0.19	3.98	560	26.7
3	55.2	0.21	3.71	525	34.4
4	54.6	0.20	3.76	546	32.9
5	55.0	0.22	3.88	500	37.6
6	52.2	0.23	4.33	453	41.6

M CALCULATION. The hyperbolic-exponential horn formula has a free parameter M that allows reactance annulling at the flare frequency. Leach[4] gives the formula for M as:

$$M = \frac{2\pi F_O V_{AS}}{(\alpha + 1)\, S_T c}$$

where F_O is the flare frequency. This formula makes two assumptions. First, the horn is an infinite hyperbolic-exponential horn. If you don't use this assumption, the mathematics become very messy, and besides, if you take the horn expansion out to the proper mouth size and don't try to foreshorten it, the assumption is fairly good. Second, the formula assumes that the capacitive reactance of the back chamber is exactly cancelled by the inductive throat reactance at the flare frequency, F_O.

Again substituting the EVM12L parameters into the above formula, we obtain a value for M of 0.51. In fact, if you place the flare rate anywhere near the driver resonant frequency, you will always obtain an M of 0.5 with Leach's formulation.

The real part of the throat impedance tells us how the horn should load, given a proper mouth size. R_T, the throat resistance for the infinite horn case, is given by:

$$R_T = \frac{R_{AL}\sqrt{1 - \left(\frac{F_o}{F}\right)^2}}{1 - (1 - M^2)\left(\frac{F_o}{F}\right)^2}$$

where $R_{AL} = \rho c / S_T$, F = frequency, and ρ = density of air. The throat resistance is plotted out in *Fig. 2* for several values of M. M = 1 corresponds to an exponential horn, and M = 0 corresponds to the cantenoid horn. For values of M between 0 and 1, you have a hyperbolic-exponential horn. Notice that for M between 0.5 and 1.0 in *Fig. 2*, you have fairly uniform throat resistance behavior. But for M below 0.5, the throat resistance peaks severely; so avoid values of M below 0.5. For M between 0.5 and 0.6, you can obtain response very close to the flare rate and uniform loading above the flare frequency.

After examining *Fig. 2*, I decided an M of 0.5 might have a slightly peaky bass character and 0.6 would sound better. However, such a change in M would violate the alpha calculation in Step 4. But after reviewing Leach's assumptions for his alpha formula, I'm not sure it exactly applies to a horn design. In any case, you may also regard alpha as an independent variable. I will clarify the matter in Step 9.

HORN PLACEMENT. When most builders think about a bass horn, they almost immediately think of a corner horn, *a la* Klipsch. The corner horn offers distinct advantages over other placements. For example, it allows a mouth size one eighth of what it would be in free space. The smaller mouth means a shorter horn length and overall smaller size. The one disadvantage of a corner horn is that few people have free corners for horn placement, and usually those corners are too widely spaced. (See the Klipsch interview, *SB* 3/89, for Paul's solution to this problem.)

Thus, for reasons of simplicity, I chose

Continued on page 14

TABLE III

AREA EXPANSION FOR THE 50Hz M = 0.6 HORN

x (in.)	A (sq. in.)
0	40.0
4	45.0
8	51.0
12	58.4
16	67.3
20	78.2
24	91.2
28	107.1
32	126.2
36	149.2
40	176.8
44	210.0
48	250.0
52	298.9
56	357.0
60	427.1
64	511.7
68	610.3
72	735.9

Continued from page 12
for this initial work a one-eighth-size corner horn design. For a free space horn with a circular mouth, the proper mouth size is one whose circumference is equal to a wavelength (c/F_O) at the flare frequency, F_O. Thus, if r is the radius, this condition may be expressed as:

$$2\pi r = c/F_O.$$

The area for the free space horn is:

$$A = \pi r^2, \text{ or}$$

$$A = \frac{1}{4\pi}\left|\frac{c}{F_o}\right|^2$$

The mouth area, S_M, for a one-eighth-size horn is:

$$S_M = \frac{1}{32\pi}\left|\frac{c}{F_o}\right|^2$$

For a one-eighth-size 50Hz horn, S_M is 725 square inches, assuming a speed of sound (c) of 13,500 inches per second.

DRIVER VARIATIONS. When you try to generate a speaker design, it pays to look at a number of drivers to check the production tolerances. *Table II* lists the measured Thiele/Small parameters and calculated mass rolloff frequencies and throat sizes of six EVM12L drivers. As you can see, the resonant frequencies are fairly close to the spec of 55Hz, but the Qs are much lower, which gives mass rolloff frequencies which are mostly higher than 500Hz. A large variation in the V_{AS} between drivers gives a corresponding wide variation in the calculated throat sizes. I decided to use drivers 5 and 6 and to use a common throat size (S_T) of 40 square inches.

HORN EXPANSION CURVE. The hyperbolic-exponential horn curve is given by the following equation:

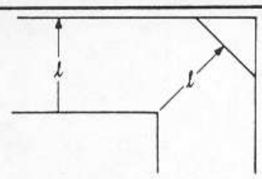

FIGURE 4: Radius corner reflector.

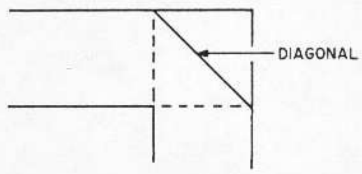

FIGURE 5: Diagonal corner reflector.

$$S = S_T\left|\text{COSH}\,\frac{X}{X_o} + \text{MSINH}\,\frac{X}{X_O}\right|^2$$

where:

$X_O = c/2\pi F_O$
S = cross-sectional area
X = linear distance along the horn
COSH = hyperbolic cosine function
SINH = hyperbolic sine function

A simpler alternative form is:

$$S = \frac{S_T}{4}\left|(1 + M)e^{X/X_o} + (1 - M)e^{-X/X_o}\right|^2$$

which is easily programmed on a computer or a hand calculator. The horn expansion is listed in *Table III* for the case of F_O = 50Hz, M = 0.6, S_T = 40 square inches, and S_M = 725 square inches. These parameters give alphas of 5.5 and 6.25 and calculated back volumes of 1,227 and 1,197 cubic inches for drivers 5 and 6, respectively.

FOLDING GEOMETRY. George Augspurger once remarked in one of his patent reviews, "Of a thousand ways of folding a horn, this is one of them." He was implying there are a great many ways to fold a bass horn, and unfortunately, most are wrong from a wide bandwidth viewpoint. Most designers in the past were forced by economics and marketing to engineer the most compact volume for a given horn. But this design philosophy will give you many 180° turns which tend to roll off the response above 300Hz. If you have a driver with a mass rolloff of 300Hz, 180° bends in the horn are not a bad choice. However, if the mass rolloff frequency is above

Continued on page 16

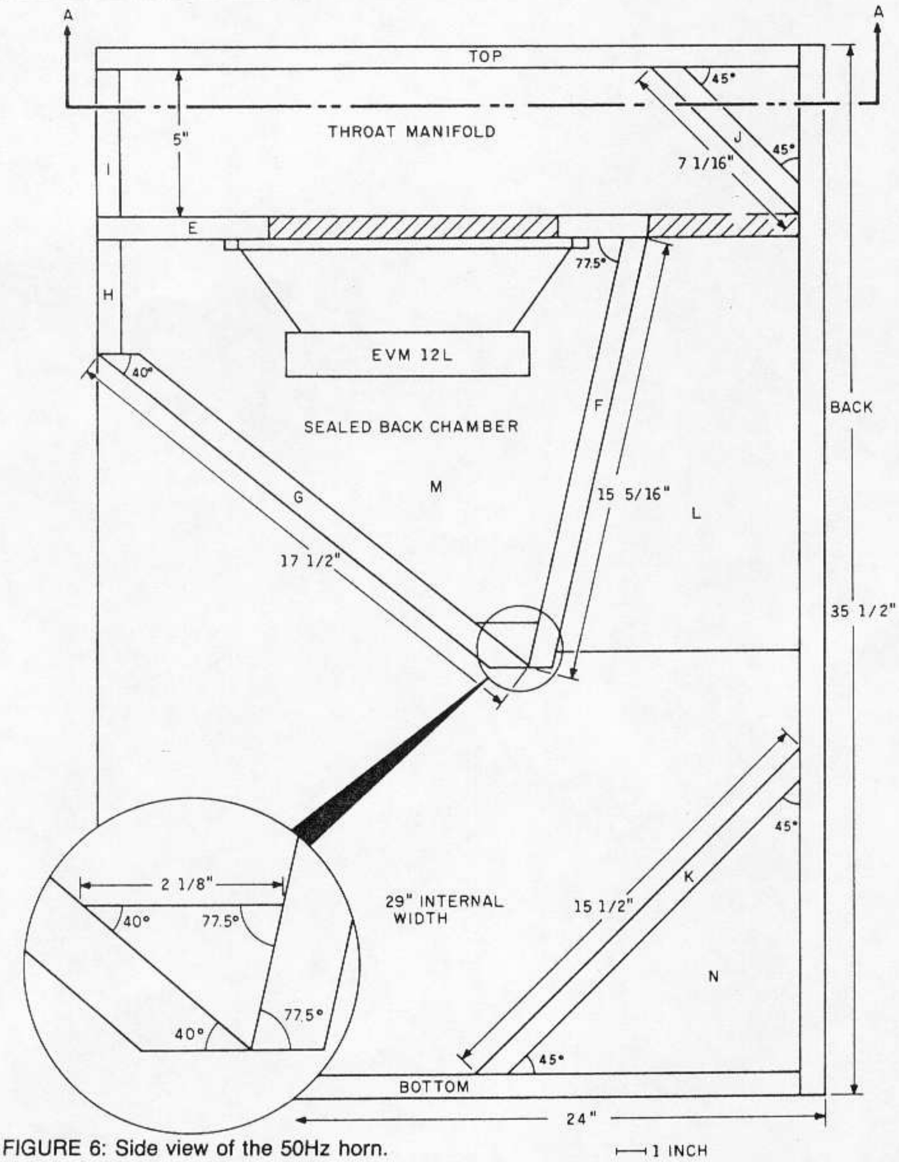

FIGURE 6: Side view of the 50Hz horn.

Continued from page 14
500Hz, as in the EVM12L driver, it would be wise to keep the number of 180° folds to a bare minimum.

Is there a right way to fold a horn for wide bandwidth? Yes, if you use only 90° folds. The best example of this design criterion is Abraham Cohen's old University Classic horn design introduced in 1956[7] (*Fig. 3*). Unfortunately, Cohen had to use a 15" driver with a mass rolloff below 300Hz, so his beautiful folding geometry went for naught.

Another consideration is the design of the corner reflector in a 90° bend. In previous horn designs, I had approximated the corner reflector position to be tangent to the arc of the radius (*Fig. 4*). But subsequent wave front calculations showed that the corner reflector should be aligned along the diagonal (*Fig. 5*). For reasons I will not discuss here, a wave front will remain intact going through a 90° bend if the corner reflector is aligned along the diagonal, but it will be distorted if the reflector is smaller.

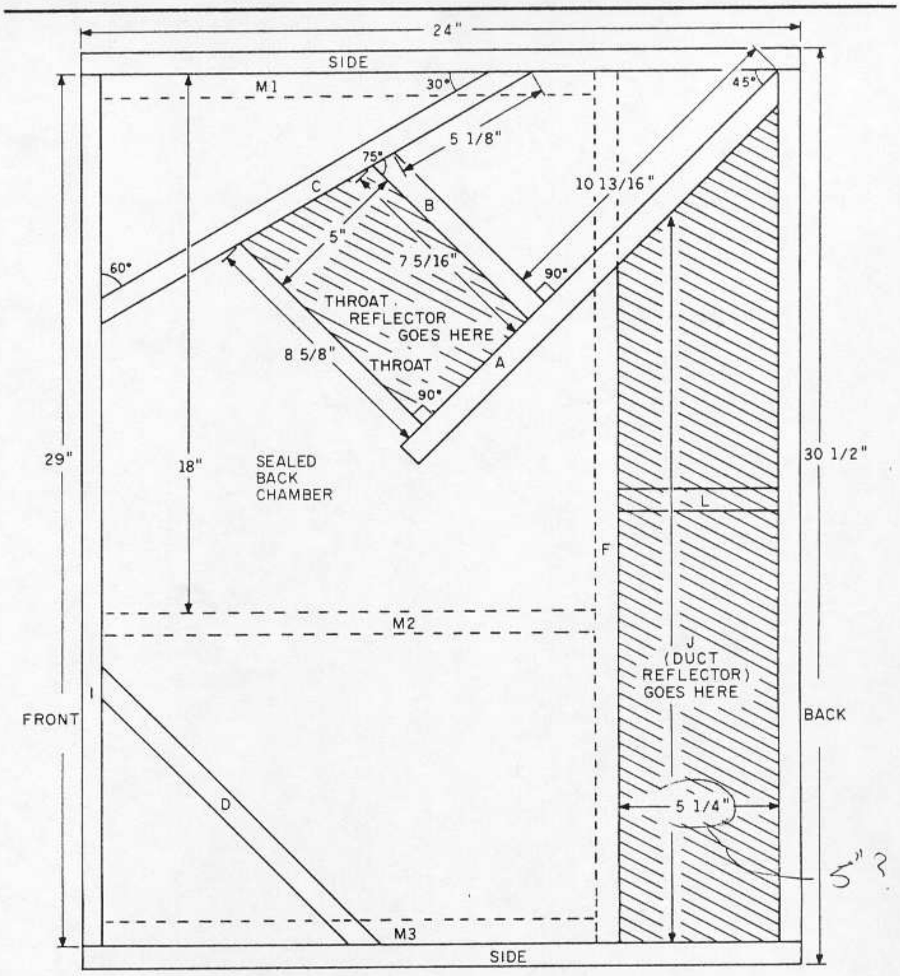

FIGURE 7: Top view of the throat manifold.

50Hz HORN DESIGN. *Figures 6* and *7*, are the sectional views of the bass horn. As you can see, I tried to use the University Classic folding geometry as much as I could in *Fig. 4*. But because a hyperbolic-exponential horn is quite long, I had to compromise with a quasi-180° bend to fit all the throat manifold in the enclosure. Another compromise was the shortening of the horn from 72 to 70 inches because the folding worked out better. But I'm not sure how and where these compromises affect the overall response. The parts are shown in *Fig. 8* with a gross dimensions list in *Table IV*. You can cut out one bass horn from two 4 by 8′ sheets of ¾" plywood. I used a good grade birch that was fairly void free. At the lumberyard where I buy my plywood, I paid a mill charge to have them make the coarse width cuts of 29 and 24". I made the rest of the cuts on my table saw. *Figure 9* is a cutout diagram. You can make the horn out of

Continued on page 18

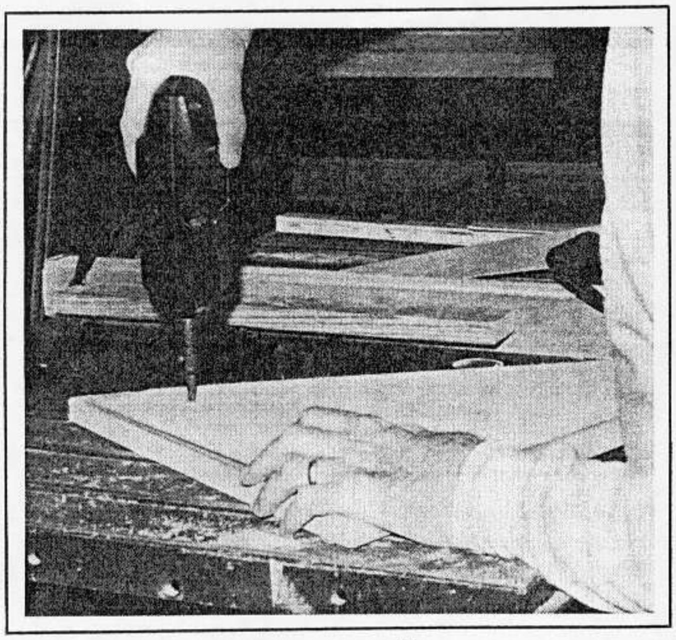
PHOTO 2: Attaching the pattern to part M.

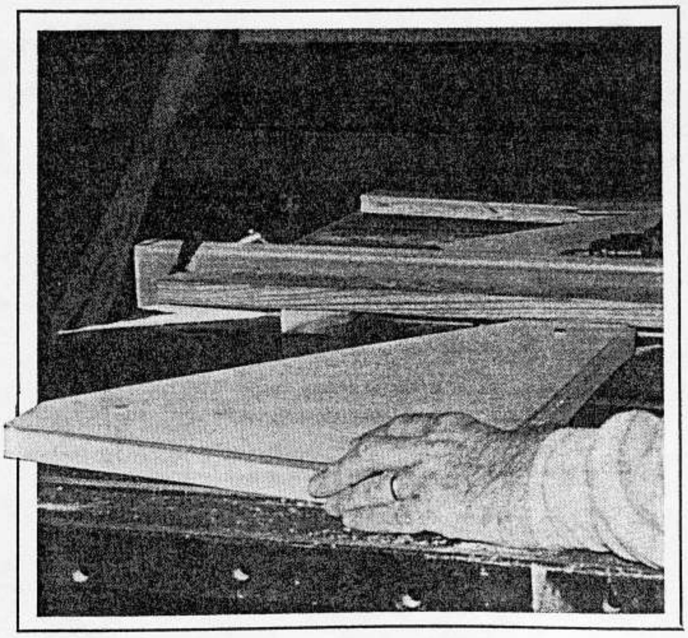
PHOTO 3: Using a feeler gauge for pattern sawing.

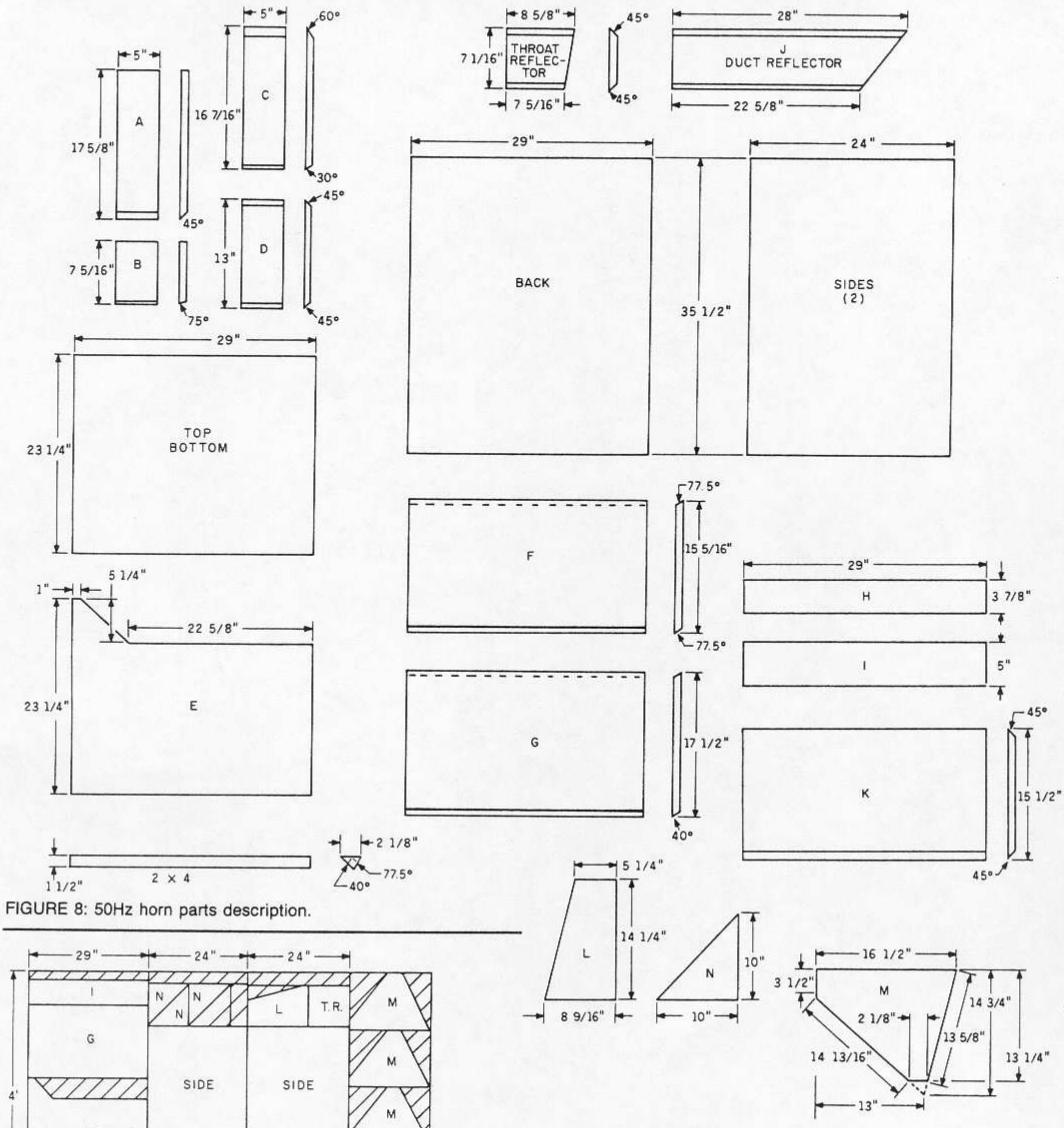

FIGURE 8: 50Hz horn parts description.

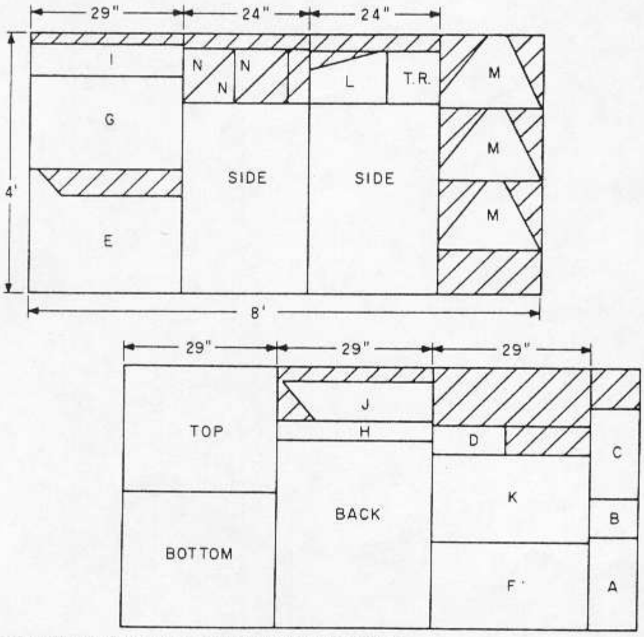

FIGURE 9: Sawing guide for ¾" plywood.

TABLE IV

PARTS LIST AND DIMENSIONS

PART	SIZE	PART	SIZE
A	5″ x 17⅝″	K	29″ x 15½″
B	5″ x 7⁵⁄₁₆″	L	14¼″ x 8⁹⁄₁₆″
C	5″ x 16⁷⁄₁₆″	M(3)	16½″ x 13¼″
D	5″ x 13″	N(3)	10″ x 10″
E	29″ x 23¼″	Top, Bottom	29″ x 23¼″
F	29″ x 15⁵⁄₁₆″	Back	29″ x 35½″
G	29″ x 17½″	Sides(2)	24″ x 35½″
H	29″ x 3⅞″	Throat reflector	7¹⁄₁₆″ x 8⅝″
I	29″ x 5″		
J	28″ x 7¹⁄₁₆″		

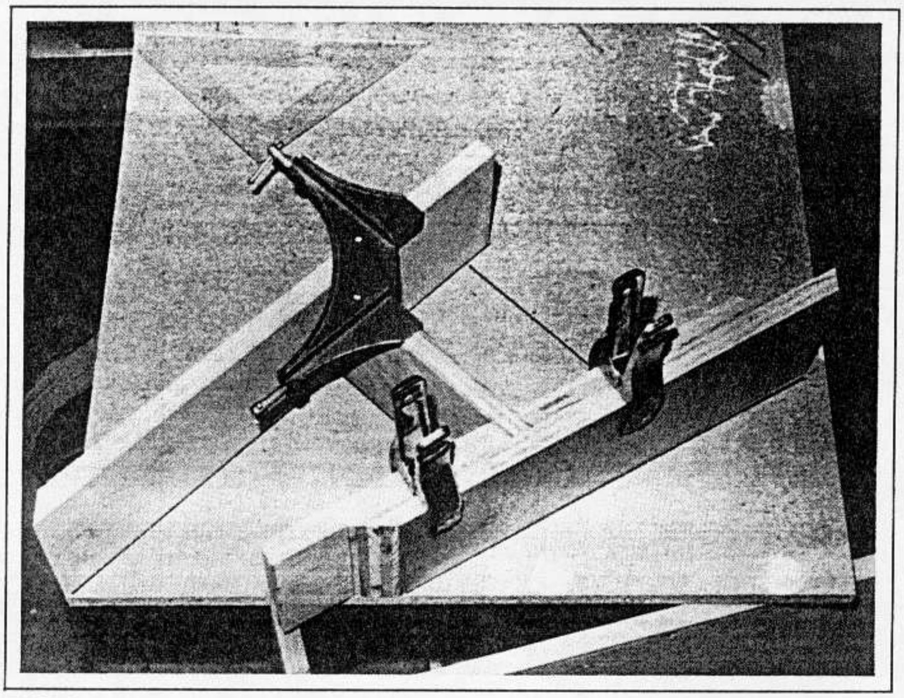

PHOTO 4: Aligning parts A, B and C on the top board.

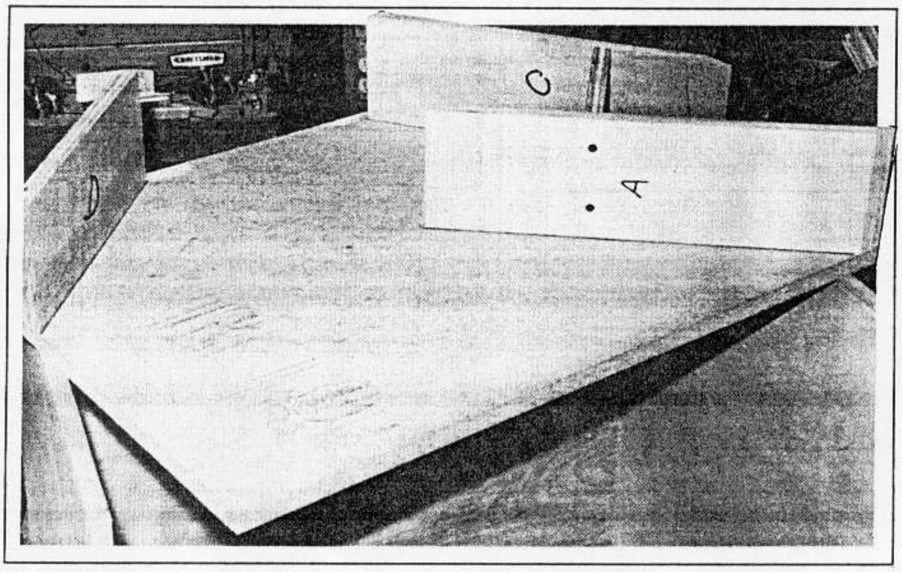

PHOTO 5: Parts A, B, C and D on the underside of the top board.

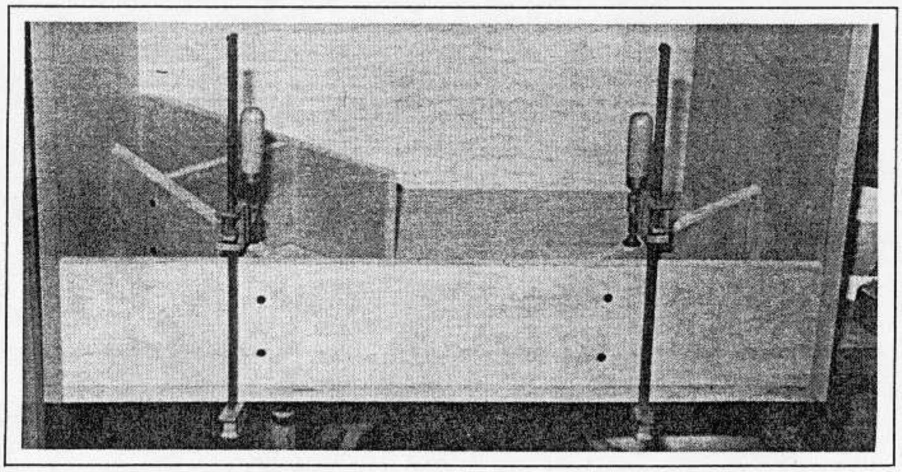

PHOTO 6: Fitting in piece I.

Continued from page 16

heavier particle board, but I chose the lighter plywood to make it easier to bring to the Stereophile Show.

As you can see from *Figs. 6* and *7*, most of the joints are butt type. I used hardened furniture screws and a cordless power screwdriver (*SB* 1/89) to join most of the pieces. Glue and nails will work just as well, but screws allow you to disassemble a part to change a partition. For exposed plywood edges, I glued a strip of solid birch to the edge and recut the board to the original size.

To aid in assembly and lining up the parts, I plotted *Figs. 6* and *7* to full scale on inch-scale transparent engineering graph paper. This procedure allows checking of parts dimensions and angles. I traced the critical angles, glued the tracings to poster board and cut the angles out with a sharp knife. These templates became my angle guides for setting up the saw.

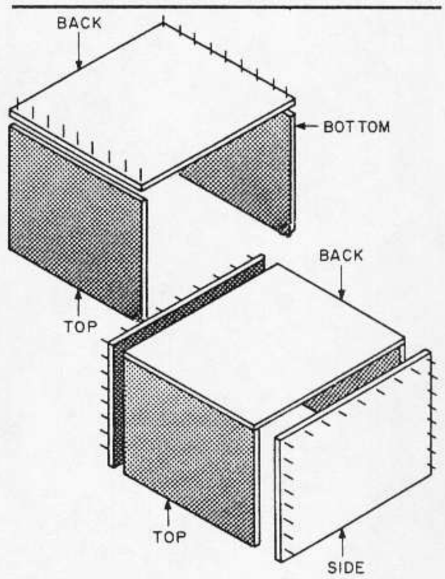

FIGURE 10: Attaching the back to the top and bottom, and attaching the sides to complete the box.

For parts such as pieces M and N, I also made templates for pattern sawing. I screwed these templates to boards cut just larger than the exact dimensions (*Photo 2*). I mounted a feeler gauge board to the saw fence and set it up so its vertical edge lined up exactly with the saw blade edge on the left side. I aligned the lower edge of the feeler gauge so it would index against the template but just clear the top of the board (*Photo 3*). To cut out the piece, I ran the template/board through the saw on one side, rotated the piece to the next cut, repeated the process, and so on. If you have the feeler gauge set up well, you

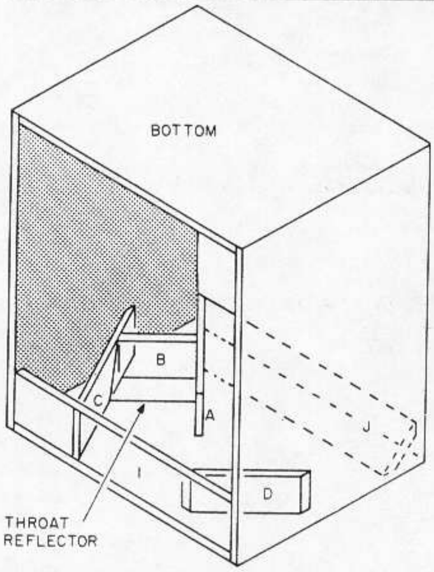

FIGURE 11: Fitting in the corner reflectors.

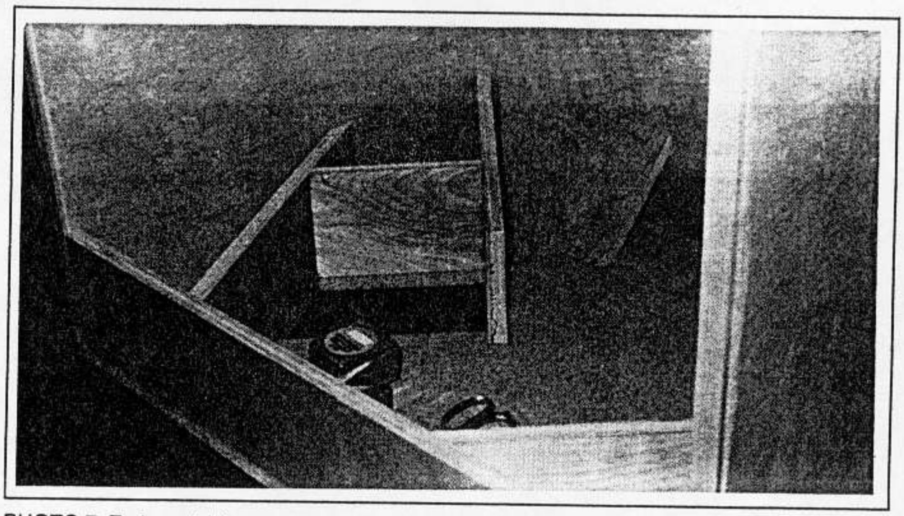

PHOTO 7: Trying a trial compound angle for the corner reflector J. Note: The throat opening, shown cut on a temporary top piece, is for experimentation purposes.

can reproduce the same part as many times as required.

HORN ASSEMBLY. Using a template based on *Fig. 7*, draw off the alignment lines for parts A, B, C and D on the top piece. Then attach parts A, B, C and D to the underside of the top piece (*Photos 5* and *6*). For this procedure, it helps to have a variety of clamps. Attach the top, bottom, back and side pieces together (*Figs. 10*). Using clamps as demonstrated in *Photo 6*, fit part I in the front. Avoid gaps between the top piece and part I.

Now you do some cut-to-fit operations. As shown in *Fig. 11*, the throat reflector and part J each require cutting a compound angle on one side. Because accuracy in parts cutting and assembly vary from builder to builder, I did not specify the exact dimensions of the two corner reflectors. Take some scrap stock and cut a length with the same cross section as part J and the throat reflector. Then try some approximate cuts on short sections of the scrap stock and check the fit as shown in *Photo 7*. If you get the fit somewhat close but there are still gaps, use Mortite or other caulking material to fill in the gaps.

Use the top template to transfer the throat opening position and placement of parts A, B, C and D onto part E. Cut out the throat opening with a saber saw. Fit part E into position and attach to parts A, B, C and D and to the sides and the back. After this step, the box should look like *Fig. 12*.

Next comes the back chamber assembly. First, attach parts F and H to the three M pieces with glue and screws/nails because the back chamber has to

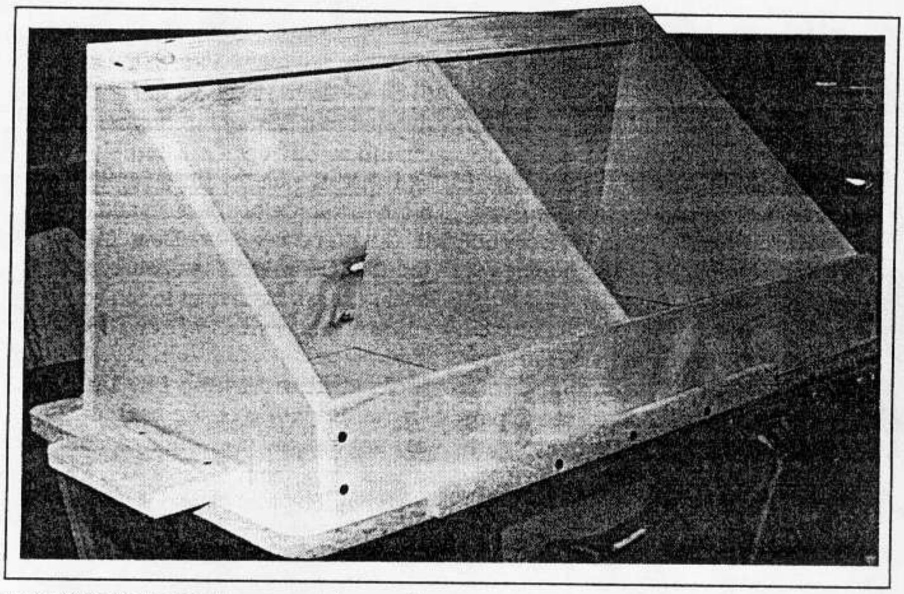

PHOTO 8: Back chamber assembly on a jig.

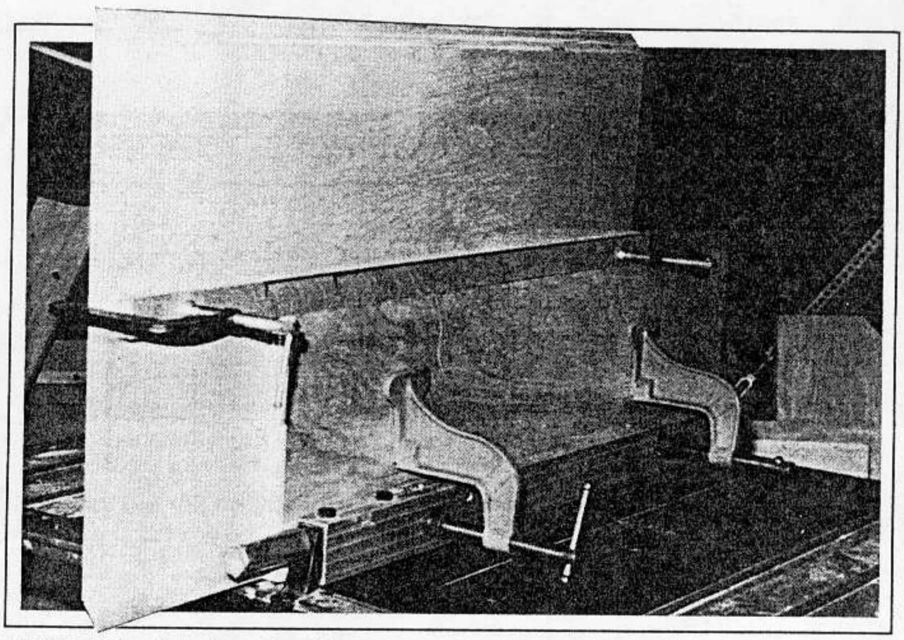

PHOTO 9: Auxiliary fence for table saw to aid cutting part G.

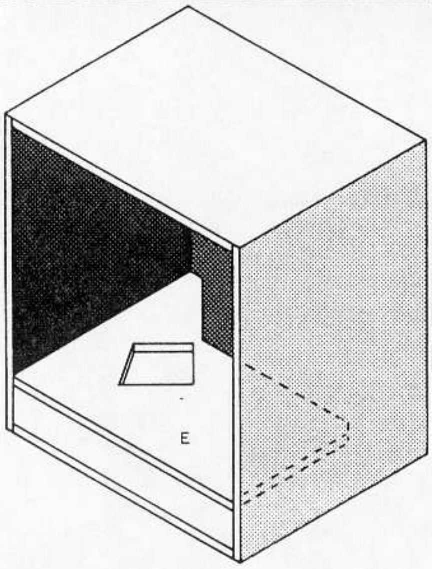

FIGURE 12: Part E in place.

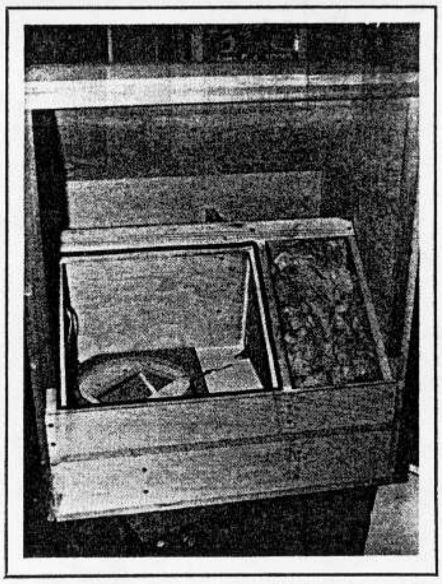

PHOTO 10: Finished back chamber with speaker mounting board.

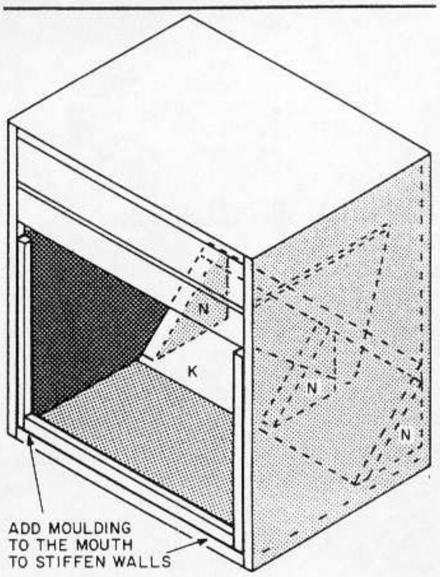

FIGURE 14: Installing the K corner reflector.

be sealed. Then attach the beveled 2 by 4 to the top of the M pieces and to part F. It helps to build a jig (*Photo 8*) to keep all the parts properly aligned. It is especially hard to cut the 40° angles on part G because you must keep the board vertical on the table saw. To solve the problem, I made an auxiliary fence (*Photo 9*) clamped to the regular fence with hold-down clamps made by Pony. I clamped a straight 1 by 1 piece to part G, allowing it to ride on top of the auxiliary fence in a level fashion. Check to see if part G fits properly but don't mount it. Attach divider piece L to F with screws.

You are now ready to install the back chamber assembly. Slide in the assembly to check on fit as shown in *Fig 13*. Draw lines on part E where it contacts the back chamber. Lift up the assembly so you can spread glue on those contact areas. Slide the assembly back in and attach it to E with corner L brackets. Make sure the divider (part L) is flush against the back. Attach the divider to the back with screws. Screw parts M1 and M3 to the side pieces.

Next take some scrap 1 by 1 stock and frame the inside of the back chamber, making a slight inset while mounting the pieces for a foam tape gasket. I recommend drilling a 2″ diameter hole through the side piece and M1 for a banana connector cup. As an optional procedure I also made a board with an 11″ diameter cutout to mount the driver (*Photo 10*). Also fill the extra cavity with fiberglass to prevent any extra resonance problems. Part G is now ready for mounting with screws. Make sure you have a sufficient number of screws around the foam gasket.

Turn the box over and install the K corner reflector (*Fig. 14*). I used the triangular pieces N to help the proper alignment and stiffen the reflector. As you can see in *Photo 1*, I framed the mouth with

Continued on page 22

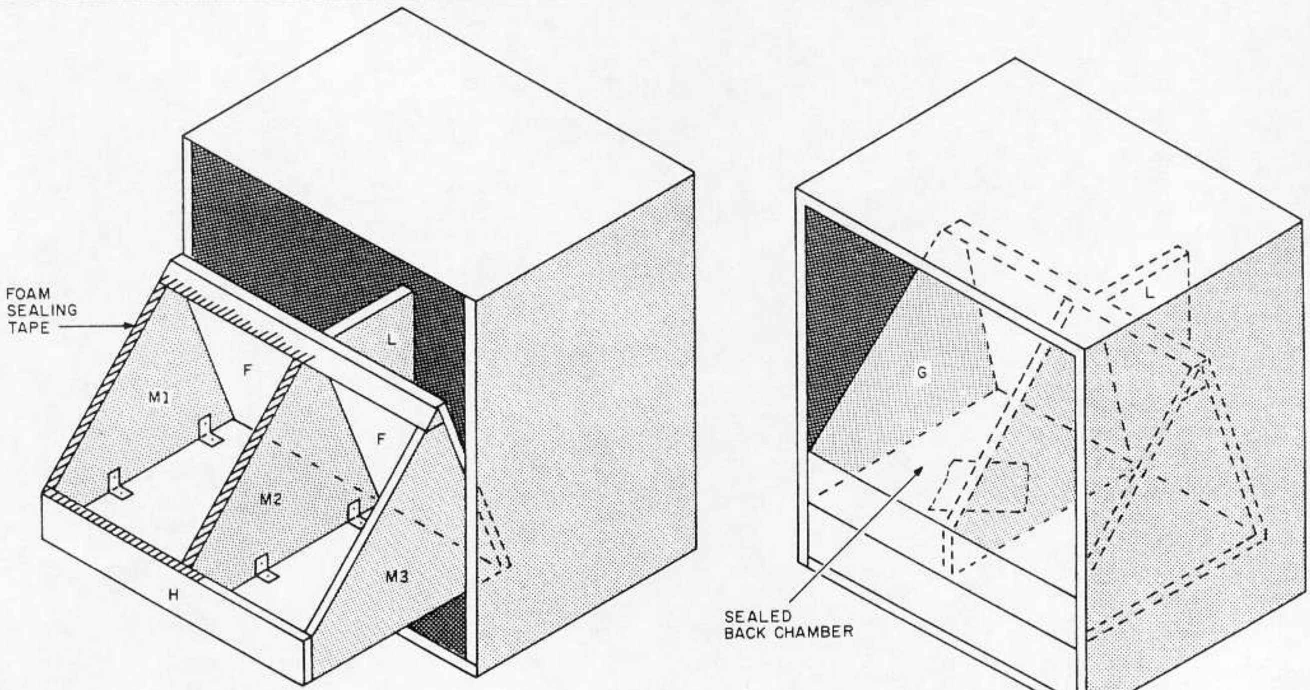

FIGURE 13: Installing the back chamber assembly.

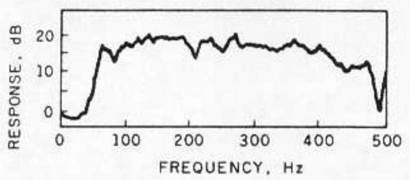

FIGURE 15: Response of the 50Hz horn against a wall.

Continued from page 20

some 1 by 2 birch stock, leaving a gap at the top to slide part G in and out.

STEP 9. You might wonder how I determined the back chamber volume. When I constructed the first prototype, I made an identical top piece from particle board and cut the throat opening in it (*Photo 9*). I didn't cut the throat in part E until later. Then I mounted the EVM12L driver on top and fitted several trial back volume boxes until I found one that resonated at 50Hz. *Photo 11* shows the test setup. I determined the test volume to be 2,644 cubic inches including driver volume, about twice the calculated volume. The reason for the discrepancy is our formula was derived for an infinite horn and this model is a one-eighth size. For quarter-size horns that I have built, the experimental back volume approaches the theoretical value.

Photo 12 shows the EVM12L driver installed in the back chamber. After installation attach part G to the back chamber with screws and measure the system resonance. It should be about 50Hz. If it is higher by a few Hz, put more stuffing in. But the stuffing will lower the resonance by only a few Hz. Normally I tack a layer of fiberglass to the back of part G just to damp the panel and cut down any back radiation. If the resonance is too low by a few Hz, the volume is too large. Reduce the volume experimentally by putting polyethylene bottles filled with water in the back chamber. When the system resonance is raised enough, approximate the volume of the bottles with blocks of wood attached to the sides of the back chamber. If the system resonance is very low, say 35Hz, you have a serious air leak in the back chamber. Go back and recaulk any suspicious voids along the joints.

STEP 10. Many builders have arrived at the system integration step and faltered because many of the normal speaker building rules of thumb don't apply to horn systems due to their high efficiencies and bandpass characteristics. Depending on the location of the horn in relation to corners and walls, you can obtain a 3 or more dB variation in apparent sensitivity. Normally, in a corner you will measure almost 110dB SPL sensitivity.

Pull the horn away from the corner but still against a wall, and the sensitivity will go down 3dB. You can get good bass response with a wall position (*Fig. 15*), and in many situations a wall position may be the only solution. But the bass will sound deeper with a corner position. Try another variation: turn the horn on its side to see whether the response sounds better. A hand-held pink noise analyzer, such as the Audiosource RTA (*SB* 4/86), will help sort out the sensitivity levels.

Most midrange horns I build (*SB* 1/86) have sensitivities between 100 and 105dB, so to integrate the bass horn with these midranges you must either attenuate or biamp. I have had reasonable success with L-pads made from high power sand-filled fixed resistors. My limited attempts to biamp have resulted in degraded sound quality. However, readers are invited to experiment with biamping and report their results to *SB*.

Because horns have steep mechanical rolloffs in their responses, they are bandpass loudspeakers. Horns trade off wide band response and lower efficiency for narrow band response and high efficiency. The steep mechanical rolloffs also produce many 360° phase rotations that make it almost impossible for higher order passive crossovers to function properly. But the simple 6dB crossover at 400Hz works nicely between a bass and midrange horn as found by Klipsch many years ago (Klipsch interview, *SB* 4/89).

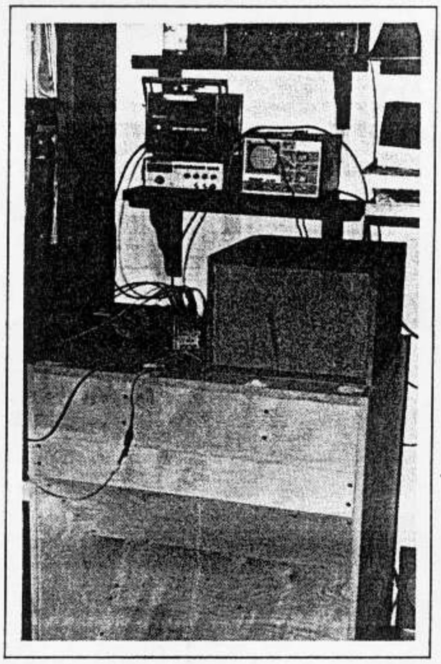

PHOTO 11: Experimentally determining the back chamber volume.

RESULTS. As shown in *Fig. 15*, the response as measured against a wall is quite flat between 60 and 400Hz within ±3dB. Unfortunately I was not able to move our furniture away from the corners to make a corner measurement. But take my word, the response goes deeper in a corner. I measured the reponse with a Spectrum Dynamics FFT analyzer operating in an averaging mode with white noise input to the speaker. The absence

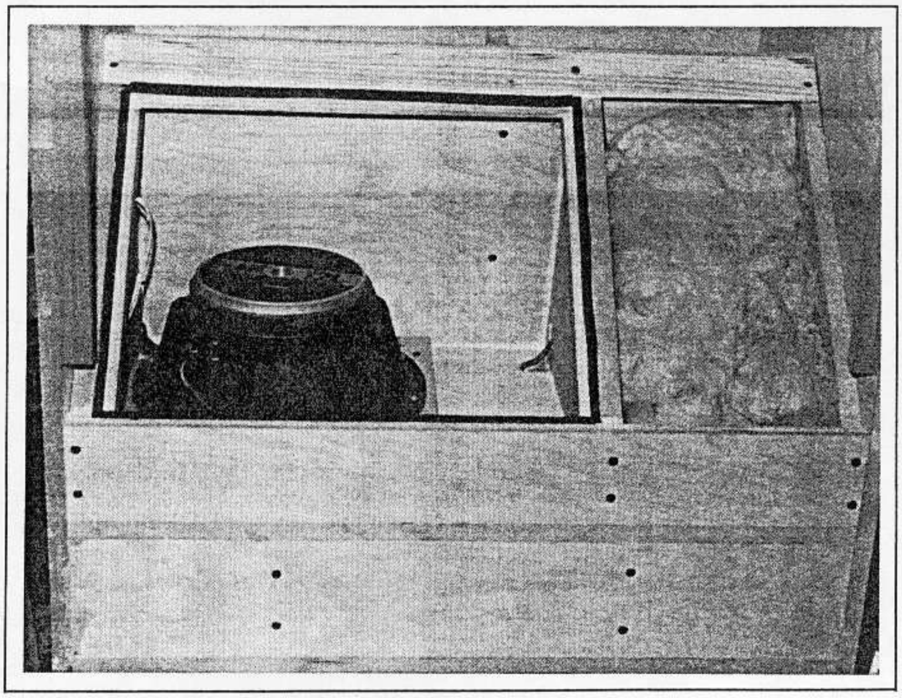

PHOTO 12: Back chamber with EVM12L driver installed.

of any major spectrum anomaly indicates that the horn folding design was done properly.

The bass response sounds tight and smooth. The large bass drum on the Telarc recordings (Holst: *Suites for Winds* CD-80038 and Prokofiev: *Alexander Nevsky* CD-80143) has real impact and character. The Sheffield recording of the *Firebird Suite* by Stravinsky (CD-24) also has physical impact. However, depending on how the recording was miked, on other recordings the bass may sound hollow since most of the frequency components are below the sharp lower horn cutoff of 50Hz.

The bass is only half the story. Most of an orchestra's large brass, woodwind, and string instruments have fundamentals in the 100-400Hz region. This bass horn makes those instruments sound real, as one friend told me. All you need do is put on a good recording of Dvorak's *Serenade for Winds* to be convinced.

CONCLUSIONS. As you can see, I've come a long way from my initial horn articles in *SB* (3/80 and 2/83). This project is a culmination of a number of experimental horns where I made mistakes in design and found out how to correct them. In this article I have given the reader a road map that can be applied to any bass horn loudspeaker. The 50Hz horn project is complicated but well within reach of any competent woodworker with a table saw. Those who attempt and finish the project will be rewarded with a unique loudspeaker presently unobtainable on the commercial market.

ACKNOWLEDGMENTS. I thank Rich Roberts for untiring assistance during the horn building and for most of the photos, Manfred Buechler for *Photo 1*, Effrain Gonzales for financing the project, Vincent Salmon and Ed McClain for technical discussions on horn design, and Larry Hitch of Madisound and Ed Dell for the opportunity to display the Show Horn at the Stereophile Show.

REFERENCES

1. Keele, D. B., "Low Frequency Horn De-

Continued on page 75

To my knowledge, the only company that publishes horn designs for its drivers is Electro-Voice in Buchanan, Michigan 49107. They sell plans (TL-4050 and TL-5050) for their EMM12L and EVM15L drivers.

If you have specific design requests, write your desires in another letter to *SB*, and maybe other readers or I can point you to the appropriate design.

SHOW HORN

continued from page 23

sign Using Thiele/Small Driver Parameters," AES Preprint #1250, 1977.

2. Leach, W. M., "On the Specification of Moving Coil Drivers for Low Frequency Horn Loaded Loudspeakers," *Journal* of the Audio Engineering Society (JAES), Vol. 27, pp. 950–959, 1979.

3. McClain, E. F., "Comments on Reactance Annulling Horn Loaded Loudspeaker Systems," *JAES*, Vol. 29, p. 523, 1981.

4. Leach, W. M., "Author's Reply to Comments by E. F. McClain," Vol. 29, pp. 523–524, 1981.

5. Plach, D. J., "Design Factors in Horn Type Loudspeakers," *JAES*, Vol. 1, pp. 276–281, 1953.

6. Salmon, V., "A New Family of Horns," J. Acoustical Soc. Am., Vol. 17, pp. 212–218, 1946.

7. Cohen, A. B., "Making the University Classic," *Audiocraft*, Vol. 1, pp. 16–18, February 1956.

TWO-WAY SYSTEM

continued from page 24

The front and rear I painted flat black. For input terminals, I used gold-plated binding posts, two sets for each speaker. The grille assemblies are black polyester fabric stretched over a frame constructed of ¼ round moulding. For the final touch, I placed some black felt around the tweeters to reduce nasty diffraction effects. For better imaging, all serious listening would be done with the grille assemblies removed.

SOUND QUALITY. When using these speakers without the subwoofer, they sound very smooth and well balanced with quite pleasing bass output for their size. They present a wide and deep soundstage with superb focus. The sound is clear, allowing me to hear details I had not previously heard in familiar recordings. They also do an excellent job of reproducing voice and string instruments—both sound natural and uncolored. Overall I am very pleased with their performance and feel these speakers compare favorably with some well known more expensive systems.

Continued on page 76