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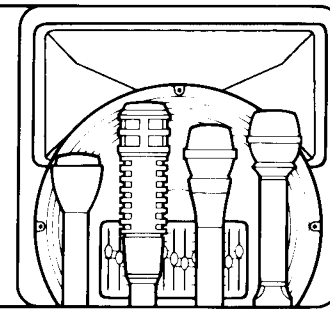
Pro Sound Facts



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DL SERIES WOOFERS—PLANS FOR RECOMMENDED VENTED ENCLOSURES AND SMALL- AND LARGE-SIGNAL PERFORMANCE IN THESE ENCLOSURES

Introduction

In 1972, Electro-Voice introduced the first American speaker system based on the vented-enclosure modeling technique of A.N. Thiele and R.H. Small. Thiele's now-classic papers—published in America ten years after their availability in Australia—have been the basis for all of our direct-radiator low-frequency systems design for over a decade. Moreover, the Thiele-Small techniques are now used world-wide for the rational design of low-frequency systems—by manufacturer and serious amateur alike.

Vented enclosures (also known as ported or bass-reflex enclosures) have been used since the early days of loudspeakers. However, no one knew how to predict the performance of a given speaker/enclosure combination. A box had to be built and then measured or auditioned. That many results were less than perfect will come as no surprise.

Thiele and Small changed all of this by showing how the speaker itself, the net internal volume of the enclosure and the tuning frequency of the vent interact to produce the overall performance of the system. Today, aided by the computer, quick, "on-paper" analysis of vented speaker systems is routine and Thiele and Small are recognized for their fundamental contribution to the art.

A good vented design provides essentially flat response to just above a low-frequency 3-dB-down point (f_3), with system output rolling at some rate below that frequency (typically 24 or 36 dB per octave). The f_3 is close to the box tuning frequency, which is determined by the stiffness of air in the enclosure and the mass of air in the vent. As frequency goes down toward box tuning, system output comes increasingly from the vent, driven to full acoustic output by an ever-reducing excursion of the woofer itself. At box tuning, output comes almost exclusively from the vent and woofer excursion is at a minimum. This is quite different from a sealed system (no vent) where cone excursion increases *four times* for every octave reduction in frequency. Reduced excursion means lower distortion, since the vent is not subject to the mechanical suspension limitations of the speaker. The excursion-controlling aspect of a good vented design is of fundamental importance, particularly in professional sound systems where high acoustic output and low distortion are desirable.

Readers familiar with Thiele's papers will know of the numerous "alignments" where certain speaker parameters work together with a specific enclosure volume and tuning frequency to produce a certain frequency response. The casual reader of Thiele's papers may conclude that a new speaker must be designed and constructed every time a different system efficiency or f_3 is desired. However, a thorough understanding of Thiele's model shows that system performance is relatively insensitive to variations in certain speaker characteristics, e.g., suspension compliance. Thus, knowledgeable deviation from specified characteristics produces very useful response shapes that depart only slightly from ideal performance. The material contained in Pro Sound Facts No. 7 is a superb example of the wide range of performance possible with a given speaker. Instead of using the Thiele model to synthesize some "ideal alignment," the Thiele model has been used to extract the best performance from a given loudspeaker over a wide range of enclosure sizes.

An annotated, selected list of papers on vented systems is given at the end of this document.

How to Select the Speaker and Enclosure You Need

Chart 1 provides a good start for selecting the speaker and enclosure:

	Low-Frequency Reproducers			Very-Low-Frequency Reproducers	
	DL12X	**DL15X**	**DL18X**	**DL15W**	**DL18W**
Application	Woofer in 2-way speech systems; midbass in 3- and 4-way systems	Woofer in 2-way speech and music systems	Subwoofer, especially for system f_3's of 40 Hz and above[2]	Compact or extended-bass woofer; compact subwoofer, especially for system f_3's of 40 Hz and above[1,2]	Subwoofer, especially for system f_3's under 40 Hz[2]
Recommended Range of Enclosure Volumes	1.3-1.8 ft^3 (35-51 liters)	2.5-7.1 ft^3 (71-200 liters)	7.0-14 ft^3 (200-410 liters)	2.5-7.1 ft^3 (71-200 liters)	7.0-20 ft^3 (200-580 liters)
Associated Range of Low-Frequency 3-dB-Down Points— Normal	80-72 Hz	69-48 Hz	48-36 Hz	52-36 Hz	40-26 Hz
Step Down (with EQ)	55-48 Hz	48-31 Hz	34-26 Hz	37-27 Hz	29-22 Hz

1. Compact enclosure requirements make it practical to use the DL15W in multiples, for increased maximum output. Multiple DL15W's can be quite appropriate for high-output, below-40-Hz subwoofer applications.
2. In general, subwoofers for dance environments and concert reinforcement are best limited to about 40 Hz. Cinema sound and special-effects applications require performance to 30 Hz and below.

Chart 1 — DL Woofer Applications,
Range of Enclosure Sizes and Low-Frequency Performance

Chart 3 on page 11 describes 34 single-speaker systems and 28 dual-speaker systems. A variety of physical and acoustic information is given for each system, including the system low-frequency 3-dB-down point. Each enclosure has a specific number, e.g., TL10-36. The first digit pair is approximately four times the net internal volume, in cubic feet. The second digit pair is the tuning frequency, in Hz. Thus, the TL10-36 is a 2.5-cubic-foot box tuned to 36 Hz. "D" indicates a front baffle cut for two woofers, e.g., TL10D-75.

Chart 2 lists selected woofer specifications which will also aid in the selection of a particular system:

	DL12X	**DL15X**	**DL18X**	**DL15W**	**DL18W**
Nominal Diameter	12 in.	15 in.	18 in.	15 in.	18 in.
Sound Pressure Level at 1 Meter, 1 Watt into 8 Ohms, 100-800-Hz Average	98 dB	100 dB	97 dB	97 dB	95 dB
Selected Thiele-Small Parameters— η_0 (half-space reference efficiency)	4.5%	5.0%	5.2%	2.7%	2.9%
X_{max} (zero-to-peak linear displacement of diaphragm)	0.16 in.(4.1 mm)	0.16 in.(4.1 mm)	0.16 in.(4.1 mm)	0.22 in.(5.6 mm)	0.22 in.(5.6 mm)
$P_{e(max)}$ (thermally limited maximum input power)	300 watts	400 watts	400 watts	400 watts	400 watts

Chart 2 — Selected DL Woofer Specifications

A review of Charts 1, 2 and 3 shows that:

1. The larger speakers and enclosures tend to have lower f_3's.
2. Within a given series (DLX or DLW), for the same f_3 the smaller speakers tend to have smaller enclosures. This may be of particular interest when woofers are used in multiples (see Use in Multiples section).
3. The DLW's tend to have more extended bass response than the DLX's. This is achieved at the expense of efficiency (about 3 dB) but with a similar increase in peak output ability ($X_{max} = 0.22$ inches versus 0.16 inches). This increase in peak output is particularly useful for high-level reproduction of frequencies below 40 Hz. See the Small- and Large-Signal Performance section for more details.

For each speaker model, the smallest and largest enclosures were chosen subjectively, taking into account smoothness of response, appropriateness of the f_3 and excursion limiting within the passband. This third factor is a "large-signal" consideration discussed separately in the Small- and Large-Signal Performance section. This section gives much more detail than the f_3's shown in Chart 3, for each speaker/enclosure combination. Readers will want to consult this section particularly when the high-level reproduction of very low frequencies is of interest.

Step-Down Operation

Half of the systems shown on Chart 3 operate in the "step-down" mode, which approximates a B_6 Thiele alignment. Step down is a good way to extend system low-frequency response by increasing amplifier power at certain frequencies instead of enclosure size.

In step down, the enclosure is tuned to a lower-than-normal frequency. This increases system output at the new tuning frequency and reduces output slightly in the region of original tuning. The smoothly falling response which results can be equalized to provide a new system 3-dB-down point that is about 0.7 that of the original. To achieve a similar response extension without equalization would require an enclosure at least *twice* the size.

In the step-down mode, system input is increased at the lower end of the operating range, by a maximum of 6 dB close to the new tuning frequency. Note that this boost does not affect system instantaneous peak output, which is related only to the speaker's linear displacement ability and effective diaphragm area.

XEQ-2 Crossover/Equalizer. The EV XEQ-2 crossover/equalizer can provide the equalization required for step-down operation. It has five switchable peak-boost frequencies, some of which are precisely those recommended in Chart 3. Others are sufficiently close, within ±5%, to provide no significant performance compromise. The XEQ-2 can be modified to provide other peak-boost frequencies.

Pro Sound Facts No. 8, available from Electro-Voice at no charge, describes this modification.

Subpassband Speaker Protection

Below the enclosure tuning frequency, cone excursion increases rapidly. Since acoustic output is also falling rapidly, there is no utility in driving the system with signals much below the tuning frequency. While such signals may be in the program material, they are often extraneous—such as from record-surface irregularities or a dropped microphone. DL woofers are ruggedly designed and have a high maximum excursion before damage (±0.5 inch). Thus, in the many installations where subpassband signals are moderate in level, the probability of speaker damage is very slight and overall system performance should not be compromised in a noticeable way. However, *high-output systems, especially subwoofer systems, should be protected by a high-pass filter with a 3-dB-down corner frequency of about 0.8 the enclosure tuning frequency listed in Chart 3.* Below the corner frequency, a rolloff of 12 dB per octave is usually sufficient.

Without protection, subpassband signals may "bottom" the woofer. Damage will probably result, especially after repeated occurrences. Even if bottoming does not occur, the subpassband signals waste amplifier power and modulate (distort) the frequencies which are within the system's operating range. *Much "woofer distortion" or "muddy bass" can be attributed to lack of subpassband protection.*

The step-down equalization described previously provides protection automatically. The Electro-Voice XEQ-2 crossover/equalizer also provides protection in it's "flat" low-frequency switch position; response is 3-dB-down at 30 Hz and falls at 12 dB per octave below that frequency. Other high-pass filters are commercially available. Such protection is also provided in some ⅓-octave equalizers.

Small- and Large-Signal Performance

The response curves on pages 13, 14 and 15 show the small- and large-signal acoustic power output versus frequency for each speaker/enclosure combination. This presentation reveals much more performance detail than Chart 3, which only shows the low-frequency 3-dB-down points.

All curves are of the speaker system's total acoustic output. This is different from the typical free-field frequency response curve, which represents output at a given point, usually on the axis of the speaker or system. For most "woofer frequencies" (below about 500 Hz), these two measurements are similar and the similarity increases as frequency decreases. In any case, the curves shown relate usefully to perceived performance in most environments. The items contained within the parenthesis in the following paragraphs are certain Thiele-Small parameters, as listed in Chart 2 for all of the DL woofers.

Small-Signal Relative Output. Refer to Curve 21, which shows a DL18X in a 7.0-cubic-foot enclosure tuned to 45 Hz (TL28-45). Three separate performance characteristics are shown in Curve 21. The middle curve represents small-signal performance, relative to a 0-dB reference equivalent to the DL18X's half-space reference efficiency ($\eta_0 = 5.2\%$). (The small-signal curve is coincident with the bottom curve over much of the frequency range, but this is not always the case.) The f_3 shown in Chart 3 for the TL28-45/DL18X is taken from the small-signal curve. This curve may be loosely interpreted as the system's frequency response. "Small signal" means that the speaker's thermal power capacity ($P_{e(max)}$) and linear cone-excursion ability (X_{max}) have not been exceeded. While the small-signal curve gives in indication of system performance at low-to-moderate levels, it gives no indication of potential problems in high-output applications.

Large-Signal Relative Output. The lowest curve on Graph 21 shows the large-signal output, relative to a 0-dB reference equivalent to the DL18X's maximum midband acoustic output, the product of it's half-space reference efficiency and thermal power capacity (5.2% × 400 input watts = 21 acoustic watts out).

If system output were limited only by the speaker's thermal power capacity, the large- and small-signal responses would be coincident. However, as is often the case, a speaker's displacement limit—the point beyond which cone excursion no longer responds linearly to an increasing input—may occur at an input power that is less than the thermal power capacity, especially for high-power-capacity speakers. This causes the large-signal response curve to fall below the small-signal curve. This does not usually occur at high woofer frequencies because large excursions are not required to produce a given sound pressure level at these frequencies. However, as frequency is decreased, the cone excursion required to maintain a constant sound pressure level increases substantially and displacement limitation is likely to occur. In optimally vented designs, the displacement limitation usually disappears near the enclosure tuning frequency (usually close to the system's f_3) because system output comes almost entirely from the vent, which is not subject to mechanical speaker-suspension limitations.

A review of Curve 21 shows that the maximum excursion limitation within the passband (above the f_3) is about 6 dB at 70 Hz. Below 70 Hz, the excursion limitation reduces and disappears at about 50 Hz. Note that the limitation is with respect to the 400-watt thermal power capacity. A speaker with a 100-watt capacity (6 dB under 400 watts) would show no excursion limitation, although it's actual peak output ability would be the same.

A review of the normal-mode curves (those without step-down equalization) shows that excursion limitations tend to be less for the higher f_3's and the larger cone diameters. Note also that excursion limitations tend to be less for the DLW series ($X_{max} = 0.22$ inches) compared to the DLX series ($X_{max} = 0.16$ inches).

Please note! The open and wide-spread distribution of detailed information on speaker excursion limitations has, to our knowledge, never before occurred. Keep in mind that all speakers are subject to the performance limitations herein described. These limitations have nothing to do with "advertising" specifications like voice-coil diameter, flux density or magnet weight. They are related solely to a speaker's linear cone-excursion ability (X_{max}) and effective cone area. The X_{max} specification for Electro-Voice DL woofers is equivalent or superior to that of other popular professional speakers. Pro Sound Performance Comparisons No. 5 presents interesting comparative information. This document is available from Electro-Voice at no charge.

Maximum Acoustic Output. The top curve in Curve 21 shows maximum output in absolute terms. It has the same shape as the relative large-signal output curve described earlier. However, in this case, actual sound pressure level and acoustic power output can be read from the graph. Of course, the sound pressure level depends not only on the system's maximum acoustic power output but also on the acoustic environment. The sound pressure levels shown are in the reverberant field (several feet from the speaker and beyond) of a space whose room constant, R, is 200 ft^2. This room constant describes a typical living room with a volume of about 3,000 cubic feet and average absorption. The sound pressure levels associated with other room constants may be calculated as follows:

$$SPL_{new} = SPL_{curve} - 10 \log_{10} \frac{R_{new}}{200}$$

where SPL is the sound pressure level in dB and R is the room constant in ft^2.

Note that all maximum-output curves are shown for single-woofer enclosures. Add 6 dB for the dual-woofer designs.

Systems in Step Down. For systems in the step-down mode, the relative small-signal output curve includes not only the performance of the system itself but also the effect of the boost-and-cut equalization. The equalization has no effect on the large-signal output but does have the effect of separating the small- and large-signal curves except at the very top of the frequency range shown. Refer to Curve 22, which shows the TL28/DL18X combination of the previous example (Curve 21) except that the box has been tuned to a lower frequency and the appropriate equalization applied. Note the extension of system low-frequency limit (f_3 reduced from 48 Hz to 34 Hz).

It is interesting to compare Curve 22 to Curve 29. Curve 29's TL56 enclosure is large enough (twice the size) to achieve Curve 22's extended response without equalization. Note that the large-signal and maximum-output peformance in Curves 22 and 29 is virtually identical, despite the equalization used in Curve 22. The EQ boost of Curve 22 "exposes" the DL18X's thermal power limit only over a very narrow frequency range (33-39 Hz).

Use in Multiples

Speakers may be used in multiples to increase acoustic output. In the following discussion, it is assumed that all speaker cones are operating in unison (in phase) when a common signal is applied.

A 6-dB increase in maximum acoustic output results when two speakers are located side by side. For operation at very low frequencies, the woofer cones "mutually couple," acting as one speaker with cone area and power-handling capacity twice that of a single speaker. The doubling of cone area doubles efficiency, providing a 3-dB increase in sound pressure level. The second 3 dB comes from the doubling of power capacity.

Mutual coupling occurs when the frequency is such that the center-to-center distance between the two speaker cones is less than about one-quarter wavelength. For a given frequency, the maximum center-to-center distance can be calculated from the following formula:

$$D_{max} \cong \frac{3{,}000}{f},$$

where D_{max} is the distance in inches and f is frequency in Hz. When D_{max} is greater than one-quarter wavelength, as would occur if two single-woofer systems were widely spaced, the level increase tends to be limited to the 3-dB power-handling increase.

More than two speakers can be used for increased output. In general, maximum acoustic power output ability increases as the square of the number of mutually coupled cones. For example, four cones would provide 4^2 or 16 times the power output of a single cone, an increase of 12 dB. A "two-by-two" array of four cones results in maximum coupling. The four cones can also be placed side by side, but the 12-dB increase in maximum output will be somewhat reduced since the two end cones are not closely coupled except at very low frequencies.

Multiple Small Speakers versus Multiple Large Speakers. For the same occupied volume, multiple small-diameter speakers can have more acoustic output than multiple large-diameter speakers. This occurs because, for the same f_3, the smaller speakers in a given series (DLW or DLX) tend to have smaller enclosures. When space is at a premium and cost is a secondary object, this output advantage can be attractive.

For example, consider the TL20-40/DL15W versus the TL28-38/DL18W. Three TL20-40 enclosures occupy about the same volume as two TL28-38 enclosures (15.3 ft^3 versus 14.0 ft^3). Which configuration has the highest maximum output ability?

Singly, the TL28-38/DL18W has a 1.5-2.5-dB maximum-output advantage in the 50-100-Hz range, primarily due to the DL18W's larger cone area. See Curve 35. However, the three 15-inch speakers, due to mutual coupling, have $3^2 = 9$ times the output of a single speaker, an increase of 9.5 dB. The two 18-inch speakers have only a $2^2 = 4$ times the output of a single speaker, an increase of 6 dB. Thus, the 15-inch configuration now has the maximum-output advantage, 1.5-2.5 dB in the 50-100-Hz range previously noted and about 3 dB in the 40-50-Hz range. See Curve 36.

Enclosure Plans

The following information describes in detail each of the 60 enclosures listed in Chart 3.

Vents. For simplicity, the vent material is standard PVC tubing with the inside diameter as listed in Chart 3. The locations and diameter of the vent opening in the baffle must accommodate the outside diameter of the PVC tubing and must clear any internal bracing. The vent length given in Chart 3 is the total length as measured from the front (outside) of the baffle into the enclosure.

Some vents are too long for the enclosure depth. See the vent-modification instructions of Figure 13.

Front Baffles. The front-baffle sketches shown in Figures 1 through 12 are dimensioned for worst-case (largest) vent configurations and speaker combinations, and are associated with the specific enclosures listed, which have no specific baffle drawings, a dimensional baffle layout should be made to insure that enough clearance is provided between the speaker(s), vent(s), grille frame (if used) and the interior enclosure braces. The overall baffle dimensions for *all* enclosures are shown in Chart 4 on page 12.

Caution should be exercised when locating the speakers and vents on the front baffle to avoid interference with the internal bracing or any grille frame placed over the front baffle. Also, the grille frame or braces must not interfere with speakers or vent openings.

Other Enclosure Piece Parts. A general drawing, Enclosure Piece-Part Exploded View, covers all of the Chart 3 enclosures. See page 19. This drawing shows simple butt-joint construction and contains reference numbers for parts whose dimensions are listed in Chart 4.

Grilles. The construction shown in the Enclosure Piece-Part Exploded View accommodates a recessed grille. The grille framework may be constructed of 1-inch square wood, except for the small TL5 enclosures which require ¾-inch wood. The grille framework will require braces if it is very large.

Speaker Mounting. The DL woofers may be mounted on the front or rear surface of the front baffle. Details are given in the individual engineering data sheets.

Front mounting (from the outside of the enclosure) provides the simplest enclosure construction, since no removable panels are required. Front mounting also means convenient system maintenance, as long as the front of the enclosure is accessible. The optional Electro-Voice SMH-1 speaker mounting kit facilitates front mounting. It includes four speaker-holding clamps and all necessary hardware.

If the speakers are rear mounted, the front baffle or rear panel of the enclosure must be removable. Removable panels should be secured with wood screws and weather-stripping tape.

Treatment of Inside Surfaces. Three mutually adjacent inside surfaces of the enclosure (top, one side and rear) should be lined with a 1- or 2-inch thickness of glass wool or similar acoustic absorbing material, to prevent internal reflections from affecting midrange performance. Building insulation with its paper backing removed is satisfactory. Securely staple the material into place.

No absorbing material should be placed over or within the vent.

Enclosure Variations

The following guidelines apply if the Chart 4 enclosure dimensions are not appropriate.

Different Box Dimensions. It is not necessary to use the suggested enclosure dimensions if a different height, width or depth is desired, provided the net internal volume is not changed. However, it is important to avoid extreme proportions. Particularly to be avoided are long, narrow cabinets. In general, for most applications, the shortest dimension of the enclosure should not be less than one-third the longest dimension. A good recommendation is width about two-thirds the height and depth about one-third the height.

The depth of the cabinet must allow the vent to operate freely. Minimum clearance should be one-quarter the internal depth of the enclosure. The vent-modification instructions of Figure 13 will be helpful when a vent is too long.

Volume Tolerances. Variations of ±5% of the specified net internal volume will not materially affect performance. To calculate the precise net internal volume, the space taken up by the vent, bracing and the speaker itself should be considered. These volumes can be ignored in the large boxes, but in the small enclosures can take up a sizable amount of the gross box volume. DL woofers have the following approximate volumes: 325 in.^{3} (DL12X); 500 in.^{3} (DL15W and DL15X); 750 in.^{3} (DL18W and DL18X).

Construction Guidelines

The following information covers general guidelines for material selection, piece-part fabrication, enclosure and grille assembly, and finishing, including commentary of interest to the inexperienced woodworker.

Plans. If the specific plans described in this guide are not used, dimensional drawings to the selected proportions should be prepared. These drawings should include all styling details, such as recessed or flush grilles and the type of corner construction (butt or mitered joints).

Materials. It is recommended that ¾-inch plywood or particle board be used for all six enclosure sides, although smaller enclosures (approximately two cubic feet and under) can be successfully constructed of ⅝-inch material.

The grille material is often cloth or perforated metal. Many acoustically transparent grille cloths, woven especially for audio use, are available. The simplest way to determine whether or not the material is acoustically transparent is to hold it up to a light source. If you can readily see through the material, it will probably not restrict system performance. Fuzzy cloth should be avoided.

Fabrication. To minimize material waste, lay out all cabinet sides on the sheets of plywood or particle board that will be used, according to the dimensional drawings. Speakers can be used as a template to locate their mounting holes in the front panel.

Cut all panels to size and perform the drilling and hole-cutting operations that are required on the front and back panels. At this point, the front and back panels may be painted, if desired. Cut the panel-support braces to length, making certain that the front and rear panel-support braces will meet at the corners to assure a complete seal at these points.

Cabinet Assembly. Cover the work surface with a clean, nonabrasive cloth, such as a blanket.

All enclosure joints must be securely glued together to assure strong construction. Polyvinyl wood glues are satisfactory, such as Elmer's Glue-All. All internal braces must be securely glued and nailed or screwed down into position. The nails or screws through the braces will retain all wood parts until the glue sets up. The nonremovable front and rear panels also must be securely glued and nailed into position. The front and rear panels may be used to square up the enclosure during assembly. The internal bracing is then installed for strength. Remove all excess glue from outside surfaces immediately, with a clean, damp cloth.

In the largest boxes—greater than about six cubic feet—extra internal bracing is usually required for the largest expanses of wood in order to prevent sympathetic vibrations from affecting overall system performance. It is recommended that a brace be glued and nailed between the front and rear panels, as near to the center of the panels as possible without interfering with the speakers.

After the glue has dried, apply a bead of sealer (such as GE or Dow-Corning adhesive/sealant) to all internal joints to assure an airtight enclosure.

Grille Assembly. Securely glue and nail the wood grille frame together. If additional bracing is added, be certain that it does not interfere with speakers or vents. Paint the wood frame with a color that will not show through the grille material.

Grille cloth should be gently but firmly stretched around the frame and stapled to the rear side. The stretching should be done in a uniform fashion to maintain a "straight-line" appearance in the weave of the cloth. Care must be taken to assure a neat appearance at the corners if they will be exposed in use. Trim excess cloth from the frame (a sharp knife or single-edged razor blade works well). Velcro fasteners are handy for retaining the grille. Attach them to the back of the grille frame and to the corresponding location on the front panel of the enclosure. Use staples and glue for this.

Finishing. Sand and fill outer surfaces to develop a smooth, clean surface. Paint front and rear panels if they were not painted prior to assembly. Apply external finish according to the material supplier's recommendations.

Checking the Frequency of Vent Tuning. Cone excursion is at a minimum at the tuning frequency. This minimum can be identified easily. Connect the system under test to the output of a power amplifier which is in turn driven by an audio oscillator. With the oscillator an octave or so above the desired tuning frequency, drive the speaker hard enough so that your hand can feel the cone motion. With one hand on the cone and the other on the oscillator dial, reduce the frequency. Excursion will at first increase and then begin to decrease. Eventually, excursion will reach a minimum and then begin to increase again. By "rocking" the oscillator dial back and forth across the minimum, the frequency of minimum excursion can be quickly identified. Oscillator dial-calibration accuracy should be ±5% or better. If this is in doubt, use a frequency counter.

Lengthening the vent will decrease the tuning frequency; shortening it will increase the frequency.

Speaker Hookup. Because of the very short runs encountered inside an enclosure, 18-gauge wire is more than satisfactory. Any holes through enclosure panels associated with speaker hookup should be carefully sealed to avoid air-turbulence noise.

Tools, Accessories and Supplies Required. The following list will facilitate successful enclosure construction:

1. Radial-arm saw or table saw. If not available, the lumber supply mill often will cut pieces to supplied dimensions for a nominal charge.
2. Hand-held jig saw, to cut openings for speaker components and vents. These openings also can be cut be the lumber supply mill.
3. Drill and bits for screw clearance and speaker-mounting holes.
4. Phillips- and slotted-head screwdrivers.
5. Hammer.
6. Stapler and ½-inch-long staples.
7. Hand saw.
8. Paint brush, good quality, about 2-inches wide.
9. Sand paper, coarse and fine grit.
10. Nails, #4D, 1½-inches long. Approximately 100 are required to retain the front baffle, rear panel and internal wood strips. Alternatively, #8, 1½-inch-long wood screws may be used. They require a $^{11}/_{64}$-inch diameter hole for clearance and a $^{3}/_{32}$-inch diameter pilot hole for the threads.
11. Polyvinyl wood glue, about 16 ounces, such as Elmer's Glue-All.
12. Silicone RTV sealer, about two tubes, for use around terminals and to seal inside cabinet joints. GE or Dow-Corning adhesive/sealant is satisfactory.
13. Caulking gun (makes sealer application easier).
14. Paint. Spray or brush on the front and rear panels.
15. Stain, oil, varnish or paint for exterior enclosure finish.
16. Putty stick for touch-up. Color is dependent on finish.
17. Glass wool or similar acoustic absorbing material, 1-2 inches thick. Building insulation with its paper backing removed is satisfactory.
18. Velcro tape, hook and loop, approximately 1-inch wide and 6½-inches long, used to retain the grille frame to the enclosure.
19. Wax or soap. Apply to screws for easier installation.
20. Wood veneer tape or other material to cover exposed cabinet edges.
21. Grille material, usually cloth.
22. Component-mounting hardware. Determine the quantity and size needed (see individual DL woofer engineering data sheets). Speakers can be front mounted with the optional SMH-1 speaker mounting kit.
23. Wood parts per enclosure plans.

References

The selected articles described below give additional background on the Thiele-Small model:

1. R.J. Newman, "A.N. Thiele—Sage of Vented Speakers," *Audio,* vol. 60, pp. 30-37 (1975 Aug.). A nontechnical introduction to Thiele's papers noted below. Reprints available from Electro-Voice at no charge.
2. R.J. Newman, "A Systematic Approach to Loudspeaker Design," *Stereo Review,* vol. 46, pp. 58-61 (1981 Aug.). A nontechnical introduction to the implications of Thiele's model, including interesting comparisons to sealed direct-radiator and horn-loaded systems. Reprints available from Electro-Voice at no charge.
3. A.N. Thiele, "Loudspeakers in Vented Boxes: Part I," *J. Audio Eng. Soc.,* vol. 19, pp. 382-392 (1971 May). The classic paper on vented speaker systems, part 1.
4. A.N. Thiele, "Loudspeakers in Vented Boxes: Part II," *J. Audio Eng. Soc.,* vol. 19, pp. 471-483 (1971 June). The classic paper on vented speaker systems, part 2.
5. J.N. White, "Loudspeaker Athletics," *J. Audio Eng. Soc. (Abstracts),* vol. 26, p. 1001 (1978 Dec.), preprint no. 1399. An excellent view of how a speaker's Thiele-Small parameters can be manipulated, both mathmatically and physically, to provide a range of performance that is not immediately obvious. Reprints available from Electro-Voice at no charge.

Enclosure Number	Speaker Model	Net Internal Enclosure Volume (ft³/liters)	Mode	Enclosure Tuning Frequency (Hz)	System Low-Freq. 3-dB-Down Point (Hz)	Peak-Boost Freq. (Hz)	Vent Diameter (in./cm)	Number of Vents	Vent Length (in./cm)	Curve Number	Baffle Drawing
Single-Speaker Enclosures											
TL5-75[2]	DL12X	1.25/35.4	Normal	75	80		4/10.2	2	5.5/14.0	1	Fig. 1
TL5-53[2]	DL12X	1.25/35.4	Step Down	53	55	50	3/7.60	2	7.7/19.6	2	
TL7-63	DL12X	1.80/51.0	Normal	63	72		4/10.2	2	5.6/14.2	3	Fig. 2
TL7-45	DL12X	1.80/51.0	Step Down	45	48	45[3]	3/7.60	2	7.6/19.3	4	
TL10-51	DL15W	2.50/70.8	Normal	51	52		5/12.7	2	10.9/27.7[1]	5	Fig. 3
TL10-36	DL15W	2.50/70.8	Step Down	36	37	38	3/7.60	3	13.7/34.8[1]	6	
TL10-63	DL15X	2.50/70.8	Normal	63	69		5/12.7	2	5.3/13.5	7	Fig. 3
TL10-46	DL15X	2.50/70.8	Step Down	46	48	46[4]	5/12.7	1	6.2/15.7	8	
TL14-55[2]	DL15X	3.50/99.1	Normal	55	60		4/10.2	2	2.3/5.84	9	Fig. 6
TL14-40[2]	DL15X	3.50/99.1	Step Down	40	42	40	5/12.7	1	5.8/14.7	10	
TL14-45	DL15W	3.50/99.1	Normal	45	48		6/15.2	1	6.3/16.0	11	
TL14-32	DL15W	3.50/99.1	Step Down	32	32	32[3]	5/12.7	1	11.1/28.2[1]	12	
TL20-48	DL15X	5.10/144	Normal	48	53		4/10.2	2	1.6/4.06	13	Fig. 7
TL20-35	DL15X	5.10/144	Step Down	35	37	35[3]	5/12.7	1	4.8/12.2	14	
TL20-40	DL15W	5.10/144	Normal	40	40		4/10.2	2	4.2/10.7	15	Fig. 7
TL20-28	DL15W	5.10/144	Step Down	28	28	30[4]	5/12.7	1	9.6/24.4	16	
TL28-42	DL15X	7.10/201	Normal	42	48		4/10.2	2	1.3/3.30	17	
TL28-30	DL15W	7.10/201	Step Down	30	31	30[4]	3/7.60	2	2.9/7.37	18	
TL28-35	DL15X	7.10/201	Normal	35	36		4/10.2	2	3.7/9.40	19	
TL28-25	DL15W	7.10/201	Step Down	25	27	30[4]	5/12.7	1	8 3/21.1	20	
TL28-45	DL18X	7.00/198	Normal	45	48		5/12.7	2	2.3/5.84	21	Fig. 9
TL28-32	DL18X	7.00/198	Step Down	32	34	34[4]	5/12.7	1	3.7/9.40	22	
TL28-38	DL18W	7.00/198	Normal	38	40		5/12.7	2	5.3/13.5	23	Fig. 9
TL28-27	DL18W	7.00/198	Step Down	27	29	29[3]	4/10.2	2	9.1/23.1	24	
TL40-40	DL18X	10.0/283	Normal	40	42		5/12.7	2	1.4/3.56	25	Fig. 9
TL40-28	DL18X	10.0/283	Step Down	28	29	30[4]	5/12.7	1	3.1/7.87	26	
TL40-35	DL18W	10.0/283	Normal	35	35		6/15.2	1	1.8/4.57	27	
TL40-25	DL18W	10.0/283	Step Down	25	25	27	5/12.7	1	4.8/12.2	28	
TL56-34	DL18X DL18W	14.3/405	Normal	34	36 32		6/15.2	2	3.0/7.62	29 31	Fig. 11
TL56-24	DL18X DL18W	14.3/405	Step Down	24	26 23	27 25	6/15.2	1	4.9/12.4	30 32	
TL80-25	DL18W	20.4/578	Normal	25	26		5/12.7	2	3.1/7.87	33	
TL80-18	DL18W	20.4/578	Step Down	18	22	25	5/12.7	2	10.7/27.2	34	
Dual-Speaker Enclosures											
TL10D-75[2]	DL12X	2.40/68.0	Normal	75	80		5/12.7	2	2.5/6.35	1	Fig. 4
TL10D-53[2]	DL12X	2.40/68.0	Step Down	53	55	50	6/15.2	1	6.7/17.0	2	Fig. 5
TL20D-63	DL15X	4.80/136	Normal	63	69		6/15.2	2	1.8/4.57	7	
TL20D-46	DL15X	4.80/136	Step Down	46	48	46[4]	5/12.7	2	5.2/13.2	8	
TL20D-51	DL15W	4.80/136	Normal	51	52		6/15.2 4/10.2	2 2	10.7/27.2[1] 10.7/27.2[1]	5	Fig. 8
TL20D-36	DL15W	4.80/136	Step Down	36	37	38	6/15.2	2	18.3/46.5[1]	6	
TL28D-55[2]	DL15X	6.80/193	Normal	55	60		6/15.2	2	1.2/3.05	9	
TL28D-40[2]	DL15X	6.80/193	Step Down	40	42	40	5/12.7	2	4.5/11.4	10	
TL28D-45	DL15W	6.80/193	Normal	45	48		6/15.2	2	4.9/12.4	11	
TL28D-32	DL15W	6.80/193	Step Down	32	32	32[3]	5/12.7	2	10.0/25.4	12	
TL40D-48	DL15X	9.90/280	Normal	48	53		6/15.2	3	2.4/6.10	13	Fig. 10
TL40D-35	DL15X	9.90/280	Step Down	35	37	35[3]	5/12.7	2	3.5/8.89	14	
TL40D-40	DL15W	9.90/280	Normal	40	40		6/15.2	2	3.4/8.64	15	
TL40D-28	DL15W	9.90/280	Step Down	28	28	30[4]	5/12.7	2	8.5/21.6	16	
TL56D-45	DL18X	13.9/394	Normal	45	48		6/15.2	4	2.1/5.33	21	
TL56D-32	DL18X	13.9/394	Step Down	32	34	34[4]	5/12.7	2	2.3/5.84	22	
TL56D-38	DL18W	13.9/394	Normal	38	40		6/15.2	3	3.8/9.65	23	
TL56D-27	DL18W	13.9/394	Step Down	27	29	29[3]	6/15.2	2	8.9/22.6	24	
TL80D-40	DL18X	19.9/564	Normal	40	42		6/15.2	4	0.8/2.03	25	Fig. 12
TL80D-28	DL18X	19.9/564	Step Down	28	29	30[4]	5/12.7	2	1.6/4.06	26	
TL80D-35	DL18W	19.9/564	Normal	35	35		6/15.2	3	1.8/4.57	27	
TL80D-25	DL18W	19.9/564	Step Down	25	25	27	5/12.7	2	3.3/8.38	28	

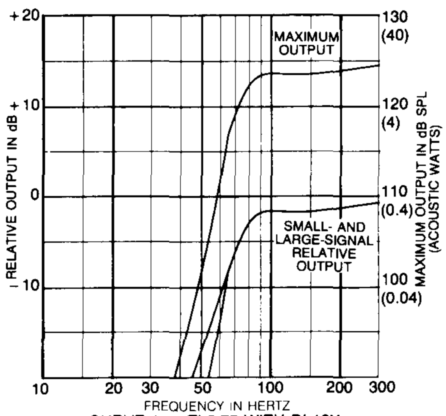
1. Vent is too long for depth of enclosure. See the vent-modification instructions of Figure 13.
2. These enclosure/speaker combinations are acoustically similar to Electro-Voice manufactured systems, as follows: TL606AX (TL14-55/DL15X and TL14-40/DL15X); TL606DX (TL28D-55/DL15X and TL28D-40/DL15X); TL806AX (TL5-75/DL12X and TL5-53/DL12X); TL806DX (TL10D-75/DL12X and TL10D-53/DL12X).
3. Available on XEQ-2.
4. Within ±5% of an XEQ-2 frequency.

Chart 3 — Enclosure Volume, Venting and System Low-Frequency 3-dB-Down Points

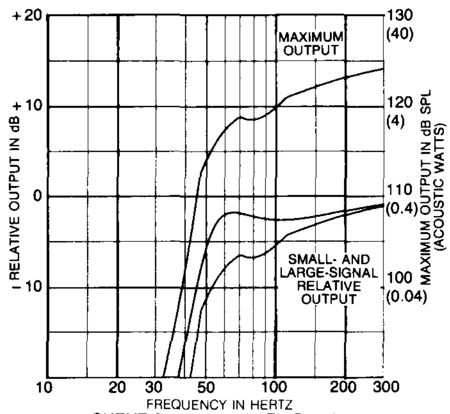
Enclosure Identification	Enclosure External Dimensions (in./cm)			Brace Material Length (in./cm)[1]			Panel Material Length × Width (in./cm)[3]			Center Brace Length (in./cm)[4]
				Ref. No. 1[2]	Ref. No. 2[2]	Ref. No. 3[2]	Ref. No. 4[2]	Ref. No. 5[2]	Ref. No. 6[2]	Ref. No. 7[2]
	Height	Width	Depth	Four Req'd	Four Req'd	Four Req'd	Top & Bottom	Sides	Front Baffle & Back	
TL5 Single 12"	18¾/47.6	15½/39.4	14/35.6	17¼/43.8	12½/31.8	6¼/15.9	15½/39.4 × 14½/36.8	17¼/43.8 × 14/35.6	17¼/43.8 × 14/35.6	—
TL7 Single 12"	20½/52.1	16½/41.9	15⅜/39.1	19/48.3	13½/34.3	7⅝/19.4	16½/41.9 × 15⅜/39.1	19/48.3 × 15⅜/39.1	19/48.3 × 15/38.1	—
TL10 Single 12" Single 15" TL10D Dual 12"	28½/72.4	18¾/47.6	13¾/34.9	27/68.6	15¾/40.0	6/15.2	18¾/47.6 × 13¼/33.7	27/68.6 × 13¾/34.9	27/68.6 × 17¼/43.8	—
TL14 Single 15"	31½/80.0	18¼/46.4	16⅜/41.6	30/76.2	15¼/38.7	8⅝/21.9	18¼/46.4 × 16⅜/41.6	30/76.2 × 16⅜/41.6	30/76.2 × 16¾/42.5	—
TL20 Single 15"	35½/90.2	21½/54.6	17/43.2	34/86.4	18½/47.0	9¼/23.5	21½/54.6 × 17/43.2	34/86.4 × 17/43.2	34/86.4 × 20/50.8	—
TL20D Dual 15"										
TL28 Single 15" Single 18" TL28D Dual 15"	39½/100	25½/64.8	17¼/43.8	38/96.5	22½/57.2	9½/24.1	25½/64.8 × 17¼/43.8	38/96.5 × 17¼/43.8	38/96.5 × 24/61.0	14¾/37.5
TL40 Single 18" TL40D Dual 15"	39½/100	25½/64.8	23⅛/58.7	38/96.5	22½/57.2	15⅜/39.1	25½/64.8 × 23⅛/58.7	38/96.5 × 23⅛/58.7	38/96.5 × 24/61.0	20⅝/52.4
TL56 Single 18" TL56D Dual 18"	48/122	31½/80.0	21⅜/54.3	46½/118	28½/72.4	13⅝/34.6	31½/80.0 × 21⅜/54.3	46½/118 × 21⅜/54.3	46½/118 × 30/76.2	18⅞/47.9
TL80 Single 18" TL80D Dual 18"	48/122	31½/80.0	28⅞/73.3	46½/118	28½/72.4	21⅛/53.7	31½/80.0 × 28⅞/73.3	46½/118 × 28⅞/73.3	46½/118 × 30/76.2	26⅜/67.0

1. Commercially available furring strips, 1 by 3 inches nominal size (2⅝ by ¾ inches actual size).
2. See Enclosure Piece-Part Exploded View, page 19.
3. ¾-inch (1.91-cm) thick.
4. Commercial two-by-four (3½ by 1½ inches actual size).

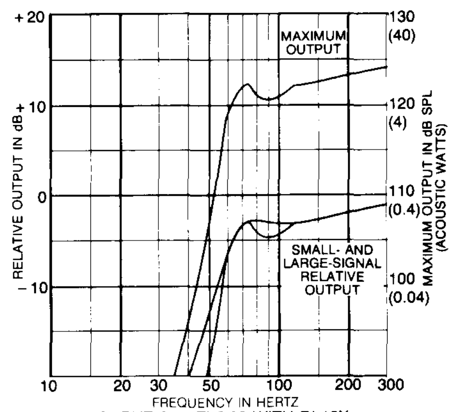
Chart 4
Enclosure Piece-Part Dimensions



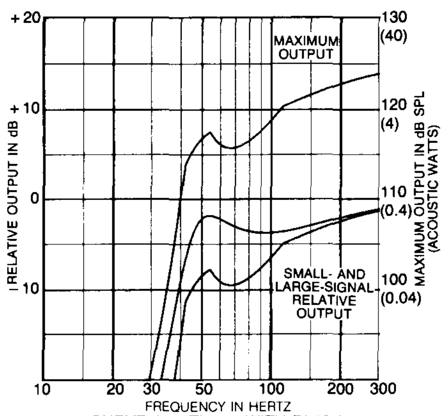
CURVE 1 — TL5-75 WITH DL12X, NORMAL MODE (TL10D-75)



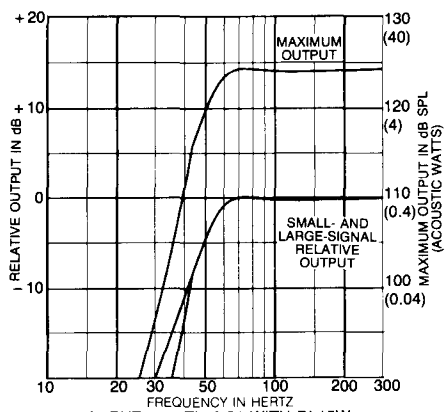
CURVE 2 — TL5-53 WITH DL12X, STEP DOWN MODE (TL10D-53)



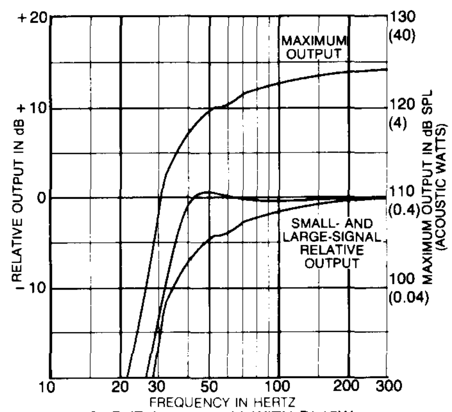
CURVE 3 — TL7-63 WITH DL12X, NORMAL MODE



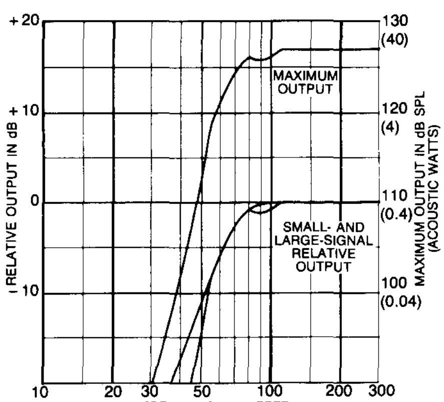
CURVE 4 — TL7-45 WITH DL12X, STEP DOWN MODE



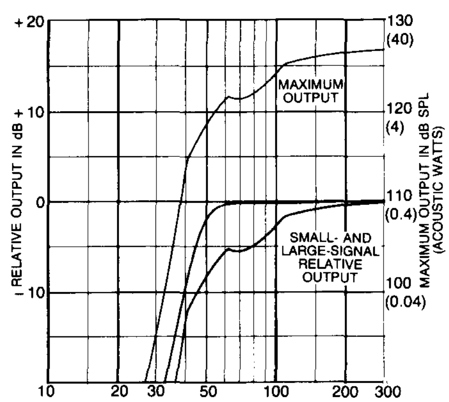
CURVE 5 — TL10-51 WITH DL15W, NORMAL MODE (TL20D-51)



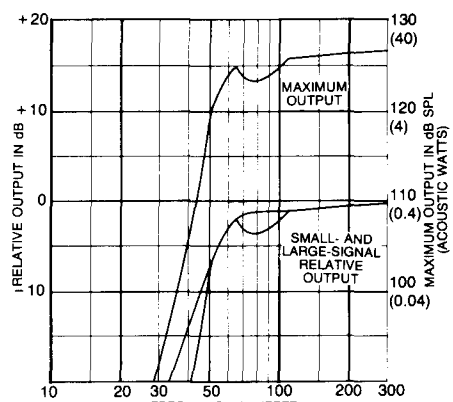
CURVE 6 — TL10-36 WITH DL15W, STEP DOWN MODE (TL20D-36)



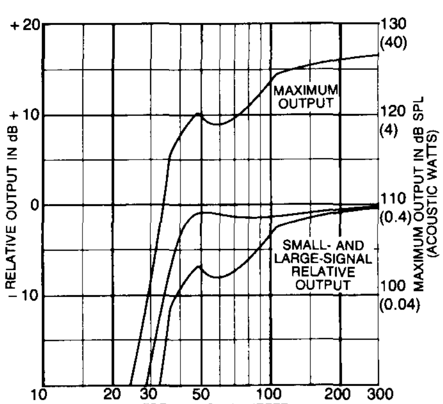
CURVE 7 — TL10-63 WITH DL15X, NORMAL MODE (TL20D-63)



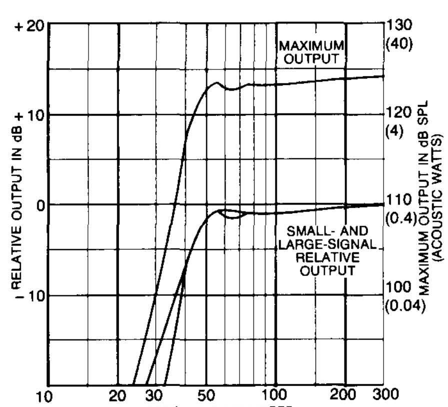
CURVE 8 — TL10-46 WITH DL15X, STEP DOWN MODE (TL20D-46)



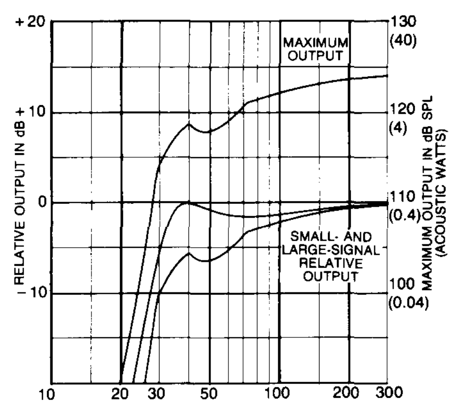
CURVE 9 — TL14-55 WITH DL15X, NORMAL MODE (TL28D-55)



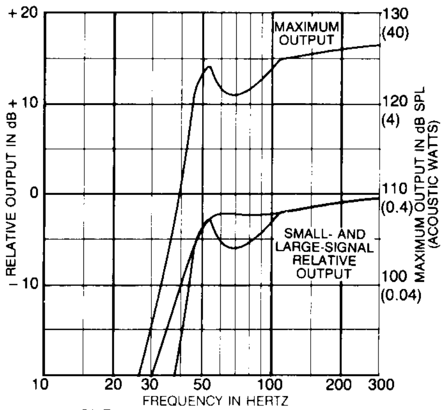
CURVE 10 — TL14-40 WITH DL15X, STEP DOWN MODE (TL28D-40)



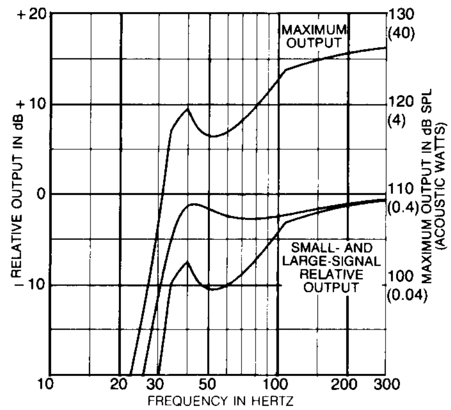
CURVE 11 — TL14-45 WITH DL15W, NORMAL MODE (TL28D-45)



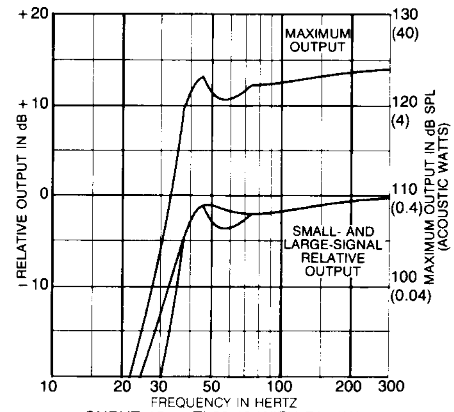
CURVE 12 — TL14-32 WITH DL15W, STEP DOWN MODE (TL28D-32)



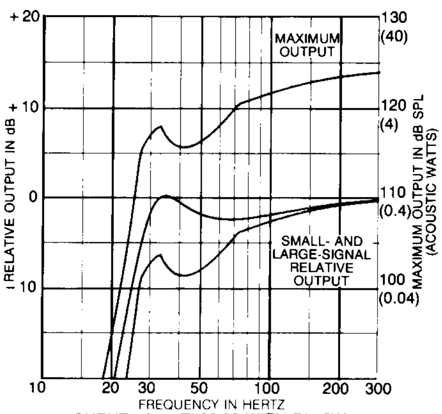
CURVE 13 — TL20-48 WITH DL15X, NORMAL MODE (TL40D-48)



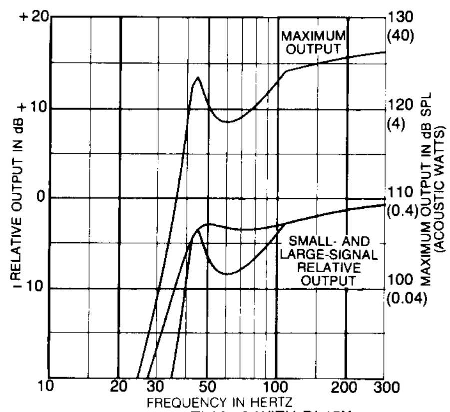
CURVE 14 — TL20-35 WITH DL15X, STEP DOWN MODE (TL40D-35)



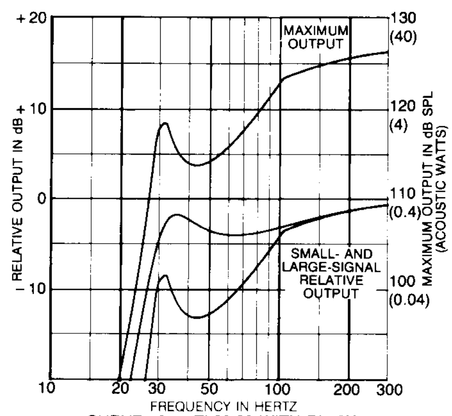
CURVE 15 — TL20-40 WITH DL15W, NORMAL MODE (TL40D-40)



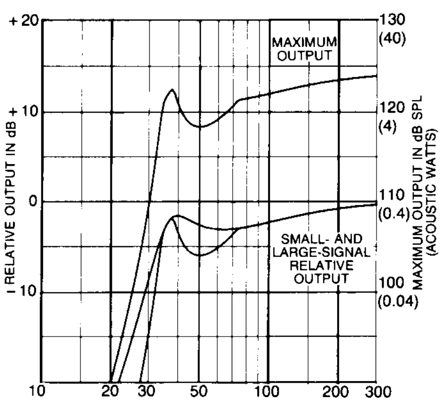
CURVE 16 — TL20-28 WITH DL15W, STEP DOWN MODE (TL40D-28)



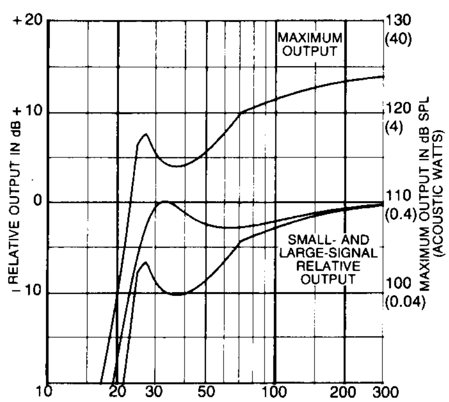
CURVE 17 — TL28-42 WITH DL15X, NORMAL MODE



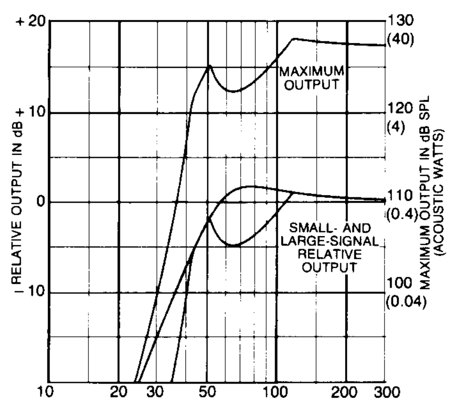
CURVE 18 — TL28-30 WITH DL15X, STEP DOWN MODE



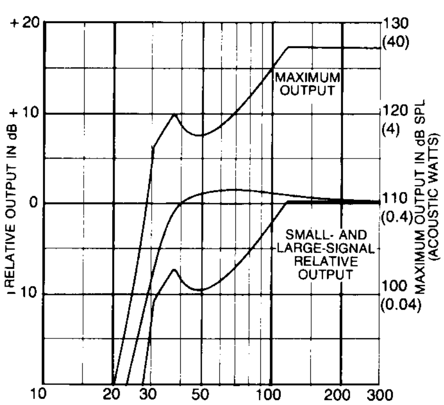
CURVE 19 — TL28-35 WITH DL15W, NORMAL MODE



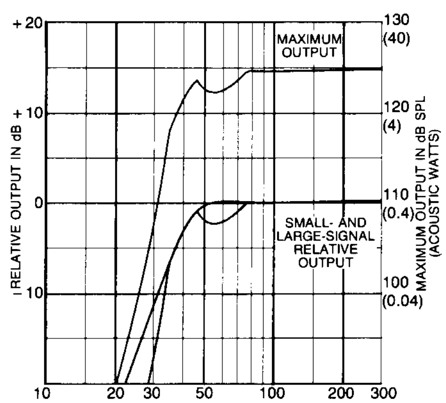
CURVE 20 — TL28-25 WITH DL15W, STEP DOWN MODE



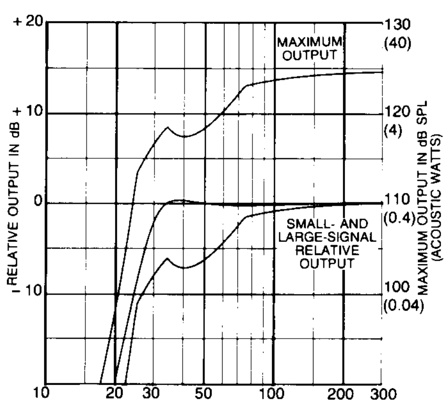
CURVE 21 — TL28-45 WITH DL18X, NORMAL MODE (TL56D-32)



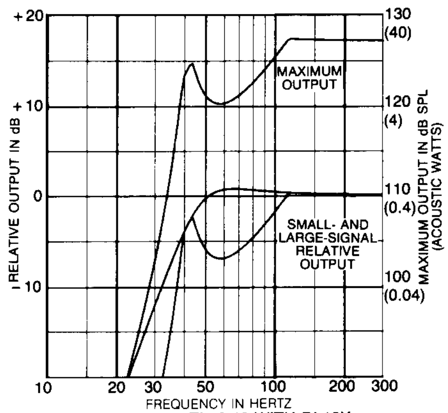
CURVE 22 — TL28-32 WITH DL18X, STEP DOWN MODE (TL56D-32)



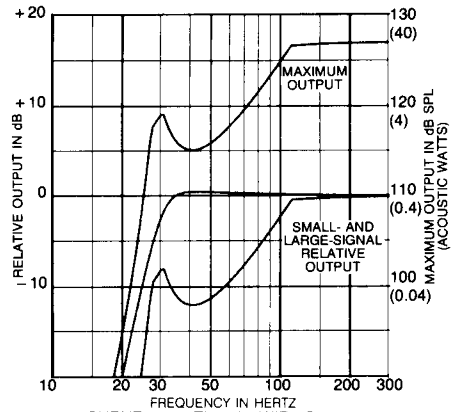
CURVE 23 — TL28-38 WITH DL18W, NORMAL MODE (TL56D-38)



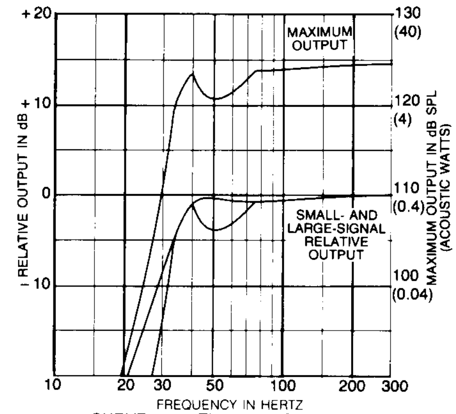
CURVE 24 — TL28-27 WITH DL18W, STEP DOWN MODE (TL56D-27)



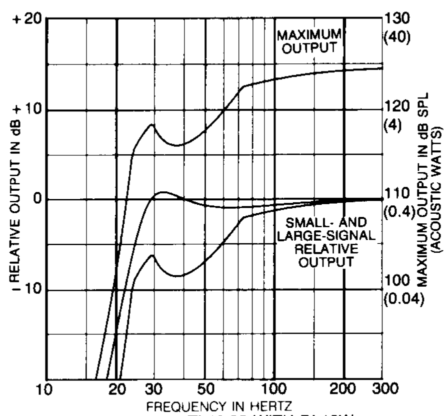
CURVE 25 — TL40-40 WITH DL18X, NORMAL MODE (TL80D-40)



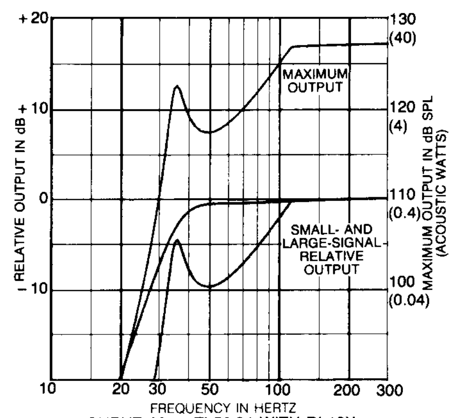
CURVE 26 — TL40-28 WITH DL18X, STEP DOWN MODE (TL80D-28)



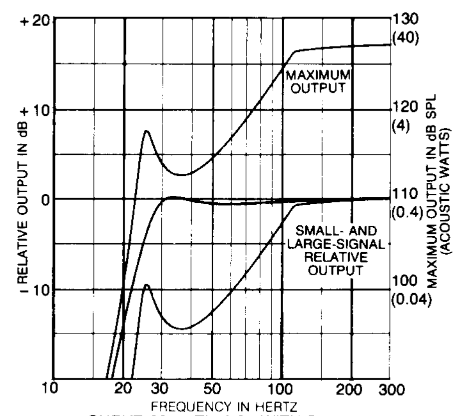
CURVE 27 — TL40-35 WITH DL18W, NORMAL MODE (TL80D-35)



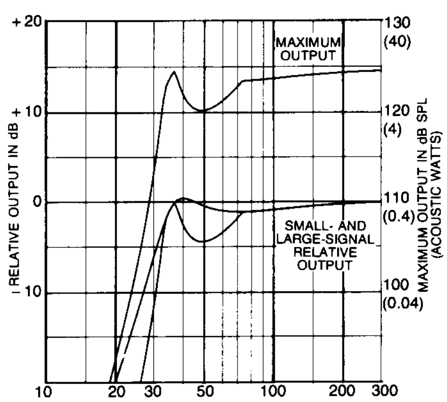
CURVE 28 — TL40-25 WITH DL18W, STEP DOWN MODE (TL80D-25)



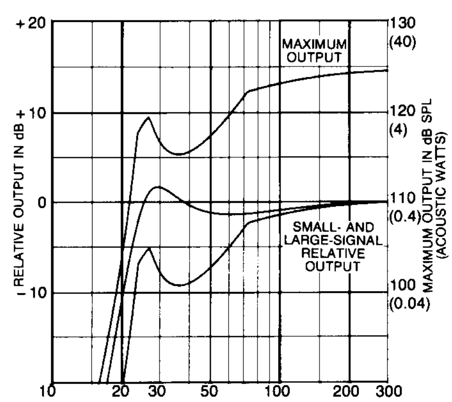
CURVE 29 — TL56-34 WITH DL18X, NORMAL MODE



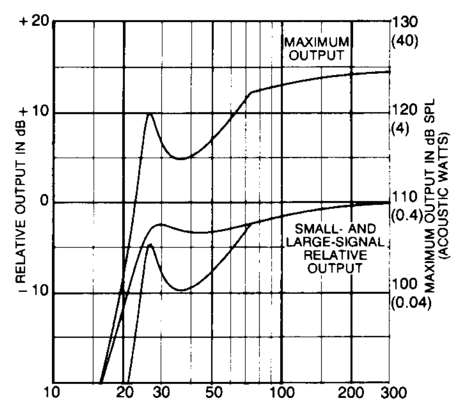
CURVE 30 — TL56-24 WITH DL18X, STEP DOWN MODE



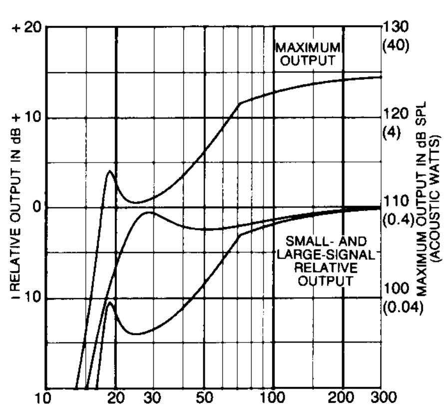
CURVE 31 — TL56-34 WITH DL18W, NORMAL MODE



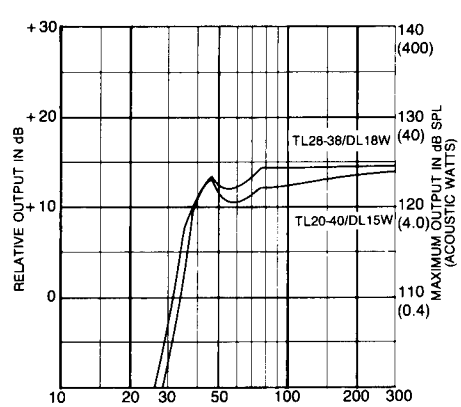
CURVE 32 — TL56-24 WITH DL18W, STEP DOWN MODE



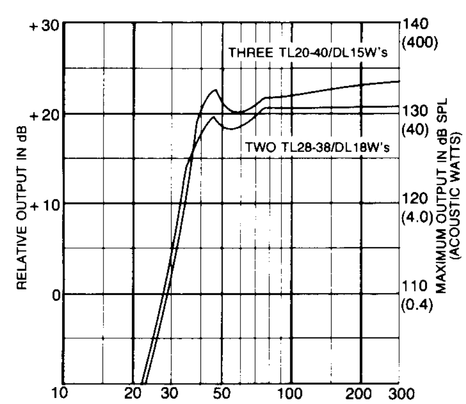
CURVE 33 — TL80-25 WITH DL18W, NORMAL MODE



CURVE 34 — TL80-18 WITH DL18W, STEP DOWN MODE



CURVE 35 — MAXIMUM OUTPUT COMPARISON TL20-40/DL15W VERSUS TL28-38/DL18W



CURVE 36 — MAXIMUM OUTPUT COMPARISON, THREE TL20-40/DL15W's VERSUS TWO TL28-38/DL18W's, MUTUALLY COUPLED

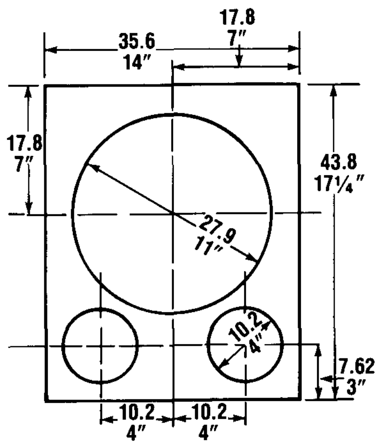


FIGURE 1

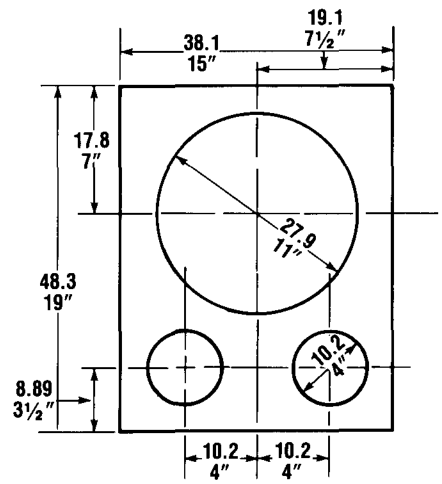


FIGURE 2

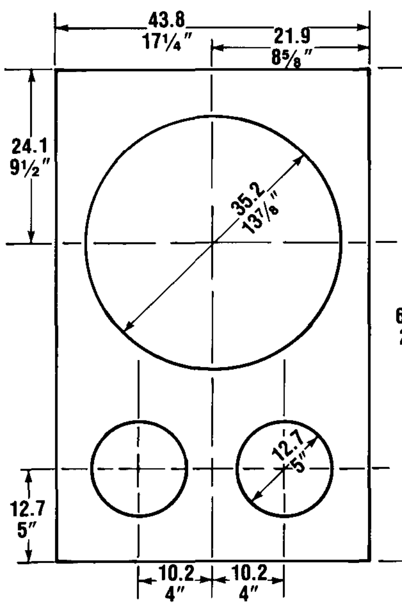


FIGURE 3

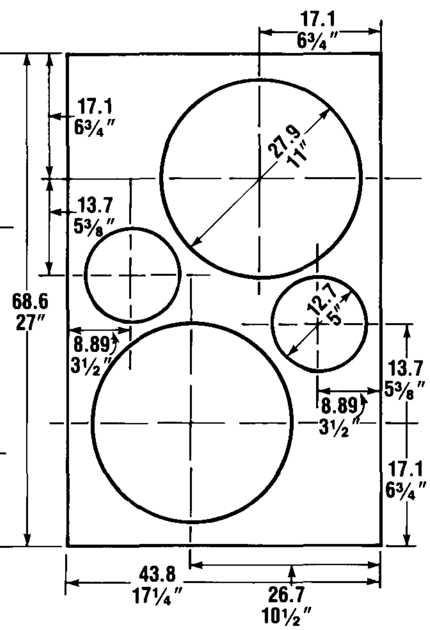


FIGURE 4

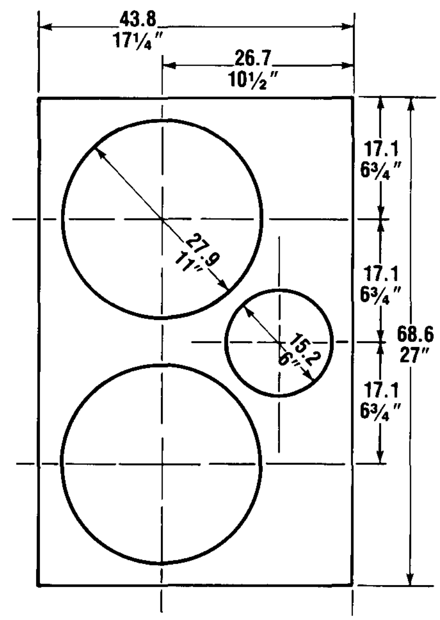


FIGURE 5

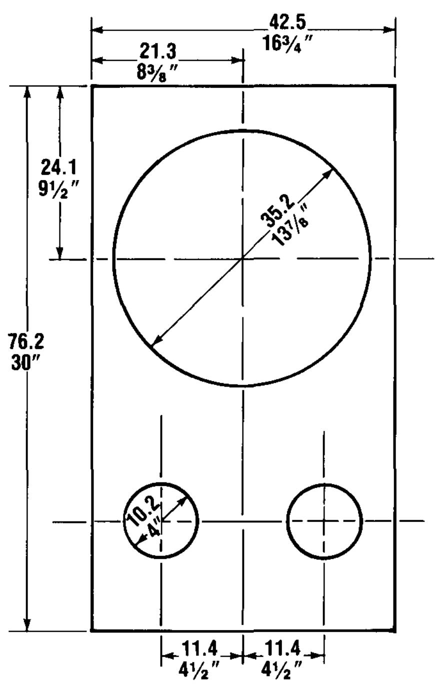


FIGURE 6

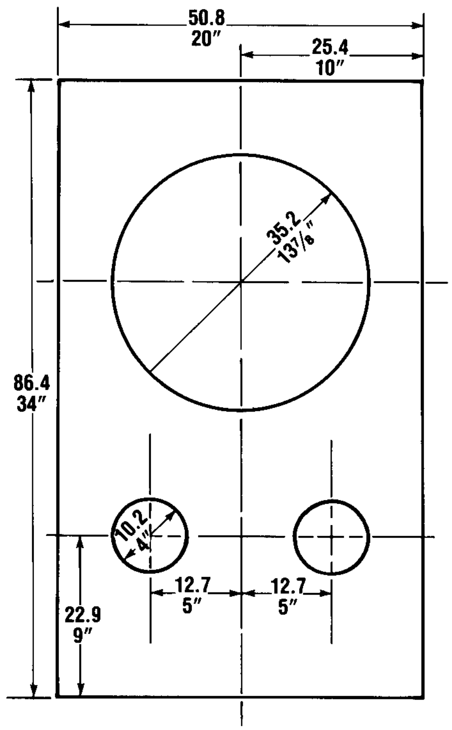


FIGURE 7

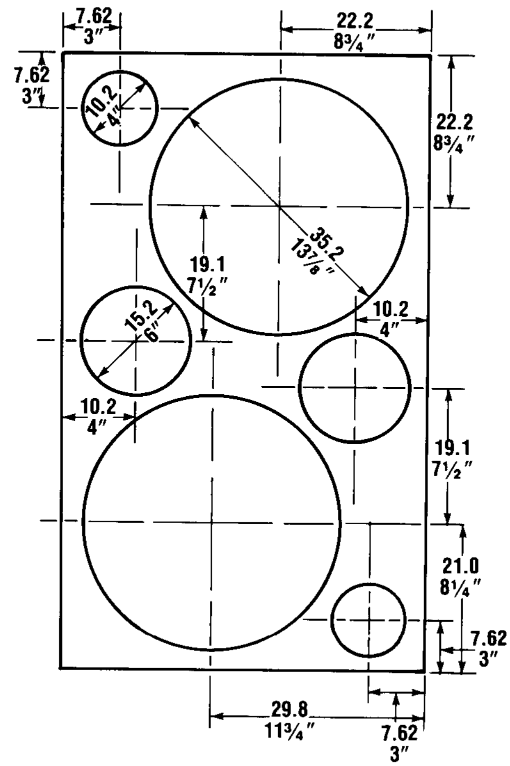


FIGURE 8

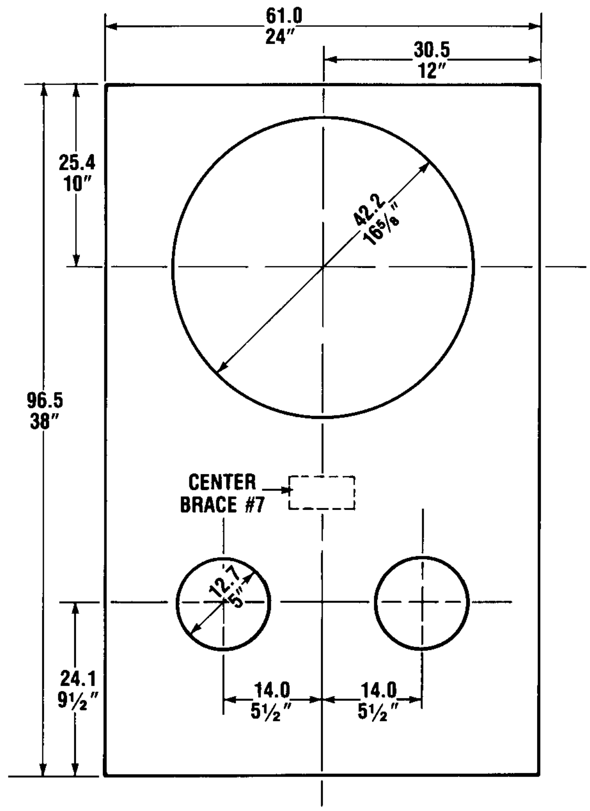


FIGURE 9

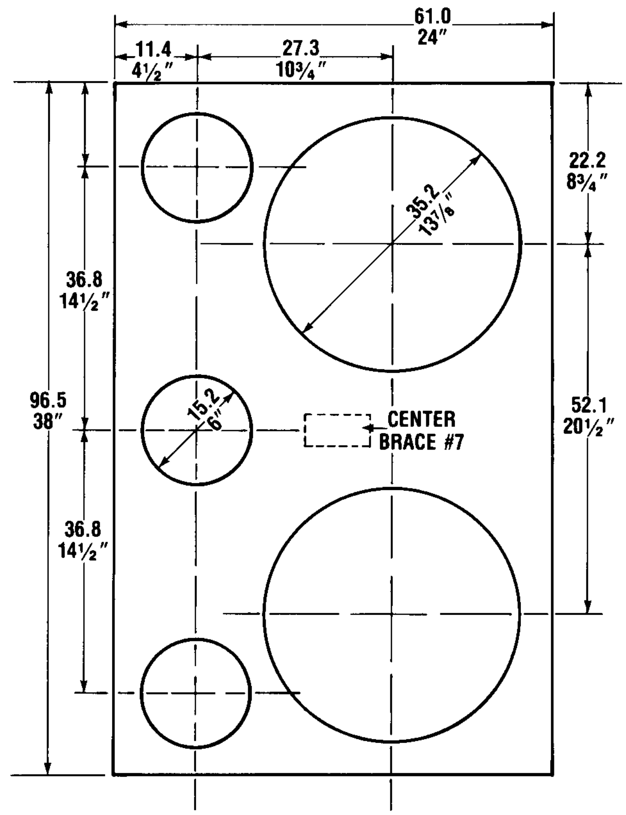


FIGURE 10

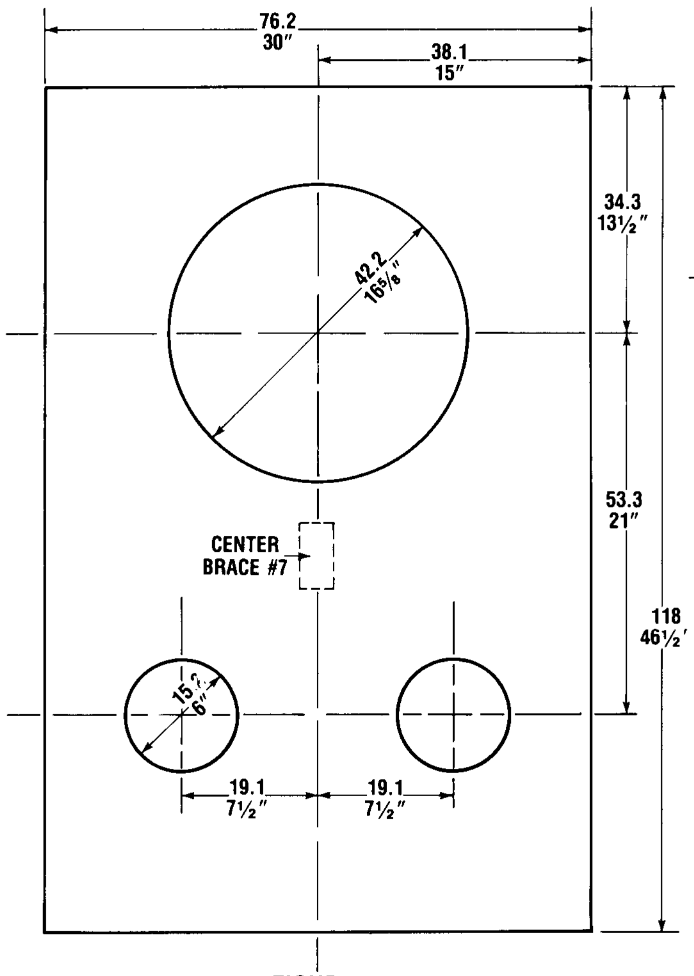


FIGURE 11

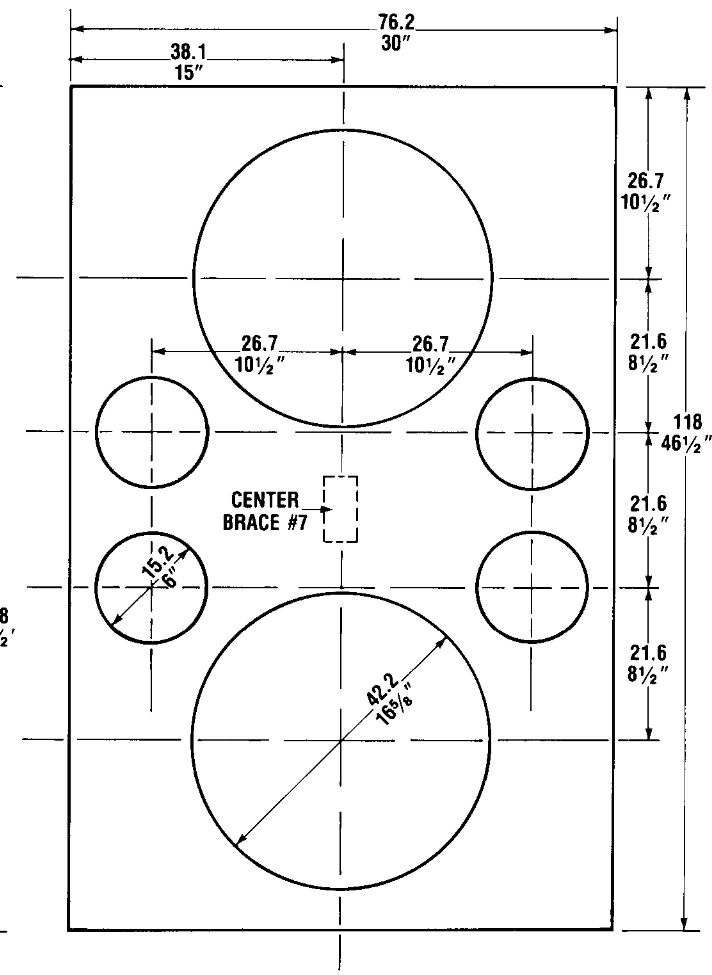
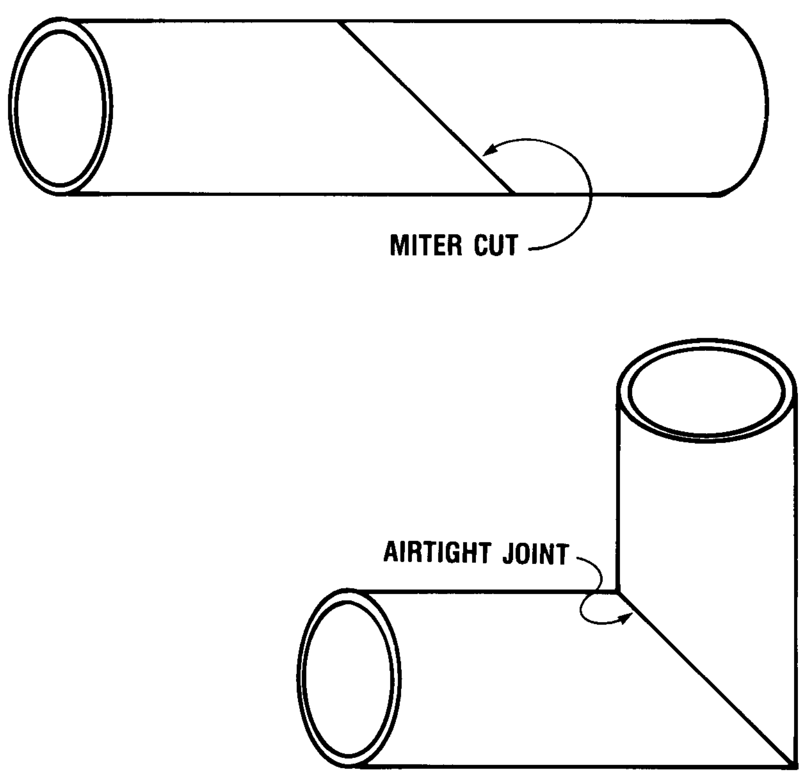
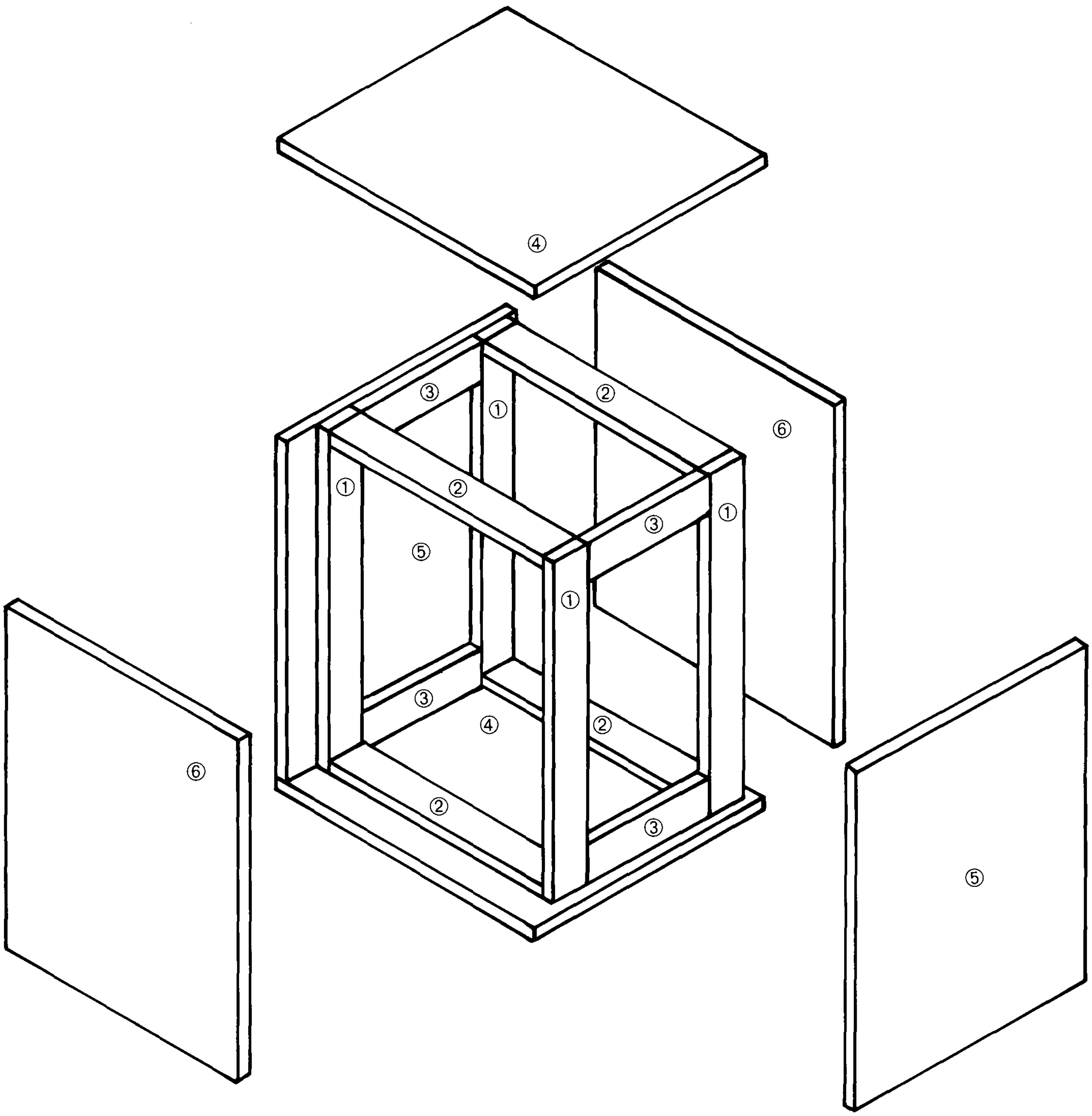


FIGURE 12

FIGURE 13 — Vent-Modification Instructions

Where duct length exceeds three-quarters of the enclosure depth, the duct must be modified to avoid air turbulance at it's internal end. This is done by making a miter cut across the tube (allowing sufficient length for clearance of the speaker magnet), rotating the miter 180° (forming a 90° corner) and then gluing the pieces together. Care should be taken to insure that there are no air leaks in the glued joint.





Enclosure Piece-Part Exploded View