is negligible, this dependence disappears. We can thus define for the driver a horn-loaded efficiency-bandwidth product EBP given by

$$EBP \triangleq \frac{R_{MB}}{2\pi M_{M2}} = \frac{f_S}{Q_{ES}} \quad . \tag{9}$$

This number, which depends only on parameters of the driver, absolutely restricts the efficiency vs bandwidth tradeoff available from the driver in any horn system. Note that maximum efficiency implies minimum bandwidth, and that extension of bandwidth requires a proportional sacrifice in efficiency. The tradeoff is controlled by the selection of S_D/S_T .

It is interesting to compare the above result with the driver properties which determine the low-frequency cutoff when the driver is used in a direct-radiator system.

For closed-box systems, it is easily shown that, provided the driver has low mechanical losses and a sufficiently low Q_{ES}, the minimum obtainable lower cutoff frequency $f_3(min)$ is about $0.7f_S/Q_{ES}$. Current design practice utilizing unity system Q gives a practical cutoff frequency f_3 of about $0.8f_S/Q_{ES}$.

For vented-box systems, provided the driver has suitably low Q to begin with, it can also be demonstrated that the cutoff frequency in a normal flat-response alignment is in the range of $0.3f_S/Q_{ES}$ to $0.5f_S/Q_{ES}$.

Thus, for extended bass in a direct-radiator system, the value of EBP for the driver must be of the order of 50 Hz for use in a closed-box system or 100 Hz for use in a vented-box system. These requirements are clearly incompatible with the obvious need for as high a value of EBP as practicable for horn applications.

6. HORN-SYSTEM POWER CAPACITY

The maximum acoustic power output available from the system of Fig. 1 is limited by the air-volume displacement capability of the driver. If the peak mechanical displacement available from the driver diaphragm with good linearity is x_{max} and the diaphragm area is S_D, then the peak displacement volume is $V_D = S_D x_{max}$. Then, at any frequency f, the displacement-limited acoustic power output P_{AR} is given by

$$P_{AR}(f) = \frac{2\pi^2 \rho_o c}{S_D} (S_D/S_T)\, V_D^2\, f^2 \quad . \tag{10}$$

If we adopt a reference condition of $S_D/S_T = 1$ and $f = 50$ Hz, then we can define a displacement-limited reference power output $P_{AR}(ref)$ for the driver in horn applications:

$$P_{AR}(ref) = 2\times10^7\ V_D^2/S_D \quad . \tag{11}$$

This parameter permits us to calculate, for any horn system using the driver, the displacement-limited power output rating for any frequency in the system passband. For example, allowing S_D/S_T to vary but keeping $f = 50$ Hz,

$$P_{AR}(50) = P_{AR}(ref) \cdot S_D/S_T \quad . \tag{12}$$

At any other frequency f_1, such as the lowest frequency for which the horn system is required to supply full power output,

$$P_{AR}(f_1) = P_{AR}(50) \cdot (f_1/50)^2 \quad . \tag{13}$$

Note that the maximum displacement-limited output available from a given system is directly influenced by the familiar ratio S_D/S_T and is thus interrelated with the system efficiency. Raising S_D/S_T to obtain increased displacement-limited power-output capability results in a reduction of efficiency and therefore a more than proportionate increase in the required input power.

Eq. 10 demonstrates that the driver large-signal parameter V_D is just as important to horn loudspeaker performance as it is to direct-radiator performance. The same thing may be said for the driver large-signal parameter $P_E(max)$ which represents the ability of the driver voice coil to dissipate heat; this parameter must have a high value if system operation at high power levels is desired. However, the usually high efficiency of horn systems does provide some advantage in that less of the input power is actually dissipated in the voice coil. For an efficiency η_T, the thermally-limited horn-system input-power rating $P_{IN}(max)$ may be $P_E(max)/(1-\eta_T)$.

As with direct-radiator systems, overall horn-system power capacity may be restricted either by displacement limitations or by thermal power limitations, depending on the system lower cutoff frequency. For a given horn-system design, the thermal input-power limit $P_{IN}(max)$ and the corresponding maximum output $P_A(max) = \eta_T P_{IN}(max)$ are not a function of frequency within the system passband. However, P_{AR} and hence the corresponding displacement-limited input-power rating $P_{ER} = P_{AR}/\eta_T$ are strong functions of frequency. This implies that if the designer wishes to use the full available thermal power capacity of the driver without exceeding its displacement limit, he must restrict the minimum operating frequency f_{min} such that at f_{min}, $P_{AR}(f_{min}) = P_A(max)$, or equivalently

$P_{ER}(f_{min}) = P_{IN}(max)$. For this condition, f_{min} is a function not only of the driver parameters but also of S_D/S_T and therefore interrelated with the other performance factors already discussed.

7. JUDGING DRIVER SUITABILITY

The EBP is clearly an important small-signal indicator of the usefulness of a driver in horn-loaded applications. A high value of EBP implies that for a specified level of efficiency the driver-mass-limited upper cutoff frequency can be high or that for a given upper cutoff frequency requirement the efficiency can be high.

Knowledge of $\eta_T(max)$ is also important, because this sets the limit to freedom of bandwidth-efficiency tradeoff. And clearly, high system efficiency is not obtainable from a driver with low $\eta_T(max)$, regardless of its EBP.

While V_D and $P_E(max)$ are adequate indicators of relative driver suitability in horn applications, some advantage can be gained by examining $P_{AR}(ref)$ in place of V_D. This new parameter has the familiar dimension of watts and permits rapid calculation of system displacement-limited performance for any values of S_D/S_T and low-frequency cutoff.

The horn-application parameters for a selection of drivers are listed in Table 1. Some of the drivers included were specifically designed for direct-radiator use; none are cheap skimped-magnet specials. There is about a 2:1 variation in $\eta_T(max)$, and the potentially good direct-radiator woofers and potentially good horn woofers are clearly distinguished by their low and high values respectively of EBP. The larger drivers have a clear advantage in obtaining high values of $P_E(max)$ and $P_{AR}(ref)$.

8. SYSTEM PERFORMANCE

The relationships developed in this paper may be used not only to compare the performance potential of drivers but also to assess the specific system capabilities of a particular driver and to determine the required ratio of S_D/S_T in a practical application.

As an example, let us examine the horn-loaded capabilities of the type 365 12-inch driver. This driver was designed for horn-loaded applications and has the given, measured or calculated parameters expressed below in mechanical form.

M_{M2}	52 g	
R_{ME}	60 N·s/m	
R_{MS}	9 N·s/m	(assumed value for R_{M2})
R_{MO}	21 N·s/m	
S_D	511 cm^2	
V_D	255 cm^3	
$P_E(max)$	130 W	

From these were calculated the parameters for Table 1:

EBP	180 Hz
$\eta_T(max)$	48 %
$P_{AR}(ref)$	26 W

The performance capabilities of the 365 in a horn system are displayed in Fig. 4 as a function of the ratio S_D/S_T.

The curves of Fig. 4a show how η_T, f_H and f_{min} vary with S_D/S_T. Those of Fig. 4b show the variations in the 50-Hz displacement-limited power ratings $P_{AR}(50)$ and $P_{ER}(50)$, and in the thermally-limited power ratings $P_{IN}(max)$ and $P_A(max)$, as a function of S_D/S_T.

A choice of S_D/S_T may now be made on the basis of the system design goals. Of the many possibilities, three examples are explored below.

a) Maximum possible efficiency is desired.

The maximum possible efficiency is $\eta_T(max)$, and it is obtained by setting $S_D/S_T = 1$. The upper frequency limit is then f_H = 275 Hz. Note that for this condition f_{min} is 107 Hz. Thus if the horn is designed to have its low-frequency cutoff above this frequency, the system will be thermally limited to ratings of 250 W input and 120 W output. If response to below f_{min} is desired, the system will be displacement limited to lower ratings.

b) The required horn-system frequency coverage is 50-500 Hz.

To meet the requirement on f_H (voice-coil inductance and coupling volume willing), S_D/S_T must be 4.5 ; then η_T is 34 % and the large-signal operation is thermally limited to ratings of 195 W input power and 65 W output power. Note that low-frequency response could be extended to f_{min} or 39 Hz (by proper horn design) before the driver displacement limit is reached.

c) Maximum possible power ratings are required for a lower cutoff frequency of 70 Hz.

In this case we select f_{min} = 70 Hz, for which S_D/S_T must be 2.1 . Then f_H = 350 Hz, η_T = 45 % , and the power ratings are 235 W input and 105 W output.