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Heat Transfer Mechanisms in Loudspeakers; Analysis, Measurement and Design

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HEAT TRANSFER MECHANISMS IN LOUDSPEAKERS; ANALYSIS, MEASUREMENT AND DESIGN

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AUTHOR'S NOTE

This paper on heat transfer in magnetic voice coil speakers is based on an earlier one presented to the 57th convention of the AES, Spring 1977. At that time, Mr. Atoji, of Matsushita Electric's Acoustic Research Laboratory, introduced himself and presented me with a copy of his paper on the same subject, a National Technical Report published some seven years prior mine. I found that, although we both covered the same basic subject area and reached similar conclusions, our findings and specific experiments were very complementary and non-overlapping. (Mr. Atoji differs on the subject of inherent air pumping, but I have presented my findings here.) When I began editing and rewriting my original preprint for AES publication, I finally realized that a paper which included the "meat" of both works would best serve the purposes of my original intent for this document; an AES tutorial on heat transfer in electromagnetic loudspeakers. The paper would be another predictive tool for the loudspeaker designer. With this paper, I'm delighted to be able to make a more complete treatment on this important subject.

ABSTRACT

Voice coil heating is a major cause of loudspeaker damage and failure, and thus, a major limitation to power handling capacity. It increases according to electrical input and according to the overall thermal resistance, or temperature rise per unit input power of the voice coil. The "overall" thermal resistance is a direct result of a variety of heat transfer mechanisms, including conduction, radiation, natural convection, forced convection and heat storage. An analysis, including transient behavior, is presented. This analysis includes a description of all contributing factors and provides a final equation for voice coil temperature as a function of electrical input and loudspeaker parameters. Data and data-gathering methods are presented and discussed in support of the analysis, including transient heat transfer. Lastly, various designs are discussed, including several unique and patented inventions.

INTRODUCTION

One of the most important performance characteristics that a loudspeaker has is its rated power. This is determined by various factors, as follows:

1. Temperature rise of the voice coil and the thermal limit of materials which are affected by coil temperature.

2. Acceptable harmonic distortion levels.

3. Maximum deflection amplitude of the voice-coil-and-diaphragm assembly.

4. Mechanical damages caused by operating stresses.

The rated power is also dependent on the nature of the input supplied to the loudspeaker. A typical variety of signals used to rate loudspeaker power capacity is as follows:

1. Sine wave

2. Music or voice

3. Random noise or pink noise

4. Square wave, pulse, etc.

A major limitation to the power handling capacity of a moving-coil loudspeaker is the voice-coil temperature rise, which results from delivering electrical power to the loudspeaker. Excessive temperature degrades adhesives, coatings and the structure of materials, leading to failure of the unit. Therefore, a loudspeaker which gets rid of heat better than others can (at least thermally) handle more power than others. This ability to dissipate heat is characterized by the thermal resistance of the device, expressed as ^{o}C/watt or other similar units. It shows how much a thermal rise will occur "across" a thermal element when a quantity of heat is passed through it. It is, therefore, the purpose of this work to increase the understanding of and provide a computational facility for determining the thermal resistance and temperature of the voice coil of magnetic loudspeakers. In a loudspeaker, the power into its electrical terminals is equal to the acoustic power developed plus the heat power developed in the voice coil (plus any stored power). The only way to determine the real heat power in a loudspeaker is to monitor its rms input current, I, and use I^2R; R being the dc resistance of the voice coil. R changes by about .393%/^{o}C rise in temperature (for aluminum and copper) so at high powers, the dc resistance can go up considerably.

There are five basic heat transfer mechanisms which help reduce voice coil temperature in the normal operation of a loudspeaker. These are conduction, radiation, forced convection, heat storage and natural convection, as follows:

1. Conduction. This type of heat transfer depends on a physical heat path from hot source to cold sink. Heat conduction depends on physical geometry, temperature difference and the property of a material to conduct heat. Most conduction heat transfer takes place to the magnet and adjacent structures (frame, etc.) through the air gap between the voice coil and the magnetic pole tips and then out of the magnet and/or frame to ambient.[1] Other conduction may take place through the moving structure, as we will see.

2. Radiation. Electromagnetic in nature(!), radiation heat transfer depends on the difference between the fourth power of the absolute temperatures of source and sink, surface emissivity and surface area. Radiation heat transfer can occur between the voice coil and air, but it is more significant between the voice coil and the pole tips. High temperatures are required for this mechanism to be effective and is usually not a strong one in loudspeakers.

3. Forced Convection. (a) Inherent forced convection heat transfer results from the moving voice coil "scrubbing" and/or pumping the air between the voice coil and the pole pieces. This results in a lower thermal resistance relative to that with no motion. The forced convection mechanism can be improved per unit diaphragm excursion by making the loudspeaker mechanism "pump" more air through the air gap between pole pieces and voice coil. This may, however, degrade certain areas of speaker performance.

   (b) Externally forced convection is sometimes used to cool speakers. This requires an external air pump or air supply and a loudspeaker which is designed or modified for this purpose. (The extent of this is the practice of running cooling liquid, like water, through the center of hollow coil wire. This is used on high-powered shaker tables used in vibration testing.)

4. Thermal storage. Heat energy can be stored in a material according to its temperature, specific heat, size and density. This is not really heat transfer. As heat is stored in a material without a heat transfer path out, its temperature rises according to the amount of heat added. The effect is similar to that of a fluid reservoir or an electrical capacitor. Heat is introduced and temperature rises and stays that way unless a heat transfer mechanism lets heat flow out. Obviously, this introduces a transient effect with a time constant similar to an electrical "RC" constant. This can vary from fractions of a second in light coils to several hours in massive magnet and frame structures.

5. Natural Convection. Hot air rises and causes "natural" air flow. In a loudspeaker, this is the usual mechanism which removes heat from the magnet-and-frame assembly. A small amount of heat may escape from the exposed portion of an "overhung" speaker coil by natural convection.

ANALYSIS

The total sum of all these heat transfer mechanisms can be represented by an analagous electrical circuit.

Steady-state heat transfer in any element is generally in the form;

$$T = QR \qquad (1)$$

Where T is temperature drop across the element, R is the thermal resistance of the element and Q is the heat power in watts passing through the element. This allows us to think of T as voltage drop, R as resistance and Q as current. Consider a typical voice coil in a typical magnetic air gap, as shown in Figure (1).

The only apparent path shown for heat to flow out of the voice coil is through the air path in the magnetic structure and out to the ambient. An analogous circuit representing these mechanisms

is shown in Figure (2), where

R_V = thermal resistance of voice coil varnish

R_{pp} = total thermal resistance to heat flow from the inside surface of the voice coil to the pole piece

R_T = total thermal resistance to heat flow from the outside surface of the voice coil to the top plate

R_{HS} = total thermal resistance of the magnetic assembly and/or heatsink to air

These resistances can all be combined, using simple analogous dc circuit theory, to obtain a total thermal resistance from the voice coil to ambient, thereby giving a predictor of voice coil temperature rise for a given power or current into the loudspeaker. R_{TP} and R_{PP} would be a parallel combination of all air gap heat transfer mechanisms.

For a given input current, I, at any frequency, the thermal rise, T, would be

$$T = i^2 r R_T \qquad (2)$$

where R_T = total thermal resistance, ^oC/watt

r = dc voice coil resistance at ambient temperature

Solving for T, we get

$$T = T_o + i^2 r R_T \qquad (3)$$

where T_o = ambient temperature

Let's take a closer look at our heat transfer mechanisms.

CONDUCTION (Through Air Gap)

Heat may be transferred through any medium, depending on its thermal conductivity, and its geometry. This is described by the following relationship:

$$Q = AK(T_2 - T_1)/L \qquad (4)$$

where

Q = heat transferred (watts)

A = area normal to heat flow (in)

L = length of heat flow path (in)

K = thermal conductivity (watts/in-^{o}C)

T_1 = temperature at one boundary (^{o}C)

T_2 = temperature at other boundary (^{o}C)

This equation is identical to that for an electrical resistor, where Q is analogous to current, $(T_2 - T_1)$ is analogous to voltage drop and (L/AK) is the thermal resistance.

In a loudspeaker, air conduction heat transfer normally takes place across the air gap. Figure (3) is two typical configurations for conduction heat transfer, one where the voice coil is greater in area to the pole pieces, and one where the reverse is true.

The four heat conduction areas are top plate area (A_{TP}), inner voice coil area (A_{VCI}), outer voice coil area (A_{VCO}) and pole piece area (A_{PP}). Generally, radial air gap spacing is small enough relative to axial dimensions to consider the heat transfer areas to be limited by the smallest area. Case 1 illustrates conduction being determined by the voice coil areas A_{VCI} and A_{VCO}. If the voice coil support were aluminum, A_{VCI} could be assumed to be a bit larger.

In Case 2, A_{PP} and A_{TP} are the controlling areas. When calculating total conduction to the pole piece and to the top plate, thermal resistances are combined as one would in a parallel electrical circuit. Thermal conductivity of air is 7×10^{-4} watts/inch ^{o}C.

A survey was done of a variety of loudspeakers. Their static conduction heat transfer coefficients were measured and compared to calculated values. The four woofers represent a complete variety of heat paths and voice coil sizes. Measurement of real-world thermal resistances entailed mounting a complete moving

structure (cone, spiders, etc.) in an uncharged magnet assembly. In one case, the voice coil was fitted with .002" Chromel-Alumel thermocouples. Power was fed into the uncharged speaker from a variac or variable auto transformer plugged into a normal (60 Hz) ac outlet. In a second method temperature was measured by a change in coil resistance, using an instrument to be described later. Power was applied at 300 Hz (typical minimum or "trough" impedance frequency) via an audio power amplifier. Input power and temperature were measured at various input power levels and the average slope of the temperature-power curve (^{o}C/watt) was taken as the thermal resistance. Care was taken to make the measurements quickly, before the magnet assembly reached a high enough temperature to affect the experiment.

On a wide variety of larger (2" to 4") coils and configurations, I calculated thermal resistances of 3.7, 1.89, .68 and 3.5^{o}C/watt and actually measured 2.0, 1.75, 0.83 and 2°C/watt. In another study, Atoji and others reviewed smaller coils (3/4" to 1.8") and got the following correlation:

Calculated ^{o}C/Watt	Measured in Uncharged Magnet @ 300 Hz	Measured in Charged Magnet @ 300 Hz Input
14.70	13.80	12.00
18.90	17.70	16.50
8.33	7.21	7.02
14.50	13.00	12.20
8.04	7.40	7.17
14.60	14.00	11.80
3.98	3.96	3.78
3.77	3.70	3.56

Correlation here is better, but both indicate that the equations presented could be used with confidence in predicting coil-to-magnet thermal resistance. It also points the way to good heat designs; make the speaker's voice coil surface area large and its air gap very tight.

"Ferro" fluids have thermal conductivities seven to ten times greater than air and can improve air gap heat transfer proportionately. Design cautions must be taken, however, since they can add attached mass and extra damping, and can squirt out of the gap and soak into paper cones, suspensions and coil forms if allowed to. This is especially true for high-powered applications. With these variables taken into account, successful design can be accomplished using ferrofluids.

An interesting new development in high-power driver design involves improving air-gap conduction by the use of a non-magnetic pole tip extension, developed at Electro-Voice. On a coil which overhangs the air gap, as is normal design practice for high-excursion woofers, the normal thermal failure occurs on the "overhung" portion of the coil. This is expected, since there is no close-proximity surface to this portion of the coil, and the thermal resistance is relatively high here. A simple pole extension is a solution and was, in fact, a feature of earlier EV designs (Sentry III woofer). However, it was found that a higher gap flux density could be attained by keeping the pole even with the top plate and extending the heat transfer surface with a piece of aluminum, which has secondary advantages in controlling inductance and inductive distortion. As a result, it was named the Thermo-Inductive Ring or TIR[TM]. These various schemes are shown in Figure (4). Additionally, a Teflon-based coating (EV PROTEF[TM]) is used to protect the coil from high-temperature expansion. Applied to the top plate, this coating both electrically insulates the coil from the failure cause by a "rub" as well as providing very low local thermal resistance for additional cooling.

THERMAL COMPRESSION

An interesting phenomenon illustrating effects of thermal resistance of the coil in the high-power use of loudspeakers is "thermal compression." This is sometimes quite audible. When high power is applied to a "cold" speaker, its output actually decreases in the time period it takes the coil to reach its "hot" temperature. This occurs in both woofers and compression drivers.

Woofer design for efficiency and linear excursion capability can greatly affect thermal compression. High-efficiency woofers have relatively light short coils and are thin radially, so that high flux density can be had; these have high thermal resistances. On the other hand, low-efficiency designs employing heavy, overhung coils will have low thermal resistances and resulting low thermal compression "at speed."

The following experiment was conducted as a means of illustration. Various 15-inch woofers were installed in a 10-cubic-foot test enclosure. Frequency-response curves were run on these at 1 watt and then 100 watts, with the level lowered by 20 dB. A perfect, thermally non-compressing woofer would, thus, draw two coincidental curves. Curves were done on an 8 x 10-inch chart and run slowly (5 mm/sec) so that coil warmup was not an effect. Figure (5) is for a low-efficiency, high-excursion design (1-1/2% efficient) with a 4-inch diameter coil; note that

compression is about one dB. Figures (6) and (7) show similar designs (about 2.5% high excursion) using a 2-1/2-inch coil and 4-inch coil respectively; both exhibit about 1 dB of compression. Figure (8) shows a high-efficiency, limited-excursion design (about 5% efficiency) with a 2-1/2-inch coil which compresses between 1 and 2 dB. Lastly, the very high-efficiency design (8%) with a 4-inch coil compresses the most; 2 to 3 dB, as shown in Figure (9). Interestingly, similar designs for efficiency and linear magnetic excursion using different coil diameters yield similar coil surface areas and similar thermal compression. As the coil diameter is made smaller, the magnetic air gap and the axial coil length must become larger to net the same motor strength. Thus, similar designs have similar coil surface areas. The comparison between Figures (6) and (7) illustrate this. Lastly, higher efficiency designs tend to yield coils with smaller surface area, which tend to exhibit greater thermal compression.

CONDUCTION (Through moving structure)

If the moving structure of a loudspeaker is properly constructed, it can be made to be a significant heat conduction path.

Consider a compression driver with a 2.83-inch coil and aluminum diaphragm. When tested with band-limited pink noise, 2 to 3 kHz, this driver exhibits a 1.9°C voice-coil rise per watt into the device. With an approximate efficiency of 25% at this frequency, approximately 0.75 watts are dissipated in the voice coil, making the overall thermal resistance 2.53°C per watt. This is accountable to air conduction, forced convection and some radiation. Since the voice coil support is paper, conduction heat transfer is assumed negligible. We can improve conduction through the structure by making an aluminum voice coil support (.002" thick), as shown in Figure (10). The heat path is through the support, through the compliance and to thermal ground (magnetic pot assembly).

Referring to Figure (10),

R_V = thermal resistance of varnish or glue between coil stack and support

R_S = thermal resistance of support

R_C = thermal resistance of compliance

R_J = thermal resistance of support-to-diaphragm glue joint

R_H = thermal resistance of heat sink.

Using equations (1) and (2),

$$R = T/Q = L/AK \qquad (5)$$

$$R_V = (.001")/(.889\ in^2)\ \ (.01W/in\ -^oC) = .112^oC/watt$$

$$R_S = (.1)/(\pi \times 2.83 \times .002)\ (5.5\ W/in\ -^oC) = 1.022^oC/watt$$

For a radial path, where b is the path thickness,

$$R = Log\ (O.D./I.D.)/2Kb \qquad (6)$$

The diaphragm was formed from .002" aluminum stock and its "tangential" or corrugated surround surface could possibly have 20% greater path length. Also, due to forming, the local thickness could easily be .0015". Using (6),

$$R_C = Log\ (3.59/2.83)/(2)\ (5.5)\ (.0015) = 1.993^oC/watt$$

The only thermal impedance left is that of the glue joint between the support and the diaphragm (R_j) We can approximate this by

$$R_j = (.001)/(.05 \times \pi \times 2.83)\ (.005) = .45^oC/watt$$

On a handmade prototype, R_j could well be $.9^oC/watt$.

All these thermal resistances add up to be a series combination totaling $4.03^oC/watt$. This is enough to theoretically reduce the thermal resistance from $2.5^oC/watt$ to $1.56^oC/watt$. Real measurements on the system described yielded a change from 1.9^o to $1.3^oC/input\ watt$, indicating a final "real" total thermal resistance of $1.73^oC/watt$ and a calculated conduction coefficient (due to reconstruction) of $5.47^oC/watt$, pretty close to what we theorize. For a high-powered driver, driven at 100 watts, this redesign alone would reduce the voice coil temperature by at least 45^oC. This analysis technique may also be applied to heat-conducting woofer spiders, although fatigue may be a problem at high excursions.

RADIATION

Radiation heat transfer can occur between two surfaces of dissimilar temperature or between a surface and an adjacent gas of differing temperature. Generally, high temperatures are

needed (above 300°F) to produce significant radiation heat transfer in loudspeakers, compared to other effects. Radiation heat flux (watt/in.) is found by equation (7);

$$q = 3.66 \times 10^{-1} \xi (T^4 - T_o^4) \text{ watts/in} \qquad (7)$$

where

q = heat flux transferred, watts/in

T = temperature of hot surface, °K

°K = °K absolute temperature

ξ = emissivity of the radiating surface

Tables of emissivities of various surfaces can be found in any heat transfer text. Generally, painted and dull surfaces and liquids have high emissivities (.8 - .99); polished and plated surfaces have low emissivities (.01 - .10).

So, if one wants to find the effect of radiation, he would use equation (7) and use the heat transfer area to find actual heat transfer rates. The following is a case study involving a production loudspeaker.

> A high-powered 15-inch woofer has a three-inch diameter voice coil. Figure (3), Case 1 shows a configuration of voice coil and air gap, with surface areas shown. The voice coil has about 3 in^2 outer radiating surface and the voice coil support has about 9 in^2 inner radiating surface. The aluminum voice coil has a varnish coating which has an almost ideal emissivity (.94); however, the support is shiny aluminum, which is a very bad radiator (.04); hence, a good reflector. The support probably has an effective radiating surface area of about 4 in^2, since there will be a thermal gradient in the axial direction. Furthermore, the voice coil and support is surrounded by plated metal pole tips, which have poor emissivity and, consequently, excellent reflectivity. This all adds up to rather poor radiation heat transfer.

The loudspeaker under investigation, having an uncharged magnet, shows a 1.25°C rise per watt input. Using equation (3) and choosing a 100-watt heat power (4.23 amperes into approximately 5.6 ohms), we can show that the thermal rise will be approximately 119°C. This will be an effective input signal of 143 watts into 8 ohms; the power limit for the device in question.

Using equation (7) for radiation we find that, for a total radiation area of 7 in^2, approximately 3.9 watts will be dissipated if we treat the surfaces intended for radiation with the proper material (black paint, etc.). Therefore, instead of 100 watts going into conduction heat transfer, only 96.1 watts will, the rest going into radiation. This is only a 4% change and probably isn't worth it. Figure (11) shows the result of our test. There is basically no difference in coil temperature until the 100 watts heat input level is reached, where a 22°C reduction is noticed. Because of the data spread, about all that can be said is that the painting is tending to improve heat transfer at high power levels. An overall improvement for the flat black painted case indicates that an improvement has been made in increasing the average surface area, not the emissivity. A general conclusion here is that radiation does not seem to be a very powerful heat transfer mechanism for loudspeakers. The effort required for optimizing radiation heat transfer is met by diminishing returns.

FORCED CONVECTION

In the preceding section, we considered the temperature rise when the voice coil did not move in the air gap of the magnetic circuit. In this section the temperature rise will be considered while a loudspeaker is operating and is in motion.

A loudspeaker which can pump a lot of air through its air gap, and thus over the voice coil, might be able to transfer more heat out of the voice coil. The air pump mechanism is modeled as a piston pumping an incompressible liquid through two orifices, one being the vent in the magnet assembly hole and one being the inner air gap. This is illustrated in Figure (12).

If A_g is gap area, A_V is vent area and A_p is effective piston area under the dome, this volume flow will be

$$U_g = V_p A_p / (1 + A_V / A_g) \qquad (8)$$

where U_g is the volume velocity of air through the air gap

V_p is the linear velocity of the piston.

Four of the uncharged-magnet woofers used in the static air-conduction experiments were evaluated, using equation (8), on their ability to pump air through the air gap. They were then tested, each voice coil being brought up to a temperature and then vibrated and the new changed temperature recorded. Each

cone was driven by another 15-inch speaker placed over the test unit, spaced by several layers of composition rim gaskets. A mechanical depth gauge was used to monitor cone displacement. The gauge itself was used as one contact and a small piece of copper soldered to a wire lead and glued to the cone was used as the other. These connected a dc power supply to an oscilloscope; when moving contact was reached, a square wave would appear on the scope and vibration was adjusted for minimum contact period by noting the pulse width of the square waves. This type of cooling mechanism should be velocity or flow dependent. Therefore, data was plotted versus rms velocity by taking the magnitude of peak displacement and converting it (via frequency) to rms velocity. Temperature change from the static condition was recorded.

In general, the trend of the data was that temperature reduction increased with rms cone velocity and with power input, which is the same as saying that the thermal impedance of the air gap was reduced with rms cone velocity. Also, those woofers which showed the greatest capacity to pump air showed the highest temperature reduction for a given rms cone velocity. Pumping capacity was calculated for a 1 in/sec cone velocity. This is plotted in Figure (13).

Of special interest is the case of a woofer which had a vented dust cap. At the maximum cone velocity tested (26.7 in/sec rms), it reduced temperature $5^{o}C$ from a normal $100^{o}C$. The dust cap vent screen was then blocked with a thick adhesive and the test was rerun; the temperature was reduced by $60^{o}C$ at the same cone velocity! This is not the panacea it seem, however. This results in a very stiff air spring caused by trapped air under the dust cap and a sizable mechanical resistance to ground. The former is a known source of distortion (very nonlinear spring) and the latter is a power loss and will greatly influence the low frequency alignment of the speaker in a vented box. The point here is that the designer is faced with a compromise between good forced convection cooling and a change in some speaker parameters. Also, it has been observed that, for some reason, a speaker which pumps air well does so in a preferred direction. This results in a dc offset of the cone and resulting maladies in performance.

FREQUENCY-RESPONSE OF TEMPERATURE[7]

Since the impedance of all moving-coil magnetic loudspeakers varies greatly over their normal range of operation, one would naturally expect the voice coil temperature to similarly vary.

Also, at low frequencies where there is a lot of voice coil motion, temperature may also be further reduced, depending on the driver, due to inherent forced or "pumping" convection. Figure (14) shows how we would expect temperature to vary with various types of inputs to a "typical" closed box or second-order low-frequency diaphragm load. The impedance shows a typical rise at resonance, f_s, a dropoff at "minimum impedance" and high frequency. If constant power were applied independent of frequency, we would expect a constant coil temperature with frequency, in the steady-state. A constant-current drive would give more power at high impedances, or at resonance and at the inductive rise. The real-world expectation of constant voltage would give reduced power input at these high impedances. The specific design would determine the actual amount of temperature reduction at resonance.

Here are some real examples of constant voltage input (6 volts) frequency responses of temperature. Figure (15) is a relatively "high-Q" cone-type speaker with resonance at about 35 Hz. Note how temperature approximately tracks the impedance. Figure (15) shows a much lower-Q cone-type speaker with a "flatter" impedance. The temperature frequency response is also flatter, with a similar reduction at high frequencies due to inductive rise. Lastly, the compression driver on a horn in Figure (16) exhibits both the flattest impedance and temperature response. As a sub-conclusion, it should be obvious why single notes, well-placed, can either produce high or low thermal rise. A synthesizer player, not aware of the results, can easily cause much damage to the speaker of Figure (16) by playing a lagato 200 Hz to 500 Hz passage. Conversely, a manufacturer could improve the advertised power rating of the compression driver in Figure (17) by rating it with a 1600 Hz sine wave.

HEAT STORAGE AND TRANSIENT RESPONSE[7]

A thermal element will store heat according to its specific heat and its mass. It is directly analogous to an electrical capacitor. Heat will "leak" out of heat storage according to the thermal resistance of the path out, and an "RC" constant can be established. The differential heat stored in a thermal element is found by

$$E = MCdT \qquad (9)$$

where

E = heat energy stored

M = mass of element

C = specific heat of element

dT = temperature change of element

The differential equation governing the transient behavior of a simple mass-and-thermal-resistance voice coil system is as follows:[7]

$$W_e\, dt/J = M_V C\, dT + T\, dt/J\, R_T \qquad (10)$$

where W_e = total heat power (watts)

M_V = coil mass (K)

T = coil temperature (^oC)

C = specific heat

J = thermal-to-electrical energy conversion constant (watt/joule)

R_T = total thermal resistance (^oC/watt)

Solving this equation for temperature as a function of time, we get

$$T = W_e R_T \left[1 - e_{xp}(-t/JM_V C R_T) \right] \qquad (11)$$

Final temperature, T_M, at t = becomes

$$T_M = W_e\, R_T = i^2 R_V R_T \qquad (12)$$

The thermal time constant, t, when the temperature is half its maximum value, is easily obtained from (11).

$$t_{1/2} = JM_V\, C\, R_T \qquad (13)$$

Note that "tight" or precision air gap speakers with low-mass coils yield low R_T and M_V, thus low t, thus "fast" thermal tracking. The quantity "MC" is equivalent to a capacitor value. A thermal time constant, which is the product of MC and the thermal resistance of the element gives a number whose units are time only; a thermal "RC" constant.

Example:

A copper woofer voice coil weighs 24 grams and has a total thermal resistance to the magnet structure of $1^{\circ}C$/watt. The transient time constant may be found as follows:

$$t = MCR$$

$$t = (24g)X(.092 \text{ cal/g } ^{\circ}C)X(.239 \text{ joule/cal})X[1^{\circ}C/\text{joule/sec})]$$

$$t = .528 \text{ seconds}$$

which means that this voice coil will reach 63% of its asymptotic temperature in 1/2 second or so; it will "come up to final temperature" on the order of several seconds. In comparison, a typical large magnet pot structure takes typically an hour or two to stabilize. Heat storage is obviously an excellent guard against fast power peaks.

A unique test apparatus[7] was used to make actual measurements of temperature as it "tracks" the input voltage for "thermally slow" and "thermally fast" loudspeakers; a woofer and a high-frequency compression driver, respectively.

The temperature rise of the voice coil can be determined by its change in dc resistance. Then the temperature rise T is

$$T_2 = \left(\frac{r_2}{r_1} - 1\right)\left(\frac{1}{\lambda} + T_1\right) \qquad (14)$$

where r_1 = coil resistance at T_1 ($^{\circ}C$)

r_2 = coil resistance at T_2 ($^{\circ}C$)

λ = temperature coefficient of the voice coil wire;

$\lambda_{Al} = \lambda_{cu} \doteq 4 \quad X\ 10^{-3}$ at $50^{\circ}C$ for an aluminum and copper wire. Therefore,

where r_2 and r_1 are dc resistances of the voice coil at the risen temperature T_2 and room temperature T_1.

Figure 18 shows a block diagram of experiments for measuring the temperature rise of a voice coil while the loudspeaker is operating. The maximum output voltage is 10 volts, and corresponds to $200^{\circ}C$, or the output voltage one volt corresponds to $20^{\circ}C$.

This method is very useful for measuring the temperature rise of the voice coil when an instantaneous program source as music or voice is applied to the loudspeaker. Figure (19) shows the voice coil temperature response of a 12 cu cone-type speaker to two different musical inputs; Figure (19a) uses the relatively lagato "Bach: Toccata and Fugue in D Minor" (Victor SHP2310) and Figure (19b) uses the more staccato Uuliji Asaoka recording "Shimasodadri" (Toshiga JLP 5002). Note how the coil temperature has less facility in following the latter. Figures (20a) and (20b) contrast the thermal response of a "slow" woofer (30 cm) and horn tweeter (9 cm) respectively, using the same musical passage; Montovani's "Chim Chim Cheree" (SLC162). The former "averages" and the latter does a good job of "tracking" the musical input. One could interpret these different thermal responses as slow and fast thermal compression and, conversely, mild and severe thermal shock. Figure (21) shows the variations of the temperature rise to the amplifier output (or input voltage to the loudspeaker); this program is "Toccata and Fugue in D Minor" by Bach.

THERMAL TIME RESPONSE OF MAGNET/FRAME

Equations (11), (12) and (13) also hold true for a magnet/frame assembly. To illustrate a typical example, a typical-size 15-inch frame and magnet for a professional woofer (EV DL15W) is heated and later allowed to cool in free air. In both cases, the 63% thermal time constant is on the order of an hour. At two hours, about 90% of the final temperature is reached. Figure (22) shows magnet temperature and temperature just above the magnet for heat-up and Figure (23) shows cool-down.

FINAL HEATSINK

With all this heat transfer to the magnetic assembly, it will rise to its melting temperature unless the heat can flow out of it! Therefore, the thermal resistance from the magnet assembly-to-ambient is very important; a rise of temperature in the magnet assembly reflects back as the same temperature rise in all the driver components "downstream" of the magnet. This is the same effect as a "bias" voltage in an electrical circuit. The final heatsink from the magnet assembly-to-ambient is the last "link" or path to ambient or thermal ground and is an important determinant of final voice coil temperature. The thermal time constant of a massive magnet assembly is at least an hour, so this must be taken into consideration. Power tests, such as those recommended by the AES, last for several hours to allow the magnet to reach final temperature.

Some loudspeaker manufacturers have attempted to improve heat transfer from the magnetic structure by adding a variety of radial fins to the magnetic structure. Although this kind of design may improve heat transfer by increasing the area, the fins do not improve natural convection heat transfer. A heatsink similar to those used on audio power amplifiers would be a better choice, where the fins are parallel to the natural convection flow. Black paint or crinkle paint won't help radiation heat transfer at normal temperatures, but it will improve the heat transfer area over gloss paints. These are all minor effects and just the fact that heat is transferred to a large magnet and, in most cases, a massive aluminum frame has a big effect.

The following experiments were performed to explore the effects of frame and box heat transfer mechanisms: An Electro-Voice "EVM" magnet was fitted with a standard 2-1/2-inch voice coil by epoxy, bonding it into the air gap. This way, no motion resulted and all the power applied would be turned into heat. Various 15-inch frame and box configurations were experimented with per the table to follow. A "dummy" cone was held in place to simulate the cone's effect on heat. One-hundred watts was supplied by a variac ac (60 Hz) supply. Ambient temperature was about 70°F.

Condition of Magnet	°F Above Magnet	°F on Magnet	°F on Frame Leg	°F in Front of Cone
1) On Plastic Frame in Air	125.0	230.0	76.7	71.8
2) On Aluminum Frame #1 in Air	110.6	173.2	103.9	71.8
3) On Aluminum Frame #2 in Air	159.6	174.0	131.4	105.1
4) Condition 2 in Open Back Box	97.7	163.8	103.1	70.2
5) Condition 2 in Vented Box, no Fiberglass	140.0	178.8	117.7	71.4
6) Condition 2 in Vented Box, w/Fiberglass	109.6	202.0	121.9	75.6
7) Condition 2 in Closed Box, no Fiberglass	126.6	181.0	121.9	80.9
8) Condition 2 in Closed Box, w/Fiberglass	164.9	207.0	140.7	82.2

We can make a few broad conclusions here. One, the effect of the aluminum frames on magnet temperature is clear, relative to the plastic frame. Second, a closed, fiberglass-filled box is the worse case, making about a 130°F temperature rise. However, this

is only about 30% higher than the speaker in free air, which rises about 100°F for the same power.

In another independent test using a heatsink-greased heating element clamped directly to a magnet of similar size, about 1/2°C per watt was measured in free air, .7°C per watt in an unlined vented box and 1°C per watt in a lined, closed box. A variable here is the thermal resistance of the heating element. The voice coil method shows lower thermal rises per watt since its thermal impedance to the magnet is probably greater than the thermally-greased heating element. The test with the latter indicates more directly the effect of magnet-and-frame condition.

COMPLETE MODEL

Based on all the previously discussed mechanisms, a complete circuit-theory model can be constructed. This is shown in Figure (23).

Long-term voice-coil temperature can be found by elimination of the thermal masses and finding the total heat-transfer-coefficient-to-ambient of the system, R. (Short-term voice-coil temperature is found by assuming that the magnet temperature, tm, is at ambient.) Voice coil resistance is found by the expression

$$r_{VC} = r_o \ (1+.039 \ T_{VC}) \qquad (11)$$

where r_o is the voice-coil resistance at ambient temperature and T is the thermal rise of the voice coil, °C.

Current into the loudspeaker is

$$i = e/(r_{VC} + Z_m) \qquad (12)$$

where i is input voltage and Z_m is the mechanical impedance of the loudspeaker referred to the input terminals.

Heat power developed in the voice coil, i^2r, multiplied by the overall thermal resistance, will yield the temperature rise of the voice coil. Using (11), (12) and (1) yields a messy cubic:

$$T^3 \ (1.521 \times 10^{-3}) + T^2 \ (.078) \ (r_o^2 + r_o \ Z_m)$$

$$+ T[A_m^2 + 2 \ Z_m r_o + r_o^2 - .039 \ Rr_o e^2] - Rr_o e^2 = 0 \qquad (13)$$

Obviously, A_m is a frequency-dependent impedance; R will also be frequency variant, depending on the forced-convection coefficients. Not intended for use on your pocket calculator, equation (13) could easily be solved for T on a small computer and is a nice guide for thermal design of high-powered loudspeakers.

CONCLUSION

The voice coil of a typical loudspeaker transfers heat to the magnetic assembly through a variety of "natural" mechanisms. The moving structure can be constructed so that heat may be conducted through it to the magnet also. High-excursion woofer coils suffer higher temperatures in the "overhung" portion and can be thermally damaged at high power levels. Loudspeaker magnet assemblies can be constructed for improved heat transfer to this kind of coil. The design of coils for similar efficiency/excursion yields similar thermal resistance and thermal compression; smaller coils are longer and visa/versa, yielding similar coil surface areas. Conduction and radiation heat transfer mechanisms can be calculated with reasonable accuracy. Forced convection may be predicted based on the loudspeaker's ability to pump air through the air gap; however, performance maladies may arise if the speaker pumps too aggressively. The heat must then be transferred out of the magnet assembly to ambient or its temperature will get very high with a large power input to the loudspeaker. A typical large loudspeaker's cast frame and magnet assembly acts as a reasonable heatsink in free air, but in a box, this ability may be reduced by a factor of two or more. Lastly, the aggregate or overall thermal resistance of the loudspeaker can be calculated by using an electrical circuit model of all mechanisms mentioned. This is used to predict long-term voice-coil temperature for a given power input. The designer must especially take all these thermal impedances into account when designing a high-powered loudspeaker.

ACKNOWLEDGMENTS

My thanks to Douglas Button, who ran a variety of important measurements used herein, Wilma Hittle, who word-processed this all together, and to Mr. Atoji for his excellent report on this same subject.

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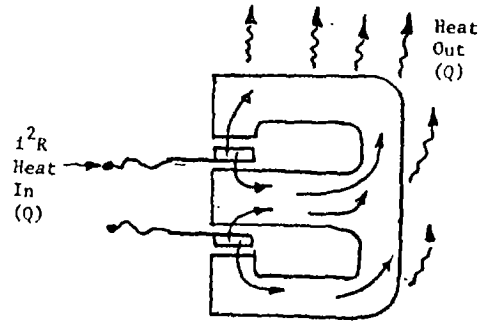
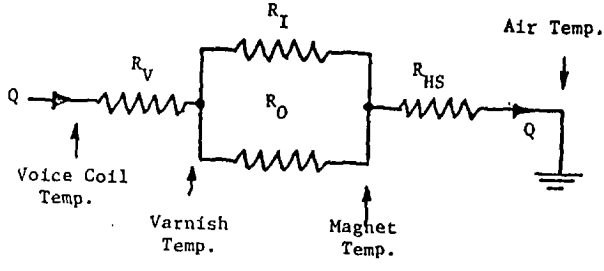
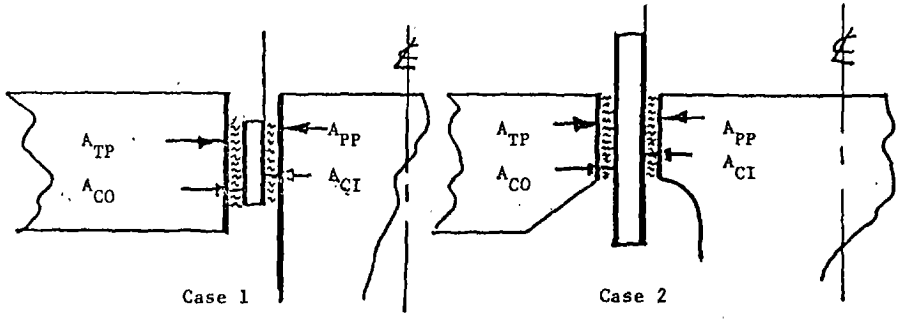


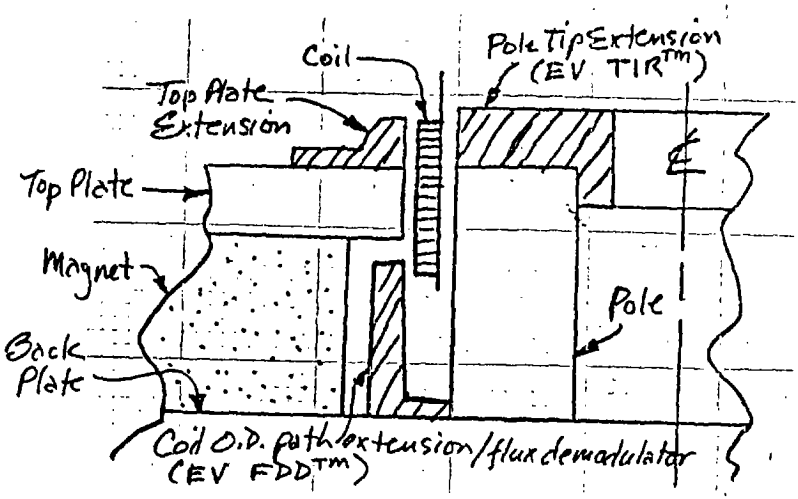
(1) Air Conduction Through Magnetic Air Gap



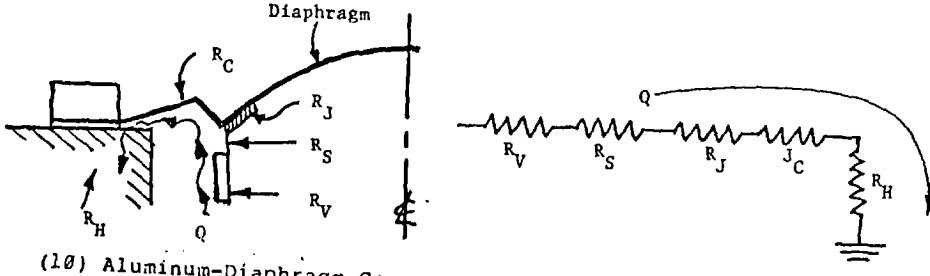
(2) Analogous Circuit for Figure (1)



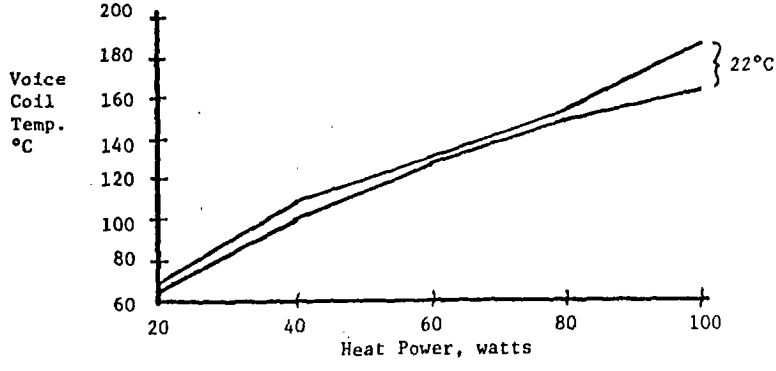
(3) Two Typical Configurations for Conduction Heat Transfer:
Case 1; Short Coil - Coil Surface Area Controls:
Case 2; Long Coil - Pole Tip Area Controls



(4) Auxiliary Heat Transfer-Engouraging Magnet Parts; Aluminum Pole and Top Plate Extensions



(10) Aluminum-Diaphragm Compression Driver with Heat-Conducting Aluminum Coil Form.



(11) Effect of Improving Radiation Heat Transfer with Black Paint on Woofer with 3" Diameter Coil.

ENGINEERING RESEARCH

(5) 100-Watt Thermal Compression Curves, Re: 1 Watt @ +20 dB
1.5% Efficient 15-Inch, Long-Excursion Woofer with 4-Inch
Diameter Coil

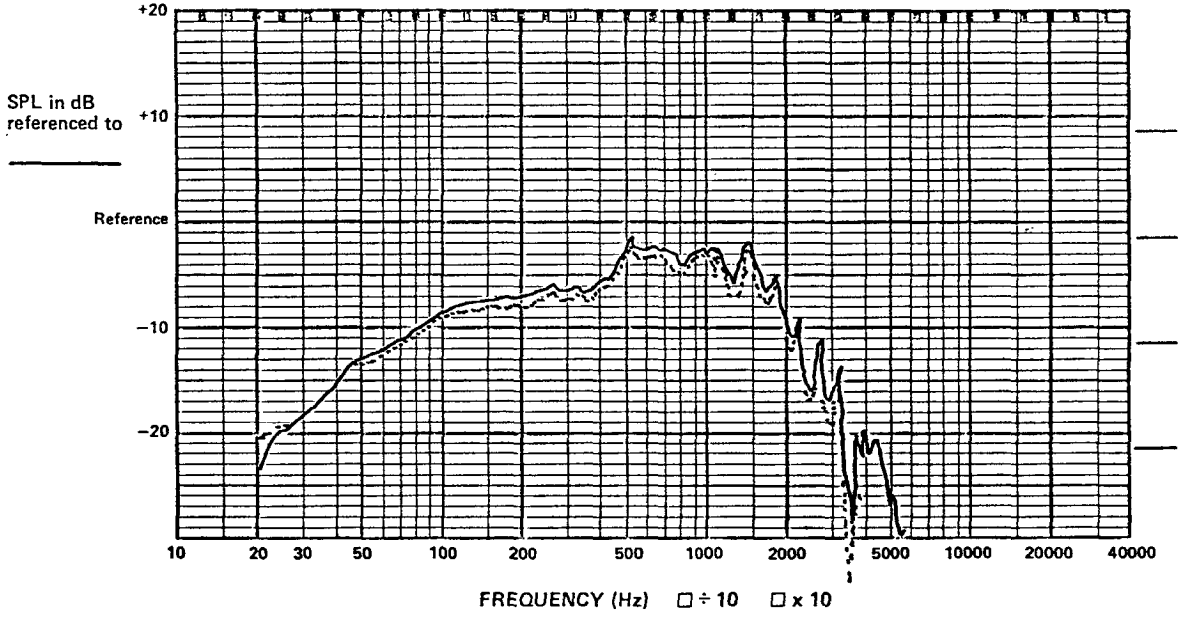
DATE _____

SPECIAL NOTES

ANALYZER BANDWIDTH _____

LOG CONVERTER SPEED
OR TIME CONSTANT _____

SWEEP SPEED _____



Litho in U.S.A.

ENGINEERING RESEARCH

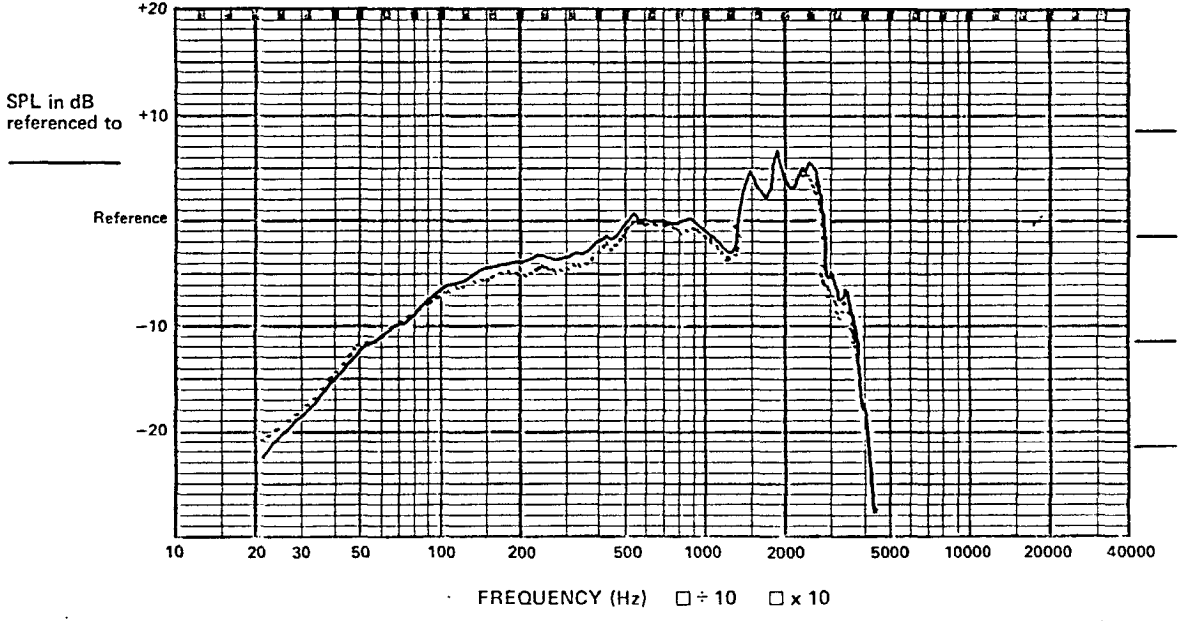
(6) 100-Watt Thermal Compression Curves, Re: 1 Watt @ +20 dB
2.7% Efficient, 15-Inch, Long-Excursion Woofer w/2-1/2" Coil DATE _____

SPECIAL NOTES

ANALYZER BANDWIDTH _____

LOG CONVERTER SPEED
OR TIME CONSTANT _____

SWEEP SPEED _____



Litho in U.S.A.

ENGINEERING RESEARCH

(7) 100-Watt Thermal Compression Curves, Re: 1 Watt @ +20 dB
2.5% Efficient, 15-Inch, Long-Excursion Woofer w/14" Coil

DATE _____

SPECIAL NOTES

ANALYZER BANDWIDTH _____

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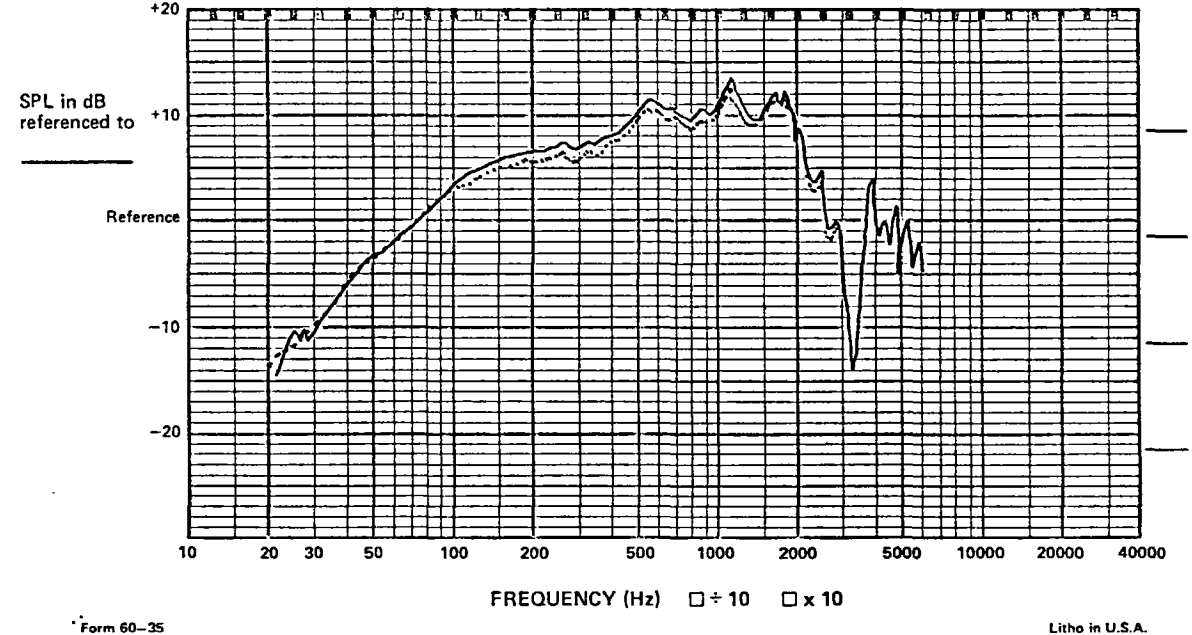
SWEEP SPEED _____



Litho in U.S.A.

ENGINEERING RESEARCH

(8) 100-Watt Thermal Compression Curves, Re: 1 Watt @ +20 dB
5% Efficient, 15-Inch, Medium-Excursion Woofer w/2-1/2" Coil

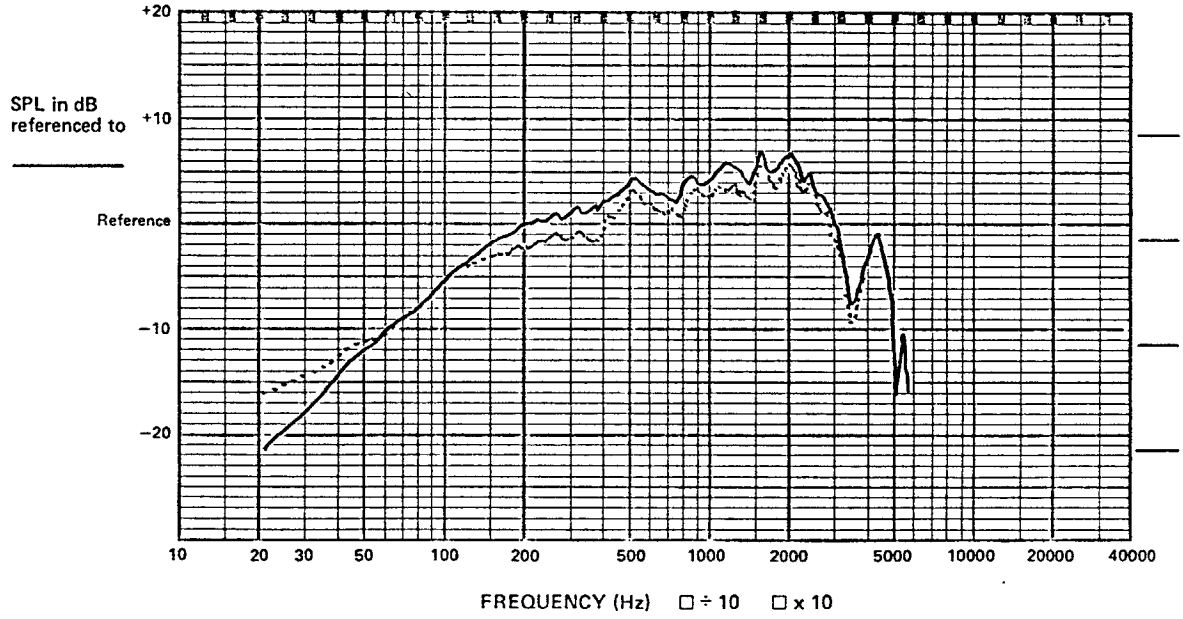
DATE _____

SPECIAL NOTES

ANALYZER BANDWIDTH _____

LOG CONVERTER SPEED
OR TIME CONSTANT _____

SWEEP SPEED _____



Litho in U.S.A.

ENGINEERING RESEARCH

(9) 100-Watt Thermal Compression Curves, Re: 1 Watt @ +20 dB
3% Efficient, 15-Inch, Short-Excursion Woofer w/4" Coil

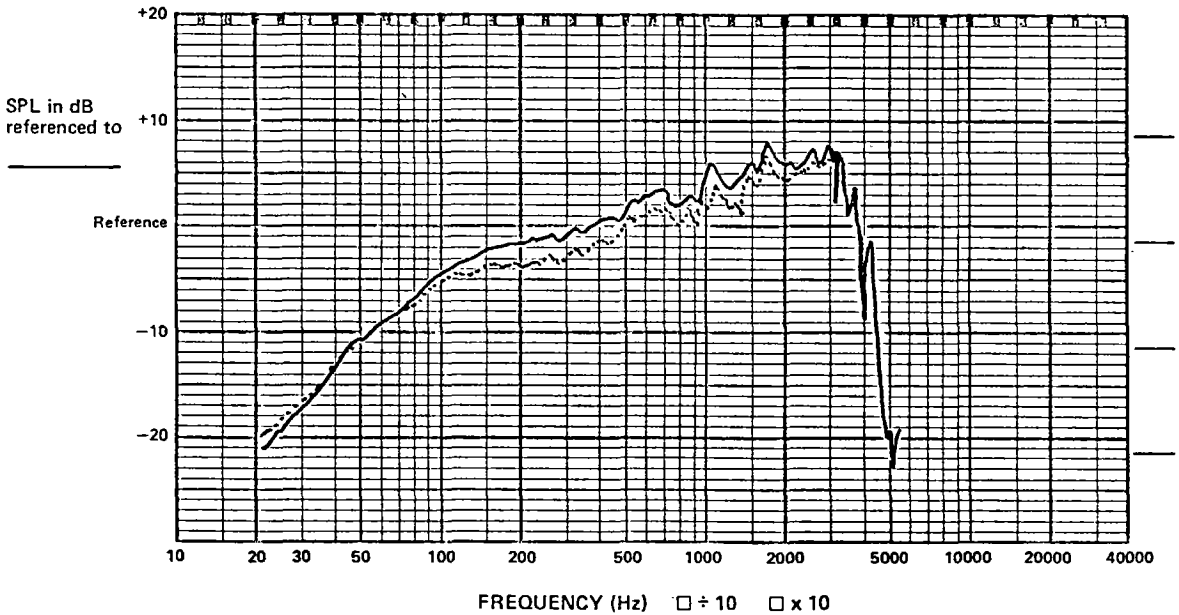
DATE _____

SPECIAL NOTES

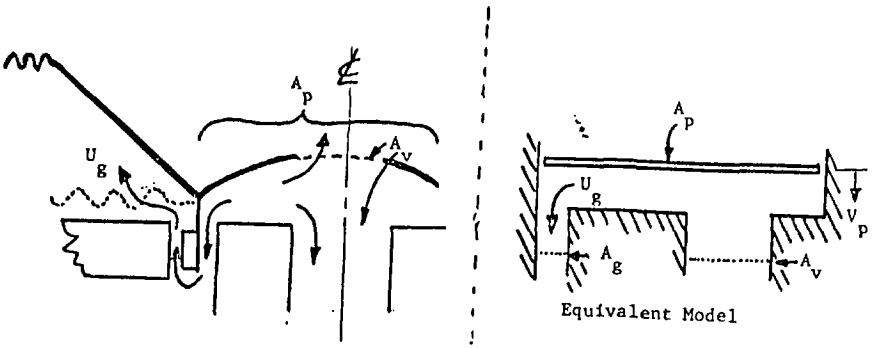
ANALYZER BANDWIDTH _____

LOG CONVERTER SPEED
OR TIME CONSTANT _____

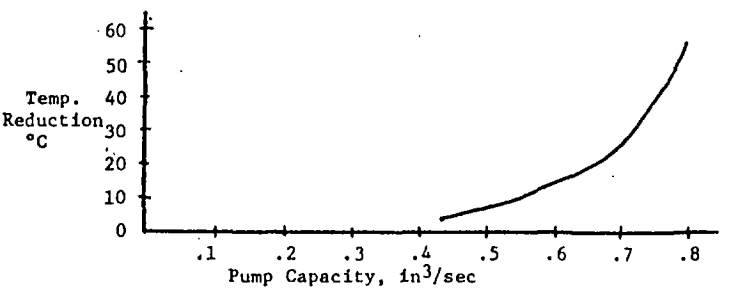
SWEEP SPEED _____



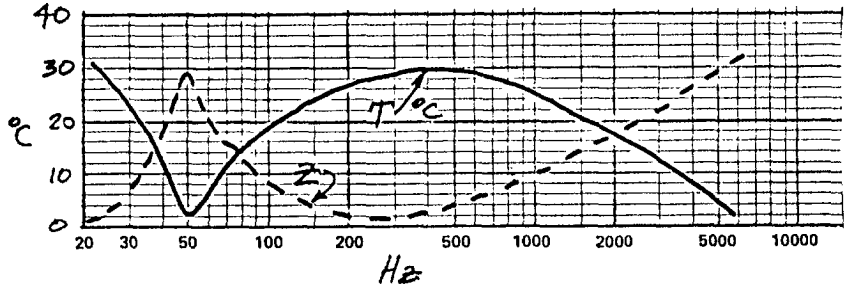
Litho in U.S.A.



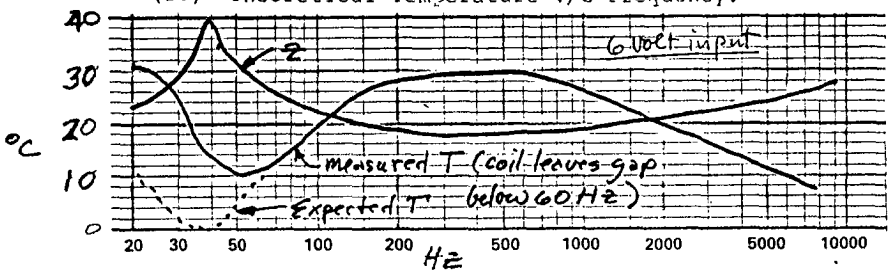
(12) Woofer Air Pumping Mechanism.



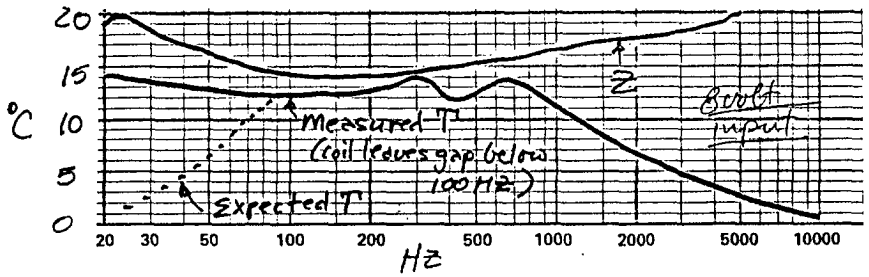
(13) Change in Coil Temperature due to Air Pumping.



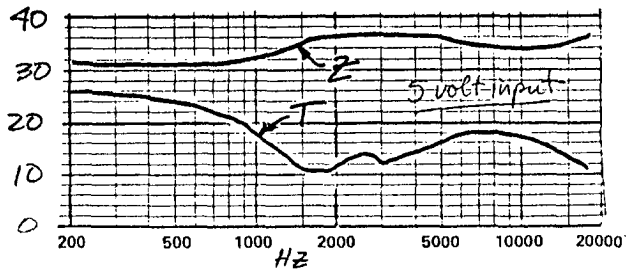
(14) Theoretical Temperature v/s Frequency.



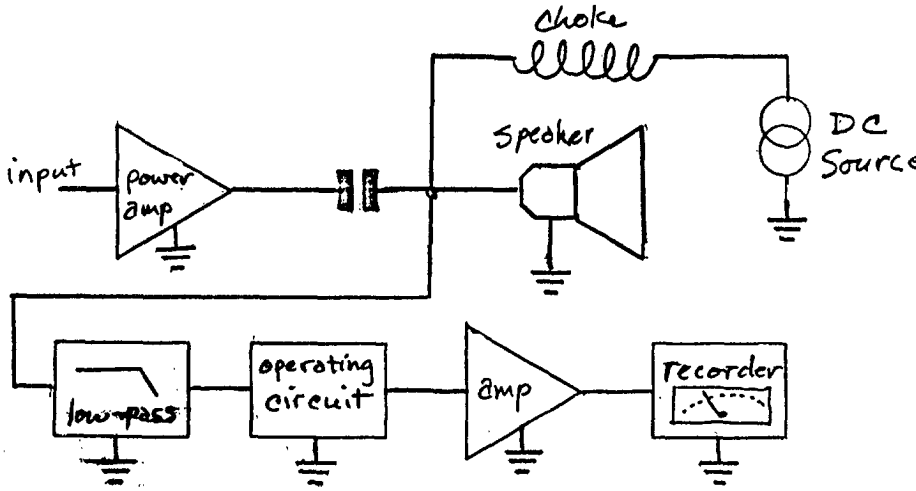
(15) Voice Coil Temperature v/s Frequency, Constant Voltage Input, High-Q Woofer.



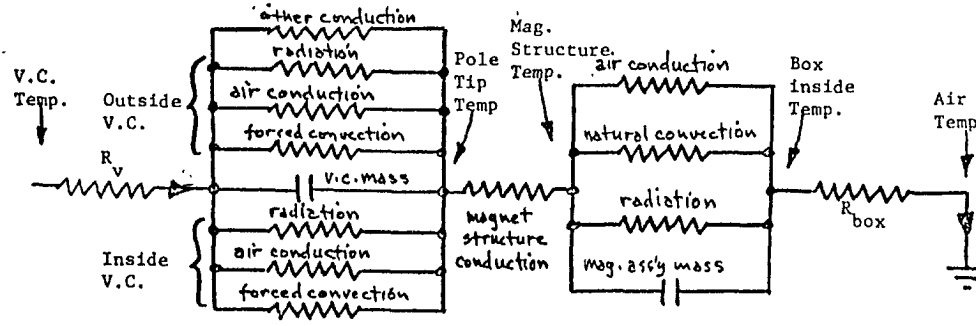
(16) Voice Coil Temperature v/s Frequency, Constant Voltage Input, Low.



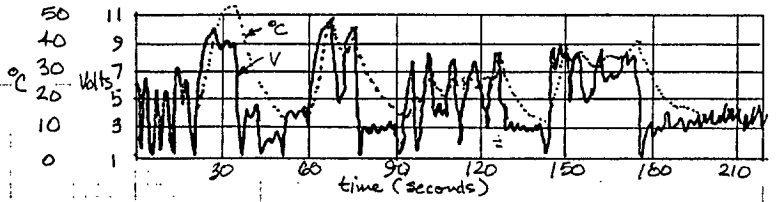
(17) Voice Coil Temperature v/s Frequency, Constant Voltage Input, Compression Driver.



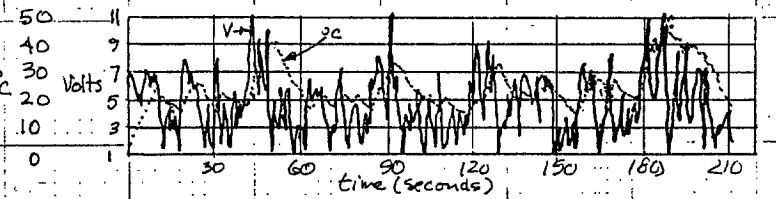
(18) Apparatus for Measuring Voice Coil Temperature of Operating Loudspeaker.



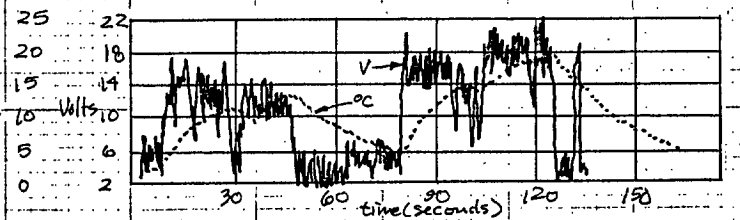
(23) Final Model



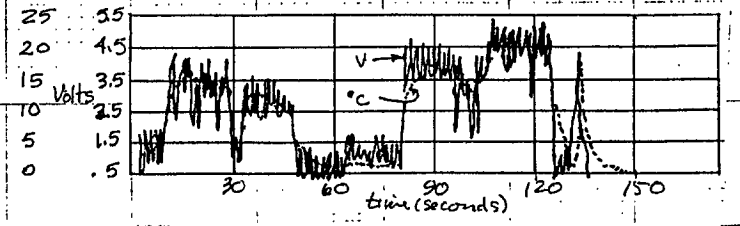
(19a) Coil Temperature v/s Time: 12 cm Cone Speaker: Lagato Music Input.



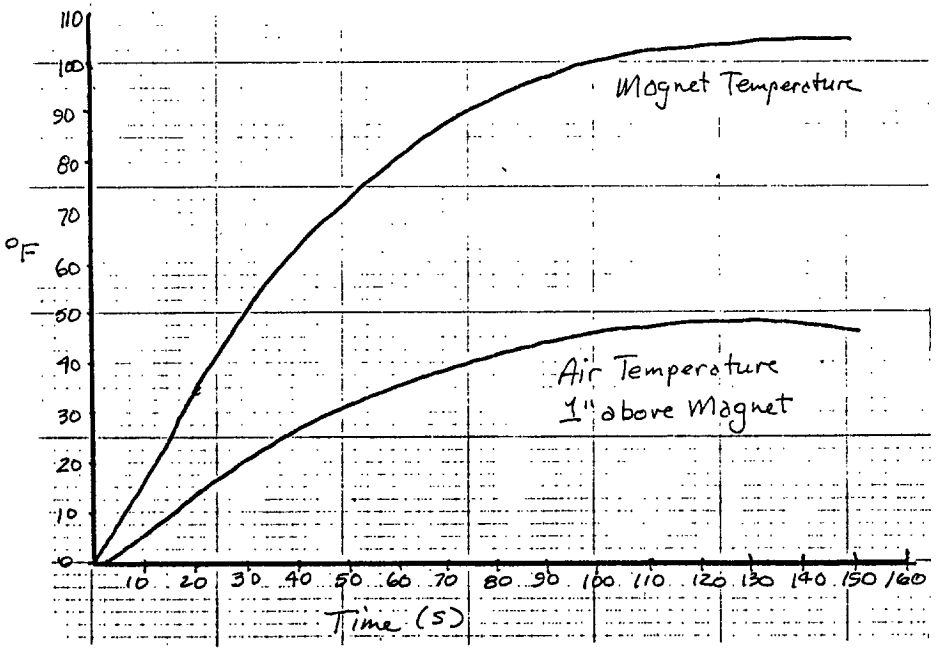
(19b) Coil Temperature v/s Time: 12 cm Cone Speaker: Staccato Music Input.



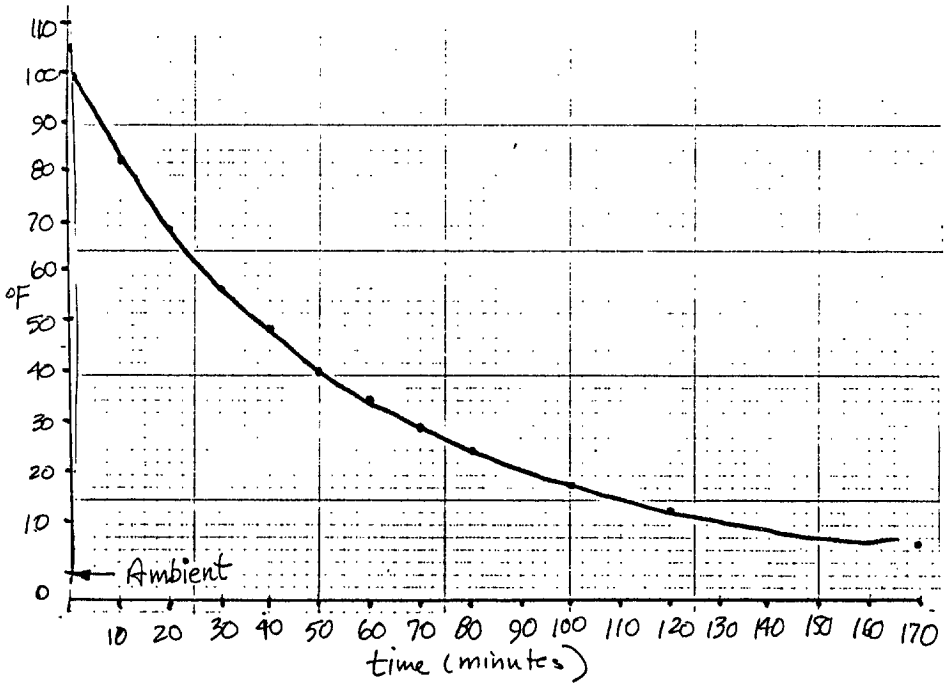
(20a) Coil Temperature v/s Time: 30 cm Woofer.



(20b) Coil Temperature v/s Time: Horn Tweeter.



(21) Heat-Up Transient: Magnet Temperature of EV DL15W Woofer.



(22) Cool-Down Transient: Magnet Temperature of EV DL15W Magnet.