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FERROFLUIDS IN LOUDSPEAKERS - AN OVERVIEW

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1. INTRODUCTION

Ferrofluidics Corporation was founded in 1968, a spin-off from a NASA research project involving the precise control of liquid rocket fuel in zero gravity. The advent of cheaper, safer and more reliable solid fuel eliminated NASA's need for this technology and three of the engineers involved in this project were granted a non-exclusive licence to research the commercial, technical and market development of a magnetic fluid (ferrofluid) technology

Today, Ferrofluidics Corporation is a $3 million business (FY ending June 30, 1995) with headquarters in Nashua, New Hampshire; subsidiaries in UK, Germany and Japan and dedicated audio ferrofluid distributors located in Denmark, India, Korea, Taiwan, China, Malaysia and Singapore.

2. WHAT ARE FERROFLUIDS ?

A ferrofluid is a stable colloidal suspension of sub-domain magnetic particles in a liquid carrier. The particles, which have an average size of about 100Å, are coated with a stabilising dispersing agent (surfactant) which prevents the particle agglomeration even when a strong magnetic field gradient is applied to the ferrofluid. In the absence of a magnetic field, the magnetic moments of the particles are randomly distributed and the fluid has no net magnetisation.

When a magnetic field is applied to ferrofluid, the magnetic moments of the particles orient along the field lines almost instantly. Thus, the magnetisation of the ferrofluid responds immediately to the changes in the applied magnetic . When the applied field is removed, the moments randomise quickly. Ferrofluids belong to a class of materials defined as superparamagnetic. (See Fig 1).

3. PHYSICAL PROPERTIES

Ferrofluids can be described as having three important physical properties; saturation magnetisation, viscosity and volatility.

Saturation Magnetisation: determined by the nature of the suspended magnetic material and the volumetric loading of the material. The greater the quantity of the magnetic material in suspension, the higher the saturation of the magnetisation of the ferrofluid. Audio ferrofluids are manufactured with a range of saturisation magnetisation values from 75 to 375 gauss. Compared with iron (saturation magnetisation = 17,000 gauss) ferrofluids are weak magnetic materials.

Viscosity: A measure of resistance to flow, viscosity is defined as a ratio of viscous shear stress to shear rate and is measured in centipoise (cp). Audio ferrofluids are manufactured with a range of viscosity values from 25 - 10,000 cp (measured at 27°C) although the most commonly used values fall within a much narrower range, typically from 100 - 2,000 cp.

Volatility: Several factors influence the volatility of ferrofluid in a loudspeaker; 1.] evaporation rate of the carrier, 2.] *average* ferrofluid temperature, 3.] exposed surface area and 4.] ferrofluid quantity.

1.] Evaporation Rate: expressed as a % weight loss or loss of material (in grams) from a surface area of one cm^2 in one second. At 175°C the evaporation rate of audio ferrofluids range from 1.0 to 8.5 x 10^{-4} gm/cm^2 -sec.

2.] Average Temperature: A temperature gradient exists across the ferrofluid in an air gap such that the fluid is warmest next to the coil and coolest next to the top plate and pole. A loudspeaker with a coil temperature of 150°C and top plate / pole temperature of 80°C suggests an average ferrofluid temperature of 115°C.

3 & 4.] Surface Area and Ferrofluid Quantity: These factors are defined by the physical dimensions of the air gap.

Other properties which influence the performance of a ferrofluid are: initial permeability, thermal expansion, coefficient of friction, pour point, density, thermal conductivity, electrical conductivity and surface tension.

A summary of the ferrofluid physical properties discussed here can be found in Table 1.

4. BENEFITS OF FERROFLUID IN LOUDSPEAKERS

Ferrofluid resides in the air gap of the magnet and completely fills the space between the voice coil ID/pole and coil OD/top plate. No physical containment is needed, the fluid is held in place by the strong permanent magnetic field.

The presence of ferrofluid in the gap enhances the performance of the loudspeaker in many ways:

Heat Transfer: Ferrofluid is roughly five times more thermally conductive than the air it displaces from the gap. The fluid provides a much lower thermal resistance between the coil and pole/top plate, lowering the voice coil operating temperature both under transient and steady state conditions. (See Fig 2).

The amount of transient thermal power handling improvement provided by the ferrofluid is dictated by the ratio of coil winding length to top plate thickness; the closer the ratio, the more dramatic the improvement.

Steady state thermal power handling improvement depends not only on the aforementioned winding length / top plate height ratio but the thermal mass and surface area of the magnet and frame. A tiny speaker will quickly run into thermal saturation and the thermal benefits of the ferrofluid will not be so obvious. A large speaker, on the other hand, possesses sufficient thermal mass and surface area such that the effect of ferrofluid on voice coil operating temperature will be obvious well into the time domain.

Damping: Ferrofluid in the gap provides a mechanical resistance to the moving coil. The amount of damping is proportional to the viscosity of the ferrofluid.(See Fig 3).

Voice Coil Centering: When the voice coil is displaced in the radial direction in the gap, a restoring force is obtained which is proportional to the displacement. This force constant is:

$K = 2Ms\ Hm\ ht/r\ N/m$

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where:

Ms = saturation magnetisation in tesla
Hm = maximum field strength in the gap in ampere meter
h = height of fluid in the gap in meter
t = width of the gap in meter
r = radius of the gap in meter

For typical values in a 25mm dome tweeter (M_s = 0.01T, H_m = 1.2 x 10^6 A/m, h= 0.003 m, t = 0.0003m and r = 0.0127m), k = 1.7 N/m. Although this force is a fraction of that provided by the suspension, it is still enough to influence the centering of the moving coil.

Distortion Reduction: Harmonistic distortion and spectral contamination caused by radial and rocking modes of the voice coil is reduced due to the centering force of the fluid upon the voice coil. Ferrofluid in the gap also creates a seal, or liquid "O" ring around the coil which eliminates air modulation noise in the gap, particularly within the piston band. Figures 4a and 4b show spectral contamination in a 1" dome tweeter with 4a without ferrofluid and 4b with ferrofluid.

Reduced Power Compression / Improves Dynamic Linearity: Minimising the temperature rise of the voice coil reduces thermal power compression effects. Figures 5 and 6 show power compression in a 4" cone midrange with and without ferrofluid. Ferrofluid in the gap not only reduces sensitivity loss but maintains the linearity of the speakers' output.

Improved Production Yields: Due to the centering and lubricating properties of the ferrofluid, manufacturers have reported improvements in production yields ranging from 30 to 60%, when introducing ferrofluids into existing products. This reduction in scrap can often offset the cost of the ferrofluid itself.

Simplified Passive Network Designs: Ferrofluid's ability to control a driver's behaviour at resonance and, to some extent, break up modes at the top end of the pass band, eliminate the need to address these problems in the crossover network, eliminating the need to address these problems in the crossover network, eliminating the need for additional , expensive resistors, caps and inductors.

Reduced Coil / Magnet Size: A 1" voice coil driver with ferrofluid can achieve the same power handling as equivalent sized drivers which utilise 1.5" or 2" diameter coils. The cost savings from the smaller magnet / coil more than offset the ferrofluid costs. The weight reduction may also be attractive in many applications.

5. FERROFLUID SELECTION - RECOMMENDED GUIDELINES

Proper selection of a ferrofluid requires a careful balance of the properties of the ferrofluid vs. the properties of the loudspeaker. The five most important factors to consider are quantity, viscosity, magnetisation and volatility and colloidal stability.

Quantity: The optimum quantity of ferrofluid for a loudspeaker is determined by the physical dimensions of the air gap and can be calculated with the use of the following formula (s):

V = 56.5A [E2 + C2 - B2 - D2]
English: All quantities in inches

V = 3.5A [E2 + C2 - B2 - D2]
Metric: All quantities in cm

where:

A = Top plate thickness
B = Radius of pole
C = Inner radius of voice coil
D = Outer radius of voice coil
E = Inner radius of top plate

Recommended tolerance of ferrofluid quantity is +/- 10% which is best maintained through the use of a positive volume displacement dispenser.

Maintaining the proper ferrofluid quantity is critical as overfilling the gap is wasteful and can lead top leakage while underfilling the gap minimises the heat transfer benefits of the ferrofluid, compromises the fluid's long term reliability and can lead to response anomalies in the loudspeaker. The effect of an underfilled gap vs. properly filled gap is shown in figures 7 and 8, the frequency response and impedance curves of a 1" dome tweeter.

Viscosity: Once the ferrofluid amount has been determined, the viscosity of the ferrofluid should then be selected with respect to the desired amount of damping.

Magnetisation: The magnetisation value of the ferrofluid should be balanced against the loudspeakers air flux density and voice coil excursion.

Tweeters or compression drivers have high air gap flux and minimal coil excursion require ferrofluid magnetisation values in the 100 - 200 gauss range. Woofers, on the other hand, typically have much lower air gap flux and much greater coil excursion and require ferrofluid magnetisation values in the 300 - 375 gauss range. High gauss ferrofluids have greater volatility as there is less liquid and more magnetic material per unit volume. Therefore, it is recommended that only as much magnetic material as needed be used to ensure long term reliability.

Compatibility: Successful ferrofluid application engineering requires that ferrofluid be fully compatible with all materials and adhesives which have the potential to come into contact with ferrofluid including:

1.) Voice coil bobbin / former material: The critical property here is that the material be non-absorbent which eliminates Kraft papers and uncoated Nomex materials. Compatible material include aluminium, TuffQuin and, of course, Kapton. A further discussion on Kapton can be found later in this paper.

2.) Collar material: Again, the critical property here is that the, material be non-absorbent. Coated Nomex, TuffQuin and Kapton have all been used successfully in this application.

3.) Voice coil wire adhesive: All popular methods (wet winding, self bonding) and related adhesives are compatible with ferrofluids, no incompatibilities are known to have been encountered. New techniques or adhesives should be analysed by Ferrofluidics Corporation to ensure their compatibility with ferrofluid.

4.) The glue joint at the bobbin / diaphragm or bobbin / cone / spider junction as well as the magnet system structural adhesive must be compatible with ferrofluid. commonly used acrylics, epoxies and cyancrylates are compatible with both ester and hydrocarbon based ferrofluids. The use of rubber based adhesives with ester based ferrofluids should be avoided. All adhesives should be fully cured before the ferrofluid is introduced as adhesive outgassing can effect the stability of the ferrofluid.

As part of the free ***FerroSound*** testing, Ferrofluidics will study the compatibility of any adhesive with ferrofluid. three tests are performed:

1.] Mixing of uncured adhesive with ferrofluid,

2.] Exposure of ferrofluid to adhesive vapours.

3.] Exposure of cured adhesive to ferrofluid.

There should also be no capillary paths present by which the ferrofluid could migrate from the gap. The most common are:

1.] Machining grooves in the magnet top plate: If these grooves terminate in the air gap, ferrofluid can travel along the grooves via capillary action.

2.] Cotton impregnated lead wires: The cotton can absorb the ferrofluid if they come into contact with each other. This type of material should be wax coated if used in conjunction with ferrofluid.

3.] Lead wire migration: Ferrofluid can travel between the collar and former along the lead wires via capillary action. The pathway has been successfully sealed using a wicking adhesive (such as Loctite 290) or a gel type adhesive (Hernon's Quantum 134) which is draped over the leadwires before the collar is applied.

4.] Bobbin slit migration: If the gap between the two ends of the voice coil former is too narrow (< 0.001") ferrofluid can travel up the slit via capillary action.

Volatility: The thermal capacity of the ferrofluid should be chosen with respect to the operating temperatures of the voice coil. Moderate to low temperature operation requires our more standard products such as the APG 800, APG 900 or APG 1000 series ferrofluids (hydrocarbon based materials while more demanding, high temperature applications should utilise the APG "O" or APG "S" series ferrofluids (ester based). A new generation ferrofluid the APG "R" series is just now becoming commercially available and is recommended for ultra high temperature / high power applications.

6. FERROFLUIDS AND KAPTON - THE SYSTEMS APPROACH TO THERMAL MANAGEMENT

Kapton is an extremely attractive bobbin material due to it's light weight, lack of electrical conductivity, good mass to strength ratio and high thermal capacity (rated at 240°C). Although higher in cost than most other commonly used bobbin materials, it's superior physical properties justifies it's use in all premium and high temperature applications.

Although voice coils wound on Kapton using speciality coatings and adhesives have been known to operate at steady state temperatures of up to 315°C, one must then deal with the resulting power compression effects which occur at these high temperatures. Ferrofluids offer a simple, practical solution to reducing the voice coil operating temperature, restoring lost sensitivity at high power / temperature operation.

Ferrofluids and Kapton have been used together for many years and both materials are completely compatible with each other. A lingering concern among loudspeaker engineers has been the long term exposure of Kapton to ferrofluid and how the physical properties of the Kapton, being somewhat hydroscopic in nature, might change over time.

To address these concerns, Ferrofluidics Corporation and DuPont's High Performance Film Division have undertaken a long term study, still in progress at the time of this writing (August 1996).

Strips of Kapton (300HP-STT and 300MTB) were placed in closed jars of hydrocarbon (APG 921) and ester (APGS14) based ferrofluids having similar properties (150 gauss / 200 cp). The jars were then placed at 100°C and the strips occasionally removed for inspection of elongation (strain), tensile (stress) and modulus.

The results, as of 1344 hours, (See Table 2) indicate that although there has been some measurable change to the Kapton, the recorded values show that these materials are still well within the limits of what is considered acceptable for either grade of this material under test.

Several months remain before the conclusion of this test. those interested in the final results should contact Ferrofluidics / AP&T Ltd or DuPont.

7. CONCLUSIONS

Ferrofluid technology and the *understanding of* it's use in loudspeakers has improved dramatically since it was first used in tweeters in 1972. Today, ferrofluids are used in just about every type of transducer imaginable including: woofers, subwoofers, midranges, compression drivers, the unique Linaeum mono/di-pole, headphones, siren drivers and full-range multi-media speakers.

A much clearer understanding of the delicate balance between the properties of the speaker and the properties of the ferrofluid has resulted in application-specific ferrofluids for all of the transducers listed above.

Continued co-operation between Ferrofluidics and manufacturers of bobbin materials and adhesives will ensure that advance *in one* technology area will not exclude the use of another due to compatibility issues.

What will the future bring ? Ferrofluids with higher thermal capacity are always under development. Researchers are also looking at ways to develop higher saturation magnetisation ferrofluids without compromising volatility, which currently limits the technology to an upper range of 375 gauss. These developments could ultimately lead to high permeability ferrofluids, a property long desired by many engineers. The future may also bring ferrofluids which exhibit less change of viscosity with temperature, bringing a completely new carrier / surfactant combination to the market place.

COMPONENTS OF A FERROFLUID

COLLOID: 1. Magnetic Particles
2. Surfactant
3. Carrier

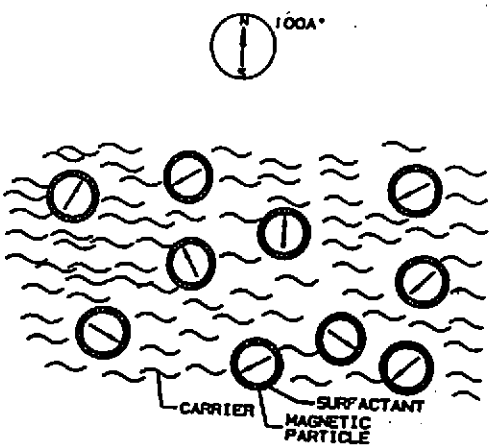


Figure 1

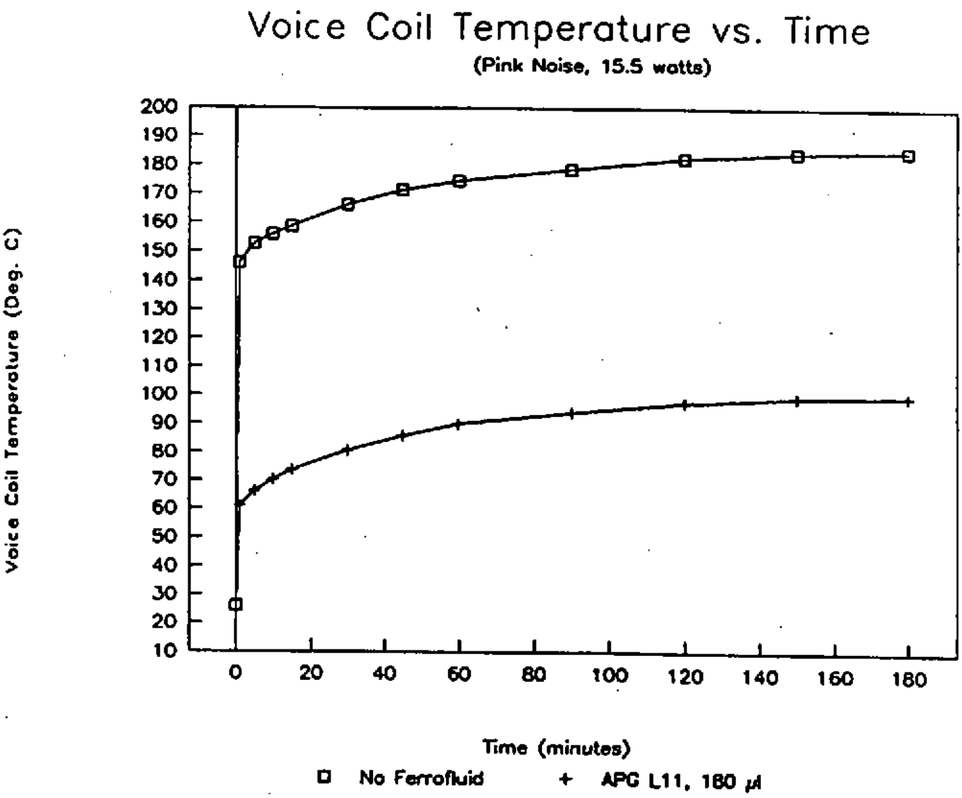

Voice Coil Temperature vs. Time
(Pink Noise, 15.5 watts)
Voice Coil Temperature (Deg. C)
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
Time (minutes)
No Ferrofluid
APG L11, 180 μl

Figure 2

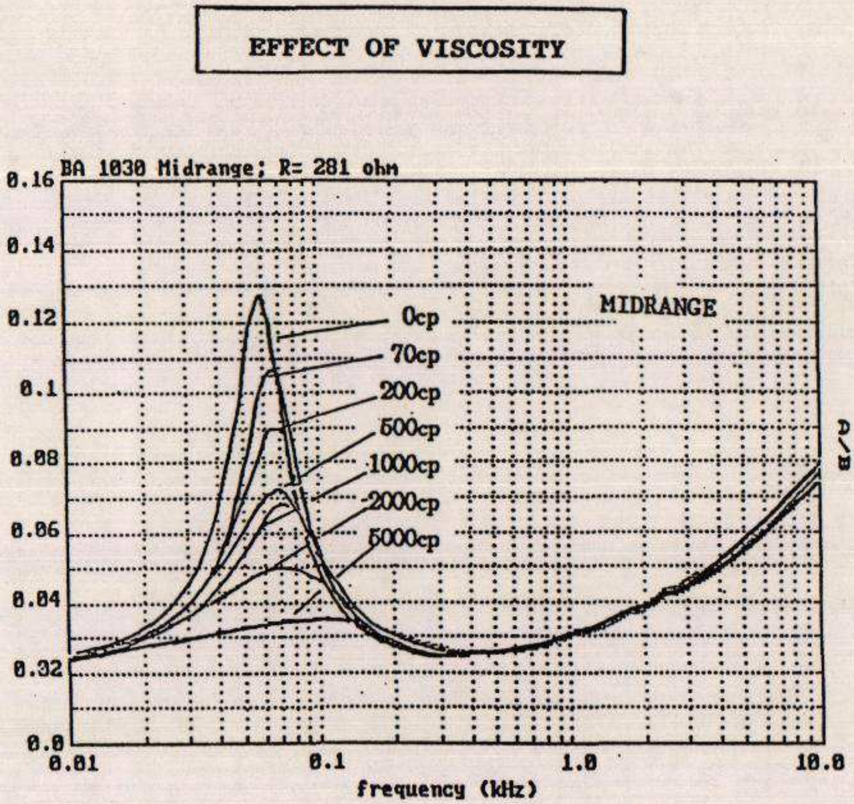

EFFECT OF VISCOSITY
BA 1030 Midrange; R= 281 ohm
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.32
0.0
0.01
0.1
1.0
10.0
frequency (kHz)
A/B
MIDRANGE
0cp
70cp
200cp
500cp
1000cp
2000cp
5000cp

Figure 3

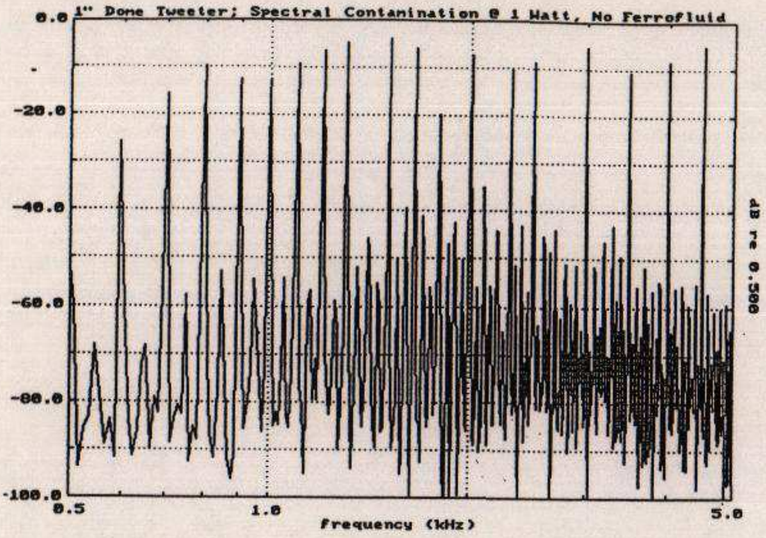


Figure 4a

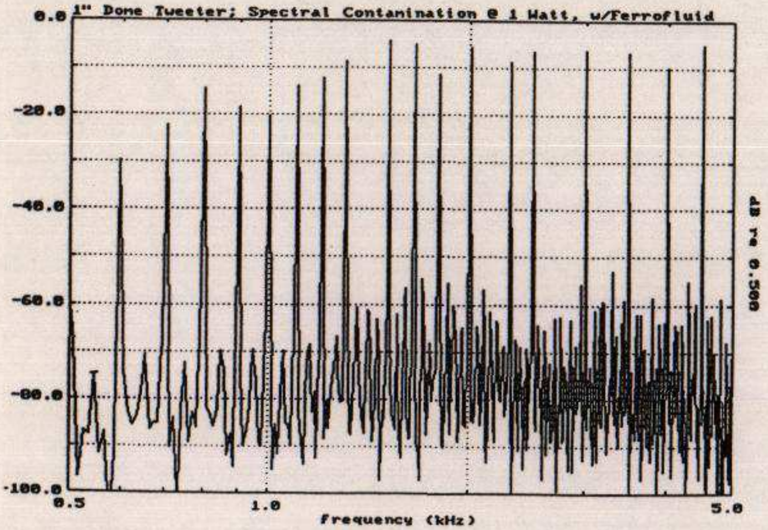


Figure 4b

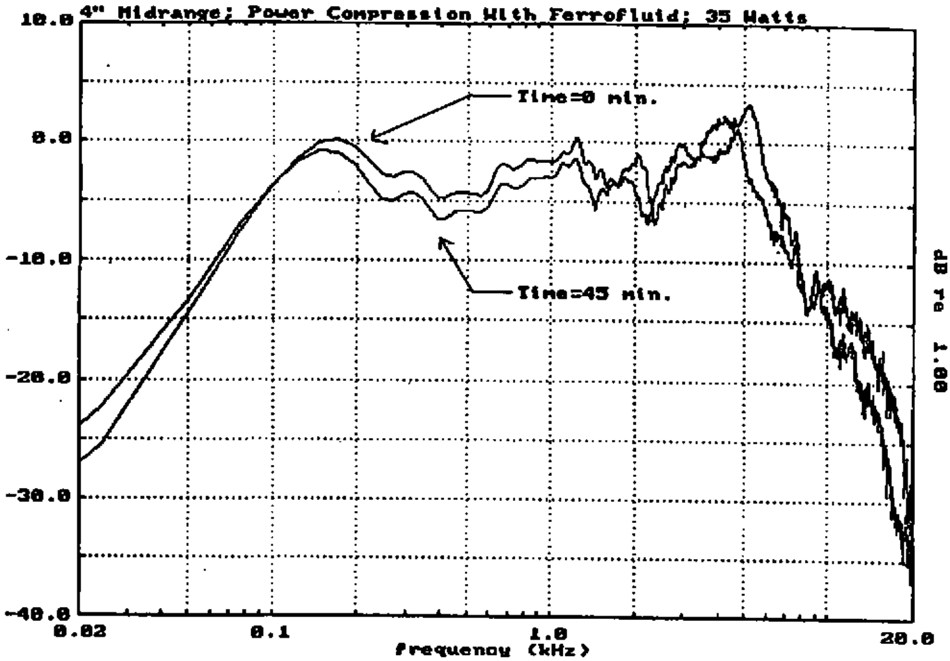

4" Midrange; Power Compression With Ferrofluid; 35 Watts
10.0
0.0
-10.0
-20.0
-30.0
-40.0
0.02
0.1
1.0
20.0
Frequency (kHz)
dB re 1.00
Time=0 min.
Time=45 min.

Figure 5

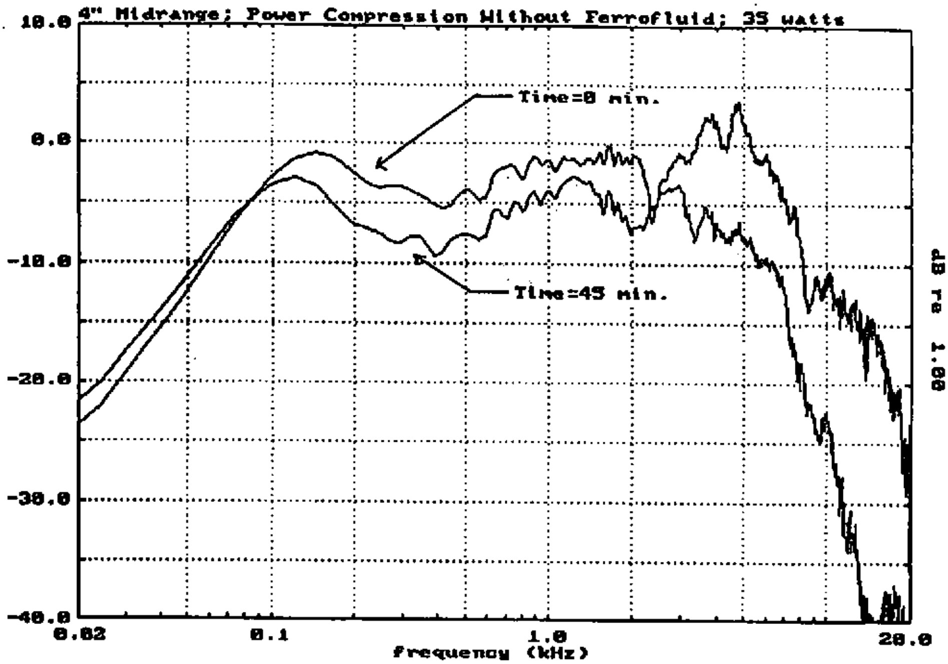
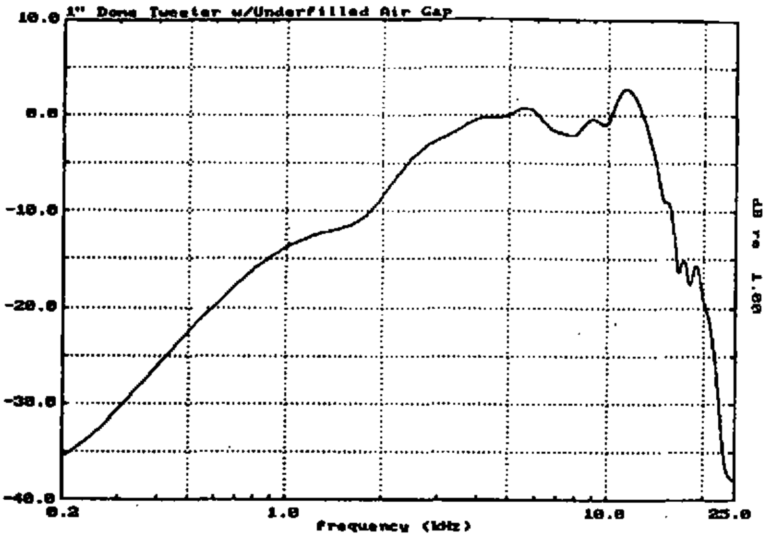

4" Midrange; Power Compression Without Ferrofluid; 35 watts
10.0
0.0
-10.0
-20.0
-30.0
-40.0
0.02
0.1
1.0
20.0
Frequency (kHz)
dB re 1.00
Time=0 min.
Time=45 min.

Figure 6


1" Dome Tweeter w/Underfilled Air Gap
10.0
0.0
-10.0
-20.0
-30.0
-40.0
0.2
1.0
10.0
25.0
Frequency (kHz)

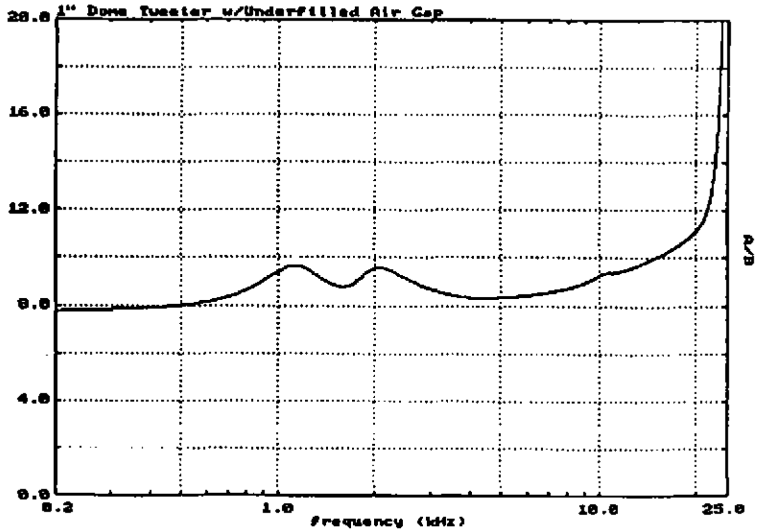
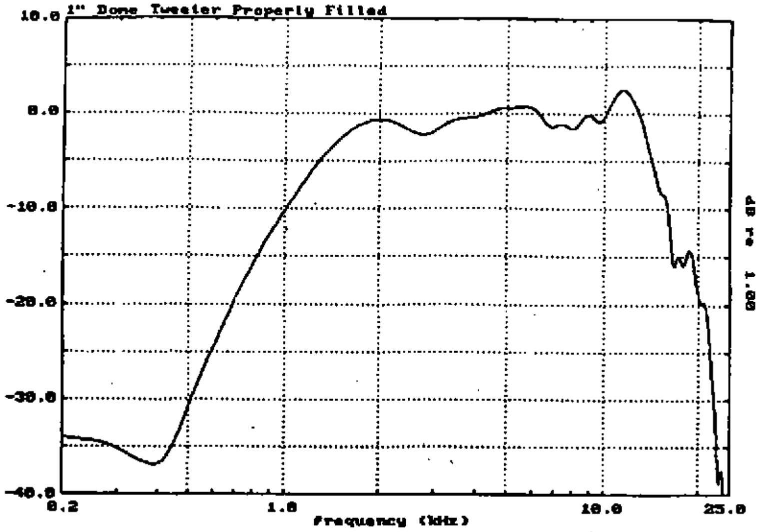

1" Dome Tweeter w/Underfilled Air Gap
20.0
16.0
12.0
8.0
4.0
0.0
0.2
1.0
10.0
25.0
Frequency (kHz)

Figure 7


1" Dome Tweeter Properly Filled
10.0
0.0
-10.0
-20.0
-30.0
-40.0
0.2
1.0
10.0
25.0
Frequency (kHz)
dB re 1.00

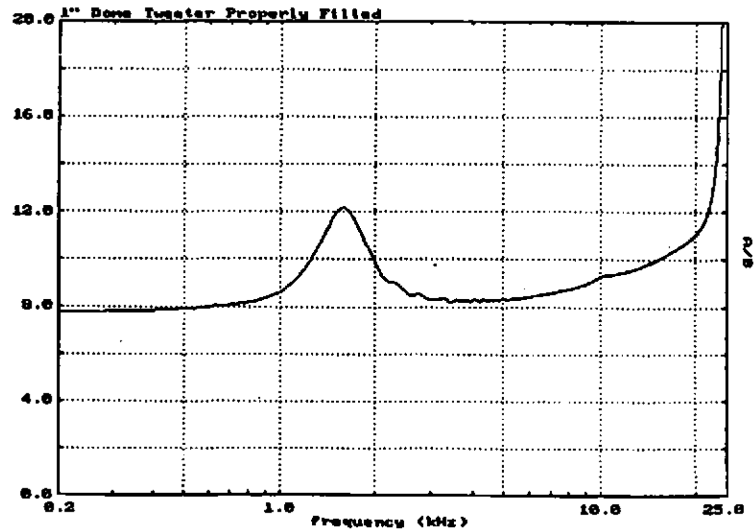

1" Dome Tweeter Properly Filled
20.0
16.0
12.0
8.0
4.0
0.0
0.2
1.0
10.0
25.0
Frequency (kHz)
R/B

Figure 8

TABLE 1

SUMMARY OF FERROFLUID PHYSICAL PROPERTIES

Property	Range of Values
Saturation Magnetization	75 - 375 gauss
Viscosity	25 - 10,000 cp @ 27° C
Initial Permeability (@ 30 Oe)	1.5 - 2.9
Thermal Expansion	4.5 - 7.0 x 10^{-4} ml/ml °C
Coefficient of Friction	0.18 - 0.30
Pour Point	-30° to -70° C
Density	0.92 - 1.38 gm/ml
Thermal Conductivity	125 - 158 mw/m °K
Evaporation Rate @ 175° C	1.0 - 8.5 x 10^{-7} gm/cm^2 - sec
Surface Tension	31 - 34 dynes/cm

TABLE 2

FERROFLUID/KAPTON®
COMPATIBILITY STUDY

300HPP-ST @IOO DEGREES C

HOURS	MODULUS	TENSILE (STRESS)	ELONGATION (STRAIN)
CONTROL	460.8	33.78	98.79
	SAMPLE #1 FERROFLUID TYPE: APG 921		
168 HRS	495.9	32.81	65.35
336 HRS	479.7	31.25	57.75
723 HRS	471.7	31.71	62.27
1344 HRS	473.3	33.27	71.52
	SAMPLE #2 FERROFLUID TYPE APG S14		
168 HRS	488.0	33.23	68.09
336 HRS	492.6	33.10	73.05
723 HRS	464.9	33.19	66.84
1344 HRS	461.5	33.78	71.31

300 MTB @100 DEGREES C

HOURS	MODULUS	TENSILE (STRESS)	ELONGATION (STRAIN)
CONTROL	651.9	18.84	68.82
	SAMPLE #1 FERROFLUID TYPE APG 921		
168 HRS	635.8	16.20	43.13
336 HRS	634.4	17.77	62.88
723 HRS	624.8	17.06	55.47
1344 HRS	618.8	17.76	64.61
	SAMPLE #2 FERROFLUID TYPE APG S14		
168 HRS	631.5	18.35	66.51
336 HRS	628.9	18.69	74.19
723 HRS	594.1	18.16	68.10
1344 HRS	574.8	18.31	71.99