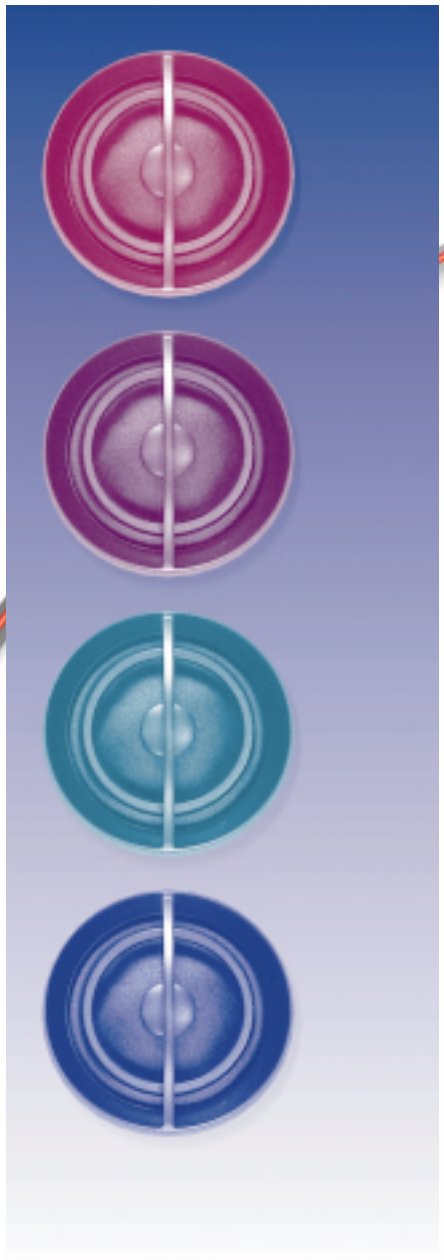
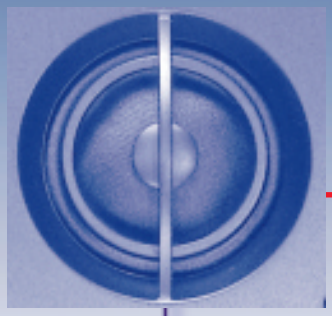
FerroTec



Audio Grade Ferrofluids

www.ferrotec.com

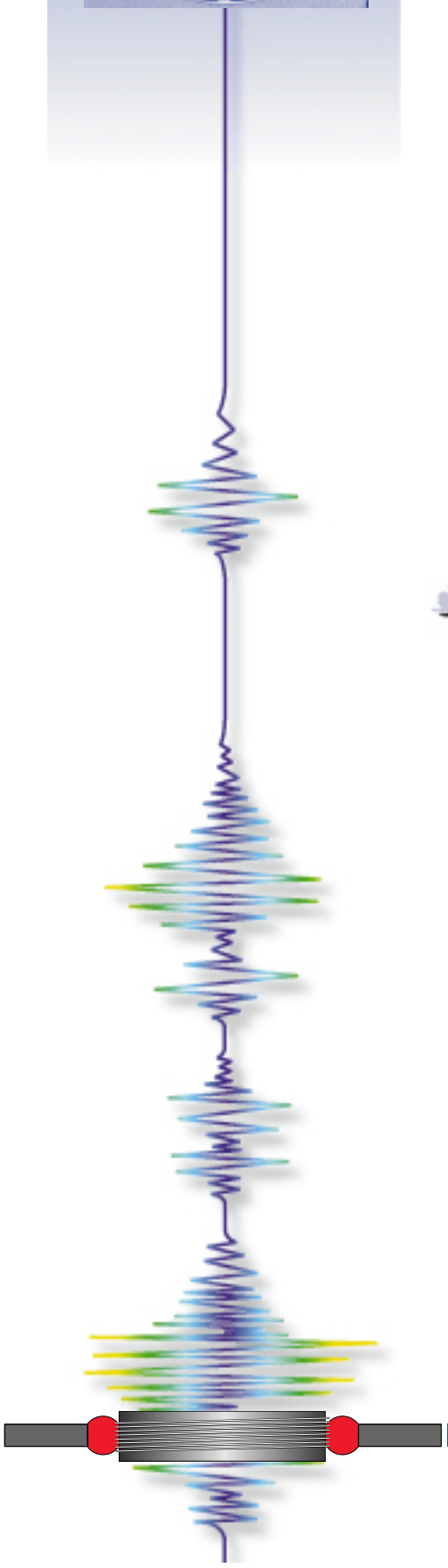


Ferrotec Corporation

Ferrotec is the world leader in Ferrofluidic® (magnetic liquid) technology. Ferrotec (USA), formerly known as Ferrofluidics, has been supplying ferrofluids for audio applications for over 30 years. The company offers an extensive range of fluids. With R&D and production in both the US and Japan, and 12 sales offices and distributors around the world, the company is well placed to serve your global ferrofluid needs.

Ferrofluids have been extensively used in audio speakers for over 30 years. They offer significant performance advantages in tweeters, mid-ranges, woofers, compression drivers and automotive speakers. Some of the advantages in using ferrofluid include increased power handling capabilities, smoothing of frequency response curve and reduced distortion.

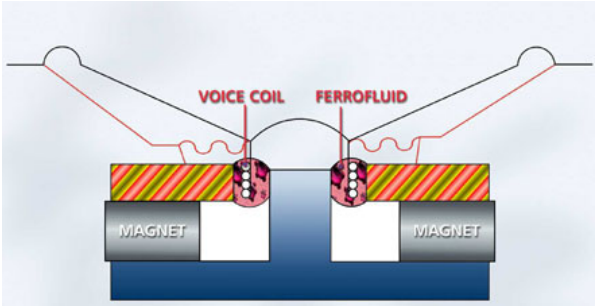
In addition to audio fluids, Ferrotec also offers fluids for domain detection, quality control of magnetic media and many other applications. The company also manufactures Ferrofluidic® rotary feedthroughs for the vacuum industry, thermoelectric modules for cooling and temperature control applications, and high precision mechanical, electrical and electro-mechanical offshore contract manufacturing capabilities.



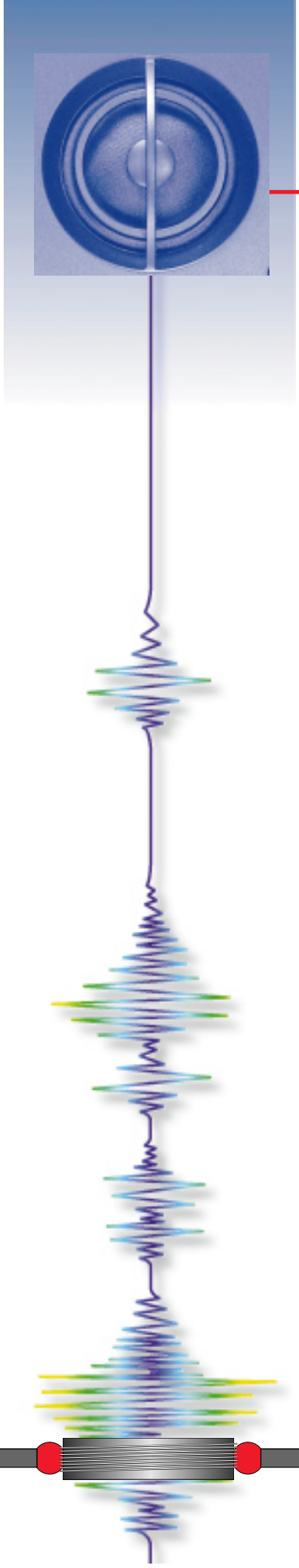
How is Ferrofluid used in speakers?

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

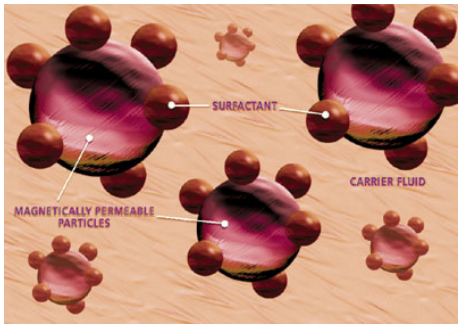
The choice of ferrofluid depends on specific loudspeaker requirements in terms of the damping required and the field in the gap. Two key properties of the fluid determine the correct fluid for any application: the viscosity and the magnetization value. The higher the viscosity of a ferrofluid, the greater the viscous damping of the moving mass. A fluid with the correct magnetization value must be chosen to ensure retention of the fluid in the air gap. All ferrofluids, independent of viscosity, essentially provide the same heat transfer from the voice coil to the magnet structure.



Every speaker design is unique. Some speakers, for example super tweeters, require only light damping but need very high colloidal stability of the fluid, whereas tweeters often require high viscosity fluids. To accommodate this there is a complete range of ferrofluids with varying viscosity values and magnetization properties. This means that whatever your requirements in terms of mechanical damping and fluid retention, there is probably a suitable fluid from one of our standard ranges. If not, our team of experienced audio engineers and research chemists can custom engineer a new fluid to meet the performance objectives of your loudspeaker.



What is a Ferrofluid ?



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 10 nm, are coated with a stabilizing dispersing agent (surfactant) which prevents 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 magnetization.

When a magnetic field is applied to a ferrofluid, the magnetic moments of the particles orient along the field lines almost instantly. The magnetization of the ferrofluid responds immediately to the changes in the applied magnetic field and when the applied field is removed, the moments randomize quickly.

In a gradient field, the whole fluid responds as a homogeneous magnetic liquid which moves to the region of highest flux. This means that ferrofluids can be precisely positioned and controlled by an external magnetic field. The forces holding the magnetic fluid in place are proportional to the strength of the external field and the magnetization value of the fluid. This means that the retention force of a ferrofluid in a gap can be adjusted by changing either the magnetization of the fluid or the magnetic field in the gap.

Audio ferrofluids are based on two classes of carrier liquid: synthetic hydrocarbons and esters. Both oils possess very low volatility and high thermal stability. The choice of fluid is dictated by the environmental considerations of the application (e. g. humidity, adhesives, contact with water, solvent vapors and reactive gases) combined with the best balance of magnetization and viscosity values to optimize the acoustical performance.

By varying the quantity of magnetic material in a ferrofluid, and by using different carrier liquids, it can be tailored to meet a variety of needs. The saturation magnetization (the maximum value of the magnetic moment per unit volume when all the domains are aligned) is determined by the nature of the suspended magnetic material and by the volumetric loading of the material. The physical and chemical properties such as density and viscosity correspond closely to those of the carrier liquid.

Ferrotec's highly refined manufacturing process, combined with a long term quality assurance program is the key to its repeatable, reproducible product quality.

Ferrofluid benefits:

- Increased thermal power handling
- Reduced thermal power compression
- Smoothing of frequency response curve
- Reduced distortion
- Reduced warranty returns
- Increased production yields

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

Increased Thermal Power Handling: Ferrofluid is roughly 5 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 under both transient and steady state conditions. This increases thermal power handling capabilities.

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.

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. Although this force is a fraction of that provided by the suspension, it is still enough to influence the centering of the moving coil. This spring constant is given by:

$$k = M_s H_m h \frac{t}{d}$$

where:

k =spring constant in N/m
M_s =saturation magnetization in T
H_m =maximum field strength in the gap in A/m
h =height of fluid in the gap in m
t =width of the gap in m
d =diameter of the gap in m

Reduced Distortion: Harmonic 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.

Reduced Power Compression/Improved Dynamic Linearity: Minimizing the temperature rise of the voice coil reduces thermal power compression effects. Ferrofluid in the gap not only reduces sensitivity loss but maintains the linearity of the speaker's output.

Increased Production Yields: Due to the centering and lubricating properties of the ferrofluid, manufacturers have reported improvements in production yields ranging from 30%...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 behavior at resonance and, to some extent, break-up modes at the top end of the pass band, may minimize the need to address these problems in the crossover network. This reduces the need for additional expensive resistors, capacitors and inductors.

Reduced Coil/Magnet Size: A 25.4 mm (1") voice coil driver with ferrofluid can achieve the same power handling as equivalent sized drivers which utilize 38.1 mm (1.5") or 50.8 mm (2") diameter coils. The cost savings from the smaller magnet/coil more than offset the ferrofluid cost. The weight reduction may also be attractive in many applications.

Ferrosound **Audio Ferrofluids**

APG Series based on a synthetic ester carrier

Synthetic esters tend to be slightly more aggressive to elastomer plastics, have a good thermal stability but a moderate tolerance to extended contact with water.

J Series	Fluid Type	J [mT]	γ [mPa s]	T tr [°C]	T op [°C]
J-Series Ferrofluid are used in alarm systems and headset drivers for heat transfer and centering.	APG J10	27,5	70	175°C	80°C
	APG J12	22,0	40		
	APG J14	16,5	30		
	APG J16	11,0	25		

L Series	Fluid Type	J [mT]	γ [mPa s]	T tr [°C]	T op [°C]
L-Series Ferrofluid has elevated colloid stability for high flux applications in tweeters and supertweeters.	APG L11	22,0	200	175°C	100°C
	APG L12	22,0	500		
	APG L14	22,0	2000		
	APG L17	11,0	60		
	APG L19	22,0	1500		
	APG L23	33,0	350		

O Series, S Series	Fluid Type	J [mT]	γ [mPa s]	T tr [°C]	T op [°C]
O-Series Ferrofluid are used in woofers, midranges, full ranges and tweeters.	APG O17	33,0	350	225°C	125°C
	APG O27n	35,8	175		
	APG O37	8,3	110		
	APG O47n	16,5	65		
	APG O57	16,5	1500		
	APG O67	41,3	250		
	APG O77n	27,5	115		
	APG O87	27,5	750		
S-Series Ferrofluid are based on the same chemistry as the O-Series, and thus their properties are similar. Their saturation magnetization or viscosity values are customized to specific requirements.	APG S10n	44,0	300	225°C	125°C
	APG S11n	22,0	85		
	APG S12n	41,3	250		
	APG S14	16,5	200		
	APG S15n	16,5	75		
	APG S16n	27,5	400		
	APG S17n	11,0	55		
	APG S18	38,5	375		
	APG S21	22,0	500		
	APG S32	22,0	250		
	APG S38n	22,0	135		
	APG S51	38,5	500		

APG CD Series	Fluid Type	J [mT]	γ [mPa s]	T tr [°C]	T op [°C]
Compression driver series Ferrofluid. They provide highest colloid stability and excellent lifetime in high flux applications.	APG CD 1120	11,0	200	245°C	125°C
	APG CD 1635	16,5	350		
	APG CD 2250	22,0	500		

W Series	Fluid Type	J [mT]	γ [mPa s]	T tr [°C]	T op [°C]
W-Series Ferrofluid are used for maximum centering in woofers and full ranges.	APG W02	30,0	175	225°C	125°C
	APG W05	40,0	500		
	APG W10	40,0	1000	245°C	

Audio Ferrofluids

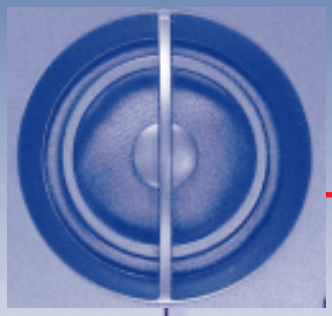
APG Series based on a synthetic hydrocarbon carrier

Synthetic hydrocarbons have a good thermal stability and a good tolerance to extended contact with water.

1100 Series	Fluid Type	J [mT]	γ [mPa s]	T tr [°C]	T op [°C]
1100-Series Ferrofluid is a low cost series of Ferrofluid with consumer quality in terms of lifetime and stability.	APG 1110	11,0	100	175°C	100°C
	APG 1112	11,0	200		
	APG 1114	11,0	500		
	APG 1115	11,0	1000		
	APG 1116	11,0	1500		
	APG 1117	11,0	2000		
	APG 1117.10	11,0	10000		
	APG 1117.3	11,0	3000		
	APG 1117.5	11,0	5000		
	APG 1120	11,0	4000		
	APG 1121	16,5	200		
	APG 1132	22,0	200		
	APG 1133	22,0	500		
	APG 1134	22,0	1000		
	APG 1135	22,0	1500		
	APG 1136	22,0	2000		
	APG 1136.3	22,0	3000		
	APG 1140	22,0	4000		
	APG 1141	22,0	5000		
	APG 1142	22,0	10000		

2100 Series	Fluid Type	J [mT]	γ [mPa s]	T tr [°C]	T op [°C]
2100-Series Ferrofluid is the premium quality material for medium and high temperature applications.	APG 2112	11,0	200	220 °C	125°C
	APG 2114	11,0	500		
	APG 2115	11,0	1000		
	APG 2116	11,0	1500		
	APG 2117	11,0	2000		
	APG 2117.3	11,0	3000		
	APG 2118.6	11,0	6000		
	APG 2120	11,0	4000		
	APG 2127.6	22,0	6000		
	APG 2133	22,0	500		
	APG 2134	22,0	1000		
	APG 2135	22,0	1500		
	APG 2136	22,0	2000		
	APG 2136.3	22,0	3000		
	APG 2140	22,0	4000		

Viscosities are measured at 27°C.
T tr is the transient temperature capacity
T op is the recommended operation limit which should not be exceeded for extended periods.
J is the saturation magnetization of the material
Discontinued products that are no more available: APG 900 series
Older products not listed here are not recommended for new developments: APG 800 series, APG 300 series
For individual data sheets and safety data visit: http://www.ferrotec-europe.de/en/htmls/fluid.data.php



Products

Standard Ferrofluid Series

See pages 6 - 7.

Custom Ferrofluids

Custom ferrofluids can be tailored for individual applications. Contact your local sales office for full details.

Development kits

A new application generally requires experimenting with different ferrofluids to meet precisely the performance objectives of the speaker. Based on our extensive experience in the loudspeaker industry, we have produced a range of development kits which contain an appropriate selection of four different types of ferrofluids for a particular application. The available kits are outlined below. Please call your local sales office (details on back cover) for details of the fluids contained in each kit. Development kits can also be custom-assembled to meet your specific needs. Please call your local sales office for further details.

Kit	Part Number
Home Hi-Fi Tweeter	88AB000001
Automotive Tweeter	88AB000002
Pro Sound Tweeter	88AB000003
Midrange	88AB000004
Woofer/Subwoofer	88AB000005
Super Tweeter	88AB000006
Compression Driver	88AB000007
Full Range	88AB000008

Retrofit kits

Ferrotec offers a number of retrofit kits. These can be used to replace the ferrofluid in speakers, or in some cases retrofitting fluid to speakers originally built without ferrofluid. Each kit contains a pre-measured quantity of application specific ferrofluid supplied in a ready to use dispenser, absorbent paper for removing any existing ferrofluid and full instructions. Retrofit kits are available for speakers from a wide range of manufacturers. To find out if we have a kit that is suitable for your speaker, call your local sales office (details on back cover).

There are three important physical properties of ferrofluid that must be understood to successfully design fluid-filled audio speakers and select the best fluid: saturation magnetization, viscosity and volatility.

Saturation Magnetization: Saturation magnetization is determined by the nature of the suspended magnetic material and the volumetric loading of this material. The greater the quantity of magnetic material in suspension, the higher the saturation magnetization of the ferrofluid. Audio ferrofluids are manufactured with a range of saturation magnetization values from 7.5…40 mT.
Compared with iron which has a saturation magnetization of 2 T, ferrofluids are weak magnetic materials.

Viscosity: Viscosity is a measure of resistance to flow. It is defined as a ratio of viscous shear stress to shear rate and is measured in Pa s. Audio ferrofluids are manufactured with a range of viscosity values From 25… 10000 mPa s (measured at 27 °C). The most commonly used values fall within a much narrower range, typically from 100… 2000 mPa s.

Volatility: Several factors influence the volatility of ferrofluid in a loudspeaker:

• Evaporation rate of the carrier: Evaporation Rate: expressed as % weight loss or loss of material (in grams) from a surface area of one cm^2 in one second. At 175 °C, the evaporation rates of audio ferrofluids range from 1.0 to 8.5×10^{-7} g $cm^{-2} s^{-1}$.

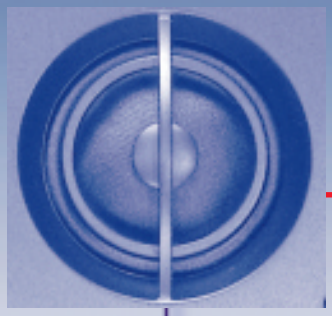
• **Average ferrofluid temperature**: A temperature gradient exists across the ferrofluid in an air gap such that the fluid is warmest next to the coil and coolest next to the top plate and pole. A loudspeaker with a coil temperature of 150 °C and top plate/pole temperature of 80 °C suggests an average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

• **Exposed surface** 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.

Quick Reference Selection Chart

Ferrofluid Type	Driver Type
APG 027n	Woofer
APG S12n	Subwoofer
APG S15n	Compression Driver
APG J12	Alarm type, Headset speaker
APG 1136	Home hi-fi tweeter, damping
APG 2136	Automotive tweeter, damping
APG S14n	Horn loaded tweeter
APG 047n	Automotive tweeter, heat transfer
APG 017	Full range, home hi-fi, automotive
APG 077n	Midrange, automotive, heat transfer
APG 2133	Midrange, automotive, damping
APG 1133	Midrange, home hi-fi, damping
APG L11	Supertweeter, home hi-fi, light damping



Designing with Ferrofluid

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, magnetization, compatibility and volatility.

Quantity: The optimum quantity of ferrofluid for a loudspeaker is determined by the physical dimensions of the air gap and voice coil and be calculated with the use of the following formulae:

$$V[ml]=0.000875A(E^2+C^2-B^2-D^2)$$

All measurements in mm

where:

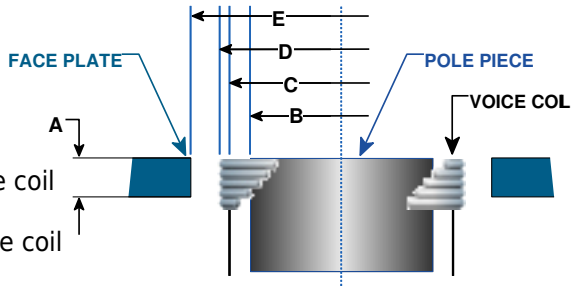
A= Top plate thickness

B= Diameter of pole

C= Inner diameter of voice coil

D= Outer diameter of voice coil

E= Inner diameter of top plate



B, C, D, E are diameter

The recommended tolerance on 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 to leakage while underfilling the gap minimizes the heat transfer benefits of the ferrofluid, compromises the fluid's long term reliability and can lead to response anomalies in the loudspeaker.

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.

Magnetization: The magnetization value of the ferrofluid should be balanced against the loudspeakers air gap flux density and voice coil Excursion. Tweeters or compression drivers having high air gap flux and minimal coil excursion require ferrofluid magnetization values in the 10...20 mT range. Woofers, on the other hand, typically have much lower air gap flux and much greater coil excursion and require ferrofluid magnetization values in the 30...40 mT range.
High gauss ferrofluids generally have a shorter life at high temperatures. To ensure long term reliability, it is therefore recommended that only as much magnetic material as needed is used.

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

- 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 materials include aluminum and Kapton®
- Collar material: Again, the critical property here is that the material be non-absorbent. Coated Nomex and Kapton have all been used successfully in this application.
- Voice coil wire adhesive: All popular methods (wet winding, self bonding) and related adhesives are compatible with ferrofluids and no incompatibilities are known to have been encountered. New techniques or adhesives should be analyzed by Ferrotec Corporation to ensure their compatibility with the appropriate ferrofluid.
- Adhesive joints: 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 cyanoacrylates are compatible with virtually all hydrocarbon based fluids and most ester based fluids. Ester based fluids should not be used in conjunction with rubber based adhesives. When introducing ferrofluid into a design, or if changing the adhesives used, compatibility should be fully tested.

Avoiding fluid migration
Care should be taken to ensure that there are no capillary paths present by which the ferrofluid could migrate from the gap. The most common are:

- Machining grooves in the magnet top plate: If these grooves terminate in the air gap, ferrofluid can travel along the grooves via capillary action.
- 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.
- Lead wire migration: Ferrofluid can travel between the collar and former along the lead wires via capillary action. This pathway can often be successfully sealed using a wicking adhesive (such as Loctite 290) or a gel type adhesive (Hernon's Quantum 134) which is draped over the lead wires before the collar is applied.
- Bobbin slit migration: If the gap between the two ends of the voice coil former is too narrow (< 0.025 mm) 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 1100 series ferrofluids (hydrocarbon based materials) while more demanding high temperature applications should utilize the ester based APG "O" or "S" series or the hydrocarbon based APG 2100 series.

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Version: 2015-03

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