PRINCIPLES AND HEAD CHARACTERISTICS IN VHF RECORDING

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Summary. Concepts of VHF analog magnetic recording are discussed; problem areas are reviewed; and solutions are outlined. Attention is drawn to the conductive-gap-spacer recording head. The unique field contours of this recording head with Alfesil pole faces are analyzed in relation to the recording of very short wavelengths. The field gradients of the unloaded head are computed for various conditions such as maximum magnetization depths, positions in the tape coating, and gap lengths. Comparison of the driven-gap-spacer head using Alfesil pole faces with the ferrite driven-gap-spacer head and the conventional ring-core head shows the Alfesil type to be the most effective for a-c bias VHF recording at very short wavelengths. Problems associated with short-wavelength recording and reproduction are reviewed. In spite of good short-wavelengths capabilities of the Alfesil head, the requirement for a high head-to-tape speed continues to be mandatory to minimize wavelength reproduction losses.

Introduction. A major obstacle facing ultrawideband recording is the inherently limited capability of the reproducing heads to resolve short-wavelength recordings. Modern, high-resolution heads are able to distinguish recorded wavelengths no shorter than 40 µin. In view of head limitations and other short-wavelength losses, VHF recording can be achieved, in principle, by increasing the tape velocity relative to the head. However, simply increasing the speed of a standard 120-ips recorder would, in practice, lead to insurmountable problems. For one thing, the air film between the tape and the recording head would enlarge, thereby aggravating the already difficult head-to-tape contact problem. Furthermore, as head-to-tape velocities are increased, wear and frictional heating become dominating factors. Few improvements can be expected from standard recording approaches utilizing a fragile, elastic, poorly-supported tape drawn across a head.

Narrow-gapped heads, while more efficient for high-frequency recording, are particularly sensitive to degradation in contact and positional integrities. Tape-tracking errors and longitudinal perturbations during high-speed recording would also lead to larger timing errors at reduced playback speed. Therefore, under normal recording conditions, high packing density and high tape velocity appear to be mutually exclusive. Enhanced electrical losses at high frequencies present still another serious impediment to ultrawideband recording. Consequently, standard design practices had to be abandoned.

The approach taken by the Harry Diamond Laboratories utilized a high-speed tape transport of unique design.[1] This transport permits VHF signals to be recorded at wavelengths that conventional instrumentation recorder/reproducers can reproduce at their slower speeds. The recording-head design employs a conductive gap spacer placed between the pole faces. This gap spacer is driven by both the a-c bias current and the signal current to produce the composite recording flux. This ferrite head may, or may not, include Alfesil (or Sendust)[2,3] pole tips.

The gap-spacer approach to recording-head design[4] is, to date, the only practical way known to achieve tape magnetization with bias frequencies of 80 MHz and above. In a conventional ring-core head, not only are the core losses prohibitive at these frequencies, but also the large number of coil turns may reduce the resonance frequency below acceptable values. Some of the principal factors controlling the VHF recording process will now be analyzed in more detail.

Driven-Gap-Spacer Recording Heads. A serious problem facing the designer of a VHF recording system concerns the generation of sufficient a-c bias flux. A compromise must be made between selecting a sufficiently high bias frequency and controlling the core losses. A higher bias frequency would require a larger driving current to overcome these core losses. It is apparent that satisfying the more demanding VHF flux requirements by an increase in the number of turns would reduce the resonance frequency.

The ring-core head is also limited by its inadequate field gradient. The field gradient determines the width of the recording zone, wherein the magnetic field intensity ranges within ±10% of the tape coercivity. If a coercive force H_c = 290 oe is assumed, the recording zone extends from about 320 to 260 oe. The effect of the recording-zone width upon the recorded wavelength is similar to that of the gap width. In a ringcore head, the recording zone extends 30 to 60 μin. at the head-to-tape interface. It increases with bias level, thereby resulting in additional short-wavelength signal suppression.

New recording vistas were opened by the driven-gap-spacer heads. These recording heads, used in the high-speed tape transport,[1] are made of a Ni-Zn ferrite and may have Alfesil pole faces (5.7% Al, 9.5% Si and remainder iron).[2] The gap spacer is either a vacuum deposit, or a thin foil, of silver sandwiched between the pole faces.

The conductive gap spacer is driven by both the VHF bias and the signal currents. A tuned bias trap prevents the bias current from entering the signal circuit. For optimum operating efficiency, the head impedance is tuned for parallel resonance at the bias frequency. The driving arrangement of the recording head is shown in figure 1.

Efficient operation is in part due to the abrupt field gradient within the Alfesil pole faces. The flux around the gap spacer is confined to a very thin layer at each pole face by the magnetic skin effect. The frequency and the pole material determine the thickness of this layer according to

$$\delta = \frac{2.6}{\sqrt{f}} \left[\left(\frac{1}{\mu_r}\right) \left(\frac{\rho}{\rho_c}\right) \right]^{1/2} \tag{1}$$

where

- δ = skin depth in mils
- f = frequency in MHz
- μ_r = relative permeability
- ρ_c = resistivity of copper (1.724 μΩ·cm)
- ρ = resistivity of pole material.

The skin depth for Alfesil was calculated by selecting[2]

$$\mu_r = 20{,}000$$
$$\rho = 106\ \mu\Omega \cdot \text{cm}$$

which yields

$$\delta = \frac{144}{\sqrt{f}}\ \mu\text{in.}$$

For a bias frequency of 100 MHz and a signal frequency of 25 MHz the respective skin depths are 14.4 and 28.8 μin. Either is substantially less than the gap length. Since the bias field attenuates through the recording zone about twice as rapidly as the signal field, a more realistic anhysteretic magnetization process is achieved.

In addition to Alfesil, skin depth calculations were made for a Ni-Zn ferrite (Ferroxcube 4R5, Bulletin 1026). For

$$\rho = 10^7\ \mu\Omega \cdot \text{cm}$$
$$\mu_r = 1600$$

$$\delta = \frac{156.5}{\sqrt{f}}\ \text{mils}$$

If the bias frequency again corresponds to 100 MHz, the skin depth for the ferrite is 15.7 mils, or about three orders of magnitude larger than that of Alfesil. Because of its large skin depth, the driven-gap-spacer ferrite head has field contours similar to those of a ring-core head. Therefore, its field gradient and its short-wavelength capabilities are more nearly like those of the ring-core head than that of the Alfesil head. Nevertheless, the high-frequency capability of the driven-gap-spacer ferrite head is far superior to that of the ring-core head. If emphasis is placed on high-frequency, short-wavelength recording, the Alfesil head will have a definite advantage over the ferrite head because of its much larger field gradient. A detailed discussion of this characteristic follows later.

The electrical skin depth of the silver gap spacer is calculated to be 250 μin. at 100 MHz. Consequently, for a 100-μin.-thick gap spacer, the electrical current will be essentially uniform over the cross section of this conductor.

A significant improvement in the field gradient and a corresponding reduction in the recording-zone width is achieved by adding Alfesil pole faces. Because the skin depths in the Alfesil pole faces are less than one-tenth the effective gap length, the magnetic poles can be regarded as magnetic line sources. An expression for the field gradient can now be derived from figure 2 under this two-dimensional approximation. Let

$$F(z) = U + jV \tag{2}$$

where U(x,y) and V(x,y) are conjugate solutions of Laplace's equation in the complex variable z = x + jy. For two equal magnetic line charges of opposite polarity

$$F(z) = A \ln \frac{r_1 \exp(j\theta_1)}{r_2 \exp(j\theta_2)} = A \ln\left(\frac{r_1}{r_2}\right) + jA(\theta_1 - \theta_2) \tag{3}$$

so that U = Re F represents the magnetic potential function, and V = Im F represents the magnetic stream function. A is a constant determined by the magnitudes of the equivalent magnetic line charges. Thus,

$$V = A\,(\theta_1 - \theta_2)$$

$$U = A \ln \frac{r_1}{r_2}$$

and

$$H_x = (\nabla U)_x = \frac{\partial U}{\partial x}$$

$$(\nabla H)_x = \frac{\partial H_x}{\partial x} = \frac{\partial^2 U}{\partial x^2}$$

According to figure 2, the potential function, U, can be written in terms of a, x, and y as

$$U = \frac{1}{2}A \ \ln \frac{(x+a)^2 + y^2}{(x-a)^2 + y^2} \qquad (4)$$

The x component of the magnetic field intensity is therefore given by

$$H_x = \frac{\partial U}{\partial x} = 2aA \frac{\left[(x^2-a^2) - y^2\right]}{\left[(x^2-a^2) - y^2\right]^2 + 4x^2y^2} \qquad (5)$$

Midway between the pole faces, where x = 0, the magnetic field intensity is given by

$$H_x\Big|_{x=0} = -2A \frac{a}{y^2 + a^2} = -2 \frac{A}{(y^2 + a^2)^{\frac{1}{2}}} \cos \theta \qquad (6)$$

as shown in figure 2. The constant A in equation (6) is determined for given values of the field intensity, magnetization depth, and gap length.

The equation for the magnetic field gradient can be simplified to

$$(\nabla H)_x = \frac{\partial H_x}{\partial x} = 4Aax \left[-\frac{1}{b} + \frac{4y^2(x^2 + a^2 + y^2)}{b^2} \right] \frac{\text{oe}}{\mu\text{in.}} \qquad (7)$$

where

$$b = \left[(x^2 - a^2) - y^2\right]^2 + 4x^2y^2$$

The equation for the field gradient further simplifies if the gradient is examined along the field line that forms the semicircular arc centered at the coordinate origin and, of course, passes through the line charges at $x = \pm a$, $y = 0$. Along this line, $x^2 + y^2 = a^2$, and the field gradient is given by

$$\frac{\partial H_x}{\partial x} = \frac{Ax}{a\ y^2} \qquad (8)$$

If a tape magnetization depth of y = a (the radius of the semicircular flux arc) at x = 0 is assumed, the magnetic field intensity along this arc is uniform. Letting this intensity be equal to the coercivity of the tape coating, H_c = 290 oe, the constant A of equation (6) can be evaluated for a given gap length, 2a. For each value of the gap length, the field gradient can then be calculated for any point on the semicircle using equation (8). Table I summarizes the calculated field gradients in terms of the coordinate angle, ϕ = arc tan (y/x), and the gap half width, a.

TABLE I. FIELD GRADIENT ($\frac{\partial H_x}{\partial x}$) IN OE/μIN.

ϕ / x / y \ a(μin.)	~0° / a / .1a	10° / 0.985a / 0.174a	30° / ($\sqrt{3}/2$)a / (1/2)a	45° / ($1/\sqrt{2}$)a / ($1/\sqrt{2}$)a	60° / (1/2)a / ($\sqrt{3}/2$)a	90° / 0 / a	-A
50	582	190	20	8	4	0	14500
75	388	126	12	6	3	0	21800
100	290	94.5	9.7	4	2.7	0	29000
150	194	64	6	2	1.4	0	43500
250	117	36.7	3.3	1.7	0.7	0	72500

($\theta = 45°$)

Curves based on table I and equation (8) are displayed in figures 3 and 4. Figure 3 exhibits the field gradient as a function of depth, y, into the recording medium. The curves were constructed for various gap half-lengths ranging from 50 to 250 μin. The field gradient versus gap half-length for the semi-circular field contours at angle $\phi = 30°$ is shown in figure 4. Figure 5 relates the field gradient to the magnetization depth. A field intensity of $H_c = 290$ oe was assumed for various depths, y, into the medium at x = 0, corresponding to angles θ of 30°, 45°, and 60°. The field gradient was calculated at points x,y corresponding to $\phi = 30°$ using equation (7).

The graphs clearly indicate how various factors influence the field gradient in an Alfesil driven-gap-spacer head. Although the skin depth in Alfesil is negligibly small for most purposes, the magnetic line charge approximation is not accurate very near the magnetic poles of the recording head. In the proximity of the poles, e.g., for $y < 0.174a$, $\phi < 10°$, the calculated field gradients are substantially larger than the actual values. Nevertheless, the field gradient does become very large, particularly in the outer region of the tape coating. This becomes evident if a comparison is made to a typical ring-core head for which the field gradient in this region is only about 1 oe/μin.

The Alfesil driven-gap-spacer head is represented by the magnetic line charge model most accurately at higher bias frequencies. For short-wavelength recording, a high bias frequency will therefore be most effective.

The effect of the gap length on the field gradient is shown in figure 4. Although lower magnetic field intensities result using shorter gaps, the field gradient shows a corresponding definite improvement. However, the advantages of a gap of less than 100 μin. are not warranted for any short-wave length recording at this time.

In contrast to the ring-core head, the field gradient in the Alfesil gap-spacer head increases with the depth of magnetization as shown in figure 5. For the latter head, increasing the magnetization depth steepens the slope of the field contours at the ends of the recording zone. This effect is indicated in figure 2 for the various contours at, for example, $\phi = 30°$. This improvement of the gradient is effective only up to a maximum recording depth of $\sqrt{3}$ a, thereafter, the improvement becomes negligible.

To estimate the length of the recording zone, let $H_c = 290$ oe. The recording range then extends from 320 to 260 oe, or $\Delta H = 60$ oe. For a magnetization depth, y = a at x = 0, and an effective gap length of 150 µin., the gradient at y = 0.5a is 12 oe/µin. The width of the recording zone is then only 5 µin. and becomes still smaller for the outer regions of the tape coating (y < 0.5a). Therefore, Alfesil driven-gap-spacer heads can easily record wavelengths as short as 15 or 20 µin. The field lines and the recording zone for such a head are shown in figure 6.

Losses and Practical Limitations. The advancements in VHF recording design is impeded by various limitations. Head losses continue to be a problem in recording very high frequencies, but this problem has been reduced to a point where it is no longer a dominant limitation. The principal remaining difficulties are in maintaining intimate head-to-tape contact at high recording velocities and with the limited resolution and lossy reproduction processes available for short-wavelength recordings. At tape speeds exceeding 2000 ips, extreme care must be exercised to maintain adequate head-to-tape contact. This is particularly important for narrow-gapped recording heads since the separation loss is directly proportional to the ratio of separation to gap length. At high speed, this contact problem is compounded by an increased air film, frictional heating, oxide ruboff onto the head, and runout and vibrational problems. Aside from higher driving current requirement due to lower sensitivity, high-energy tapes, because of higher surface roughness, are even more adversely affected by oxide ruboff and frictional heating. Effective utilization of high-energy tapes for high-speed recording is therefore rather doubtful.

The VHF capability of the Alfesil gap-spacer head to record at extremely short wavelengths, still encounter problems in the reproducing process. Even if narrow-gapped ferrite reproduce heads prove effective at resolving wavelengths shorter than 40 µin, the wavelength-dependent reproduction losses would be extremely large. The dependence of the reproduce-head core flux upon the recorded wavelength is given by[5]

$$\phi_c = \left\{ \left[\frac{1 - \exp(-2\pi T/\lambda)}{2\pi T/\lambda} \right] \exp\left(-\frac{2\pi S}{\lambda}\right) \frac{\sin(2\pi a/\lambda)}{2\pi a/\lambda} \left[1 + \sum_{n=1}^{\infty} \frac{A_n}{U_o} \frac{4\pi n(-1)^n}{4-n^2\lambda^2} \right] 4\pi T M_{x(max)} \cos\left(\frac{2\pi vt}{\lambda}\right) \right\} \tag{9}$$

where

ϕ_c	= core flux in reproduce head
λ	= recorded wavelength
S	= head-tape separation
T	= tape coating thickness
2a	= reproduce head gap length.

Assuming

λ	= 40 µin
S	= 10 µin
T	= 200 µin
a	= 10 µin

the various reproduction losses appearing as factors in equation (9) are:

the thickness loss

$$L_T = 20 \log_{10} \left[\frac{2\pi T/\lambda}{1-\exp(-2\pi T/\lambda)} \right] = 30 \text{ dB}.$$

the separation loss

$$L_S = 20 \log_{10} \exp(2\pi S/\lambda) = 54.6\,(S/\lambda) = 13.7 \text{ dB}.$$

the gap loss

$$L_g \simeq 20 \log_{10} \left[\frac{\sin(2\pi a/\lambda)}{2\pi a/\lambda} \right] = 4 \text{ dB}.$$

Obviously, the short-wavelength losses can be severe. The thickness loss is particularly high, therefore, a thin coating and a shallow recording depth should be sought for short-wavelength recording. The necessity for good head-to-tape contact is also clear. Certainly, the rather poor efficiency of a 20-μin. head gap cannot be ignored. In particular flux shunting will incur additional losses. Therefore, reducing the recorded wavelength does not completely answer the VHF recording problem. Consequently, the relative head-to-tape velocity should be maintained as high as practicable.

Conclusion. Of the heads considered, the Alfesil driven-gap-spacer head appears to be the most effective choice for a-c bias recording of VHF signals at very short wavelengths. Due to its gap-spacer configuration and minimal skin depth, an extremely large field gradient can be obtained compatible with the recording requirements of the shortest wavelengths. In contrast to the ring-core head, increasing the bias level has been shown to improve the short-wavelength response up to a limit but tape depth losses are still to be considered. Graphs were presented for the theoretical field gradient as functions of intensity level, gap length, and tape penetration. During most of the experimental testing, the gapspacer was driven by both the bias current at 100 to 200 MHz and the VHF signal current. A variation of this head utilizes a coil consisting of a few turns wrapped around the core and driven by the signal current.

The ferrite driven-gap-spacer head shares many of the advantages of the Alfesil head. However, because of its higher resistivity, the skin depth is very much larger and, consequently, the field gradient is only slightly better than that of a similar ring-core head.

Wavelength reduction, however, is not the complete answer to VHF recording. Reliable high-speed tape transports--for some applications complimented by rotating head arrangements--as well as more compatible tapes will continue to be of importance.

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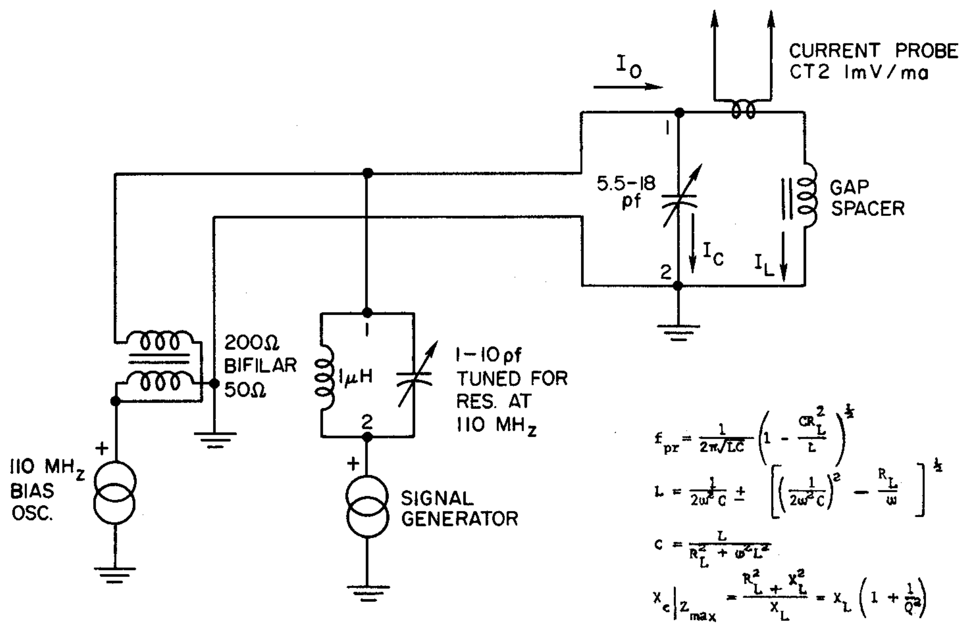

Fig. 1 - Recording-Head Driving Arrangement.

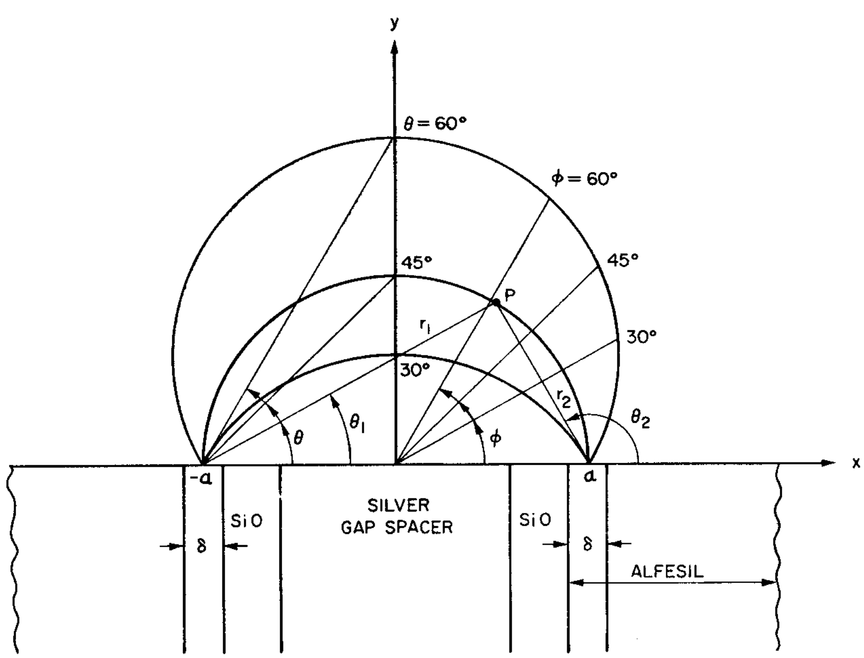

Fig. 2 - Magnetic Line-Source Analogy.

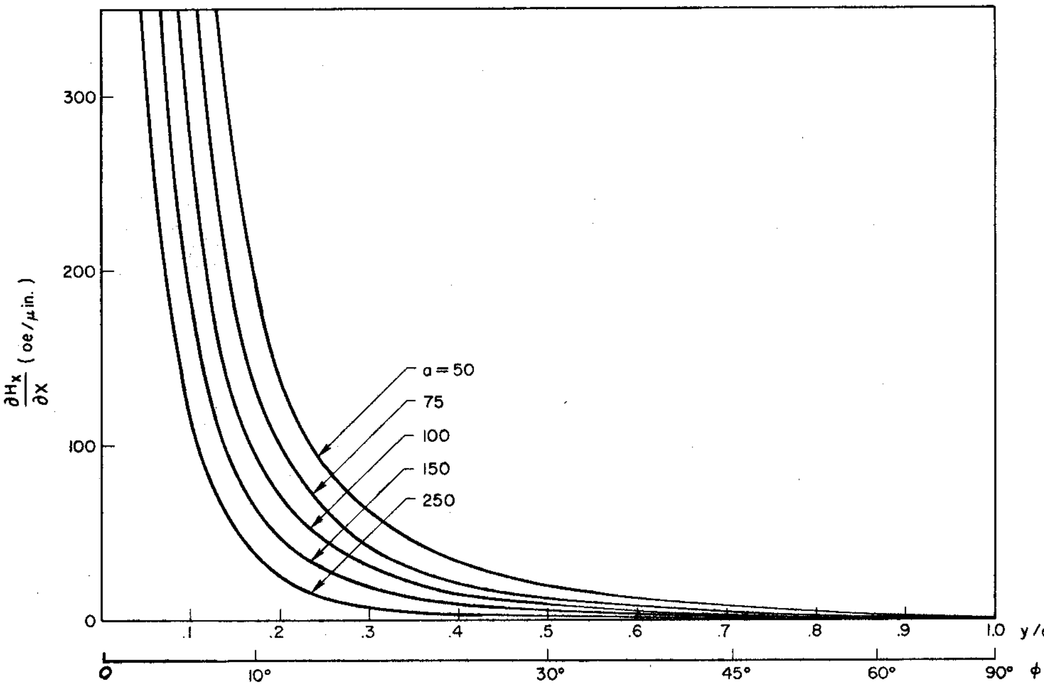

Fig. 3 - Field Gradient for the Semicircular Field Contour as a Function of y for Various Gap Half Lengths, a.

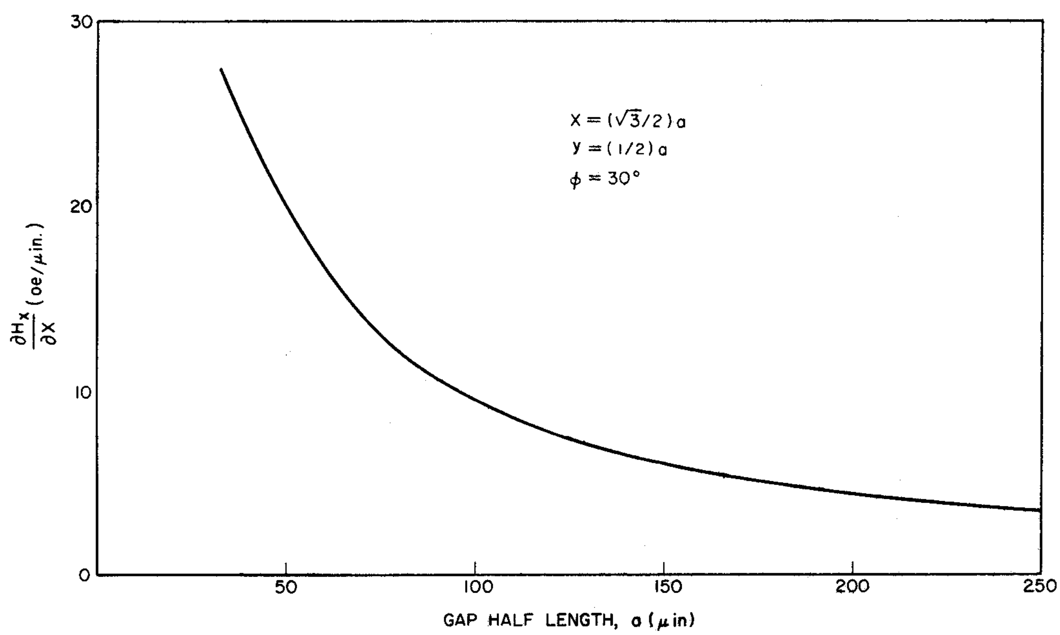

Fig. 4 - Field Gradient for the Semicircular Field Contour as a Function of the Gap Half Length, a.

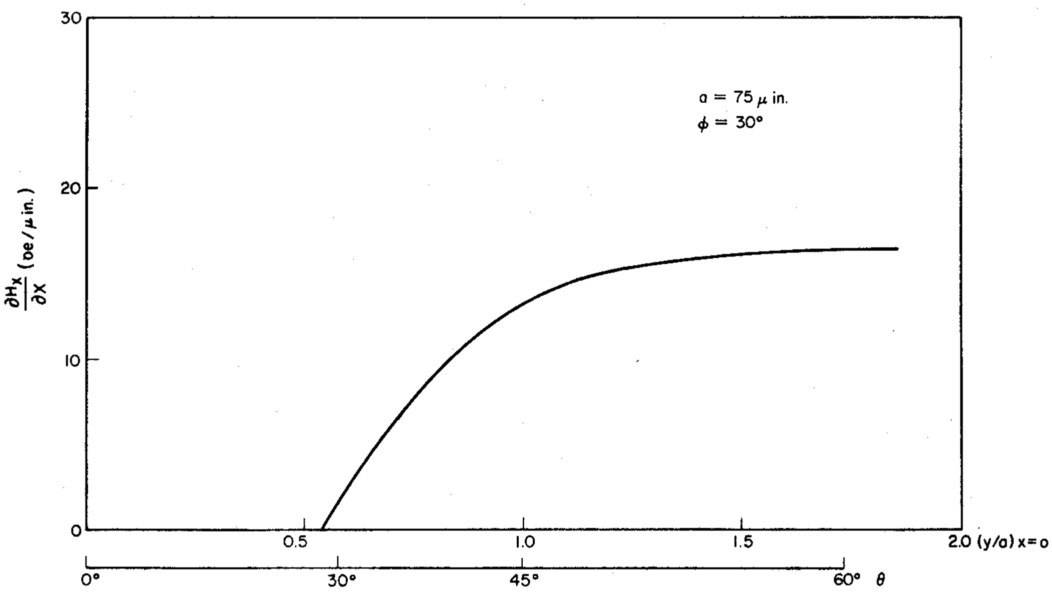

Fig. 5 - Field Gradient as a Function of Magnetization Depth, y at x = 0.

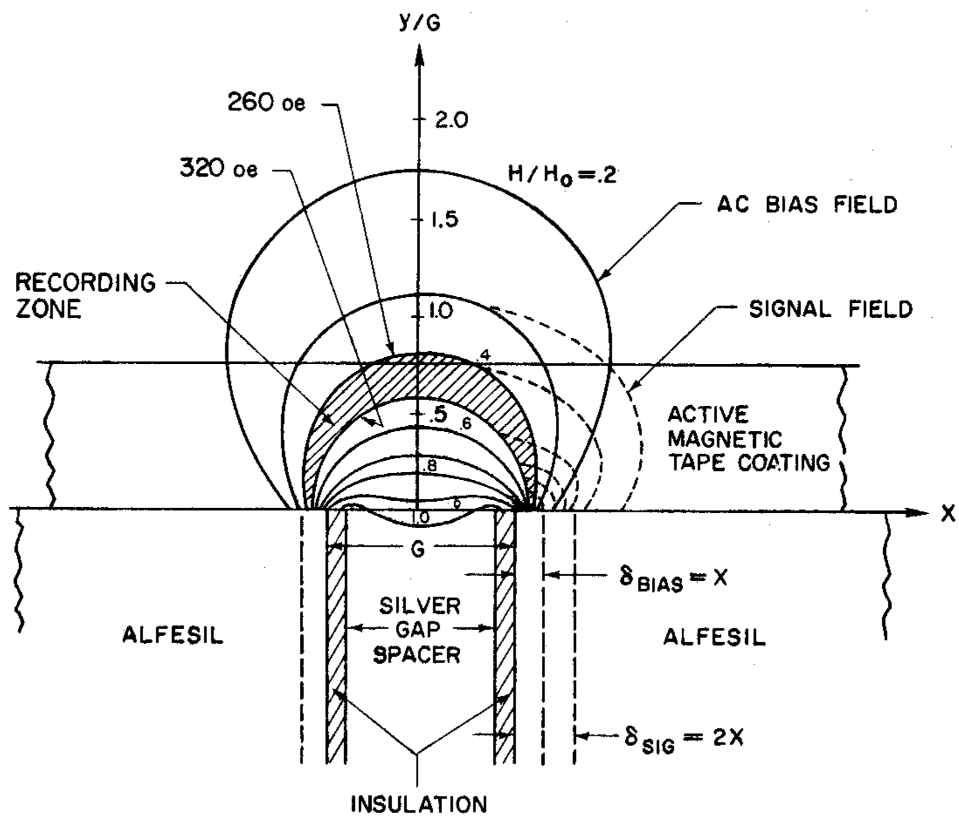

Fig. 6 - Magnetic Field Lines Across the Gap of an Alfesil Driven-Gap-Spacer Head.