Magnetic Head Wear Investigation

By MICHAEL RETTINGER

For a given magnetic head, head life is proportional to the film pressure on the head produced by the film tension, kinetic friction coefficient of the film and the angle subtended by the film on the head (film-wrap angle). For a given film and film-wrap angle, magnetic head life is proportional to the film pressure on the head produced by the film tension, the square root of the core radius, the 3/2 power of the pole face depth, the core width, and in some undetermined manner to the core hardness. More briefly, one may say that (for a constant film and film-wrap angle) head life is proportional to the film pressure, volume of removable core material, and core hardness.

Wear on magnetic heads used for sound-on-film recording is controlled by various factors: (1) type of film, (2) pressure exerted by film on head, (3) volume of removable core material, (4) film-wrap angle, (5) core material and (6) miscellaneous operating conditions. These factors will now be considered in detail.

Type of Film

The magnetic coating used on the film consists of red or black iron oxide or a mixture of those oxides in various concentrations, held in place by any one of a large variety of binders such as cellulose acetates, cellulose nitrates, vinyl compounds, and others. It is a mild abrasive, and closely related to the material known as crocus, widely used as a polishing agent.

Pressure Exerted by Film on Head

The force—hereafter called pressure—which the film exerts against the head is proportional to the film tension and the sine of the film-approach angle (see Fig. 1). It will be considered constant throughout the life of the head.

The unit area pressure is obtained by dividing the film pressure by the core contact area. Since this area increases during the wear process (but the pressure does not) the pressure per unit area will decrease during the wear process. For this reason we have various stages of unit area pressure — initial, average and final. However, to speak of an initial (or average or final) pressure per unit area would be misleading, because the terms initial, average or final tend to qualify the word pressure of the compound noun, pressure per unit area, which is not the intention. The pressure remains essentially constant, because the film-approach angle remains essentially constant. In the following, therefore, there will be used instead the terms pressure per unit initial (or average, or final) area.

The pressure per unit area is not solely determined by the film-approach angle and film tension but must include the peripheral contact area of any additional supports, be they other heads or so-called "shoes." Thus the total pressure on a head with 0.200-in. wide cores is cut in half when a 0.200-in. wide shoe (with the same radius as the head core) is placed near the head and in contact with the film.

Volume of Removable Core Material

The life of a head is also limited by the volume of core material which can be removed before the head is worn out. This volume has very much the shape of a cylindrical segment, and is determined by the radius, the segmental height and the segmental width.

The height of the segment is given by the pole face depth. Figure 2 shows for a constant core radius the cross-sectional segmental areas as a function of the pole face depth. It is seen, for instance, that a head with a 15-mil pole face depth has a segmental volume approximately 80% larger than a similar head with a 10-mil pole face depth.

Figure 3 shows the variation of the cross-sectional segmental area as a function of the radius (if it could be changed) for a constant pole face depth of 0.015 in. It is seen that doubling the radius provides a 41% increase in the core material volume available for removal during the wear process.

Film-Wrap Angle

Another factor determining magnetic head life is the film-wrap angle, as shown in Fig. 1. In general, an increase in the film-wrap angle (which is twice the film-approach angle) results in a lower head life.

One explanation for this condition lies in the fact that, for the same film tension, the total pressure on the head increases with the sine of the film-approach angle, while the amount of core material volume available for removal during the

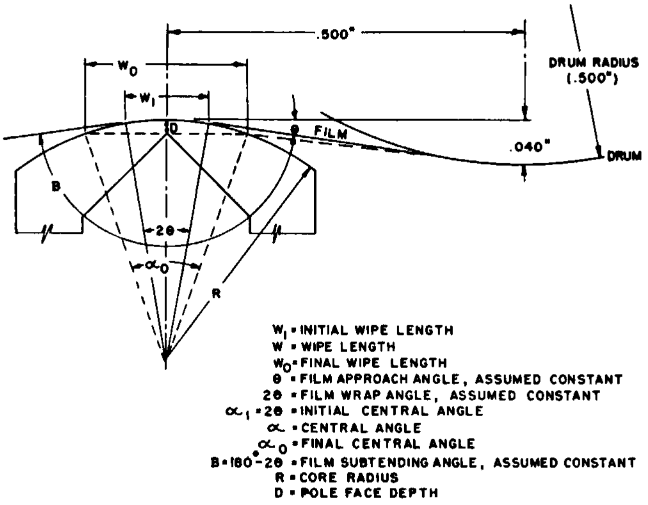

Fig. 1. Illustration of terms used in text.

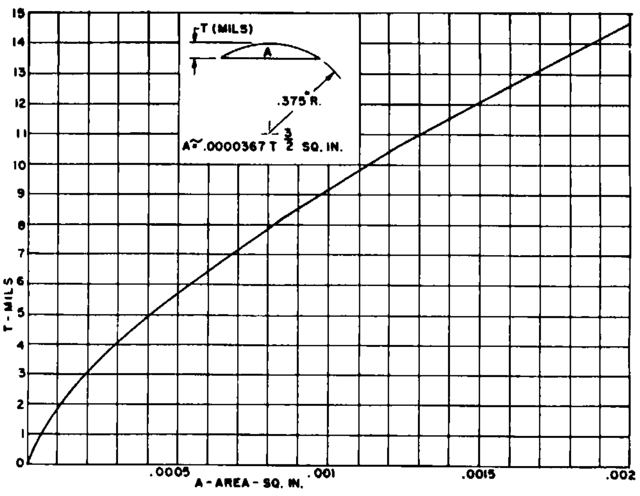

Fig. 2. Cross-sectional segmental core area as a function of the segment height for constant 0.375-in. core radius.

Presented on October 20, 1954, at the Society's Convention at Los Angeles by Michael Rettinger, Radio Corp. of America, 1560 N. Vine St., Hollywood 28, Calif.
(This paper was first received on October 23, 1954, and in shortened form on February 2, 1955.)

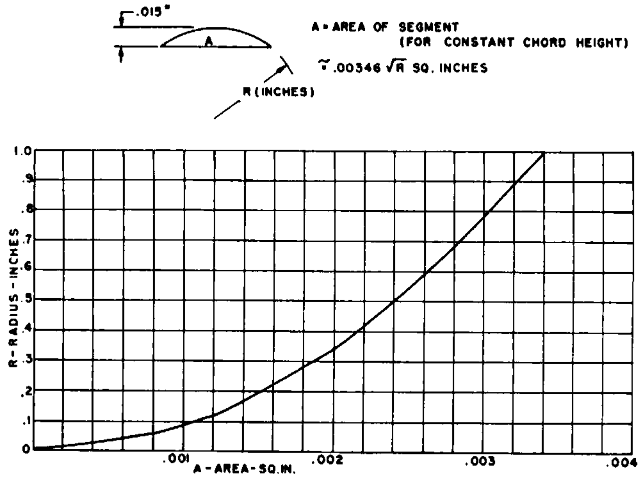

Fig. 3. Cross-sectional segmental core area as a function of the core radius for constant 0.015-in. segmental height.

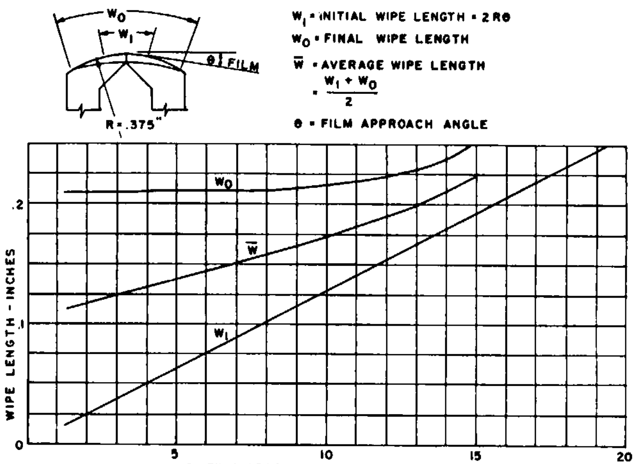

Fig. 4. Core contact wipe length as a function of the film approach angle.

wear process remains essentially independent of this angle.

Another explanation concerns the pressure per unit area throughout the wear process. In a later part of this paper it will be shown mathematically that the pressure per unit initial area is the same for all film-approach angles less than 20°. However, while the pressure per unit final area for a head with a large film-approach angle is practically the same as the pressure per unit initial area, the pressure per unit final area for a head with a small film-approach angle is but a fraction of the pressure per unit initial area. In other words, for a head with a large film-approach angle the pressure per unit area remains essentially constant throughout the wear process, while for a head with a small film-approach angle the pressure per unit area decreases materially. Since, again, the volume of core material available for removal remains essentially the same for the two cases, the head with the small film-approach angle will last longer because it is subject to a smaller total as well as smaller unit (abrasion-determining) pressure.

Core Material

The Permalloy or mu-metal laminations conventionally used for the cores of ring-shaped magnetic heads are usually softer than the iron oxide of the magnetic coating. For this reason, various attempts have been made to employ other materials, although to date no really satisfactory substitute for the conventional core stock has been found.

Miscellaneous Factors

There are other factors besides type of film, film pressure, film-approach angle, core volume and core material which influence head life. One is film speed; and another, closely related to it, pertains to the rates of acceleration and deceleration of a film during starts and stops, and the number of starts and stops in a given time. A recorder which is started and stopped frequently may be expected to have a greater wear effect on the heads than one with fewer such intermittent film motions. The reason lies in the greater film friction which exists at slow speeds. Indeed, in physical and mechanical engineering, a large distinction is made between static and kinetic friction, the former being defined as the force required to start the body from rest and the latter as force required to keep the body moving. Static friction is always greater than kinetic friction, the probable reason for this difference being the better interlocking of the surfaces in the case of static friction.

It has also been found in practice that record heads are subject to greater wear than monitoring heads. One reason for this condition lies in the fact that when new film is used, any projecting hard particles on the magnetic coating of the film pass first over the record head, where some of them may be removed by the cores, thus providing a smoother magnetic coating for the monitoring head.

THE THEORY OF MAGNETIC HEAD WEAR

For a given type of head and film, only two factors appear to be essential in the evaluation of wear: (1) pressure per unit area throughout the wear process and (2) the volume of material which can be removed until the head is worn out. The reason why we must consider the pressure per unit area throughout the wear process lies in the fact that it is not constant throughout the life of the head, but decreases at various rates depending on the amount of film wrap on the head. At first, this pressure per unit area is large, because the contact area is small. After some wear has taken place, the film pressure, which remains constant throughout the life, becomes spread over a large contact area. Hence, the unit area pressure decreases during the wear process.

The total pressure on the head is given by the vectoral sum of the vertical components of the tension. This sum is $2T \sin \theta$, or simply $2T\theta$, if θ is in radians and less than 0.261 (15°), because for angles smaller than 15° the angle in radians is practically equal to the sine of the angle. Thus the sine of an angle of 0.261 radians is 0.259, the difference amounting to less than 1%.

No matter what the contour of the contact area of the head is — flat, round, triangular, etc. — the total force applied on the head is $2T \sin \theta$. Because the contour of the contact area is circular, this force or pressure is evenly distributed over the periphery of the head, except perhaps at the very edges where the film enters and leaves the head, where a pressure gradient of a sort may be said to exist.

In arriving at a relative figure for head life we assume, therefore, that head life is proportional to a ratio which contains some measure of the contact area in the numerator and pressure ($2T \sin \theta$) in the denominator. For the calculations two cases of film pressure should be considered: when the film tension is constant with the film-approach angle, namely, 24 oz; and when it is gradually reduced with the approach angle according to the equation $T = 26 - 2\theta/3$ (which gives a tension of 24 oz for a film-approach angle of 3° and a tension of 16 oz for a film-approach angle of 15°, as was found desirable by test).

Next we have to establish the initial and final contact areas. Figure 4 shows the wipe lengths as a function of the film-approach angle. When they are multiplied by the core width, we obtain the contact areas. Shown also on the figure is the average wipe length as a function of the film-approach angle, obtained by adding the initial and the final wipe length, and then dividing this

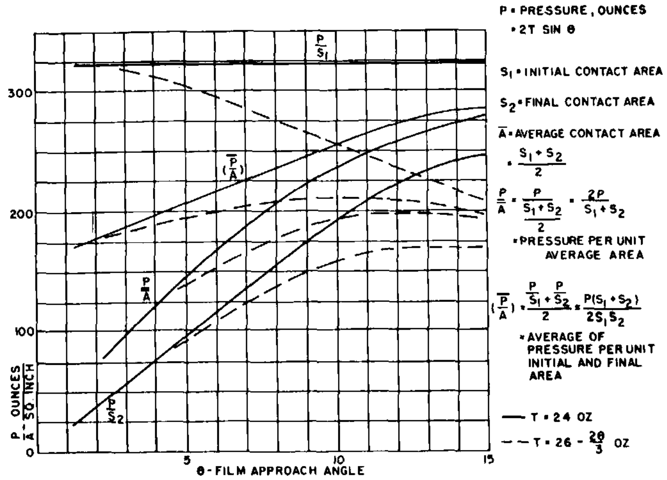

Fig. 5. Pressure per unit core contact area as a function of the film approach angle.

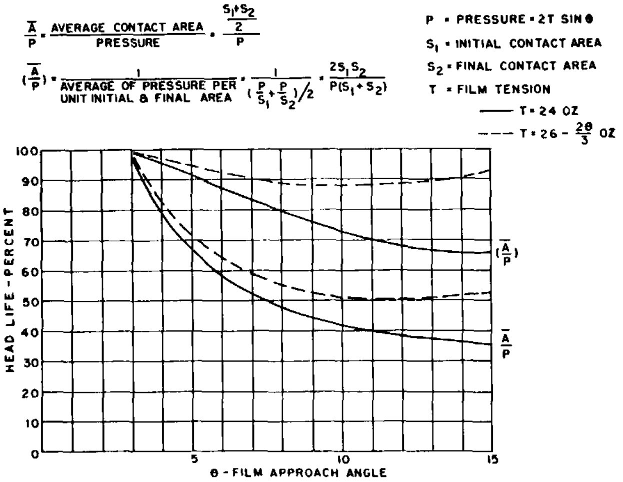

Fig. 6. Magnetic-head life as a function of the film approach angle.

sum by 2. Again, when this average wipe length is multiplied by the core width we obtain the average contact area.

Next we establish the pressure per unit initial contact area and the pressure per unit final contact area as a function of the film-approach angle. This relationship is shown on Fig. 5. It is seen that the pressure per unit final contact area is constant with the film-approach angle, and that the pressure per unit final contact area increases with the film-approach angle. This relationship is shown both for the case when the film tension is constant with the film-approach angle and when it decreases according to the equation $T = 26 - 2\theta/3$.

The reason why the pressure per unit initial contact area is the same for all film-approach angles may be shown as follows. Let (see Fig. 1)

R = core radius, inches
b = core width, inches
θ = film-approach angle, radians
W = initial length of arc of circular core segment contacted by film
$= 2R\theta$, inches
A = initial area of circular core segment contacted by film
$= Wb$
$= 2R\theta b$
T = film tension, ounces
P = pressure on core
$= 2T \sin\theta$

$$\frac{P}{A} = \frac{2T\sin\theta}{2R\theta b}$$

$$= \frac{T}{Rb} \text{ (because for small angles } \sin\theta = \theta)$$

It is seen that for the film-approach angles used by us (θ smaller than 15°) the pressure per unit initial contact area is independent of the film-approach angle because increasing the angle increases the total pressure on the head in the same proportion as it increases the contact area.

In respect to the average of the above term which contains pressure in the numerator and a measure of contact area in the denominator (the reciprocal of which is to give us a head life factor) we have two choices. We can form the relationship "pressure per unit average area" (as a function of the film-approach angle), and we can form the mean of the pressure per unit initial contact area and pressure per unit final contact area (as a function of the film-approach angle). The former is obtained by dividing the pressure ($2T \sin\theta$) by the average contact area (obtained by multiplying the average wipe length of Fig. 4 by the core width). The latter is obtained by adding, for every film-approach angle, the pressure per unit initial contact area and pressure per unit final contact area, and dividing this sum by two.

These two relationships may be formed both for the case of constant film tension and for the case where the film tension varies according to the equation $T = 26 - 2\theta/3$. These four averages are also shown on Fig. 5. The reciprocals of these averages are the "head lives" as a function of the film-approach angle and are shown, in a relative manner, in Fig. 6. In every case, the head life of a head approached by a film with an approach angle of 3° was chosen as a "standard" and given 100% head life. It is seen that in every case, head life decreases with an increasing film-approach angle.

To obtain an algebraic expression linking feet of film passed over the head with the volume removed, we have to establish an equation for a segmental element of the volume in terms of the pole face depth. Let (see Fig. 1)

W = wipe length, mils
R = core radius, mils
$= 375$
d = pole face depth when wipe length is W, mils. When $W = 0$, $d = 15$ mils
t = pole face depth reduction, mils
$= 15 - d$

$$W = 2\sqrt{R^2 - (R - t)^2}$$
$$= 2\sqrt{750t - t^2}$$
$$\cong 55\sqrt{t}$$
$$\cong 55\sqrt{15 - d}$$

To calculate the total core material volume available for removal when the core width $b = 0.200$ in., and a small change in pole face depth is dd, we may write

$$dV = bWdd$$

$$\text{or} \int dV = \int_0^{15} bWdd$$

$$= 55b\int_0^{15}\sqrt{15 - d}\,dd$$

$$= 420 \text{ microcubic inches}$$

Assume, for instance, that it takes a million feet of film passed over the head to remove this total available core material volume (0.000420 cu in.), then one microcubic inch is removed after 1,000,000/420, or 2380 ft of film.

Therefore, if we wish to know how many feet of film are required to remove a certain volume of core material — or, inversely, what the pole face depth is after a certain number of feet of film have passed — all that we have to do is to multiply 2380 ft (required to remove 1 microcubic inch) by the removed volume of core material when the pole face depth is d, or

$$F = 2380\, b\int_0^{15} 55\sqrt{15 - d}\,dd$$

$$= 17{,}200\,(15 - d)^{3/2}$$

where F = number of feet of film passed.

Similarly, if it takes 2 million feet of film to wear out a head, we get:

$$F = 34{,}400\,(15 - d)^{3/2}$$

This expression gives the film footage passed as a function of the pole face depth. However, the curves in this paper are plotted "the other way around," employing the film footage as the independent variable. Hence, if we are to follow conventional mathematics, which uses the ordinate values for the dependent variable, we must solve the preceding equations for d. Thus we obtain, for the case where the total available core volume is removed in one million feet of film

$$d = 15 - 0.015F^{2/3}$$

A quick check will show that when the film footage is zero (F = 0), the pole face depth is 15 mils; and when it is 2,000,000 the pole face depth will be zero.

Any of the above equations can be used for only one purpose, and that is correlatingly to plot the pole face depth as a function of film footage when the total case history of a head is available. It can then be used in substantiation of the theory outlined above, namely, that a given amount of footage of a specified type of film will remove a certain amount of core material volume under the condition of constant film pressure but variable pressure per unit contact surface. Nothing has been said about the magnitude of the pressure, the initial pressure per unit area, film-wrap angle, core material, type of film, etc. This does not mean that the equation could not be made to include factors which consider these conditions.

EXPERIMENTAL

To measure the wear on magnetic heads, a machine was constructed which allowed the simultaneous testing of a maximum of ten magnetic heads. Half of the film loop employed the tension used on our recorders (24 oz at the tension rollers) and the other half employed the tension on our soundheads (12 oz at the tension rollers). The following heads were tested with the tight loop:

No. 1: A single-track magnetic record head with 0.200-in. wide laminated Permalloy cores having a 0.375-in. radius. It was used in connection with a film supporting shoe, and the film-wrap angle employed was 12°.

No. 2: Same as Head No. 1, except ferrite cores were used instead of laminated Permalloy cores.

No. 3: Same as Head No. 1, except that the Permalloy laminations had been chromium-plated before they were cemented together into cores, as shown on Fig. 7A. It also employs a film supporting shoe, and the film-wrap angle was 12°. This was an experimental unit to learn how the chromium plating on the side of the laminations would affect head life.

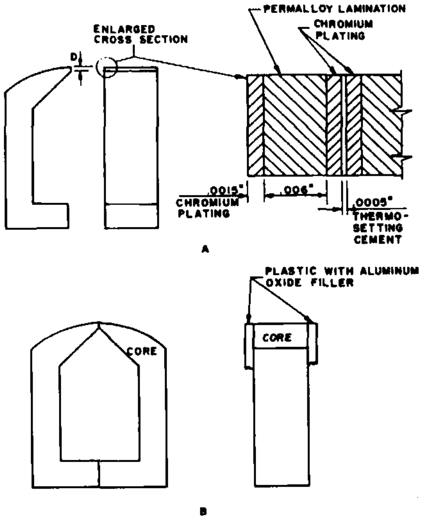

Fig. 7. Two types of long-life heads.

No. 4: Same as Head No. 1, but using on the side of the cores a plastic 0.030-in. wide containing an aluminum oxide filler, as shown in Fig. 7B. This was also an experimental head constructed to learn how the hard plastic on the side of the cores would affect head life. A previous head with 0.020-in. wide sapphire shoes cemented to the sides of the cores suffered from undercutting of the cores, with a consequent deterioration of the high-frequency response, because the sapphire was so hard that little wear took place on it. The aluminum oxide filled plastic is softer than the sapphire and hence, it was felt, would wear to some extent, thereby reducing the effect of undercutting. No undercutting was observed in the tests.

No. 5: Same as Head No. 1, but employing no film supporting shoe. Its counterpart was Head No. 1, which also has a 12° film-wrap angle, but was equipped with a shoe, unlike Head No. 5.

Simultaneously, the following heads were tested with the soft film loop:

No. 6: Same as Head No. 1, but using a 24° film-wrap angle, and a film supporting shoe. Its counterpart was again Head No. 1, operated with a tight film loop and a 12° film-wrap angle.

No. 7: Similar to Head No. 1, but using 0.050-in. wide instead of 0.200-in. wide laminated cores. The film-wrap angle was 24°, and a film supporting shoe was employed.

No. 8: Same as Head No. 7, but using no shoe.

The film speed employed was 90 ft/min.

Because the film tension varied from head to head, due to the friction exerted by the film against the heads, as pointed out in the first part of this paper, the film pressure was measured for every head position.

Periodic measurements of the front gap pole face reduction were made with a micrometer.

The film loop was 72 ft long. It was changed after every 200 passages.

In Table I the various heads are tabulated, together with their life expectancy factors. The computations for the factor were so made that the smallest factor would be unity. A head with a life expectancy factor of 5, therefore, would mean that it should last five times as long as one with a unity factor.

The life expectancy factors for Heads 2 and 3, also shown on Table I, were figured on the basis of having standard cores, which of course they do not have. This was done to enable calculating a proportionality factor for the heads, provided the life expectancy factor for the other heads rang true.

Two life expectancy factors are shown. The one shown as A/P refers to the

Table I

Head No.	Description	θ, film-wrap angle	P, film pressure on head, oz	Life-expectancy Factor $\frac{A}{P} \times 625$	$\frac{A}{P} \times 613$	Film passed, million ft
1	A single-track magnetic record head with 0.200-in. wide laminated Permalloy cores having a radius of 0.375 in. and a film supporting shoe	12°	1.5	12	9.7	12(estimated)
2	Same as No. 1, but uses ferrite cores	12°	1.5	12	9.7	24(estimated)
3	Same as No. 1, but Permalloy laminations were chromium-plated before being cemented together into cores	12°	1.75	10.3	8.5	60(estimated)
4	Same as No. 1, but using on the side of the cores a plastic 0.030-in. wide containing aluminum oxide filler	12°	1.75	10.3	8.5	21(estimated)
5	Same as No. 1, without film supporting shoe	12°	3.65	4.95	4	4.5
6	Same as No. 1	24°	4	5.75	5.75	5.2
7	Same as No. 1, but cores are 0.050-in. wide	24°	1.15	5	5	4.0
8	Same as No. 7, without shoe	24°	4.75	1	1	0.8

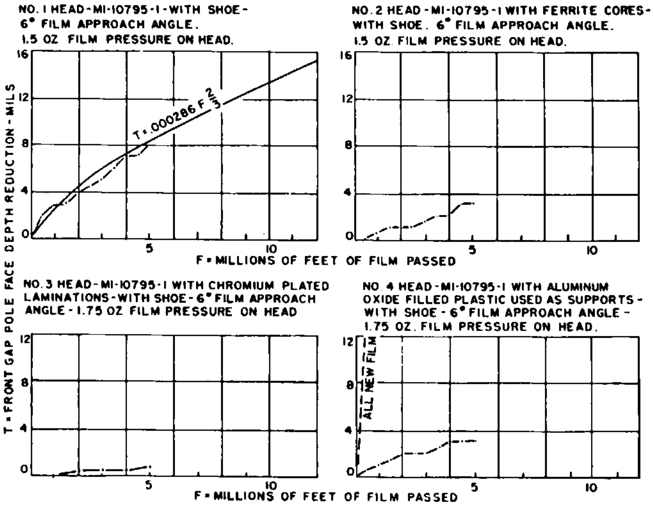

Fig. 8. Magnetic-head life as a function of film footage passed over the heads.

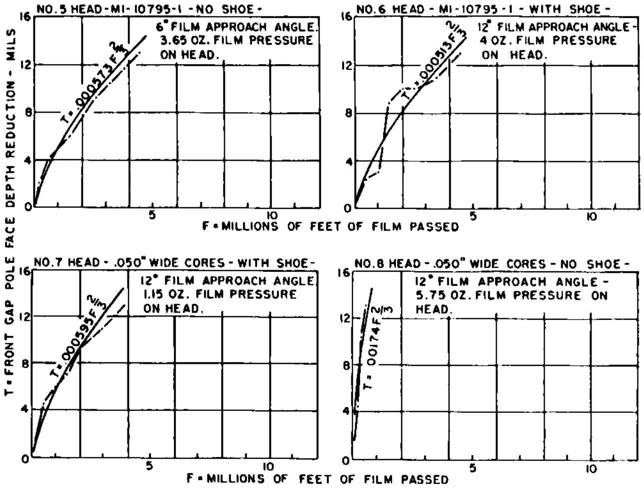

Fig. 9. Magnetic-head life as a function of film footage passed over the heads.

average contact area divided by the film pressure. The one shown as A/P refers to the reciprocal of the mean of the pressure per unit initial contact area and pressure per unit final contact area. Both life expectancy factors were discussed in detail under the section on theory above.

On Figs. 8 and 9 are shown the experimental results. The solid curves represent the theoretical values. The experimental curves approach the calculated curves rather well. There is a definite trend, as wear progresses, toward an asymptotic limit, which is due to the decrease in pressure per unit area.

On Fig. 8 (Head No. 4) there is also shown the lifetime of a head of this type when only new film is used. This head is identical to the one employed in the wear machine. It had been sent to the sound department of a motion-picture studio, where it was used as a monitoring head on a recorder which passed only new film. The enormous difference between the effect of the new film and that of old film is readily evident.

Note that head wear was determined by the front gap pole face reduction, in mils, and not by the change in head inductance. The reason for this is that different types of heads show a difference in inductance change with pole face reduction.

Discussion

E. S. Seeley (*Altec Service*): The point was once suggested to me, and I've demonstrated it a number of times since, that when the film contacts the head it doesn't seem to conform to the shape of the head as your early figures indicated. These might fit the case of a very limp or highly pliable tape, but film is pretty stiff and it seems to contact the head over an incredibly small area when the head is new. Wear at first is very rapid and appears as a flattening of the core. As time goes on the worn area widens. We have applied dye to the cores in a number of instances to observe the variation of contact area, care being taken to eliminate possible variation in the position of film during the starting operation. It was qualitatively confirmed that a contact corresponds to what would result if the film is a stiff beam. Under these conditions, if the film is flat and the head itself is curved, the point of contact would be extremely small and lead to very rapid initial wear followed by a great reduction in wear rate after the area of contact has widened. Possibly, conclusions concerning wear based on the stiff film concept would not be greatly different from those based on a limp film.

Mr. Rettinger: It is true that as long as the film-approach angle is small, say less than 12°, the contour is essentially a straight line — a flat surface — and it is only when the film angle exceeds that 12° that the contour becomes curved. It so happens that in most of our recorders the film-approach angle does not exceed 20°.

So, I feel justified in assuming that the removed core material volume had the shape of a cylindrical segment. You mentioned something else, that is, that a change in the speed may have an effect on the wear, which is true. A machine, for instance, which is started more frequently than a machine which is not interrupted so often produces more wear on a head than if it had been running continuously. There are other factors. One condition which I did not fully investigate concerns speed of the film itself. We may assume that speed must have some effect. In other words, if the head is operated with the film speed of 25 ft/min, may one expect the same amount of footage to go over the head when the film speed has been changed to 90 ft or even more? That is a condition which I did not investigate because it concerns the dynamic frictional coefficient. This work was merely to learn what effect the film approach angle had on head life. Secondly, I wanted to obtain some sort of a head life figure, a criterion which would allow me to predict head life, and while that was rather simple for certain types of heads using Permaloy laminations, it became considerably more difficult when the material was changed to ferrite or if sapphire shoes were applied next to the cores or if chrome-plated heads were used. But these were the general conclusions that I was able to arrive at.

Anon: Have you had any determination of the head wear on splices?

Mr. Rettinger: No, I did not investigate that condition at all.

Wallace V. Wolfe, Chairman of the Session (*Radio Corp. of America*): I am sure you all realize that two points that Mr. Rettinger did not specifically mention in his paper are very obviously factors that are involved—one is the particular characteristics of the abrasive of the film itself and the other is the hardness of the head material. His discussion in this analysis has been based on the assumption that those were constant factors, and that variations in those factors would obviously cause a shift of the curve insofar as they are expressed in terms of feet of film and volume of material to be removed.