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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

*Technical Report 32-1548*

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## Preface

The work described in this report was performed for the Astrionics Division (Spacecraft Data Systems Section) by the Propulsion Division (Polymer Research Section) of the Jet Propulsion Laboratory.

# Acknowledgement

The authors wish to express their appreciation to L. Renfroe and S. L. Shuler for technical assistance during the preliminary phase of this study, to V. H. Culler for his valuable assistance during the second phase, and to C. Feldstein for assistance in setting up the electronic instrumentation and providing other technical support.

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# Abstract

Methods were developed to determine the coefficient of friction and the extent of stick–slip of magnetic recording tapes. After a preliminary phase during which experimental procedures were established and screening of candidate tapes was carried out, the frictional and stick–slip behavior of four selected tapes, using four different kinds of magnetic heads, was studied at various temperatures, under dry and humid conditions, and in various gaseous atmospheres, such as argon, helium, nitrogen and air. The effects of tape speed and outgassing on the drag properties of the tapes were also studied.

A rank was assigned to each tape and magnetic head as a result of these tests. This study helped in the selection of a magnetic tape in a flight project, and will be useful in the consideration of tapes and magnetic heads for future spacecraft applications.

# A Study of the Frictional and Stick–Slip Behavior of Magnetic Recording Tapes

## I. Introduction

Magnetic tape recorders exhibit various types of failure. Those ascribable to friction between tape and magnetic head cause phenomena such as seizure (stick) and seizure and release (stick–slip). The frictional interactions between head and tape can be influenced by many factors, among which are environmental conditions such as temperature, relative humidity and the kind of fluid atmosphere surrounding the tape-head system. Significant among those related to the components themselves are the nature of the binder for the magnetic oxide coating and the surface conditions of both the tape and the magnetic head, materials of head construction, tape speed and "wrap" angle.

A *quantitative* estimation of the frictional (drag) force acting on the tape in motion or at rest and the degree of stick–slip would be of paramount importance in the study of magnetic tape-to-head behavior. This report discusses the techniques developed and used to determine the friction coefficient and the extent of stick–slip of a number of magnetic tapes. Further, it discusses the effects on the performance of magnetic tapes and heads of such factors as temperature, relative humidity, the nature of the surrounding gaseous atmosphere, tape speed, outgassing and coating the tape with a lubricant.

Prior to the main investigation, namely the evaluation of a selected number of tapes and various kinds of magnetic heads, preliminary testing (henceforth, Phase I) was conducted to establish relevant test conditions and to screen out tapes of inferior performance. Only brass-bracketed magnetic heads were used during Phase I, and testing was less expensive than that carried out during the investigations involving four different kinds of magnetic heads and a group of selected tapes (henceforth, Phase II).

Information, particularly quantitative experimental data concerning the frictional behavior of magnetic recording tapes, is scarce. The methods described and the data supplied in this report should contribute to the understanding of the frictional behavior of magnetic recording tapes and, to an extent, to that of magnetic heads.

## II. Scope

The present study was limited to developing methods for the quantitative determination of the frictional force (drag) and the seizure–release (stick–slip) of magnetic recording tapes and the influence of various environments and conditions on drag and stick–slip. The number of tapes studied was limited to a selected few, and the types of magnetic heads used were limited to four. Each tape specimen was passed 100 times over a pair of the same kind of magnetic head in the following environments: dry argon, nitrogen, helium, moist argon (RH = 25%), and ambient air (all at 25°C) and dry and moist argon at 55°C. In addition to the untreated tape, outgassed samples were also tested at both temperatures to observe the effect on the drag and stick–slip properties of the tape of removing volatile products such as plasticizers, residual moisture and low-molecular-weight polymer fractions from the binder. The magnetic performance of the tape in the presence of drag and stick–slip was not included, it being outside the scope of the study.

## III. Experimental Procedure

### A. Test Methods

**1. Determination of the coefficient of friction $\mu$ of tapes.** The test method used was based on ASTM D-1894-63, titled "Coefficient of Friction of Plastic Film." The standard method was modified to take into account the tape contact or "wrap" angle. This angle, illustrated in Fig. 1, is that between the tape and the line tangent to the circular tip of the magnetic head and perpendicular to the head's longitudinal axis. The equation for flexible band friction may be expressed as follows (Refs. 1, 2):

$$F_2 = F_1 e^{\mu\beta}$$

or

$$\log \frac{F_2}{F_1} = 0.434\,\mu\beta$$

where,

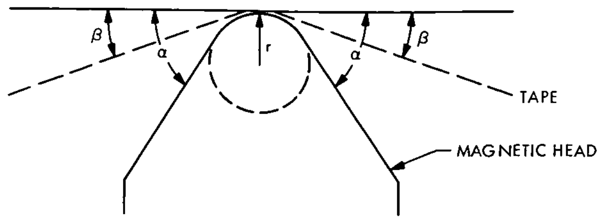
$F_2$ = force necessary to sustain motion

$F_1$ = supported weight

$\mu$ = coefficient of sliding friction

$\beta$ = angle of contact or "wrap" angle, in radians

In the present experiments $F_1$ was 110 g. Throughout this report the product $\mu\beta$ is used instead of $\mu$. The reason for this is to avoid using correction factors for the determination of the absolute value of the coefficient of friction, factors which have an extent of uncertainty themselves. Although the "wrap" angles of the heads used during Phase II were measured carefully, the same cannot be said for the "wrap" angles of the five brass heads used in Phase I. The usage of $\mu\beta$ avoided the introduction of any error from the measurement of $\beta$. Since the purpose of this investigation is to make a comparative evaluation of the frictional performance of magnetic recording tapes, and not the determination of the absolute value of $\mu$, the use of the quantity $\mu\beta$ was justified.




$\alpha$ = HEAD ANGLE

$\beta$ = WRAP ANGLE

$r$ = RADIUS OF HEAD CURVATURE

**Fig. 1. Description of terms associated with magnetic heads**

Although efforts were made to set the same "wrap" angle for the heads used in Phase II, this could not be realized because of the differences in the geometry of the magnetic heads. The $\beta$ values for each set of heads were as follows:

| | | |
|---|---|---|
| Brass heads | = | 22° |
| Monel heads | = | 21° |
| Havar heads | = | 15° |
| Aluminum heads | = | 10° |

In order to make the comparative evaluation of the tapes and the magnetic heads possible, the $\mu\beta$ values obtained must be corrected for the differences in $\beta$. This was achieved by taking the "wrap" angle of the brass heads as a reference and multiplying the experimental $\mu\beta$ values obtained with each head by the following correction factors:

| | | | |
|---|---|---|---|
| Brass heads: | 22/22 | = | 1.00 (reference) |
| Monel heads: | 22/21 | = | 1.05 |
| Havar heads: | 22/15 | = | 1.47 |
| Aluminum heads: | 22/10 | = | 2.2 |

**2. Measurement of stick–slip.** Stick–slip (seizure–release) manifests itself as a variation of tape-to-head speed. Sticking will decrease and slipping will increase the speed of the tape passing over the magnetic heads. If the instantaneous speed of the tape could be determined, then this would serve as a measure of the degree of stick–slip.

Instead of attempting the very difficult direct measurement of the instantaneous speed of the tape, another factor, which is related directly to the change in speed, was measured. This factor is the apparent period of a cycle of a signal prerecorded on the tape. If the speed of the tape passing over the heads remains constant, then the period of the recorded electrical signal will also be constant. If, however, the speed of the tape varies as a result of sticking and slipping, then the apparent period of the prerecorded signal will also vary. The extent of the variation of the period from its original value, or the standard deviation $\sigma$, is a measure of the degree of stick–slip. In the following calculation of the value $\sigma$, it is first noted that frequency $f$ is inversely proportional to period $\pi$:

$$f = \frac{1}{\pi}$$

The relationship below is assumed to hold true and should yield the standard deviation for speed:

$$\frac{f}{\sigma_f} = \frac{s_{ch}}{\sigma_s}$$

or because of Eq. (2),

$$\frac{\sigma_\pi}{\pi} = \frac{s_{ch}}{\sigma_s}$$

or

$$\sigma_s = \frac{s_{ch} \times \pi}{\sigma_\pi}$$

where

$\sigma_f$ = standard deviation of frequency values

$s_{ch}$ = crosshead speed

$\sigma_\pi$ = standard deviation of period values

$\sigma_s$ = standard deviation of speed values

**3. Determination of the effect of static contact on tape-to-head sticking.** There were indications from previous tests that when the tapes were left in static contact with the heads, adhesion sometimes occurred. This phenomenon could be easily detected by the apparatus used in the determination of the coefficient of friction; it was sensitive enough to measure the small force necessary to "peel" the adhering tape. Samples of tape, after the usual 100 passes in dry argon, were kept 96 h in contact with the heads in an atmosphere of nitrogen. The difference between the $\mu\beta$ values obtained right before and after the "wait" period indicated the extent of adhesion.

## B. Test Apparatus and Procedure

**1. Determination of the coefficient of friction.** The experiments were performed in a variable-speed, universal testing machine (Instron Table Model, Instron Manufacturing Co., Canton, Mass.). The tape sample, 68.6 cm (27 in.) long and 1.27 cm (0.5 in.) wide was passed 50 times in Phase I experiments over 5 brass-bracketed heads, and 100 times in Phase II experiments over 2 heads each of four different kinds of bracketing (brass, Monel, aluminum and Havar). The number of passes was increased to 100 because $\mu\beta$ values were observed to be levelling off after that many passes. A temperature chamber (MK 88129, Delta Design, Inc., La Mesa, Ca.), housing the grips of the universal tester and the tape-head fixture (Fig. 2ab), was modified to make it as gas-tight as possible. The chamber was capable of maintaining constant temperatures from −45.6 to 148.9°C (−50 to 300°F) within ±0.1°C.

A strip-chart recorder (Leeds and Northrup Co., Philadelphia, Pa.) was used to record the output voltage of the loadcell. The recorder had a 0.25% full-scale sensitivity. The capacity of the loadcell used in the universal tester was 22.7 kg (50 lb).

**2. Determination of variation in signal period (estimation of stick–slip).** A sinusoidal electrical signal of 4500 Hz was first recorded at a tape speed of 0.381 m/s (15 in./s) on the magnetic tape to be evaluated. The equipment used was a Hewlett–Packard Model 651B test oscillator and an Ampex Model FR-600 magnetic tape test recorder. The tape was then mounted in the Instron tester in the same manner as described for the determination of $\mu\beta$ values (Fig. 2ab). The pickup coils of the magnetic head were connected to an Astrodata Model 120 nanovolt amplifier. The signal from the latter was fed into a digital period counter and a paper printout (Hewlett–Packard Model 553LA electronic counter/Model H-43562Z digital recorder). The period of the prerecorded signal was measured accurately by oscilloscopic examination of the tape during the initial recording. The measured period of 0.02000 s agreed well with the calculated value of 0.02001 s, obtained from the recording frequency, and the recording tape speed given above, as follows:

$$f = \frac{\text{Recorded frequency (Hz)} \times \text{crosshead speed (m/s)}}{\text{Tape speed at recording (m/s)}}$$

$$= \frac{4.500 \times 10^3 \times 0.00423 \text{ m/s}}{0.381 \text{ m/s}} = 49.98 \text{ Hz}$$

$$\pi = \frac{1}{f} = \frac{1}{49.98} = 0.02001 \text{ s}$$

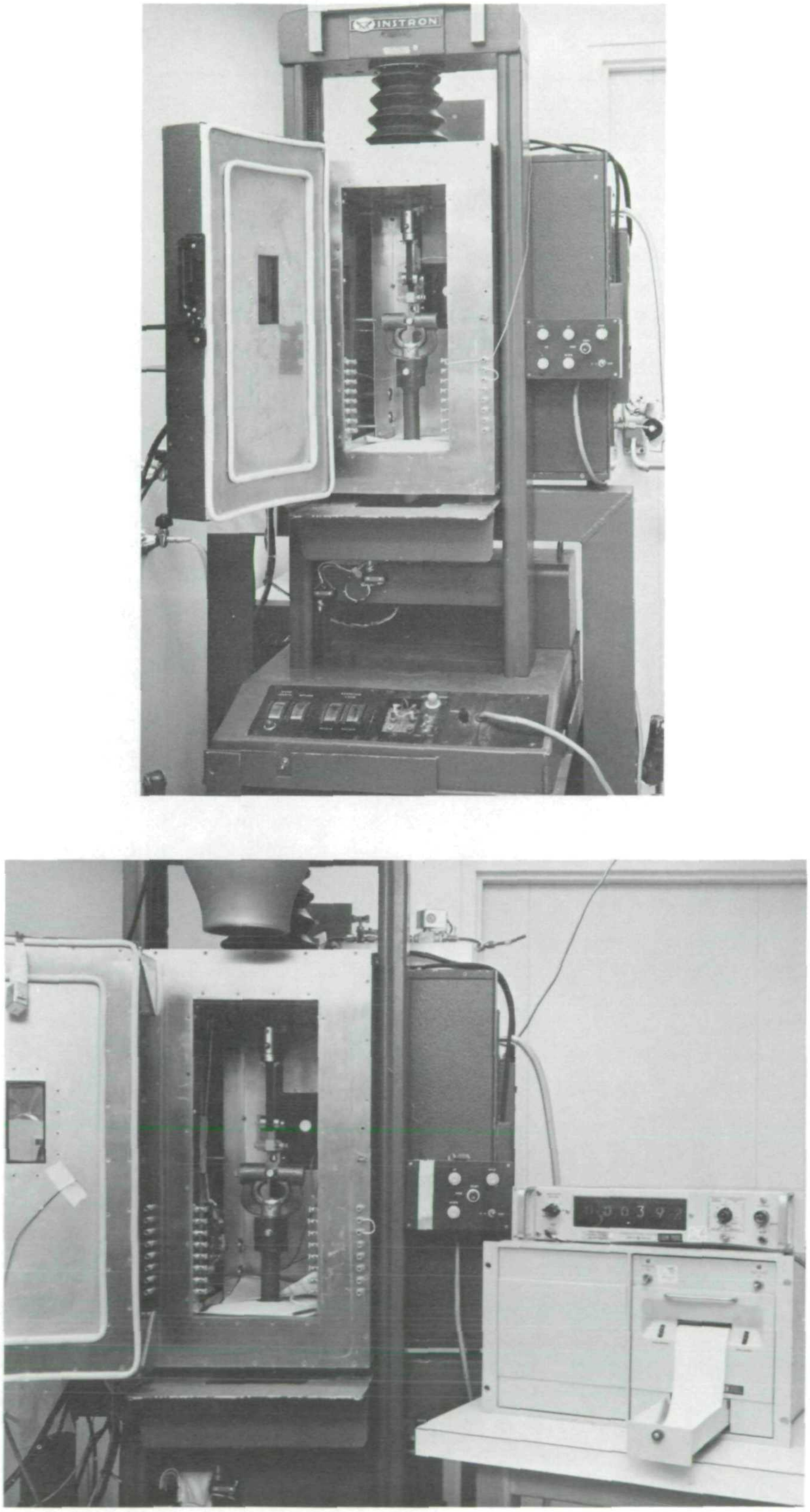



Fig. 2. Setup used to evaluate magnetic recording tapes and magnetic heads used in spacecraft

3. **Establishing the desired atmosphere.** Whenever experiments were performed in gaseous atmospheres other than air, the chamber was purged with the gas under consideration for a certain period and the test then started. Thereafter a positive gas pressure was sustained. The purge period was established by analyzing the effluent gas by mass spectroscopy. A typical analysis, when argon was used, ran as follows:

| | | |
|---|---|---|
| After 10-min purging: | Ar | = 99.97 mol% |
| | $H_2O$ | = 0.009 |
| | $N_2$ | = 0.009 |
| | $O_2$ | = 0.003 |
| After 20-min purging: | Ar | = 99.99 |
| | $H_2O$ | = none |
| | $N_2$ | = 0.006 |
| | $O_2$ | = none |
| After 40-min purging: | Ar | = 100.00 |

Based on the results of such analyses, the chamber was flushed for a minimum of 20 min before each test. Other inert gases used were helium and nitrogen.

4. **Humidification procedure and measurement.** For experiments performed in humid atmospheres the particular gas was fed into a valve-controlled system composed of a relay and two solenoid valves, one to admit dry gas, the other to admit moisture-saturated gas into the test chamber. The valves were controlled by a hair-type humidity sensor (Honeywell type H63A) located in the chamber near the inlet port. When the relative humidity (RH) of the chamber fell below the preset value, the dry-gas valve closed automatically and the gas was forced to bubble into a distilled water flask to be saturated with moisture before entering into the chamber. When the %RH of the chamber reached the prescribed value, the moist-gas valve closed and the dry-gas valve opened. Repetition of this process established a constant %RH in the test chamber. Humidity measurements were made by an Alnor type 7000 Dew-pointer, which was connected into the system to enable rapid readings at any time during the course of the experiments.

5. **Preparation of magnetic heads for testing and handling of tapes.** Before each run, the mounted magnetic heads were cleaned by passing "lapping" tape over them six to eight times and then wiping them with Freon TF (trichlorotrifluoroethane). Tapes were handled with clean white cotton gloves, care being taken not to touch the area that would contact the magnetic heads.

## C. The Graphical Output of the Loadcell

Figure 3 illustrates a typical graph obtained when the tape makes one complete cycle, i.e., two passes. The force used in computing $\mu\beta$ was *e*, which is the sum of *a*, the 110-g suspended weight, and *b*, the frictional force experienced by the tape when the 110-g weight is moving upward (Fig. 4).

The loadcell output is larger during the suspended weight's upward journey than during its downward journey; i.e., $b > d$ (Fig. 3). (During the upward journey the force transmitted to the loadcell is the sum of the force of the suspended weight and the frictional force between the tape and the heads. During the downward journey the frictional force between the tape and the heads opposes the force of the suspended weight, and as a result the loadcell registers a smaller force (Fig. 3), lower than 110 g.) A 110-g weight was chosen to simulate the actual tension on the tape used in a flight magnetic tape recorder.

The curves shown in Fig. 3 are not smooth, indicating that the frictional force encountered may not be constant, but may vary considerably, more so when the weight is moving upward (upper curve) than when it is moving downward (lower curve).

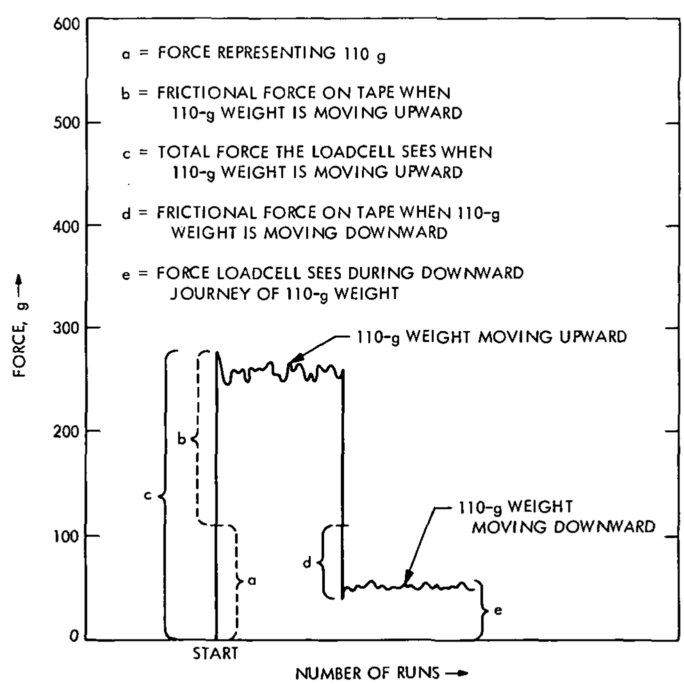



Fig. 3. Graphical output of load cell showing 1 cycle (2 runs)

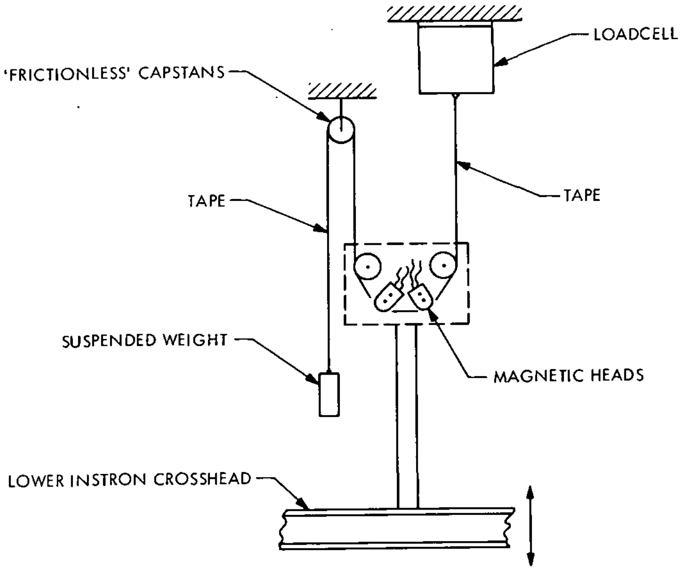



**Fig. 4. Diagram of the setup used for the determination of the coefficient of friction and drag of magnetic recording tapes**

## D. Test Conditions

The experimental conditions used for tape evaluation during Phase I are given in Table 1. Those used during Phase II are shown in Table 2.

## E. Description of Materials

The following is a brief description of materials used during this investigation.

*Tapes*

CEC W-4

Manufacturer: Consolidated Electrodynamics Corp., Pasadena, Calif.
Base material: polyethylene terephthalate (polyester).
Binder material: polyurethane (polyether-based) (for magnetic coating).

3M 990

Manufacturer: Minnesota Mining & Mfg. Co., Minneapolis, Minn.
Base material: polyethylene terephthalate (polyester).
Binder material: polyester-based polyurethane.

3M 20250

Manufacturer: Minnesota Mining & Mfg. Co., Minneapolis, Minn.
Base material: polyethylene terephthalate (polyester).
Binder material: polyester-based polyurethane.

3M 20294

Manufacturer: Minnesota Mining & Mfg. Co., Minneapolis, Minn.
Base material: polyethylene terephthalate (polyester).
Binder material: polyester-based polyurethane.

Battelle No. 1

Manufacturer: Battelle Memorial Institute, Columbus, Ohio
Base material: polyimide (Kapton).
Binder material: polyurethane, polyester-based (for magnetic coating).

Graham Epoch 4

Manufacturer: Graham Magnetics, Inc., Graham, Tex.
Base material: polyethylene terephthalate (polyester).
Binder material: polyester – epoxy (for magnetic coating).

BASF-MP

Manufacturer: Badische Anilin und Soda Fabric.
Base material: polyethylene terephthalate.
Binder material: not available.

*Magnetic Heads*

Brass heads

Manufacturer: Applied Magnetics Corp., Goleta, Calif.
Bracketing: 1/2 hard brass, 61% of contact area, Rockwell B62.
Core material: Permalloy (Hi Mu 80), 39% of contact area.
Adhesive and potting material: epoxy, Emerson & Cuming 2651 MM.

Monel heads

Manufacturer: Applied Magnetics Corp., Goleta, Calif.
Bracketing: KR Monel, 61% of contact area, Rockwell C24
Core material: Permalloy (Hi Mu 80), 39% of contact area.
Adhesive and potting material: epoxy, Emerson & Cuming 2651 MM.

Table 1. Evaluation of magnetic recording tapes: tests conducted during Phase I[a]

| Tape | At 25°C | | | At 55°C | | |
|---|---|---|---|---|---|---|
| | Crosshead speed, m/s | | | | | |
| | 0.00338 | 0.00846 | 0.00338 | 0.00338 | 0.00846 | 0.00338 |
| | % RH | | | | | |
| | Dry | Dry | 60 | Dry | Dry | 60 |
| 3M 20250, new | X | X | X | X | X | X |
| 3M 20250, used | X | X | X | X | X | X |
| 3M 990, new | X | X | X | X | X | X |
| 3M 990, used[b] | X | X | X | X | X | X |
| CEC W-4, new | X | X | X | X | X | X |
| CEC W-4, used | X | X | X | X | X | X |
| BASF (Badische Anilin und Soda Fabric) | | | X | | | |

[a] All experiments performed in argon using five brass-bracketed magnetic heads.
[b] Also tested at 0 and 30°C.

Table 2. Evaluation of magnetic recording tapes: tests conducted during Phase II[a]

| Magnetic head | At 25°C | | | | | | At 55°C, in argon, 96-h wait[c] | | |
|---|---|---|---|---|---|---|---|---|---|
| | In argon | | | | | | | | |
| | Untreated tape | Outgassed tape | At 25% RH | In air[b] (ambient) | In helium (dry) | In nitrogen (dry) | Untreated tape | Outgassed tape | At 25% RH |
| Brass | X | X | X | X | X | X | X | X | X |
| Monel | X | X | X | X | X | X | X | X | X |
| Havar | X | X | X | X | X | X | X | X | X |
| Aluminum | X | X | X | X | X | X | X | | X |

[a] Performed with four tapes: 3M 20250, 3M 20294, Battelle No. 1 and Graham Epoch 4, at 0.0427 m/s (0.166 in./s) crosshead speed.
[b] The relative humidity of ambient air varied from 10–50%.
[c] Dry nitrogen was used during the 96-h wait period.

Aluminum heads

Manufacturer: Applied Magnetics Corp., Goleta, Calif.

Bracketing: 6061T6 aluminum, 61% of contact area, Rockwell B70.

Core material: Permalloy (Hi Mu 80), 39% of contact area.

Adhesive and potting material: epoxy, Emerson & Cuming 2651 MM.

Havar heads

Manufacturer: United Control Corp.

Bracketing: Aluminum 6061T6, Havar shield, 50% of contact area, Rockwell 46-50 C

Core material: Permalloy (Hi Mu 80), 13% of contact area; Alfesil tipped, 37% of contact area.

Adhesive and potting material: Shell Epon 810 with aromatic amine curing agent, catalyst No. 5.

## IV. Results and Discussion

### A. Phase I Experiments

The principal objective of Phase I experiments was to select, among the tapes available at the time, one that performed best under certain pertinent conditions. Both used (i.e., tapes that had passed more than 800 times over magnetic heads in an actual *Mariner* Mars 1971 tape recorder) and unused tapes were tested. The frictional behavior of the tapes was studied at different temperatures and tape speeds and also in the presence of moisture. In a number of cases, tapes were left in static contact with the heads for periods ranging from 1/2 to 16 h. The object was to determine whether they would "stick" to the heads and, if so, to measure the force of adhesion or "sticking." Results of these efforts are discussed below.

**1. Effect of temperature.** Testing was performed at 25 and 55°C in dry argon at 0.00338 m/s (0.133 in./s) crosshead speed. Both used and unused CEC W-4 tape showed an increase in $\mu\beta$ value with temperature increase, whereas 3M 20250 and 3M 990 tapes showed a decrease. An exception was used 3M 990 tape, which showed an increase in $\mu\beta$ values towards the end of the test. Results are given in Fig. 5.

**2. Effect of tape speed.** Measurements were made at tape speeds of 0.00338 m/s (0.133 in./s) and 0.00846 m/s (0.333 in./s) in dry argon at 25 and 55°C. Increase in tape speed caused detectable increases in the $\mu\beta$ values of all the tapes under all conditions, except those of unused 3M 990, tested at 25°C. Results are given for unused tapes tested at 25°C in Fig. 6.

**3. Effect of humidity.** Tests were conducted at 60 ±2% RH at both 25 and 55°C. Humidity had no effect on the frictional behavior of new 3M 20250 tapes at both temperatures. Similarly, used 3M 990 experienced no change. At 25°C, however, used 3M 20250, unused 3M 990, and both used and unused CEC W-4 experienced considerable increases in $\mu\beta$ values. In certain cases the friction generated was so high that tape failure occurred at the grips. For example, used and unused CEC W-4 and 3M 990 tapes broke when tested at 55°C. Figure 7 gives results for unused tapes; Fig. 8 gives results for used tapes.

**4. Used vs unused tape.** Used specimens of both 3M 990 and 3M 20250 tapes under all test conditions (temperature, humidity and tape speed) showed higher $\mu\beta$ values than new tapes. The opposite was the case with CEC W-4. New specimens of this tape showed higher $\mu\beta$ values than used ones at all experimental conditions. Results for tests conducted at 25°C in dry argon at 0.00846 m/s are shown in Fig. 9.

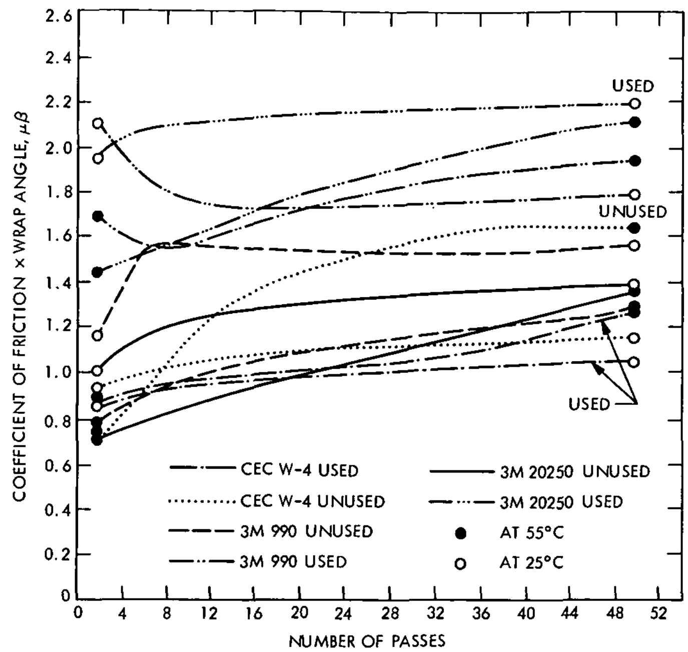



**Fig. 5. Effect of temperature on the frictional behavior of used and unused tapes, crosshead speed 0.00338 m/s**

**5. Effect of static contact or "wait" on the adhesion of tapes to magnetic heads.** In a spacecraft tape recorder, the tape is not in constant motion all the time but is under tension for long periods in static contact with the magnetic heads. It is important, then, to know if a tape will stick to a head when left motionless for prolonged periods. During Phase I, some tape specimens were left in contact with the brass-bracketed heads after the completion of the dynamic tests. Static contact time, or "wait" periods, ranged from 1/2 to 16 h. The difference between the force experienced by the loadcell immediately after the "wait" period, when the tape was set in motion, and the force indicated at the 50th pass was taken as a measure of the strength of the adhesive "bond." The gaseous atmosphere surrounding the specimens was not controlled, and therefore results obtained were not indicative of what would occur in the strictly controlled atmosphere of a spacecraft tape recorder. These tests indicated, however, that the adhesive "bond" strength is dependent on contact time, temperature, humidity and tape type.

Static contact tests were performed under controlled conditions during Phase II; results will be discussed in a following section.

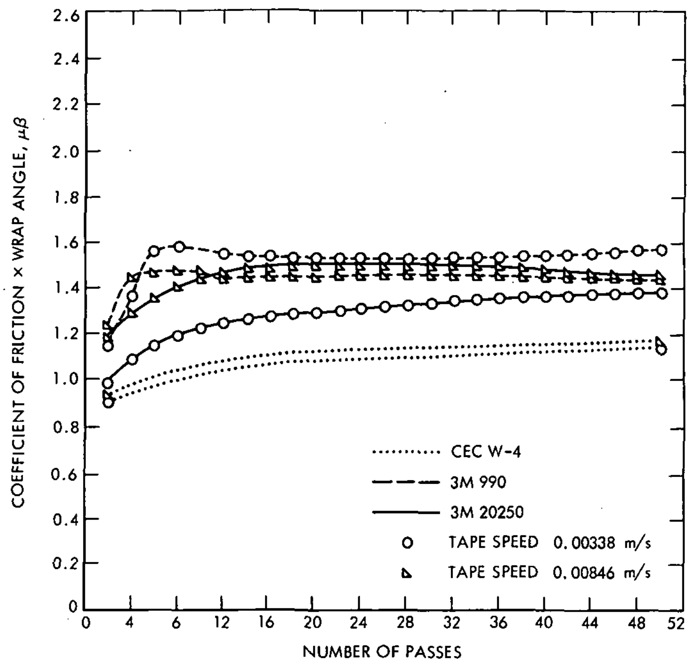



Fig. 6. Effect of tape speed on frictional behavior of unused tapes at 25°C in dry argon

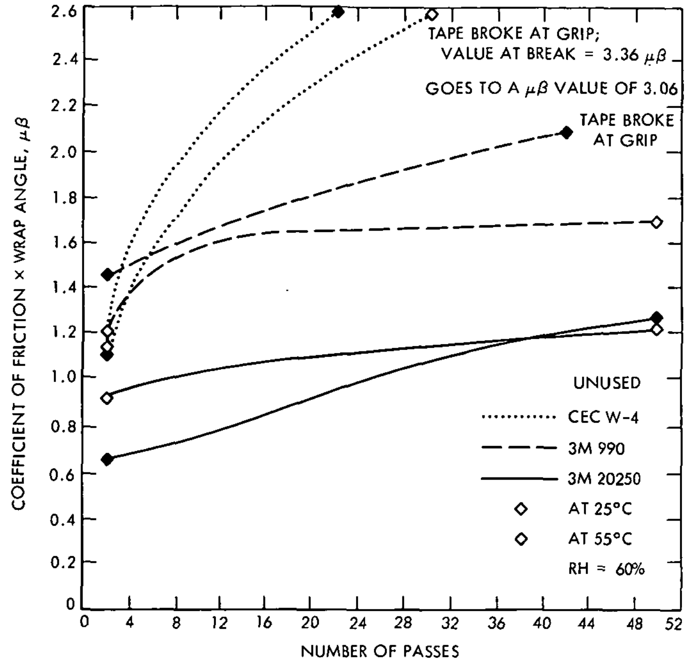



Fig. 7. Effect of humidity on the frictional performance of unused tapes

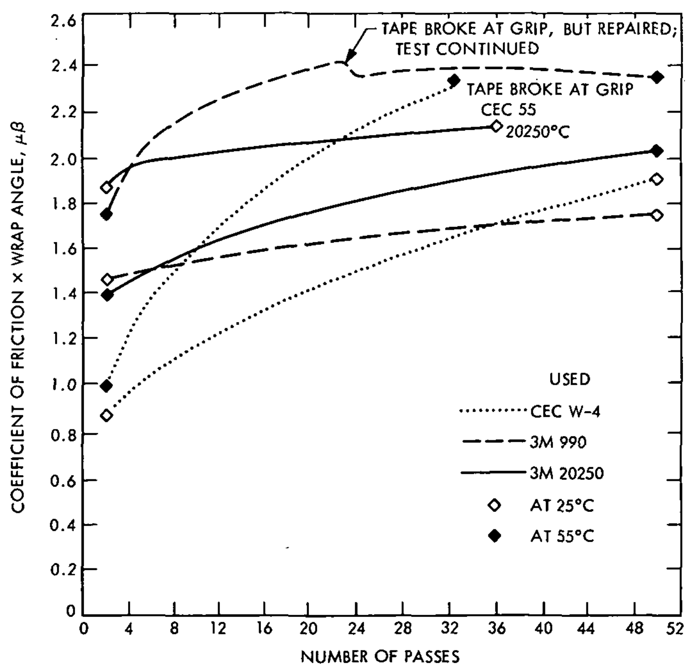



Fig. 8. Effect of humidity on the frictional performance of used tapes

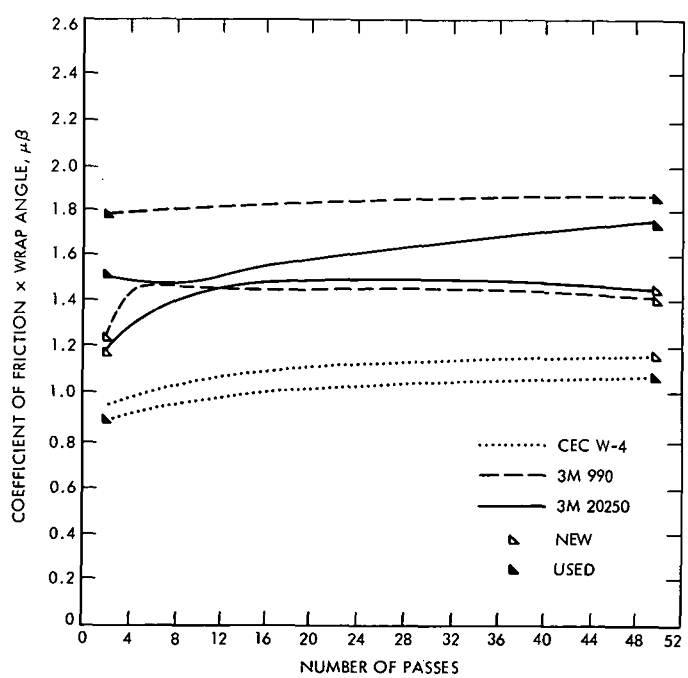



Fig. 9. Comparison of used with unused tape with respect to frictional behavior at 25°C in dry argon, crosshead speed 0.00846 m/s

6. **Conclusions from Phase I tests.** It was shown during Phase I that the adaptation of ASTM test method D 1894-63 to the study of the frictional behavior of magnetic recording tapes is useful in providing quantitative information about the dynamic frictional forces involved between head and tape in motion and the adhesive force involved between heads and tape when they are in static contact.

Determination of the quantity $\mu\beta$ for various tapes under different conditions of temperature, gaseous atmospheres and relative humidity assisted in the screening of magnetic recording tapes for use in spacecraft. Thus, such determinations entered into the selection of 3M 20250 tape as the best candidate for further study. This tape showed the least sensitivity to changes in temperature and humidity (Figs. 4, 7). Static contact tests showed that CEC W-4 tape adheres much more strongly to brass bracketed heads than 3M 990 or 3M 20250. However, in humid atmospheres the 3M 990 tape failed by breaking, while 3M 20250 showed no signs of damage (Fig. 7).

## B. Phase II Experiments

1. **Results of measurement of frictional behavior (mechanical method).** Several objectives were pursued in Phase II. First, an adequate "wait" period was established for the JPL Type Approval (TA) testing. Then the quantitative estimation was made of both the stick-slip and drag forces acting on four makes of tapes, namely: 3M 20250, 3M 20294, Graham Magnetics Epoch 4, and Battelle No. 1. Tests were performed under different conditions, using four different kinds of magnetic heads, to observe the effects of temperature, gaseous atmospheres such as argon, nitrogen and helium, moist argon and ambient air. The effect of outgassing the tape on drag and stick-slip properties was studied at 25 and 55°C. Furthermore, the effect of a dry lubricant ("Vac Kote," a proprietary process of Ball Brothers Research Corp., Boulder, Colo.) on 3M 20250 was also investigated. Table 2 shows the various test conditions used during Phase II with each of the four tapes. Of the tapes tested, 3M 20250 was selected on the basis of test results obtained during Phase I, as already mentioned. The other three were chosen from among half a dozen others as a result of such tests as the determination of vacuum condensed material (VCM) and total volatiles (TV) evolved from specimens, corrosion effects on copper and zinc, and qualitative adhesion tests performed by wrapping tape specimens on brass, aluminum and stainless steel tubing (Refs 3–5).

*a. Establishing an adequate "wait" period.* Originally 12 days at 55°C was specified as the static tape-to-head contact period for TA testing. This length of time severely limited the number of tests planned. Consequently, establishing a shorter but still an adequate "wait" period was considered. Samples of unused 3M 20250 tape were first passed 100 times over the two magnetic heads in an atmosphere of argon at 55°C and then kept in nitrogen at the same temperature for "wait" periods of 4, 24, 72, 96 and 144 h. Nitrogen was used during the "wait" periods because the duration of the tests prohibited the use of the expensive argon. The results of these experiments are shown in Fig. 10. The quantity $\Delta(\mu\beta)$ is the difference between the first $\mu\beta$ value obtained after the "wait" period and the last $\mu\beta$ value obtained before the "wait" period. As shown, these values are all positive, except for the 4-h period, which is zero. Maximum $\Delta(\mu\beta)$ was obtained after 96-h "wait"; at longer periods the $\Delta(\mu\beta)$ leveled off. Thus the specified 12-day period was considered excessive and the 96-h period was adopted as adequate for the static contact tests. Similar tests carried out at 25°C showed negative $\Delta(\mu\beta)$, indicating that sticking of 3M 20250 to brass heads was not a problem at this temperature.

*b. Effect of crosshead (or tape) speed on the coefficient of friction.* During Phase I, a slight increase in $\mu$ or $\mu\beta$ was observed when the tape speed was increased from $3.38 \times 10^{-3}$ m/s to $8.46 \times 10^{-3}$ m/s. The effect of tape speed on $\mu\beta$ was tested with 3M 20250 tape in dry argon at 25°C using wider speed ranges, i.e., $8.46 \times 10^{-5}$ m/s, $3.38 \times 10^{-3}$ m/s and $3.38 \times 10^{-2}$ m/s (0.0033, 0.133 and 1.33 in./s, respectively). When the $\mu\beta$ obtained were plotted against the logarithm of crosshead speed, the straight line shown in

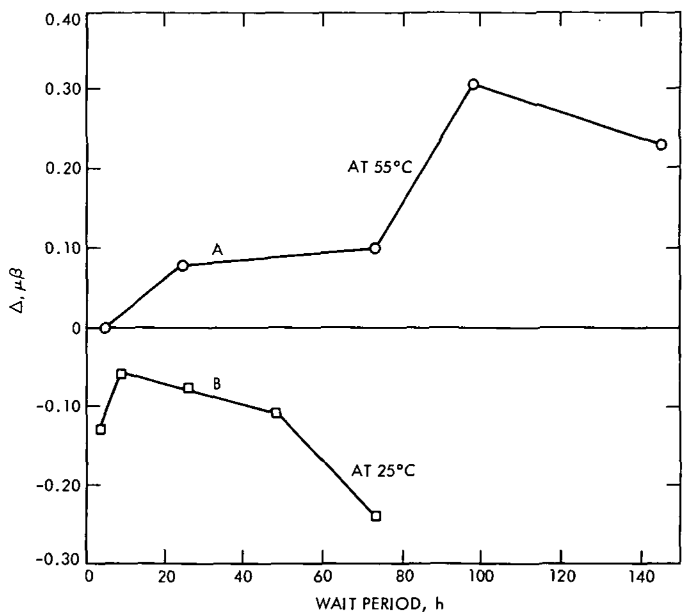



**Fig. 10. Relationship of "wait" period to $\Delta(\mu\beta)$**

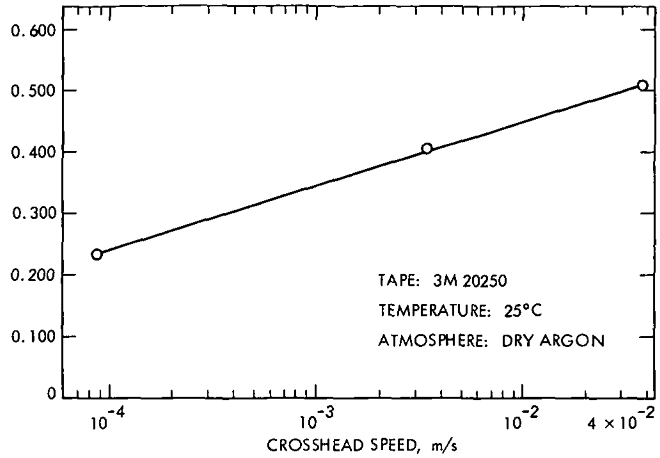



**Fig. 11. Relationship of crosshead speed to coefficient of friction**

Fig. 11 was obtained. Each of the $\mu\beta$ values plotted in Fig. 11 is the average of at least five values obtained from five consecutive passes. These values were also corrected for the increase in $\mu\beta$ that would have been experienced normally. Thus it is shown that $\mu$ increases with speed at the ranges tested, and the relationship is exponential.

Except for the test described above, all other experiments in Phase II were performed at a crosshead speed of $3.38 \times 10^{-3}$ m/s (0.133 in./s), which closely matched the low tape speed employed in the tape recorder application.

*c. Effect of temperature on drag properties.* The dependence of drag values ($\mu\beta$) on temperature varied with the kind of tape and the kind of magnetic head used. The following were observed when the untreated tapes were tested in dry argon (Figs. 12–15):

3M 20250: $\mu\beta$ values were lower at 55 than at 25°C with all heads (brass, Monel, aluminum, Havar).

3M 20294: $\mu\beta$ values were lower at 55 than at 25°C with all heads except brass.

Battelle No. 1: $\mu\beta$ values were lower at 55 than at 25°C with all heads except brass.

Graham Epoch 4: $\mu\beta$ values were lower at 55 than at 25°C with aluminum heads only, in which case the difference was not great. The other three heads showed higher values at 55°C.

In general, then, increase in temperature lowered the $\mu\beta$ values, except those of Graham Epoch 4 tape, with which the opposite was the case.

Tests were also performed at 25 and 55°C in moist argon, and in dry argon using outgassed tape (Figs. 16–27). The temperature dependence observed in dry argon was not the same as experienced in humid argon (RH = 25%). For example, the situation observed in dry argon with 3M 20250 tape was reversed in humid argon, $\mu\beta$ values being higher at 55°C with all types of heads, except aluminum heads, which showed no change (Fig. 18). The temperature-dependence picture was also reversed with Battelle No. 1 and 3M 20294 tapes when these were tested with brass heads in humid argon (Fig. 25).

The binder used in the two 3M tapes and the Battelle tape are similar, i.e., a polyester-based polyurethane. That of the Graham Epoch 4 tape is reported to be polyester-epoxy (Refs. 3 and 4). Indications are that the binder of Epoch 4 tape is less sensitive to moisture than the polyurethane binders used in Battelle No. 1 and the two 3M tapes, but that its frictional resistance increases with temperature unlike the polyurethane binders, whose frictional resistance generally decreases with temperature.

*d. Effect of outgassing on drag properties.* Outgassing was carried out at 110°C for approximately 20 h at a pressure of $1.333 \times 10^{-4}$ N/m$^2$. After outgassing, the specimens were stored under nitrogen in sealed glass tubing.

The effect of outgassing on the drag properties was dependent on the nature of the tape. The following conclusions can be made by examining Figs. 16–27: Outgassed 3M 20250 tape showed slight improvement in its frictional performance over non-outgassed tape when tested with brass and Havar heads at 25°C (Fig. 16). No improvement was noticeable when testing was done with Monel or aluminum heads at 25°C, or with any of the heads at 55°C (Figs. 17 and 18).

Unlike 3M 20250, outgassed 3M 20294 showed significant lowering of drag ($\mu\beta$) when tested at 25°C with brass and Monel bracketed heads (Fig. 19) but no significant changes when tested with Havar and aluminum bracketed heads (Fig. 20). At 55°C, diminution of frictional resistance was noticeable with all the heads (Fig. 21).

The outgassed Battelle No. 1 showed some improvement over non-outgassed tape with respect to drag at 55°C when tested with brass and Monel heads (Fig. 24), but showed less improvement at 55 and 25°C with Havar and aluminum heads (Figs. 22, 23).

Outgassing had the most significant effect on Graham Epoch 4 tape when it was tested with brass and Monel heads at both 25 and 55°C, yielding much lower $\mu\beta$ values (Figs. 25–27). Lower $\mu\beta$ values were also obtained with aluminum heads at 25 and 55°C, and with Havar heads at 55°C (Figs. 25–27).

Outgassing had another effect on tape behavior. It reduced or eliminated sticking to magnetic heads during the static contact or "wait" experiments. These were performed at 55°C, with 96-h contact periods. The outgassed 3M 20250 tape was tested with all the magnetic heads. The outgassed 3M 20294 and the Graham Epoch 4 tapes were tested with brass heads only and the outgassed Battelle tape with Havar heads. In all cases the $\Delta(\mu\beta)$ values were negative; that is, there was no further increase in tape drag as a result of the long-term static contact with the magnetic heads. These results are not shown in the figures.

*e. Effect of humidity on drag properties.* The effect of humidity at 25% RH level was tested in an atmosphere of argon. Experiments were performed at 25 and 55°C using all four tapes and all four heads. Examination of Figs. 16–27 shows the following results as compared with those obtained in dry argon (RH < 1%):

(1) 3M 20250 tape: Significant increase in $\mu\beta$ values (drag) was observed with all heads at 55°C. At 25°C, Monel and brass heads showed increases, but Havar and aluminum heads did not show any change (Figs. 16–18).

(2) 3M 20294 tape: Increases in drag values were registered with all heads at 55°C, similar to 3M 20250 tape. At 25°C, Monel, brass and Havar heads showed significant increases, and aluminum heads showed only slight increase in $\mu\beta$ values (Figs. 19–21).

(3) Battelle No. 1 tape: This tape was affected somewhat differently by 25% RH. At 55°C there was either a decrease or no change in its drag behavior with any of the magnetic heads, with the exception of the Monel-bracketed ones (Fig. 24). At 25°C, increase in drag was experienced with brass and Monel heads; no increase or insignificant increase was experienced with Havar and aluminum heads (Figs. 22 and 23).

(4) Graham Epoch 4 tape: This tape showed significant increase in $\mu\beta$ values at 55°C with brass and Monel heads, but only slight increases with Havar and aluminum heads (Fig. 27). At 25°C, increases were registered with all the heads (Figs. 25 and 26).

Generally, then, moisture increased the drag or the frictional resistance of the tapes. The increase was more pronounced when Monel and brass heads were used at both 55 and 25°C. There was an observable difference in the behavior of Battelle No. 1 tape. It showed less drag than the other three at 25% RH.

*f. Effect of the nature of the gaseous atmosphere.* In addition to testing in dry and moist argon, all four tapes and heads were also tested in ambient air and in dry He and dry $N_2$ at 25°C. During experiments performed in air, relative humidity varied between 25 and 55%. Results given below are compared again with those performed in dry argon.

*Effect of ambient air.* The 3M 20250 tape showed increases in $\mu\beta$ values when tested in air with brass and Monel heads, but no significant changes in these values were observed when the tapes contacted Havar and aluminum heads (Figs. 16 and 17). The 3M 20294 tape showed increases with all the heads, the increase being only slight with aluminum heads (Figs. 19 and 20). Ambient air increased the drag properties of Battelle No. 1 tape when tested with any of the four magnetic heads (Figs. 25 and 26). Similarly, the $\mu\beta$ values of Graham Epoch 4 tape increased in air when tested with any of the heads (Figs. 25 and 26).

Thus, in general, ambient air, compared to dry argon, had a deleterious effect on the frictional behavior of the tapes when tested with brass and Monel heads. With Havar and aluminum heads, however, the effects were either absent or much less pronounced.

*Effect of the inert gases helium and nitrogen.* It was of interest to know if nitrogen and helium would have any advantage over argon as gaseous media. Helium is 10 times less dense than argon (helium, 0.1785 g/l; argon 1.784 g/l) and is much more fluid. Nitrogen is also less dense (1.250 g/l) and more fluid than argon. It is also much less expensive. Results of experiments carried out in these gases at 25°C were as follows:

(1) 3M 20250 tape with any of the heads tested in helium or nitrogen did not show any advantage over argon. Moreover, $\mu\beta$ values were higher in helium with Monel heads (Figs. 16 and 17).

(2) With 3M 20294 tape the case was somewhat different. The $\mu\beta$ values (drag) were lower in both nitrogen and helium using brass, Monel and aluminum heads, and no significant change was observed with Havar heads. In all cases, drag was lower in the helium atmosphere than in the nitrogen atmosphere (Figs. 19 and 20).

(3) With Battelle No. 1 tape, slight lowering of drag was observed using the lighter inert gases, and again in all cases drag was lower in helium than in nitrogen (Figs. 22 and 23).

(4) With Graham Epoch 4 tape there was a definite advantage in using helium with Monel and brass heads and, to a lesser extent, in using nitrogen. With the aluminum and Havar heads no significant differences in drag were observed between the three gases (Figs. 25 and 26).

g. *Effect of lubrication (Vac Kote).* The 3M 20250 tape, coated with Vac Kote, was tested at 55°C in dry argon. Results showed that application of this lubricant did not improve the frictional behavior of the tape but reduced its sticking to brass, Monel and Havar heads during the 96-h "wait" period in dry nitrogen. No samples were available to carry out the test with aluminum heads.

h. *Effect of static contact on tape-to-head sticking.* Samples of all of the four tapes were left in static contact with all of the four heads for 96 h at 55°C in both dry and humid nitrogen. Results based on the $\Delta(\mu\beta)$ values obtained (see Section IV-B-1-a) were as follows: The 3M 20250 and 3M 20294 tapes showed adhesion both in dry and moist nitrogen (RH = 25%) with brass and Monel heads. The $\Delta(\mu\beta)$ values were higher in the moist atmosphere. With aluminum and Havar heads, $\Delta(\mu\beta)$ was either zero or negative. The Battelle No. 1 tape showed negative $\Delta(\mu\beta)$ values with all the four heads under dry and moist conditions. The Graham Epoch 4 tape showed some adhesion, i.e., positive $\Delta(\mu\beta)$ with the four heads at 25% RH but zero or negative values in the dry gas.

It should be pointed out that in most cases when $\Delta(\mu\beta)$ was negative, the $\mu\beta$ obtained after the 96-h "wait" period was still larger than the initial $\mu\beta$ values (first 10–20 passes) obtained during the pre "wait" period.

**2. Stick-slip characteristics obtained from measurement of period of a prerecorded signal (electronic method).** Simultaneously with the measurement of $\mu\beta$ or drag, the instantaneous velocity or period (Section III-A-2) of the tape was measured electronically, and the percent standard deviation $\sigma$ from the prerecorded signal period of 0.02000 s was computed. To avoid gathering an enormous amount of data, output from only 11 out of 50 downward passes of the suspended weight of 110 g was considered. Moreover, during each run, data were printed 1/3 of the time only, representing 25 readings. Each $\%\sigma$ value given in Table 3, then, is the average of 11 × 25 or 275 readings. Table 3 includes other data as well, such as $\mu\beta$ values and ranks assigned to each head–tape–temperature combination based on $\%\sigma$ and $\mu\beta$ values obtained in dry argon at 25 and 55°C. A detailed discussion of the data of Table 3 is given in a subsequent section.

Drag values or $\%\sigma$ were also obtained under other environmental conditions, such as humid argon, ambient air, dry helium and nitrogen, and in dry argon using outgassed tape. Results will be discussed briefly in a subsequent section.

For the drag and stick-slip performance evaluation of tapes (and heads) the ratings of Table 4 were used.

The $\%\sigma$ data of Table 3 permit the following conclusions:

(1) Stick-slip is low or moderate for 3M 20250 tape under all conditions.

(2) Stick-slip is high for 3M 20294 under all circumstances.

(3) Stick-slip is low or moderate for Battelle No. 1 tape except with aluminum heads at 25°C, when it is high.

(4) Stick-slip is high or very high for Graham Epoch 4 tape with brass and Monel heads at 25 and 55°C but low at 25°C and moderate at 55°C with Havar and aluminum heads.

(5) The temperature dependence of $\%\sigma$ varied with both the kind of tape and the kind of magnetic head. With Graham Epoch 4 tape, alone, increase in temperature increased $\%\sigma$ with all heads. With the other tapes, results did not allow a generalization (Table 3).

The stick-slip performance of the four tapes, including outgassed tapes, was also measured under other environmental conditions but not as extensively as their frictional performance. Other environments included dry helium and nitrogen, moist argon and ambient air, at 25 and 55°C. Their performance under these conditions was very similar to that in dry argon. A noteworthy change was the stick-slip of 3M 20294, which increased much more when the environment contained moisture (argon at 25% RH and ambient air). This was particularly true with Monel and brass heads.

**3. Correlation of results from the electronic and mechanical methods.** It is of interest to know the relationship between the frictional (drag) behavior of a tape and its stick-slip behavior. In very recent studies it was definitely

Table 3. Frictional and stick–slip behavior of tapes in dry argon

| Magnetic head | Property | 3M 20250 | | 3M 20294 | | Graham Epoch 4 | | Battelle No. 1 | | Average | Rank of head | Rank of head based on overall performance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 25°C | 55°C | 25°C | 55°C | 25°C | 55°C | 25°C | 55°C | | | |
| Brass | $\mu\beta$ | 0.83 (25) | 0.35 ( 5) | 0.91 (27) | 1.11 (28) | 0.72 (21) | 1.60 (32) | 0.59 (17) | 0.77 (22) | 0.86 | (3) | (3) |
| | %$\sigma$ | 4.12 (10) | 3.65 ( 5) | 24.12 (25) | 23.71 (24) | 45.07 (30) | 74.65 (31) | 5.40 ( 9) | 4.01 ( 9) | 23.09 | (3) | |
| Monel | $\mu\beta$ | 0.70 (19) | 0.34 ( 6) | 1.34 (30) | 1.30 (29) | 0.82 (23) | 1.40 (31) | 0.84 (26) | 0.72 (20) | 0.93 | (4) | (4) |
| | %$\sigma$ | 2.59 ( 1) | 3.94 ( 8) | 34.20 (29) | 25.04 (26) | 21.34 (23) | 131.96 (32) | 3.65 ( 6) | 3.41 ( 3) | 28.26 | (4) | |
| Aluminum | $\mu\beta$ | 0.53 (13) | 0.36 ( 9) | 0.34 ( 7) | 0.32 ( 3) | 0.35 ( 8) | 0.33 ( 4) | 0.62 (18) | 0.56 (16) | 0.43 | (1) | (2) |
| | %$\sigma$ | 5.22 (15) | 8.57 (17) | 13.19 (22) | 27.14 (28) | 3.63 ( 4) | 9.22 (19) | 12.69 (21) | 4.22 (11) | 10.48 | (2) | |
| Havar | $\mu\beta$ | 0.55 (14) | 0.30 ( 1) | 0.38 (10) | 0.56 (15) | 0.52 (12) | 0.83 (24) | 0.49 (11) | 0.31 ( 2) | 0.49 | (2) | (1) |
| | %$\sigma$ | 5.04 (14) | 4.68 (13) | 11.88 (20) | 25.07 (27) | 3.80 ( 7) | 8.77 (18) | 3.15 ( 2) | 4.59 (12) | 8.37 | (1) | |
| | $\mu\beta$ (avg) | 0.65 ( 5) | 0.33 ( 1) | 0.74 ( 6) | 0.82 ( 7) | 0.60 ( 3) | 1.04 ( 8) | 0.63 ( 4) | 0.59 ( 2) | | | |
| | %$\sigma$ (avg) | 4.24 ( 2) | 5.21 ( 3) | 22.10 ( 6) | 25.24 ( 7) | 18.46 ( 5) | 56.15 ( 8) | 6.22 ( 4) | 4.06 ( 1) | | | |
| | | $\mu\beta$ of tape (average of 2 temperatures) | | | | | | | | | | |
| | | 0.98 | | 1.56 | | 1.64 | | 1.22 | | | | |
| | | %$\sigma$ of tape (average of 2 temperatures) | | | | | | | | | | |
| | | 9.45 | | 47.34 | | 74.61 | | 10.28 | | | | |
| | | Rank of tape based on overall performance | | | | | | | | | | |
| | | (1) | | (3) | | (4) | | (2) | | | | |

established that, as the frictional force on the tape increased, the instantaneous velocity (as manifested by the decrease in the frequency of the prerecorded signal) decreased, and as the force decreased the velocity increased. The mechanical and electronic measurements were made simultaneously during the downward motion of the 110-g weight.

The $\mu\beta$ values used in this report were those calculated from the loadcell readings obtained during the upward motion of the 110-g weight, whereas the %$\sigma$ values used were computed from readings obtained during the downward motion of the 110-g weight. Although the forces registered during the upward and downward journey are not the same, they are, however, proportional. The mechanical data ($\mu\beta$ values), then, were obtained when the tape was travelling in the opposite direction to that when the electronic data (%$\sigma$ values) were obtained. It is possible that the tape surface in contact with the magnetic heads during the downward journey was slightly different from the one during the upward journey because of the possible piling of asperities. This fact should be borne in mind when $\mu\beta$ values are compared with %$\sigma$ values. Such a comparison can be made from the data shown in Table 3. Each $\mu\beta$ value given there is the average of the readings obtained from the last 10 passes from a total of 100 made for each specimen. The figures in parentheses are ranks assigned to each tape-head-temperature system. For example, Havar - 3M 20250 - 55°C combination ranks first with respect to frictional performance (lowest $\mu\beta$ value), and the Monel - 3M 20250 - 25°C combination ranks first with respect to stick-slip (lowest %$\sigma$ value). It can be seen from this table that, in most cases, when the drag was high, the stick-slip

Table 4. Ratings for magnetic heads

| Rating | %$\sigma$ | $\mu\beta$ |
|---|---|---|
| Low | ±2.6 – ±4.6 | 0.30 – 0.5 |
| Moderate | ±4.6 – ±10.0 | 0.50 – 0.72 |
| High | ±10.0 – ±35.0 | 0.72 – 1.00 |
| Very high | ± more than ±35 | more than 1.00 |

was also high, and vice versa. The reason for the apparent exceptions to this rule should probably be sought in the phenomenon suggested above, namely the change or the difference encountered on the tape surface when it is travelling in opposite directions.

## C. Comparative Evaluation of Magnetic Tapes

It is evident from the preceding discussions that the drag behavior as well as the stick-slip behavior of a tape is dependent on a number of factors, among which are temperature, humidity, nature of the gaseous atmosphere in which the head-tape system functions, the kind of tape and the kind of magnetic head. Experimental results point out that no one tape behaves better than any other tape with respect to friction and seizure-release phenomena under all circumstances. For example, the 3M 20250 tape shows the lowest $\mu\beta$ values with Havar heads in dry argon at 55°C, but it shows higher values than Graham Epoch 4 tape when both are tested with aluminum heads in dry argon at 55°C (Table 3). Likewise, Battelle No. 1 tape shows considerably lower stick-slip (low $\%\sigma$) than Graham Epoch 4 tape when both are tested with Monel heads in dry argon at 55°C, but it shows more stick-slip than the Graham tape when both are tested with aluminum heads in dry argon at 25°C (Table 3).

Examinations of Figs. 28 and 29 and Table 3 show that the five cases below give the lowest $\mu\beta$ values in the following order:

(1) 3M 20250 at 55°C in dry argon with Havar heads.

(2) Battelle No. 1 at 55°C in dry argon with Havar heads.

(3) 3M 20294 at 55°C in dry argon with aluminum heads.

(4) Graham Epoch 4 at 55°C in dry argon with aluminum heads.

(5) 3M 20250 (outgassed) at 55°C in dry argon with aluminum heads.

It can also be seen that the six cases which give the highest drag values are the following (highest $\mu\beta$ value first):

(1) 3M 20294 at 25°C in air with Monel heads.

(2) 3M 20294 at 25°C in moist argon with brass heads.

(3) Graham Epoch 4 at 55°C in dry argon with brass heads.

(4) Graham Epoch 4 at 55°C in dry argon with Monel heads.

(5) 3M 20294 at 55°C in moist argon with brass heads.

(6) 3M 20294 at 25°C in moist argon with Monel heads.

A few noteworthy observations can be made from the lists above: (1) Only Graham Epoch 4 and 3M 20294 tapes are involved in the worst drag performance; (2) 3M 20294 tape is exceptionally susceptible to moisture; (3) lowest $\mu\beta$ values are obtained in dry argon at 55°C; and (4) lowest $\mu\beta$ values are obtained with either aluminum-bracketed heads or Havar-shielded heads.

The determination of $\%\sigma$ values under conditions other than dry argon was not as extensive as the determination of $\mu\beta$ values. Lists given above were based upon frictional performance observed under all the conditions listed in Table 3. With the exception of those in dry argon at 25 and 55°C, measurements of cycle period under the other conditions were not complete. Thus lists similar to the above, based on $\%\sigma$, were not prepared.

Examining the data obtained in dry argon (Table 3), however, it can be concluded that based on both the $\%\sigma$ and $\mu\beta$ values obtained under the test conditions used, 3M 20250 ranks first, Battelle No. 1 second and 3M 20294 and Graham Epoch 4 rank third and fourth, respectively.

## D. Comparative Evaluation of Magnetic Heads

A comparison can also be made of magnetic heads based on the $\mu\beta$ data obtained in dry argon and given in Figs. 30 and 31 and Table 3. The performance of magnetic heads varied somewhat with the kind of tape and temperature.

With 3M 20250 tape the heads showed drag in the following order:

At 55°C, Havar < aluminum < brass < Monel.

At 25°C, aluminum < Havar < Monel < brass.

With 3M 20294 and Graham Epoch 4 tapes at both 25 and 55°C the order was:

Aluminum < Havar < brass < Monel.

The Battelle No. 1 tape order was:

At 55°C, Havar < aluminum < Monel < brass.

At 25°C, Havar < brass < aluminum < Monel.

The overall order considering all four tapes was:

Aluminum < Havar << brass < Monel.

This order, obtained by the examination of Figs. 30 and 31, agrees perfectly with the rank assigned to magnetic heads in the last column of Table 3. Rankings were based upon the average $\mu\beta$ of the four tapes with a single magnetic head. Rank, based on $\mu\beta$ values, was as follows:

(1) Aluminum heads.

(2) Havar heads.

(3) Brass heads.

(4) Monel heads.

The positions of Havar and aluminum were interchanged when rank was assigned on the basis of $\%\sigma$ values. Brass and Monel heads kept the same rank as above (Table 3, last column).

The rank assigned on overall performance was as follows: Havar (1), aluminum (2), brass (3), and Monel (4), with very little difference shown in the performance of Havar and aluminum heads. There was no correlation between the hardness of the bracketing material of the heads coming in contact with the tape and the frictional performance of the heads.

## V. Conclusions

The determination of the coefficient of friction $\mu$ or $\mu\beta$, where $\beta$ is the tape-to-head "wrap" angle, and the measurement or computation of the percent deviation in the period of a prerecorded signal $\%\sigma$ provided an insight into the frictional and stick-slip behavior of magnetic recording tapes. A comparative evaluation of a number of candidate tapes for spacecraft usage was thus made possible under various environmental conditions. With one exception, the base material or the backing of the tested tapes was polyethylene terephthalate. The one exception, Battelle No. 1 tape, had a polyimide backing. Although the physical or mechanical properties of the tape backing affect its frictional behavior, it is the properties of the magnetic coating or the polymeric binder used in the coating that are most significant, because the binder surface is in direct contact with the magnetic heads.

The differences observed during the present study in the performance of tapes with the same magnetic heads are ascribed largely to the differences in binder composition. Although the general type of the base polymer used in the binder was known, the nature of the compounding ingredients, such as processing aids, plasticizers, curing or vulcanizing agents, fungicides, antioxidents and lubricants, and the particular variety or grade of the polymer were not known because of the proprietary nature of this information. Consequently, binder composition to tape performance relationships could not be evaluated.

All the magnetic tapes tested in Phase II showed stick-slip. The amounts ranged from low or acceptable to very high and unsuitable for spacecraft usage. Similarly, frictional resistance or drag shown by the tapes ranged from low and satisfactory to high and unsatisfactory for spacecraft application. Both drag and stick-slip were dependent on a number of factors. In addition to the nature of the tape binder, the kind of magnetic head in contact with the tape, the temperature, the presence of humidity, the nature of the gaseous environment and tape speed were the more important factors. In general, increase in temperature lowered the frictional resistance of the tapes. An exception was the Graham Epoch 4. Generally, the presence of moisture at the 25% RH level increased the drag of the tapes as compared to the situation in dry argon. The exception again was Graham Epoch 4, which was not affected significantly by the presence of water vapor. This tape has a basically different binder material than the other three.

Lower drag was experienced by 3M 20294, Battelle No. 1 and Graham Epoch 4 when tested in the higher inert gases helium and nitrogen instead of argon. The 3M 20250 tape, on the contrary, showed less drag in argon. The coefficient of friction of 3M 20250 tested in argon at 25°C increased with tape speed. The speed range used was $8.46 \times 10^{-5}$ m/s to $3.38 \times 10^{-2}$ m/s (0.0033 in./s to 1.33 in./s). A definite correlation was observed between drag and stick-slip. Increase in stick-slip accompanied an increase in drag.

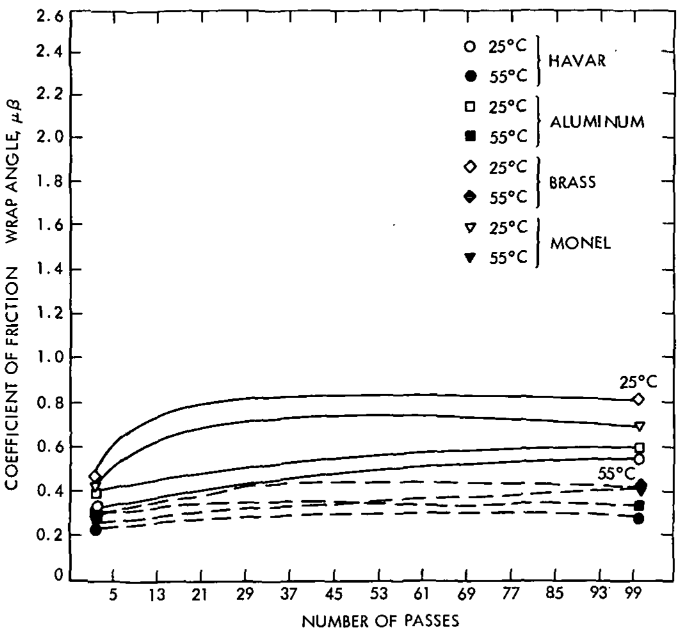



**Fig. 12. Effect of temperature on the performance of 3M 20250 tape with four magnetic heads (tested in dry argon)**

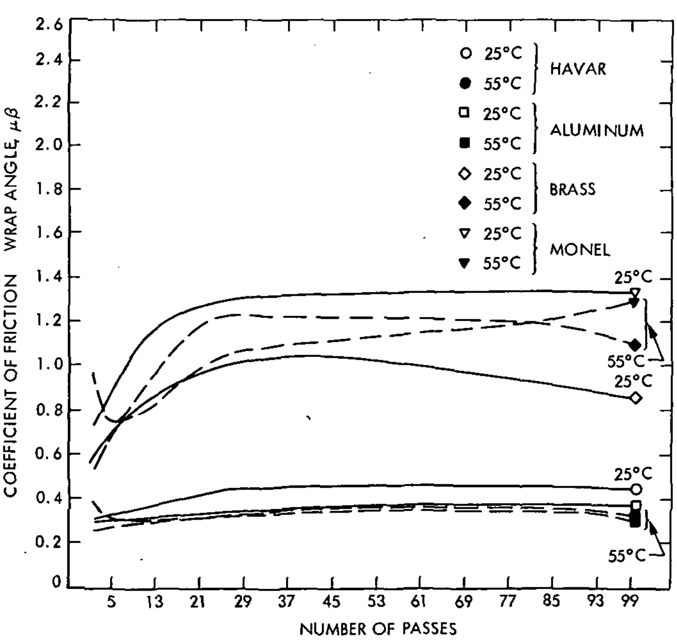



**Fig. 13. Effect of temperature on the performance of 3M 20294 tape (tested in dry argon)**

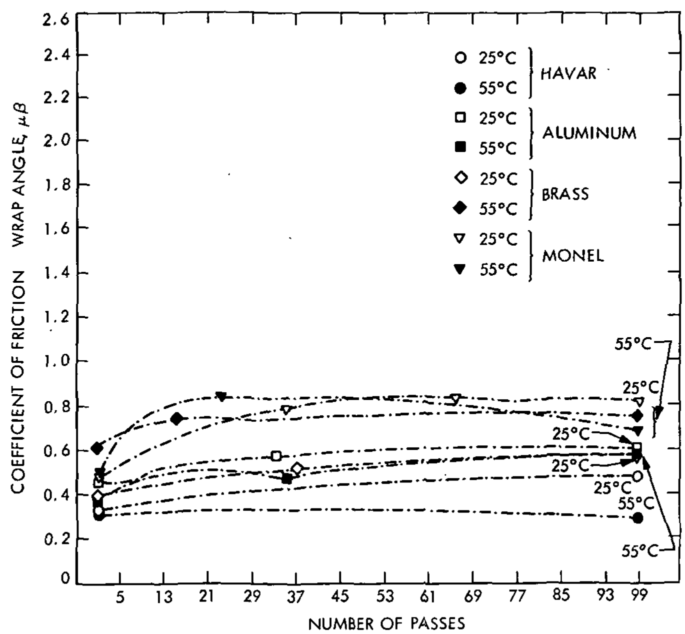



**Fig. 14. Effect of temperature on the performance of Battelle No. 1 tape with four magnetic heads (tested in dry argon)**

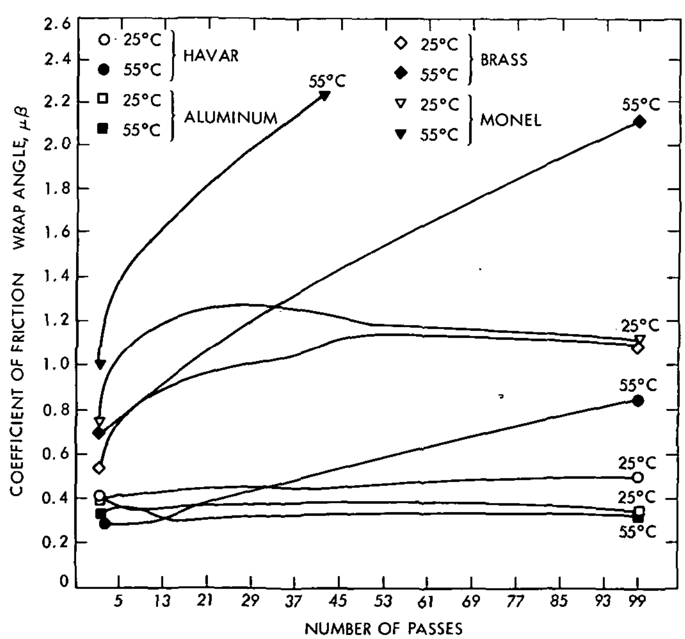



**Fig. 15. Effect of temperature on the performance of Graham Epoch 4 tape with four magnetic heads (tested in dry argon)**

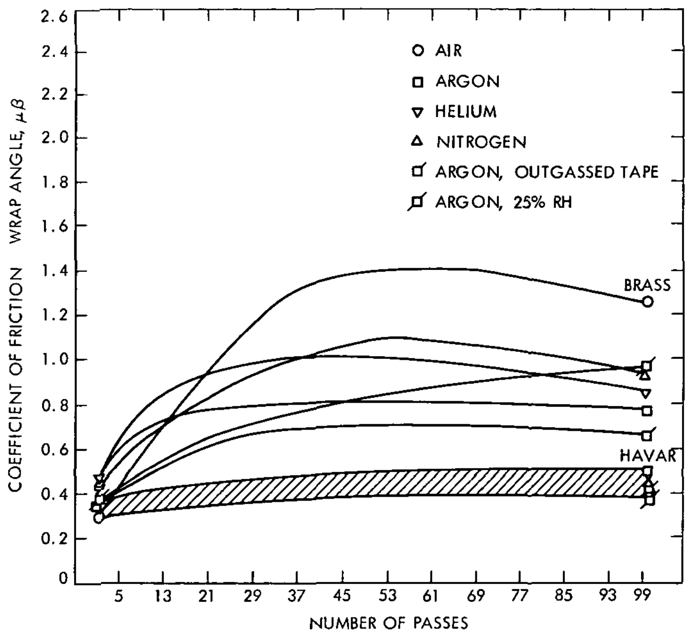



Fig. 16. Effect of various environments on the performance of 3M 20250 tape at 25°C (tests with brass and Havar heads)

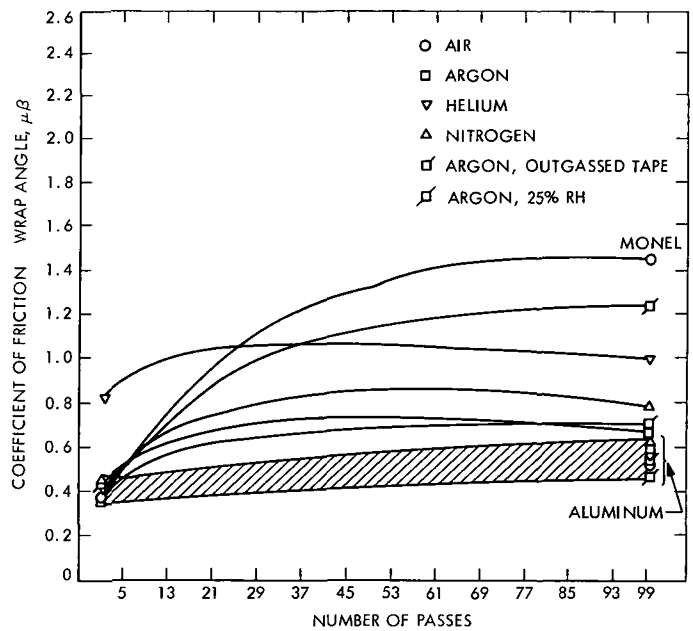



Fig. 17. Effect of various environments on the performance of 3M 20250 tape at 25°C (tests with Monel and aluminum heads)

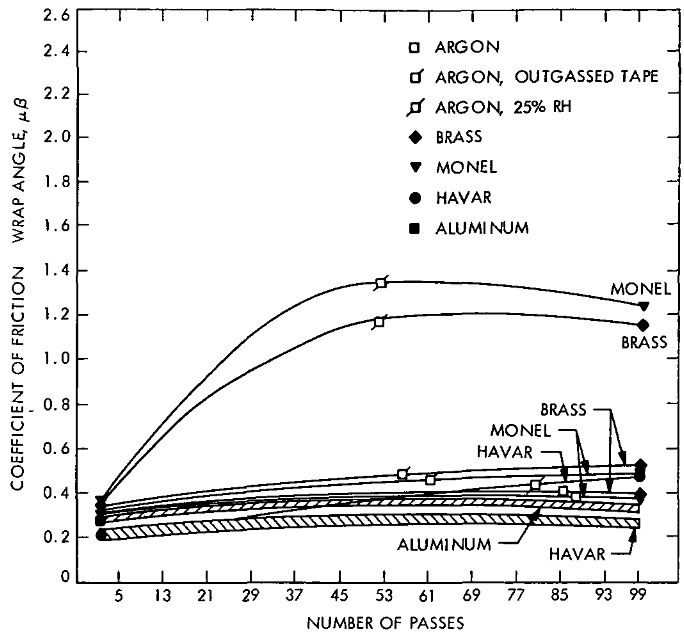



Fig. 18. Effect of various environments on the performance of 3M 20250 tape at 55°C

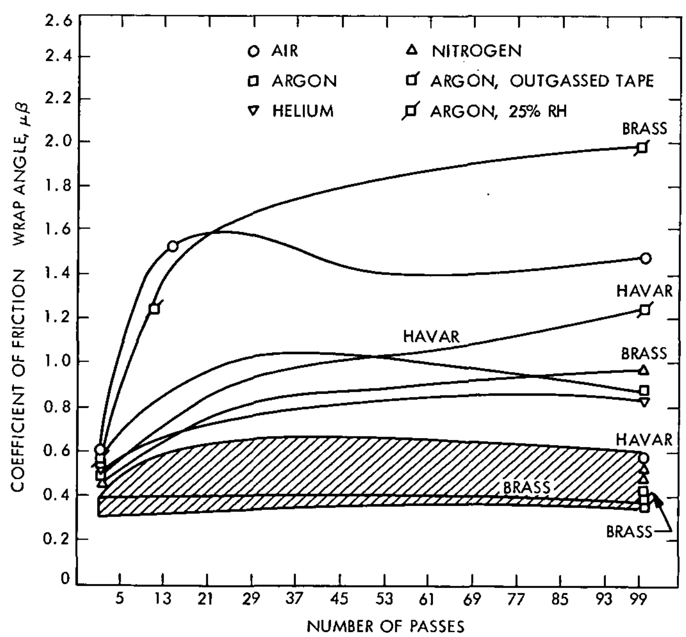



Fig. 19. Effect of various environments on the performance of 3M 20294 tape at 25°C (tested with brass and Havar heads)

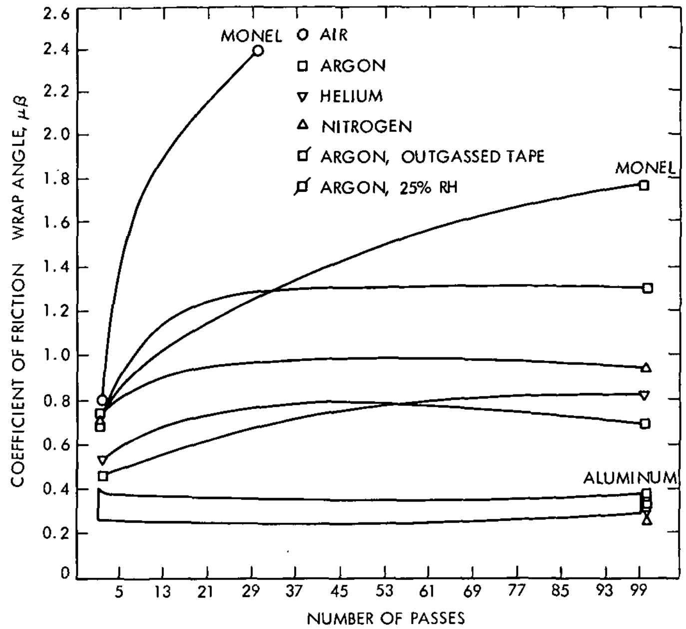



**Fig. 20. Effect of various environments on the pertormance of 3M 20294 tape at 25°C (tested with Monel and aluminum heads)**

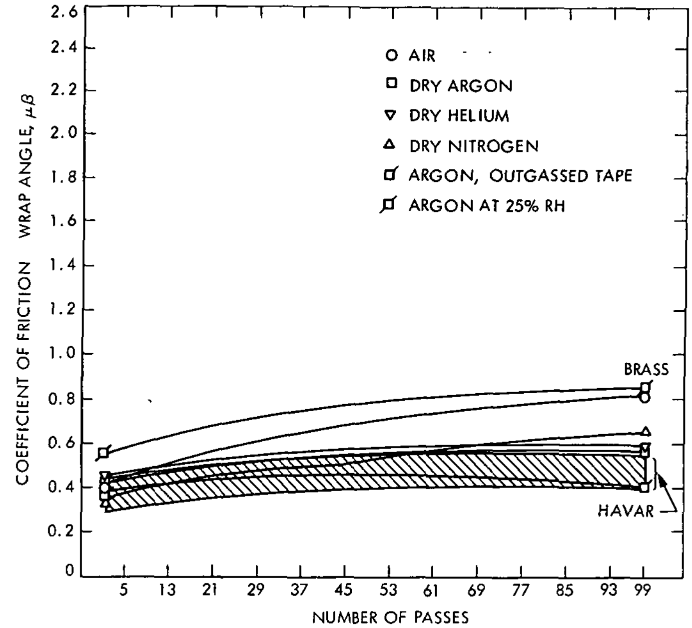



**Fig. 22. Effect of various environments on the performance of Battelle No. 1 tape at 25°C (tests with brass and Havar heads)**

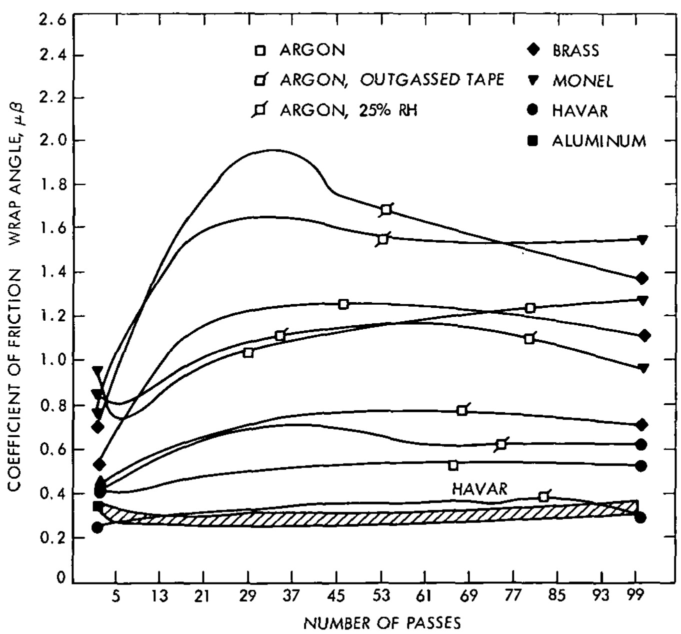



**Fig. 21. Effect of various environments on the performance of 3M 20294 tape at 55°C**

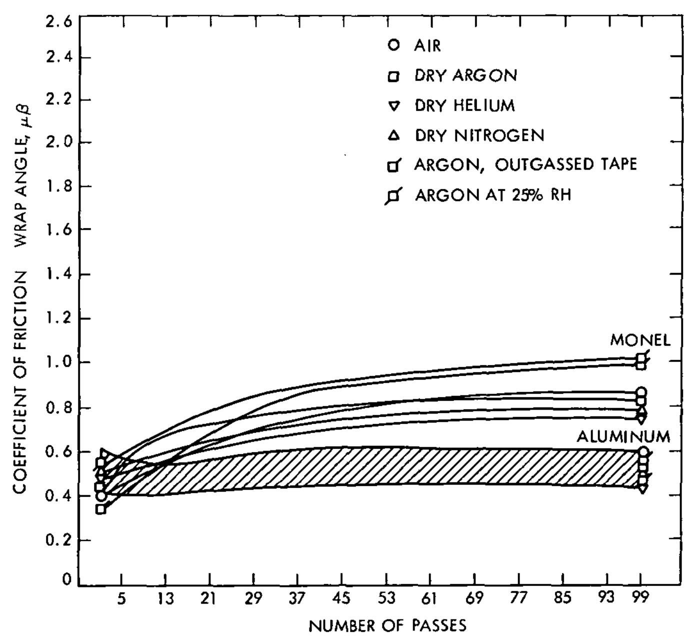



**Fig. 23. Effect of various environments on the performance of Battelle No. 1 tape at 25°C (tests with Monel and aluminum heads)**

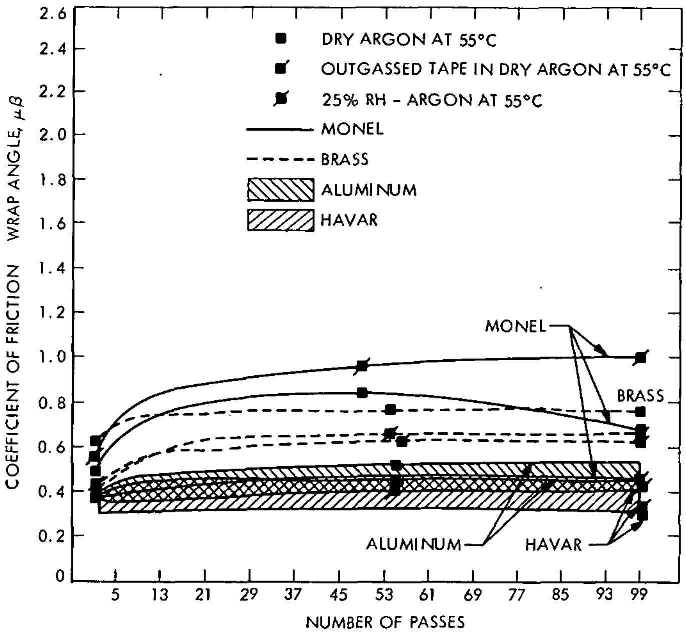



**Fig. 24. Effect of various environments on the frictional behavior of Battelle No. 1 tape at 55°C (tests with Monel and aluminum heads)**

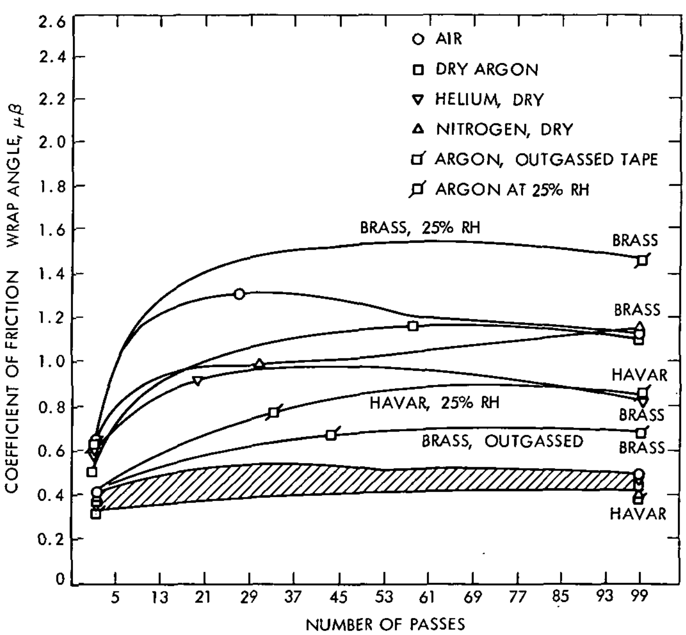



**Fig. 25. Effect of various environments on the performance of Graham Epoch 4 tape at 25°C (tests with brass and Havar heads)**

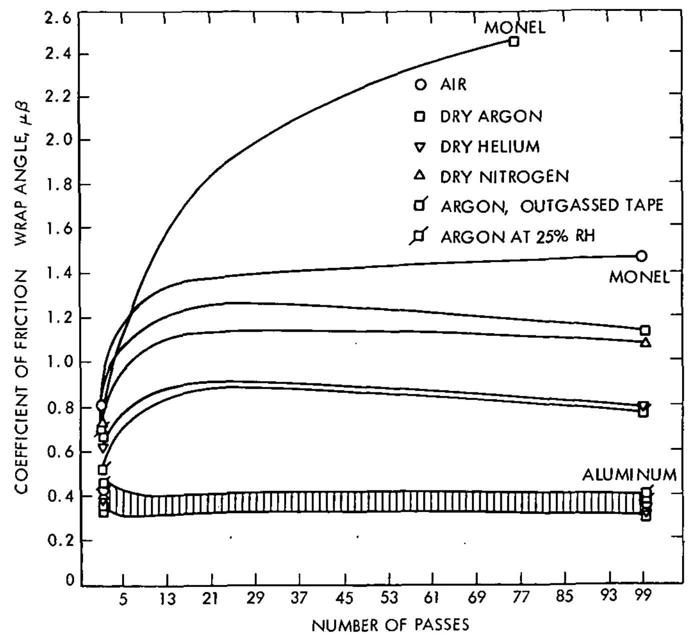



**Fig. 26. Effect of various environments on the performance of Graham Epoch 4 tape at 25°C (tests with Monel and aluminum heads)**

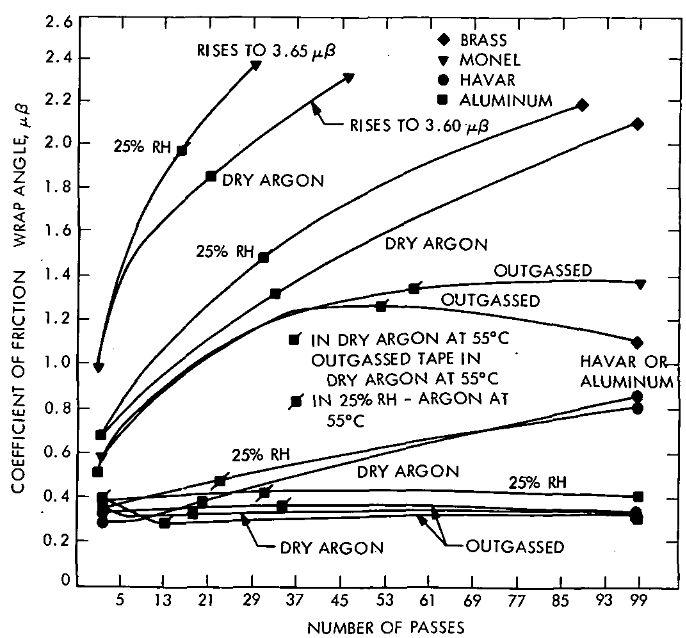



**Fig. 27. Effect of various environments on the frictional behavior of Graham Epoch 4 tape at 55°C**

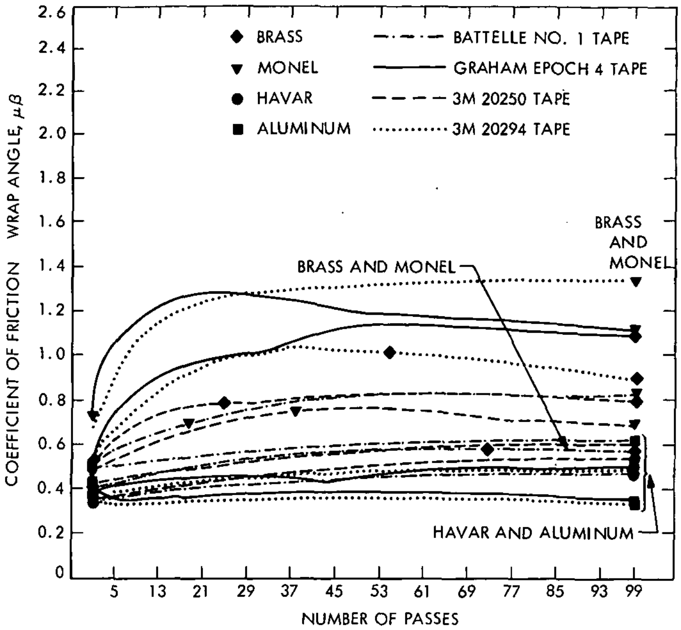



Fig. 28. Comparison of four tapes at 25°C in dry argon

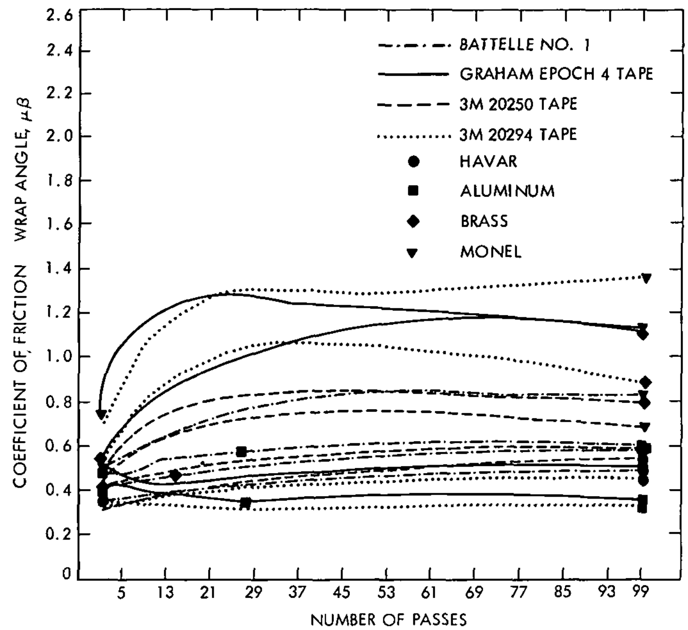



Fig. 30. Comparison of magnetic heads at 25°C in dry argon

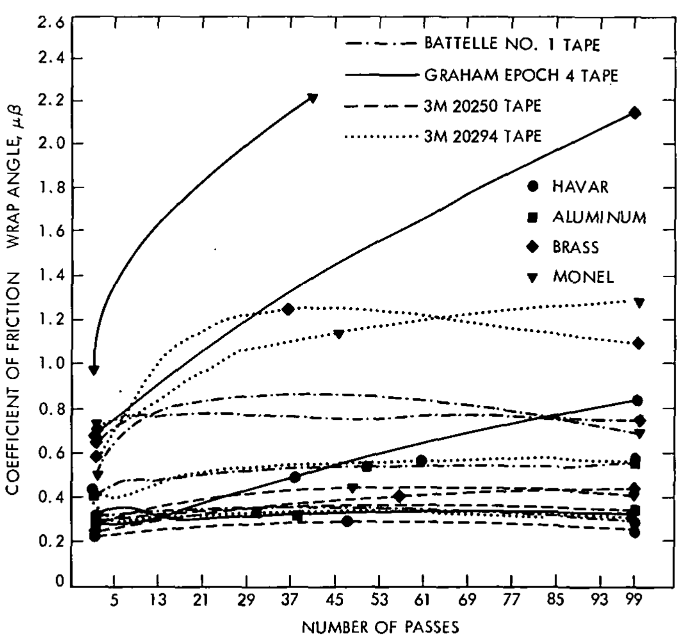



Fig. 29. Comparison of four tapes at 55°C in dry argon

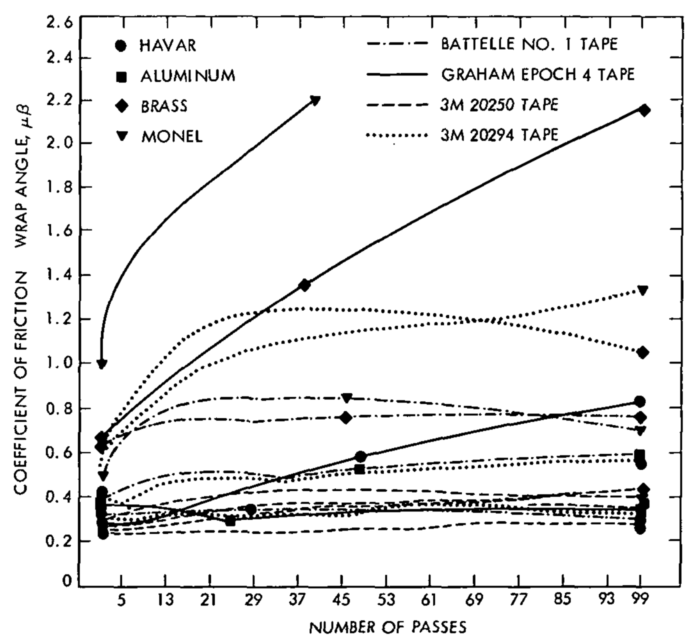



Fig. 31. Comparison of magnetic heads at 55°C in dry argon

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