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Tape Recorder Failure Investigation

M.D. Higgins*, S.H. Loewenthal*, C.C Carnahan*, and G.L. Snyder*

Abstract

Two end-item tape recorders lost 4:1 mode data recording mode capability at less than half of their 16,000-cycle, 4-year operating life. Subsequent life tests on two spare recorders also experienced 4:1 mode data loss at 8,000 and 11,700 cycles. Tear down inspection after completion of the life tests showed that the tape had worn through the alfesil record and reproduce heads. An investigation was initiated to understand the cause of excessive tape head wear and the reasons why the 4:1 mode data rate, low-speed mode is more damaging than the 1:1 mode data rate, high-speed recording mode. The objective was to establish how operating conditions (tape speed, humidity, temperature, stop/start cycles) affects head life with the goal of extending head life on the remaining in-service tape recorders. Another interest was to explain why an earlier vendor life test showed capability beyond 16,000 cycles.

Background

This paper addresses discrepancies between the results of tape recorder life tests performed at the vendor in 1984 and at Lockheed Martin Missiles and Space (LMMS) in 1994, as they relate to the friction and head wear. The unit tested by the vendor accumulated 19,000 cycles before the head was inspected and found to be in relatively good health. LMMS tested two units, both of which were terminated due to head failure. Unit #1 failed at 17,100 cycles, while unit #2 failed at 15,300 cycles. Post-test examinations found significant head wear in both units.

Additional tests, reported here, were performed to help determine the cause of the recorder failure. These tests dynamically measured tape tension and tape head friction of an end-item recorder by using a specially designed load cell platform. The effects of tape speed, temperature, humidity, and operation mode were investigated. The results of these tests and how they relate to the head failure are presented.

In order to identify the operating parameters that are critical to head wear, it was necessary to design a friction force/tape tension sensor with a sensitivity to a fraction of a newton and with accurate support and alignment of the read head within the confines of the tape recorder housing. The transducer has to fit within the small space left between the tape transport mechanism and the hermetically sealed case. The humidity within the case must be carefully controlled around 30%, since higher humidity is believed to be detrimental to head life, and lower humidity will increase static electricity and noise.

* Lockheed Martin Missiles and Space, Sunnyvale, CA

This paper describes the development of a novel load cell platform for both measuring force and moment loads with sub-newton sensitivity and for fitting within the required package envelope. The use of the two sub-miniature load cells not only eliminated parasitic friction but also allowed a direct measurement of tape head friction and tape tension. Problems associated with load cell cross talk and initial locked-in loads (bias) are addressed.

A description and method for calculating the friction energy is also presented. Results of subsequent head wear testing and its relationship between the friction energy and the head wear are established.

Tape Recorder

The end-item tape recorder contains two coaxial reels that contain 840 meters of wide-band polyester magnetic tape. The ends of the tape are designated as the Beginning of Tape (BOT) and the End of Tape (EOT). The tape transport mechanism contains three individual tape heads for recording, reproducing, and erasing operations.

The record and reproduce heads each contain 5 alfesil cores, housed in an aluminum case. The erase head contains a single alfesil core, which is also housed in an aluminum case. The entire tape recorder is housed in a 20 x 23 x 22-cm hermetically sealed case. The case is back-filled with dry nitrogen, and distilled water is included to raise the relative humidity within the case from 27% to 40%. As mentioned above, higher humidity is detrimental to head life, while lower humidity increases static electricity and noise. The recorder typically operates at temperatures between -2°C and 35°C.

In order to determine the effects of operating conditions on tape head wear, a means to measure dynamically the contact force between the tape and the read heads, along with its friction force, needed to be developed. Furthermore, the "sensor" not only had to fit in the same location as the actual read head (5 x 5 x 2.5 cm) but also needed to incorporate an actual read head with the proper geometry.

The major design challenge was to record very small tape head load levels (1 to 1.5 N) simultaneously with dynamic friction levels on the order of 0.05 to 0.1 N. At these low levels, any form of hysteresis would significantly contaminate the results. Thus, "floating" some sort of sliding bearing system was eliminated. A "teeter totter" beam, supported by a flexure pivot at the fulcrum and reacted by a load cell, was also considered but was eliminated because it was too complicated to measure normal force and moment (friction) simultaneously. Furthermore, it required too much room to package and was thought to be too susceptible to dynamic excitation.

The force platform that was finally selected directly mounted two sub-miniature 0.5-N load cells to a bracket to which the read head is directly mounted (Figure 1). This arrangement not only provided the smallest package size with the required load sensitivity but also eliminated hysteresis through the hard mounting of the tape head directly to the load cells. Furthermore, both the tape tension and the friction force could be deduced from the normal and moment loads that were measured directly.

The drawback to this arrangement, as later found, was that the desired stiffness and load sensitivity was also accompanied by an equally high sensitivity to temperatures and thermal gradients. Using dead weights, the load cell temperature sensitivity was calibrated statistically. To account for temperature effects, a technique was developed to remove biases and thermally induced loading of the sensor. This was done by equating friction forces produced in the forward and reverse direction at points where matching measured normal loads exist. This technique allowed for the reliable in-place calibration at dynamic operating conditions within the tape recorder.

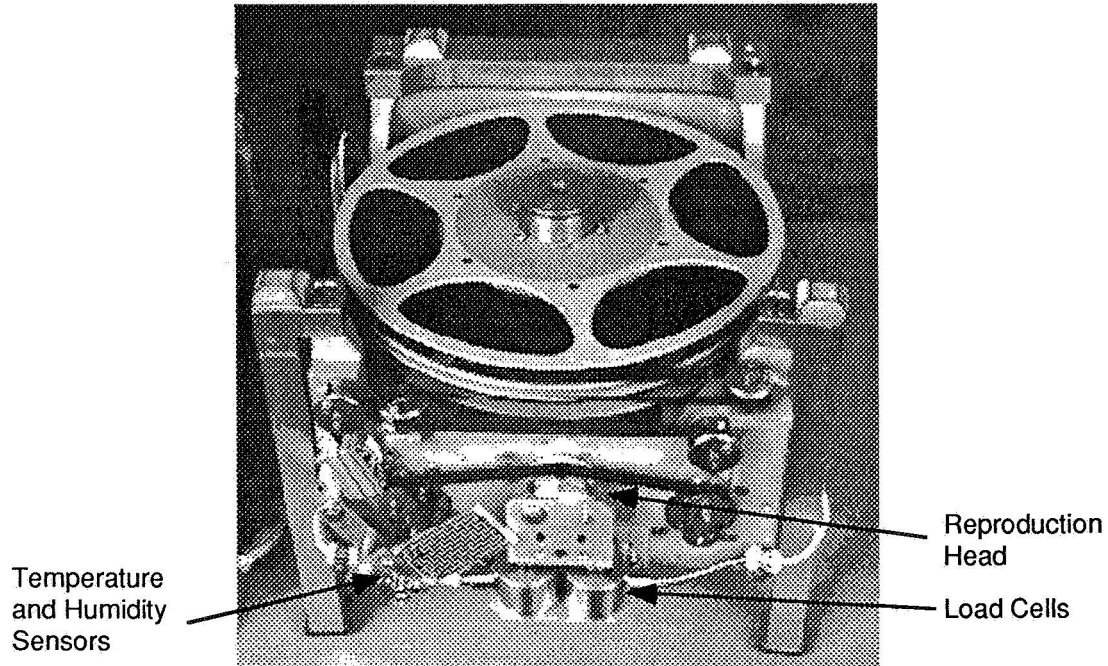


Figure 1. The end-item tape recorder fitted with the tension/friction transducer and the temperature/humidity probe

Performance Testing Setup

A diagram of the test setup is presented in Figure 2. The tape recorder mechanism was housed in a normal end-item recorder case. The tape recorder was placed in an environmental chamber where the external temperature was controlled from -2°C to 35°C . The recorder was fitted with the load cell platform for use during the performance testing. Internal temperature, relative humidity, and load cell readings were monitored with the LabviewTM program and stored on disk.

Operational Modes and Recording Rates

A description of the recording modes evaluated during performance testing is presented in Table 1. The 4:1 Interrupt mode is the primary recording mode in service. This particular mode runs at a tape speed of 0.42 m/s, records to all 840 meters of tape in a single pass, and contains 5 to 7 recording interruptions.

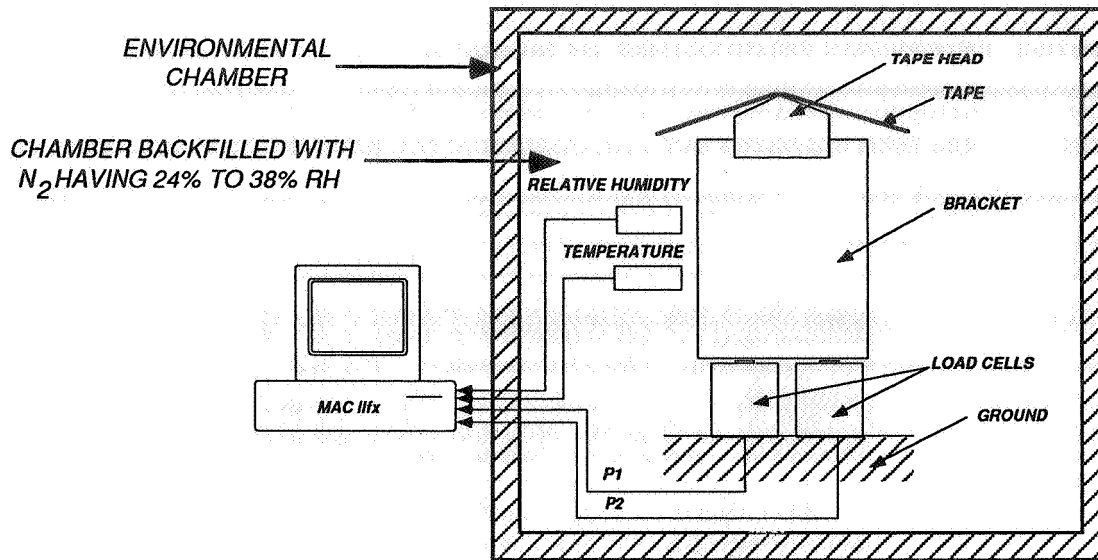


Figure 2. The test setup

Table 1. Operational Mode Definitions

Mode	Tape Speed (m/s)	Number of Recording Interruptions	Temperature and Humidity Stabilization	Description
1:1 Clean	1.6942	NONE	Temperature and humidity is stabilized before preceding to the next cycle	Baseline recording rate used during the test. "Clean" refers to the absence of pauses (or interruptions) during the recording cycle.
4:1 Clean	0.4235	NONE	Both are stabilized before preceding to the next cycle	25% lower speed allows for 4x higher data density on tape.
1:1 Interrupt	1.6942	5 to 7	Both are stabilized before preceding to the next cycle	Baseline recording rate. Interrupt refers to the absence of pauses (or interruptions) during the recording cycle
4:1 Interrupt	0.4235	5 to 7	Both are stabilized before preceding to the next cycle	25% Lower speed allows for 4x higher data density on the tape
1:1 Multi-Cycle	1.6942	NONE	Temp is stabilized, RH is NOT stabilized before preceding to next cycle	Baseline recording rate. Temperature and humidity are not stabilized before moving to additional cycles. Represents accelerated life test operating mode.
Reproduce	1.6942	NONE	Function of recording mode	The baseline reproduce cycle. The reproduce cycle always runs at this tape speed without interruptions.

The reproduction cycle is not initiated until all 840 meters of tape have been recorded. The life tests performed at the vendor match the 1:1 multi-cycle recording mode, which is absent of any recording interruptions. No attempt was made to stabilize the relative humidity between recording cycles in this recording mode.

Test Methodology: General Equations

A schematic of the loads acting on the system is presented in Figure 3. The schematic shows both the forces due to the tape sliding across the tape head and the reaction forces produced by the load cells.

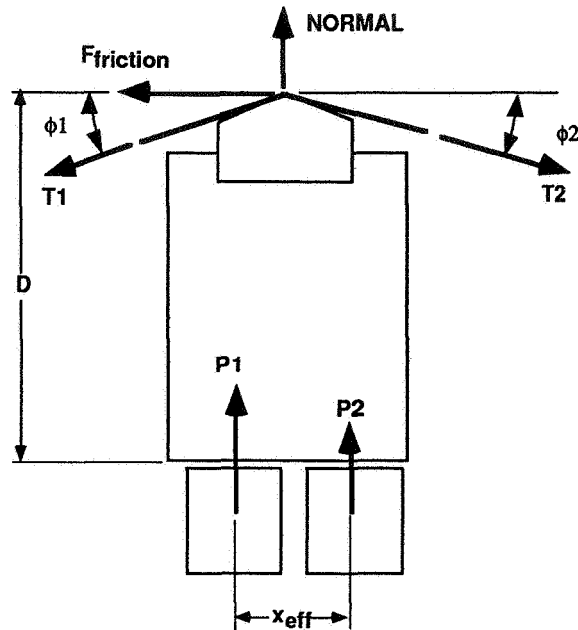


Figure 3. Schematic of forces acting on the tape head

The load cells attached to the bottom of the bracket that supports the head were used to record the loads required to calculate the normal and moment loading. The normal force is a function of the sum of the load cell forces, while the moment is a function of their difference and the distance between the two load cells. The normal and moment loads are used to determine the tape tension, friction, coefficient of friction (μ), and the friction energy. The normal force is determined by considering the equilibrium of the forces in the vertical direction.

$$N = P_1 + P_2 \quad (1)$$

The relationship between the friction and the load cell forces was derived by considering the equilibrium of the moment acting on the bracket. The term on the left side of the equal sign represents the moment produced by the friction force, and the term on the right side represents the couple produced by the load cells:

$$DF_{friction} = x_{eff} (P_1 - P_2) \quad (2)$$

The expression for the friction force is obtained by dividing both sides of the above equation by D :

$$F_{friction} = \frac{x_{eff}(P_1 - P_2)}{D} \quad (3)$$

The coefficient of friction, μ , is the ratio of the friction force to the normal force.

$$\mu = \frac{F_{friction}}{N} \quad (4)$$

The tape tension is calculated, once the friction and normal forces are known. The equilibrium equations in the horizontal and vertical directions produce the following two equations:

$$T_1 \sin \phi_1 + T_2 \sin \phi_2 = N \quad (5)$$

$$T_1 \cos \phi_1 + F_{friction} = T_2 \cos \phi_2 \quad (6)$$

Equations 5 and 6 reduce to two equations and two unknowns, since the normal and the friction forces are known (Equations 1 and 3).

The Friction Force Bias Removal

Data analysis revealed the presence of a bias in the friction force. The bias was found to be a consequence of a locked-in load cell residual moment load that tends to shift the true null point with a reversal in tape direction. To account for the bias, the friction force, as well as the normal force of sequential record and reproduction runs, was required. Testing and previous experience showed that the normal force (used to derive the tape tension) tends to build steadily from start to finish (Figure 4), regardless of whether recording or reproducing tape data was being performed.

The friction force also exhibits the same increase in magnitude over the length of the recording cycle. Figure 5 shows the unbiased friction force of sequential record and reproduction runs.

Figure 4 shows that the normal force of the record cycle was found to be equal to that of the reproduction cycle at only one tape position. This position, referred to as the "normal cross over" position, provides us with a key piece of information needed to remove the bias. At the cross over position, the record and reproduction normal forces are known to be equal. Assuming that the coefficients of friction at this position in either direction are also equal leads us to the relationship that shows that the friction force, in either direction, are equal and opposite:

$$\therefore F_{repro} = -F_{record} \quad (11)$$

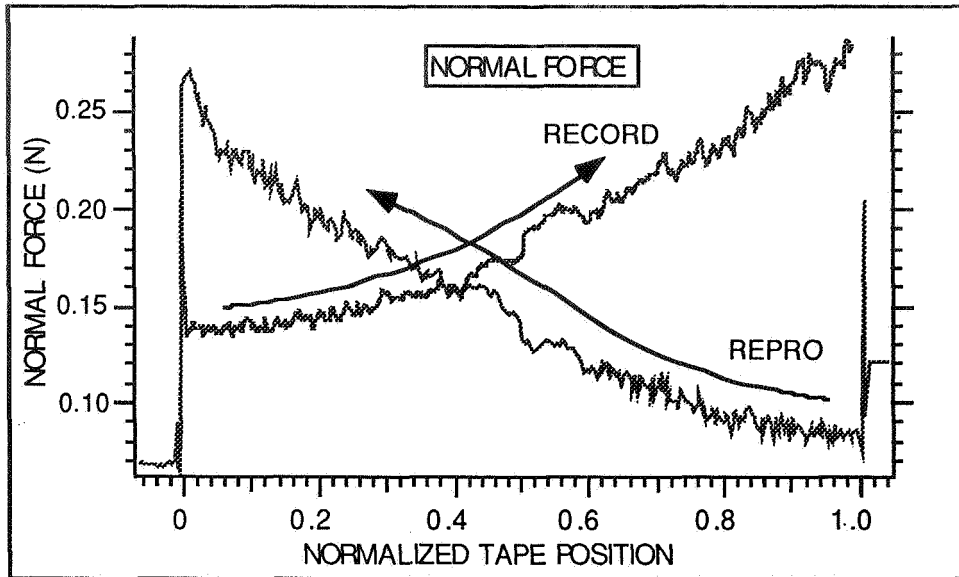


Figure 4. The typical Normal Force vs. Normalized Tape Position profile of sequential record and reproduction runs.

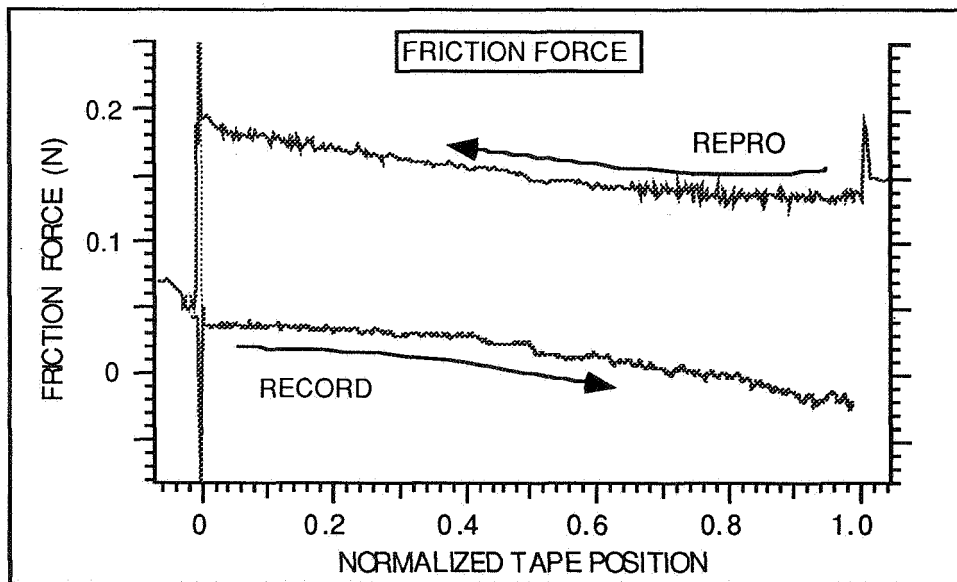


Figure 5. The biased Friction Force vs. Normalized Tape Position of sequential record and reproduction runs

Thus, to remove the bias from the friction force, the location of the cross over point and the biased friction forces formed from sequential record and reproduction cycles must be known. The relationship between the biased friction force (the uncorrected measurement), the bias, and the unbiased friction (the true friction force) becomes:

$$F_{rec}^{biased} = F_{bias}^{friction} + F_{rec}^{unbiased} \quad (12)$$

$$F_{repro}^{biased} = F_{bias}^{friction} - F_{repro}^{unbiased} \quad (13)$$

Assuming that the unbiased friction forces are equal at the cross over point results in the following relationship between the bias and the biased friction forces:

$$F_{bias}^{friction} = \frac{F_{repro}^{biased} + F_{rec}^{biased}}{2} \quad (14)$$

Air Bearing Effects

A hydrodynamic air bearing, due to the convergent passage or "wedge" formed by the tape and tape head, begins to form at tape speeds above 1.0 m/s [1]. A schematic of the convergent passage formed by the tape and the tape head is shown in Figure 6.

Figure 7 is an approximate representation of the coefficient of friction vs. tape speed diagram presented in [1]. The diagram shows that the air bearing effect begins to form at 1.0 m/s and is strong enough to produce complete separation between the tape and head at speeds of 2.0 m/s.

As denoted in Figure 7, the 1:1 record mode operates at a tape speed of 1.6 m/s, thus which placing it in a region where the air bearing effect is significant but not strong enough to cause complete separation between the tape and the head. On the other hand, the friction is noticeably higher for the 0.4-m/s speed of the 4:1 mode. The differences in friction observed in our tests between the 4:1 and 1:1 recording modes is generally supported by this phenomenon.

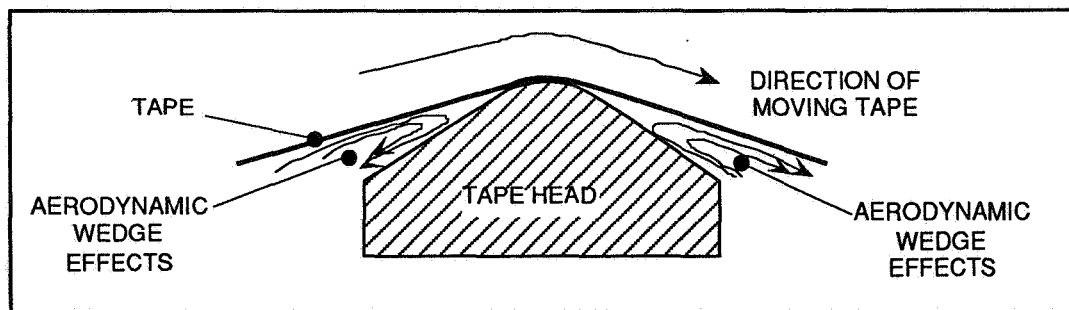


Figure 6. Schematic of air bearing effect

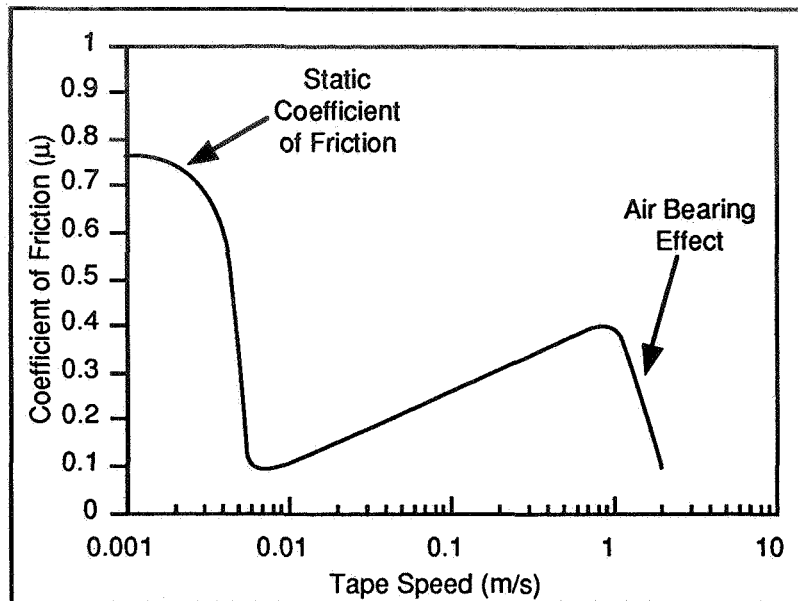


Figure 7. Coefficient of Friction vs. Tape Speed [1]

Friction Energy Approach

The main interest of this investigation was to determine the effect of the tape recorder's dynamic operating conditions (speed, temperature, humidity, etc.) on the tape head wear at a given point in time. Since running many concurrent tape head wear tests was impractical, a scalar quantity, referred to as the "Friction Energy" (FE), was formulated. To define the friction energy, we must first consider the classic wear¹ between two bodies. The equation used to calculate the classic wear is known to be proportional to the magnitude of the sliding friction between the two bodies in contact and the distance slid. The quantity can be expressed as the integral of the friction acting over the differential sliding distance dx .

$$Wear \propto \int_{x=0}^{x=1} F_{friction} dx \quad (15)$$

¹ Archard's classic wear equation states that the wear volume between two hard bodies in sliding contact is linearly proportional to the wear coefficient for the materials, the normal load, and the total distance slid and is inversely proportional to the hardness of the softer of the two bodies. Since wear data is unavailable for the magnetic tape and the tape head material in question, under the specific operating test conditions described herein, it is assumed that the wear coefficient would increase under conditions that produce an increase in friction. While this assumption is not strictly true between different material/geometry combinations, it is believed to be a reasonable way of comparing the effect of operating conditions on one specific contact material configuration.

The integral represents the energy produced by the friction force acting over the sliding distance. In the case of the tape recorder, the FE represents energy imparted by the tape to the tape head. Consideration of sequential record and reproduction runs leads to the formation of a friction hysteresis loop. A typical friction hysteresis loop is presented in Figure 8.

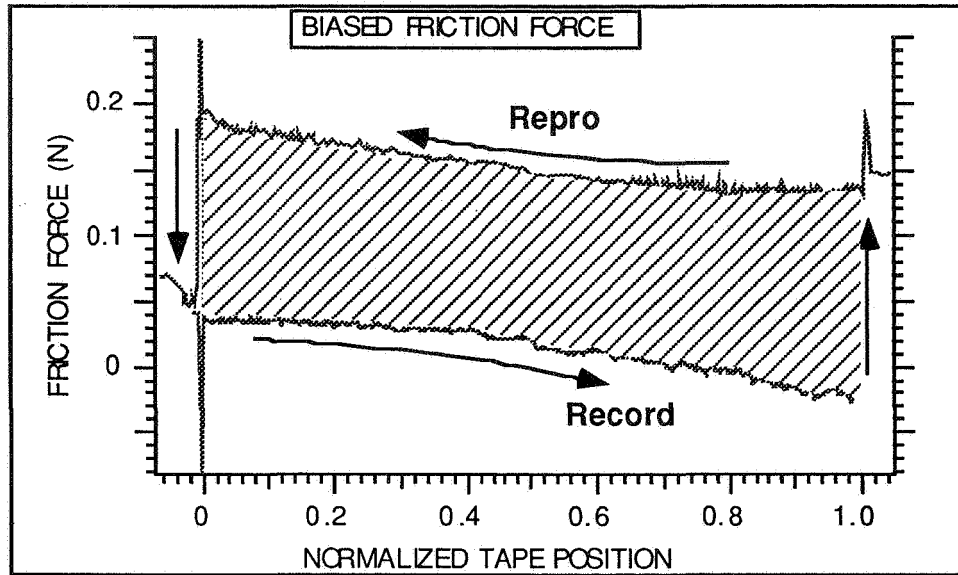


Figure 8. The FE is the area inside the friction hysteresis loop created by sequential record and reproduction runs.

The area in the enclosed loop represents the friction energy produced by one complete record and reproduction cycle. The equation for the FE for the sequential runs requires integrating over the closed path:

$$FE = \oint F_{friction}(x)dx = \int_{x=0}^{x=1} F_{frict}^{record} dx + \int_{x=1}^{x=0} F_{frict}^{repro} dx \quad (16)$$

By integrating over the closed path, we are able to disregard the steps required to remove the bias. It was for this reason that Equation 16 was used to calculate the FE terms presented in the preceding and forthcoming sections.

The FE is a valuable quantity for several reasons: 1) It is a scalar quantity proportional to the head wear; 2) Unlike μ , it can easily be calculated without removal of the bias in the friction force; 3) The area inside the hysteresis loop is unaffected by the bias; 4) The FE can be used to estimate the amount of head life that a recorder has left, provided life test data and the FE of the typical record/reproduction cycles are available; 5) The FE values of different recording modes can be combined with life test data to estimate the number of cycles to failure.

Results: Tape Tension

The load cell platform was used to gather the raw data used to calculate the tape tension, friction, and coefficient of friction vs. tape position. A typical tape tension profile is presented in Figure 9.

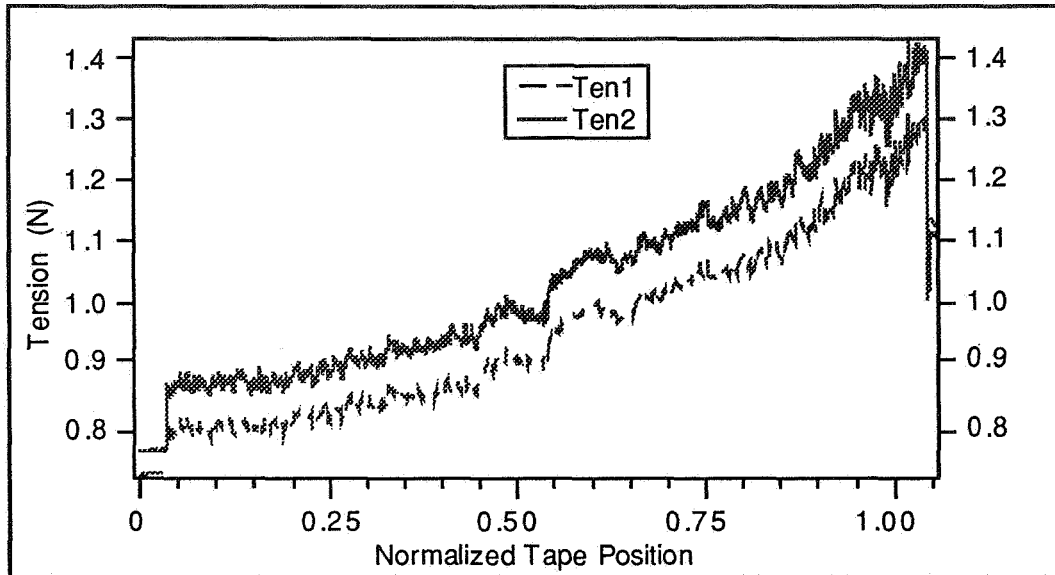


Figure 9. Tape Tension vs. Normalized Tape Position

The tension in all the profiles show the same increase in magnitude over the length of the tape. This is a characteristic of tape recorders that have negator spring tensioning mechanisms. These results generally agree with static measurements made by hand with a mechanical tape tension gage.

The tension at the BOT and EOT positions and its variation with recording speed and temperature is depicted in Figure 10. The tape tension profile was found to be insensitive to recording rate. The tension was found to be sensitive to temperature. The testing shows that the tension at the BOT position drops 0.278 N between -2°C and 35°C . The tension profile always shows the same increase of 0.55 N in magnitude from BOT to EOT, regardless of recording rate.

Results: Speed Effects

Typical friction profiles, produced by the recorder operating in the 1:1 and 4:1 recording mode, are presented in Figure 11. The friction force was also found to increase in magnitude when moving from the BOT and EOT positions. The initial friction in the 4:1 recording mode is approximately twice its 1:1 counterpart. The 0.278-N difference is maintained for the duration of the recording cycle.

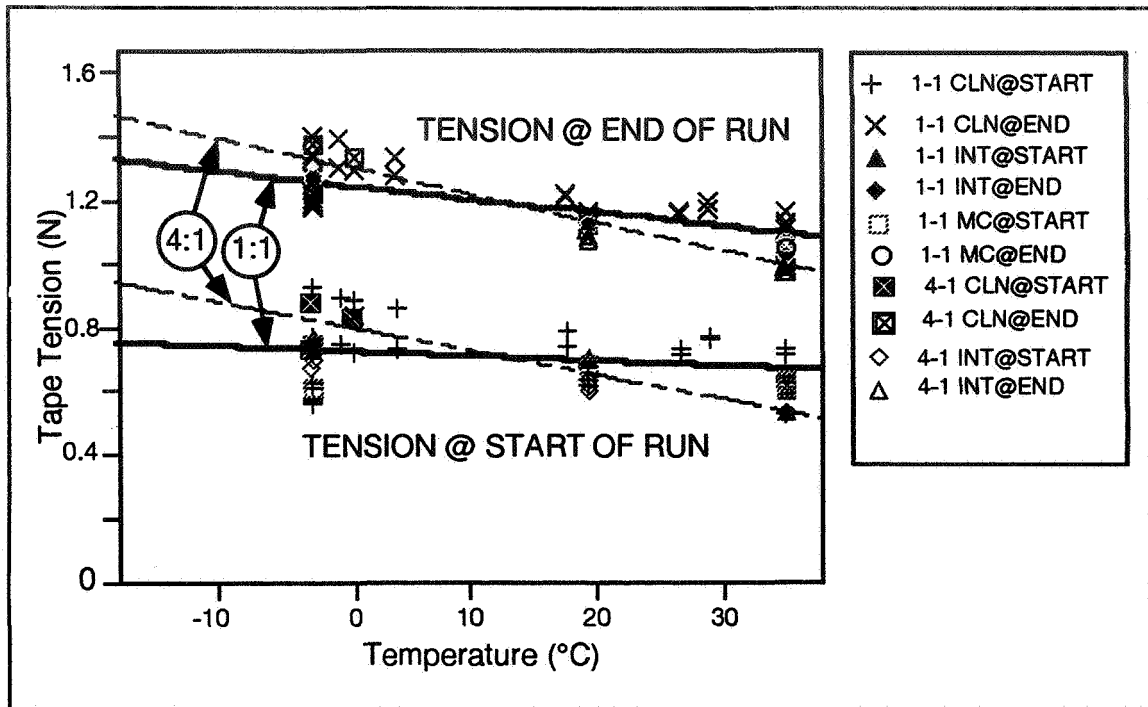


Figure 10. The tape tension at BOT & EOT positions

The reduction in friction with increased speed is generally attributed to an air bearing effect. The tape tension and friction profiles were used to derive the coefficient of friction as it varies with tape position.

The coefficient of friction variation over the length of the tape was used to calculate the mean coefficient of friction (Figure 13). At temperatures above 4°C, the friction and μ doubled in value over its 1:1 counterpart. The temperature was found to have a comparatively small effect on the μ associated with the 1:1 recording mode. This is also believed to be due to a more prominent air bearing effect that is present at the higher recording rates. The higher friction values of the 4:1 recording mode were found to be more strongly influenced by temperature effects in the absence of the air bearing effect. The coefficient of friction (μ) is consistent with values published in [1].

The Friction Energy and its variation with temperature and recording mode are presented in Figure 14. The figure shows that the FE of the 4:1 clean and 4:1 interrupt modes are sensitive to temperature. The curves fitted to the data are meant to show general trends. The sample sizes for all the recording modes, with the exception of the 1:1 clean mode, were not large enough to form any meaningful statistics. The data that are available shows that the FE produced by the 4:1 clean and 4:1 interrupt modes have three things in common: 1) both recording modes produced FE profiles that show the same general trends over the temperature range considered; 2) both recording modes produced nearly constant FE levels at temperatures above 4°C; 3) the FE drops nearly 20% at temperatures below 4°C.

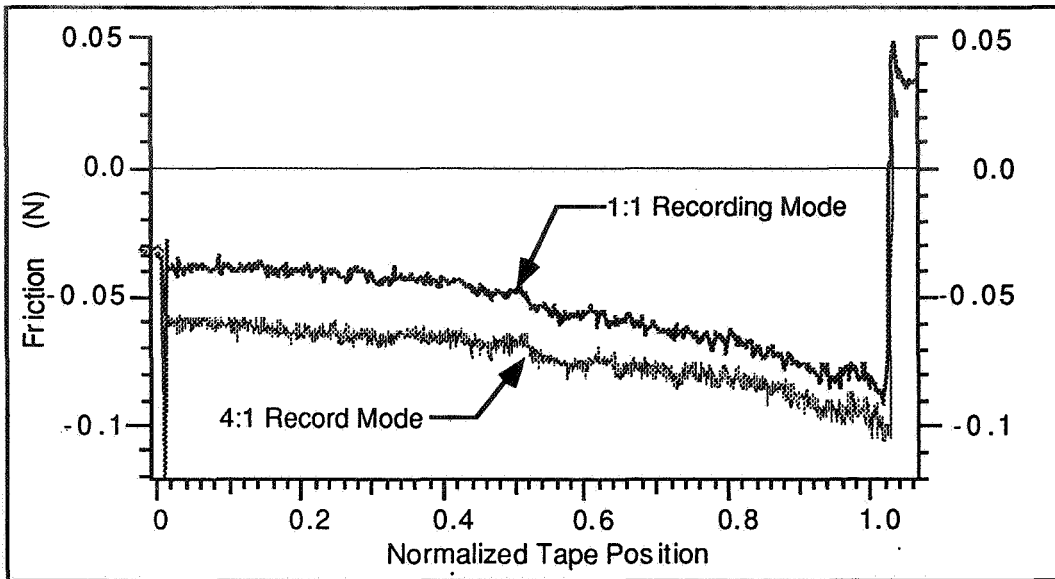


Figure 11. Friction Force vs. Tape Position

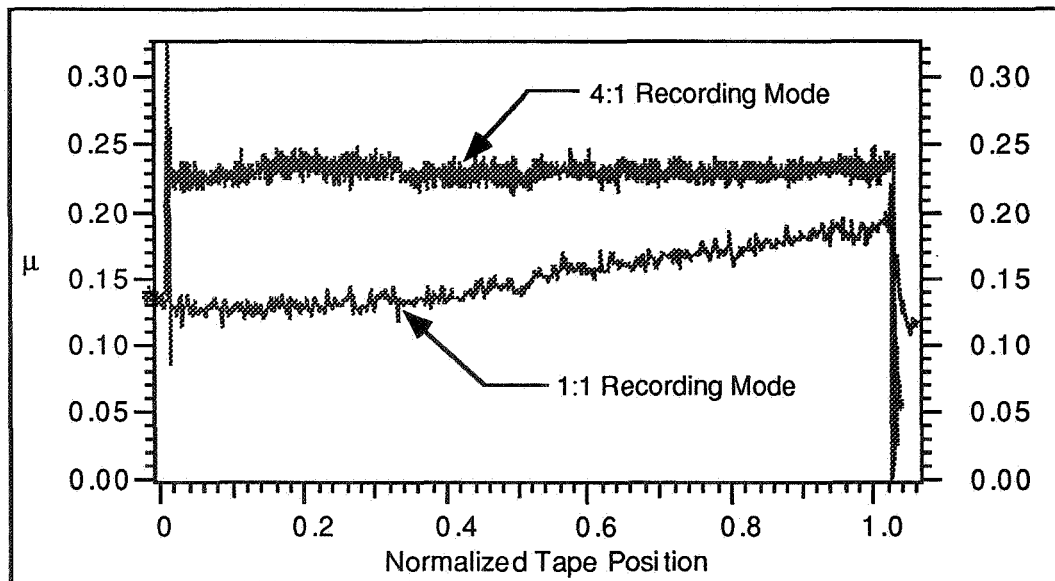


Figure 12. Coefficient of Friction vs. Tape Position

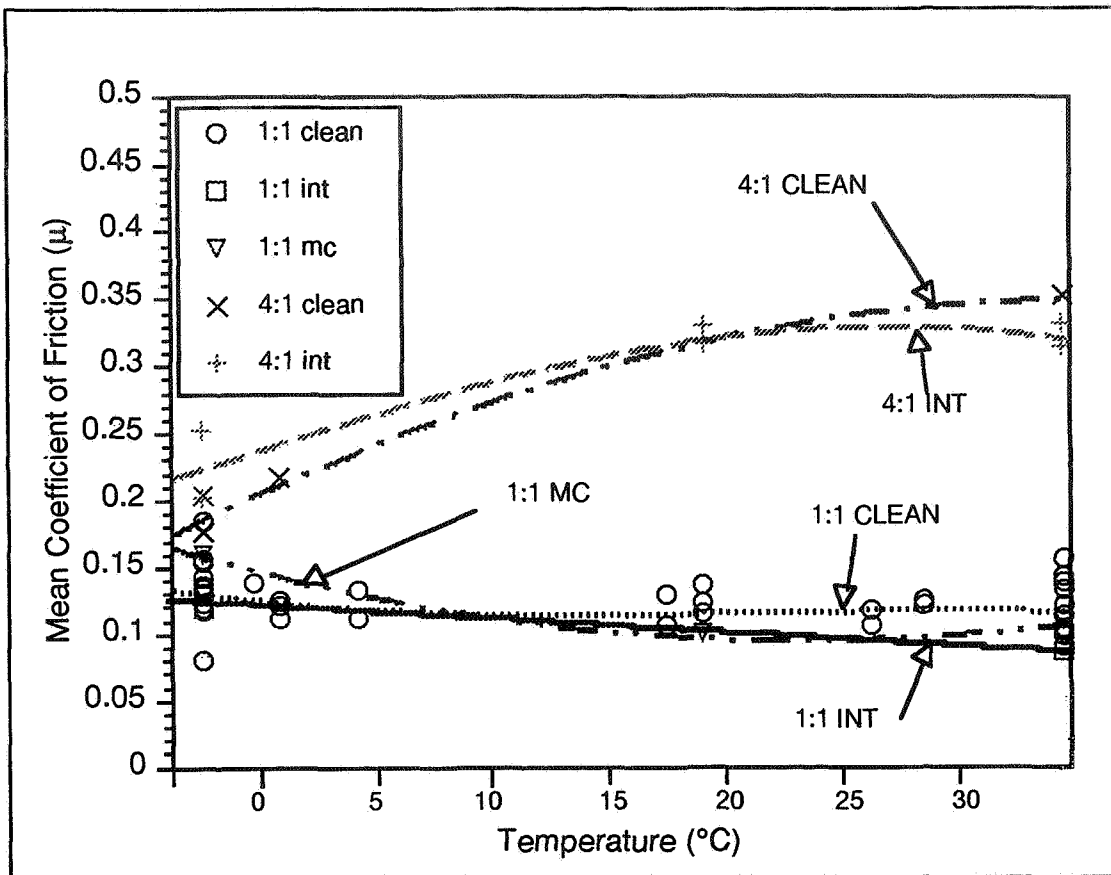


Figure 13. The mean coefficient of friction

Friction Energy and Head Life

The FE data presented in Figure 14 provided a basis for determining the differences between the life tests performed at LMMS and the vendor. The life test performed at the vendor accumulated 19,000 cycles, all of which were performed at 19.4°C with crude control over the relative humidity. An uninterrupted "1:1 multi-cycle" recording mode was used for the duration of the vendors life test. Inspection of the recorder after accumulating 19k cycles revealed a healthy tape head that was still capable of operation.

The two recorders used for life testing at LMMS did not fair as well. The recorders, designated as the LMMS recorder #1 and #2, accumulated 17,100 and 15,300 cycles respectively. Both recorders were tested a total of 7 days per week, 5 of which were tested at -1.1°C and the remaining 2 days at 35°C. The 1:1 interrupt mode was used for the duration of the test. The life tests were terminated after the recorders had failed operation tests. Inspection of the recorders revealed significant wear in the tape heads of both recorders.

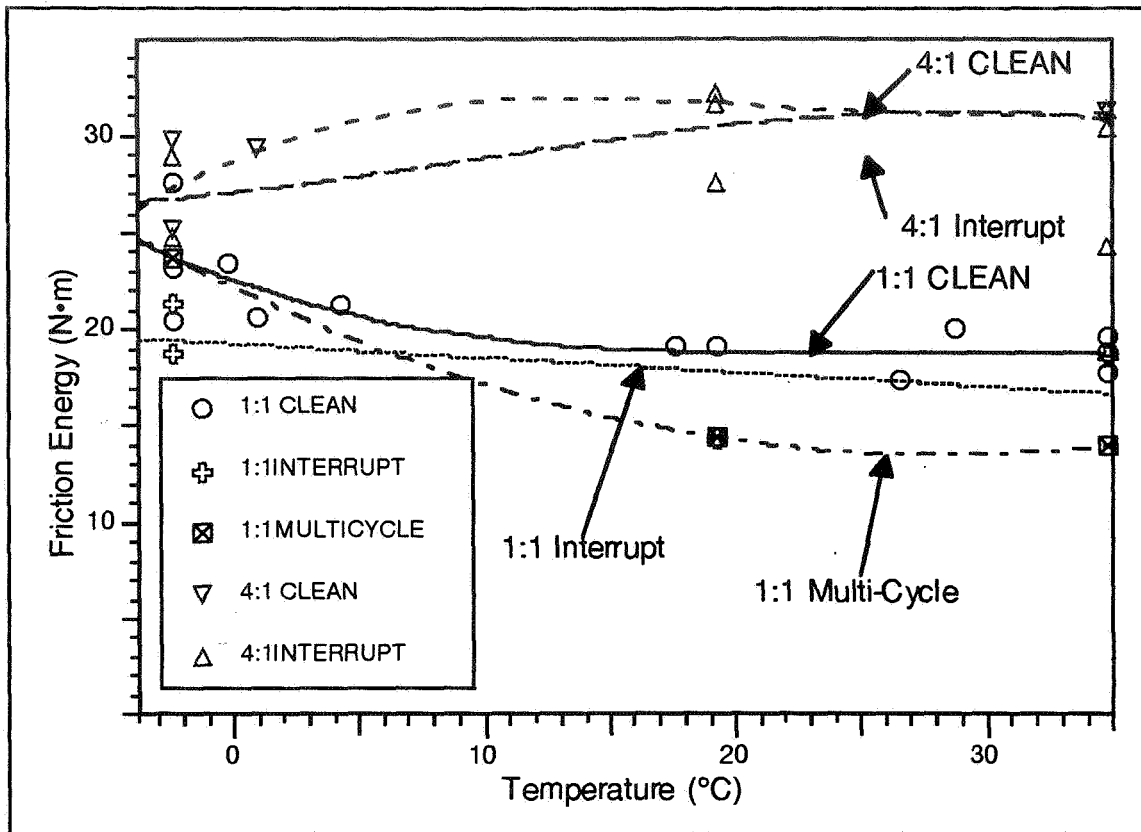


Figure 14. FE vs. Temperature

The differences between the results of the life tests performed at the vendor and LMMS are believed to be due to differences in the temperature, humidity level, and operating modes used during the life test. The duty cycle, total number cycles, and friction energy data from this investigation were used to evaluate the differences in head wear. The results presented in Table 2 support the relative test lives between tests performed at LMMS and the vendor. Table 2 shows that, while the recorder tested at the vendor accumulated the largest number of cycles, the recorders tested at LMMS were subjected to a more difficult test based on the larger amount of friction energy. The LMMS recorder #1 incurred 28% more total FE, while the #2 unit incurred 14% more total FE than its counterpart at the vendor. These differences are due to the fact that the friction energy associated with the 1:1 interrupt mode in the -1.1°C range is 50% larger than the FE associated with the multi-cycle recording mode at 19.4°C (used for testing at the vendor), and that 71% of the testing Lockheed performed was at the colder temperature (Figure 14).

Table 2. FE Comparison of Recorders Tested at LMMS and Vendor

Recorder Designation	Total No Of Cycles (k)	Days/Week	Days @ -1°C	Days @ 19°C	Days @ 35°C	FE per Cycle @ -1°C (INTERRUPT)	FE per Cycle @ 19°C (Multi-Cycle)	FE per Cycle @ 35°C (INTERRUPT)	Total Friction Energy (N-m)
The Vendor	19	7	0	7	0		14.7		279.3 k
LMMS Recorder # 1	17.1	7	5	0	2	21.56		19.11	356.7 k
LMMS Recorder # 2	15.3	7	5	0	2	21.56		19.11	319.5 k

Head Wear Testing

Head wear testing of the spare tape recorders was initiated to 1) prove or disprove the findings predicted during performance testing; 2) develop algorithms for tape head wear-out using the health of the recorder, recording speed, temperature, and humidity levels; 3) obtain data to better manage the long term use of the recorders still in the field. The head wear test consisted of two recorders operating in the same environment at different recording rates (1:1 and 4:1).

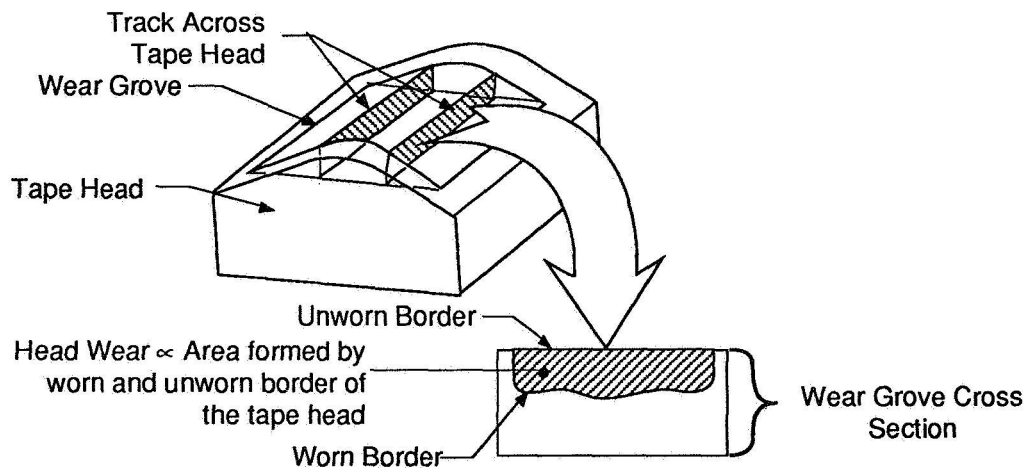


Figure 15. Profilometer measurements used to measure head wear

The heads of both recorders were periodically measured for wear with a profilometer. The cross-sectional area of the wear notch was evaluated at two locations across the head (Figure 15). The borders of the cross section consist of the worn and unworn sections of the head. The cross-sectional area values at the two locations were then averaged. The wear notch cross-section vs. cycle number is presented in Figure 16. The results show that the 4:1 recording mode produces twice as much head wear as its 1:1 counterpart. The results of the head wear testing support the findings and prediction formed during performance testing.

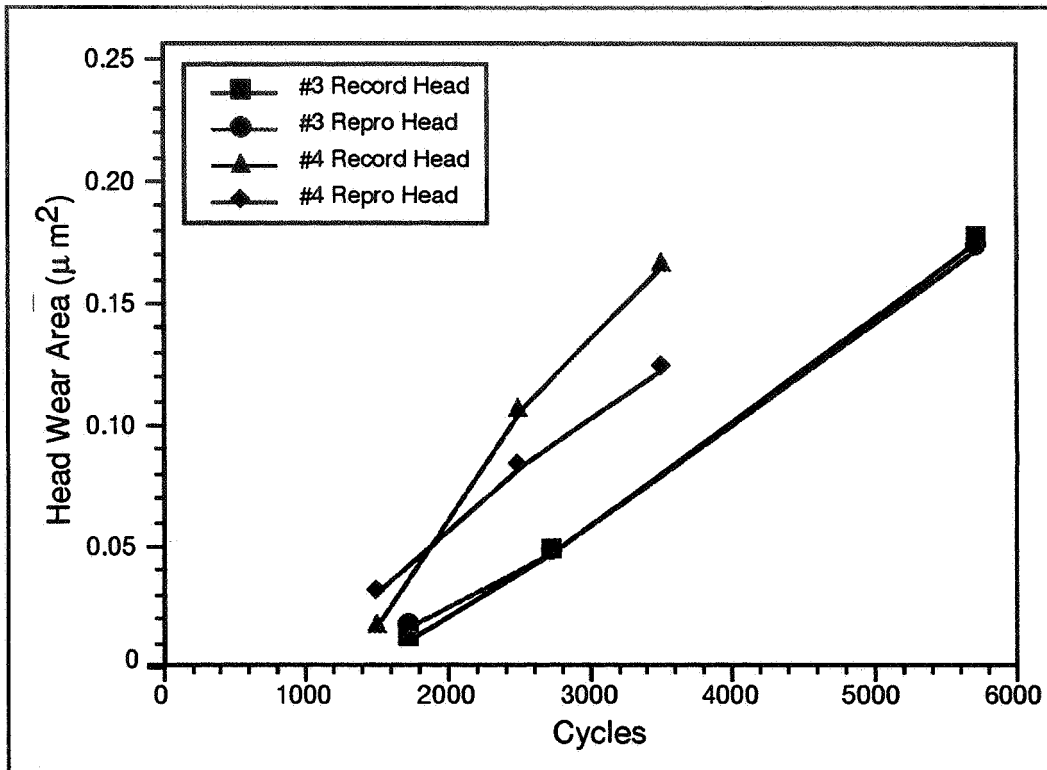


Figure 16. Measured head wear

Conclusion

The investigation successfully provided dynamic friction and tape head wear measurements in an operational tape recorder. The sub-miniature load cell platform provided the necessary sensitivity but required an in-place calibration.

The friction energy provides a useful scalar quantity for evaluating relative wear without the need for frequent disassembly and head wear measurements. The larger friction energy associated with the LMMS life test appears to explain qualitatively the observed shorter life. The end-item recorder head wear test shows a strong correlation between increased head wear and lower recording speeds, as predicted by the friction energy method described in this study. This is consistent with the higher friction at low tape speeds reported in the literature [1].

References

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2. Cuddihy, E.F, "Hygroscopic Properties of Magnetic Recording Tape," IEEE Transactions on Magnetics, Vol. Mag-12, No. 2, March 1976.