

Kinetics of the Humid Aging of Magnetic Recording Tape

H. NEAL BERTRAM, SENIOR MEMBER, IEEE, AND EDWARD F. CUDDIHY

Abstract—The kinetics of the hydrolysis of polyester urethane binders of magnetic recording tape is described. Kinetic data were generated from measurements of acetone-extractable hydrolyzed binder products versus time for various humidity-temperature environments. These data can be described by a linear, single product, reversible rate equation. This equation, coupled with measurements on the effect of hydrolysis on recorded tape performance, is used to predict proper environmental storage conditions for magnetic tape.

I. INTRODUCTION

MAGNETIC RECORDING tapes enjoy widespread use as a popular recording medium ranging from home and personal use, to the entertainment industry, and for many diverse business and scientific applications. For virtually all applications, tapes perform exceptionally well, without user complaint, but occasional problems are encountered. Chief amongst the problems are manifestations related to the tapes becoming sticky, and in some cases, to the tapes shedding gummy and tacky materials which can spread undesirably over various mechanical components of tape drive and recording equipment. These gummy products can lead to increased error rates in high density digital recording. A common feature generally associated with these problems has been a history of tape exposure in a humid environment.

Fig. 1 illustrates the basic construction and components of almost all of the common magnetic recording tapes which are in use today. The tapes consist of a thin (from 0.25 to 1.50 mil) plastic film substrate with an oxide coating and for some tapes an additional backcoat. The oxide coating (from 0.1 to 0.5 mil) consists of magnetic oxide particles dispersed in a polymeric binder, while the backcoat, if used, consists of carbon particles also dispersed in a polymeric binder. Typically, the substrate is biaxially oriented poly(ethylene terephthalate) film (PET) and the polymeric binders in common use are polyester urethane elastomers. In humid environments, these elastomeric materials are susceptible to degradation by hydrolysis [1]–[4].

Previously one of the authors [5] investigated the environ-

Manuscript received November 5, 1981; revised May 17, 1982. This work was performed in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

H. N. Bertram is with Ampex Corporation, 401 Broadway, Redwood City, CA 94063.

E. F. Cuddihy is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

mental aging of a commercial magnetic recording tape in air, nitrogen, and hermetically sealed containers, and found that the primary mechanism of tape aging and degradation resulted from hydrolysis of its polyester urethane binder, for temperatures up to 75°. The chemical reaction was also found to be chemically reversible in a dry gas environment. Based on this experimental study a kinetic analysis was performed as part of a larger contractual study of archival attributes of magnetic recording [6].

This paper is organized as follows. Section II briefly summarizes the pertinent experimental techniques and results from the previous publication for air aging [5], and Section III gives an expanded presentation of the kinetics from [6] of the hydrolysis of tape binder. Section IV describes the generation therefrom of predicted acceptable and nonacceptable temperature and humidity conditions for tape use and storage and discusses experimental evidence which corroborates the conclusions.

II. EXPERIMENTAL

The previous study [5] was carried out with a commercial backcoated wide-band instrumentation tape that has a cross-linked polyester urethane binder for the oxide and backcoat layer. The binder content of the tape averaged about 9.3 wt% of the total tape weight, divided as 5.9 wt% oxide binder and 3.4 wt% backcoat binder. The quantity of hydrolyzed binder product was monitored by acetone extraction, referred to as acetone-extractable content, which was determined by weighing the tape pieces before and after acetone extraction and calculating the percentage extraction on the basis of the "before" weight. Extraction times were about 20 min in a stirred beaker. A generalization of the hydrolysis and extraction principle is illustrated schematically in Fig. 2.

At the start of the study, the tape had an acetone-extractable content of 0.64 wt% of total tape weight which, by infrared (IR) analysis of the extract, was found to be essentially all polyester urethane binder material. No acetone-extractable materials were found to originate in the polyester film substrate, nor was there any chemical evidence of extracts from the substrate during the degradation studies.

The precision of extraction values is about ± 0.004 wt%, which results primarily from the hygroscopic property of tape. Tape readily absorbs and desorbs atmospheric water vapor, with the amount of absorbed water depending on the level of

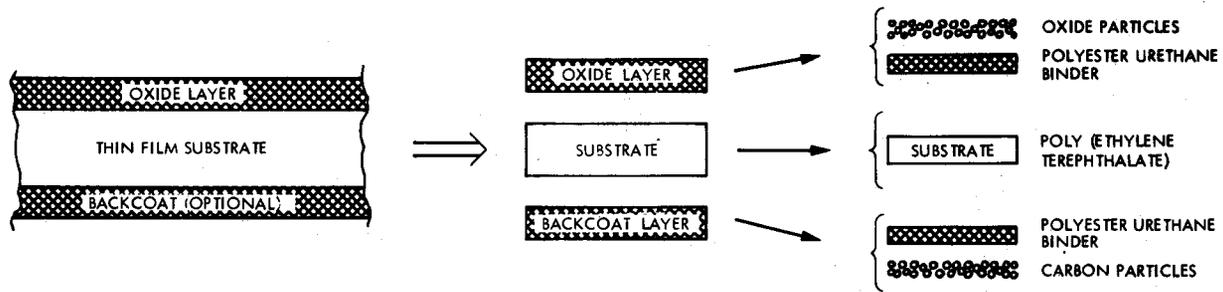


Fig. 1. Basic components of magnetic recording tape.

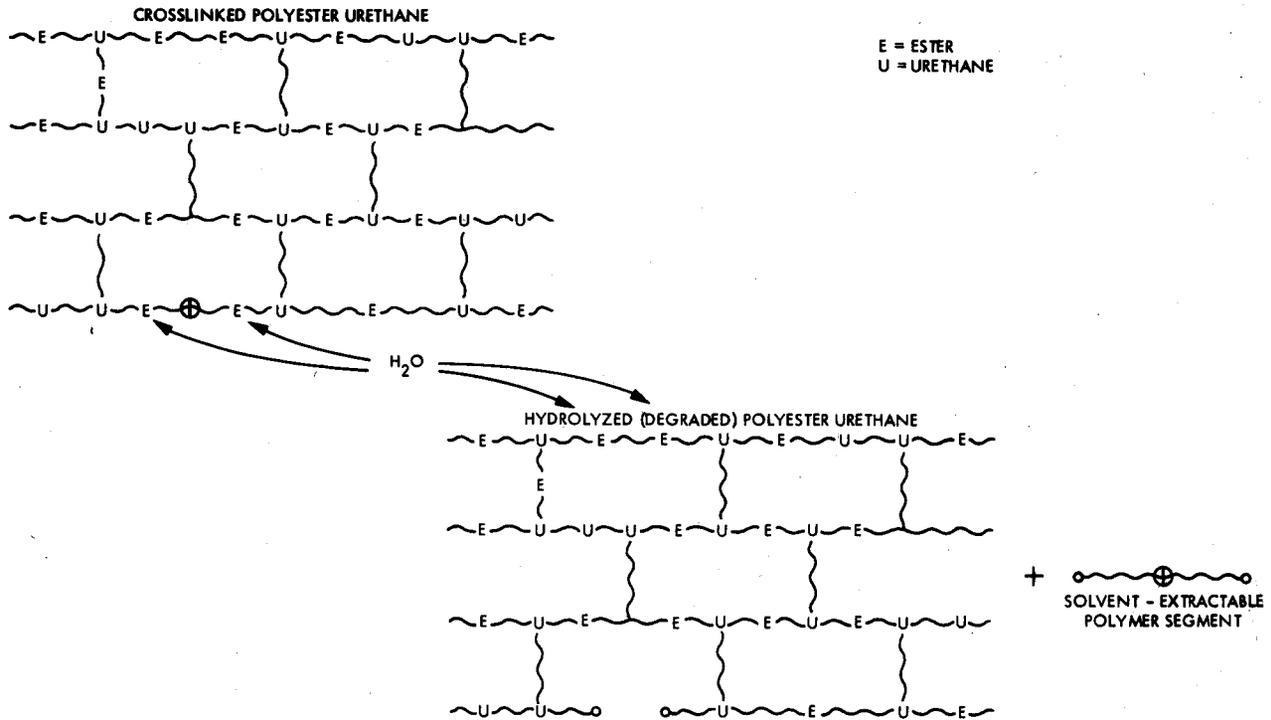


Fig. 2. Hydrolysis of tape binder to produce a solvent-extractable polymer segment.

relative humidity. The tape of this study has a water absorption coefficient of 0.008 wt% per one percent RH [7], and tape pieces were weighed in a laboratory room having RH regulated to 45 ± 5 percent RH. With a ± 5 percent RH fluctuation in room humidity, the absorbed water content of the tape pieces could fluctuate ± 0.04 wt%. All tape pieces, extracted and unextracted, were exposed to the laboratory environment for at least 1 h before weighing. Preliminary experimentation demonstrated that acetone completely volatilizes out of unwound tape pieces within 15 min, and unwound dry tape pieces equilibrate to 45 percent RH in about 30 min.

The data used in this paper are for tape pieces aged in air at relative humidity levels of 0, 30, and 100 percent, and for each humidity at four temperature levels of 36, 48, 61, and 75°C. The nominal relative humidity of 30 percent RH was established by the use of a saturated salt solution of calcium chloride. The high humidity of 100 percent RH was established with distilled water, and zero percent RH from the use of commercial tanks of dry air. Quart jars were filled to about 1 in with the solution or distilled water, and glass beakers containing

pieces of tape which were about 5 ft in length were also placed inside the quart jars. The glass beakers isolated the tapes from direct contact with the liquids. Tape pieces were removed at weekly intervals for extraction analysis. A more expanded description of the experimental techniques is reported in [5].

Figs. 3 through 6 are semilog plots of acetone-extractable content in weight percent versus exposure time in weeks for humid aging in air. These curves were previously published in [5], without the raw data points, and are essentially comparable to the curves generated from humid aging in nitrogen. Up to 75°C, atmospheric oxygen was previously observed to have a negligible contribution on the chemical degradation of the polyester urethane binders.

For aging at 36 and 48°C, using the saturated calcium chloride solutions, excessive data scatter was encountered, and it is speculated that some of the solutions used in the quart jars for these two temperatures were not completely saturated with calcium chloride. For these two temperatures, the raw data points are bounded by upper and lower dotted envelope lines. At all four temperatures the binder of the tape is observed to

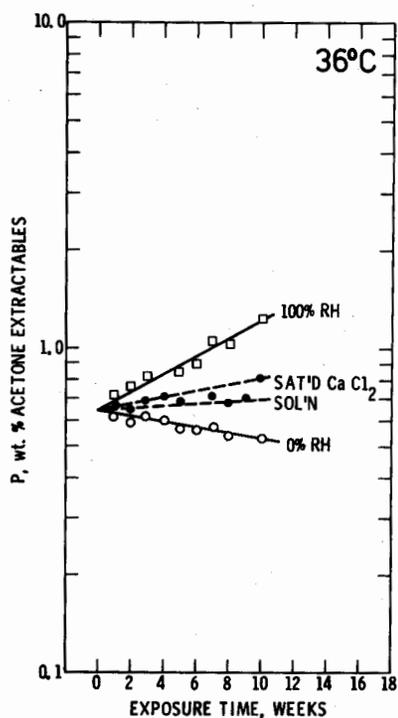


Fig. 3. Humid air aging at 36°C.

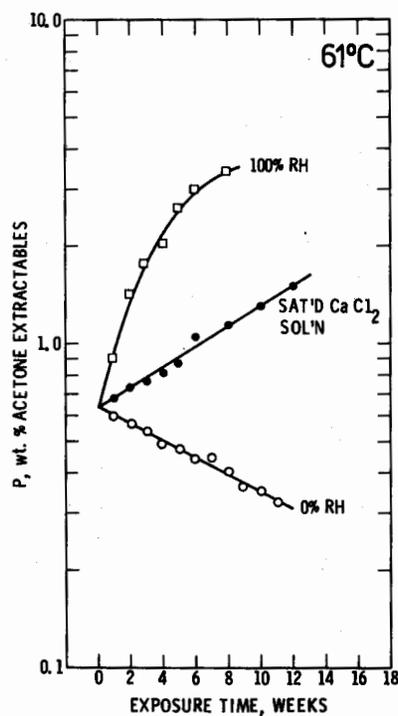


Fig. 5. Humid air aging at 61°C.

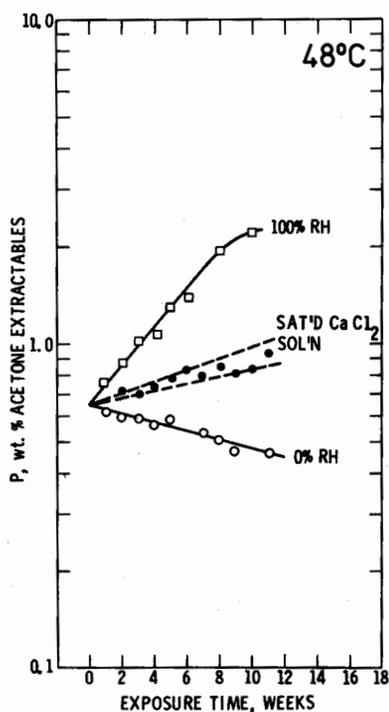


Fig. 4. Humid air aging at 48°C.

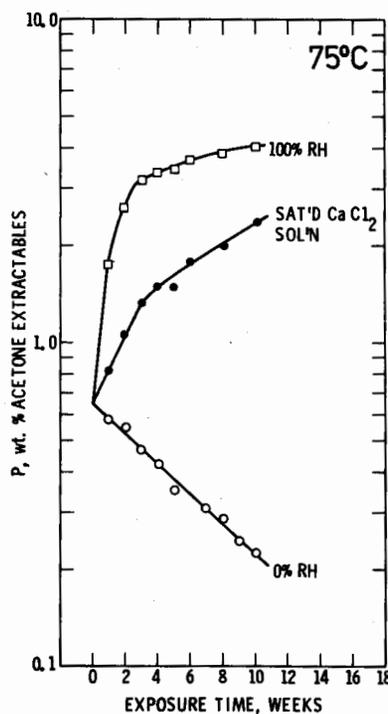


Fig. 6. Humid air aging at 75°C.

degrade at 30 (CaCl₂ solution) and 100 percent RH, and chemically improve at 0 percent RH, suggesting that the hydrolysis reaction is a reversible chemical reaction.

Further, for 30 and 100 percent RH, the semilog plots are initially linear, and then for the higher temperatures, depart from initial linearity and appear to approach asymptotes. This is also an expected behavior of a reversible chemical reaction. If aging exposure had been continued beyond 11 weeks (the

limit of the previous study), it would be expected that all of the high humidity data curves of Figs. 3-6 would have eventually approached an asymptotic limit of acetone-extractable content, which would be different for each condition of temperature and humidity. The semilog data traces for 0 percent RH are linear over the 11 weeks of exposure, suggesting, that with respect to chemical kinetics at 0 percent RH, the reverse chemical reaction is first order.

III. KINETIC ANALYSIS

The purpose of a kinetic analysis is to allow the prediction of the effect of various environments on tape hydrolysis. With this knowledge environments which lead to tape degradation can be predicted and the value of accelerated aging tests can be understood. The analysis presented here was first discussed in an Ampex Corporation contractual study [6]. The essential chemical process of polyesterurethane hydrolysis is the reaction



or, in words, ester plus water combines to yield alcohol plus carboxylic acid. In a tape system the kinetics can be altered by the presence of a wide variety of additives in the binder system, such as lubricants and dispersing agents and, approximately 33 percent by volume loading, the magnetic particles. To provide a complete chemical understanding of the hydrolysis process of filled polyester urethane elastomers entails detailed measurements of the concentrations of all the reaction constituents as well as thorough understanding of the binder constituents and those interactions.

The data presented in Section II is in the general form of measurements of total binder extract and available water. The former which does result from hydrolysis includes not only the carboxylic acid and alcohol but tape additives, particles, and broken polyester urethane chains as well. Thus an exhaustive chemical kinetic analysis cannot be performed. Nevertheless the reaction rates of binder dissolution have been measured as a function of temperature and humidity and from this an empirical kinetic expression describing these measurements can be written as



or, in words, binder B plus absorbed water W yields extractable products P . A simple linear analysis with one reaction product is assumed. The notation used here is not identical with that in [6] to emphasize clearly that the specific chemical process is not being characterized. The simplest most reasonable rate equation to describe (2), which encompasses reversibility is

$$\frac{dP}{dt} = K_f B W - K_r P \quad (3)$$

where K_f , K_r are, respectively, the forward and reverse empirical reaction rates, and P , B , W are now taken to mean the concentrations of these components. It is assumed that the molecular weight of the hydrolyzed and unhydrolyzed polymer segment is identical and therefore B and P can be expressed in weight rather than mole units. For consistency with experimental data, it is convenient to express B and P as weight percent of total tape. Thus P is identically the quantity of acetone extractable material which is experimentally reported. B_0 is defined as the total quantity of binder, which for the tape examined in Section II, was 9.3 wt%; so we may write

$$B + P = B_0. \quad (4)$$

In a previous study in which the hygroscopic properties of magnetic recording tape were investigated [7], it was experimentally observed that the quantity of atmospheric water vapor absorbed by the tape binder at 25°C is virtually proportional to relative humidity. Thus W in (3) can be replaced by

the fractional humidity R with a temperature dependent proportionally constant included in the forward reaction rate K_f . It was also shown that hygroscopic absorption times were on the order of 1-3 days. Since this is a short time with respect to hydrolysis it is sufficient to assume that absorbed water is always in equilibrium with its environment. Equation (3) can then be written in the convenient form

$$\frac{dP}{dt} = K_f B_0 R - P(K_f R + K_r). \quad (5)$$

The solution to this expression for constant R is

$$P(t) = P_e - (P_e - P_0) \exp(-t(K_f R + K_r)) \quad (6)$$

where P_0 , P_e are, respectively, the initial and final equilibrium total extracted product. P_e is given, from (5), by

$$P_e = K_f B_0 R / (K_f R + K_r). \quad (7)$$

The essence of (5) is, that dependent on the temperature and humidity, the amount of binder extractable can increase (hydrolysis) or decrease (binder reconstruction) as the process proceeds. In fact, no matter what the temperature, in a dry atmosphere ($R = 0$), the process always reverses so that the equilibrium state is zero extractable product.

For evaluation of the reaction rates, it is convenient to define the initial logarithmic rate

$$K \equiv \frac{1}{P_0} \left[\frac{dP}{dt} \right]_{t=0} = K_f R \left[\frac{B_0}{P_0} - 1 \right] - K_r \quad (8)$$

or from (7):

$$K = \frac{P_e - P_0}{P_0} (K_f R + K_r). \quad (9)$$

Therefore, at zero percent humidity ($R = 0$) the initial rate is simply from (8):

$$K = -K_r. \quad (10)$$

Thus the first order reaction constant K_r can be determined directly from the slopes of the straight lines of Figs. 3-6 for zero percent RH. These values are listed in Table I.

The values of K determined from the initial linear portion of the data of Fig. 3 through 6 for 100 percent and 30 percent RH are tabulated in Table II, along with the calculated values of $K + K_r$. For the data measured in the presence of calcium chloride solutions at 36 and 48°C, the values of K and K_r associated with the maximum and minimum dotted envelope lines are tabulated in Table II. Since at constant temperature K_f is a constant, (8) predicts that the relative humidity of the saturated calcium chloride solution is calculable from the ratio of $K + K_r$ values for 100 percent RH ($R = 1$) and $K + K_r$ values for the solution. The last column of Table II tabulates the calculated ratios where it can be observed that the predicted relative humidity at 61 and 75°C is on the order of 30 percent which agrees very well with the predictions at 36 and 48°C using $K + K_r$ values determined for the minimum dotted line. The values of K_f can be calculated from (8) using the $K + K_r$ values for 100 percent RH ($R = 1$), $P_0 = 0.64$ wt% and $B_0 = 9.3$ wt%. The calculated values of K_f are tabulated in Table I.

Arrhenius plots of K_r and K_f are shown in Fig. 7. Least squares analysis of these plots yields activation energy values

TABLE I
 FIRST ORDER REACTION RATE CONSTANTS, K_r AND K_f

Temperature °C	K_r (Weeks ⁻¹)	K_f (Weeks ⁻¹)
36	1.9×10^{-2}	0.6×10^{-2}
48	3.1×10^{-2}	1.2×10^{-2}
61	6.2×10^{-2}	3.0×10^{-2}
75	10.4×10^{-2}	8.2×10^{-2}

TABLE II
 VALUES OF $K = (1/P_0)(dP_0/dt)_{t=0}$, AND $(K + K_r)$ FOR TAPE AGING AT 100% RH, AND IN THE RELATIVE HUMIDITY GENERATED BY A SATURATED CALCIUM CHLORIDE SOLUTION

Temp. (°C)	K (Weeks ⁻¹)		$(K + K_r)$ (Weeks ⁻¹)		Ratio ^(1,2) $(K + K_r)$ (Sat'd CaCl ₂ Soln) × 100 / $(K + K_r)$ (100% RH)
	100% RH	Sat'd CaCl ₂ Soln ¹	100% RH	Sat'd CaCl ₂ Soln ¹	
36	6.3×10^{-2}	0.8×10^{-2} to 2.3×10^{-2}	8.2×10^{-2}	2.7×10^{-2} to 4.2×10^{-2}	32.9 to 51.2
48	13.6×10^{-2}	2.6×10^{-2} to 4.1×10^{-2}	16.7×10^{-2}	5.7×10^{-2} to 7.2×10^{-2}	33.7 to 42.7
61	34.5×10^{-2}	7.1×10^{-2}	40.7×10^{-2}	13.3×10^{-2}	32.6
75	100.6×10^{-2}	24.9×10^{-2}	111.0×10^{-2}	35.3×10^{-2}	31.8

¹Because of excessive raw data scatter at 36 and 48°C for the saturated CaCl₂ solution experiment, the maximum and minimum values of K , rather than an average value are quoted in this table.

²The ratio of the $(K + K_r)$ values are calculated estimates of the relative humidity of the saturated CaCl₂ solution.

of $\Delta H = 9.5$ kcal/mole for K_r and 14.2 kcal/mole for K_f . Arrhenius expressions for K_r and K_f generated by least squares analysis of the values in Table I are

$$K_r = (9.7 \times 10^4) \exp\left(-\frac{9.5 \times 10^3}{1.987T}\right), \text{ weeks}^{-1} \quad (11)$$

$$K_f = (6.4 \times 10^7) \exp\left(-\frac{14.2 \times 10^3}{1.987T}\right), \text{ weeks}^{-1} \quad (12)$$

or conveniently,

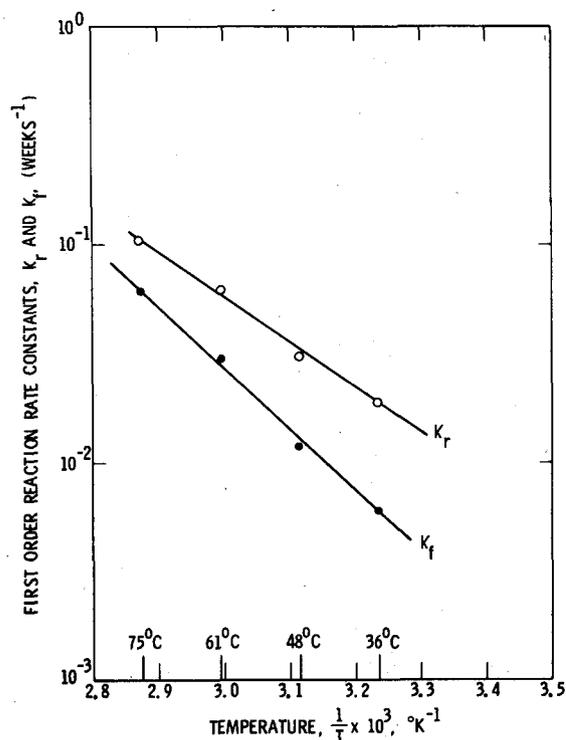
$$K_r \cong \exp(11.5 - 4750/T), \text{ weeks}^{-1} \quad (13)$$

$$K_f \cong \exp(18 - 7100/T), \text{ weeks}^{-1}. \quad (14)$$

These data may be utilized to determine two important expressions relative to the environmental storage of magnetic recording tape. The first is the environmental equilibrium curves for which there is neither hydrolysis nor binder regeneration ($K = 0$) and represents environments giving specific hydrolysis levels. The second is the time required to reach equilibrium for a given environment.

For any environmental condition of temperature and humidity, hydrolysis will proceed according to (5) and (6). The process will stop (or not begin) when equilibrium is achieved or when $dP/dt = 0$. This occurs from (5) for certain conditions of storage environments and extractable binder concentrations as given in (7). Thus we can answer the question: what is the temperature/humidity environment to yield a given percentage binder consumed or given equilibrium state. Rewritten, (8) yields

$$R = \frac{K_r}{K_f} \left/ \left(\frac{B_0}{P_e} - 1 \right) \right. \quad (15)$$


 Fig. 7. Arrhenius plots of K_r and K_f values tabulated in Table I.

where P_e here means the equilibrium concentration. Using the rates from (11)–(14), (15) can be expressed in the form

$$T = 2350 / \left(6.52 + \ln R + \ln \left[\frac{B_0}{P_e} - 1 \right] \right) \quad (16)$$

which is simple in form. In (16), as in (11)–(14), T is in de-

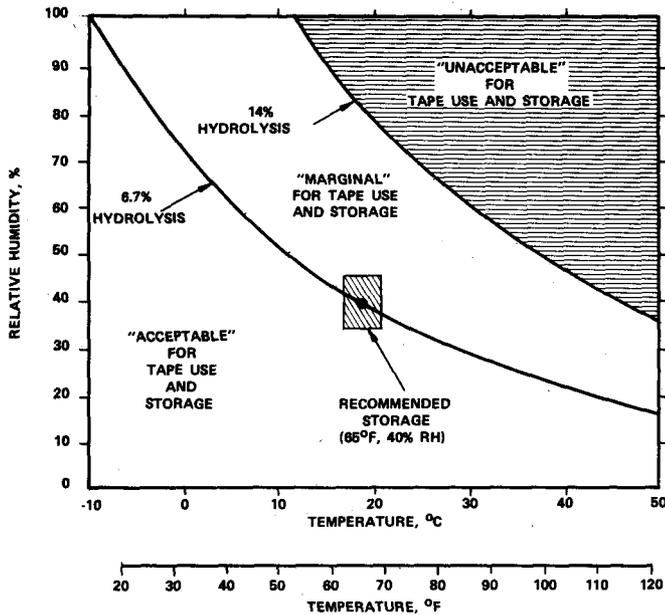


Fig. 8. Hydrolysis equilibrium curves versus humidity and temperature. Suggested limits on recommended storage environment are $\pm 3^\circ\text{F}$, ± 5 percent RH.

degrees Kelvin. Curves of constant hydrolysis level in a temperature, humidity plane may be plotted and two examples are shown in Fig. 8 for $P_e/B_0 = 6.7$ percent and $P_e/B_0 = 14$ percent. The first is the hydrolyzed concentration (P_0) of the as-received specific tape used in the experimental analysis. Storage at conditions along this line would allow no further hydrolysis from the as-received state. It is reasonable that this curve passes through nominal room environment of 65°F , 40 percent RH.

The second quantity is the time to reach equilibrium. From (6) the process reaches 90 percent of completion approximately in a time

$$\tau = 2.3/(K_f R + K_r) \quad (17)$$

For example, the time to reach equilibrium when stored at 50 percent RH, 94°F (which yields 14 percent binder dissolution) is 109 weeks or approximately two years. However storage at 100 percent humidity and 54°F (which also yields 14 percent binder dissolution) requires approximately six years to reach that state.

IV. REASONABLE STORAGE ENVIRONMENTS

It was pointed out in the introduction that tape exposure to or storage in humid environments was a recognized factor when performance problems with tapes were encountered. One consequence of humid exposure which has been discussed in this paper is the generation of acetone extractable material, whose quantity may be treated as an index of the extent of humid degradation.

It is probable that performance difficulties in a tape system occurs when the level of hydrolysis reaches a critical level. Such a level would be dependent, of course, on the particular tape system: the effect of a gummy binder would depend on the head geometry, tape tension, recorded bit density. Never-

theless, limited data on this question had been obtained on the tape utilized in this study by exposing 1000 ft reels to 100 percent RH, 75°C environment [5]. The reels were removed at increasing incremental levels of acetone extractable material and operated on an instrumentation recorder. In general, operational problems with the tape were always noticed when the acetone extractable content exceeded 1.5 wt% and not noticed when the content was less than 1.3 wt% (14 percent total binder). Storage at this environment would eventually reach an equilibrium binder degradation of 44 percent of the total binder content. Thus, accepting 1.3 wt%, or 14 percent total binder, as the maximum allowed for the quantity of acetone extractable matter in this tape, then the unacceptable conditions of relative humidity and temperature are those which promote an equilibrium concentration P_e of acetone extractable matter equal to or greater than 14 percent binder hydrolysis as plotted in Fig. 8 using (7) and (11)-(14). Thus it appears from the basis of this data that environments which allow hydrolysis to approximately 14 percent binder dissolution are acceptable before tape performance degradation occurs. For example, when stored at an environment of 50 percent humidity, the temperature could increase perhaps to 90°F , or when stored at 65°F the humidity could be increased to approximately 80 percent before tape performance suffers.

A partial verification of the general validity of the conclusions drawn here comes from studies of accelerated aging performance in an Ampex study [6]. In this study tapes of three different manufacturers were exposed for a year at 55°C , 100 percent humidity. Digital random sequences were recorded on these tapes, spanning low density computer to high density instrumentation application. The results of Section II predict 34 percent binder dissolution after 30 weeks of storage for this environment. In reasonable agreement with the 14 percent limitation, all tapes showed serious degradation by shedding sufficiently gummy products to disallow tape transport operation after 6 to 9 months storage. Increased error rates were measured after an initial three months storage period. Utilizing (6), only one month storage is required to achieve 14 percent binder dissolution which, according to studies just discussed above, is the anticipated onset of poor machine performance. Other tapes in the Ampex study were stored at room environments 40 percent humidity, 60°F and only slight error rate increase was measured over the study period.

From the experiments discussed above, it appears that measurements of hydrolysis upon one particular brand of tape may be applied to infer storage conditions for current production tapes in general. Perhaps even though tape binder systems are complicated with a multitude of additives, the end product requirements result in great similarity with respect to hydrolytic behavior of tapes from different manufacturers. It is clear, however, that further studies of chemical hydrolysis are necessary to understand completely the process and to relate specifically error rate degradation of particular tape systems and recording densities to their storage environments.

Since reversibility of the hydrolysis process entails rejuvenation of hydrolyzed binders, it is important to emphasize that rejuvenation times are in general impractically long. For example, suppose a tape is inadvertently exposed for three months

(e.g., a summer) to an environment of 100 percent RH and 95°F; utilizing (6) yields a hydrolysis state of $P/B_0 = 12$ percent. Such a level of degradation may lead to poor machine performance. If it is desired to restore the tape to the original chemical condition, say $P_0/B_0 = 6.9$ percent by storage at 0 percent humidity, 95°F, (6) predicts 27 weeks rejuvenation time. Restoration times are generally long and this example yields about twice the time to cause the original hydrolysis. As a practical matter, it has been shown that 1-3 days storage in room environment followed by perhaps a tissue wipe is sufficient to return the tape to a playable low error rate state. The former is the time required for hygroscopic diffusion to remove water [7] and the latter to remove gummy debris left from the hydrolysis process [6].

It has been common practice in the tape industry to qualify the tapes for environmental stability by looking at the effect on performance, error rate, RF output, etc., by storage in an adverse environment, typically 90 percent humidity, 95°F, for perhaps a month. Even though such a test may or may not yield serious performance degradation, it is clear from this study that such a test does not relate simply to storage at room environments. An accelerated test can easily cause serious hydrolysis and poor tape performance and still the tape can be stored acceptably for many years at room temperatures at nominal humidities according to Fig. 8. The principle value of such qualification tests might be perhaps to disqualify particularly bad tapes for other reasons. The best solution, of course, is to understand the various chemical processes in the tape system which lead to degradation, including hydrolysis, so that a reasonable long-term storage environment can be predicted. This is particularly important since magnetic tape is always evolving and future products may not have the same chemical constituents as those currently in use.

This paper is concerned only with the analysis of the hydrolysis of tape binder systems with regard to proper archival storage. As discussed in [6] there are mechanical considerations for optimum storage which might be considered in addition to hydrolysis in order to properly specify storage environments. Since it is inevitable that Fig. 8 can be used as a storage environment guide it is necessary to include briefly, the mechanical consideration from [6].

The essential mechanical considerations are 1) storage at high temperatures increases the stress relaxation of the pack, 2) increase of temperature above the winding temperature increases the pack pressure due to differential expansion of the pack and hub, and 3) a decrease in storage humidity below the winding humidity can lead to increased pack pressure due to hygroscopic contraction of the pack relative to the hub. These three factors can lead to pack slip or cinching once the tape has been returned to operating environment and thus to increased rewind frequency requirement. Given these considerations plus the fact that the data on increase of error rate with hydrolysis and recording density is limited, a most

reasonable storage environment would be near a lab environment of 65°F, 40% RH with tight limits in fluctuation to reduce rewind frequency.

V. CONCLUSION

The kinetics of hydrolysis of magnetic recording tapes containing polyester urethane binder systems has been studied. It is found that the process is reversible, thus definite environments exist which permit long-term archival storage of the media. Data on performance degradation versus storage environment as well as studies of the effect of environment on pack mechanical stability suggest that the most reasonable storage environment is one close to tape operating conditions and encompasses nominal human environments.

Although the data utilized in the study involved a limited number of tapes, the conclusions are expected to hold generally for polyester urethane binder systems. It is clear that further studies of chemical hydrolysis are necessary to understand completely the degradation process. In addition, detailed studies of the effect of storage environment on error rate versus packing density should be performed. With such information accelerated aging tests might become meaningful.

In conclusion, the results of this study suggest that tapes constructed with polyester urethane binder systems should not degrade during archival storage if a proper environment is maintained. An optimal environment is one close to 65°F, 40 percent humidity with tight limits on fluctuations.

REFERENCES

- [1] D. W. Brown, R. E. Lowry, and L. E. Smith, "Kinetics of hydrolytic aging of polyester urethane elastomers," *Macromolecules*, vol. 13, pp. 248-252, 1980.
- [2] J. H. Saunderson and L. C. Frisch, "Polyurethanes: Chemistry and technology," in *High Polymers*. New York: Wiley, 1974, vol. XVI.
- [3] G. Magnus, R. A. Dunleavy, and F. E. Cutchfield, "Stability of urethane elastomers in water, dry air, and moist air environments," *Rubber Chem. Tech.*, vol. 39, p. 1328, 1966.
- [4] Z. T. Ossefort and F. B. Testroet, "Hydrolytic stability of urethane elastomers in water, dry air, and moist air environments," *Rubber Chem. Tech.*, vol. 39, p. 1328, 1966.
- [5] E. F. Cuddihy, "Aging of magnetic recording tape," *IEEE Trans. Magn.*, vol. MAG-16, no. 4, pp. 558-568, July 1980.
- [6] H. N. Bertram and A. Eshel, "Recording media archival attributes (magnetic)," Final Rep. Contract #F30602:78:C-0181 AFSC Rome Air Dev. Center, 1979.
- [7] E. F. Cuddihy, "Hygroscopic properties of magnetic recording tape," *IEEE Trans. Magn.*, vol. MAG-12, no. 2, pp. 126-135, Mar. 1976.
- [8] R. C. Golike and S. W. Lasoski, Jr., "Kinetics of hydrolysis of polyethylene terephthalate," *J. Phys. Chem.*, vol. 64, pp. 895-898, 1960.
- [9] W. McMamon, H. A. Birosall, G. R. Johnson, and E. T. Camilli, "Degradation studies of polyethylene terephthalate," *J. Chem. Eng. Data*, vol. 4, pp. 57-82, 1959.
- [10] J. A. Brydson, *Plastic Materials*. New York, NY: Van Nostrand Reinhold, 1970, 2nd ed.
- [11] J. V. Schmitz, *Testing of Polymers*. New York: Wiley-Interscience, 1965, vol. 1.