ARKIVAL TECHNOLOGY CORPORATION

ENVIRONMENTAL STABILITY STUDY AND LIFE EXPECTANCIES OF MAGNETIC MEDIA FOR USE WITH IBM 3590 AND QUANTUM DIGITAL LINEAR TAPE SYSTEMS

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EXECUTIVE SUMMARY

This study investigated environmental stability and life expectancies of magnetic media used with the high density, digital storage systems, specifically the IBM 3590 and both Quantum's Digital Linear Tape (DLT) and Super DLT products for the archival preservation of electronic records.

All magnetic media of the study were subjected to several temperature/humidity environments. Environmentally conditioned tape cassettes and tape samples were periodically tested for changes in bulk magnetic properties, physical and chemical properties, recording/playback performance, errors, life-expectancy (LE) and the overall impact of these parameter changes on long term preservation.

The study determined the magnetic saturation moment to be the most sensitive to environmental storage. In all temperatures and humidities tested the DLT media exhibited the least change. A calculation of LE based on magnetic saturation changes showed the DLT media had the highest LE in almost all environmental conditions reported. In all cases, the LE of the 3590 media was less than that of the DLT; the magnitude of the difference in LE varied with the environmental storage condition.

Binder hydrolysis extracts from the evaluated tape media revealed minimum degradation and only minor changes in their compositions over time. Tapes subjected to the most severe environmental condition of 100 ^{o}C and 100% RH did show significant signs of physical breakdown. The DLT and SDLT tapes were amongst the slowest to show visual signs of degradation, although these too degraded eventually.

The changing values of resistivity with environmental exposure were substantial but within specification limits. The DLT and SDLT tapes were the most stable on both their magnetic and conductive sides.

Changes in friction coefficient resulting from time exposure to the three environmental conditions indicated the DLT and SDLT media exhibited the least change.

The frequency response of each tape media was compared to its original after each interval of temperature/relative humidity (RH) exposure. Throughout all test environments, the DLT and SDLT tapes were the most stable among the subject tapes of this evaluation.

Tape/drive errors resulting from both the first write operation and all subsequent reads were studied for the SDLT, DLT and 3590; including changes resulting from environmental exposure. Parameters of importance during write and read were correctable block errors, retries, non-correctable block errors and the error rate (B*ER). Although dependent upon the storage environment, the SDLT error correction efficiency was most favorable followed thereafter by the DLT and 3590.

Selected end-of life (EOL) criteria and mathematical models were used with actual data to predict the life expectancies (LE) of these storage systems. LE's were calculated on the basis of the media storage at the different environmental conditions. The effectiveness of each Storage Device's error correction code (ECC) efficiency influenced their resulting life expectancies. The DLT and SDLT exhibited greater LE's than the 3590 in almost every environmental condition and results were consistent with the error studies and the LE results based upon magnetic saturation.

In all technical investigation areas reported, the DLT/SDLT tape product demonstrated the most environmentally stable performance and is the most favorable archival tape storage medium.

Overall, the three products evaluated demonstrated an impressive ability to deliver data reliably and are representative of the progress of storage technology. Tape failures and data losses however were observed with all three storage products studied. It is critical to recognize the likelihood of this potential failure and plan for it accordingly.

STUDY OVERVIEW

1.1 TECHNICAL AREAS OF STUDY

The specified tasks of the study embodied six (6) technical areas significant to a magnetic storage media undergoing change. They are

- Magnetic and microstructure analysis of the recording media
- Intrinsic magnetic characteristics,
- Physical characteristics,
- Binder chemistry,
- Recording characteristics,
- Error/drive performance

A cooperative technical exchange was established with both IBM and Quantum, the storage system manufacturers. Technical issues, recommendations and revisions in the testing procedures were addressed with consideration to the study objectives and the complexity of the individual drive products. Test methods were finalized thereafter to insure resulting data was indicative of the changing state of the recording media.

1.2 DURATION OF STUDY

Each identified property was measured for change at 3-4 week intervals during the course of the study. The study duration varied by attribute depending upon its significance and/or changes noted in the course of the study. The designated attribute is listed below:

Attribute -Test
Magnetics- VSM parameter changes
Physical Properties
-Resistivity changes
-Friction changes
Binder Hydrolysis
Recording Property-RF Amplitude changes
Tape Error changes

1.3 STORAGE SYSTEM AND TAPE MEDIA STANDARDS

International standards exist for all three of the products studied. ECMA/ISO/ANSI test methods and procedures were used in this study when appropriate and applicable. Information provided in these standards and the manufacturers published product specifications were used to determine technical detail. An overview of the relevant features of the storage products studied is noted in Table A.1.1 in Appendix 1.0 along with their corresponding ECMA/ANSI specifications.

1.4 TEST ENVIRONMENTS

The selection of test environments was critical to the study and was specified by the National Archives and Records Administration (NARA). Additional environments were included in the Arkival study to accelerate changes in the tape storage medium. The following Table 1.2 compares the original equipment manufacturer (OEM) product specifications, test environments used in this study and the storage environment used by NARA.

TABLE 1.2 ENVIRONMENTAL DATA

OEM Specs		**Store**	**Operate**	**Test**
IBM 3590	ECMA 278	32 °C /80%RH	32 °C /80%RH	25 °C /60%RH
DLT IV	ECMA 286	32 °C /80%RH	32 °C /80%RH	25 °C /60%RH
Super DLT	ECMA 320	32 °C /80%RH	40 °C /80%RH	25 °C /60%RH
Arkival Study		**Condition 1**	**Condition 2**	**Condition 3**
		40 °C /50%RH	50 °C /75%RH	50 °C /85%RH
NARA ER Storage		**Storage**		
		20°C/45%RH		

1.5 DATA COLLECTION & ANALYSIS

The complexity of these new tape storage products has changed dramatically since the last NARA media report in 1988 (1). Discussion with both IBM and Quantum resulted in the determination of appropriate data to be collected and compared for the purpose of the study. The collection of additional data also insured that information significant to change would not be lost or overlooked. The extensive volume of test data being generated from the different investigatory areas of the program, particularly the error study needed management. Data management and analysis became a critical focus in the program as methods were developed to prepare the data for summary and reporting. Important data summaries are included in the appendix of this report.

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(1) Weir, T.E. National Archives Technical Information Paper #4 (June, 1988)

1 TECHNICAL STUDY

2.1 MAGNETIC AND MICROSTRUTURE ANALYSES OF THE RECORDING MEDIA

OBJECT: To characterize the recording media available for the three (3) storage devices
BASIS: To technically characterize and identify the major media types and manufacturing traits of recording tapes used in the study.

DISCUSSION
Storage device users typically have several brand name choices of recording media. A common practice in the industry is for tape manufacturers to have OEM arrangements with one another regarding specific tapes for certain storage devices. Although suggestive to users that they have different brands of choice, many brands are private-labeled as such and produced by one or two manufacturers. The aspect of the study was designed to:

- Profile the intrinsic magnetic parameters of the recording media
- Identify, compare and understand the microstructure of the recording media
- Determine the technical fingerprint(s) of recording media available for the three (3) storage devices being investigated
- Technically identify the major media sources/licensees and determine the basis for tapes used for the remainder of the study and…
- Provide NARA with alternative media sources for each storage device evaluated

Specific tape purchases were made from Distributors at 3 nationwide locations so that different lots of media could be included in the study. Tape stock was purchased with the following brand names. *See table to right.*

DLT IV:	Quantum, Fuji, Maxell, Imation, Sony.
Super DLT:	Quantum, Maxell
IBM 3590:	IBM, BASF(Emtec), Imation
IBM 3590E	IBM, BASF(Emtec), Imation

RESULTS

2.1.1 TEM ANALYSIS

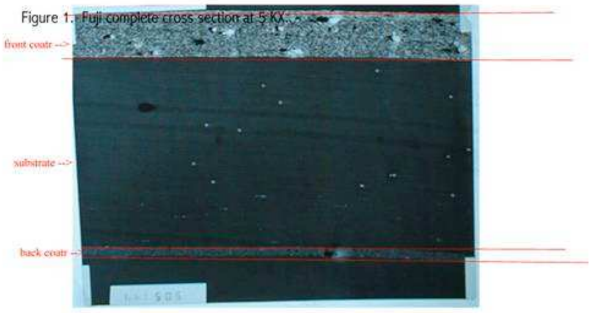


Figure 1. Fuji complete cross section at 5 KX.

Samples of various vendors' tapes were prepared for transmission electron microscopy (TEM) analysis to reveal the microstructure of the tapes in cross-section. This information was sought to determine structure, uniqueness and identity by tape manufacturer. The results of the ‘brand name’ tape study are included in Appendix 2.1 Representative results are included in the following discussion. The test tapes were studied via their TEM cross sections at several different magnifications. Two distinct media manufacturing technologies were determined from the TEM analysis; single and double layer magnetic coatings. The IBM 3590 media was all single coated and the Quantum DLT and SDLT media were all double coated. The other reference tapes in the evaluation (BaFe and MP-DLTIII) were single coated.

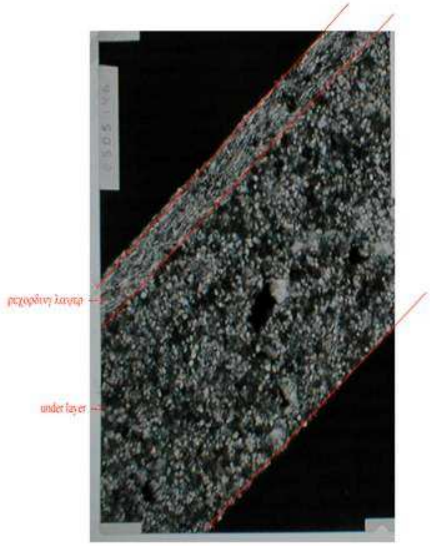


Figure 2. Fuji recording side at 25 KX showing double layer.

Figure 1 is the lowest magnification (5kx) of the Fuji DLT IV tape showing its entire cross section, the front coat (magnetic later) on top, the substrate and the backcoat (conductive layer).

Figure 2, of the same tape at 25 kx magnification illustrates the double layer magnetic coating; the magnetic layer consists of a thin layer of oriented acicular metal particles and it’s non-magnetic under layer of spherical TiO_2-type particles.

The Figure below, labeled Figure 6 is a high magnification (25kx) micrograph of the IBM 3590 tape showing its single layer technology.

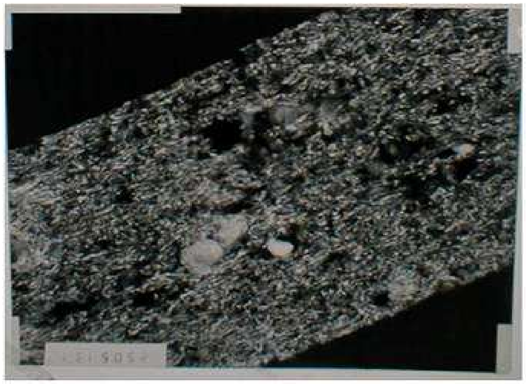


Figure 6. IBM recording side at 25 KX showing no double layer.

The actual micrographs were also used to measure media component thicknesses for the magnetic calculations. A comparison of measured thicknesses obtained from both low and high magnification TEM’s is included in Table 2.1.1.

When the Quantum DLT and SDLT tape data from the Table is grouped by likely manufacturers, Fuji (MA) and Maxell (SH), the average double-coated magnetic layer thickness' are 0.233 um and 0.312 respectively. The higher magnification indicated the Maxell SDLT and DLT IV tapes are almost identical in their thicknesses. The IBM 3590 and BaFe tapes are much thicker – representative of the single coating technology. The coating methodology selection by the storage device manufacturer is influenced by the storage capacity of the device, the recording density assigned to the storage medium, the type of magnetic heads, the read/write channel design, et. al. Double coated media has generally been associated with higher recording densities but the head/tape interface, media specifications and channel design can greatly influence the recording density capability of single coated media.

Table 2.1.1 Media Layer Thickness-obtained from TEM micrographs*

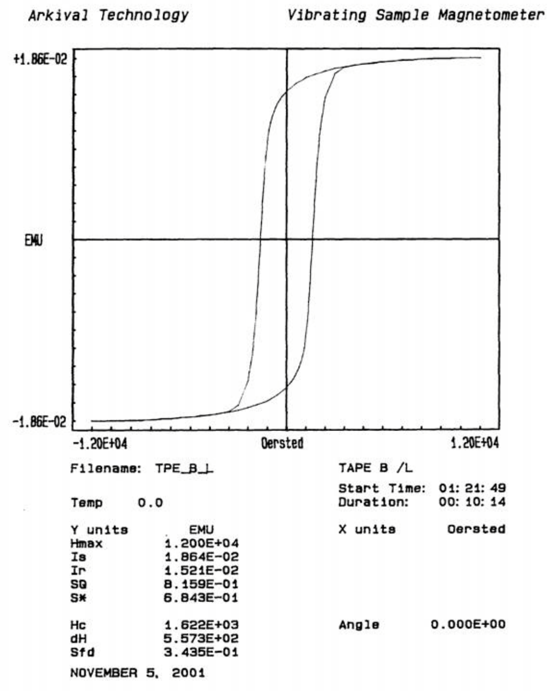
Study #	**Brand**	**Type**	**Top layer (μm)**	**Substrate (μm)**	**Back layer (μm)**	**Total (μm)**	**Magnetic layer (μm)**
A	Quantum	DLT IV	2.08	7.87	0.45	10.40	0.264
B	IBM 3590	3590	2.51	18.24	0.50	21.25	-
C	Quantum	S DLT I	2.06	8.86	0.47	11.41	0.197
D	Maxell	S DLT I	2.18	7.45	0.49	10.12	0.327
E	Fuji	DLT IV	2.08	8.62	0.47	11.17	0.321
F	Maxell	DLT IV	2.49	9.54	0.43	12.46	0.245
G	Sony	DLT IV	2.03	8.11	0.51	10.65	0.265
H	Imation	DLT IV	2.32	8.75	0.51	11.58	0.333
I	Arkival BaFe	DLT III	2.40	14.67	0.63	17.70	-
J	Quantum	DLT III	-	-	-	-	-

** See complete data file in Appendix 2.1*

2.1.2 VSM ANALYSIS

The intrinsic magnetic parameters of the tape media were measured on a Vibrating Sample magnetometer (VSM).

The hysteresis loops for several representative tapes are shown below in Figures 2.1.3 thru 2.1.6 (where B= 3590; C=SDLT; E=DLT IV; I=BaFe).



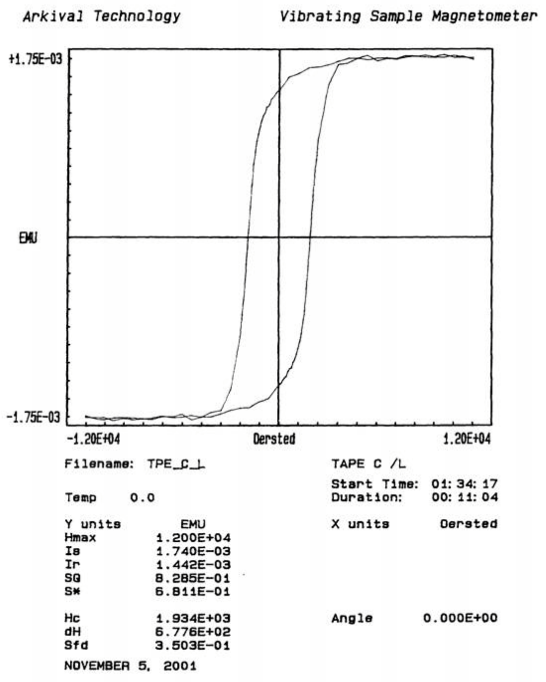
Arkival Technology *Vibrating Sample Magnetometer*

```
Filename:  TPE_B_⊥                  TAPE B /L
                                    Start Time:  01: 21: 49
Temp     0.0                        Duration:    00: 10: 14

Y units          EMU                X units         Oersted
Hmax          1.200E+04
Is            1.864E-02
Ir            1.521E-02
SQ            8.159E-01
S*            6.843E-01

Hc            1.622E+03             Angle         0.000E+00
dH            5.573E+02
Sfd           3.435E-01

NOVEMBER 5,  2001
```



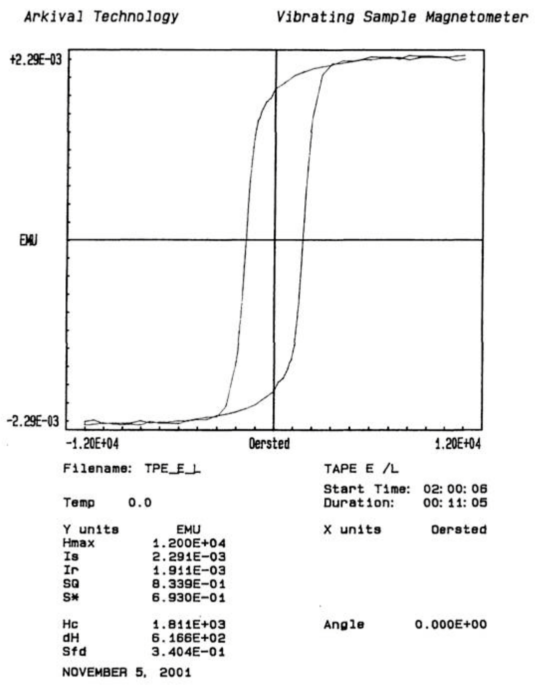
Arkival Technology *Vibrating Sample Magnetometer*

```
Filename:  TPE_C_⊥                  TAPE C /L
                                    Start Time:  01: 34: 17
Temp     0.0                        Duration:    00: 11: 04

Y units          EMU                X units         Oersted
Hmax          1.200E+04
Is            1.740E-03
Ir            1.442E-03
SQ            8.285E-01
S*            6.811E-01

Hc            1.934E+03             Angle         0.000E+00
dH            6.776E+02
Sfd           3.503E-01

NOVEMBER 5,  2001
```



Arkival Technology *Vibrating Sample Magnetometer*

```
Filename:  TPE_E_⊥                  TAPE E /L
                                    Start Time:  02: 00: 06
Temp     0.0                        Duration:    00: 11: 05

Y units          EMU                X units         Oersted
Hmax          1.200E+04
Is            2.291E-03
Ir            1.911E-03
SQ            8.339E-01
S*            6.930E-01

Hc            1.811E+03             Angle         0.000E+00
dH            6.166E+02
Sfd           3.404E-01

NOVEMBER 5,  2001
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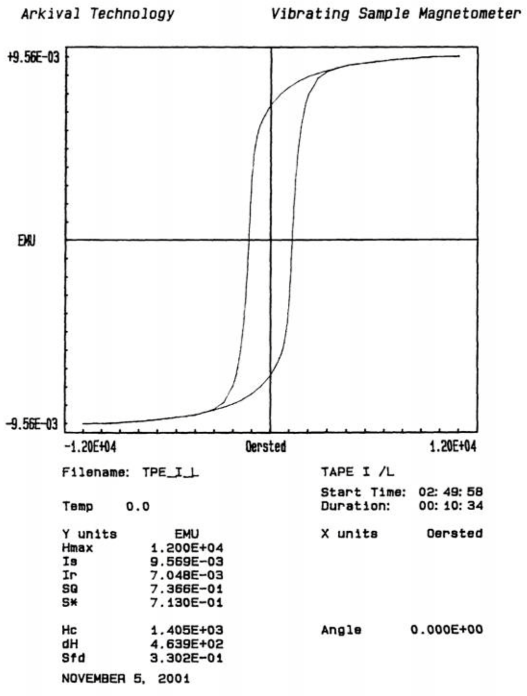


Arkival Technology *Vibrating Sample Magnetometer*

```
Filename:  TPE_I_⊥                  TAPE I /L
                                    Start Time:  02: 49: 58
Temp     0.0                        Duration:    00: 10: 34

Y units          EMU                X units         Oersted
Hmax          1.200E+04
Is            9.569E-03
Ir            7.048E-03
SQ            7.366E-01
S*            7.130E-01

Hc            1.405E+03             Angle         0.000E+00
dH            4.639E+02
Sfd           3.302E-01

NOVEMBER 5,  2001
```

A summary of the corresponding VSM results is shown in Table 2.1.2 below. There are two types of double coated tapes in the selection; one with an Is ~ 1.9 memu's and a coercivity (Hc) of 1920 oersteds (Maxell-type); the other with ~2.4 memu's and an 1810 coercivity (Fuji-type). The IBM 3590, DLT III and the BaFe tapes represent the thicker single coating technology and usually have higher saturation and remanence values.

Table 2.1.2 Summary of VSM Data*

Study #	Brand	Type	Is (memu)	Ir (memu)	SQ (Ir/Is)	Hc (Oe)	SFD	SQt	OR (Sql/Sqt)
A	Quantum	DLT IV	1.96	1.56	0.79	1915	0.35	0.40	1.98
B	IBM	3590	18.64	15.21	0.82	1622	0.34	0.37	2.19
C	Quantum	S DLT I	1.74	1.44	0.83	1934	0.35	0.35	2.36
D	Maxell	S DLT I	1.96	1.64	0.84	1930	0.35	0.37	2.26
E	Fuji	DLT IV	2.29	1.91	0.83	1811	0.34	0.37	2.25
F	Maxell	DLT IV	1.77	1.41	0.80	1920	0.35	0.36	2.20
G	Sony	DLT IV	2.40	1.99	0.83	1819	0.33	0.37	2.24
H	Imation	DLT IV	2.50	2.03	0.80	1801	0.33	0.40	2.00
I	Arkival BaFe	DLT III	9.57	7.05	0.74	1405	0.33	0.38	1.92
J	Quantum	DLT III	19.34	15.24	0.79	1479	0.35	0.38	2.07

** See complete data file in Appendix A.2.1*

The TEM and VSM results determined the manufacturing sources of tape being sold under both OEM and private label brands. It is of interest to note that neither IBM nor Quantum manufactures their own media for these tape drive products. The IBM and Quantum products are produced for them by the OEM's and sold as private labeled media. Both Quantum and IBM have also confirmed that the sources identified are the present media licensees, respectively. Also obvious from the data is that the Imation and Sony DLTIV product is most likely made by Fuji under private label. The Quantum SDLT media is very similar to that being used for the Quantum DLT IV product and is likely selected DLT IV media made by Maxell. Depending upon product source availability, this information will provide NARA with the capability of having alternative media sources for each storage device (i.e. with the exception of Super DLT media).

The five sources of OEM Tape used for the remainder of the study were:

Quantum DLT IV: Fuji, Maxell
Quantum Super DLT: Maxell

IBM 3590: BASF (Emtec), Imation

2.2 VSM/ AGING STUDY

OBJECT: To determine the changes in the recording media resulting from environmental exposure.
BASIS: Observe the intrinsic magnetic parameters of the recording media that could/will affect the media's ability to record, store and retrieve data.

DISCUSSION

The intrinsic magnetic parameters have typically demonstrated their sensitivity to changes in media performance. The effects of environmental exposure on these magnetic parameters are also an important indicator of the life expectancy of the media. A Vibrating Sample Magnetometer (VSM) was used to obtain Hysteresis curves for the magnetic tapes under study. The VSM parameters (Is, Ir and Hc) for each tape sample were compared to its original after each interval of Temperature/RH exposure. In addition to the standard test conditions (40C/50% RH and 50C/75% RH) additional test conditions were utilized to accelerate change and induce trends. (0%; 30%; 50%; 75%; 85% and 100% RH at 40, 50 and 80^{o}C).

RESULTS

Effects of Temperature and Humidity Exposure on the Magnetic Properties.

Samples of each tape studied were environmentally conditioned for periods of time from 100 hours to 3500+hours. Typical results are shown in Table 2.2.1 below for a 29 day exposure to 80C/85%RH. Tables of similar data for other study conditions are included in Appendix 2.2. Each tape sample had three replicates. The saturation magnetization (Is), remanent magnetization (Ir), and coercive force (Hc) were measured before and after exposure to 80C /85% relative humidity (RH) for 29 days. The last columns show the percent change of these parameters over this exposure period. In the case of Quantum DLT tape, there is a 21 % loss in Is, a 21.6 % loss in Ir and only a slight change in Hc (~3 %).

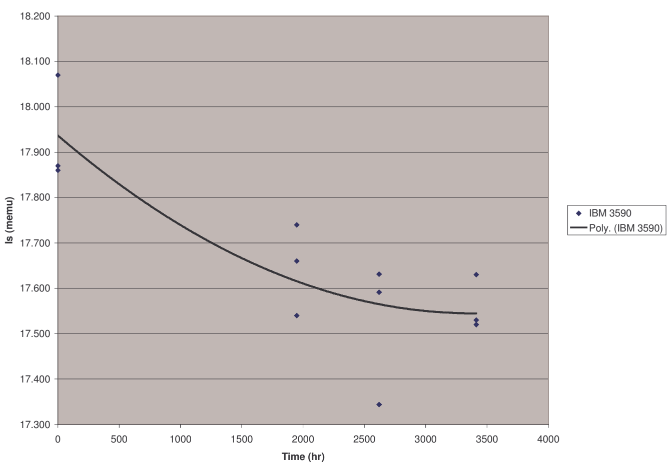
Ir and Hc are structure sensitive properties and changes in the magnetic particle as well as oxidation can affect them. The change in Is is proportional to the amount of oxidation of the metal particles (MP) when they are converted from ferromagnetic iron to non-ferromagnetic iron oxide. Little change however, is to be expected in Hc until more tape/particle oxidation takes place. The total degree of oxidation seen in this table, as measured by Is, varies from 3 to 43 %. The BaFe tape was the most stable and indicated the least amount of change. In the case of MP-DLTIII tape, a notable loss in Hc was observed after 29 days.

TABLE 2.2.1 VSM Data 80C/ 85% RH

			Case:	80 C/85 % RH					
		Initial			AFTER 29 DAYS			AVG %	AVG %
		Is	**Ir**	**Hc**	**Is**	**Ir**	**Hc**	**delta Is**	**delta Ir**
Quantum	DLT 1	1.717	1.439	1946	1.357	1.128	1890	-21.0	-21.6
	2	1.697	1.444		damaged				
	3	1.647	1.4		damaged				
IBM	3590 1	17.23	14.06	1628	12.42	9.861	1566	-28.3	-30.0
	2	16.89	13.7		12.02	9.436			
	3	16.12	13.07		11.6	9.271			
Quantum	S DLT I 1	1.512	1.341	1983	1.197	1.026	1917	-20.3	-21.5
	2	1.599	1.361		1.228	1.057			
	3	1.486	1.269		1.237	1.031			
Fuji	DLT IV 1	1.75	1.528	1861	1.463	1.289	1825	-14.8	-15.7
	2	1.927	1.672		1.66	1.42			
	3	1.883	1.67		1.614	1.395			
Arkival	BaFe 1	9.051	6.75	1395	8.746	6.431	1352	-2.9	-4.0
	2	9.054	6.778		8.835	6.514			
	3	8.802	6.6		8.553	6.382			
	MP DLT III- 1	17.25	13.7	1488	9.82	7.384	1273	-42.8	-45.8
	2	18.26	14.52		10.44	7.835			
	3	17.39	13.7		10.02	7.496			

Changes in these magnetic properties were monitored throughout the 6 month period (see the Appendix A.2.2 for complete data).

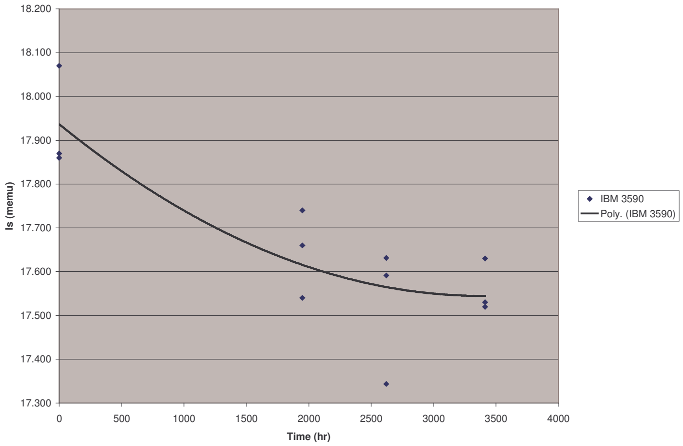
Fig. 2.2.1 Is vs Exposure Time -40C/ 50% RH



The typical behavior of Is with environmental exposure is represented in Figures 2.2.1 through 2.2.3 for a 3590 tape. The figures illustrate the media change for three of the test environments (40C/50%RH; 50C/75%RH and

50C/85%RH). The figures all show the increasing loss of magnetization (Is) with exposure time to their respective environments. A comparison of the three figures also indicates a greater loss of the magnetization (Is) with the more adverse environments.

Fig 2.2.2 Is vs Exposure Time 40C & 50 % RH



Changes in magnetic characteristics will be detrimental to performance and the most favorable tape/ media is one where little or no change takes place. Table 2.2.2 below is a summary from these findings. The observed magnetization changes are the basis for the rating order.

Fig. 2.2.3 Is vs Exposure Time- 50C/85% RH

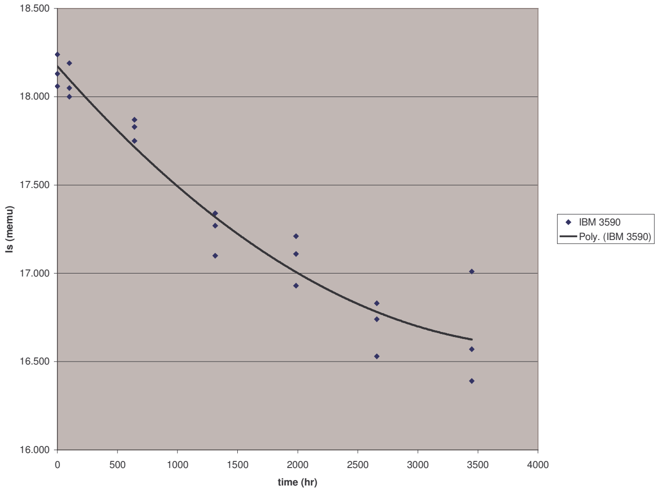


Table 2.2.2 Is Change as a function of Environmental Storage*

	40C	**50C**	**80C**
Least change	DLT-Fuji IBM-BASF (Emtec)	DLT-Fuji	DLT-Fuji
		IBM-BASF	IBM-BASF
	SDLT-Maxell	SDLT-Maxell	SDLT-Maxell

** includes all humidities tested*

The DLT Fuji media exhibited the least magnetic property change over all the environmental conditions studied. The resulting Hc data suggests no substantive changes within the present study data base.

2.3 BINDER HYDROLYSIS AND LUBRICANT STUDY

OBJECT: To determine Binder Hydrolysis and Lubrication content changes in the recording media resulting from environmental exposure.
BASIS: Observe the intrinsic binder chemistry and lubrication means of the recording media that could/will affect the media's ability to record, store and retrieve data.

DISCUSSION

The long-term stability of magnetic tape is dependent upon many factors including the integrity of the polymer binder in the magnetic recording layer. Most polymer binders are composed of polyester polyurethanes and are prone to (hydrolytic) degradation over long times and/or over shorter times under severe conditions. Early studies indicated that controlling humidity is essential for the long-term stability of polymer binder, much more so than controlling exposure to air (3). The hydrolysis of the polyester polyurethane binder was implicated as a major cause of binder degradation and because polyester hydrolyzes faster than polyurethane (4) most binder hydrolysis studies have first and foremost considered polyester hydrolysis.

Several literature reports specifically address binder hydrolysis in magnetic tape. *Partial hydrolysis* not been distinguished from *exhaustive hydrolysis* in the literature. Partial hydrolysis is defined here as the hydrolysis of large polyester chains into smaller polymer pieces that are still too large to be readily extracted by organic solvents. Exhaustive hydrolysis is the complete hydrolysis of polyester chains into low MW carboxylic acid and alcohol monomers that are readily extracted by organic solvents. One expects a breakdown in the physical structure (e.g., flaking, formation of sticky residue, etc.) and a loss of storage/retrieval performance in magnetic tape that has undergone partial hydrolysis. One does not expect, however, to form significant solvent extractable hydrolysis products until the binder is near the exhaustive hydrolysis stage.

Prior to this work, tape binder hydrolysis was studied in detail by NML (2) and Fuji(5) . The question of hydrolytic stability of magnetic tape binder was specifically addressed by subjecting several different magnetic tape samples to elevated temperatures. The NML data was fit to a kinetic model developed to describe the level of extractable binder hydrolysis product as a function of time. The model is based on a simple first order kinetic equation and makes a key assumption: magnetic tape lubricants are volatile compounds that vaporize to leave no appreciable lubricant concentration on the tapes. This assumption may not be valid under the conditions of the NML study and a significant portion of the NML solvent extracts attributed to binder hydrolysis products may in fact have been due to lubricant. See discussion in Appendix A.2.3.

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(2) Van Bogart, T.W.C National Media Labs Techl. Rept. RE0017 (June, 1994)

(3) E. F. Cuddihy, *IEEE Transactions on Magnetics*, volume MAG-16, 1980, p. 558-568

(4) J. L. Cohen and J. J. Van Aartsen, *J. Polymer. Science Symposium*, volume 42, 1973, p. 1325-1338),

(5) K. Hanai and Y. Kakuishi, *Proceedings of the 10th NASA Goddard Conference on Mass Storage Systems and Technologies in cooperation with the 19th IEEE Symposium on Mass Storage Systems*, U. of Maryland, April , 2002, p. 311-315

The data reported below, result from exposing magnetic tape samples to aging conditions that included elevated temperature and varying humidities. The purpose being:

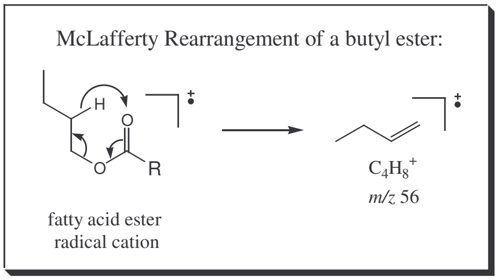
-to determine the mass of solvent extractable organic compounds from the seven magnetic tapes as a function of time spent under different aging conditions;
-to determine the molecular weight and, where possible, the molecular identity of solvent extractables;
-to determine the lubricant loss (% weight) from each tape sample as a function of time;
-to determine, where possible, the molecular identity of the lubricants used in each tape sample.

RESULTS

Table 2.3.2 summarizes the extraction data for each magnetic tape sample at time zero (i.e., before being subjected to aging conditions).

Table 2.3.2. Time Zero Extractions

Tape	Tape Sample weight (g)	Weight of CH_2Cl_2 Extractables (mg)	% Extractables	Initial GC-MS extractables (time 0)
IBM 3590-Emtec	1.015	6.0	0.6	butyl ester, trichlorobenzene
Quantum SDLT	1.003	6.0	0.6	butyl ester, cyclohexanone, trichlorobenzene
Fuji DLT IV	1.004	10.0	1.0	butyl ester, trace cyclohexanone, trichlorobenzene
Maxell DLT IV	1.001	3.0	0.3	butyl ester, cyclohexanone, trichlorobenzene
BaFe	1.005	7.0	0.7	butyl ester, trace cyclohexanone, trichlorobenzene, other esters
MP-DLT III	1.002	5.0	0.5	butyl ester, trace cyclohexanone, trichlorobenzene, other esters
IBM 3590-Imation	1.004	9.0	0.9	butyl ester, trichlorobenzene


McLafferty Rearrangement of a butyl ester:

Gas Chromatograph-Mass Spectrometer (GC-MS) studies of the extracts reveal 2-3 major components in most of the tapes at time zero. These include a butyl ester of a long chain (fatty) acid, cyclohexanone, and trichlorobenzene. The butyl ester is characterized by its MS fragmentation pattern that includes a characteristic McLafferty rearrangement fragment (*m/z* 56, $C_4H_8^+$) for an ester of a four carbon alcohol. Cyclohexanone is readily identified based on its MS fragmentation pattern. It is used in the synthesis of the polymer binder (6) and its presence in the tape samples may be unintentional. Trichlorobenzene is also identified on the basis of its MS fragmentation pattern. The MS spectrum observed is a strong match for either one of the following isomers 1,2,3- or 1,2,4- or 1,3,5-trichlorobenzene and includes the molecular ion signal at *m/z* 180, 182 and 184 due to the presence of 3 chlorine atoms, each with a ^{35}Cl : ^{37}C natural abundance ratio of 100 : 32.5.

The extraction of trichlorobenzene was unexpected and control experiments were carried out to verify that the trichlorobenzene was indeed originating with the magnetic tape samples. Pure methylene chloride samples (i.e., solvent blanks) from the same batch as used for the magnetic tape extractions were subjected to GC-MS analysis. These runs did not reveal any traces of trichlorobenzene. The trichlorobenzene likely originates with the magnetic tape samples and is not a contaminant. A search of the chemistry literature reveals multiple industrial uses for trichlorobenzene including use as a solvent (b.p. 214 ^{o}C for 1,2,4-trichlorobenzene, 218-219 ^{o}C for 1,2,3-trichlorobenzene and 208 ^{o}C for 1,3,5-trichlorobenzene), a lubricant (m.p. 16 ^{o}C for 1,2,4-trichlorobenzene, 53-55 ^{o}C for 1,2,3-trichlorobenzene and 63-65 ^{o}C for 1,3,5-trichlorobenzene), a lubricant additive, a termite exterminator, an agricultural intermediate, a dielectric fluid and a hydraulic fluid. No literature, however, was found in which trichlorobenzene was specifically mentioned as a lubricant for magnetic tape.

The GC-MS analysis for each tape enables direct comparisons between the tapes. The data reveal striking compositional similarities between the Quantum SDLT and the Maxell DLT IV tapes. See Table 2.3.2. They appear to be identical. The Fuji DLT IV is also similar to the Quantum SDLT and the Maxell DLT IV tapes, but contains less cyclohexanone. Likewise, the IBM 3590 Emtec and Imation tapes appear to be very similar to one another, but different from the others.

Tables 2.3.3 through 2.3.8 summarize the pertinent extraction data for each magnetic tape sample at temperatures ranging from 50 ^{o}C to 100 ^{o}C and % RH's ranging from 30% to 100%.

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(6) K. Nakamae, K. Yamaguchi, S Asaoka, Y. Karube and Sudaryanto, *Int. J. Adhesion and Adhesives*, volume 16, **1996**, p. 277-283)

Table 2.3.3. Percent Extractables at 50 °C and 31% RH for Indicated Times

Tape	7.1 days	14.2 days	18.7 days	36.0 days
IBM 3590-Emtec	1.0	1.2	1.1	1.4
Quantum SDLT	2.3	2.2	2.5	2.4
Fuji DLT IV	1.9	1.8	2.2	2.5
Maxell DLT IV	0.9	1.1	0.9	1.3
BaFe	1.9	2.4	2.0	2.1
MP-DLT III	1.6	1.0	1.4	1.5
IBM 3590-Imation	1.7	1.8	1.6	1.9

Table 2.3.4. Percent Extractables at 50 °C and 54.5% RH for Indicated Times

Tape	7.1 days	14.2 days	18.7 days	36.0 days
IBM 3590-Emtec	1.1	1.1	1.5	1.8
Quantum SDLT	2.2	2.0	2.6	2.5
Fuji DLT IV	2.1	2.2	2.4	2.8
Maxell DLT IV	0.9	1.0	0.6	1.1
BaFe	2.0	2.2	2.5	2.3
MP-DLT III	1.4	1.2	1.0	1.5
IBM 3590-Imation	1.8	1.6	2.1	2.2

Table 2.3.5. Percent Extractables at 75 °C and 30% RH for Indicated Times

Tape	7.1 days	14.2 days	18.7 days	36.0 days
IBM 3590-Emtec	2.1	2.9	2.4	2.7
Quantum SDLT	1.3	1.5	1.4	1.6
Fuji DLT IV	2.2	2.9	2.6	2.6
Maxell DLT IV	1.1	1.9	1.2	1.3
BaFe	2.0	2.2	2.3	2.5
MP-DLT III	1.2	0.2	1.4	1.5
IBM 3590-Imation	1.4	0.8	1.5	2.0

Table 2.3.6. Percent Extractables at 75 °C and 50% RH for Indicated Number of Days (d)

Tape	7.1 d	14.2 d	18.7 d	36.0 d	74 d	110 d	142 d
IBM 3590-Emtec	2.3	2.5	2.6	2.5	2.9	2.6	1.7
Quantum SDLT	2.3	2.6	2.8	2.2	3.0	2.5	1.6
Fuji DLT IV	2.9	2.2	3.0	2.8	3.1	1.7	1.2
Maxell DLT IV	1.7	1.6	2.5	2.5	1.9	2.0	1.5
BaFe	2.1	1.5	1.7	1.9	1.5	1.4	0.9
MP-DLT III	1.8	2.1	2.5	1.9	2.4	1.6	1.2
IBM 3590-Imation	1.6	1.8	2.2	1.9	2.3	1.7	1.0

Table 2.3.7. Percent Extractables at 75 °C and 75% RH for Indicated Number of Days (d)

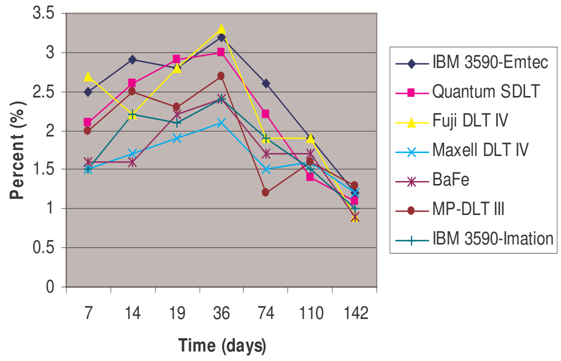
Tape	7.1 d	14.2 d	18.7 d	36.0 d	74 d	110 d	142 d
IBM 3590-Emtec	2.5	2.9	2.8	3.2	2.6	1.9	1.2
Quantum SDLT	2.1	2.6	2.9	3.0	2.2	1.4	1.1
Fuji DLT IV	2.7	2.2	2.8	3.3	1.9	1.9	0.9
Maxell DLT IV	1.5	1.7	1.9	2.1	1.5	1.6	1.2
BaFe	1.6	1.6	2.2	2.4	1.7	1.7	0.9
MP-DLT III	2.0	2.5	2.3	2.7	1.2	1.6	1.3
IBM 3590-Imation	1.5	2.2	2.1	2.4	1.9	1.5	1.0

Table 2.3.8. Percent Extractables at 100 ^{o}C and 100% RH for Indicated Number of Days (d)

Tape	2.2 d	4.4 d	7.1 d	9.5 d	11.3 d	14.4 d	16.2 d
IBM 3590-Emtec	1.0	1.2	1.0	0.8	1.2	2.5	1.9
Quantum SDLT	2.2	2.1	1.2	1.8	2.0	3.5	3.3
Fuji DLT IV	1.5	1.8	2.8	2.0	2.4	2.4	2.8
Maxell DLT IV	1.5	1.1	0.3	1.0	1.6	3.2	2.4
BaFe	2.2	2.2	1.3	2.2	2.2	2.5	2.8
MP-DLT III	1.4	0.9	1.4	1.9	1.9	1.1	0.8
IBM 3590-Imation	1.0	1.4	1.4	0.5	0.8	1.5	2.2

Most of the extraction data suggest very modest increases in percent extractables over time. For the samples held at 75 ^{o}C, this increase in % extractables is followed by modest decreases at extended times. The trend is especially noticeable in the 75 ^{o}C samples held at 50% (Table 2.3.6) and 75% (Table 2.3.7) relative humidities- *also see Figure 2.3.1.*

Fig. 2.3.1 Percent Extrables vs Exposure Time 75C & 75% RH



The initial rise in percent extractables is consistent with a slow decomposition of the tape structure which releases lubricant and other additives for extraction. The slow decline that follows is consistent with the slow evaporation of volatile additives like cyclohexanone in combination with the slow hydrolysis of ester based lubricants to form non-volatile fatty acids and volatile alcohols.

The data for the samples held at 50 ^{o}C do not show the same trend toward a maximum at intermittent times followed by a slow decrease. Much longer aging times (probably on the order of months) would likely be needed to achieve a maximum % extractables for the 50 ^{o}C samples. Overall, the extraction data are qualitatively and quantitatively (wt % extracted) similar to that reported in the NML study. Unlike the NML study, however, our extracts were subjected to GC-MS analyses. The GC-MS data reveal relatively minor changes in the compositions of the extracts over time. Even for the samples subjected to 100 ^{o}C and 100% RH, the GC-MS data largely reveal the same set of molecules as seen at time zero. Some changes monitored by GC-MS over time include the loss of volatile cyclohexanone (b.p. 155 ^{o}C) at all temperatures tested for those samples that contained it (Quantum SDLT, Fuji DLT IV, Maxell DLT IV, BaFe, MP-DLT III). Other changes include the slow depletion of the butyl ester signal at 75 ^{o}C and 100 ^{o}C, most likely due to hydrolysis. The butyl ester should hydrolyze to the corresponding fatty acid and butanol, neither of which is detected. Butanol (b.p. 118 ^{o}C) would evaporate as it is formed and the fatty acid may not be soluble in methylene chloride and/or it may further degrade. Trichlorobenzene, present in all of the tape samples at time zero, continues to be detected even after long durations at 75 ^{o}C and 100 ^{o}C. All seven tape samples showed remarkable resilience to exhaustive hydrolysis, even under the most severe conditions tested. The magnetic tape samples did not visibly change at 50 or 75 ^{o}C, even after prolonged heating at high humidity. Under the most severe conditions tested (100 ^{o}C, 100% RH), the tapes showed signs of physical breakdown, but even then the degradation was not accompanied by exhaustive binder hydrolysis.

The tapes subjected to the most severe aging conditions showed significant signs of physical breakdown. All 7 samples show visible signs of severe degradation after approximately 5 days at 100 ^{o}C and 100% RH. Specifically, the tapes became stiff and brittle with small particle flakes falling off of the substrate backing. The MP-DLT III tape degraded the fastest under these severe conditions. In addition to becoming brittle and flaky, MP-DLT III tape released rust colored particles during the decomposition. The Quantum SDLT and Maxell DLT IV tapes were amongst the slowest to show visual signs of degradation, although these too degraded eventually.

2.4 PHYSICAL PROPERTIES

OBJECT: To determine the physical and electrical changes in the recording media resulting from environmental exposure.
BASIS: Observe both the electrical resistivity and dynamic friction of the recording media that could/will affect the media's ability to record, store and retrieve data.

1.4.1 Resistivity

DISCUSSION
The resistivity specification has importance due to the static charge buildup that occurs from high speed tape motion and the stationary read/write head. Static discharge is detrimental to the recording media and read circuitry and will affect the reliability of magnetic recording and playback. Suitable binder additives and a carbon-based back-layer are employed to contain the resistivity to acceptable limits set by the manufacturers.

The resistivity tests employed the methods described in the ISO/ECMA specifications for these storage products. It was determined however that the ISO/ECMA voltage specified for the IBM 3590 product (500V) generates sufficient conductive heating to distort the test tapes and invalidate subsequent resistivity readings. Lower voltages were required for the test as well as low current measuring equipment.

RESULTS

The initial resistance (R) values for the study tapes are shown in Table 2.4.1. The resistance values of the magnetic surface (MAG) range in value from ~2 (3590 & DLT) to >300 (DLTIII) MegOhms/square. The conductive surfaces (BACK) are typically 11 to 12 MegOhms/square (except for DLT-Fuji and the 3590 BASF). These values are consistent with the requirements of ECMA 278, 286 and 320 specifications. which calls for a magnetic side R > 1 and a back side <100. There was considerable variation observed with the 3590 BASF measurements when compared to the other tapes.

Table 2.4.1 **RESISTANCE TABLE**

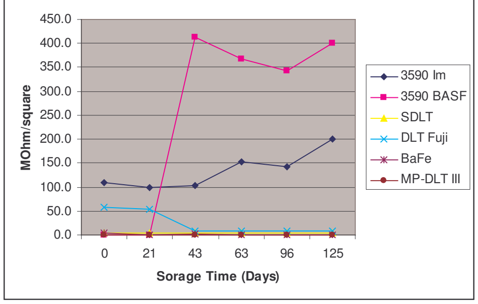
	AVE R/SQ		STD DEV	
	(megohm/sq)			
Tape/Type	Initial side		Initial side	
	MAG	BACK	MAG	BACK
3590 Imation	11	11	2.3	0.5
3590 BASF	2	1	416	272
SDLT	25	11	0.2	0.1
DLT-Fuji	2	1	3.6	0.0
Arkival BaFe	123	12	2.3	0.5
MP-DLT III	308	12	0.9	0.1

The tabulated effects of environmental exposure on the tape resistivities are included in Appendix 2.4. The data collected represents resistivity changes for both the magnetic and conductive sides of the tape media over a period of 125 days. Several representative time of exposure curves for all tapes samples are shown in Figures 2.4.1 thru 2.4.3. The

40C/30% RH MAG side exposure can be compared to the most extreme condition of 50C/85%RH in Figures 2.4.1 and 2.4.2. Figure 2.4.3 shows the time exposure curves for the BACK side at 40C/35% RH. The extent of 3590 tape resistivity changes can be readily observed in the figures.

Several tapes resistances exhibited considerable changes in resistivity but there appears to be no uniform discernable trend with temperature or humidity. The changing values of resistivity with exposure *(see Appendix 2.4)* are all within their specification limits so none of the tapes were eliminated for being out of specification. The mechanism by which these resistivity changes occur reflect some chemical or physical instability in these tapes. It is preferable that little or no change in resistivity occur with environmental exposure. Tapes were ranked therefore with regard to the degree of resistive change on exposure to these environments.

Fig. 2.4.1 Resistivity MAG SIDE 40C/30% RH



The SDLT (DLT-Maxell) was the most stable on both sides while both 3590 tapes were the most unstable on both sides. *See Table 2.4.3.*

Fig 2.4.2 Resistivity MAG SIDE 50C/85% RH

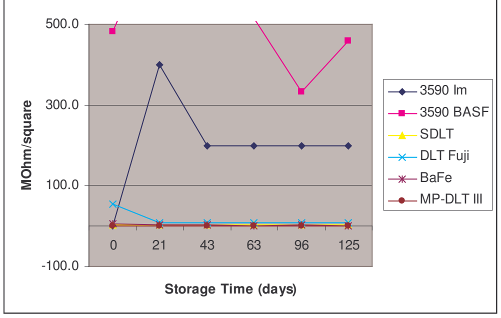
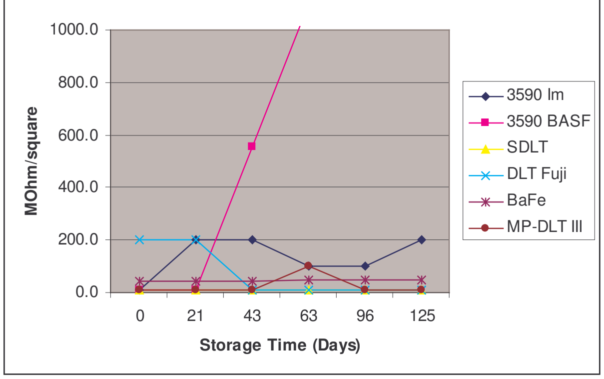


Fig. 2.4.3 Resistivity BACK SIDE 40C/35% RH



In summary, resistive changes were observed with environmental exposure. None of the tapes studied exceeded the resistivity specifications and the most favorable tapes were determined by demonstrating the least amount of change to the test environments.

1.4.2 FRICTION

DISCUSSION

The friction specification has importance relating to the high speed tape motion and the stationary read/write head. High friction coefficients will affect the tape motion over the head and the corresponding quality of the data both in a record and playback mode. Also of concern are localized high-friction areas on the tape surface where the high speed tape/head interface will cause discrete and instantaneous heating. Local temperatures at these disparities can exceed the curie point of the magnetic materials and cause data losses. High friction is detrimental to the recording media and heads and will affect the reliability of magnetic recording and playback. Binder additives are employed to deliver lubrication through the useful life of the tape. Tape Friction coefficients should be contained to limits set by the manufacturer.

RESULTS

The values of the initial coefficient of friction are shown in Table 2.4.2. The average values are shown for the samples used in the test as well as their standard deviations. The data indicates the tests were quite repeatable and consistent. The values of friction coefficient ranged from a low of 0.34 for 3590 (Imation) to a high of 0.54 for the 3590 (BASF).

Table 2.4.2 Coefficient of Friction

INITIAL COEFFICIENT OF FRICTION
(ECMA 278 test method)

	AVE*	STDEV
3590-Imation	0.34	0.02
SDLT-Maxell	0.43	0.04
DLT-Fuji	0.46	0.04
3590-BASF(Emtec)	0.54	0.05
MP-DLT III	0.53	0.04
BaFe-Arkival	0.41	0.04

*averaged over 16 measurements for each tape

The ISO/ECMA specification requires that tapes must have a coefficient of friction greater than 0.28. All of the test tapes were originally within the specification. The changes in friction as a function of relative humidity and temperature exposure are included in Appendix 2.4.2. Apparent is the fact that all of the tapes were within the specification even after environmental exposure for 105 days. Most changes observed are small and within the measurement accuracy. Several tapes showed a slight increase of about 0.1 in friction coefficient.

Tape lubricants are usually organic ester/acids which can react with water or air. The results do not indicate any notable change in friction coefficient with environmental exposure and any lubricant reaction or loss would likely be replenished from within the binder. Depletion of all available lubricant in the binder would take longer than the exposure times of this study. Figures 2.4.5 and 2.4.6 are representative friction trend data with time of exposure for four different humidities. Most of the data shows little change in the friction coefficient for the test conditions of the study.

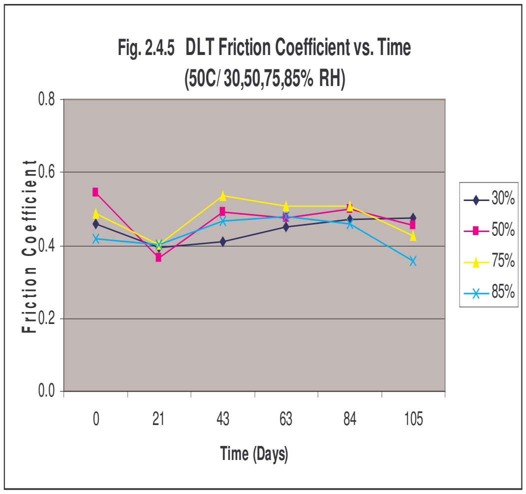


Fig. 2.4.5 DLT Friction Coefficient vs. Time (50C/ 30,50,75,85% RH)

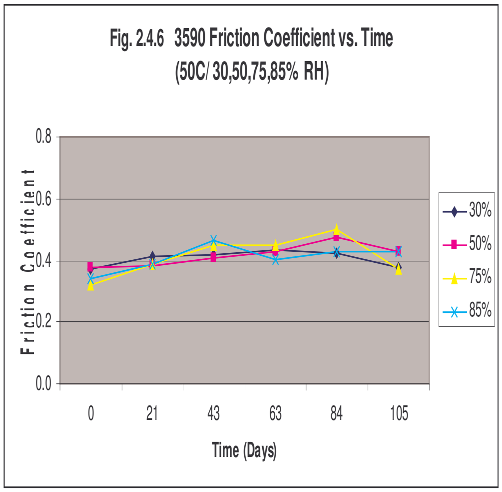


Fig. 2.4.6 3590 Friction Coefficient vs. Time (50C/ 30,50,75,85% RH)

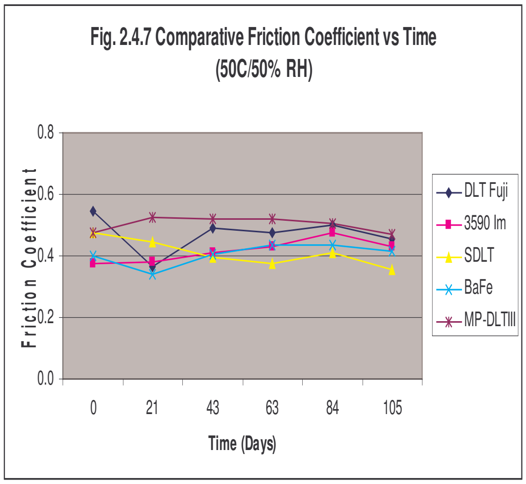


Fig. 2.4.7 Comparative Friction Coefficient vs Time (50C/50% RH)

Figure 2.4.7 compares the changes in friction coefficient for all the tapes in the study at one condition.

Long term changes in resistivity and friction could be detrimental to performance for the reasons discussed above. The most favorable tape/ media is one where little or no change takes place. On this basis, the following Table 2.4.3 is a summary of the findings.

Table 2.4.3 RANKING OF CHANGE

Resistance	**Magnetic side**	**Conductive side**
least change	SDLT/DLT -Maxell	SDLT/DLT –Maxell DLT -Fuji
Friction		
least change	SDLT/DLT-Maxell & Fuji	

2.5 RF AMPLITUDE RESPONSE

OBJECT: To determine recording property changes in the media resulting from environmental exposure.
BASIS: Observe radio frequency (RF) signal strength of the recording media that could/will affect the media's ability to record, store and retrieve data.

DISCUSSION

Tape Storage devices record data using different bit densities. It is not uncommon to have a single tape contain data written at three different bit densities *(See Appendix 2.5)*. These bit densities (bits/unit tape length) relate to specific recording frequencies (RF). The playback signal strength (dB) of these individual frequencies is an important part of the read channel functionality in the Storage Device. OEM's establish a minimum signal strength specification to assure reliable data recovery. Losses in tape signal strength resulting from environmental conditions can adversely affect data integrity and may be a result of many factors, including physical and magnetic changes. Tape drives use several electronic compensation means to accommodate for such changes but they are limited in range and extent.

Tape width changes, for example occur with the environment. The use of embedded linear control-track technology (servo tracks) provides for accurate tape position tracking of the data contained in the adjacent data tracks. In addition, storage devices employing "Partial Response Most Likelihood" (PRML) technology make fewer demands on the signal strength and signal-to-noise (S/N) ratios of the media. The digital complexity of these newer tape drive products does not provide for RF recording or playback measurements. The Quantum DLT 8000 tape drive was the only storage device that had the capability of utilizing single frequency data in its commercial configuration. A comparison of media for this study required a broader-based test. To this end an alternative testing means was used that embodied the linear control tracks in a video recorder similar to the embedded servo tracking used in these storage devices*.

Table 2.5.1 RF Amplitudes (ave.) All Storage Media- dB

RF AMPLITUDE

freq (Mhz)	2.5	5.0	7.5	10.0
SDLT	37.4	36.6	25.6	0
DLT IV (Y)	36.0	31.0	23.2	0
DLT III	34.4	33.4	7.8	0
3590 (R)	37.2	39.4	11.6	0
3590 (Br)	38.2	41.6	26.4	0
BaFe	35.2	35.2	9.6	0

STDEV CHART

freq (Mhz)	2.5	5.0	7.5	10.0
SDLT	1.0	0.5	1.4	0.0
DLT IV (Y)	1.9	1.8	12.6	0.0
DLT III	2.1	5.9	10.0	0.0
3590 (R)	1.7	1.7	14.2	0.0
3590 (Br)	0.4	0.5	1.0	0.0
BaFe	2.0	2.3	11.8	0.0

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* *Servo tracking and Partial Response technology have been employed in video recording devices for almost two decades.*

This approach employed a high bandwidth professional VCR adapted for the test. The two aspects of this study were the RF signal performance with time exposure to the test environments and the corresponding change in error performance. See discussion of the test setup in Appendix. 2.5.

RESULTS

Table 2.5.1 above shows the relative signal strength of the different tape media as a function of frequency (frequency response). The higher frequency output from the double coated tapes (SDLT, DLT) compared to the single coated tapes (3590-R, DLTIII) can be observed (*with the exception of the 3590 Br*). The signal levels at the 10 Mhz frequency were insufficient to report reliable data and change. *See Appendix 2.5 to relate frequencies to bit densities.*

The frequency response of each tape sample is compared to its original after each interval of Temperature/RH exposure. In addition to the standard test conditions (40C/50% RH and 50C/75% RH) an additional extreme condition (50C/85% RH) was used to accelerate change. The data, corresponding graphs, averages and standard deviations are included in Appendix 2.5.

Table 2.5.2 RF Amplitude Change (dB) - *4 months Environmental Storage*

40'/50%	*Freq (Mhz)*	**2.5**	**5.0**	**7.5**	**10.0**
SDLT		2.5	3.0	3.0	0.0
DLT IV Fuji		3.5	4.5	3.0	0.0
MP-DLT III		-20.0	-30.5	-7.5	0.0
3590 BASF		3.0	2.0	14.5	0.0
3590 Imation		0.0	1.0	1.0	0.0
BaFe		2.0	2.0	0.0	0.0
50'/75%	*Freq (Mhz)*	**2.5**	**5.0**	**7.5**	**10.0**
SDLT		2.0	1.5	1.5	0.0
DLT IV Fuji		1.5	4.5	14.5	0.0
MP-DLT III		-33.5	-35.5	-12.0	0.0
3590 BASF		0.5	1.5	26.5	0.0
3590 Imation		-4.0	-6.5	-13.5	0.0
BaFe		-1.0	4.5	-12.0	0.0
50'/85%	*Freq (Mhz)*	**2.5**	**5.0**	**7.5**	**10.0**
SDLT		0.0	2.0	4.0	0.0
DLT IV Y		0.0	6.0	-9.0	0.0
DLT III		-34.0	-35.0	0.0	0.0
3590 R		1.0	1.0	-4.0	0.0
3590 Br		0.0	0.0	1.0	0.0
BaFe		1.0	4.0	2.0	0.0

A summary of RF amplitude changes is shown in Table 2.5.2. The amplitude change(s) being reported occurred during the environmental exposure period of ~120 days. The amplitude differences (e.g. dB at start of test less dB at end of test) are reported as a function of frequency.

Included in the Table are the standard deviations resulting from the individual media tested at the same measurement frequencies. Greater variation exists with the high frequency measurement and is reflected in the standard deviations. Several observations can be made from the resulting data. There appears to be a general trend of higher frequency signal losses (> 7.5 Mhz) resulting from the higher temperature/humidity exposure. The DLT III media was the most sensitive to the environmental tests and its degradation consistency was observed throughout all three conditions studied. See Figure 2.5.1. In this data the frequency response of the tape is observed to be diminishing with exposure time. Behavior of this type will result in data loss. Although not a designated tape for this evaluation, the MP-DLT III tape was most affected by the storage environment. In general, the newer, higher density media (DLT, SDLT) experienced less change with environmental exposure.

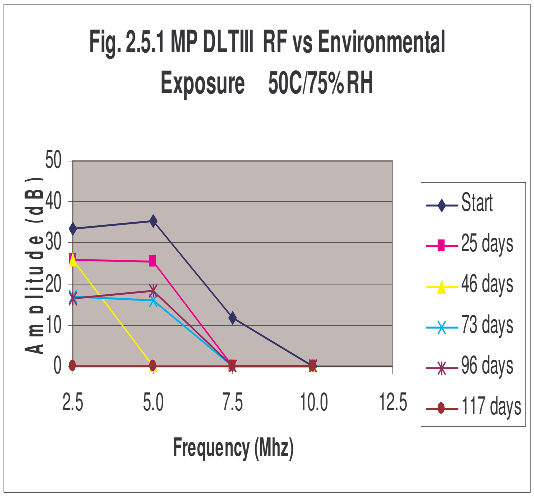
Fig. 2.5.1 MP DLTIII RF vs Environmental Exposure 50C/75%RH

Throughout all test environments, the SDLT media (Maxell DLT) was the most stable along with the BaFe tape control tape.

2.6 ERROR STUDY

OBJECT: To determine the error profile changes in the recording media resulting from environmental exposure.
BASIS: Observe all pertinent and available error data of each storage system and its recording media that could/will affect the media's ability to record, store and retrieve data.

DISCUSSION

The most critical aspect of this study was the investigation of the tape/drive error performance. It is in the study of errors that all magnetic, electrical and physical elements of tape media interact with one another. The effects of magnetic saturation loss, RF signal losses, binder hydrolysis, resistance and friction changes all manifest themselves as errors and the eventual loss of data when situations prevail such that error correction is not effective. The fact that media errors occur with time and/or environmental exposure is not a new or unexpected result. The issue was however the extent of the error change and the ability of the storage systems to correct, compensate and deliver accurate data. It was the intent of this aspect of the study to observe pertinent error information, report changes and to determine the life expectancy of the media and the storage system as they interact.

Basic to the study were correctable (corrected) errors and uncorrectable (uncorrected) errors- *see Glossary*. Error information of this type is indirectly available from the Small Computer Systems Interface (SCSI) bus system which was common to all three storage devices. This SCSI error information was the basis for determining media quality, media changes and life expectancy.

Significant to this study was the need for a common denominator to compare different media and observe error rates and changes. The error rate (B*ER) definition proved to be a meaningful measure of change and compatible with all three storage systems. Appropriate SCSI errors were recorded between periods of environmental exposure such that changes could be observed and life expectancy (LE) predicted. In addition to error profiling, other parameters such as read retries, tape test time and tape length usage also proved helpful in evaluating media quality and the effects of environmental storage.

The media testing requirement for the study made good use of Arkival's proprietary test software for error data acquisition. This test software was adapted to all three storage systems and used specific SCSI errors in a convenient report format for reporting media quality and error changes.

RESULTS

The Arkival software was used to report tape errors during the initial write process and all subsequent reads. The data written was random and block length defined to induce tape streaming for all products tested.

The following tape quality comparison was based upon first usage tape errors. Important parameters monitored during the write process were write correctable block errors, retries, non-correctable block errors and the error rate (B*ER- defined as the ratio of defective blocks reported to number of bytes read or written). *See discussion in Appendix 2.6.* Similarly during reads, the parameters were read correctable block errors, retries, non-correctable block errors and the read error rate (B*ER).

The following tables summarize the findings for the IBM 3590, Quantum DLT and SDLT products. The number of cartridges tested for each media type is approximately the same and comprised of different lots from each tape manufacturer. Differences in error rates have been seen observed in lot-to-lot sampling. Averages for all the lots are presented in Tables 2.6.1 and 2.6.2. The actual data can be found in Appendix 2.6 as Excel workbooks by Storage media type.

Table 2.6.1 First WRITE performance

Drive/Media	Lots	Block Count	Retries	Correctable Errors	Raw Write Errors	Non-Correctable Errors	Write Count	WRITE B*ER x10^9
IBM 3590-BASF	2	141706	1148	1148	n/a	0	9069178	127
IBM 3590-IMATION	3	143224	1739	1739	n/a	1	9166316	191
Quantum DLT IV-Maxell	2	613918	0	0	4508	0	47693451522	95
Quantum DLT IV-Fuji	4	613481	9	9	7080	0	47436066442	149
Quantum SDLT-Maxell	5	1740702	750	750	83765	0	143353181360	587

n/a – not available and reported as correctable errors.

Table 2.6.2 First READ performance

Drive/Media	Lots	Block Count	Retries	Correctable Block Errors	Raw Read Block Errors	Non-Correctable Block Errors	Read Count (bytes)	READ B*ER x10^9
IBM 3590-BASF	2	141799	995	995	n/a	0	8933279	111
IBM 3590-IMATION	3	142372	1231	1231	n/a	0	8969408	138
Quantum DLT IV-Maxell	2	613528	0	0	162	0	48410151360	3
Quantum DLT IV-Fuji	4	613410	0	0	15	0	48721026728	0.3
Quantum SDLT-Maxell	5	1740636	0	0	1814	0	141190454400	13

n/a – not available and reported as correctable errors0

The IBM 3590 reports correctable errors (blocks) as such but the Quantum DLT and SDLT report correctable errors (blocks) as Raw errors. *An explanation of the table fields is included in the Glossary and discussed in Appendix 2.6.* The number of correctable block errors and retries is lower in the Quantum products and indicative of either more efficient error correction, better media or a difference in the basis for the manufacturer's SCSI error report. The B*ER is also lower in the Quantum products. This is particularly of interest because of the higher storage capacity of the Quantum media.

Effects of Environmental exposure and Multiple Uses

Multiple Tape Use Observations and Effects (Room Temperature (RT) Storage)

This study employed the use of control tapes to monitor the Room Temperature/RH error performance of the media. The ambient room environment was typically 21^{o}C/ 50% RH . Control Tapes were stored on open library shelves as accessible cassettes without their protective shipping/storage jackets.

Control tapes were tested before and after the environmentally exposed tapes. The error performance and functionality of the control tapes gave added reliability information as to the performance of the test drives; particularly on the days and times the drives were used to test for and evaluate environmental media changes. The control tapes also provided an error performance history for tapes stored at room temperature/RH environments. An observation of control tape performance was noted on the basis of a greater frequency of testing. Many tapes exhibited a parabolic-type error behavior; demonstrating a higher error rate during their early use, diminishing in error rate and stabilizing for a period of time thereafter and then exhibiting an error rate increase with continuing use. A higher B*ER was observed for the first time tape use of all three tape-types but the magnitude of the B*ER was a lot dependent variable. The parabolic-type error behavior effect was observed on both the primary and secondary test drives and was not related to a tape brand or drive type.

Figure 2.6.1 shows the control tape performance of the SDLT product on both a primary and secondary drive. Typical of all control tapes in the study, general trends observed were repeatable and resulting from the media. It is likely that much of the higher B*ER seen in the early usage period has to do with the tape burnishing process performed by the media manufacturer(s). The B*ER increases observed after the stable period were considerably lower than the error rates observed in tapes undergoing environmental exposure and change.

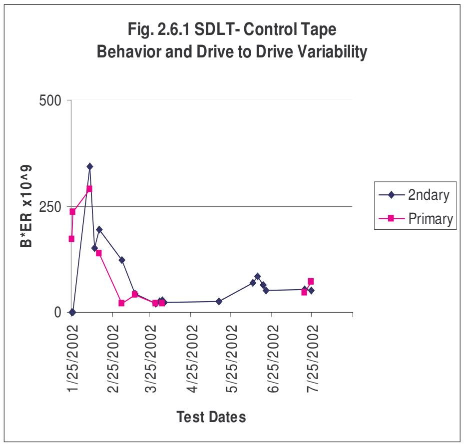
Fig. 2.6.1 SDLT- Control Tape Behavior and Drive to Drive Variability

EFFECTS OF ENVIRONMENTAL EXPOSURE

The three test environments produced results that were somewhat predictable such that higher temperatures and humidities generate higher error rates. In every media type observed humidity was a greater factor than temperature.

The effects of environmental storage

Data tables in Appendix 2.6 contain data points, standard deviations and the basis for the graphs discussed here. During the course of the study there were losses of data due to a variety of reasons and the utilization of five (5) test tapes for each condition proved advantageous to obtain the following results and conclusions. In almost all cases reported a single drive was the basis for data comparisons. In the case of the 50^{o}C/ 85% RH storage environment, a contamination issue delayed the study and fewer data points are reported for that environment.

Another item of note is the occasional and abnormally high B*ER's observed in almost all the media tested in accelerated environments. Observation of the control tape performance at that point in time suggested a definite environmentally forced tape error condition. Continued use of tapes containing such anomalies did, in most cases demonstrate their return to the average group behavior. Environmentally-induced error effects do occur and the subsequent use of the tape burnished or minimized the defect such that normal ECC was applied successfully. Root cause analysis was not possible and beyond the scope of this work. What is of importance is that in most cases, data was recoverable. Also *see Catastrophic Tape and Drive Failures-Section 2.6.1.*

The following data shows the effects of environmental storage on the B*ER over the exposure time. Figures 2.6.2, 2.6.3 and 2.6.4 show the effect of the 40°C / 50% RH, 50°C / 75% RH and 50°C / 85% RH environmental storage for the DLT, SDLT and 3590. The lower B*ER rates were evident in the SDLT and DLT products. The 3590 B*ER was about twice that of the DLT and SDLT. Most media tested showed continuing increases in the B*ER with exposure time; indicating a continuing degradation with use and exposure to the environment. These data also illustrate the similarity in behavior of both the DLT and SDLT products.

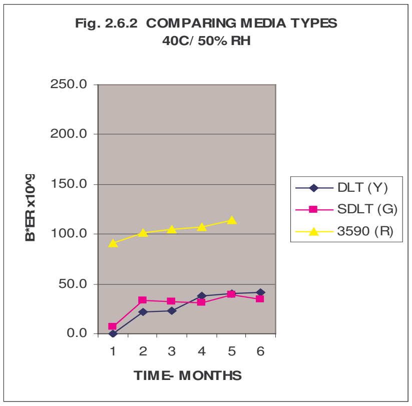
Fig. 2.6.2 COMPARING MEDIA TYPES
40C/ 50% RH

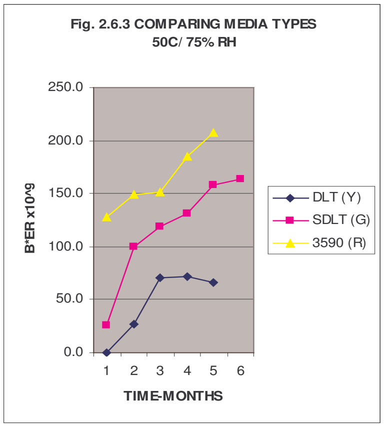
Fig. 2.6.3 COMPARING MEDIA TYPES
50C/ 75% RH

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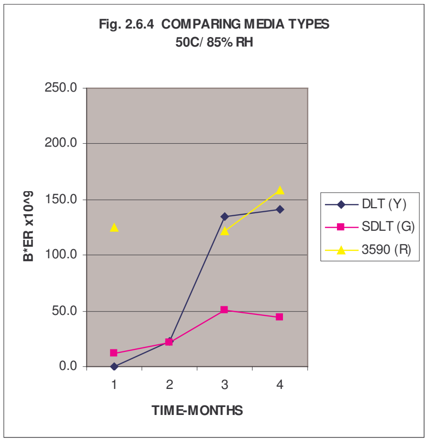
Fig. 2.6.4 COMPARING MEDIA TYPES
50C/ 85% RH

Figure 2.6.5 shows the effect of the 50°C / 75% RH environmental storage for two different 3590 tapes. The two data sets represent two supply sources and results differed. Both DLT suppliers however exhibited similar behavior in this environment.

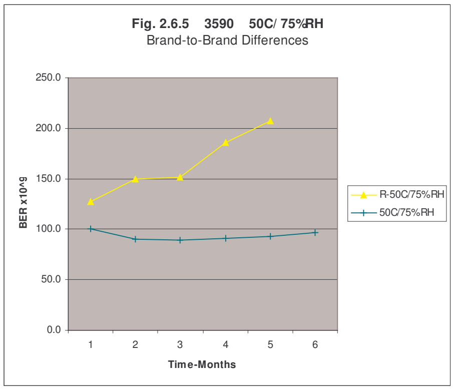
Fig. 2.6.5 3590 50C/ 75%RH
Brand-to-Brand Differences

Another perspective on the data analysis was observing the storage media at all temperature and humidity conditions. This analysis is shown in Figures 2.6.6, 2.6.7 and 2.6.8. In this case a representative tape was selected for each Storage Device-type: BASF (Emtec) for the 3590, Fuji for the DLT and Maxell for the SDLT. In almost every media case reported, independent of the Storage Device-type, the media changes (B*ER) increased the increasing temperature/ humidity storage. The higher temperature/humdities demonstrated a greater number of (absolute)errors and higher error rates (B*ER). (*note: There was no forced air circulation in the 50C/85% container and this lack of air movement in the storage environment may have had some influence on the test resllts)*

In all testing to date the typical tape degradation observed has been within the limits and error correction capabilities of the drive products being tested except when catastrophic failure occurred.

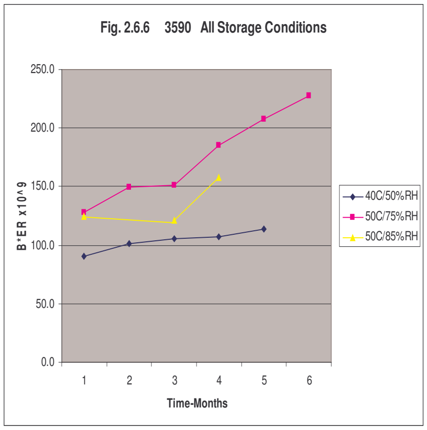
Fig. 2.6.6 3590 All Storage Conditions

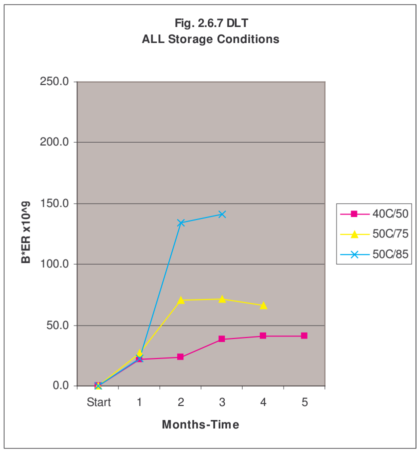
Fig. 2.6.7 DLT
ALL Storage Conditions

NON-correctable errors

Error recovery definitions have changed the meaning of Non-correctable errors: during the first write and read operations, certain tapes exhibited non-correctable errors. In the data tables included in Appendix 2.6 the occurrences of non-correctable errors have been highlighted for convenient viewing. On a write pass the occurrence of an non-correctable error causes the data to be written at another location on the tape until the data is written without error. On a read pass, the non-correctable error is considered “hard” only if it fails after the multiple read retry procedure. Non-correctable errors during read operations cause catastrophic tape failure. The occurrence of non-correctable errors at any time in the cartridge life is problematical and likely to make data recovery difficult at some point in the future. There was a greater frequency of non-correctable error occurrence in 3590 cartridges than DLT’s. Certain SDLT lots did exhibit a high frequency of non-correctable errors also.

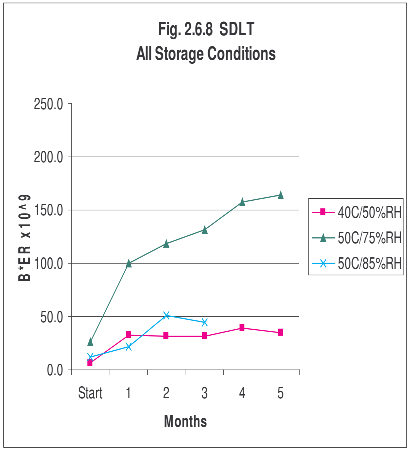
Fig. 2.6.8 SDLT
All Storage Conditions

2.6.1 Catastrophic Tape and Drive Failures

During the study, media for both the IBM 3590 and the Quantum SDLT experienced catastrophic tape failure. SDLT tape failures were experienced during first write operations evidencing media defect conditions that caused hard failures. Media defects of this type are tolerable to a degree and will likely be found and the tape cassette eliminated at incoming inspection.

The more common failure mode however occurs when the tape is being read and data recovered. Failures of this type allow useable reads of the non-failing portion of the tape until the failure point is reached (some place in its length). The tape generates a hard failure condition and all remaining data is lost. Observed failures of this type resulted from tapes stored in environments designed to accelerate media failures. The total dependence on error correcting electronics can obviously result in data loss. Storage facilities should utilize tape backups when and where possible. Further, because of the lot variations observed, the backup tapes should be stored on different tape lots than those used for master tapes.

Some 6-7 months into the study both an IBM 3590 and a Quantum SDLT tape drive failed to perform read operations. Both drives failed within a week of one another and required field engineering support. The Quantum drives, because of their smaller size and weight were easily returnable for factory repair.

2.7 LIFE EXPECTANCIES

Two methods of projecting Life Expectancy (LE) follow. First, a LE projection based upon changes in the intrinsic magnetic parameters of the tapes. Second, a LE based upon the changes in tape error rates as observed in tape drives.

2.7.1 Life expectancy (LE) on the basis of magnetic parameter change ONLY

OBJECT: To determine the life expectancies of the magnetic tapes based upon corrosion and subsequent changes in their intrinsic magnetic parameters.
BASIS: Observe the intrinsic magnetic parameter changes with environmental exposure. Determine a suitable end of life criteria that would be detrimental to performance such that the reliability of stored data is in question. Project the life expectancy of these tapes with the use of the actual data collected for magnetic loss and suitable mathematical models. Specifically, the object was to determine the time of storage in a given environment for tapes to reach their end-of-life criteria.

DISCUSSION:
Changes in the magnetic properties of tapes resulting from environmental exposure are attributed primarily to the chemical changes(corrosion) of the magnetic metal particles contained within. H_2O and/or O_2 must come in contact with the unoxidized metal for these metal particles to corrode. This happens by diffusion through the two layers separating the two reactants, the polymer binder and the metal's oxide layer. The slowest of these steps ,diffusion through the oxide layer is rate determining. The mathematical relationship of this change is used to find the rate constant, k, for each condition for each tape- *See discussion and details in Appendix A.2.7*. The rate constant can be extrapolated for any reasonable temperature and humidity and thereafter, Life expectancy (LE) forecasted.

A ten percent loss of magnetism was used as an end of life (EOL) indicator (typical losses are not necessarily uniform and defect counts do increase substantially for a tape that looses 0.1 Is.). (7)
Two typical LE charts are included below in Figure 2.7.1 and 2.7.2. These charts show the relative LE's of the different media studied. LE was found to vary between years and days depending upon the adversity of the storage environment. The complete series of LE data for all the tapes and environmental conditions studied is included in Appendix 2.7.

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(7) Djalali, A., Glatfelter, W., Judge, J.S., Seng, D. and Speliotis, D., J. Electrochem. Soc., 91, 430 (1991)

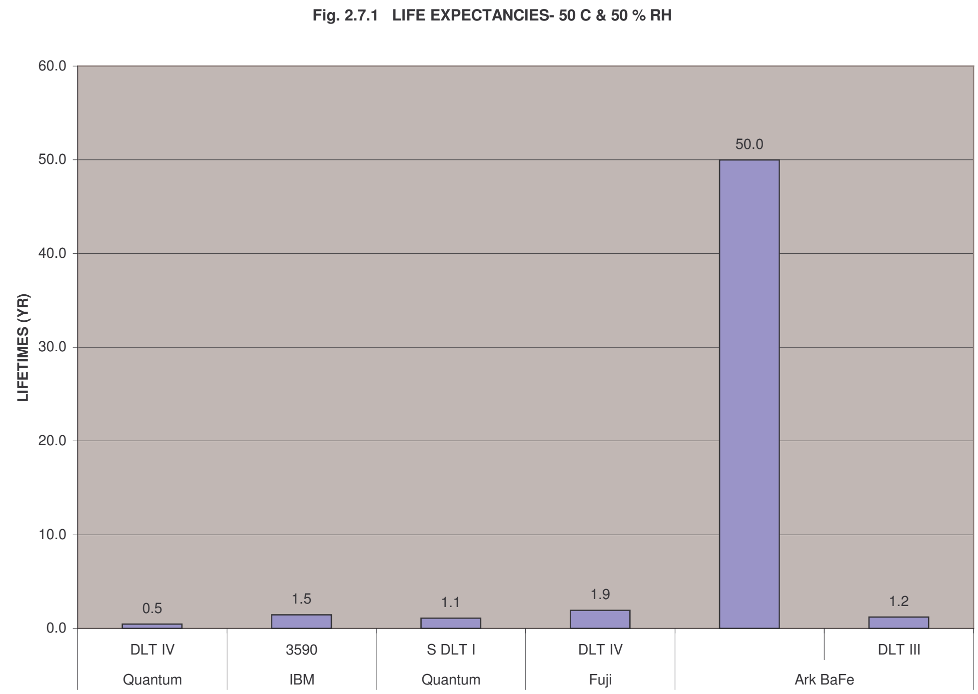


Figure 2.7.1. LE's at 50C/50%RH.

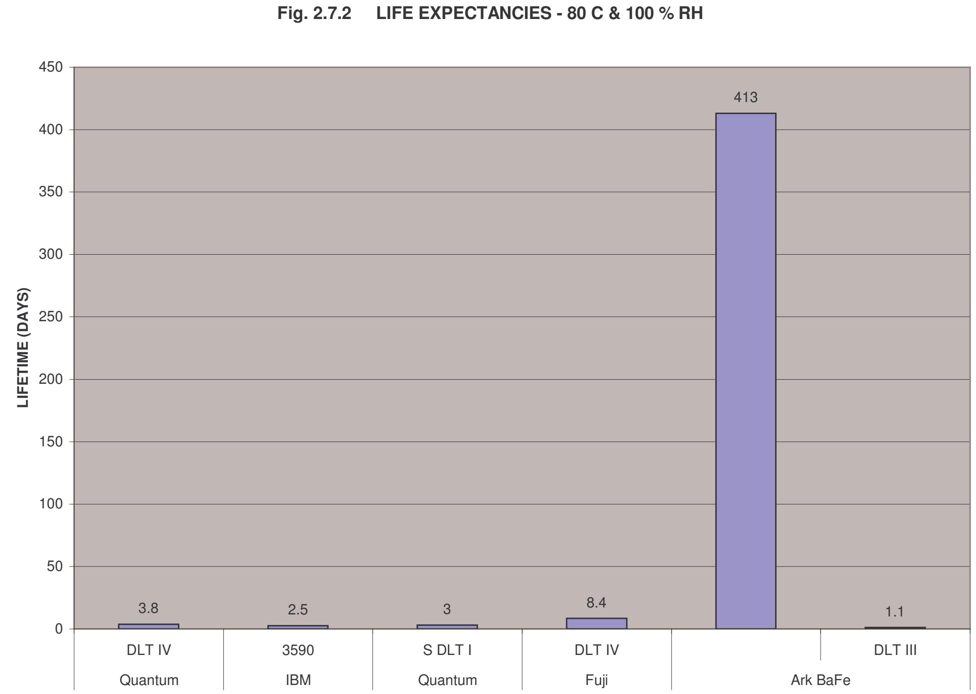


Figure 2.7.2. LE's at 80C/100%RH. (note: y-axis units- days not years)

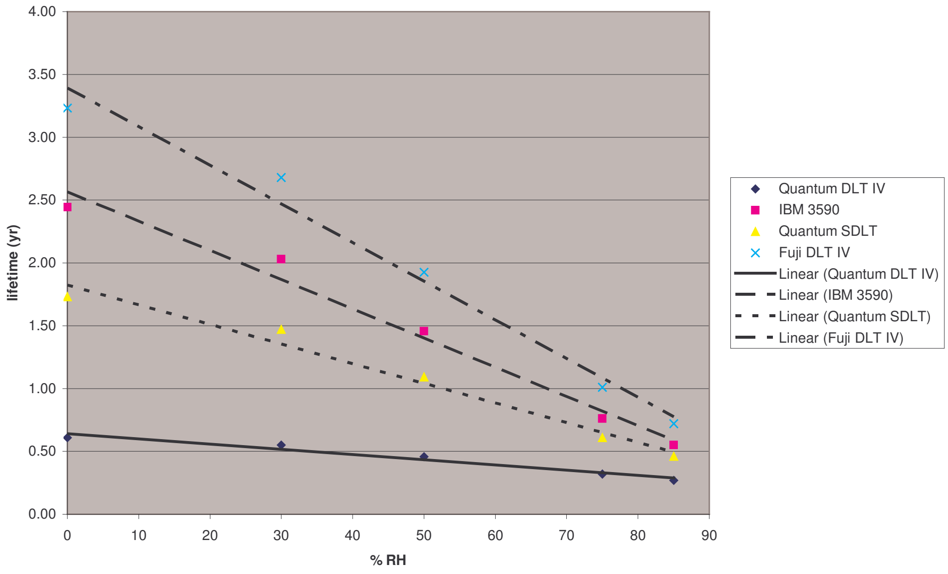
The following Table 2.7.1 summarizes Life Expectancies based upon the magnetic particle corrosion for six different environmental storage conditions.

Table 2.7.1. SUMMARY of LE's based on Magnetic Particle Corrosion
(units of years except where noted)

Temp/RH	3590 Emtec	DLT IV Maxell	DLT IV Fuji	SDLT Maxell	Arkival BaFe	MP-DLT III
40C/50%	6.3	18.3	16.3	62.1	111	7.5
50C/75%	0.8	1.0	1.2	1.4	26	0.6
	LE below (days)					
80C/100%	2.7	5.7	8.4	5.2	413	1.1

The data also provided a comparative LE media analysis at specific temperatures and humidifies. One such example is Figure 2.7.3. In this Figure the LE's of all the study tapes (without controls) are plotted for the 50C temperature and full range of humidities.

Fig. 2.7.3 LIFE EXPECTANCIES- 50 C vs. RH



Changes in intrinsic magnetic characteristics (e.g. saturation magnetization)will be detrimental to performance and the most favorable tape/media is one where little or no change takes place. Although rankings are condition dependent, the DLT media (either Fuji or Maxell) exhibited the least magnetic property change among the study group in almost all cases and exhibited less change than the 3590 media (either Emtec or Imation).

2.7.2 Error Rate (B*ER) Life Expectancy (LE)

OBJECT: To determine the life expectancies of the magnetic tapes when used in conjunction with their respective Storage Systems (IBM 3590, Quantum DLT and SDLT)

BASIS: Observe the tape error changes resulting from environmental exposure and use. Determine a measure of life expectancy or end-of-life criteria that is common to all three products being evaluated and representative of a condition such that the reliability of stored data is in question. To forecast the life expectancy of these tape products based upon the actual data and suitable mathematical models (trend analysis).

DISCUSSION:

Life Expectancies

This study and others before it make use of different environmental storage conditions to accelerate media change and/or accelerate changes in media properties that are essential to data integrity. Information derived from such changes is used for the expectation of media life, or the prediction of life expectancy. In a prior study (1) the storage system's life expectancy was based on the most vulnerable tape property; binder hydrolysis. The tapes in this study showed little, if any signs of binder hydrolysis. Furthermore, newer storage systems utilize many physical and electronic means to correct and compensate for media changes as they occur. It is for this reason LE is best measured by using those compensation and correction means when the media is considered part of the storage system.

In the previously referenced NML study, an effort was dedicated to determine appropriate "end-of-life" (EOL) criteria to determine Life Expectancy (LE) values. EOL criteria are system specific but not available from Storage System manufacturers. At best, they offer guidelines for use. This study used the drive/cartridge guidelines and system performance specifications as a basis for establishing EOL criteria. *See discussion in Appendix 2.7.*

When published, Error Rates for correctable (recoverable) error are stated in terms of bits read, e.g. Quantum states their "Recoverable READ Error Rate as 1 in 10^6 bits read" and IBM states that "no single cartridge can have a dropout error in 1x10^7 bits. For this study, EOL criteria was defined in terms of the Error rate (B*ER). Table 2.7.2 lists EOL criteria by cartridge type, native storage capacity and B*ER maximum values.

Table 2.7.2 **END OF LIFE Table**

PRODUCT	Capacity(1)	Capacity (MB) *x10^6*	MAX errors/GB	EOL Error Rate *Number/MB*	B*ER MAX. (2)
Published…					
IBM 3590	10 GB	1000	-	1	-
Quantum DLT	40 GB	40000	-	1	-
Quantum SDLT	110 GB	110000	-	1	-
Study Criteria…			*(Blocks)*		
IBM 3590	10 GB	1000	500	2242	2500
Quantum DLT	40 GB	40000	500	3296	3500
Quantum SDLT	110 GB	110000	500	6252	6500

(1)Native Mode Storage Capacity: Data capacity- non-compressed.

(2)Round-off values for LE projection

Notes:

Published Error rates:

Quantum:	Recoverable Read Error rate: 1 in 10^6 bits read
IBM:	dropout spec: max 1 dropout in 10^7 bits read.

Definitions

B*ER (Arkival)	Block error rate - Number of "raw Read Errors(Blocks)/ Read Count"(in bytes) 64K block size

Assumptions:

Bad Blocks:	1 or more bad bits in a Block makes the total Block defective
3590 DF	DF = 4000; using ; 4000 ftpmm; 80 um track width; 4K block size
DLT DF	DF = 8000; using ; 2578K ftpmm; 39 um track width; 4K block size
SDLT DF	DF = 16000; using ; 2700 ftpmm; 14 um track width; 4K block size

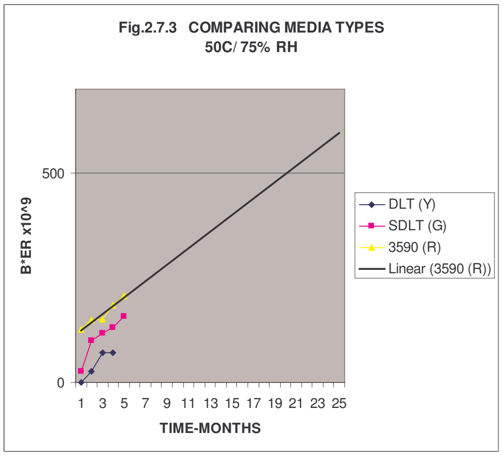


Fig.2.7.3 COMPARING MEDIA TYPES
50C/ 75% RH

Data from the Error study, Section 2.6 was used to determine Life Expectancy at various environmental conditions. LE was predicted on the basis of experimental data, best curve fit for the Trend analysis (usually linear) and the projected time to reach the EOL criteria defined as the B*ER maximum in Table 2.7.2. Typical data used for the projections is shown Figure 2.7.3.

The EOL results for all three tape storage systems were forecasted for the different tape exposure environments. The 40C/ 50% RH environment for example, resulted in a LE for the 3590 of 4 years, the DLT for 52 years and the SDLT for 98 years. The results are noteworthy and representative of the significant technology advancements. Most notable is the ECC efficiency of the DLT and SDLT products.

The LE prediction itself should serve only as a general guideline with the understanding that it predicts average trends only. An LE prediction of 100 years for a specific media will serve little purpose when an error condition violates the ECC capabilities of the system in less than a year. Section 2.6.1 describes both the catastrophic tape and drive failures experienced during the course of this study.

A review of both the LE's forecasted by the corrosion analysis and that of the B*ER show a similar ranking order with the DLT and SDLT media performing best in most environments. In these tape products one expects some form of media failure to occur before the system failure. The system employs sophisticated error correction and compensation means to overcome changes like those forecasted in the corrosion analysis. The corrosion analysis forecast however is significant because it predicts the most likely cause of media failure that results in error generation. The generation of error clusters is most problematic in that it increases the probability of catastrophic failure by violating the multiple error-per-block condition that excludes error correction and block replacement; causing non-correctable hard errors and making data recovery unlikely.

CONCLUSION

Two different media technologies were determined by TEM and VSM analysis. The results made obvious the distinction between the single and double coated tape technology; single coated tape for the 3590 and double coated tape for the DLT and SDLT storage systems. Neither IBM nor Quantum manufactures their own media for these tape drive products and this analysis helped identify the manufacturers of tape media being sold as OEM and private label products; 3590 tapes are manufactured by BASF (Emtec) and Imation, DLT tapes are manufactured by Fuji and Maxell and SDLT by Maxell only.

The results indicated DLT media exhibited the least change in remanent magnetization at all three environmental storage conditions. All the tapes studied demonstrated a decrease in their remanent magnetization with environmental exposure time. Higher temperatures and higher humidities increased their magnetization loss. The DLT Fuji media demonstrated the least remanent magnetic loss for the environmental conditions studied, when compared to the 3590 and SDLT

Extractable organic compounds were identified from all tapes by GC-MS and only a minor change in the extractables was found at the higher temperature and humidity conditions (100^{o}C and 100% RH). These extreme conditions also revealed minor changes in the compositions of the extractables over time. Significant signs of physical breakdown were determined at 100^{o}C and 100% RH; the SDLT and DLT tapes were amongst the slowest to show visual signs of decomposition, although these too decomposed eventually.

The values of tape resistivity exhibited significant change with environmental exposure but the changes observed were within specification limits. Tapes were ranked with respect to the magnitude of resistive change on exposure to these test environments. The SDLT tapes were the most stable on both magnetic and conductive sides.

Friction coefficient changes were relatively small in the three environments investigated. On the basis that friction coefficient changes will affect tape performance, the most favorable media was one where little or no change occurred. The results indicate the SDLT and DLT media exhibited the least change in friction coefficient.

Losses in the RF amplitude were generally observed with exposure to higher temperature and humidity; particularly higher frequencies (>7.5 Mhz). The frequency response data measured after each cycle of Temperature/RH exposure showed the SDLT was the most stable among the tapes of this evaluation.

The error study examined tape errors in new media and error changes in the media resulting from environmental exposure. Error types observed during the first write and subsequent reads were correctable block errors, retries, non-correctable block errors and the error rate (B*ER). The DLT-Maxell and DLT-Fuji media demonstrated lower write and read error rates than the 3590 media during first write and read testing. All tapes tested showed an increase in the number of correctable errors and error rate with higher temperatures and higher humidities. Among the study group, lower error rates were observed with DLT and SDLT tapes compared to the 3590 tapes. The error correction capability of each Storage Device type is demonstrated in the error rates reported. The SDLT product performance was best and typically followed by the DLT and 3590.

The life expectancies of the test tapes were predicted on the basis of magnetic saturation. Although LE was found to be condition dependent, the DLT-Fuji media exhibited the least saturation change among the tape group in almost all temperatures and humidities studied (e.g. storage at 50C/ 75% RH resulted in a DLT LE of 1.2 years compared to a 3590 LE of 0.76 years); the magnitude of the difference varied by environmental storage condition. Compared to the DLT and 3590, the SDLT exhibited more variability in the LE results; perhaps due to the stress imposed by the laser burning of the servo tracks.

LE's were also predicted on the basis of tape performance in their respective tape drives. The error-based LE was found to be condition dependent as was the saturation-based LE. The SDLT demonstrated the best LE for the tape exposure environments studied followed by the DLT and the 3590 (e.g. storage at 50C/ 75% RH resulted in a DLT LE of 16 years compared to a 3590 LE of 10 years). In this case the LE predictions had the benefit of the drive error correction capability. The effectiveness of the different Storage Device's ECC efficiency is observed via the differences in life expectancies reported.

In every technical investigation areas reported above, the DLT and SDLT tape product demonstrated the most environmentally stable performance and is the most favorable archival storage medium. Tape failures and data losses however were observed with all three storage products studied. It is critical to recognize this potential failure likelihood and to plan for it accordingly.

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Pat Judge
Prof. Glen Miller
Jim Richardson
Bob Schmidt
Ed Wiatrzyk

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Appreciation is also extended to Dr.Vivek Navale, of the National Archives and Records Administration for his guidance and technical advice throughout the program.

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Glossary

ANSI. American National Standards Institute
BaFe. Barium Ferrite
BER. Bit Error rate
B*ER. Error Rate
Blocks.
BOT. Beginning of Tape
BUER. Burst Error rate. Four or more SER's
bus. An electrical pathway that consists of an adapter card installed in a host computer and one or more SCSI devices connected with cables.
CD. Compact disc
dB. decibels
DLT. Digital Linear Tape. A Quantum Corporation Tape Storage product.
DSC. Differential scanning calorimetry
ECMA. European Computer Manufacturers Association
ECC. Error Correction Code
emu. electromagnetic units
EOL. End of life
EOT. End of Tape
Extractables. Tape binders and lubricants that can be extracted with a solvent.
Exhaustive Binder Hydrolysis. The complete hydrolysis of polyester chains into low MW carboxylic acid and alcohol monomers that are readily extracted by organic solvents.
ftp. Flux changes per ___. Usually mm or inches
GC-MS. Gas Chromatography-Mass Spectrometry
GPC. Gel permeation Chromatography
Hc. Coercivity of a magnetic material. the magnetic field strength necessary to reduce the samples magnetization to zero after being saturated.
Hydrolysis. A chemical reaction in which water reacts with a compound to give 2 or more products. Many hydrolysis reactions are known. Esters hydrolyze to give carboxylic acid and alcohol products. Long chain esters, like those used as lubricants in magnetic tape, hydrolyze to give fatty acids (long chain carboxylic acids) and alcohols. The process is very similar to saponification whereby triglycerides present in animal fats are reacted with caustic water to produce glycerol and a fatty acid salt called soap.

Hydrolytic Stability. A measure of a tape binder's ability to avoid hydrolysis.
Hz. Hertz (cycles/second)
Ir. The remanence magnetization of the sample – the magnetization remaining after the sample has been saturated and the external field is removed, i.e. reduced to zero.
Is. The saturation magnetization of the sample. The highest value of magnetization attainable for the sample.
ISO. International Standards Organization

McLafferty Rearrangement. A common electron impact fragmentation pathway for molecules containing a C=O double bond (i.e., carbonyl compounds) and a hydrogen atom in the □-position (i.e., 4 atoms removed from the C=O double bond).

LE. Life Expectancy. The time that a storage medium is capable of successfully delivering its pre-recorded data
Methylenedianiline. A hydrolysis product of polymers prepared from the monomer methylenebis(phenyl isocyanate). The 2002 Fuji study includes the hydrolysis of a polyester polyurethane binder prepared in part from methylenebis(phenyl isocyanate).
Mhz. Megahertz
MOT. Middle of Tape
MP. Metal Particle
MW. Molecular weight
NARA. National Archives and Records Administration
OEM. Original Equipment Manufacturer
OR. Orientation Ratio. A hysteresis loop relationship defined as SQ_l/SQ_t
Partial Binder Hydrolysis. The hydrolysis of large polyester chains into smaller, but still relatively large polymeric pieces that are not readily extracted by organic solvent.
Phthalic Acid. A common monomer used in the formation of various polymers including polyesters.
PRML. Partial Response Most Likelihood.
RF. Radio Frequency
RH. Relative Humidity
SCSI. Small Computer Systems Interface. An industry standard computer interface for connecting SCSI devices such as tape drives, hard disk drives, etc..
SDLT. Super Digital Linear Tape. A Quantum Corporation Tape Storage product.
SER Symbol Error Rate
SFD. Switching Field Distribution. A hysteresis loop parameter
S/N. signal-to-noise
STE. Single Track Error
SQ. Squareness. A hysteresis loop relationship defined as Ir/Is.
TEM. Transmission Electron Microscope
UBER. Uncorrected Bit Error rate
VSM. Vibrating Sample Magnetometer

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APPENDIX

The appendix of this study is comprised of two parts; the following written section and the Excel work sheets included in the CD version of the report. The written Appendix sections correspond to the report sections and contain an "A." prefix. The Excel worksheets correspondingly contain the "AE. "Prefix.

A.1.0 STUDY OVERVIEW

A.1.3 STORAGE SYSTEM & TAPE MEDIA STANDARDS

TABLE A.1.1 below is an overview of applicable features of the storage products investigated in this study. Also noted are corresponding ECMA/ANSI specifications.

Table A.1.1 OVERVIEW OF RECORDING PROPERTIES

Tape Drive	**DLT4000**	**DLT7000**	**DLT8000**	**SDLT220**	**IBM 3590**	*Units*
Tape Format	DLT4	DLT5	DLT6	SDLT1	3590	
ECMA spec #	231	259	286	320	278	-
Recording Media	DLT III	DLT IV	DLT IV	SDLT	3590	-
Tape Speed	2.49	4.06	4.26	2.946	2	m/s
Write Gap Length	89	89	64	10	90	um
Write Gap Width	22	22	22	2	n/a	mm
Read Gap Length	89	18	18	3.7	n/a	um
Read Gap Width um	43	43	39.4	14	n/a	um
Physical Recording Densities **4f**	n/a	n/a	n/a	n/a	10200	ftpmm
Physical Recording Densities **2f**	2142	2254	2578	5400	n/a	ftpmm
Physical Recording Densities **1f**	1071	1127	1289	675	2550	ftpmm
Bandwidth of Read Amplifier	4.5	10	10	25	n/a	MHz
Highest Physical Recording Density	2142	2254	2578	5400	10200	ftpmm
Frequency	2,666,790	4,575,620	5,748,940	7,954,200	10,200,000	Hz

A.1.5 DATA COLLECTION & ANALYSIS

A cassette color coding scheme was used for testing and processing convenience. The scheme correlates a color code with a specific cassette type/manufacturer. Several Figures and Tables in this report make brand reference by color designation (e.g., Y, B, G, R…).

Quantum DLT IV:	Fuji– YELLOW (Y) Maxell– BLUE (B)
Quantum SDLT:	Maxell– GREEN (G)
IBM 3590:	BASF– RED (R) IMATION– BROWN (Br)
DLT 4000	Arkival BaFe-GOLD MP-DLTIII- PURPLE

A.2.0 TECHNICAL STUDY AREAS

A.2.1 Magnetic & Microstructure Analyses of the Recording Media

The tape brands studied, type and their identifier designations are shown in Table 2.1.1 below:

Table A.2.1 Tape Brands, Types and Codes

Study #	Brand	Type	Serial Number	Identifier #2
A	Quantum	DLT IV	432966	SH 105M2554 79
B	IBM	3590	N4044023546135	
C	Quantum	S DLT I	534232 222	SH 138M2060 114
D	Maxell	S DLT I	519451 204	SH 136M1778 114
E	Fuji	DLT IV	366065	MA139F632 47
F	Maxell	DLT IV	353562	SH 130M8787 51
G	Sony	DLT IV	135958	MA139F481 42
H	Imation	DLT IV	106671	MA134F451 21
I	Arkival BaFe	DLT III		
J	Quantum	DLT III		

A.2.1.1 Tape Supply

Availability of certain tape media was an issue at the period in which the study was initiated. Specifically the IMATION product for the IBM 3590 was difficult to obtain from normal distribution outlets. Supply was obtained after contacting IMATION directly.

A similar situation prevailed with the SDLT tape media. Tape media was readily available from normal distribution sources, although limited to the Maxell brand only. At a point later in the program additional SDLT media had to be obtained directly from Quantum.

DLT tape was readily available from normal distribution sources both locally and nationally. There are also multiple sources for the DLT IV tape product but several of these sources appeared to be private labeled stock made via OEM arrangements with either of the two manufacturers, Fuji and Maxell.

A.2.1.1Tape Performance

Early in the program certain unexplained tape drive/ media performance issues were experienced with the Quantum Super DLT error testing using the Arkival test software. Discussions with Quantum led to Arkival being provided with a (non-SCSI) software diagnostic tool called GS-Link. Error correlations were attempted with the two test programs and problem SDLT media returned to Quantum for analysis. Quantum’s test results on the returned media suggested the presence of tape edge damage that was not repeatable from drive to drive. This study continued with new SDLT replacement media supplied by Quantum.

Additional tape media had to be purchased for the study due to the experimental problems encountered in the high humidity (85%) salt chamber and failing media experienced at first write and read operations.

A.2.1.1 Tape Test Requirements

The following Table A.2.1 summarizes the Tape quantity requirements for the study. Some variation did take place as the experimental conditions dictated alternative requirements. *The Table can best be viewed in the ‘Normal Page View’ mode.*

Table A.2.1 PROJECT TAPE REQUIREMENTS

		TAPE TYPE	DLT IV					TAPE TYPE	S DLT	
OEM	**DLT IV**	**2.1(2) Aging**	**2.3 Binder**	**2.4 Physcl**	**2.5(1) UBER**	**2.6(2) Degradn**	**SDLT**	**2.1(2) Aging**	**2.3 Binder**	**2.4 Physc**
Maxell	X	1	1	see 2.1	10+1		X	1	1	see 2.1
Fuji	X	1	1	see 2.1	10+1					
Emtec										
Imation										

Tape requirements for studies **DLT IV** **24+2** **Super DLT**

NOTES:

(1) 10 tapes each drive type (in cartridges)+ 2 control tapes/drive type **@ 50'C/7**

(2) Tape sections only and not complete cassettes. **@ 40'C/5**

@ 50'C/85% RH

TEM Analysis

The Tables below list the TEM's taken for each tape and the magnifications used:

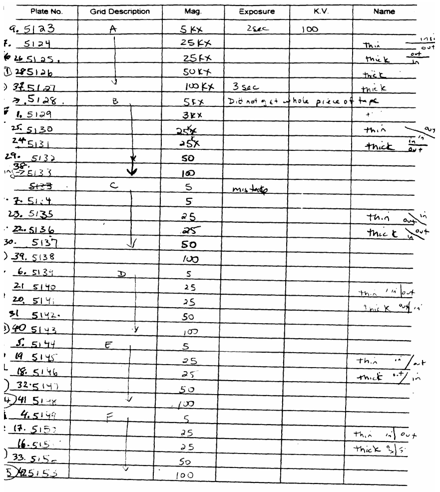


Plate No.	Grid Description	Mag.	Exposure	K.V.	Name
9. 5123	A	5KX	2sec	100	
7. 5124		25KX			Thin in/out
26 5125.		25KX			thick out/in
28 5126		50KX			thick
37 5127		100KX	3 sec		thick
7. 5128.	B	5KX	Did not get whole piece of tape		
1. 5129		3KX			+
25. 5130		25KX			thin out/in
24 5131		25KX			thick in/out
29. 5132		50			
38. 5133		100			
~~5133~~	C	5	mistake		
7. 5134		5			
23. 5135		25			thin out/in
22. 5136		25			thick in/out
30. 5137		50			
39. 5138		100			
6. 5139	D	5			
21 5140		25			thin in/out
20. 5141		25			thick out/in
31 5142.		50			
40 5143		100			
5. 5144	E	5			
19 5145		25			thin in/out
18. 5146		25			thick out/in
32. 5147		50			
41 5148		100			
4. 5149	F	5			
17. 5150		25			thin in/out
16. 5151		25			thick o/i
33. 5152		50			
42 5153		100			

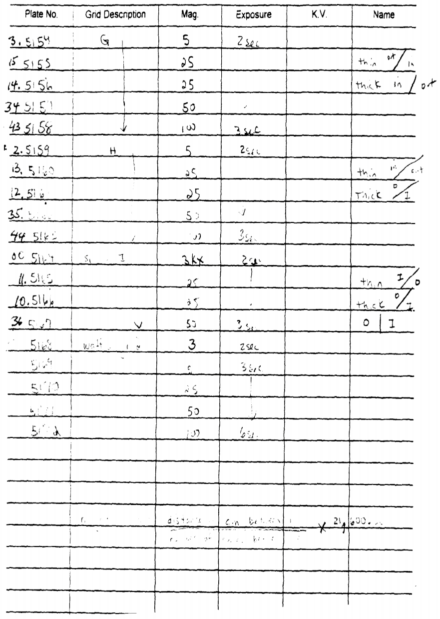


Plate No.	Grid Description	Mag.	Exposure	K.V.	Name
3. 5154	G	5	2sec		
15 5155		25			thin out/in
14. 5156		25			thick in/out
34 5157		50			
43 5158		100	3sec		
2. 5159	H	5	2sec		
13. 5160		25			thin in/out
12. 5161		25			Thick O/I
35. [illegible]		50			
44 5162		100	3sec		
[illegible] 5163	[illegible] I	3kx	2sec		
11. 5165		25			thin I/O
10. 5166		25			thick O/I
36 5167		50	3sec		O | I
5168	[illegible]	3	2sec		
5169		5	3sec		
5170		25			
5171		50			
5172		100	6sec		
	[illegible]	distance [illegible]	can between [illegible]	X 21,600	

Some typical TEM's are shown in Figures 1-6 – the first five of DLT-Fuji tape displaying the double coating characteristic at various magnifications and the sixth of the 3590 Emtec tape at 25 kx demonstrating its single layer characteristic.

Figure 1 is the lowest magnification (5kx) of the Fuji tape showing its entire cross section, the front coat on top, the substrate with its typical white spots and the backcoat. In Figure 2, one observes the entire front coat (at 25 kx), the magnetic layer with its oriented acicular particles and its underlayer with its spherical TiO2-like particles. Figure 3 is a cross-section showing the back coat – note the fine carbon particles in this photo. The next two photos are higher magnification to observe more detail in the magnetic top layer.

Figure 6 is the IBM 3590 tape shown for contrast with its single layer coating; confirmed later with the magnetic measurements.

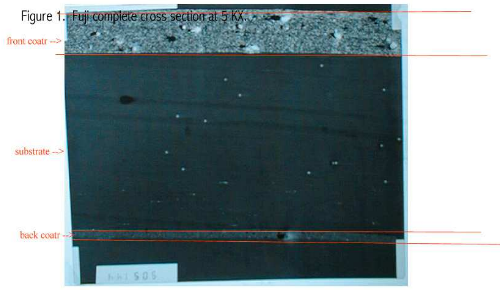


Figure 1. Fuji complete cross section at 5 KX.

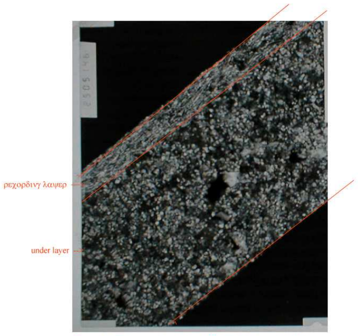


Figure 2. Fuji recording side at 25 KX showing double layer.

Figure 3. Fuji front side at 25 KX.

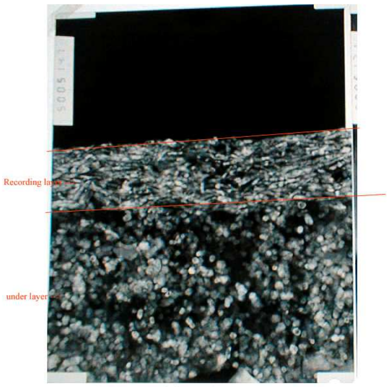


Figure 4. Fuji front side at 50 KX.

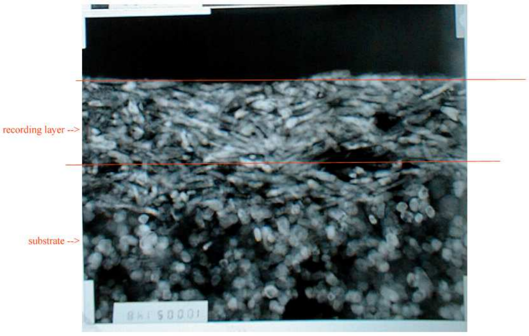


Figure 5. Fuji recording side at 100KX

Figure 6. IBM recording side at 25 KX showing no double layer.

Table 3A is a summary of the low mag results on these tapes. The comparisons of the low mag results are shown in Table 3B.

The tapes are grouped by suspected manufacturers (SH for Maxell and MA for Fuji and the BaFe and IBM. The Fuji and Maxell are almost identical in their thicknesses. BaFe and IBM are much thicker.

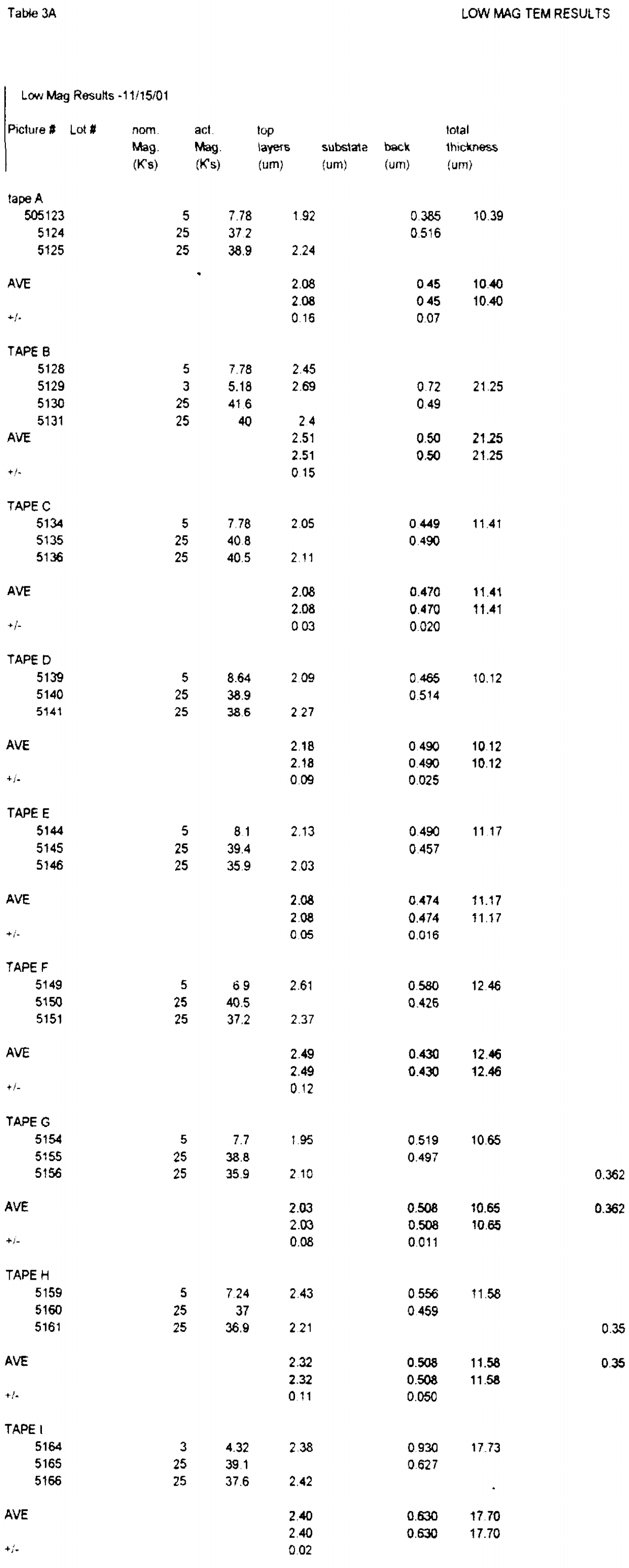


Table 3A

LOW MAG TEM RESULTS

Low Mag Results -11/15/01

Picture #	Lot #	nom. Mag. (K's)	act. Mag. (K's)	top layers (um)	substate (um)	back (um)	total thickness (um)	
tape A								
505123		5	7.78	1.92		0.385	10.39	
5124		25	37.2			0.516		
5125		25	38.9	2.24				
AVE				2.08		0.45	10.40	
				2.08		0.45	10.40	
+/-				0.16		0.07		
TAPE B								
5128		5	7.78	2.45				
5129		3	5.18	2.69		0.72	21.25	
5130		25	41.6			0.49		
5131		25	40	2.4				
AVE				2.51		0.50	21.25	
				2.51		0.50	21.25	
+/-				0.15				
TAPE C								
5134		5	7.78	2.05		0.449	11.41	
5135		25	40.8			0.490		
5136		25	40.5	2.11				
AVE				2.08		0.470	11.41	
				2.08		0.470	11.41	
+/-				0.03		0.020		
TAPE D								
5139		5	8.64	2.09		0.465	10.12	
5140		25	38.9			0.514		
5141		25	38.6	2.27				
AVE				2.18		0.490	10.12	
				2.18		0.490	10.12	
+/-				0.09		0.025		
TAPE E								
5144		5	8.1	2.13		0.490	11.17	
5145		25	39.4			0.457		
5146		25	35.9	2.03				
AVE				2.08		0.474	11.17	
				2.08		0.474	11.17	
+/-				0.05		0.016		
TAPE F								
5149		5	6.9	2.61		0.580	12.46	
5150		25	40.5			0.426		
5151		25	37.2	2.37				
AVE				2.49		0.430	12.46	
				2.49		0.430	12.46	
+/-				0.12				
TAPE G								
5154		5	7.7	1.95		0.519	10.65	
5155		25	38.8			0.497		
5156		25	35.9	2.10				0.362
AVE				2.03		0.508	10.65	0.362
				2.03		0.508	10.65	
+/-				0.08		0.011		
TAPE H								
5159		5	7.24	2.43		0.556	11.58	
5160		25	37			0.459		
5161		25	36.9	2.21				0.35
AVE				2.32		0.508	11.58	0.35
				2.32		0.508	11.58	
+/-				0.11		0.050		
TAPE I								
5164		3	4.32	2.38		0.930	17.73	
5165		25	39.1			0.627		
5166		25	37.6	2.42				
AVE				2.40		0.630	17.70	
				2.40		0.630	17.70	
+/-				0.02				

Table 3B

LOW MAG. COMPARISONS

Mfgr.	Type	Serial No.	Serial No. 2nd line	top layers (um)	substate (um)	back (um)	total thickness (um)	MAG LAYER (um)
Quantum	DLT IV	432966SH105M2554 79		2.08	7.87	0.45	10.40	
Maxell	DLT IV	353562	SH130M8787 51	2.49	9.54	0.430	12.46	
Quantum	S DLT I	534232 222	SH 138M2060 114	2.08	8.86	0.470	11.41	
Maxell	S DLT I	519451 204	SH 136M1778 114	2.18	7.45	0.490	10.12	
			AVE	2.2075	8.43	0.46	11.0975	
Fuji	DLT IV	366065	MA139F632 47	2.08	8.62	0.474	11.17	
Sony	DLT IV	135958	MA139F481 42	2.03	8.11	0.508	10.65	
Imation	DLT IV	106671	MA134F451 21	2.32	8.75	0.508	11.58	
			AVE	2.14	8.49	0.50	11.13	
Ark BaFe				2.40	14.67	0.630	17.70	
IBM	3590	N4044023546135		2.51	18.24	0.50	21.25	

Table 4 below contains the high magnification results for these tapes and allows a comparison of the magnetic layer thicknesses. The results are similar but there is a slightly thicker layer for the Fuji tapes (0.31 +/_.04) than the Maxell tapes (0.23 +/_.06). The magnetic results also support this relationship (Is for Maxell is about 20% less than for Fuji).

Table 4

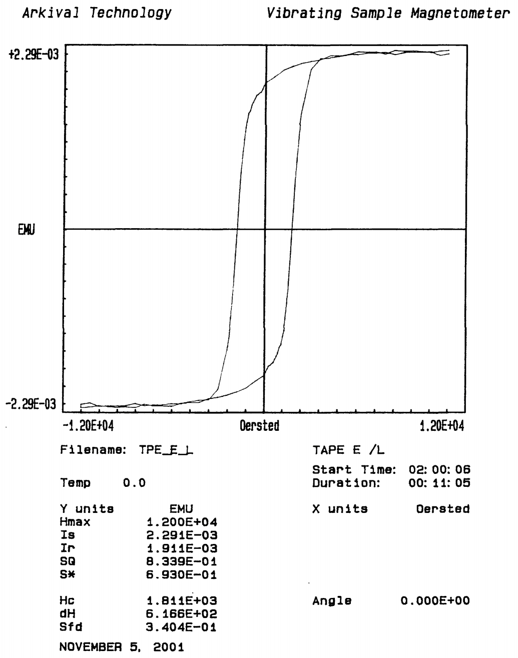
HIGH MAG. TEM RESULTS

ID	Mfgr.	Type	Serial No.	Serial No. 2nd line	Picture #	comment	nom. Mag. (K's)	act. Mag (K's)	top layers (um)	mag. layer (um)
A	Quantum	DLT IV	432966SH105M2554 79		5126		50	78.3		0.18
					5127		100	130.7		0.264
B	IBM	3590	N4044023546135		5132	no DC	50	84.2		
					5133	error	100			
C	Quantum	S DLT I	534232 222	SH 138M2060 114	5137		50	78.3		0.193
					5138		100	137.2		0.197
D	Maxell	S DLT I	519451 204	SH 136M1778 114	5142	??	50	76.7		0.277
					5143		100	136.1		0.327
E	Fuji	DLT IV	366065	MA139F632 47	5147		50	77.2		0.356
					5148		100	140.4		0.321
F	Maxell	DLT IV	353562	SH130M8787 51	5152		50	81		0.185
					5153		100	142.3		0.245
G	Sony	DLT IV	135958	MA139F481 42	5157		50	78.3		0.338
					5158		100	136.1		0.265
H	Imation	DLT IV	106671	MA134F451 21	5162		50	102.1		0.26
					5163		100	141.5		0.333
I	Ark BaFe				5167	no DC				

sh(Maxell)	0.18	ma	0.356
	0.264	(Fuji)	0.321
	0.193		0.338
	0.197		0.265
	0.277		0.26
	0.327		0.333
	0.185		
	0.245	ave	0.312
		stdev	0.040
ave	0.2335		
stdev	0.057		

VSM Analysis

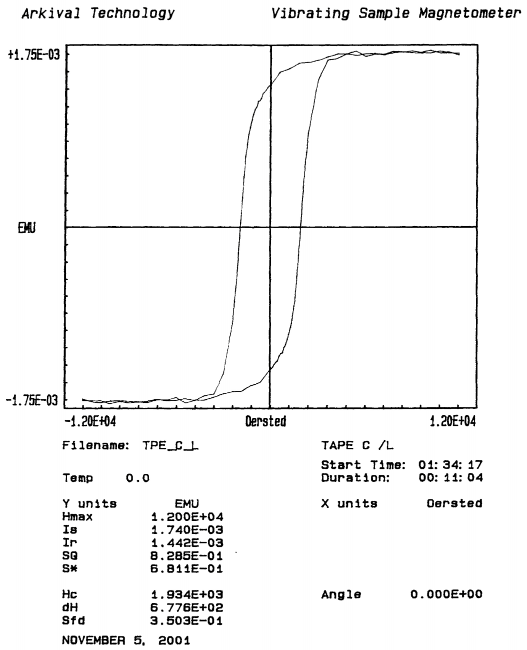
The hysteresis loops for these tapes are shown in the Figures below.



```
Filename:  TPE_E_⊥                 TAPE E /L
                                   Start Time:   02: 00: 06
Temp     0.0                       Duration:     00: 11: 05

Y units         EMU                X units        Oersted
Hmax          1.200E+04
Is            2.291E-03
Ir            1.911E-03
SQ            8.339E-01
S*            6.930E-01

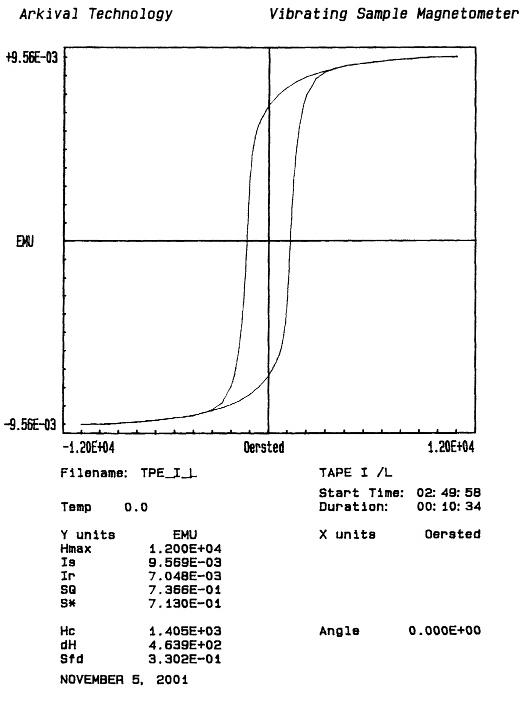
Hc            1.811E+03            Angle       0.000E+00
dH            6.166E+02
Sfd           3.404E-01
NOVEMBER 5, 2001
```



```
Filename:  TPE_C_⊥                 TAPE C /L
                                   Start Time:   01: 34: 17
Temp     0.0                       Duration:     00: 11: 04

Y units         EMU                X units        Oersted
Hmax          1.200E+04
Is            1.740E-03
Ir            1.442E-03
SQ            8.285E-01
S*            6.811E-01

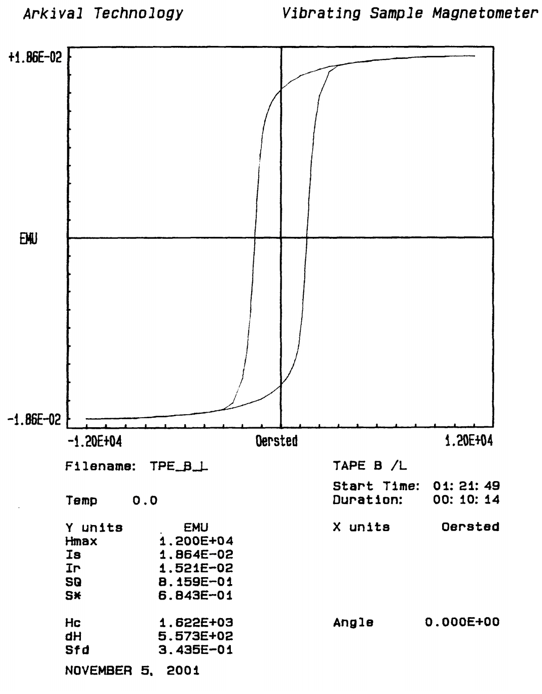
Hc            1.934E+03            Angle       0.000E+00
dH            6.776E+02
Sfd           3.503E-01
NOVEMBER 5, 2001
```



```
Filename:  TPE_I_⊥                 TAPE I /L
                                   Start Time:   02: 49: 58
Temp     0.0                       Duration:     00: 10: 34

Y units         EMU                X units        Oersted
Hmax          1.200E+04
Is            9.569E-03
Ir            7.048E-03
SQ            7.366E-01
S*            7.130E-01

Hc            1.405E+03            Angle       0.000E+00
dH            4.639E+02
Sfd           3.302E-01
NOVEMBER 5, 2001
```

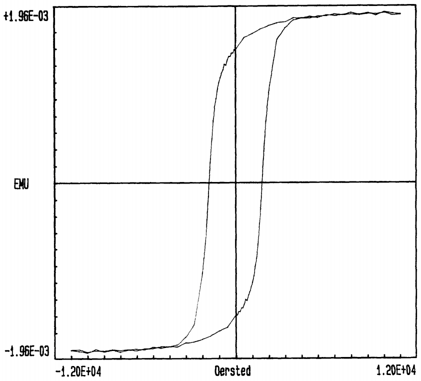


```
Filename:  TPE_B_⊥                 TAPE B /L
                                   Start Time:   01: 21: 49
Temp     0.0                       Duration:     00: 10: 14

Y units         EMU                X units        Oersted
Hmax          1.200E+04
Is            1.864E-02
Ir            1.521E-02
SQ            8.159E-01
S*            6.843E-01

Hc            1.622E+03            Angle       0.000E+00
dH            5.573E+02
Sfd           3.435E-01
NOVEMBER 5, 2001
```

Arkival Technology *Vibrating Sample Magnetometer*



```
Filename:  TPE_A⊥                    TAPE A /L

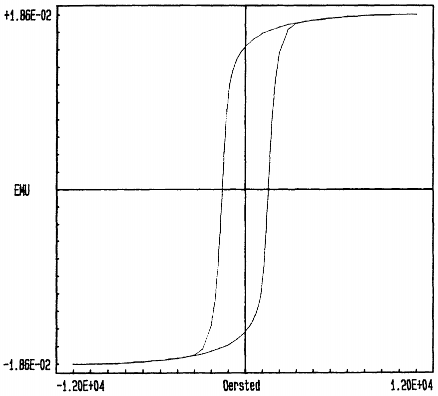
                                     Start Time:  01: 09: 17
Temp    0.0                          Duration:    00: 11: 04

Y units        EMU                   X units       Oersted
Hmax        1.200E+04
Is          1.961E-03
Ir          1.557E-03
SQ          7.943E-01
S*          6.892E-01

Hc          1.915E+03                Angle      0.000E+00
dH          6.681E+02
Sfd         3.488E-01

NOVEMBER 5, 2001
```

Arkival Technology *Vibrating Sample Magnetometer*



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Filename:  TPE_B⊥                    TAPE B /L

                                     Start Time:  01: 21: 49
Temp    0.0                          Duration:    00: 10: 14

Y units        EMU                   X units       Oersted
Hmax        1.200E+04
Is          1.864E-02
Ir          1.521E-02
SQ          8.159E-01
S*          6.843E-01

Hc          1.622E+03                Angle      0.000E+00
dH          5.573E+02
Sfd         3.435E-01

NOVEMBER 5, 2001
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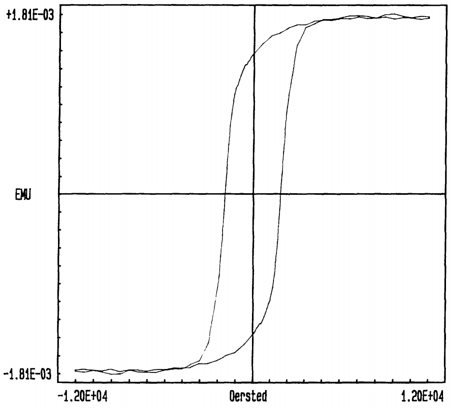
Arkival Technology *Vibrating Sample Magnetometer*



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Filename:  TPE_F⊥                    TAPE F /L

                                     Start Time:  02: 12: 29
Temp    0.0                          Duration:    00: 11: 08

Y units        EMU                   X units       Oersted
Hmax        1.200E+04
Is          1.770E-03
Ir          1.412E-03
SQ          7.976E-01
S*          6.817E-01

Hc          1.920E+03                Angle      0.000E+00
dH          6.670E+02
Sfd         3.474E-01

NOVEMBER 5, 2001
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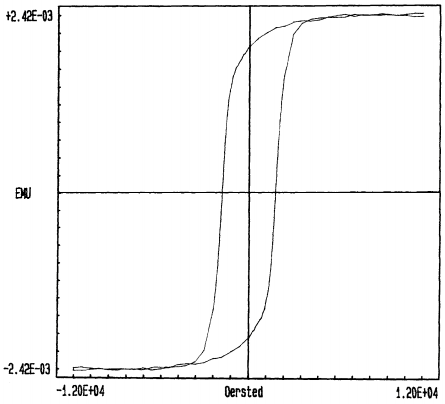
Arkival Technology *Vibrating Sample Magnetometer*



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Filename:  TPE_G⊥                    TAPE G /L

                                     Start Time:  02: 25: 05
Temp    0.0                          Duration:    00: 11: 08

Y units        EMU                   X units       Oersted
Hmax        1.200E+04
Is          2.399E-03
Ir          1.989E-03
SQ          8.289E-01
S*          7.036E-01

Hc          1.819E+03                Angle      0.000E+00
dH          5.911E+02
Sfd         3.250E-01

NOVEMBER 5, 2001
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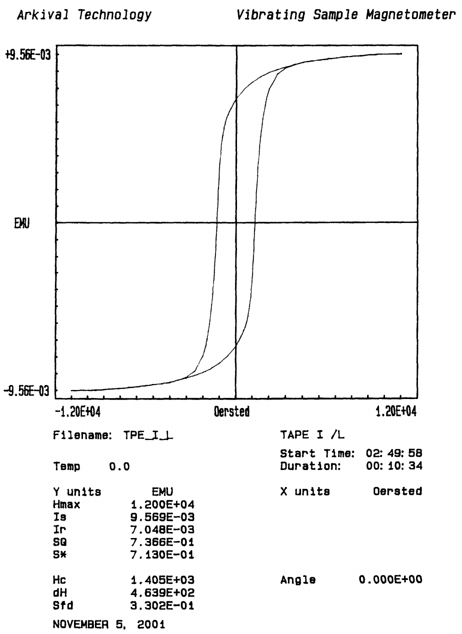

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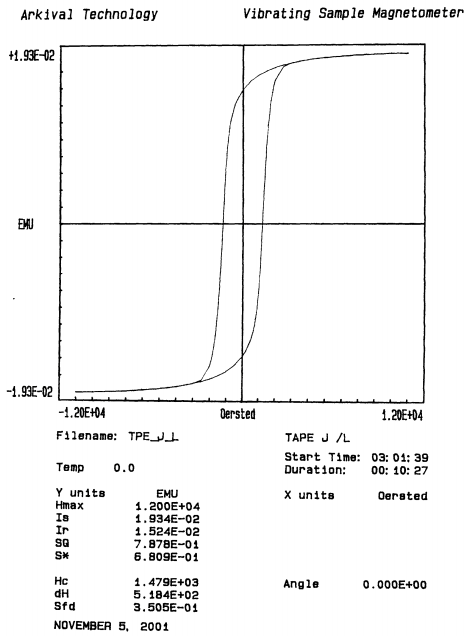
Arkival Technology          Vibrating Sample Magnetometer

Filename:  TPE_I⊥                  TAPE I /L
                                   Start Time:  02: 49: 58
Temp    0.0                        Duration:    00: 10: 34

Y units        EMU                 X units       Oersted
Hmax        1.200E+04
Is          9.569E-03
Ir          7.048E-03
SQ          7.366E-01
S*          7.130E-01

Hc          1.405E+03              Angle      0.000E+00
dH          4.639E+02
Sfd         3.302E-01
NOVEMBER 5,  2001
```



```
Arkival Technology          Vibrating Sample Magnetometer

Filename:  TPE_J⊥                  TAPE J /L
                                   Start Time:  03: 01: 39
Temp    0.0                        Duration:    00: 10: 27

Y units        EMU                 X units       Oersted
Hmax        1.200E+04
Is          1.934E-02
Ir          1.524E-02
SQ          7.878E-01
S*          6.809E-01

Hc          1.479E+03              Angle      0.000E+00
dH          5.184E+02
Sfd         3.505E-01
NOVEMBER 5,  2001
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A summary of these VSM results are shown in Table A.2.2.5 below.

Table A.2.2.5 VSM Data Analysis

Study #	Brand	Type	Is (memu)	Ir (memu)	SQ (Ir/Is)	Hc (Oe)	SFD	SQt	OR (Sql/Sqt)
A	Quantum	DLT IV	1.96	1.56	0.79	1915	0.35	0.40	1.98
B	IBM	3590	18.64	15.21	0.82	1622	0.34	0.37	2.19
C	Quantum	S DLT I	1.74	1.44	0.83	1934	0.35	0.35	2.36
D	Maxell	S DLT I	1.96	1.64	0.84	1930	0.35	0.37	2.26
E	Fuji	DLT IV	2.29	1.91	0.83	1811	0.34	0.37	2.25
F	Maxell	DLT IV	1.77	1.41	0.80	1920	0.35	0.36	2.20
G	Sony	DLT IV	2.40	1.99	0.83	1819	0.33	0.37	2.24
H	Imation	DLT IV	2.50	2.03	0.80	1801	0.33	0.40	2.00
I	Arkival BaFe	DLT III	9.57	7.05	0.74	1405	0.33	0.38	1.92
J	Quantum	DLT III	19.34	15.24	0.79	1479	0.35	0.38	2.07

It is clear that there are two types of double coated tapes, magnetically – one with an Is ~ 1.9 memu's and a coercivity of 1920 oersteds (Maxell) and the other with an Is ~2.4 memu's and a coercivity of 1810 oersteds (Fuji). The IBM tapes represent a thicker, single coated technology (Is ~19 memu; Hc ~1600 oersteds).

The SDLT media was very similar to that being used for the Quantum DLT IV product and may indeed be selected DLT IV media with an embedded servo pattern on the back side.

The study determined likely manufacturing sources for tapes sold under both OEM and private label brands. The TEM results and the VSM results were the basis for this determination. It is of interest to note that neither IBM nor Quantum manufactures their own media for these tape drives products. Both Quantum and IBM have also confirmed that the sources identified are the present media licensees.

A.2.2 VSM/ Aging Study- Experimental Procedures

The seven-(7) different media types/brands used in the Aging Study included the five standard type/brands used throughout the study with the addition of BaFe

Quantum DLT IV: Fuji, Maxell
Quantum Super DLT: Maxell

IBM 3590: BASF (Emtec), IMATION

and MP-DLT III tape as references- making a total of seven (7) samples. Three (3) VSM samples of each of the seven- (7) different media were used for the environmental exposure along with the control tapes. This quantity of samples allowed for sample averaging and accidental sample loss. The individual VSM samples were circular elements uniformly punched from a designated tape. The elements are assigned a number and position on a high temperature storage jar cap and were mounted with double-sided tape (magnetic surface exposed to the temperature/humidity environment). *See photo at left.* The saturated salt solution in the jar determined the humidity and the oven selection, the temperature. The closed jars were set in designated temperature ovens for prescribed periods, removed, room temperature acclimatized and measured on the VSM.

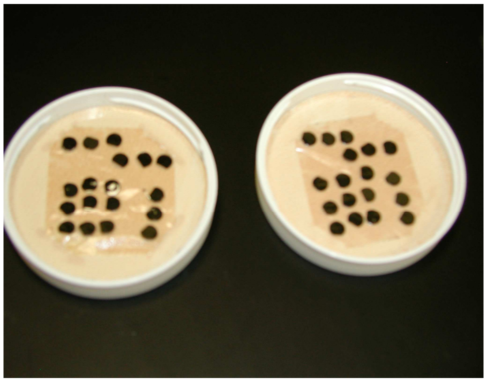

Table A.2.3 shows the saturated salt make-up used for establishing temperatures and humidities for the Aging (VSM) environmental tests.

Table A.2.3 SATURATED SALT SOLUTION EXPOSURES
(based on the data from J. F. Young, J. App. Chem., v17, p241 (1967))

Humidity (% R.H.) **Temp.** (°C)	**100**	**85**	**75**	**50**	**30**	**0**
25	D/I H2O	KCl	NaCl	Co(NO3)2	MgCl2	Drierite
40	D/I H2O	KCl (83°C)	NaCl	Na2Cr2O7	MgCl2 (32 °C)	Drierite
50	D/I H2O	K2CrO6 (86 °C)	NaCl	NaBr (49)	MgCl2 (31 °C)	Drierite
80	D/I H2O	BaCl2 (85+ °C)	NaCl (73 °C)	NaBr (52)	MgCl2 (29 °C)	Drierite

( ) indicates slight variations from the nominal humidity values.

The basis for the selected temperatures and humidities follow from the published ISO/ECMA specifications for the three tape products.

Table A.2.4 ISO/ECMA Environments

Product	ISO/ECMA Spec. No.	Condition	Temp	RH	Conditioning time
IBM 3590	278				
		Tape Test Environment	23^o+/- 2^o C	40-60%	24 h min
		Cartridge Operating	16^oC-32^oC	20-80% (26^o wet bulb)	24 h min
		Cartridge Storage	5^oC-32^oC	5%-80% (26^o wet bulb)	
Quantum DLT	286				
		Tape Test Environment	23^o+/- 2^o C	40-60%	24 h min
		Cartridge Operating	10^oC-40^oC	20-80% (26^o wet bulb)	24 h min
		Cartridge Storage	16^oC-32^oC	20%-80% (26^o wet bulb)	
Quantum SDLT	320				
		Tape Test Environment	23^o+/- 2^o C	40-60%	24 h min
		Cartridge Operating	10^oC-40^oC	20-80% (26^o wet bulb)	24 h min
		Cartridge Storage	16^oC-32^oC	20%-80% (26^o wet bulb)	

A.2.3 Binder Hydrolysis

A.2.3.1 Experimental Procedures

Different magnetic tape samples were to be exposed to accelerated aging conditions that include elevated temperature (50, 75 and 100^{o}C) and varying humidities (30%, 50%, 75% and 100% RH). The purpose being:

-to determine the mass of solvent extractable organic compounds from the seven magnetic tapes as a function of time spent under accelerated aging conditions;
-to determine the molecular weight and, where possible, the molecular identity of solvent extractables;
-to determine the lubricant loss (% weight) from each tape sample as a function of time;
-to determine, where possible, the molecular identity of the lubricants used in each tape sample.

Seven different magnetic tapes were studied: IBM 3590-Emtec and Imation, Quantum SDLT (Maxell), Fuji and Maxell DLT IV, BaFe and MP-DLT III. Each type of magnetic tape was cut into strips of approximately 1 gram size, accurately weighed and carefully wound into a spool. The spools were placed into open ended glass vials and the glass vials were neatly packed in an upright position inside aluminum cages. The cages were placed in autoclavable polypropylene bins (see photo at left) that were filled with approximately 1 inch of distilled, deionized water. The water level was sufficiently low that none of the glass vials were immersed in the aqueous drink. The aqueous solutions in some bins were saturated with the appropriate inorganic salts in order to maintain a constant relative humidity (% RH) within the bins. The polypropylene bins were sealed and placed in one of three ovens each at a constant temperature (± 3 ^{o}C), for specified times.

Table A.2.3.1. Description of Accelerated Aging Bins

/Bin #	T (^{o}C)	Salt (sat'd)	% RH
1	50	$MgCl_2$	31
2	50	$Na_2Cr_2O_7$	54.5
3	75	$MgCl_2$	30
4	75	NaBr	50
5	75	NaCl	76
6	100	none	100

Salt solutions for maintaining constant humidity: *Lange's Handbook of Chemistry*, 13th Ed., McGraw-Hill: NY, 1985.

At known intervals, each bin was removed from its respective oven, opened, and samples of each type of magnetic media were removed. Each sample was allowed to cool and then transferred to a glass flask for methylene chloride (CH_2Cl_2) extraction. After adding a clean stir-bar and methylene chloride, the tapes were magnetically agitated in the solvent for 24 hours (see photo left). The methylene chloride layer was then decanted into a clean, pre-weighed round-bottomed flask. The solvent was then evaporated from each round-bottomed flask using a commercial rotary evaporator. Weighing the round-bottomed flasks after evaporation of all solvent revealed the mass extracted from each tape and the % extractable.

Approximately 1-3 milligram (mg) of each extract was dissolved in 1 mL of fresh CH_2Cl_2 and submitted for GC-MS analysis on an HP 5890A gas chromatograph coupled to a 70 eV electron impact (EI) mass spectrometer. For molecules with a molecular weight of 100 atomic mass units (amu), this would correspond to a solution with a concentration between $1x10^{-2}$ and $3x10^{-2}$ M (molar or moles/L). For much larger molecules with a molecular weight of 1000 amu, this would correspond to a solution with a concentration between $1x10^{-3}$ and $3x10^{-3}$ M. This entire concentration range is appropriate for the GC-MS technique utilized. The GC-MS analysis was qualitative in nature and designed to identify but not quantify compounds present in the solvent extracts. Following each GC-MS run, an electronic MS library was searched to help identify each compound present in the solvent extracts.

A.2.3.2 Earlier Binder Studies and Discussion

Prior to this work, tape binder hydrolysis was studied in detail by NML (1). The question of hydrolytic stability of magnetic tape binder was specifically addressed by subjecting several different magnetic tape samples to elevated temperatures. The NML data was fit to a kinetic model developed to describe the level of extractable binder hydrolysis product as a function of time. The model is based on a simple first order kinetic equation and makes a key assumption: magnetic tape lubricants are volatile compounds that vaporize to leave no appreciable lubricant concentration on the tapes. This assumption may not be valid under the conditions of the NML study and a significant portion of the NML solvent extracts attributed to binder hydrolysis products may in fact have been due to lubricant. In fact, the NML report offers no compelling data to support the notion that lubricants present in the magnetic tape readily evaporate. The NML assumption is based upon a gas chromatography study designed to measure butyl myristate concentrations as a function of time spent under accelerated aging conditions. Butyl myristate is a common magnetic tape lubricant. The data indicate a slow reduction in butyl myristate concentration over a period of about 80 weeks at 58 °C. Most interesting, the loss of lubricant was found to be humidity dependent, the most rapid rate of loss occurring at the highest %RH levels tested. A much more plausible explanation

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(1) van Bogart, J W. C., National Media Lab Technical Report RE0017, 1994

for the humidity dependent loss of butyl myristate is its slow hydrolysis to myristic acid and butanol. As such, the kinetic model developed to explain the time dependence of acetone extracts is flawed.

The NML kinetic model also predicts that the concentration of binder hydrolysis extraction products should reach an equilibrium "plateau" at long times. This is not observed. The weight percent of acetone extracts reaches a maximum at intermittent times before falling off to a non-zero value (~0.5 wt %) at long times. The NML kinetic model was adjusted to explain why "it appears as if the extractable binder [hydrolysis] products are further reacting to produce a 'non-extractable' binder component." There is no physical or chemical evidence presented to support the further reaction of binder hydrolysis products into "non-extractable" products and the existence of these latter species must be questioned. A less complicated explanation for the NML experimental data is presented here. This reinterpretation of NML data distinguishes partial from exhaustive binder hydrolysis. Thus, although visible signs of partial binder hydrolysis (e.g., sticky tape formation) are noted by NML upon exposing magnetic tapes to accelerated aging conditions, *the extent of exhaustive binder hydrolysis resulting in the formation of low MW, readily extractable hydrolysis fragments was minimal*. Instead, the extracts consisted largely of lubricants and a few volatile components either left over from the chemical manufacture of the tapes or used as additives. Partial hydrolysis of the polyester containing binder releases lubricants and other components present in the interior of the tape structure resulting in an initial rise in % extractables as a function of time spent under accelerated aging conditions. Over extended times, however, the more volatile components are lost and the ester lubricants are slowly hydrolyzed to non-volatile fatty acids. The net result is a steady decline in percent extractables at long reaction times.

Recently, a study concerning storage stability of metal particle media (6) reported a polymer binder consisting of polyester polyurethane and PVC cross-linker was extracted with tetrahydrofuran (THF) and analyzed by gel permeation chromatography (GPC) using an ultraviolet detector. It is unclear which species were actually detected by UV and there was no mention made of the detected molecule(s) molar absorptivity, an important constant for back-calculating concentrations. The proceedings paper does not indicate magnetic tape sample sizes utilized in the study. Consequently, it is difficult to compare and contrast the Fuji study to the NML or other studies. The Fuji results, plotted as the number of extracted molecules versus time, show a steady increase in the number of extracted molecules as a function of time spent under ambient conditions. Given the limited amount of information available, we project that somewhere between 1.0 and 2.0 milligrams of exhaustive hydrolysis products were apparently isolated by GPC. This would correspond to 0.001 to 0.002 weight percent of hydrolysis product collected for a 100 gram sample. With limited experimental detail it appears possible that the weight percent of exhaustive hydrolysis product collected by the Fuji group could easily fall within the experimental noise of the extractables collected in the NML study (i.e., between 0.5 and 3.1 weight percent). In other words, the mass of exhaustive binder hydrolysis products collected in the Fuji study may be minimal compared to the total mass of acetone extracts collected from the NML magnetic tape.

1994 NML Binder Hydrolysis Study. The most thorough investigation reported to date concerning binder hydrolysis in magnetic tape was that performed by Dr. John W. C. van Bogart of the National Media Lab (NML) in 1994. In the NML study the question of hydrolytic stability of magnetic tape binder was specifically addressed by subjecting several different magnetic tape samples to elevated temperatures (40 and 75 ^{o}C) and varying relative humidities (0 to 90% RH) for periods of up to 3 years. At intermittent times, samples of each tape were extracted with acetone. *The acetone extracts were not submitted for detailed chemical analysis. No attempt was made to characterize the chemical composition of any species present in the acetone extracts save butyl myristate, a suspected lubricant.* Under the most severe conditions tested (75^{o}C, 90% RH), the weight percent of acetone extracts from a high grade VHS tape gradually rose from ~1.4% (time zero) to ~3.1% (~16 weeks) before slowly dropping off and eventually reaching 0.5-1% (140 weeks). A lower grade VHS tape behaved similarly with the weight percent of acetone extracts reaching a maximum of 2.6% at approximately 16 weeks before slowly falling off to 0.6% at approximately 140 weeks.

Without the aid of chemical analysis, the NML data was fit to a kinetic model that was developed to describe the level of extractable binder hydrolysis product as a function of time. The model is based on a simple first order kinetic equation and makes a key assumption: magnetic tape lubricants are volatile compounds that vaporize to leave no appreciable lubricant concentration on the tapes. This assumption may not be valid under the conditions of the NML study.

The NML report notes that some of the tapes investigated contained the butyl ester of myristic acid as lubricant. The literature reports a melting point of 6.5-7.2 ^{o}C for butyl myristate (Z. Phys. Chem. (Leipzig), **251** (1972), p. 303) and a boiling point of 195 ^{o}C at a pressure of 18 Torr (Justus Liebigs Ann. Chem., **473** (1929), p. 255). There are no literature values available for the boiling point for butyl myristate at atmospheric pressure, but one can use a pressure-temperature nomograph to estimate a boiling point of 340 ^{o}C at atmospheric pressure. A molecule with this boiling point should not be considered volatile at either 40 or 75 ^{o}C, the temperatures employed in the NML binder hydrolysis study. The NML belief that lubricants including butyl myristate are volatile under the conditions of the aging experiments is based upon data collected from two separate labs. These labs utilized gas chromatography to measure butyl myristate concentrations as a function of time spent under accelerated aging conditions (58 ^{o}C and varying %RH). Although the data from the labs "show a considerable amount of scatter" that "differ by as much as 30%," the data indicate a slow reduction in butyl myristate concentration over a period of about 80 weeks at 58 ^{o}C (see Figure 7.4, page 40, National Media Lab Technical Report RE0017, 1994). Most revealing, the loss of lubricant was found to be humidity dependent, the fastest losses occurring at the highest humidity levels tested. It is unlikely that %RH would have a profound effect on lubricant volatility. A much more plausible explanation for the loss of butyl myristate at 58 ^{o}C is its slow hydrolysis to myristic acid and butanol. Like polyester binder, the butyl ester of myristic acid should hydrolyze faster at higher humidities (i.e., higher concentrations of water). In summary, the NML report offers no compelling data to support the notion that lubricants present in the magnetic tape completely evaporate at or below 75 ^{o}C. Their slow hydrolysis to fatty acid and alcohol is a much more likely scenario. As such, the kinetic model developed to explain the time dependence of acetone extracts is flawed. Aside from problems associated with evaporation of lubricant, other problems with the NML model also exist. The model predicts that the concentration of binder hydrolysis extraction products should reach an equilibrium "plateau" at long times. This is not observed. As described above, the weight percent of acetone extracts reaches a maximum at intermittent times before falling off to a non-zero value (~0.5 wt%) at very long times (see Figure 7.1, page 37, National Media Lab Technical Report RE0017, 1994). In order to fit the flawed model to the experimental data, a fudge factor was introduced. Thus, the model is adjusted to explain why "it appears as if the extractable binder [hydrolysis] products are further reacting to produce a 'non-extractable' binder component." There is no physical or chemical evidence presented to support the further reaction of binder hydrolysis products into "non-extractable" products and the existence of these latter species must be questioned. Finally, the model includes an additional term for unspecified "other low MW extractables," a second fudge factor needed for an acceptable fit. In total, the kinetic model is designed to account for 3 types of components in the acetone extracts: low MW binder hydrolysis components, tape lubricant and "other low MW extractables." None of these components were identified by modern methods (e.g., GC-MS). The only basis for the creation of 3 distinct types of extracts seems to be a combination of expectation (i.e., experimental bias) and data fitting.

A less complicated explanation for the NML experimental data is presented here. This reinterpretation of NML data distinguishes partial from exhaustive binder hydrolysis. Thus, although visible signs of partial binder hydrolysis (e.g., sticky tape formation) are noted by NML upon exposing VHS tapes to accelerated aging conditions, *the extent of exhaustive binder hydrolysis resulting in the formation of low MW, readily extractable hydrolysis fragments may be minimal*. Instead, the extracts consist largely of lubricants and a few volatile components either left over from the chemical manufacture of the tapes or used as additives. Partial hydrolysis of the polyester containing binder releases lubricants and other components present in the interior of the tape structure resulting in an initial rise in % extractables as a function of time spent under accelerated aging conditions. Over extended times, however, the more volatile components are lost and non-volatile fatty acid ester lubricants are slowly hydrolyzed to non-volatile fatty acids. The net result is a steady decline in percent extractables at long reaction times. This reinterpretation of NML data is based partly on the experimental data collected by the UNH group in the present study (see below).

2002 Fuji Photo Film Report. Very recently, Kazuko Hanai and Yutaka Kakuishi of the Fuji Photo Film Company reported a study concerning storage stability of metal particle media (K. Hanai and Y. Kakuishi, *Proceedings of the 10th NASA Goddard Conference on Mass Storage Systems and Technologies in cooperation with the 19th IEEE Symposium on Mass Storage Systems*, University of Maryland, College Park, **April 16, 2002**, p. 311-315). In the study, polymer binder consisting of polyester polyurethane and PVC cross-linker were extracted with tetrahydrofuran (THF) and analyzed by gel permeation chromatography using an ultraviolet detector. It is unclear which species were actually detected by UV and it is worth noting that multiple UV active species including lubricants could be extracted from the tape. No mention is made of the detected molecule(s) molar absorptivity, an important constant for back-calculating concentrations. The authors do mention that phthalic acid and methanediphenyl diisocyanate (or more appropriately methylene diphenyl isocyanate (MDI) of formula $O=C=N-C_6H_4CH_2C_6H_4-N=C=O$) were utilized in the formation of the polyester polyurethane binder, both of which could potentially be detected by UV (methanediphenyl diisocyanate as the corresponding hydrolysis product) following exhaustive hydrolysis of the binder. Unfortunately, the proceedings paper does not indicate magnetic tape sample sizes utilized in the study. Moreover, hydrolysis product(s) are reported in terms of molecule numbers rather than weight percents or concentrations. Consequently, it is difficult to compare and contrast the Fuji study to the NML or other studies. The Fuji results, plotted as the number of extracted molecules versus time, show a steady increase in the number of extracted molecules as a function of time spent under ambient conditions. The number of extracted molecules varies from approximately 3.6×10^{18} to 6.8×10^{18} for samples stored between 0.1 and 14 years, respectively. Since one mole corresponds to 6.02×10^{23} (Avogadro's number) molecules, the Fuji samples containing hydrolysis products contain between 5.9×10^{-6} and 1.12×10^{-5} moles. Assuming an average molecular weight of 182 for the hydrolysis products (4, 4'-methylenedianiline from MDI and phthalic acid have a MW's of 198.27 and 166.13, respectively), somewhere between 1.1 and 2.0 milligrams of exhaustive hydrolysis products were apparently isolated by GPC. If the Fuji group started with 1 gram of magnetic tape for each analysis, then this would correspond to 0.11 to 0.20 weight percent of hydrolysis product collected. If the Fuji group started with 10 grams of magnetic tape, then this would correspond to 0.011 to 0.020 weight percent of hydrolysis product collected. If the Fuji group started with 100 grams of magnetic tape, then this would correspond to 0.0011 to 0.0020 weight percent of hydrolysis product collected. Without further experimental detail reported, it is difficult to compare the Fuji data to the NML study, but it appears possible that the weight percent of exhaustive hydrolysis product collected by the Fuji group could easily fall within the experimental noise of the total weight percent extractables collected in the NML study (i.e., between 0.5 and 3.1 weight percent). In other words, the mass of exhaustive binder hydrolysis products collected in the Fuji study may be minimal compared to the total mass of acetone extracts collected from magnetic tape. The use of GPC with UV detection to isolate such small quantities of exhaustive binder hydrolysis product is intriguing and certainly deserves further consideration.

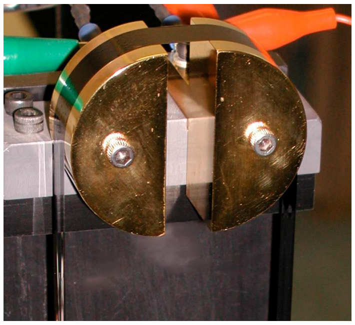
A.2.4 Physical Properties

A.2.4.1 Experimental Procedures

Resistivity

The test procedures followed the test method(s) outlined in the ISO/ECMA specifications. Test fixtures were designed, constructed and plated to specification. *See photo below.* The Resistivity Pre-Tests evolved experimental observations that required necessary modifications to the ISO/ECMA specifications. It was determined that the ISO/ECMA voltage specified for the IBM 3590 product (500V) generates sufficient conductive heating to distort the test tapes and invalidate resistivity readings. Lower voltages were required for the test as well as low current measuring equipment.

A length of ~1m of each tape evaluated was loosely wound on a small cassette spool along with an equal length sample for the friction measurement. The spools were affixed to an environmental container cover that was designed to suspend the samples over a saturated salt solution. Tapes in this study were also exposed to a range of temperatures and humidities. There were a total of 4 jars per oven temperature (both 40C and 50C) representing 8 test conditions (2 temperatures and 4 humidities in each); the conditions were: 40C and 50C and 30%, 50%, 75% and 85% relative humidities.

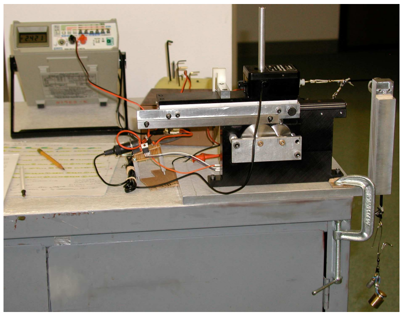


Tape samples were weighted for the measurement to insure a firm contact with the ISO/ECMA resistivity fixture. Surfaces were kept clean and the measurement performed in a dust free environment.

Friction

The ISO/ECMA specification does not specify the experimental hardware for the friction test. The test describes the procedure for pulling tape sections over a specified rod. One side of tape section was weighted, makes a 90° wrap around the rod, and pulled with a uniform force. Starting and sliding force (friction) was recorded. In many labs, such friction measurements are done manually with weights and spring gages. A manual pre-test of the friction measurement proved totally inadequate and non-repeatable. A more accurate sample holding method, appropriate fixturing and motor control (1mm/sec) was required for this test. It was further noted that the ISO/ECMA ceramic material specified for the friction test was outdated and irrelevant for the drive products being evaluated. An AlSiMag 2 material for the head equivalent friction test was ordered but was not be available in time for the study. The test fixture was also designed to accommodate interchangeable ceramic rods and tape heads for the friction test but the proposed rod material change was never approved by Quantum or IBM.

Friction measurements are reported therefore for tape surface (magnetic layer side) to tape surface (conductive coating side) only. *See experimental setup in photo.*



A length of ~1m of each tape being evaluated was loosely wound on a cassette spool along with an equal length sample for the resistance measurement. The spools were affixed to an environmental storage container cover that was designed to suspend the samples over a saturated salt solution. There were a total of 4 jars per oven temperature (both 40C and 50C); representing 8 test conditions (2 temperatures and 4 humidities in each). The conditions were: 40C and 50C and 30%, 50%, 75% and 85% relative humidities.

Samples were placed back into their respective chambers for additional environmental exposure after data was obtained. The full data set is included in Appendix AE.2.4.

A.2.5 RF Amplitude Response

A.2.5.1 Experimental Procedures

The tape drives for the study could not be used for RF measurements. An alternative test means was used that employed professional video recorders. The use of linear control tracks in video recorders provides accurate tape position tracking for the video data contained in the video tracks. Access to these control tracks allowed for customized single frequency recording and subsequent RF measurements of the recording media under study.

Special video amplifier circuits were integrated into the VCR to overcome the complexity of the measurement, the necessity to write specific data frequencies (2f, 4f, etc.) and the measurement of very low level amplitudes from the recording media being evaluated. RF signals were written using a precise frequency source via a commercial chipset designed for high-end video applications.

The tapes under test contained the recorded RF analog region and simplified data recorded with three different data patterns. A comparison of the data files on the test tapes was made against the same patterns on disc and differences reported as errors. There was no compression and no error correction used in the test.

The subject test tapes were reloaded into professional videocassettes and evaluated as such. Considerable care given to loading detail, edge feathering and tape pre-tensioning. The process resulted in a series of high quality beta cassettes containing the three (3) data tape stocks of the study along with a BaFe tape and a MP-DLT III metal particle tape for reference.

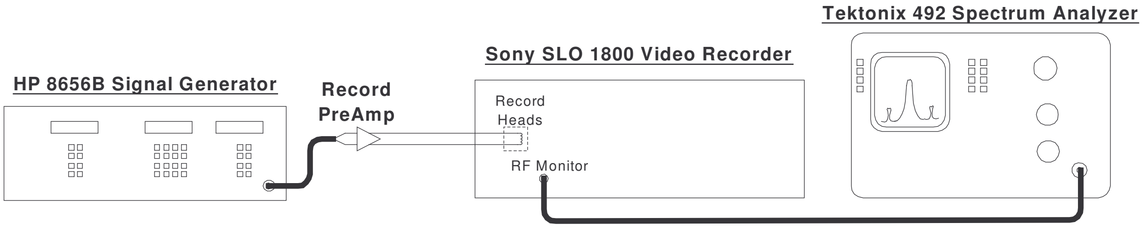
The following Table A.2.5.1 describes the Storage Devices investigated, their recording densities (defined as 1f, 2f, and 4f) and information regarding recording frequencies and bandwidth.

Table A.2.5.1 Recording Properties

Tape Drive	**DLT 4000**	**DLT 7000**	**DLT 8000**	**SDLT 220**	**3590**	***Units***
Highest Physical Recording Density	2142	2254	2578	5400	10200	ftpmm
Frequency	2,666,790	4,575,620	5,748,940	7,954,200	10,200,000	Hz
Bandwidth of Read Amplifier	4.5	10	10	25	n/a	MHz

The tests tapes were written with four RF signals (2.5, 5.0, 7.5 and 10 MHz). RF signals were written using a precision frequency source shown below.

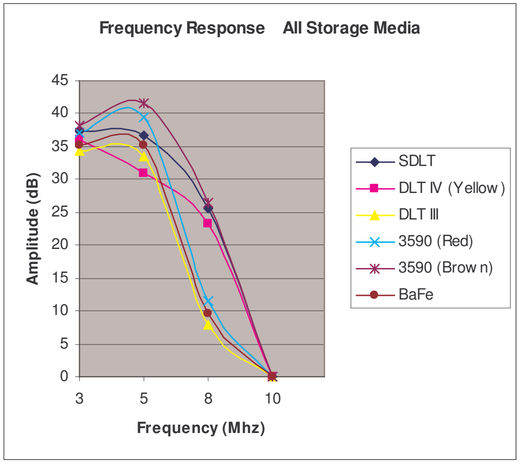
RF Amplitude response- Test Stand Diagram



The test setup consisted of a HP 8656B Signal Generator, a Record Preamp, a SLO 1800 Video Recorder, and a Tektronix 492 Spectrum Analyzer. The Record Heads are detached and connected to a Record Preamp for media writing to eliminate any filtering from the Sony SLO 1800. The Record Heads are reattached to the SLO 1800 for tape media playback. The RF Monitor output has a 10:1 Gain from the RP24 (record/playback) board. During the record mode, the HP 8656B Signal Generator is programmed to output 2.5MHz, 5MHz, 7.5MHz, and 10MHz. The record amplitude is adjusted to generate a 2.5 Volt output at the Record Preamp. Each frequency is applied for a specified time on to the tape media being tested. The tapes are placed in environmental chambers and re-measured for RF signal degradation.

A periodic tape re-winding schedule in the environmental chambers was employed such that the entire tape length was exposed to the test environment; thereby eliminating the BOT, MOT and EOT issue. Custom tape rewinders were used to provide continuous environmental tape exposure within the chambers. Daily rewinding at elevated temperatures proved harmful to several of the recording tapes. The fragility of the thin tape media was prone to edge damage and slight stretching while being continuously wound and rewound on the guides and rollers of the recyclers.

Figure A.2.6.1 Circuit Frequency Response



Changing the test cycle(s) in the environmental chambers to a single rewinding schedule at the beginning of each exposure cycle proved satisfactory.

The recording of simplified data for error analysis did not prove applicable to the double coated DLT and SDLT media. Limitations in the circuitry complicated by the very low signal outputs made this error test unlikely to yield useable results. Error performance was only available via the error part of this study. *See section 2.6.*

The circuit frequency dependence, with the appropriate test media was measured to assure reliable data collection. The data in Figure A.2.6.1 confirmed the expected frequency roll-off and signal weighting. The signal levels at the 10 MHz frequency were insufficient to report reliable data and change.

The complete set of test tapes were written and initial data recorded. Cassettes were placed in their in their appropriate environmental chambers and environmentally rewound. At 3-4 week intervals the test tapes were removed from the test environments, acclimatized to room temperature and read. Control tapes stored at room temperature were typically run before and after each environmental test group to assure that the test drive was functioning properly

Environmental Storage

Two Tenney Environmental chambers were used to store tapes and the recyclers at the 50°C/ 75% RH and 40°C/ 50% RH conditions. Each chamber was equipped with time programmable Temperature/RH data loggers to assure the consistency and accuracy of the storage environment over the life of the study.

The 50°C/ 85% RH environment was accomplished via a custom designed storage box that accommodated the test tapes and the recycler. Both were suspended over a saturated salt (K_2CrO_6) solution but unlike the environmental chambers there was no forced air circulation within the box.

A.2.6 Error Study

A.2.6.1 Experimental Procedures

Tape Media

The tape media for the error study represented five (5) test tapes for each drive type (3590, DLT and SDLT) at each of three environmental conditions- along with two (2) RT control tapes for each drive type. When applicable, the media quantity was doubled to include one additional media manufacturer for each drive type.

The study included tapes from the following OEM/Type's:

Quantum DLT IV: Fuji (15 tapes); Maxell (15 tapes)
Quantum SDLT: Maxell (15 tapes)
IBM 3590: BASF (15 tapes), IMATION (15 tapes)

The five tapes for each storage condition provided for both performance variations and the averaging of data as well as protection against unanticipated tape losses in the three (3) controlled environments:

40ºC/ 50% RH
50ºC/ 75% RH
50ºC/ 85% RH

Two tapes from each OEM were kept at room temperature (20º C and 50% RH) and used as control tapes throughout the study. The periodic testing of these control tapes enabled the determination of error changes (and trends) resulting from multiple use which was inherent also in the environmental test data.

Each environmental chamber included one or more tapes made with traditional recording media. The BaFe and MP-DLTIII control tapes were monitored in a Quantum DLT 4000 drive.

Tapes were stored in the test environments in their manufactured cassettes and not in plastic shipping or storage containers *.

The study utilized two drives of each type (3590, DLT and SDLT) to provide for drive-to-drive variability data and a drive backup in the event of any drive-type failure.

** Note: IBM 3590 type cassettes are not supplied in protective outer shipping/handling cases.*

Environmental Storage

Two Tenney Environmental chambers were used to store tapes at the 50ºC/ 75% RH and 40ºC/ 50% RH conditions. Each chamber was equipped with time programmable Temperature/RH data loggers to monitor the storage environment over the life of the study. *See photo at left.*

The 50ºC/ 85% RH environment was accomplished via a custom designed high temperature storage box that accommodated the 27 test tapes suspended over a saturated salt (K_2CrO_6) solution. At one point in the study, the test cartridges in the box were covered with caked salt from the saturated salt solution and had to be discarded. The vapor pressure buildup within the test box caused a vapor loss due to a leaky seal. The test had to be restarted with new replacement tapes and an improved method of sealing and containing the vapor pressure.

Test Procedure

At 3-4 week intervals the test tapes were removed from the test environments, acclimatized to room temperature* and error-evaluated in their respective tape drives with the test software. Due to the extensive tape testing time per storage condition the 27 test tapes in each lot were time-staggered such that only one lot was out of the environmental chambers at a time. The ambient stored control tapes were typically run before and after each environmental test group to assure that the drives were functioning properly. All tapes were tested on both the primary and secondary drive of each type. The average test time for each tape was 20 minutes for the IBM 3590 type, 2 hours for the DLT IV types and 3 hours for the SDLT type.

The two IBM 3590 drives were obtained via an IBM selling partner, the two Quantum DLT drives thru a national Distributor and the SDLT drives from Compaq and Quantum. Early in the drive testing program a high failure rate was experienced with the SDLT test system configuration. Ensuing discussions with Quantum resulted in their providing replacement drives for test and analysis. Error testing was re-started with new SDLT drives that incorporated the latest engineering changes and software modifications. The Quantum firmware also included the necessary VSC's (vendor specific codes) for collecting error data.

** Note: particular care and handling was used to assure that condensation did not occur when tapes were removed from environmental chambers.*

A.2.6.2 Arkival Test Software

The software was used to study variations in data error rate for multiple vendors' tape cartridges. The test tapes were written once and read many times throughout the study. During *reads,* the program read the data blocks and periodically captured designated SCSI log pages. The software contains commands to monitor

- Data patterns
- Block sizes
- File marks
- Log page sampling
- Host data compare control

The program also maintained event files which contained the following types of information:

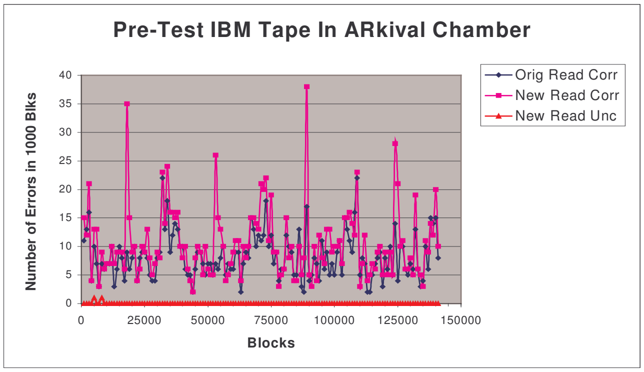
- Tape identification
- Target tape drive identification
- Time-stamp of events
- Summary statistics (number and size of the blocks written and read)

The program communicated to the drives via the ASPI (Advanced SCSI Programming Interface) driver. The OS for the program was Microsoft NT version 4.0.

The post processing and analysis of the log page data took place after the data collection process.

A.2.6.3 Additional Tape/Drive Analysis

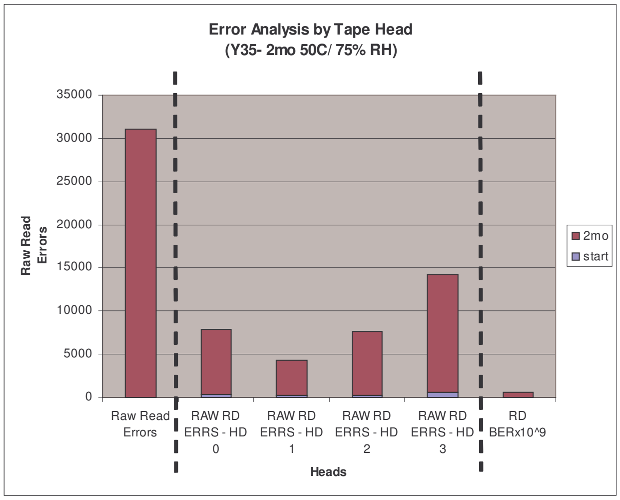
Fig. A.2.6.1 Error Summary by Block



The individual tapes employed in the study reported error data on a block-basis. This reporting method enabled an in-depth study of individual blocks containing errors. Error blocks are representative of physical tape regions that are prone to either error generation and/or multiple error clustering. The generation of multiple errors in a particular data block will increase the probability of violating error correction capabilities and causing hard read errors- making data recovery unlikely. An error analysis by block count enabled such a determination to be made. Figure A.2.6.1 is representative of an error study by block. In the 3590 example, the starting data for both the initial write and read pass is compared with ~480 hours of environmental storage at 50°C and 85% RH.

In addition to the reporting and analysis of the major error categories and rates there still remain other technical areas of interest that could be addressed for detailed error analysis and cause. Due to the fact that Storage Device manufacturers restrict available data detail, analysis of this type is limited to storage devices that make this information available. One such analysis is the study of the Raw Error rate by head. In the DLT (Y 35) example shown in Figure A.2.6.2 an error analysis by head is presented. In this case the starting data is compared to the data obtained some 2 months after environmental storage at 50 C/ 75% RH. Errors changes by head number are highlighted between the dashed lines. Additional information of this type is helpful in determining drive anomalies and causes of media failure.

Fig. A.2.6.2 Error Analysis by Tape Head



A.2.6.4 Catastrophic Failures

During the course of the study, media for both the IBM 3590 and the Quantum SDLT experienced catastrophic tape failures. Tape failures (SDLT) were also experienced during first write operations suggesting a media defect condition that caused a hard failure. Media defects of this type are likely to be found at incoming inspection. The more common failure mode however tends to occur as the tape is being read and data recovery attempted. Failures of this type do allow multiple reads of the good portion of the tape until the failure point is reached. Data at and after the failure point is considered lost.

A.2.7 Life Expectancies

A.2.7.1 Life expectancy (LE) on the basis of Magnetic Saturation

Changes in the magnetic properties of tapes resulting from environmental exposure are attributed primarily to the chemical changes of the magnetic metal particles contained within. In order for these metal particles to corrode the H_2O and/or O_2 must come in contact with the unoxidized metal. This happens by diffusion through the two layers separating the two reactants, the polymer binder and the metal's oxide layer. First water must diffuse through the polymer binder and then through the ever present oxide layer before reaching the elemental metal. The slowest of these steps, diffusion through the oxide layer is rate determining. The rate of oxidation slows as the oxidation proceeded and the oxide layer is thickened. The mathematical relationship of this change is used to find the rate constant, k, for each condition for each tape. From this data a rate constant can be extrapolated and/or interpolated for any reasonable temperature and humidity.

A ten percent loss of magnetism is used as an end of life (EOL) indicator (a 10% loss in Is would imply a 10 % loss in average signal, but typical losses are not uniform and defect counts do increase substantially for a tape that looses 0.1 Is.).

A typical Life Expectancy chart is included in Figure A.2.7.1.

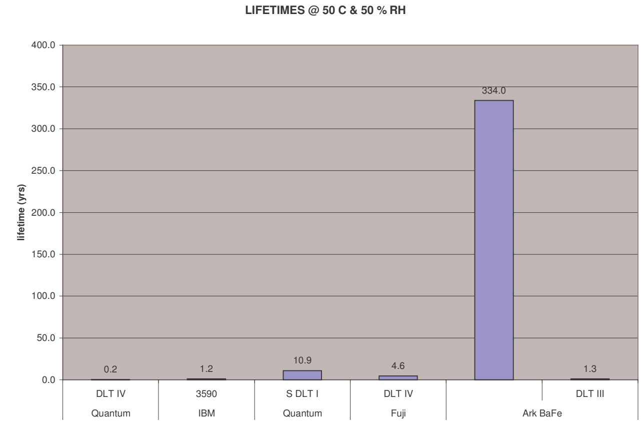


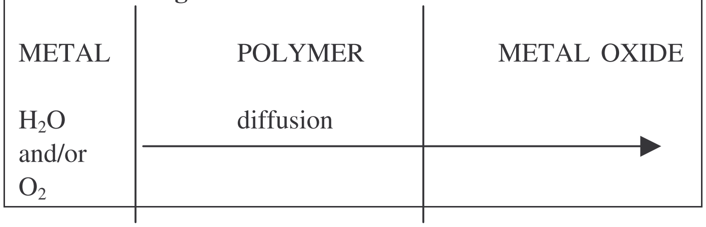
Fig. A.2.7.1. Lifetimes at 50 C/50 % RH.

A.2.7.1 Discussion

The physical nature of the corrosion reaction can be understood by reference to Figure A.2.7.2 below. In order for the metal to corrode the H_2O and/or O_2 must come in contact with the unoxidized metal. This happens by diffusion through the two layers separating the two reactants. First water must diffuse through the polymer binder and then through the ever present oxide layer before reaching the elemental metal. The reaction would have three steps:

1. Diffusion through polymer.
2. Diffusion through oxide.
3. Reaction with the metal.

Figure A.2.7.2 Corrosion Reaction



The slowest of these steps would be rate determining. Step 3 would be almost instantaneous relative to diffusion processes. Diffusion through the polymer would be fast compared to the oxide as the polymer is of much lower density and somewhat porous. Therefore, step 2 would be rate determining. This being the case, the rate of oxidation would slow as the oxidation proceeded and the oxide layer thickened. This can be expressed as follows:

Let x = the thickness of the oxide.
t= time
then the rate of oxidation = $r = dx/dt = k/x$

or $xdx = kdt$

or $x^2 = kt + C$, but when $t = 0$, $x = 0$, so $C = 0$

Therefore, we may expect that $(\Delta Is)^2 = kt$. This relationship may be used to find the rate constant, k, for each condition for each tape. Figure 2.7.2.3 below is an example of how the data may be treated. Series 2 is a plot of delta Is versus time and clearly exhibits the parabolic shape which we anticipated. Series 1 is a plot of ΔIs^2 vs. time and is clearly a linear relationship. Much of the data is not as clear as this, but the reasonableness of this treatment justifies treating all the data similarly and obtaining rate constants from the slope of plots of ΔIs^2 vs. time. These rate constants for 85 % RH are shown in **Table A.2.7.1**. From the values of these rate constants an Arrhenius plot can be made to determine the temperature dependence of the rate of corrosion.

Fig. A.2.7.2.3
CORROSION VS TIME
(IBM 3590 AT 80 C/85 %RH)

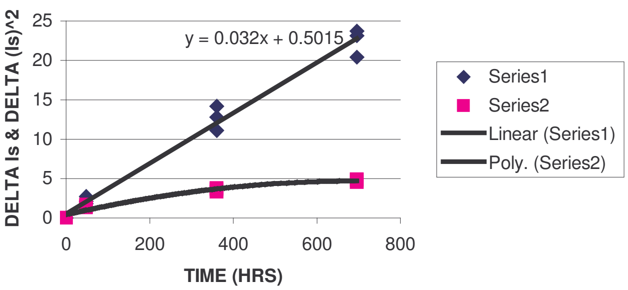


Table A.2.7.1 Corrosion Rates

Corrosion Rates

sample		RH (%)	T (Deg C)	rate const. (k in (memu)^2/hr)	1000/T (deg K)	log k	ΔE	Z
		85						
Quantum	DLT IV		40	1.00E-06	3.19	-6.00		
			50	2.00E-05	3.10	-4.70	5.83	12.9
			80	2.00E-04	2.83	-3.70		
IBM	3590		40	2.00E-04	3.19	-3.70		
			50	7.00E-04	3.10	-3.15	6.13	15.9
			80	3.20E-02	2.83	-1.49		
Quantum	S DLT I		40	2.00E-06	3.19	-5.70		
			50	6.00E-06	3.10	-5.22	4.68	9.27
			80	1.00E-04	2.83	-4.00		
Fuji	DLT IV		40	2.00E-07	3.19	-6.70		
			50	5.00E-06	3.10	-5.30	7.83	18.6
			80	2.00E-04	2.83	-3.70		
Arkival	BaFe		40	1.00E-06	3.19	-6.00		
			50	7.00E-06	3.10	-5.15	5.15	10.6
			80	9.00E-05	2.83	-4.05		
MP	DLT III		40	2.00E-04	3.19	-3.70		
			50	1.30E-03	3.10	-2.89	7.14	19.2
			80	8.21E-02	2.83	-1.09		

A typical plot is shown below in Figure A.2.7.4. The slope of this line is the energy of activation for transport of the oxidizing species through the oxide layer.   The interpretation of the intercept is vague, but none the less, allows the calculation of the oxidation rate at any other temperature at this humidity. The tables and graphs for the other tapes and other RH conditions are compiled in AE.2.7.

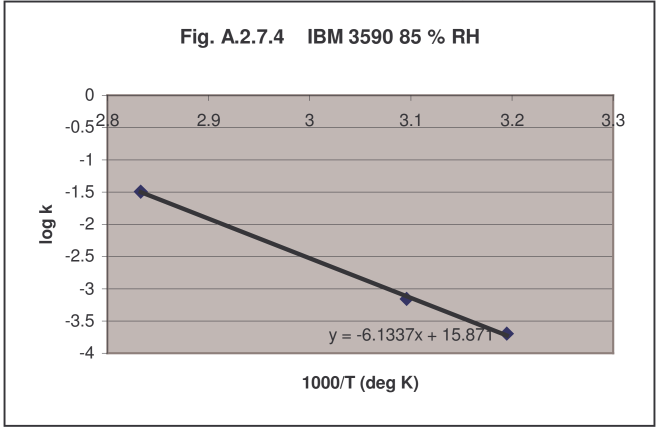


Fig. A.2.7.4   IBM 3590 85 % RH

A summary of these determined values are shown in Table A.2.7.2. Here ΔE is the activation energy and Z is the pre-exponential term as follows:

$$k = 10^{Z} * 10^{-\Delta E/RT}$$

Table A.2.7.2 Data Summary

ΔEα

sample		% RH 0	30	50	75	85	100
Quantum	DLT IV	6.58	4.95	4.39	2.3	5.83	5.02
IBM	3590	7.47	7.91	2.47	6.53	6.13	6.69
Quantum	S DLT I	9.11	3.17	0.78	4.24	4.68	4.98
Fuji	DLT IV	7.39	3.32	6.45	4.55	7.83	5.09
Arkival	BaFe	2.76	5.68	4.27	6.38	5.15	4.45
MP	DLT III	6.71	4.91	7.55	7.33	7.14	6.43

Z

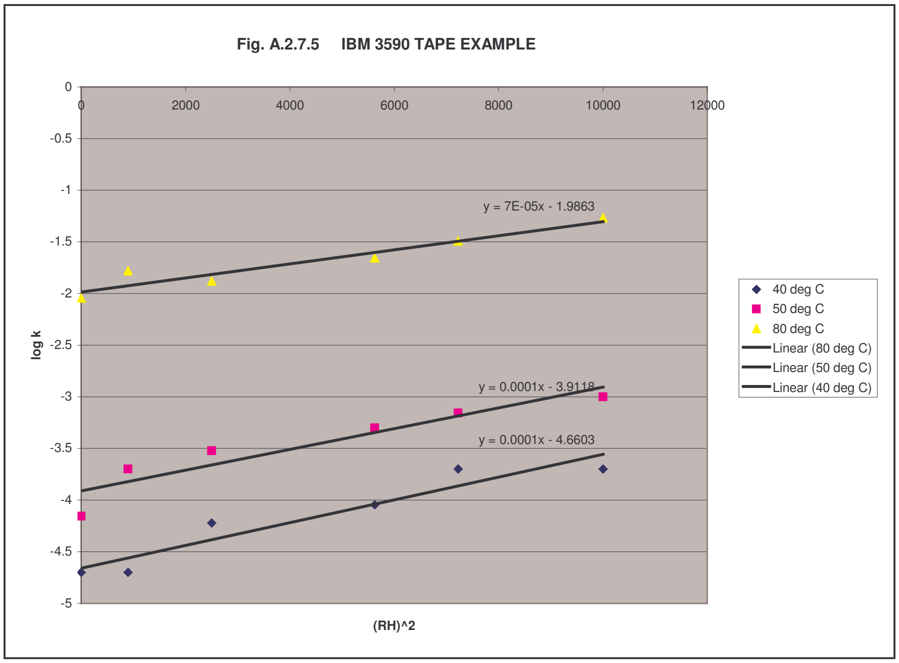
sample		% RH 0	30	50	75	85	100
Quantum	DLT IV	14.6	10.1	7.98	2.08	12.9	10.8
IBM	3590	19.1	20.6	4.91	16.9	15.9	17.7
Quantum	S DLT I	29.8	4.88	-2.7	7.66	9.27	10.6
Fuji	DLT IV	16.4	5.37	14.1	8.91	18.6	10.7
Arkival	BaFe	3.13	11.7	7.5	14.4	10.6	8.58
MP	DLT III	17.2	12.2	19.8	19.4	19.2	17.3

There appears to be no obvious trend in these values with humidity.

Regarding the relationship of k to humidity: The value of log k was found to be best represented as a function of $(RH)^2$. This relationship is plotted for the IBM sample in Figure 3. It can be seen that the dependence of log k on humidity can be approximated by a quadratic dependence:

$$\text{Log k} = A\,[\,RH\,]^2 + B$$

Where A and B represent the slope and intercept for the lines shown in Figure A.2.7.5. Similar graphs have been constructed for the other tapes and are available in Appendix AE.2.5. These relationships should be thought of as merely empirical as no theoretical interpretation comes to mind.



The determined values for A and B are listed in Table A.2.7.3 below.

Table A.2.7.3 EFFECT OF HUMIDITY ON RATE CONSTANT

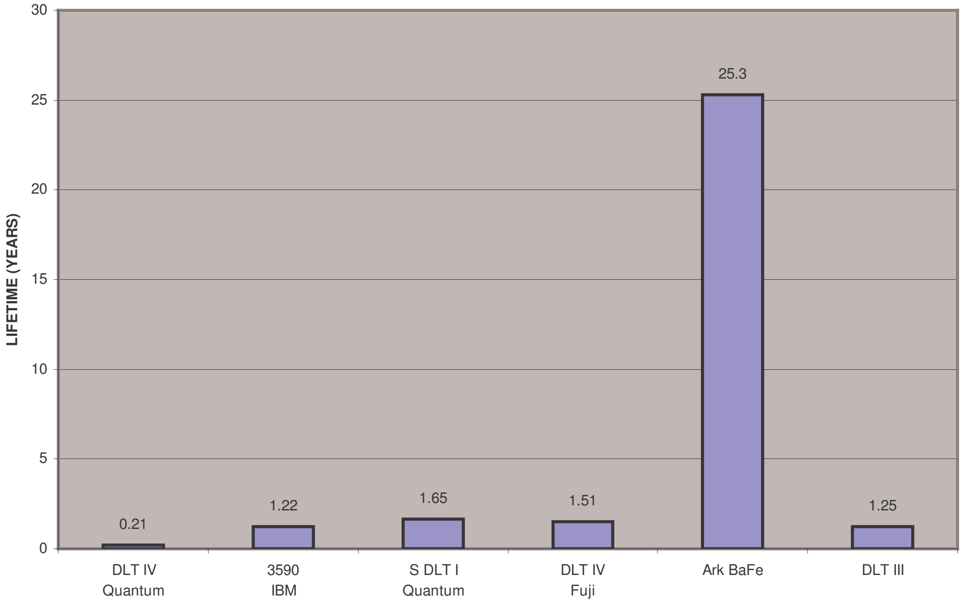
		TEMP (C)	A SLOPE	B INTERCEPT
Quantum	**DLT IV**	40	1.00E-04	-6.45E+00
		50	5.00E-05	-5.17E+00
		80	7.00E-05	-4.36E+00
IBM	**3590**	40	1.00E-04	-4.66E+00
		50	1.00E-04	-3.91E+00
		80	7.00E-05	-1.99E+00
Quantum	**SDLT I**	40	-4.00E-05	-5.06E+00
		50	1.00E-04	-6.22E+00
		80	1.00E-04	-4.76E+00
Fuji	**DLT IV**	40	6.00E-05	-6.44E+00
		50	7.00E-05	-5.72E+00
		80	7.00E-05	-4.33E+00
Arkival	**BaFe**	40	4.00E-05	-6.22E+00
		50	5.00E-06	-5.26E+00
		80	7.00E-05	-4.52E+00
MP	**DLT III**	40	1.00E-04	-4.41E+00
		50	8.00E-05	-3.50E+00
		80	9.00E-05	-1.82E+00

With the relationships above, the value for the rate constant can be extrapolated or interpolated for any reasonable temperature and humidity. As an end of life indicator, one can identify the time for the tape to loose ten percent of its magnetism. *(note: tape losses are not necessarily uniform and defect counts will be large for a tape that looses 0.1 Is.)* $T_{0.1}$ is defined as this tape life, then:

$$T_{0.1} = 0.01\ (Is)^2 / k$$

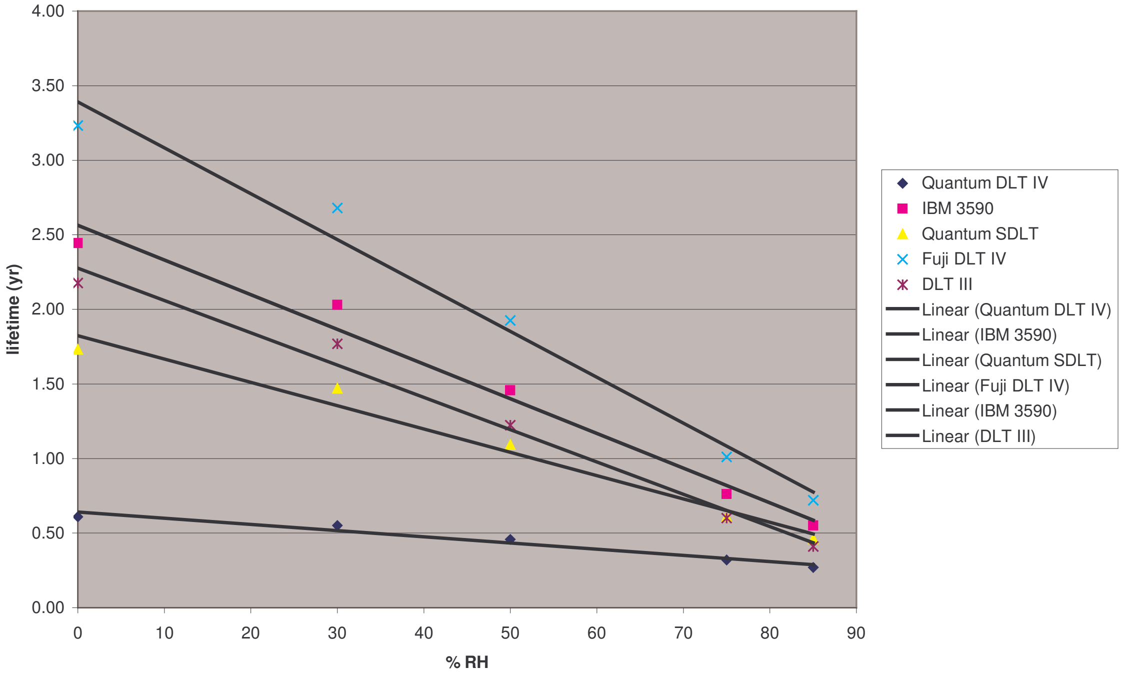
These values of effective tape lifetimes are shown in Figure A.2.7.6 for a storage condition of 50C and 50 % RH. LE values range from less than 1 year to more than 25 years for the BaFe tape. In general, the lifetimes are quite long – probably longer than the lifetime of the drive that one would need to interpret them.

Fig. A.2.7.6 LIFETIMES AT 50 C/ 50 % RH



Life Expectancies can be determined for all tapes tested at various temperatures and Relative Humidities. The values for 50 C and different humidities is shown in Figure A.2.7.7 below

Fig. A.2.7.7 All Tapes- Life Expectancy @ 50 C vs. RH

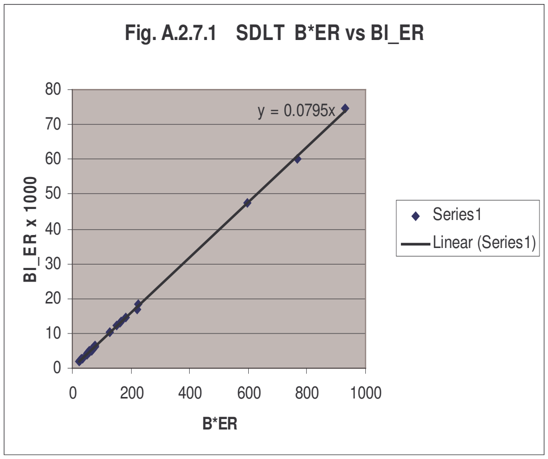


The conclusions therefore are based upon such trends rather than the data at the designated conditions (40C/50%RH & 50C/75%RH). Changes in magnetic characteristics will be detrimental to performance and the most favorable product/tape media is one where little or no change takes place. The rankings are somewhat condition dependent, but in all cases the raw data indicates the DLT Fuji media exhibited the least magnetic property change.

A.2.7 Life Expectancies (LE's) based on media errors

Newer tape storage systems utilize both physical and electronic means to correct and compensate for tape errors. It is for this reason LE of the tape is best measured when employing all error compensation and correction means, i.e., when the tape is considered part of the storage system. The effectiveness of the Storage Device's ECC efficiency is obviously inherent in the differences of the life expectancies reported.

Manufacturers of media and tape storage products no longer publish specifications for error types, quantities or maximum errors allowable. This information does exist and is likely used for internal product specifications that are not available to the user. Information of this type may be found indirectly in drive performance specifications or at times published as guidelines (" exceptional, good, normal and high"). When published, Error Rates for correctable (recoverable) error are stated in terms of bits read, e.g. Quantum states their "Recoverable READ Error Rate as 1 in 10^6 bits read" and IBM states that "no single cartridge can have a dropout error in 1x10^7 bits. Unfortunately, bit error rates are only of use at an engineering level and not directly beneficial to the end user that only has access to block data.



All the products studied use block architecture and errors are reported only in terms of blocks. The block size determination is arbitrary and decided by the user. Tape errors vary in size and area and blocks can contain one or more errors. For the purpose of this study, it was determined that any block containing one or more errors be considered part of the error statistics. For the tape storage systems being studied, a general review of the block error rate (number of bad blocks/ total blocks read) for different block sizes suggested that an average of 1 error per defective block was a reasonable determination.

Using the conclusions above an end of life (EOL) criteria was defined in terms of an Error rate (B*ER) based upon the number of bits or bytes read. B*ER was defined as the number of defective blocks/the total number of bytes read. This definition allowed a general comparison with the bit error rate reported in product specifications. A correlation between the B*ER and the corresponding block error rate (Bl_ER) was examined for all three storage systems. In all case there was a linear correlation *(see Figures A.2.7.1 and A.2.7.2)*. Although the B*ER is not a unique definition, it was applicable to all three products investigated.

EOL criteria are system specific and Storage System manufacturers do not make EOL criteria known; at best, they offer guidelines for use. This study used the drive/cartridge performance guidelines and published system error rates as a basis for establishing EOL criteria. The determination of the EOL criteria for each Storage Device type took into consideration the storage density of the system; a figure of merit based upon the published bit density (ftpmm), the read track width of the Storage Device and a (test) block size of 4K bytes. Also considered was the nature of error generation and error clustering that increases the probability of catastrophic failure by violating the multiple error per block condition.

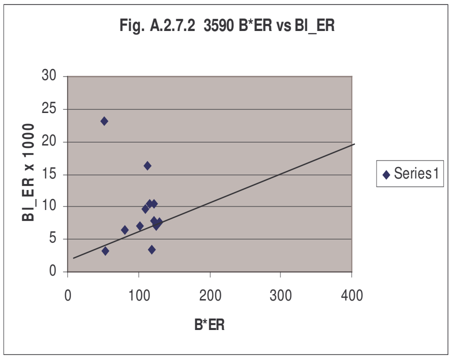


Fig. A.2.7.2 3590 B*ER vs BI_ER

Table 2.7.2 lists EOL criteria by cartridge type, native storage capacity and B*ER maximum values. The information reported for media error rates could not be referenced to any OEM published specifications.

Table 2.7.2 **END OF LIFE Table**

PRODUCT	Capacity(1)	Capacity (MB)	MAX errors/GB	EOL Error Rate	B*ER MAX. (2)
		x10^6		*Number/MB*	
Published…					
IBM 3590	10 GB	1000	-	1	-
Quantum DLT	40 GB	40000	-	1	-
Quantum SDLT	110 GB	110000	-	1	-
Study Criteria…			*(Blocks)*		
IBM 3590	10 GB	1000	500	2242	2500
Quantum DLT	40 GB	40000	500	3296	3500
Quantum SDLT	110 GB	110000	500	6252	6500

(1) Native Mode Storage Capacity: Data capacity- non-compressed.
(2) Round-off values for LE projection

Notes:

Published Error rates:
Quantum: Recoverable Read Error rate: 1 in 10^6 bits read
IBM: Dropout spec: max 1 dropout in 10^7 bits read.

Definitions
B*ER (Arkival) Block error rate - Number of "raw Read Errors(Blocks)/ Read Count"(in bytes) 64K block size

Assumptions:
Bad Blocks: 1 or more bad bits in a Block makes the total Block defective
3590 DF DF = 4000; using ; 4000 ftpmm; 80 um track width; 4K block size
DLT DF DF = 8000; using ; 2578K ftpmm; 39 um track width; 4K block size
SDLT DF DF = 16000; using ; 2700 ftpmm; 14 um track width; 4K block size

DATABASE: Magnetic Stability Predictive Model

This study developed data to predict the life expectancies of the IBM 3590, Quantum DLT and SDLT magnetic tapes based upon their corrosion and subsequent changes in their Saturation Magnetization (I_s). The report projects the life expectancy (LE) of these tapes with the use of the actual data collected for magnetic saturation loss and suitable mathematical models. The Magnetic Stability Predictive Model was developed to specifically determine the time of storage in a given environment for tapes to reach their end-of-life criteria.

These LE's were calculated from the smoothed curves derived from the raw data from the six RH points for each tape and temperature. The temperature dependence was then obtained from an Arrhenius plot for each humidity and used to calculate the LE's for the various temperatures. *(See Appendix AE.DB.1-4)*. This method of calculation smoothes out raw data fluctuations and the resulting LE's do not directly correlate point by point with the raw measurements. The LE's for the DLT tapes are generally higher (similar to the SDLT tape) while the 3590 tape results are lower. The LE for the study tapes are shown in the following tables (Tables DB.1-DB.4). The highlighted areas represent the environmental conditions of interest.

Table DB.1 LIFE EXPECTANCY (YEARS) FOR QUANTUM SDLT I

TEMP (C)	RH (%)	0	30	50	75	85	100
10		5.95E+05	1.95E+05	2.46E+04	4.15E+02	5.11E+01	1.41E+00
20		4.54E+04	1.74E+04	2.92E+03	8.63E+01	1.41E+01	6.39E-01
30		4.10E+03	1.83E+03	4.00E+02	1.99E+01	4.26E+00	3.05E-01
40		4.32E+02	2.21E+02	6.21E+01	5.03E+00	1.38E+00	1.53E-01
50		5.22E+01	3.04E+01	1.08E+01	1.39E+00	4.82E-01	7.98E-02
60		7.18E+00	4.73E+00	2.10E+00	4.12E-01	1.79E-01	4.33E-02
70		1.11E+00	8.18E-01	4.47E-01	1.32E-01	7.03E-02	2.44E-02
80		1.90E-01	1.56E-01	1.04E-01	4.49E-02	2.91E-02	1.42E-02
90		3.59E-02	3.28E-02	2.62E-02	1.62E-02	1.27E-02	8.50E-03
100		7.43E-03	7.46E-03	7.10E-03	6.20E-03	5.77E-03	5.24E-03

Table DB.2 LIFE EXPECTANCY (YEARS) FOR FUJI DLT IV

TEMP (C)	RH (%)	0	30	50	75	85	100
10		1.48E+04	8.04E+03	2.86E+03	3.10E+02	1.09E+02	1.57E+01
20		1.86E+03	1.10E+03	4.55E+02	6.63E+01	2.72E+01	5.10E+00
30		2.67E+02	1.71E+02	8.14E+01	1.57E+01	7.43E+00	1.79E+00
40		4.34E+01	3.00E+01	1.63E+01	4.08E+00	2.21E+00	6.71E-01
50		7.90E+00	5.86E+00	3.60E+00	1.15E+00	7.07E-01	2.67E-01
60		1.59E+00	1.26E+00	8.70E-01	3.52E-01	2.42E-01	1.13E-01
70		3.52E-01	2.97E-01	2.29E-01	1.15E-01	8.85E-02	4.99E-02
80		8.50E-02	7.61E-02	6.48E-02	4.00E-02	3.42E-02	2.31E-02
90		2.22E-02	2.10E-02	1.97E-02	1.48E-02	1.39E-02	1.12E-02
100		6.21E-03	6.20E-03	6.37E-03	5.74E-03	5.95E-03	5.63E-03

Table DB.3 LIFE EXPECTANCY (YEARS) FOR QUANTUM DLT IV (MAXELL)

TEMP. (C)	RH (%)	0	30	50	75	85	100
10		4.83E+04	2.32E+04	5.50E+03	3.65E+02	8.86E+01	7.84E+00
20		4.60E+03	2.47E+03	7.21E+02	7.13E+01	2.13E+01	2.69E+00
30		5.11E+02	3.06E+02	1.08E+02	1.55E+01	5.61E+00	9.87E-01
40		6.54E+01	4.32E+01	1.83E+01	3.72E+00	1.61E+00	3.87E-01
50		9.50E+00	6.90E+00	3.45E+00	9.76E-01	4.99E-01	1.60E-01
60		1.55E+00	1.23E+00	7.19E-01	2.77E-01	1.66E-01	7.02E-02
70		2.81E-01	2.42E-01	1.64E-01	8.47E-02	5.89E-02	3.23E-02
80		5.61E-02	5.22E-02	4.09E-02	2.77E-02	2.22E-02	1.55E-02
90		1.23E-02	1.23E-02	1.10E-02	9.62E-03	8.81E-03	7.74E-03
100		2.90E-03	3.12E-03	3.16E-03	3.54E-03	3.67E-03	4.01E-03

Table DB.4 LIFE EXPECTANCY (YEARS) FOR IBM 3590

TEMP. (C)	RH (%)	0	30	50	75	85	100
10		3.49E+03	2.22E+03	1.29E+03	6.28E+02	4.60E+02	1.52E+02
20		4.90E+02	3.20E+02	1.94E+02	1.01E+02	7.75E+01	2.74E+01
30		7.83E+01	5.25E+01	3.31E+01	1.85E+01	1.47E+01	5.54E+00
40		1.41E+01	9.67E+00	6.33E+00	3.75E+00	3.09E+00	1.24E+00
50		2.81E+00	1.98E+00	1.34E+00	8.42E-01	7.18E-01	3.05E-01
60		6.19E-01	4.45E-01	3.11E-01	2.06E-01	1.82E-01	8.15E-02
70		1.49E-01	1.09E-01	7.87E-02	5.49E-02	4.99E-02	2.35E-02
80		3.88E-02	2.90E-02	2.15E-02	1.58E-02	1.47E-02	7.30E-03
90		1.09E-02	8.29E-03	6.32E-03	4.84E-03	4.65E-03	2.41E-03
100		3.27E-03	2.53E-03	1.98E-03	1.59E-03	1.56E-03	8.46E-04

Note: The calculations for these Tables are given in the Excel Appendices:
temp-rh SDLT (C);
temp-rh fuji DLT IV (E);
temp-rh QUANTUM DLT IV (A);
temp-rh ibm.