Reliability testing of R-DAT tapes subjected to mechanical and environmental stress.

by

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ABSTRACT

This thesis is concerned with an examination of the reliability of R-DAT recording media in regard to professional and archival applications. Four brands of R-DAT tapes were subjected to mechanical stress, environmental stress, and a combination of both the mechanical and environmental stresses. Data generated from these tests were analyzed objectively, subjectively evaluated, and subsequently compared. Findings showed that in the majority of cases, the subjective evaluation results corroborate the objective measurements The study concludes that only one brand of tape exhibited no deterioration of data, while the other three brands failed at various points throughout the testing.

RÉSUMÉ

Dans cette thèse, l'auteur analyse la fiabilité des supports d'enregistrement R-DAT par rapport aux applications professionelles et archivistiques. Quatre marques de ruban R-DAT ont été soumises à un stress mechanique, à un stress environnemental et à une combinaison des deux types de stress Les données resultant de ces test ont été analysées objectivement et évaluées subjectivement avant d'être comparées. Les conclusions révèlent que dans la majorité des cas, le résultats de l'evaluation subjective corroborent ceux des mesures objectives. Selon l'étude, une suele marque de ruban n'a affiché aucune détérioration des données alors que les trois autres ont échoué à diverses étapes du test.

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Introduction

The purpose of this thesis is to examine the durability of various brands of Rotary Head Digital Audio Tapes (R-DAT) with respect to frequent usage and/or exposure to extreme environmental conditions during short and long term storage

The hypothesis, that R-DAT media is unsuitable for rigorous operational requirements in professional audio applications, as well as for archival storage, is tested in this study. This hypothesis is derived from intrinsic properties of the recording media with respect to requirements inherent to R-DAT system design.

With the advent of R-DAT format, the highest longitudinal recording bit density was obtained However, the extension of the bit density required extreme downward scaling of critical magnetic parameters and thickness of the media in order to prevent excessive recording demagnetization, self-demagnetization, and adjacent bit demagnetization. Thus, high coercivity, very small thickness, and relatively low magnetization of the media had to be attained to reduce the antagonistic effects. This, in turn, reflects adversely on media imperfections, defects, stability and durability, as well as particle contamination. [Speliotis (1984)]

The concept of digital audio cassette, based upon a scaled down version of helical scan technology implemented in Video Tape Recorders (VTR), was first unveiled by Sony Corporation in 1983. The first R-DAT format prototype was introduced by Sony in 1986, and a year later the DAT standard was stipulated at the DAT Conference in Japan. From six data formats allowed by the DAT standard, only two are currently used for audio recording. Both formats utilize two audio channels recorded on the same track with 16-bit two's complement linear quantization. The formats are characterized by the following: subcode rate of 273.1 kb/s (kilobits per second); tape speed of 8.15 mm/s; 13.591 μm track width and 23.501 mm track length; 30 mm drum diameter revolving at 2000 rpm; tape wrap angle of 90°; and minimum recorded wavelength of 0.67 μm. Two hours of audio can be recorded with 120-minute length cassettes. These two formats differ only in the sampling rates used, 48 kHz and 44.1 kHz, respectively.

The DAT cassette is a flangeless type and is the same for all formats. The basic dimensions of the cassette are 73x54x10.5 mm; the hub span is 30 mm, and the hub diameter is 15 mm The cassette is loaded with a metal particle (MP) tape, 3.81 mm wide, 13 μm thick, and up to 60 m long To protect the tape from external contaminants, a slider and a lid are incorporated into the dust-free cassette design. The lid is interlocked with nail hub locks that prevent the hubs from rotating when not in use. When the cassette is inserted into the transport of the R-DAT recorder, slider locks are released and the slider is pushed back, releasing the lid lock and exposing the hub holes The cassette is then lowered onto the tape guides and hub drive spindles, and the lid is lifted to allow access to the tape. Even though MP tape, 13 μm thick, is used exclusively at the present, four standard recognition holes are provided on the lower shell to accommodate future thinner tape formulations such as metal-evaporated (ME) tape, wider track width (20.41 μm) formats, and prerecorded tapes Detailed descriptions of the R-DAT formats are given by Benson (1988), Dare & Katsumi (1987), Itoh et al. (1986), Monforte (1989), and Watkinson (1988).

Although the DAT cassette is half the size of the analog Compact Cassette, the DAT format offers 1.3 GB (gigabytes) of data storage capacity which could be realized only with very high packing density The areal density of 17.7 million bits per square centimeter (114.1 million bits per square inch) is the highest packing density ever achieved in magnetic media recording. As the

R-DAT employs guardband-free track recording (with crosstalk controlled by the azimuth angle), 736 tracks/cm (1870 tracks/inch) are laid down with over 24000 bits/cm (61000 bits/inch) along the track. The track density is also unparalleled by any other magnetic media, while the linear density (the bit density along a track) is unparalleled by any data storage technology.

Such high densities and short recorded wavelengths require not only media that has high coercivity, small thickness and low magnetization, but also, media with smaller particle size. It must be defect free and smooth as even a small defect or asperity can affect many bits and cause dropouts. A dropout can be described as any defect, contamination, or hole in a magnetic recording tape that causes a physical separation of the recording head from the magnetic media, resulting in magnetic signal loss.

Tapes containing fine metal particles (also called "metal powder" in related literature) are well suited for high density digital applications. Metal particles have acicular shapes. They are small (about one fourth the volume of gamma-ferric oxides), and have high coercivity (1500 Oe), higher saturation, and higher signal output with better signal-to-noise ratio. Their retentivity is about three times as high as that of oxides. These high energy particles facilitate short wavelength recording at slower speeds and minimize self-erasure However, their small size and high retentivity make their dispersion difficult. As they are chemically unstable (highly reactive and pyrophoric in open air), the particles have to be stabilized. [Perry & Nishimura in Kirk-Othmer (1981), Lehtinen (1989)]

The very short recording wavelengths used in R-DAT format require a tape manufacturing process which applies strict quality control, this because base film irregularities, undispersed particles, coating defects, slitting debris, and extraneous contaminants causing even minute spacing loss, become unforgiving. Tensilized polyethylene terephthalate (PET) base film, 9 μm thick, serves as a substrate on which metal particles dispersed in organic polymer binder are coated. The magnetic coating is 3 μm thick. In addition to magnetic particles and thermoset binder, it contains dyes, dispersants, stabilizers, conductive pigment and lubricants. Stabilizers prevent aging of the binder. The conductive pigment is added to reduce static charge buildup, common to high head-to-tape speed recording formats, where electrical discharges can affect performance of electronics, cause dropouts, and attract contaminants. Lubricants are added to reduce head-to-tape friction which causes head and tape wear, and to reduce the tendency for stick-slip oscillation. In order to prevent the PET substrate from sticking to anything in its path, back coating, 1μm thick, is applied to the base to promote slip properties. The sticking is called "blocking" in related literature, and is caused by high dynamic surface friction of PET. Magnetic particles are longitudinally orientated in the direction of the intended recording to improve the squareness ratio (the ratio of saturation flux to remanent flux). Prior to slitting, the web is calendered (compacted) to remove large asperities and to increase the effective magnetic-pigment volume concentration to a level closer to that of the theoretical formulation. [Busby in Benson & Whitaker (1990), White (1988), Perry & Nishimura in Kirk-Othmer (1981)]

Web and Young (1990) used infrared microspectroscopy to analyze dropouts and their origin in brand new video tape. They were interested in dropouts resulting from small particle inclusions that can arise from materials associated with the coating formulation, environmental contamination, or contaminations from the base film. They found that magnetic coating agglomerations accounted for over 60% of analyzed dropouts. Less than 10% could be attributed to lubricant and the PET base film; the remaining 30% were due to impressions placed on the magnetic media by the coater's process. Their findings underline the importance of strict quality control to be maintained by the magnetic media manufacturers, especially when very high packing density media, such as R-DAT, is involved. Their study also implies that, according to tape formulations and processes used, the quality of the magnetic media will vary from manufacturer to manufacturer.

As R-DAT format was originally designed for consumer applications, while Digital Audio Stationary Head (DASH) and ProDigi (PD) formats (having lower packing density) were intended fo: audio professionals, the R-DAT media was not subjected to the scrutiny of professional requirements. However, in 1985 the SMPTE (Society of Motion Picture and Television Engineers) Committee on Video Recording and Reproduction Technology (VRRT) established a Study Group on New Magnetic Media to investigate MP tape and its suitability for professional VTR applications. The MP tape had already permeated the consumer 8-mm VCR (Video Cassette Recorder) market, but its proposed application in the new M-II professional format was stirring controversy among broadcasters participating in deliberations on VTR formats standardization. Therefore, the Study Group, assembled from engineers representing relevant broadcast and tape industries (including magnetic particle, tape and cassette manufacturers), set out to analyze the MP media and to clarify unresolved issues. Even though the papers presented to the Study Group were confidential, and therefore not published, the findings were encouraging As the chairman describes the results:

> "...metal particle tape was gradually being acquitted of the adverse reputation originally associated with it. More and more evidence was being received that MP tape will quite likely fulfill the rigorous requirements of broadcasters. Such was the intensive search for possible deficiencies in MP tape that we soon realized many of the questions being

> asked of its characteristics had never even been asked of oxide tape!
>
> This is not to say there are no unknowns about MP media, but the principal ones, such as stability in hostile storage conditions, head wear, and product availability seem to be under control, if not fully resolved." [Thomas (1986)]

Although it can be argued that the packing densities in video formats using the same type of media, such as 8-mm, M-II, D-2, are not nearly as critical as those of R-DAT, the tape tension in these systems is much higher, due to higher head to tape speeds, wider track formats, larger drum diameters and tape wrap angles. This, in turn, leads to increase of the head-to-tape friction. Thus, the mechanical stress exerted on the video media formats is far more severe.

Since the 1987 introduction of R-DAT on the North-American market, the format was not available to the consumer until 1990 because of prolonged discussions between DAT manufacturers and the record industry. Copyright protection issues prevented sale of consumer machines (48 kHz sampling rate recording only) not equipped with SCMS (Serial Copy Management System) in the United States. Therefore, it was the professional audio industry who embraced the format first, as the low cost of hardware and DAT media, the small size of cassettes, and the high quality of sound made the format irresistible. Originally used by record producers and engineers for backup copies, client reference copies, and rough mix reference (alleviating the Compact Cassette quality variables), it soon proliferated into much more sensitive areas of the recording chain.

Stokes (1990) reports on R-DAT becoming quite popular with film producers for both on location film production and gathering original sound effects for television spots. He also claims that CD mastering facilities

(Masterfonics in Nashville and Frankford/Wayne Mastering Labs in New York) are receiving more and more finished studio masters on R-DAT format. Quadim duplication facility in California receives 70% of masters from major record labels on R-DAT cassettes. Merges (1990) reports on use of R-DAT as the primary and sole recording source for the Chicago Symphony's Ravinia Festival concert and recording dates, as well as for recording of the orchestra's many tour dates. Schwartz (1990) states that television broadcasters are improving audio and stereo production, and upgrading for full stereo capability, with new R-DAT hardware being on their checklist. They are interested in automated R-DAT systems such as, Radio Systems' RS-DAT, R-DAT machines with time code, and R-DAT editing systems. A report in One to One (September/October 1991) says that, according to Finesplice (the UK digital audio post production facility), up to 60% of source material, both classical and popular music, now arrives on R-DAT format and many of these masters contain time code. Another report in the same publication states that more and more material available to the British Library's National Sound Archive is on R-DAT media, and the Archive itself uses R-DAT recorders out on location in order to compile a, "...compendium of sounds alive for future generations". In addition to these reports, the Pro Sound News Studio Operations Survey (based on the U.S. studio respondent's information), claims that 53% of studios reporting incomes at or over $250 000, and 35% of studios with incomes under $250 000, own a R-DAT recorder. Another 16% of studios (both categories combined) are planning to buy one. [Pro Sound News (No. 9, 1990)] Finally, increasing numbers of sound and sound effect libraries are being offered on R-DAT cassettes, which were previously available on Compact Discs only.

As can be seen above, the R-DAT format is steadily gaining acceptance by audio professionals, even in such applications where reliability and media archival attributes are of paramount importance. A review of the existing literature yields both scarce and conflicting reports on performance and test results of R-DAT tapes. Most of the published literature is related to the stability of metal particles and the suitability of very high packing density media for archival considerations.

A consensus among authors who examined metal particles in relation to magnetic recording, and MP tapes in relation to archiving, has not been evident. Their test results and opinions vary as reflected in following quotations:

> "When it is required to coat the particles on to a recording surface, the protective liquid is replaced by the solvent-binder mixture. However, even after the coating has dried, there is the possibility with some binder compositions that air may diffuse in and oxide the particles. Wearing of the recording surfaces during use can also be expected to exacerbate this process. The published literature on this subject is extremely sparse." [Bate & Alstad (1969)]

> "Making metal particles is relatively easy but protecting them from corrosion by the atmosphere and binder polymers is a much more challenging task. ...Complete stabilization of such highly reactive materials will probably never be achieved and the best that can be expected is to slow down the corrosion sufficiently to give a useful life of 5-10 years." [Bate (1981)]

> "...serious problem associated with metal pigment coatings is a large reduction (about 15%) in their magnetization when exposed to an elevated temperature and humidity environment." [Speliotis (1984)]

> "Iron acicular particles are excellent material for magnetic recording because of the high saturation magnetization. However, the decrease in their magnetization by the oxidation becomes significant as the particle size is decreased for the purpose of achieving high recording densities. ...The ratio of decrease in magnetization by standing the particle for about 1 year in air was within 2%. ...The particles showed quite stable character against further oxidation." [Kishimoto et al. (1986)]

"The demonstrated superiority of MP over other oxide pigments for high density recording derives from its higher moment and coercivity. However, its inherent susceptibility to corrosion (oxidation) is of great concern since it would lead to deterioration in the tape performance. In this respect it is surprising that virtually no published information exist on the effects of temperature/humidity on the recording characteristics of MP media. ...we compared an experimental BF 8mm tape with four brands of MP tapes, for remanent magnetic flux (Ør) stability... Under the most severe conditions (150F/90%RH) the BF tape experienced an output loss of only 0.6 dB in 30 days compared to 2.5 - 3.0 dB losses observed for MP tapes. ...To our knowledge, this is the first published article where MP media has been shown to degrade in signal amplitude (output) due to corrosion caused by exposure to elevated temperature/humidity. Corrosion induced effects on other recording characteristics such as noise, overwrite, eye patterns, etc., are presently being investigated." [Wollack et al. (1989)]

"Whilst the R-DAT's achievement...the fact that each bit occupies an area of 13x0.4 μm^2 only is clearly not conductive to a long archival life!

Metallic iron particles are, of course, subject to oxidation... In order to combat this, the particle manufacturers "inhibit" the particles by partial controlled oxidation. Additionally, the tape manufacturers claim that, by using appropriate plastic binder systems which are supposed to "encapsulate" the particles, a satisfactorily stable tape can be produced. A typical claim is that no measurable change occurs after 1 month's exposure to 60° C and 80% RH." [Mallinson (1990)]

"Since MP media employ dispersions of very fine iron particles, it is understandable that corrosion of such media would be of very high concern, in view of their inherent susceptibility to oxidation, particularly when they are used in sensitive data recording applications with archival requirements. .. The MP media are very susceptible to corrosion, particularly when certain pollutant gaseous species are present. Therefore, the use of MP media for archival data storage raises serious concerns, unless certain environmental restrictions regarding their use and storage conditions are observed." [Speliotis (1990)]

"We examined the corrosion stability of the magnetic properties of the tape prepared using the stabilized metal particles when the tape was stored in the various

> environmental atmospheres. The results obtained were as follows.
> (1) Exposure to 60°C/90%RH for 4 weeks resulted in a decrease of magnetization of only about 7%.
> (2) It was shown that the oxidation of the particles uniformly proceeded through the magnetic layer.
> (3) The change of magnetization of the tape was only about 0.6% when the tape was stored in the mixed gas environment of Cl_2, H_2S and NO_2.
> (4) These properties showed that the tape was suited for the media for data storage." [Yamamoto et al. (1990)]

Although the above quotations exhibit noticeable differences in the presented data and opinions, the fact that the quotations reflect two decades in MP development has to be taken into account. Since the use of MP media in magnetic coatings for the computer industry and High Definition Television (HDTV) applications has been seriously considered, the continuing development of the media was accelerated in recent years.

The published literature pertaining to R-DAT media format reliability testing is also not abundant. Although only seven studies were found documented in the related literature, it can be assumed that more studies were performed. As magnetic media manufacturers consider the test results generated in their research labs highly confidential, an increase in publicly available data on this topic cannot be expected. Stepped up activity concerning reliability testing by independent organizations and researchers would thus be beneficial to audio professionals in forming a concentus on R-DAT's suitability to professional requirement needs.

Most of the R-DAT media reliability tests encountered in the related literature are part of broader studies on R-DAT format; hence, the presented data is often incomplete. Othake et al. (1986) investigated magnetic recording characteristics of R-DAT system using MP and Barium-ferrite tape. Although their study was focussed on verification of practicality of the proposed DAT standards, a durability test involving over 200 reproduction passes was included. However, their findings that, "...the block error rate remained less than 10^{-3} up to 200 repeated play-backs", are not indicative of the media durability as the end of tape life should extend well beyond that. In addition to this, no indication was offered for which of the tested media the findings were given.

In a study authored by Ogiro et al. (1988), the high precision DAT mechanism was investigated. In the course of their study the researchers discovered that by rounding off the edge of the rotating drum aperture, tape damage could be reduced. Consequent testing revealed significant improvement in media reliability as, after 5000 passes, the error rate did not exceed the R-DAT's error concealment capability, and reliability of less than 10^{-2} block error rate (the limit of correction capability) was maintained up to 2000 passes.

The performance of a newly developed cassette "AXIA DA" is described in a paper of Mori et al. (1988). Their report is the most comprehensive paper delving into R-DAT media reliability and performance, as the provided data is most complete. The research included media durability tests related to stop-motion framing, repeated playback and search, and loss torque characteristics. The stop-motion test was held for 60 minutes; the playback and search were repeated 300 times; and, the repeated search test was performed in four different environments (40°C/80%RH, 25°C/60%RH, 23°C/10%RH, 5°C/30%RH). A drop in radio frequency (RF) output and block error rates (B.E.R.) were measured. Even though the AXIA DA cassette tapes were declared to be, "...endowed with reliable transducing characteristics, the durability to withstand harsh conditions in various running modes, and tape running stability", it is apparent that the study was not intended to examine the media's suitability with any kind of extensive use, either consumer or professional.

A paper by Goto et al. (1989) describes proposed modifications of a R-DAT recorder that would allow the R-DAT technology be applied to data storage systems. With the increase of a hard disk capacity exceeding the storage capacity of analog magnetic tapes, the R-DAT's 1.3 GB capacity, fast access time, subcode addressing, and its capability to record and reproduce digitized signal, are advantageous in establishing R-DAT storage systems (DATA/DAT). As such data storage requires frequent record/reproduce and start/stop operations over the same portion of the tape, a higher data retrieval reliability is imperative. Therefore, the occurrence of errors caused by the repeated use was measured in this study. The study indicates that dropouts occur after 2500 reproduction passes.

Herla (1989) investigated R-DAT format recording with respect to professional requirements. Testing involved measurement of the total harmonic distortion (THD), errors, concealments, and dropouts (mutes) of eight brands of tape. Three 60-minute cassettes of each brand were recorded with 1 kHz sinusoidal tone; then a 30-minute portion of the tape was reproduced three times. The results indicate that, "...all tape types show interpolations and consequently a degradation of the audio signal [and] ...not detected errors produce sometimes a worse audio quality than error indicators of the DAT recorders will show". In addition to this test, five 120-minute DAT cassettes of one brand were recorded and then reproduced 100 times on the same R-DAT recorder. Findings show that, "...there are cassettes with interpolations during the whole test, others starting with audio signal degradation after 25 passes or later. After 40 playback passes cassette No. 3 already shows mutings, other cassettes follow after 55, 88 or more playback cycles. Therefore the use of DAT recorders, e.g. as jingle machine cannot be recommended at the moment".

Rumsey (1990) claims that, "...a recent test by Panasonic showed that a DAT tape, which had been played over a thousand times in one place, still did not drop out but some users in the workshop were claiming only four playings before a drop-out".

Finally, Mountain (1991) compared two DAT tapes (Maxell and Sony) after twenty generations of digital copying between Panasonic and Sony DAT recorders. The DAT tapes were previously used and were,"...recorded over at least 50 times", before the study begun. Printouts from a diagnostic software application (Micro Analyst's SUM), displaying hexadecimal codes of "data forks", were checked, and "...the results came in the same". Thus, his findings indicate that after more than 50 overwrites, no degradation of data has occurred

The following excerpt from Rumsey's article can be used to summarize the review of the literature discussing R-DAT media reliability and its suitability for professional applications·

> "The PCM-1630 format is certainly steam technology when compared with DAT but has fostered a wealth of experience and a wide adoption as the CD mastering format. It also works moderately well but is probably no less prone to drop-outs than DAT. Users have found tape types that work well and they stick to these. Similarly, certain DAT tapes are more reliable than others."

The above data has been obtained through only objective measurements while the end product of any sound recording, the actual sound which is heard, has not been considered. It can be pointed out that demagnetization, print-through, and a wear-related loss of high frequencies, which are easily perceivable in analog recordings, did not preclude the analog media from being used in professional applications and archiving. In addition to this, the metal particle stability cannot be the only concern related to the media archiving attributes. Other compounds used in tape formulations, such as binders and plasticizers, have significant influence on the media life span and have been shown to end the life of analog tapes long before expected. [Fox: Studio Sound and Broadcast Engineering, December-1990; New Scientist, September 22-1990; New Scientist, December 8-1990] Thus, a subjective evaluation of the sound quality of R-DAT media, subjected to mechanical and environmental stresses, was conceived in order to generate a valuable data contribution that may prove this media to be either suitable or unacceptable for storage of high quality sound in professional and archival applications.

Methodology

The methodology which was applied to verify the hypothesis consisted of a pre-recorded test sequence applied to three groups of tapes. The first group of tapes (one from each brand) was subjected to mechanical stress only. The second group was subjected to mechanical stress in combination with a limited environmental stress. The third group was subjected first, to an environmental stress, then to a mechanical one. (See Figure 1)

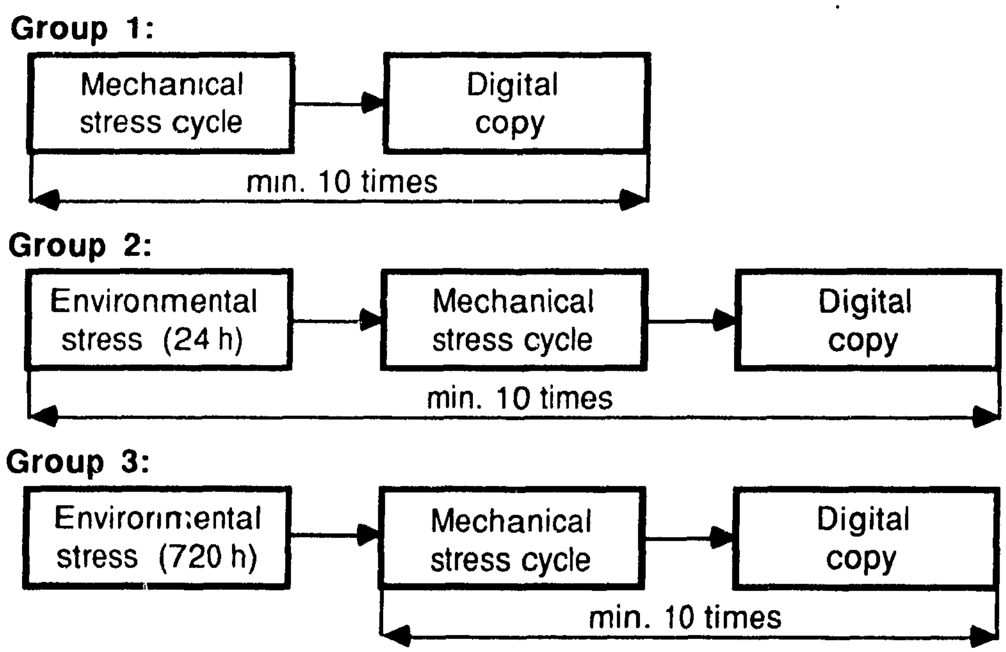


FIGURE 1

In this study, the term, 'mechanical stress', refers to deterioration of the media performance caused by rubbing of the tape against the heads and other mechanical parts of the recorder. This experiment which was designed to emulate rigorous, professional-use conditions, was originally planned for 10 cycles, carried out on each tape. One cycle included 200 reproduction passes, 4 overwrites, 200 mode switchings, and a six-minute still frame test. (See

Figure 2) However, as the actual cycling progressed faster than originally anticipated it was decided to use the extra time to expand the experiment by 3 more cycles. Since no perceptible degradations in the audio output of the still frame test segment and both overwrite test segments were observed after 10 cycles, the last 3 cycles were redesigned to include a ten-minute still frame test and 5 overwrites per cycle A digital copy of the test sequence was made after each mechanical stress cycle, this for the purposes of subjective evaluation. A total of 90 minutes of still frame tests, 2600 mode switchings, 2600 reproduction passes, and 55 overwrites were achieved on each tape during the experiment

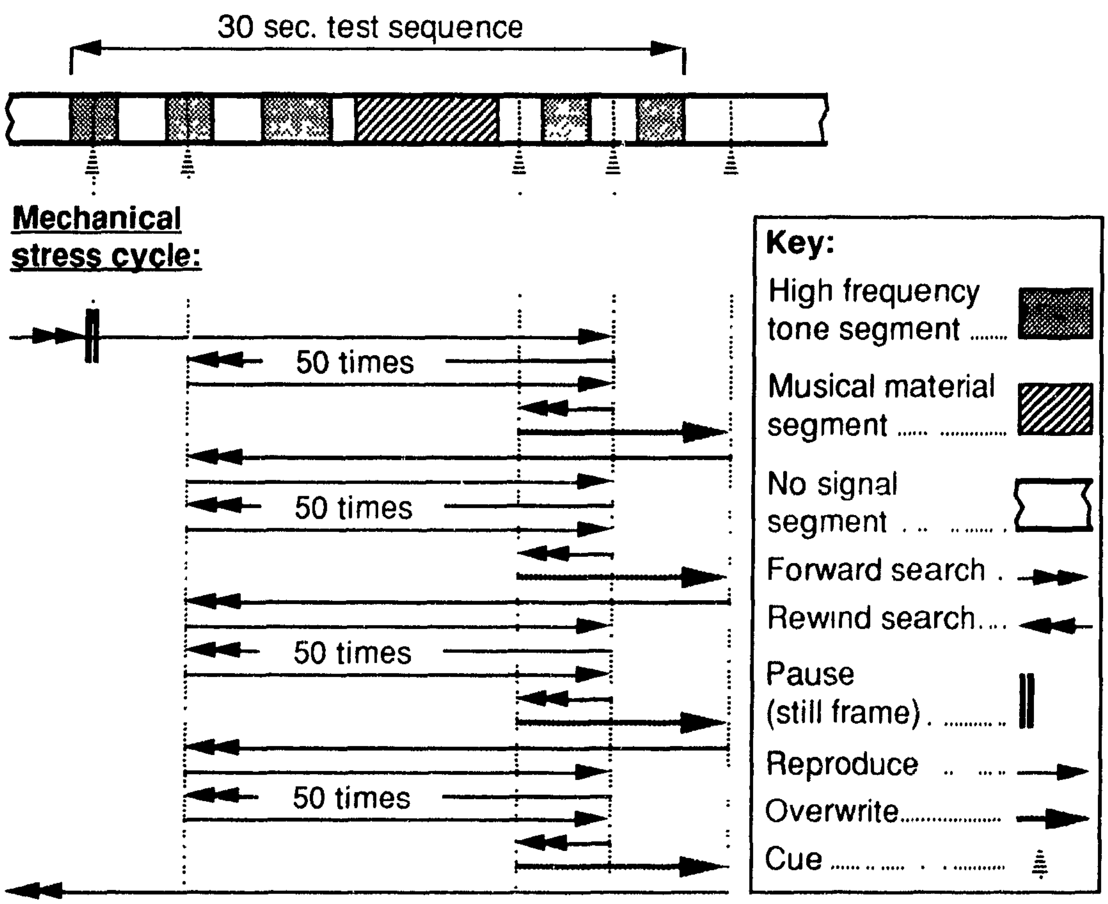


FIGURE 2

The term, 'environmental stress', refers herein to deterioration of the tape performance resultant from chemical changes due to exposure to elevated temperature and humidity. This exposure called, "accelerated aging", in related literature, was conceived to simulate long-term storage conditions as required in archiving situations. The task was achieved through storage of tapes in an environmental chamber for a period of thirty days (720 hours) with the temperature set at 40 degrees Celsius and relative humidity set at 90%. Selection of the above mentioned temperature and humidity settings were governed by limitations inherent to the environmental chamber available for this experiment. Used for research in biology at McGill University, the Conviron Growth Chamber (model no. PGW36) could not sustain higher settings for a prolonged period of time. While these limitations precluded harsher environmental stress conditions from being implemented, these settings are more in line with naturally occurring environmental conditions, described by Huijser et al. (1983) as, "wet tropical ambient". The duration of the environmental stress exposure was simply defined by the maximum length of time that could be appropriated for the research by the biology lab director at the time of the request.

This part of the study was modelled after accelerated aging technique developed mainly by the electronics industry for the purpose of testing electronic components. The accelerated aging technique became an important quality control tool, but its suitability for life expectancy extrapolations remains controversial. In this study, extrapolations for life expectancy were not attempted as the research was focused on the deterioration of performance and how this is influenced by the environmental and mechanical stress, only.

Although the accelerated aging technique was adopted by the recording media manufacturers and independent research organizations, they, in the majority of cases, modified the procedures to better serve their needs. As the aim of accelerated aging tests is to reproduce the normal effects of aging in a shorter period of time, tests producing effects not occurring during a natural aging process would render generation of data useless. Thus, various modifications of this technique have been applied by individual manufacturers and independent organizations, this due to their interpretations of natural aging effects as well as their considerations of intended specification requirements. Detailed description of various modifications and different accelerated aging techniques is described by Winterbottom (1989).

Two basic accelerated aging tests, standardized by the International Electrotechnical Commission, the, "constant high temperature and humidity test", and, "cyclic humidity and temperature variation test", were carried out in this experiment, although both were extensively modified. Modifications included humidity and temperature settings as well as duration of these conditions. The cyclic humidity and temperature variation test conditions were followed only in principle as time constraints, limitations of the environmental chamber, and chronological organization of this study permitted. The cyclic humidity and temperature variation test is intended to reveal defects in test specimens caused by, "breathing", as distinct from the absorption of moisture. [Winterbottom (1989)] Therefore, the environmental stress conditions applied to tapes in group 2 can be described as the ones falling under this category.

The combination of mechanical and environmental stress was conceptualized to imitate conditions of frequent tape use with intermittent short-term storage periods. In this portion of the study, the tapes were subjected to a 24 hour period in an environment controlled chamber, under the conditions described above, followed by one cycle of mechanical stress. Preceding each mechanical stress cycle, with cassettes well acclimated, the tapes were wound and rewound in order to relieve the accumulated tape stress as suggested by Smolian (1987) and Wheeler (1983). Subsequent to every mechanical stress cycle, the test sequence was digitally copied. Then, the tapes were wound to the end of tape (EOT), rewound back to the beginning of tape (BOT), and ultimately placed back in the chamber for the next 24 hour period. This combined stress cycle, involving a 24-hour period of high temperature and humidity controlled conditions followed by a 48-hour period of uncontrolled low temperature and humidity conditions, integrated with exposure to one cycle of mechanical stress, was repeated 13 times. The resulting environmental stress totaled 936 hours and consisted of 312-hour exposure to the high temperature/humidity, and of 624-hour exposure to the room conditions.

Cassettes designated for environmental stress testing were marked with red permanent ink and two codes were used to distinguish which group they belonged to: EN30 for group 3 tapes (30 days), and EN24 for group 2 tapes (24 hours). As the cassettes were stored in the environmental chamber in their own plastic boxes (in keeping with standard storage procedures), the boxes were coded in the same fashion as the cassettes, with a brand name added to the code. This was done in order to ensure that they were always stored in the same box thus reducing the possible intervening variables. However, the paper insert cards (J cards) were removed to prevent tape contamination with leached paper chemicals and abrasive paper dust. [Smolian (1987), Jenkinson (1984)] When placed in the environmental chamber, the boxes were stored on their edges, resting on two convex plastic rails (about 6 mm high). This provided elevation and prevented contact with the surface on which condensed water droplets were collecting. The boxes were separated by a few centimeters to allow for free air circulation around them.

With the conclusion of high temperature/humidity exposure, boxes with cassettes were removed and brought to the room where the mechanical stress testing was conducted. Prior to the mechanical testing, they were left to acclimate for 24 hours for the tapes in group 2, and, for a minimum three-day period, for the tapes in group 3.

The room where the the cassettes were stored and mechanical stress tests were conducted was housed in a concrete and brick, centrally air conditioned, residential high-rise. The small room (about 1200 cubic feet, 360 cubic meters) had its own thermostat-controlled electrical heating. During the research (from January to April) the thermostat setting was held at 70° F (22°C) and a little thermometer, placed on a shelf side by side the cartridges, was monitored daily. The humidity conditions were neither controlled nor monitored The room was ventilated daily for a brief period of time and the room temperature never dropped below 60°F (15°C). Digital copying of test sequences was done at the Faculty of Music, McGill University, where the tapes and the R-DAT recorder had to be transported. In addition to this, tapes from groups 2 and 3 had to be transported to the Conviron Growth Chamber where the environmental stress testing was conducted. During the short outdoor transport, the boxes with cassettes were wrapped in a plastic bag and carried inside a leather briefcase.

Four brands of tape, AGFA DA 90, AMPEX 467 R-90, SONY DT-90R and 3M R90 were selected for the test. The process of selecting these particular brands of tape for the study was influenced by the three following factors. First, these brands of tape were the only ones distributed by professional audio equipment suppliers in the province of Quebec at the time that this study was first conceptualized (January-March 1990). Thus, the availability of these brands of tape on the local market was a determining factor to their usage by audio professionals in this region. Second, assurances were given by manufacturer's representatives that these brands of tape were intended for the professional audio industry applications. Third, the fact that the equipment necessary to perform this study was available only for a limited period of time affected the decision making process, as the time constraints would not allow for the testing of more than four brands of tape. These same time constraints were influential in establishing the length of the test sequence as well. After consultations with the tape vendors as to which length of DAT tapes is the most popular with their clients, the 90 minutes tape duration was chosen for this experiment. Three 90 minute tapes of each brand were donated to the study by manufacturers or distributors of their products. In order to ensure similar quality of each tape, the three cassettes were taken from the same packaging box as these would most probably come from the same batch, hence providing the same consistency in quality.

Each tape was then unwrapped, wound (fast-forward), and rewound concurrently ten times on a Sony DTC 1000 DAT recorder with its heads and tape path cleaned prior to insertion of each cassette. The process of fast winding (FF) and rewinding (REW) was employed not only to relieve accumulated tape stress, but also to dislodge any particles and contaminants embedded in the tape. In addition, the wind/rewind (FF/REW) procedure was timed in order to investigate increases in friction torque during tape running. As described by Mori et al. (1988), by the adoption of a hub in R-DAT cassette construction, as opposed to reels with flanges construction previously used in cassettes of helical-scan magnetic record/playback systems, greater compactness was achieved. However, a resistive force, expressed as a friction torque, acts within the cassette when the tape is drawn out from the cassette and the tape rubs against the slip sheet. Depending on the characteristics of magnetic tapes and slip sheets, and the precision of hubs and cartridges, the initially low friction torque of 2 gcm or less, as stipulated in The DAT Conference Standard, may rise. With the rise in friction torque, the FF time increases and this generally leads to a full stop within ten FF/REW cycles.

The next step in the preparation of tapes for the experiment was to select a region on the tape where a test sequence would be recorded. The sequence designed to test the hypothesis was only 30 seconds long, with a 1 minute guard band with no signal recorded (record mute on), preceding and following it. (See Fig. 2) These guard bands were to act as a protection against static electricity charges which often affect unrecorded digital tapes stored for an extensive period of time. Therefore, a total of a 2.5 minute section on the tape had to be selected to generate results most representative of the whole tape. Placing the sequence at the beginning of tape was the least desirable option since DAT tapes are automatically rewound when the EOT (end of tape) sensor is activated. Consequently, they are stored in a "Head Out" position, exposing the beginning of tape to airborne contaminants when the lid and the slider are not locked properly or remain accidentally open. Furthermore, both the beginning and the end of the tape could be affected by deformations caused by the hub, the clamp, and/or the splicing tape when any of these items is manufactured or mounted with a substandard precision. Therefore, the middle section of the tape was chosen for the placement of the test sequence. In addition to avoiding the contamination and deformation of the tape, this placement of the test sequence provides yet another safeguard against possible contamination. Any contaminating particle deposited within the R-DAT recorder's tape path, prior to insertion of the cassette, would be deposited onto the tape during the fast forward search preceding the localization of the test sequence area.

The test sequence was designed to investigate particular modes of R-DAT recorder operations which have the most profound effect on a mechanical stress of the media. Four tests incorporated in the sequence were devised to delve into the still frame mode of operation, the mode switching, multiple reproduction passes, and overwrite characteristics. The test sequence was assembled from five short segments (ca 3 seconds) of 10 kHz sine wave tones, and one segment of musical material, approximately 8 seconds long. High frequency sine wave tones were chosen for the non-musical part of test sequence in order to facilitate the ensuing subjective evaluation, as dropouts are easier to perceive at high frequencies. [private conversation with Eilers,D.A. (1990)] The musical material segment, included in the sequence, consisted of an excerpt from Rondo of Beethoven's Piano Sonata No. 21 in C major, Opus 53, "Waldstein". This particular selection from a digitally recorded and mastered Compact Disc was chosen because it exhibits extremely wide dynamic range from a fortissimo to a pianissimo fade out. Including this musical material had its importance in providing comparison in perception of dropouts between non-musical and musical data, as well as in evaluation of a tape degradation effect on ambient sound during the chord decay and rise in the noise floor. The segments were separated by about 3 seconds of silence (record mute on), with the exception of the first and second segments, where separation of 8 seconds was necessary to accommodate writing of ID sub-codes in the middle of each segment.

All segments were recorded in stereo with the input selection switch on R-DAT recorder set to the analog input position. A sampling frequency of 48 kHz was chosen to record the test sequence, even though 44.1 kHz is used in most professional applications, as the latter is compatible with the Compact Disc standard. However, knowing that the test sequence was going to be digitally copied numerous times from and to R-DAT recorders that may not have AES/EBU digital ports, the selected sampling frequency (48 kHz) seemed like good insurance against the possible infusion of a copy prohibit flag which could seriously hamper the progress of the study.

The widest dynamic range of digital audio recorders is achieved when peak-to-peak modulation reaches the most significant bit (MSB), without surpassing it, as exceeding MSB resolution leads to a signal being clipped. In order to fully exploit the wide dynamic range capability (96 dB) of 16 bit Linear PCM (Pulse Code Modulation) recorders, recording levels, especially for musical materials, must be set in such a way that the highest peak displayed on the peak level meter indicators would read zero. Therefore, the adjustment of recording levels for musical material used in this study was done so the highest peak would just reach the zero mark. For adjustment of recording levels for non-musical material included in this study, the ensuing subjective evaluation had to be taken into consideration. As the need to provide balanced perceived loudness in monitoring situations required the least of the audio output level adjustments to be performed, the recording levels of the high frequency tones were set to the 6 dB below zero mark on the peak level meters display.

The first segment was assigned to the still frame (stop-motion function) test, this being the rubbing of heads against the tape at one location while the tape recorder is in a pause mode. This mode of operation can inflict irreversible damage on a magnetic tape due to extreme friction caused by rotating heads over the same area of a non-moving tape. However, the extent of the damage is closely dependent upon the quality of lubricants and durability of the coating layer. The still frame test is considered to be an important part of testing procedures for the helical scan format and is generally conducted for a period of five to sixty minutes. [Mori et al. (1988); private conversation with Eilers,D.A.

(1990)] The R-DAT recorder's built-in protection against excessive stress disengages the pause mode after a predetermined elapse of time (10 minute limit for Sony DTC 1000). Thus, the duration of the test set for one hour in this study precluded the test from being undertaken in its entirety in one session. Accordingly, the test had to be divided into smaller sections, with durations of 6 minutes per one mechanical cycle. For the reasons mentioned above, the study was expanded by 3 mechanical cycles during which the still frame test was set at 10 minutes per cycle. Altogether, 90 minutes of still frame testing were performed in the course of the study.

The second segment, assigned to a mode switching test, has its significance in providing data on the influence of a high speed sub-code search capability of R-DAT systems with respect to the media durability. In this mode of operation, an identification code (ID) is written in the sub-code area via automatic (AUTO) or manual (MAN) start identification (START ID) buttons. When required, the ID point can be accessed through automatic music sensor buttons (AMS FF, AMS REW) or, in situations where a program number is assigned to the ID, numeric buttons for program number selection and the START button can be used. On the R-DAT recorder used for the testing (DTC 1000), the machine enters automatically into the playback mode after stopping at the desired ID; thus, the mode switching operation takes effect.

As rationalized by Mori et al. (1988), frequent mode switching at the same ID can cause degradation of the tape properties due to the added load. In this study, the added load during mode switching operation was further increased by the exclusive use of the fast rewind search mode (AMS REW) to locate the selected ID. In REW mode, the contact between the tape and heads becomes severe, due to the increase of running friction of the tape. The rise in friction is generated by the tape running in reverse to the rotating direction of the drum with heads, leading to a diminishing inhalation air flow by the drum as a result of counteracting exhaust flow by the tape. Consequently, this leads to the reduction of air film between the tape and the drum, and to the increase in the running friction of the tape. The higher the speed of tape and drum, the larger the load on the tape transport becomes, bringing about tape sticking and flapping which eventually induces jitter, tracking error and, ultimately, head to tape contact which is damaging to the tape. [Ogiro et al. (1988)]

In the course of this study, the AMS REW button was activated after each completed reproduction pass, locating the ID placed in the middle of second segment, and performing a total of 2600 mode switching operations.

The third and fourth segment within the test sequence were appropriated for the evaluation of the aftermath of multiple reproduction passes. A simple test, consisting of repetitive reproductions of recorded data, was carried out in order to examine the reliability of this particular mode of operation. As the failure to reproduce recorded data has enormous consequences, the R-DAT system design incorporates a strong error detection and correction (EDAC) scheme, doubly-encoded Reed-Solomon Code (RSC). However, when the playback friction induces damage to the tape exceeding the error correction and concealment capability of the R-DAT system, the failure to reproduce the data becomes audible.

According to Steinberg (1987), 95% of all magnetic media failures are caused by adhesive wear, when friction-induced interface temperatures at microscopic contact points between the coating and the head exceed the softening temperature of the polymer alloy. This interaction is caused by excessive pressure at an asperity and/or lack of adequate lubrication. As a result, a small amount of composite may stick to the head or be smeared out. The process will repeat itself on the next pass over the same region and eventually the coating will be torn out down to the substrate.

Goto et al. (1989) conducted an experiment with R-DAT system in which playback reliability was tested. During 5000 reproduction passes, the block error rate (B.E.R.), with more than one bit error in a block, was measured. They reported the B.E.R. exceeding 10^{-1} was measured after 2500 passes, while the capability limit of the doubly-encoded RSC to correct data is the B.E.R. of 1.6×10^{-1}, if only random errors occurred. With respect to their findings, and in accordance with the forth set objective of evaluating audio output only, the number of reproduction passes attributed to the mechanical stress in this study was set to 2600.

Finally, the last two segments were intended for the study of overwrite function performance. The first segment of the two was overwritten after every 50 reproduction passes. Even though the second segment was overwritten at the same time as the first, it was not reproduced in between the overwrites. Therefore, the first segment was mechanically stressed while the second was reproduced only twice with every overwrite pass; thus it was not considered to be mechanically stressed. The concept of overwriting a mechanically stressed segment and a non-mechanically stressed segment was included in this study to evaluate the extent of reusability of the media after it was subjected to: no-stress conditions, environmental stress conditions only, mechanical stress conditions only, or a mixture of environmental and mechanical stress conditions. Overall, a total of 55 overwrites were achieved for each of the last two segments in this study.

The original assembly of the test sequence was done on a Sony DTC 1000 DAT recorder, with the sequence recorded in stereo. Analog inputs were used to record the high frequency tones from an analog sine wave tone generator. For reasons explained above, analog inputs were also used for the transfer of musical material from a digitally recorded (DDD) compact disc. However, the individual cassettes used in this study were dubbed digitally on a Sony PCM 2500 DAT recorder (professional model) via SPDIF ports from the DTC 1000 recorder. The mechanical stress was performed on the DTC 1000 and digital copies, made after each mechanical stress cycle, were recorded on the PCM 2500 via SPDIF ports. In cases where a dropout could could be perceived on the DTC 1000, additional digital copy was made with the PCM 2500 used as a reproducer and the DTC 1000 used as a recorder. Thus, a digital copy of the test sequence, reproduced by the same R-DAT recorder that was used to record it was obtained.

With the completion of environmental and mechanical procedures, digital copies of individual test sequences had to be edited and segments had to be assembled for the ensuing subjective listening test. The listening test edits and assembly was done on a Dyaxis digital audio workstation (DAW) to which the segments were transferred digitally, from a Sony PCM 7030 DAT recorder via AES/EBU ports. Once assembled, the subjective listening test was transferred back onto a DAT tape via AES/EBU ports on the PCM 7030 recorder.

The subjective evaluation was structured in such a way that the digital copy of the very first recording, the original (before any damage to the tape could occur), was compared with the last digital copy, this made after 2600 mechanical stress passes. In situations where a dropout was known to be in a particular segment prior to the final cycle, a number of digital copies of the same segment were incorporated into the subjective evaluation as follows:

1) The original copy versus the copy of segment prior to the dropout.

2) The original copy versus the copy of segment with the dropout.
3) The original copy versus the copy of segment with the dropout, but reproduced by the same R-DAT recorder (PCM 2500) that was used to record the original test sequence.
4) If no dropout in "3)" was perceived, then original copy versus the copy of segment from a next cycle where dropout was reproduced by the same R-DAT recorder (PCM 2500) that was used to record the original test sequence.

All subjects who participated in the subjective evaluation test were trained. The training consisted of playing various length dropouts which occurred during mechanical stress testing in segments with a high frequency sine wave tone. In addition to this, one, three-samples (3/48 kHz) dropout, and one, one-sample (1/48 kHz) dropout, were artificially created to examine whether such short dropouts are perceptible to the human ear and whether the minute differences in their size can be effectively evaluated. The two short dropouts were created on Dyaxis DAW through tedious manipulation and editing of existing segments with dropouts Following the training of subjects, they were asked to evaluate a "test run" part of the listening test, structured in the same manner as the listening test itself. When the test run was completed, individual evaluations were looked at in order to verify that all subjects thoroughly understood the subjective listening test procedures.

The structure of the listening test was based on a simple A/B comparison method where two digital copies of the same segment, one prior to any stress exposure, and the other following the stress exposure, were evaluated. The subjects were asked to check one of three boxes provided for each pair of segments. The first box was inscribed with "same", meaning that no difference between the pair of segments could be perceived. The second box had a "2 better" inscription which, if checked, would show that the subject had found the second segment of the pair to be of superior quality. Finally, the third box was inscribed with "2 worse" and a subject was to check this box when the quality of second segment was inferior to the quality of the first segment. The pair of segments were separated by one second of silence; five seconds of silence were utilized to separate the individual pairs The subjective listening test was, in its entirety, almost 40 minutes long. However, it was divided into eleven parts and the subjects were free to take a break after completing any part. (See Appendix A, for Subjective Listening Test form)

The last six parts included in the subjective listening test were conceptualized to evaluate if any changes to audio output had occurred after six months of storage following the conclusion of environmental and mechanical testing. During this period (April to October, 1991) the DAT tapes were stored in the same room where the mechanical stress was previously conducted. As described above, the room was centrally air conditioned and even during the hottest summer days, the temperature in the room did not exceed 75°F (24°C). However, throughout the summer the window stayed partially open and humidity was neither controlled nor monitored. The A/B listening test (part 6 to 11) was therefore assembled from digital copies of segments made after the last mechanical stress cycle (segment "A"), and from digital copies of segments made six months later (segment "B").

The results of the subjective listening test were analyzed and tabulated. Additional observations, annotated during the course of the study, were also included in the following discussion in order to provide a reference for subjective evaluations.

Results and discussion

The following discussion of the subjective listening test results will include overall presentation of generated data. Then, individual aspects of the influence of mechanical and/or environmental stress on R-DAT tapes will be examined. Performance of individual brands of tape will be evaluated and brands of tape will be ranked according to their overall performance reliability throughout the testing. The results of the subjective evaluation of media stability following a short term storage (six months) will be included in the discussion. Data obtained through notes taken of the error correction display on the R-DAT recorder, displays of segments on Dyaxis DAW, and other relevant observations will be presented to supplement the subjective listening test results. The subjective and objective findings will be compared and possible explanations of discrepancies between the findings will be presented.

The listening test was administered to a group of 12 subjects. Six subjects were graduate students in the sound recording program at McGill University and one subject was an undergraduate student attending prerequisite courses for the sound recording program. Two subjects were professional sound engineers and one subject was an electrical engineer with experience in sound reinforcement. The last two subjects were accomplished studio musicians with a limited recording engineering experience.

The subjects were free to select either headphones or speakers to monitor the listening test. Only three subjects selected headphones. A higher percentage of answers corroborating the objective findings, especially in the part of the test involving 10 kHz sine wave evaluation, was achieved by the subjects using headphones. The lower percentage of agreement with objective results by subjects using speakers can be mainly attributed to the lack of awareness of a phase effect caused by the movement of their heads while monitoring 10 kHz sine wave tones. They often interpreted the wavering sound as a change in quality of the reproduced segment. Their scoring improved dramatically after they were notified of the phasing effect and instructed to either keep their heads still or not to include the effect in quality judging criteria.

The collected data from the individual subjective listening tests was compounded and the resulting totals are shown as follows:

1) 3M tapes do not contain any dropouts in any group, [82.5% of subjects agree]. (See Table 1)

LISTENING TEST RESULTS OF 3M TAPES

	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
GROUP 1:							
Segment no. 1:	100%	-	-	Segment no. 2:	84%	8%	8%
Segment no 3.	100%	-	-	Segment no. 4:	92%	8%	-
Segment no 5	58%	25%	17%	Segment no. 6:	84%	8%	8%
GROUP 2:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1	75%	25%	-	Segment no. 2:	92%	-	8%
Segment no. 3	66%	17%	17%	Segment no. 4:	92%	-	8%
Segment no 5	75%	-	25%	Segment no. 6	58%	25%	17%
GROUP 3:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no. 1	75%	25%	-	Segment no. 2	75%	17%	8%
Segment no 3	84%	8%	8%	Segment no. 4	100%	-	-
Segment no 5	83%	17%	-	Segment no. 6	92%	8%	-

NOTE Bold framed box indicates objective findings.

INTERPRETATION 82.5% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS.

TABLE 1

2) AMPEX 467 tapes contain only one dropout in group 2 with the dropout being perceived after 2000 passes in segment 3, [96% of subjects agree]. (See Table 2)

LISTENING TEST RESULTS OF AMPEX 467 TAPES							
GROUP 1:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1	**100%**	-	-	Segment no. 2.	**100%**	-	-
Segment no. 3	**100%**	-	-	Segment no 4:	**92%**	-	8%
Segment no. 5.	**100%**	-	-	Segment no. 6.	**92%**	8%	-
GROUP 2:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1:	**92%**	-	8%	Segment no. 2	**92%**	-	8%
Segment no. 3.	-	-	**100%**	Segment no. 4.	**84%**	8%	8%
Segment no 5	**100%**	-	-	Segment no. 6.	**100%**	-	-
GROUP 3:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1:	**100%**	-	-	Segment no. 2:	**92%**	-	8%
Segment no 3.	**100%**	-	-	Segment no. 4	**83%**	17%	-
Segment no 5	**100%**	-	-	Segment no 6.	**100%**	-	-

NOTE Bold framed box indicates objective findings

INTERPRETATION 96% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS.

TABLE 2

3) AGFA tapes contain two dropouts: One in group 1, perceived after 1800 passes in segment 3; the other in group 3, perceived after 800 passes in segment 3, [95% of subjects agree]. (See Table 3)

LISTENING TEST RESULTS OF AGFA TAPES							
GROUP 1:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1.	**92%**	-	8%	Segment no 2:	**100%**	-	-
Segment no 3:	-	-	**100%**	Segment no 4:	**100%**	-	-
Segment no. 5.	**92%**	-	8%	Segment no 6	**92%**	-	8%
GROUP 2:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1	**100%**	-	-	Segment no 2	**92%**	-	8%
Segment no 3	**100%**	-	-	Segment no 4	**92%**	8%	-
Segment no 5:	**92%**	-	8%	Segment no 6.	**92%**	8%	-
GROUP 3:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no. 1	**83%**	17%	-	Segment no 2	**100%**	-	-
Segment no 3	-	-	**100%**	Segment no 4	**92%**	8%	-
Segment no 5:	**92%**	8%	-	Segment no 6.	**92%**	8%	-

NOTE. Bold framed box indicates objective findings

INTERPRETATION 95% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS

TABLE 3

4) SONY tapes contain four dropouts: One in group 1, perceived after 400 passes in segment 3 and one in group 2, perceived after 1600 passes in segment 3. Then, two dropouts can be heard in group 3 where one, in segment 2, was perceived after 1600 passes and the other was perceived after 1000 passes in segment 3, [95.5% of subjects agree]. (See Table 4)

LISTENING TEST RESULTS OF SONY TAPES

	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
GROUP 1:							
Segment no 1:	**100%**	-	-	Segment no 2:	**100%**	-	-
Segment no 3	-	-	**100%**	Segment no 4:	**92%**	-	8%
Segment no 5	**100%**	-	-	Segment no. 6:	**100%**	-	-
GROUP 2:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1.	**100%**	-	-	Segment no 2:	**100%**	-	-
Segment no 3	-	-	**100%**	Segment no. 4:	**83%**	17%	-
Segment no 5	**83%**	17%	-	Segment no. 6:	**84%**	8%	8%
GROUP 3:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1	**100%**	-	-	Segment no 2	-	-	**100%**
Segment no 3.	-	-	**100%**	Segment no 4:	**92%**	-	8%
Segment no 5	**92%**	-	8%	Segment no 6:	**92%**	8%	-

NOTE Bold framed box indicates objective findings.
INTERPRETATION. 95 5% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS.

TABLE 4

The effect of phase, due to the head movement by the subjects using speakers is clearly evident above (see Table 1), as only 82.5% of subjects found the quality of compared segments on 3M tapes in agreement with objective findings. This percentage is lower than percentages for other brands of tape, which were over 95%. The explanation for this can be twofold. First, the effect of phase was explained to subjects only after the completion of part one of the listening test, which was devoted to the evaluation of 3M tapes. Second, the lack of familiarity with the presented material could also have been an important factor. Although the subjects have been trained to distinguish between various length dropouts and have achieved 92% of correct answers during the test run (see Table 5), the instructions emphasized that there was the possibility of unknown variations in quality that were not covered by the training procedure.

LISTENING TEST RESULTS OF TEST RUN

	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Part no. 1:	8%	**92%**	-	Part no. 2.	8%	-	**92%**
Part no. 3.	**92%**	8%	-	Part no. 4	8%	**92%**	-

Key:

Part no 1 Segment with dropout (3 samples)* versus segment without dropout
Part no 2 Segment without dropout versus segment with dropout (1 sample)*
Part no. 3 Segment without dropout versus segment without dropout.
Part no 4 Segment with dropout (3 samples) versus segment with dropout (1 sample)

NOTE Bold framed box indicates correct answers

INTERPRETATION. 92% OF SUBJECTS ANSWERED CORRECTLY.

* See Appendix B, for displays of dropouts.

TABLE 5

A slightly lower percentage of agreement (91%) is also evident in the evaluation of segments containing musical material. Even though no dropouts were observed in these segments, the musical material was harder to evaluate due to its unsteady character, longer duration, and a variety of noises included on the recording which may have been interpreted as changes in quality by some subjects.

However, the most challenging part of the listening test was the evaluation of tape stability after six months of storage. Some discrepancies between the objective and subjective data are evident in this part of the evaluation. Most of the segments were evaluated as being identical to those prior to storage. Two segments were judged to be better in audio output quality. A consensus was not reached on the status of one segment and subjects perceived two segments as being of worse quality after the storage. (See Tables 6, 7, 8)

LISTENING TEST RESULTS OF GROUP 1 TAPES AFTER STORAGE

	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
3M:							
Segment no 1	100%	-	-	Segment no. 2:	92%	-	8%
Segment no 3	92%	-	8%	Segment no. 4:	92%	-	8%
Segment no 5:	100%	-	-	Segment no. 6:	84%	8%	8%
AMPEX 467:							
Segment no 1	100%	-	-	Segment no. 2:	100%	-	-
Segment no 3:	100%	-	-	Segment no. 4:	92%	8%	-
Segment no. 5.	100%	-	-	Segment no 6:	100%	-	-
AGFA:							
Segment no. 1	100%	-	-	Segment no. 2.	100%	-	-
Segment no 3.	8%	75%	17%	Segment no 4:	100%	-	-
Segment no 5	100%	-	-	Segment no 6:	92%	-	8%
SONY:							
Segment no 1.	92%	-	8%	Segment no 2.	100%	-	-
Segment no 3	8%	92%	-	Segment no 4	100%	-	-
Segment no 5	100%	-	-	Segment no. 6	92%	-	8%

NOTE Bold framed box indicates objective findings.

INTERPRETATION 96% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS.

TABLE 6

LISTENING TEST RESULTS OF GROUP 2 TAPES AFTER STORAGE

	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
3M:							
Segment no 1.	92%	8%	-	Segment no 2	100%	-	-
Segment no 3	100%	-	-	Segment no 4.	84%	8%	8%
Segment no 5	100%	-	-	Segment no. 6.	100%	-	-
AMPEX 467:							
Segment no 1	100%	-	-	Segment no. 2	100%	-	-
Segment no 3	50%	50%	-	Segment no. 4.	75%	8%	17%
Segment no 5	100%	-	-	Segment no. 6:	92%	8%	-
AGFA:							
Segment no 1	100%	-	-	Segment no. 2:	100%	-	-
Segment no. 3	100%	-	-	Segment no. 4	92%	8%	-
Segment no 5	100%	-	-	Segment no 6	92%	8%	-
SONY:							
Segment no 1	92%	8%	-	Segment no 2	92%	-	8%
Segment no 3	83%	17%	-	Segment no 4:	100%	-	-
Segment no 5.	92%	-	8%	Segment no 6:	100%	-	-

NOTE Bold framed box indicates objective findings

INTERPRETATION 90% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS.

TABLE 7

LISTENING TEST RESULTS OF GROUP 3 TAPES AFTER STORAGE							
3M:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1:	**100%**	-	-	Segment no. 2:	**100%**	-	-
Segment no. 3.	**92%**	8%	-	Segment no 4.	**83%**	17%	-
Segment no. 5:	**100%**	-	-	Segment no 6	**100%**	-	-
AMPEX 467:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no. 1:	**100%**	-	-	Segment no 2.	**100%**	-	-
Segment no. 3:	**100%**	-	-	Segment no 4.	**92%**	8%	-
Segment no 5.	**100%**	-	-	Segment no. 6:	**100%**	-	-
AGFA:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no. 1:	**100%**	-	-	Segment no. 2.	**100%**	-	-
Segment no 3·	17%	**17%**	66%	Segment no 4	**100%**	-	-
Segment no 5:	**100%**	-	-	Segment no. 6.	**100%**	-	-
SONY:	SAME	2 BETTER	2 WORSE		SAME	2 BETTER	2 WORSE
Segment no 1	**92%**	-	8%	Segment no 2·	-	**-**	100%
Segment no 3	**100%**	-	-	Segment no 4:	**92%**	-	8%
Segment no. 5:	**92%**	8%	-	Segment no 6	**100%**	-	-

NOTE: Bold framed box indicates objective findings
INTERPRETATION· 90% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS.

TABLE 8

The interpretation of objective data related to this part of the study posed some difficulties as well. The sensitive issue was that of interpreting the amount of damage on particular tapes as a number of factors had to be considered. The total length of the affected area was of the utmost importance. In cases where the difference in duration of damaged portions of two segments being compared was within 24 samples (0.5 ms), additional factors were considered. The 0.5 ms difference in the duration of a dropout's affected area is insignificant in objective data interpretation and so imperceptible that a subjective evaluation would be impossible. Therefore, the extent of the damage also became an instrumental factor in the interpretation process. Thus, segment 3, on Ampex 467 tape in group 2, was attributed a lower qualitative ranking as more severe dropouts were evident although the affected area was smaller than that of the other segment of the pair. In the case of segment 3, on Agfa tape in group 3, the severity of dropouts was a decisive factor as well. (See Figures 3, 4, 5, 6)

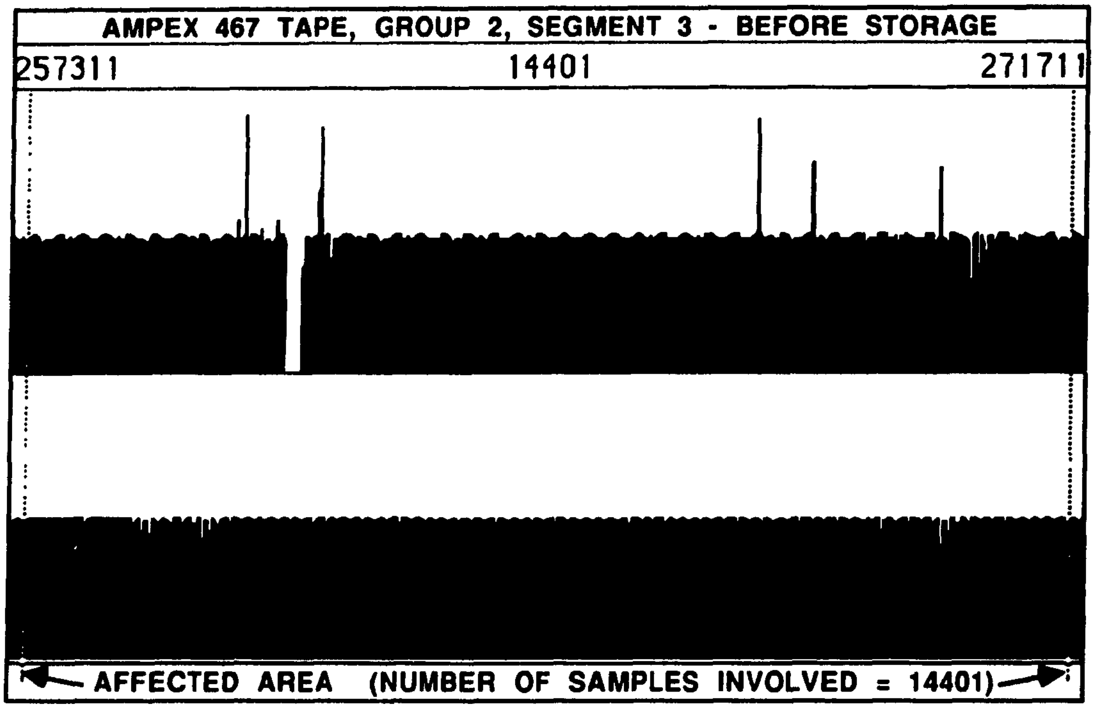


FIGURE 3

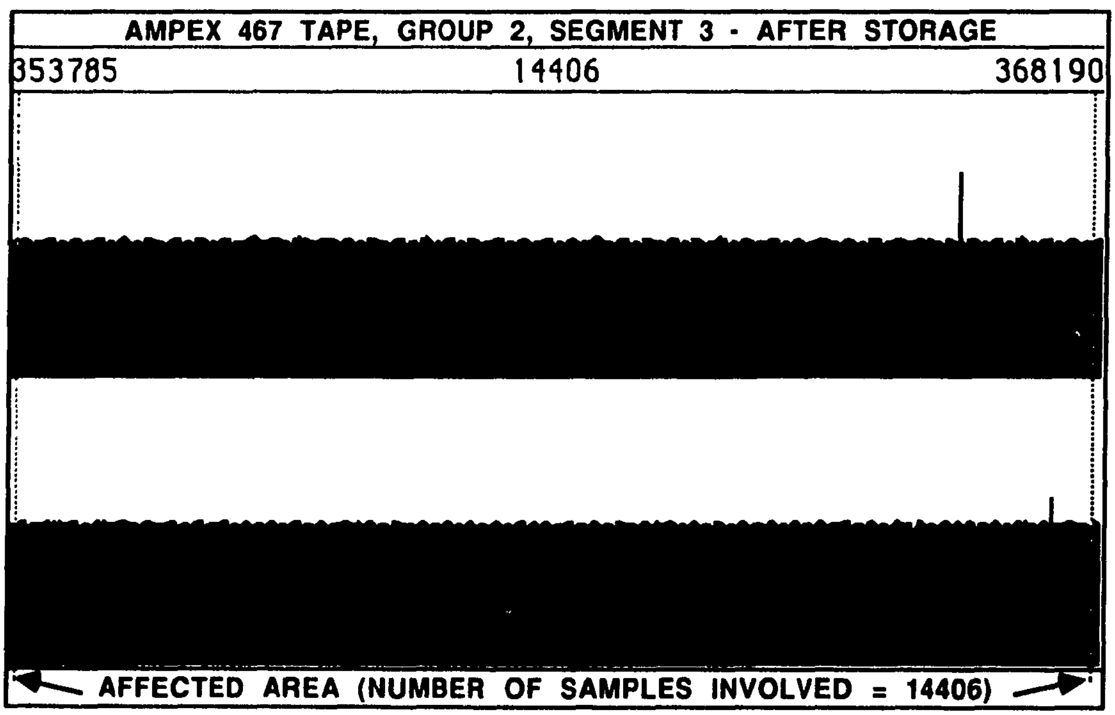


FIGURE 4

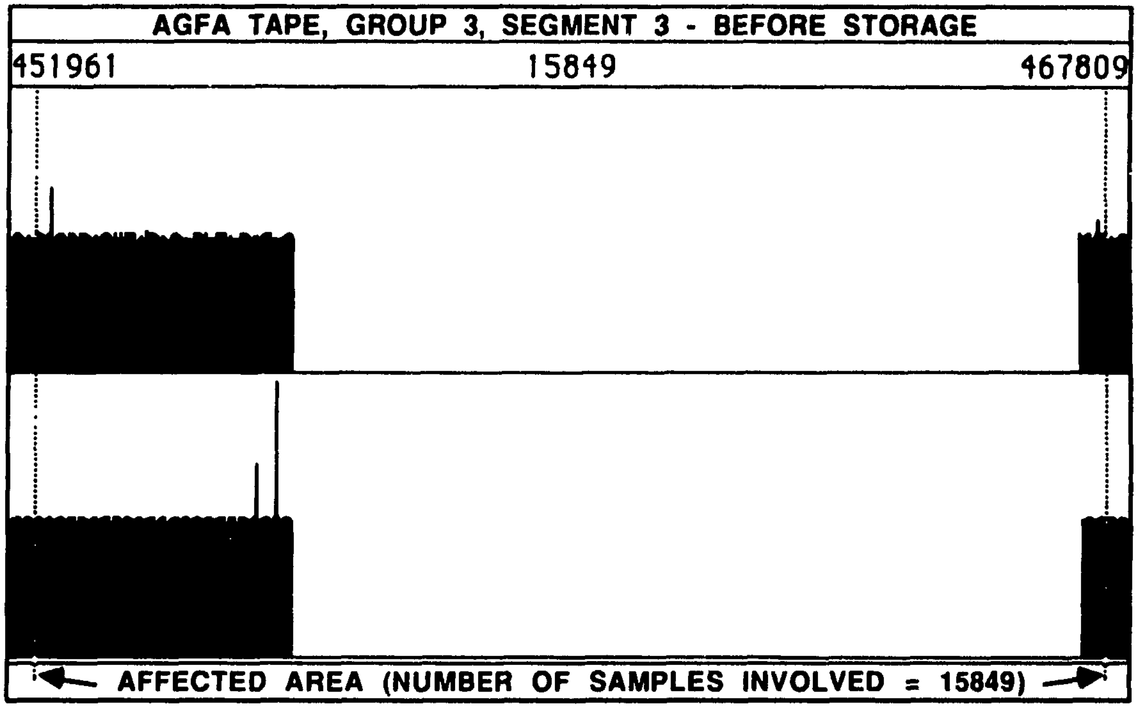


FIGURE 5

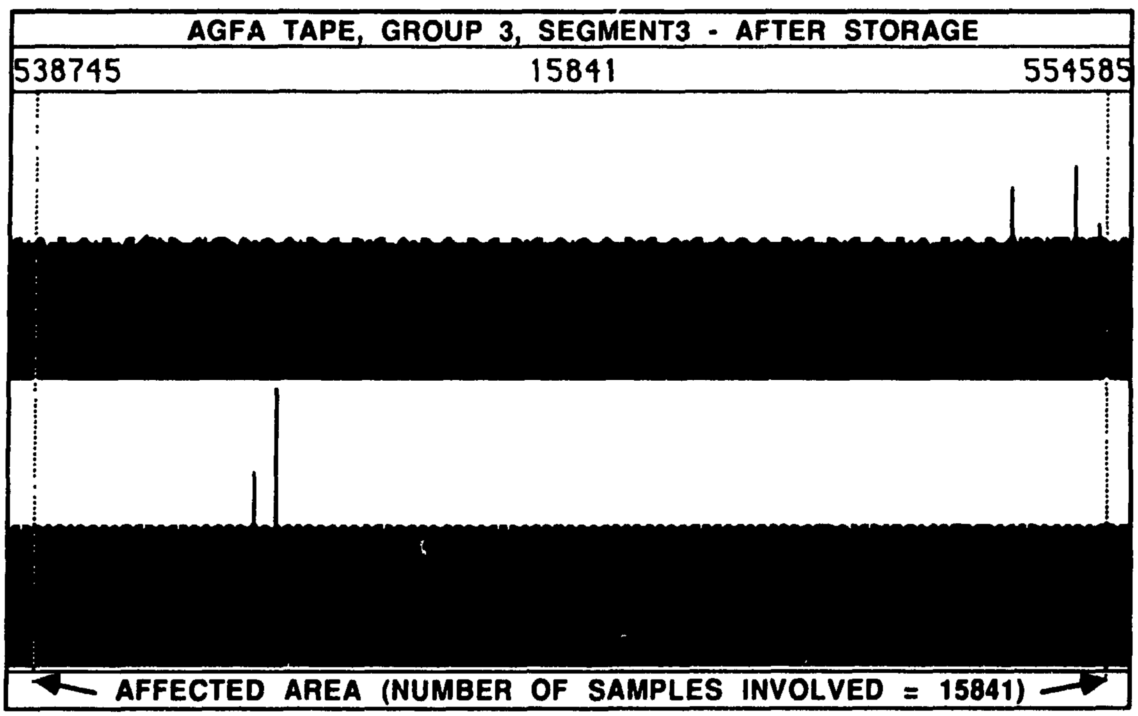


FIGURE 6

The severity of damage could not be used to asses segment 3, on Sony tape in group 2, as the pair looked identical. The only obvious difference was the length of affected area. Although it was negligible, it was the only factor in interpretation of objective data. (See Figures 7 and 8)

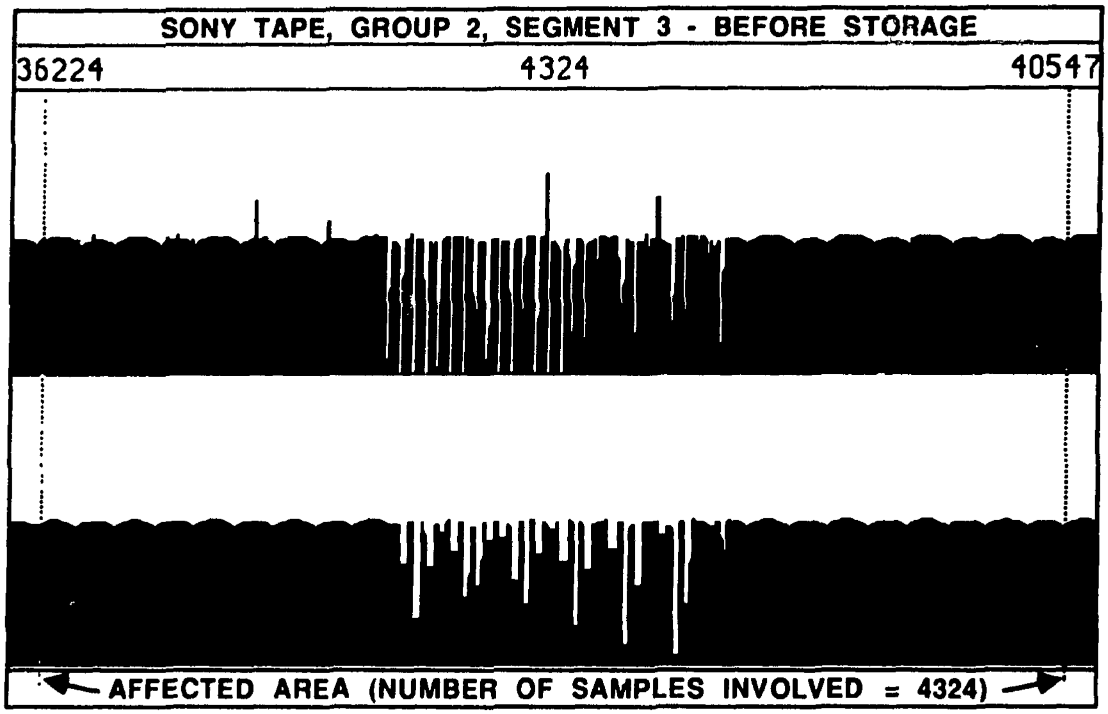


FIGURE 7

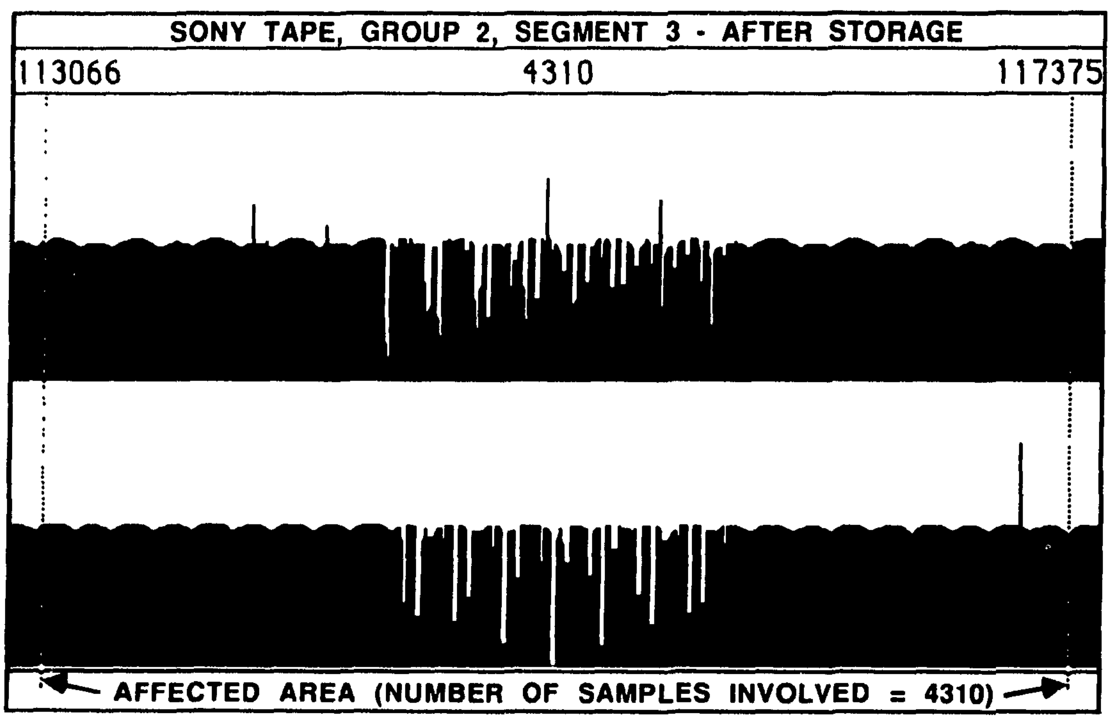


FIGURE 8

Although one segment (Sony tape: group 1-segment 3) actually got corrected when reproduced after the storage, the improved quality of other segments with dropouts can be attributed to the following: As the audio data was digitally copied onto another DAT tape prior to storage and subsequently recopied for the purposes of subjective evaluation, the glitches before dropouts were clipped twice due to an overload of both the R-DAT recorder and Dyaxis inputs. Therefore, the audio data copied directly onto the hard disk at the conclusion of 6 months of storage resulted in a perception of better audio quality as the glitches were clipped only once.

The lack of consensus among subjects on the quality of segment 3, on Ampex 467 tape in group 2, could be attributed only to the fact that the severity of damage in the segment preceding storage was not sufficient to promote perceptual certainty in the majority of subjects.

The two segments, (Agfa tape: group 3-segment 3, and Sony tape: group 3-segment 2) which subjects evaluated as being worse after the storage were actually better according to objective data. In the case of Agfa tape, this was also due to overloads of the R-DAT recorder and Dyaxis inputs. However, in this situation the double clipping resulted in muting an area with glitches and this seemed to be less objectionable to subjects. (See Figures 5 and 6) The extreme discrepancy between objective and subjective results related to the Sony tape could only be explained by the subjects' perceptual preferences. According to the objective data, the duration of the affected area in segment after the storage is 116 ms (5565 samples) shorter than the affected area in segment before the storage. (See Figures 9 and 10) However, the subjects were unanimous in their evaluation of the segment after the storage as being worse in quality. Thus, the difference in severity and duration of damage in a particular short section of the affected area is the only possible explanation for the results of subjective evaluation. (See Figures 11 and 12)

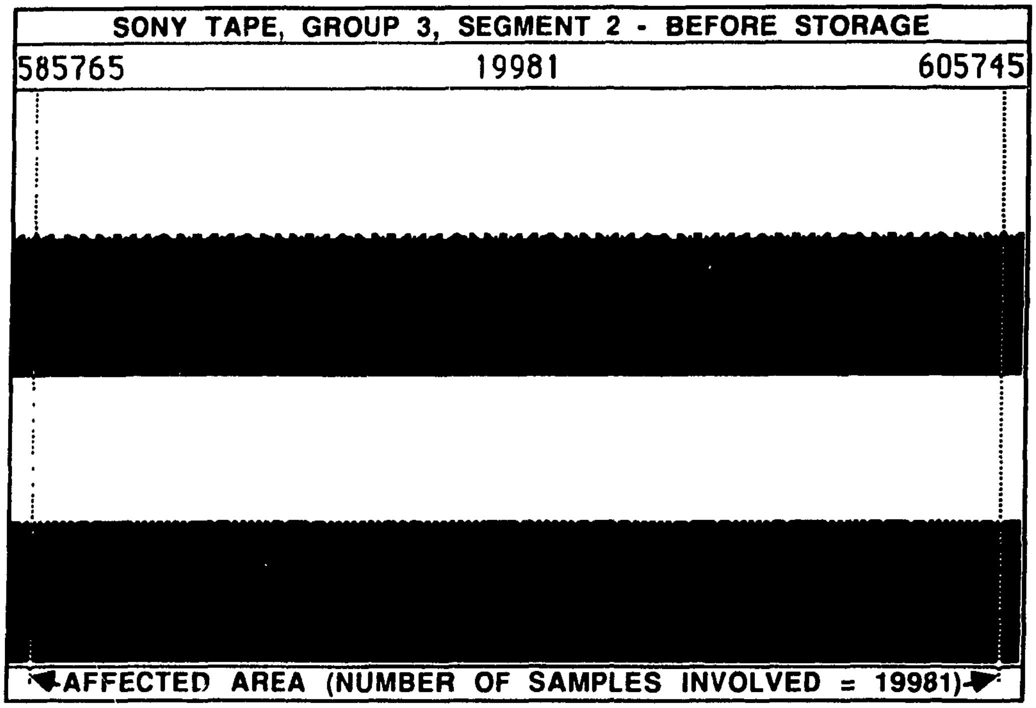


FIGURE 9

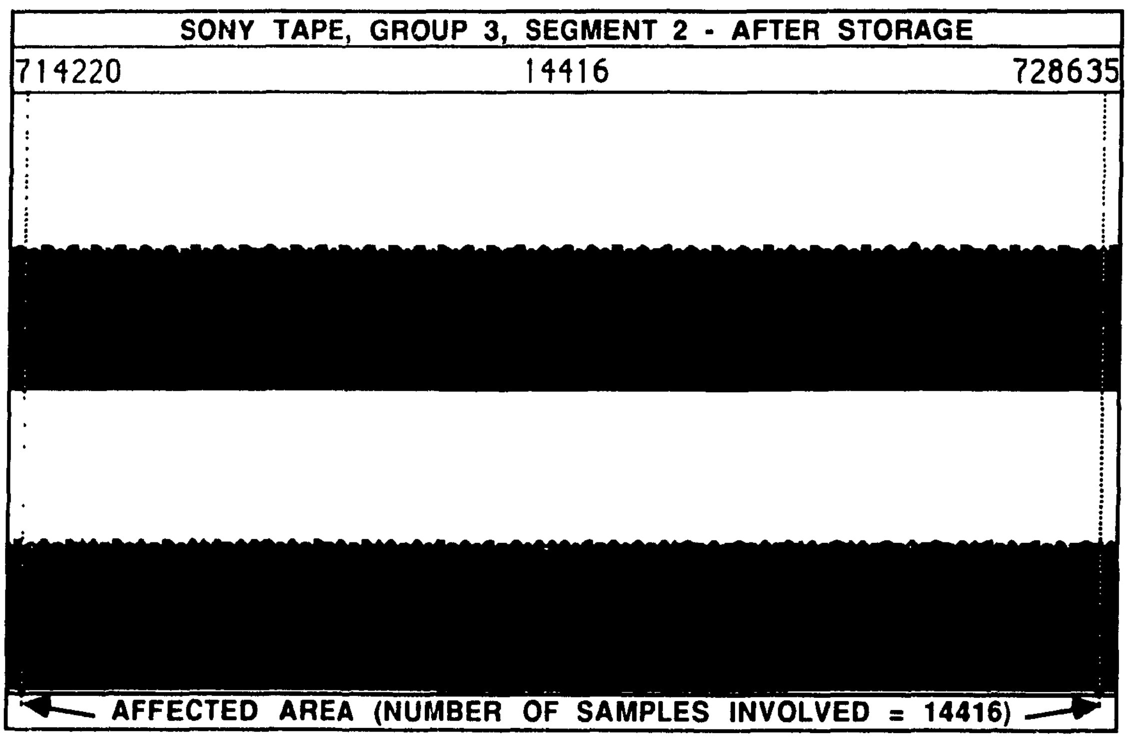


FIGURE 10

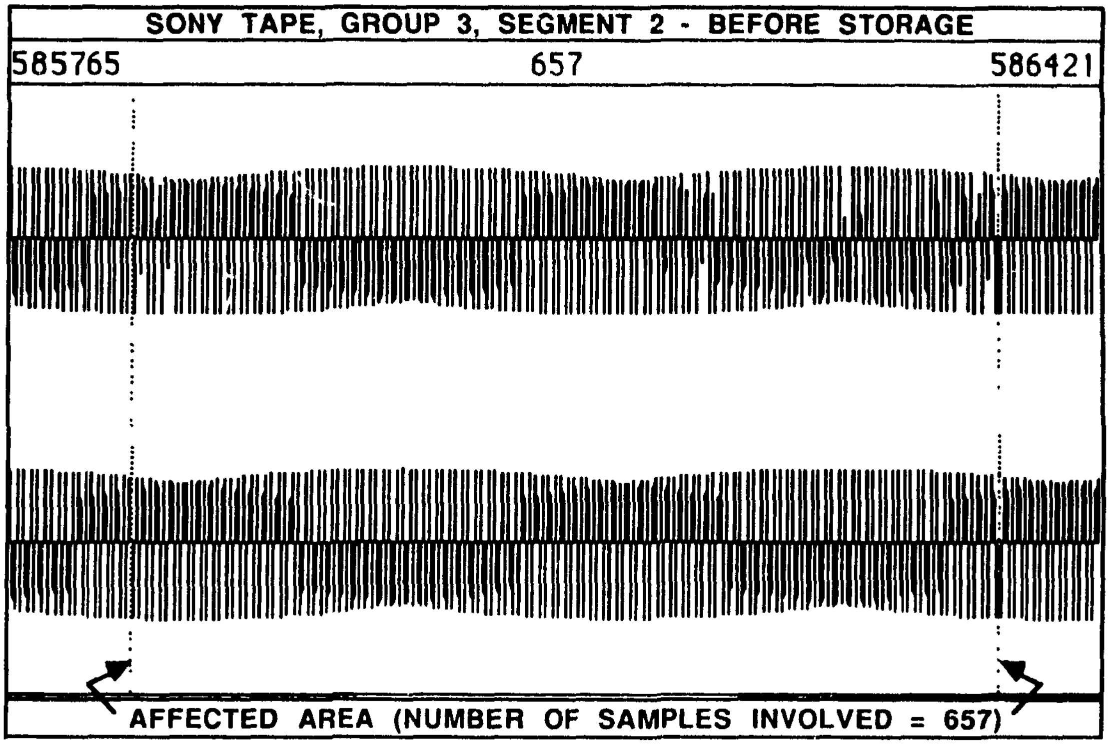


FIGURE 11

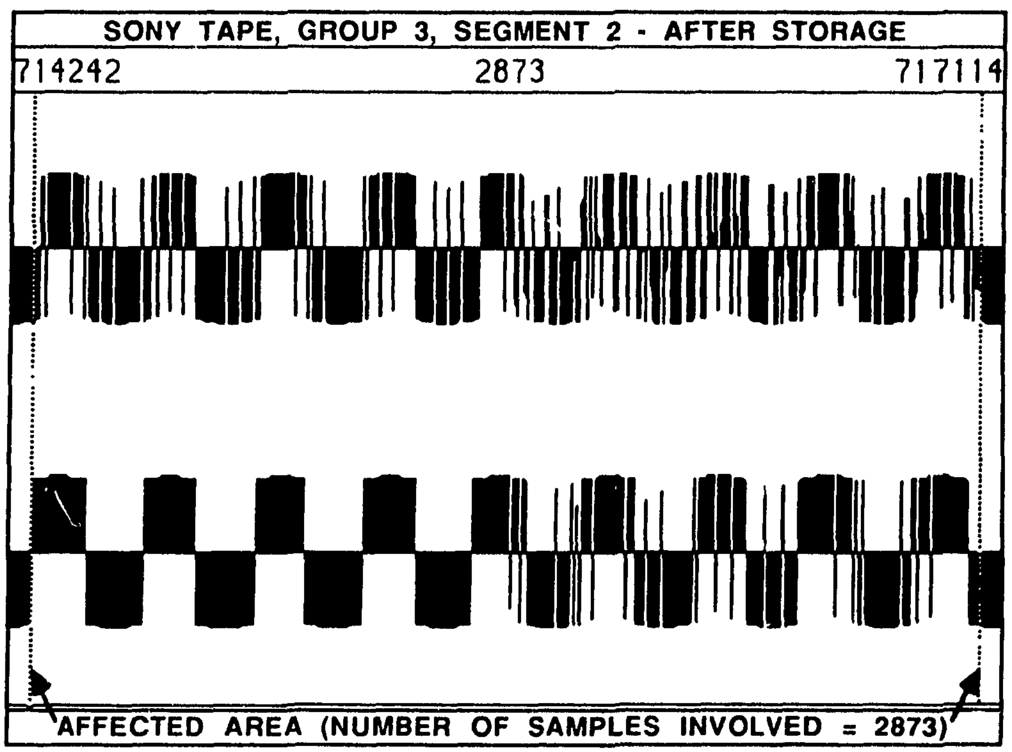
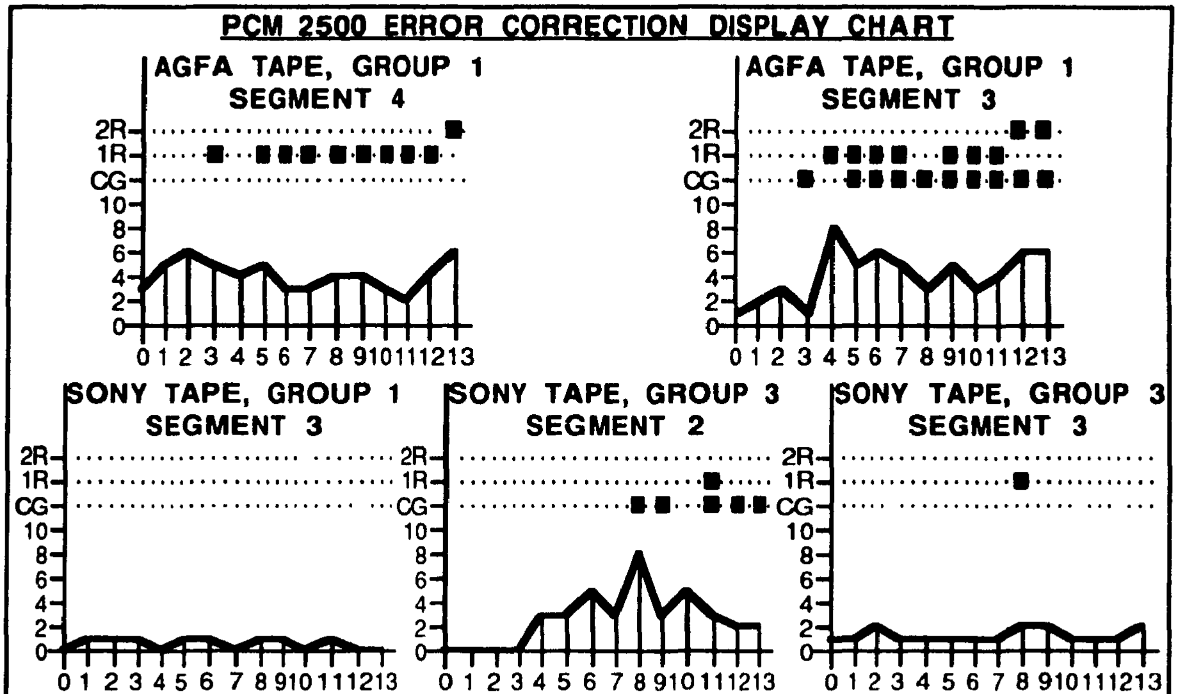


FIGURE 12

As has been demonstrated above, variations in both duration of affected areas and severity of dropouts were related to causes other than the influence of storage. The only real change in audio output after the short term storage was the correction of data on the Sony tape in group one. It can thus be concluded that the six months of storage did not impact adversely on the media stability. It can be argued that because of the correction of data in one segment, an improvement in media stability was achieved. However, in a discussion presented further on it will be shown that this was not the case.

With the exception of the discrepancies explained above, the subjective evaluation results corroborate the objective data of the Dyaxis DAW display. Nevertheless, in one instance the data obtained through the error correction display of the R-DAT recorder is in disagreement with both the subjective results and the display of the Dyaxis DAW. One musical material segment (Agfa tape: group 1-segment 4) was evaluated by subjects as being 100% identical with the original. (See Table 3) But, the error correction display data shows consistent interpolation after 1000 passes and two interpolations at the conclusion of the mechanical stress. (See Figure 13) Even though two flashes of the red LED can indicate a mute outlined by interpolations, it is not the case in this segment as one interpolation is at the beginning and the other at the end of the segment. Should the red LED represent a miniature dropout, it could be very difficult to spot as the ever changing wave-form of the musical material does not lend itself well to a visual examination. Nonetheless, viewing and comparing the original with the final test segment on Dyaxis DAW also did not reveal any differences More sophisticated equipment, which could both perform analysis in greater detail and compare two wave-forms with a higher precision than the human eye, would be needed to clarify the issue. However, this kind of equipment not being available, the problem remains unsolved.



KEY:

2R = TWO RED - Red LED displays interpolation Twice flashing red LED can indicate a mute outlined by interpolations

1R = ONE RED - Uncorrectable error is concealed by interpolation

CG = CONTINUOUS GREEN - Green LED displays error correction The LED was continuosly lit from 1 to 2 seconds

Numbers 0-12 on the vertical axis - Number of individual green LED flashes (corrections).

Number 0 on the horizontal axis - Activity of error display LEDs anotated before the tape was exposed to any stress

Numbers 1-13 on the horizontal axis = NUMBER OF MECHANICAL STRESS CYCLES - Activity of error display LEDs anotated after individual mechanical stress cycles

FIGURE 13

The objective data that consisted of monitoring and annotating the error correction display activity of PCM 2500 R-DAT recorder reveals this data as being inconsistent with the data obtained from the Dyaxis DAW and the subjective listening tests in four additional segments. Two possible explanations for the dichotomized data are discussed in the following paragraphs.

First, the interpolation indicator on PCM 2500 R-DAT recorder lights up when interpolation is attempted, whether or not the interpolation is successful in concealing apparent data loss. This is probably the case with segment 3, on Agfa tape in group 1, with interpolation being indicated after 800 passes, while data loss can be observed after 1800 passes only. (See Figure 13 and Figures 14,15)

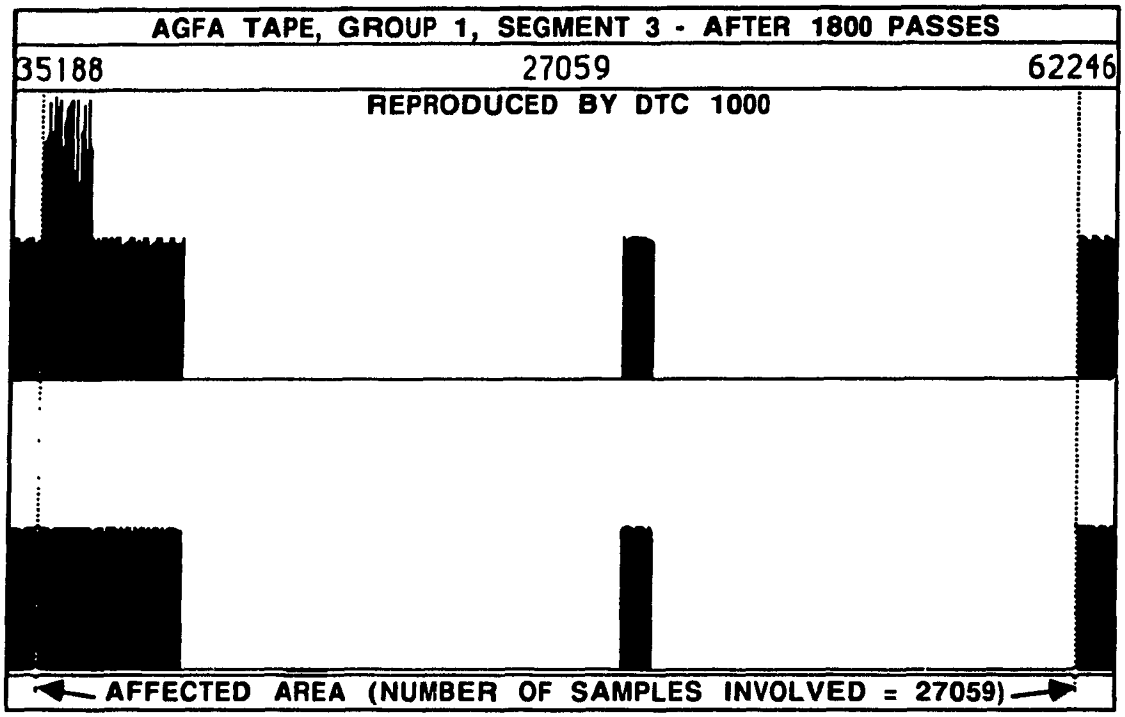


FIGURE 14

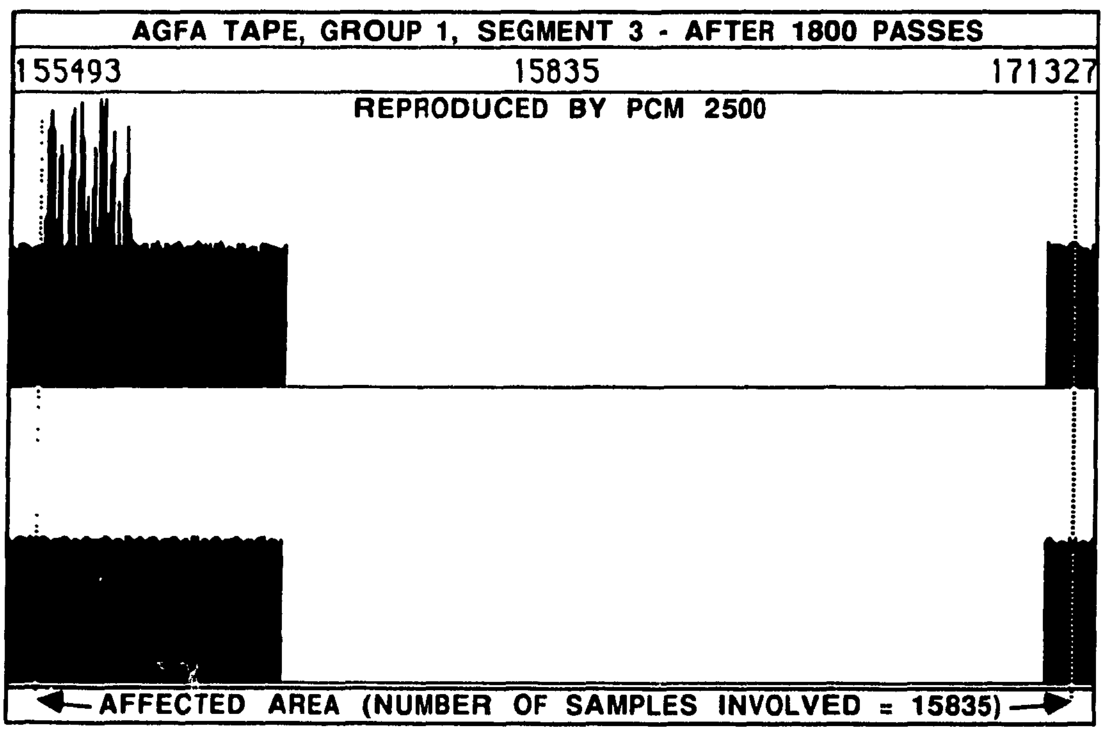


FIGURE 15

Second, the error correction data for segments on Sony tapes, shown in Figure 13, indicates lack of interpolation or, total absence of interpolation being performed on segments with apparent dropouts. (See Figures 16, 17, 18, 19, 20 and 21) In these cases, remarkable improvements in data correction were achieved when the same recorder that recorded the data (PCM 2500) was used to reproduce it. In the case of segment 3, on Sony tape in group 1, the PCM 2500 recorder consistently corrected the data throughout the experiment, even though dropouts were clearly noticeable after 400 passes when reproduced by the DTC 1000 recorder. Similar results were obtained for segment 3 in group 3. However, in this segment the dropout did not get corrected on one of the two copies made at the conclusion of mechanical stress testing. The uncorrected copy was later used in the part of subjective listening test designed to evaluate correction performance when the data is reproduced by different R-DAT recorders. The error correction data for segment 2, on Sony tape in group 3, reveals only one interpolation after 2200 passes, while dropouts were evident after 1600 passes when reproduced by the DTC 1000 recorder. Although the PCM 2500 recorder kept correcting the data up to and including 2000 passes, no corrections were found on any copy made after 2200 passes. Therefore, the discrepancy between the data obtained from the error correction indicators on PCM 2500 and the Dyaxis DAW display of segments could have only one explanation: As digital copies of the test sequence made after each mechanical stress cycle were not made while the error correction display was being annotated, the data may have been corrected during one pass while not during another. According to notes taken throughout the tests, the Sony segments shown in Figure 13 were corrected from time to time, even when reproduced by the DTC 1000 recorder.

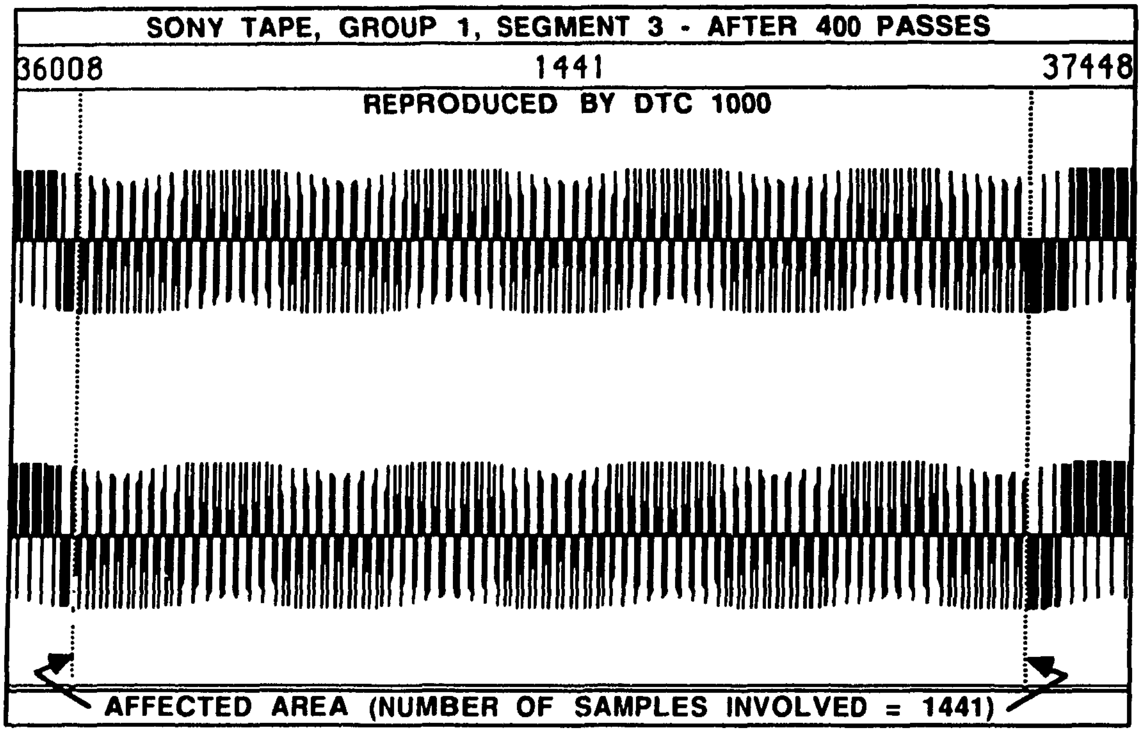


FIGURE 16

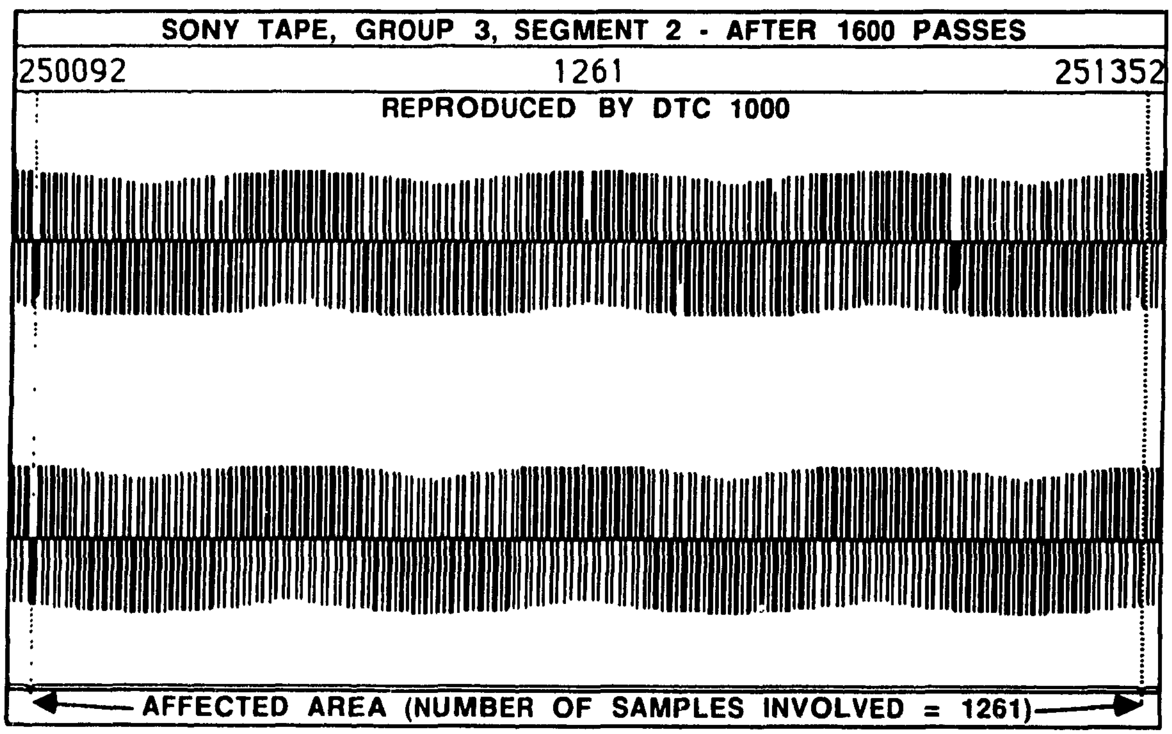


FIGURE 17

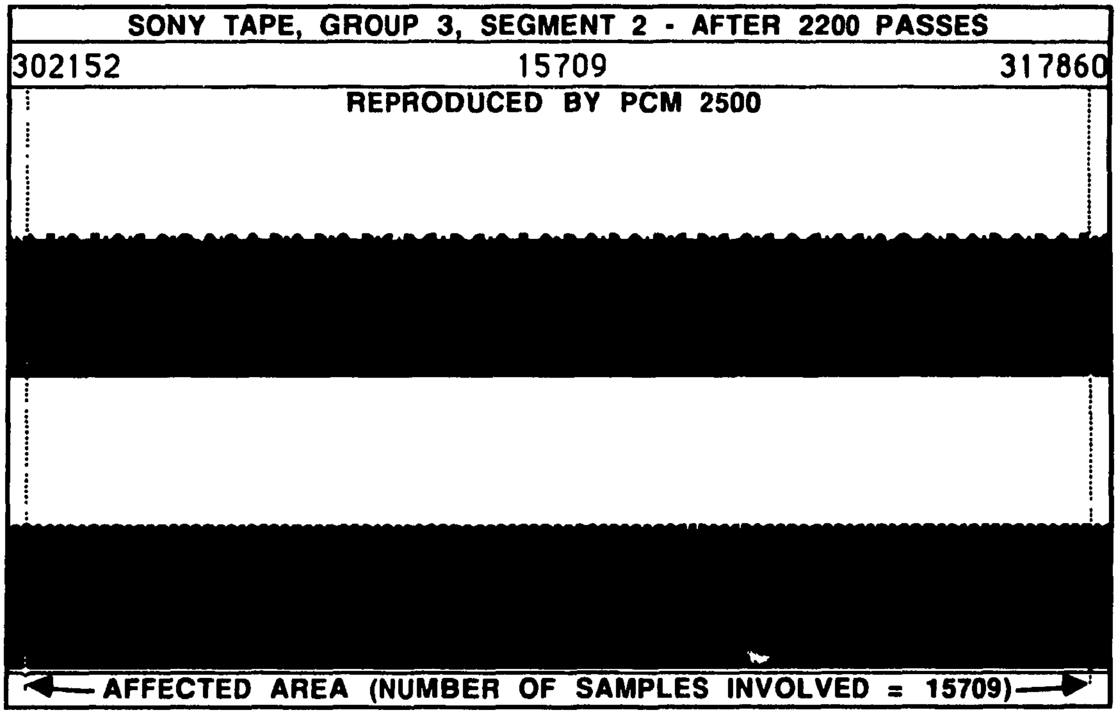
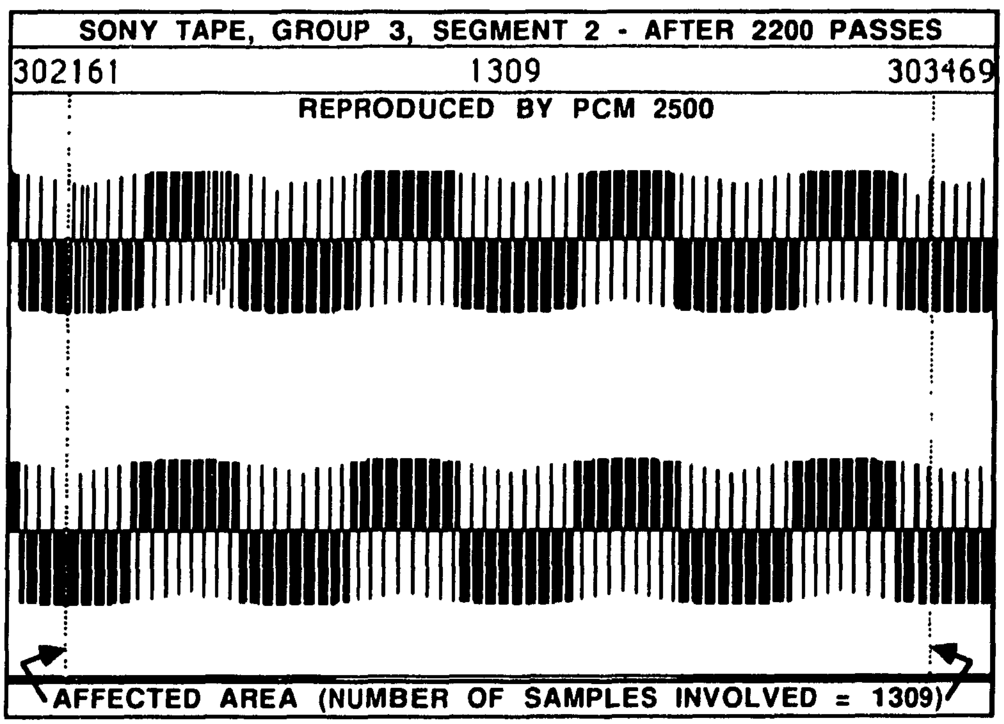


FIGURE 18



ENLARGEMENT OF A SECTION FROM FIGURE 18

FIGURE 19

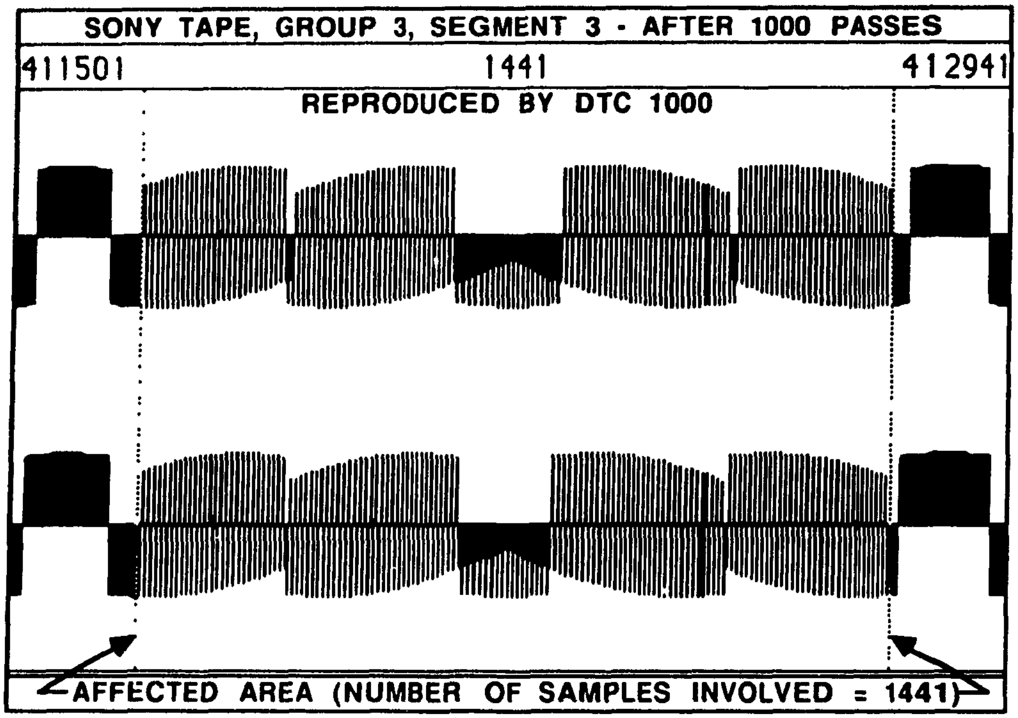


FIGURE 20

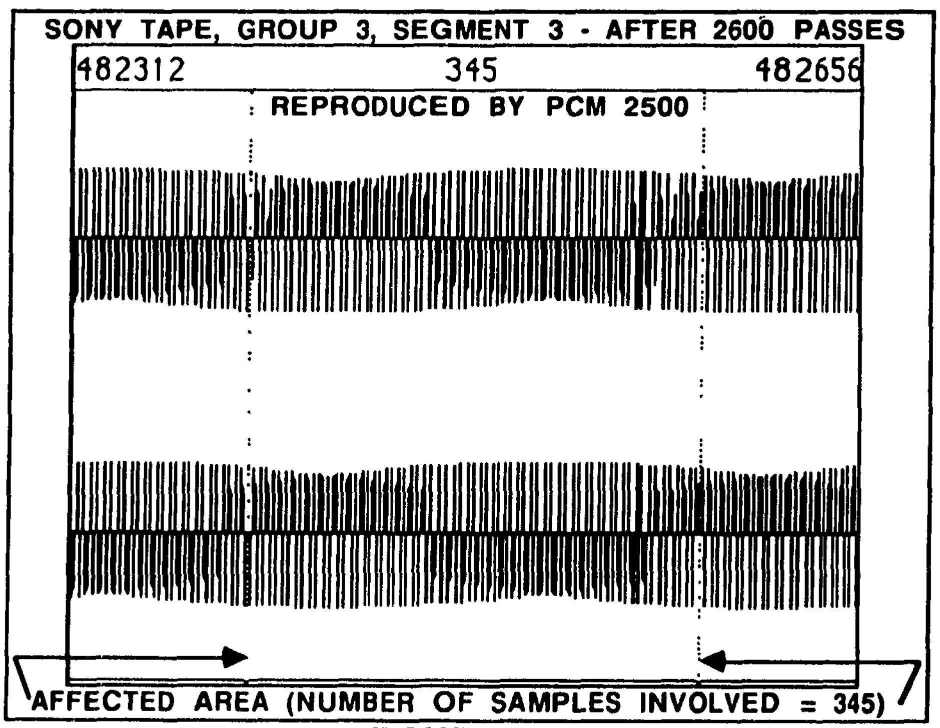


FIGURE 21

A part of the subjective listening test was designed to evaluate possible variations in capabilities of two different R-DAT recorders to correct dropouts. One recorder (PCM 2500) was used to record the original test sequence on each tape; the other (DTC 1000) was used for the mechanical stress testing. Results of this part of the subjective evaluation are shown in Table 9.

LISTENING TEST RESULTS OF SEGMENTS WITH DROPOUTS AS REPRODUCED BY DIFFERENT R-DAT RECORDERS

		SAME	2 BETTER	2 WORSE
AMPEX 467 TAPE, GROUP 2, SEGMENT 3				
REPRODUCED BY DTC 1000 RECORDER.	After 1800 passes.	**100%**	-	-
	After 2000 passes:	-	-	**100%**
REPRODUCED BY PCM 2500 RECORDER:	After 2000 passes:	-	-	**100%**
AGFA TAPE, GROUP 1, SEGMENT 3		SAME	2 BETTER	2 WORSE
REPRODUCED BY DTC 1000 RECORDER.	After 1600 passes:	**92%**	-	8%
	After 1800 passes.	-	-	**100%**
REPRODUCED BY PCM 2500 RECORDER	After 1800 passes.	-	-	**100%**
AGFA TAPE, GROUP 3, SEGMENT 3		SAME	2 BETTER	2 WORSE
REPRODUCED BY DTC 1000 RECORDER	After 600 passes	**100%**	-	-
	After 800 passes.	-	-	**100%**
REPRODUCED BY PCM 2500 RECORDER	After 800 passes.	-	-	**100%**
SONY TAPE, GROUP 1, SEGMENT 3		SAME	2 BETTER	2 WORSE
REPRODUCED BY DTC 1000 RECORDER	After 200 passes	**92%**	8%	-
	After 400 passes	-	-	**100%**
REPRODUCED BY PCM 2500 RECORDER	After 400 passes	**92%**	8%	-
	After 2600 passes	**92%**	8%	-
SONY TAPE, GROUP 2, SEGMENT 3		SAME	2 BETTER	2 WORSE
REPRODUCED BY DTC 1000 RECORDER.	After 1400 passes	**100%**	-	-
	After 1600 passes	-	-	**100%**
REPRODUCED BY PCM 2500 RECORDER.	After 1600 passes	-	-	**100%**
SONY TAPE, GROUP 3, SEGMENT 2		SAME	2 BETTER	2 WORSE
REPRODUCED BY DTC 1000 RECORDER	After 1400 passes	**92%**	8%	-
	After 1600 passes	-	-	**100%**
REPRODUCED BY PCM 2500 RECORDER	After 1600 passes	**92%**	8%	-
	After 2200 passes	-	-	**100%**
SONY TAPE, GROUP 3, SEGMENT 3		SAME	2 BETTER	2 WORSE
REPRODUCED BY DTC 1000 RECORDER	After 800 passes.	**92%**	8%	-
	After 1000 passes	-	-	**100%**
REPRODUCED BY PCM 2500 RECORDER	After 1000 passes:	**92%**	-	8%
	After 2600 passes	-	-	**100%**

NOTE: Bold framed box indicates objective findings from Dyaxis DAW display
INTERPRETATION 97% OF SUBJECTS AGREE WITH OBJECTIVE FINDINGS

TABLE 9

As can be seen in Table 9, 97% of subjects are in agreement with objective data as displayed by Dyaxis DAW. The Dyaxis displays are shown in Figures 14-21, shown previously, and Figures 22-27 below. With the exception of segments on Sony tapes discussed above, only segment 3, on Agfa tape in group 3, shows some data correction improvement when reproduced by the same R-DAT recorder that was used to record it. Two other segments show larger areas and more severe damage of data affected by dropouts when reproduced by the same recorder that recorded the sequence. (See Figures 22, 23, 24, 25) Furthermore, the segments which actually got corrected had areas affected by dropouts of less than 1500 samples. Thus, it is plausible to suggest that the size of the area affected by dropouts may be the main determining factor in successful data correction, while the influence of the recorder's relation to the data may be minimal.

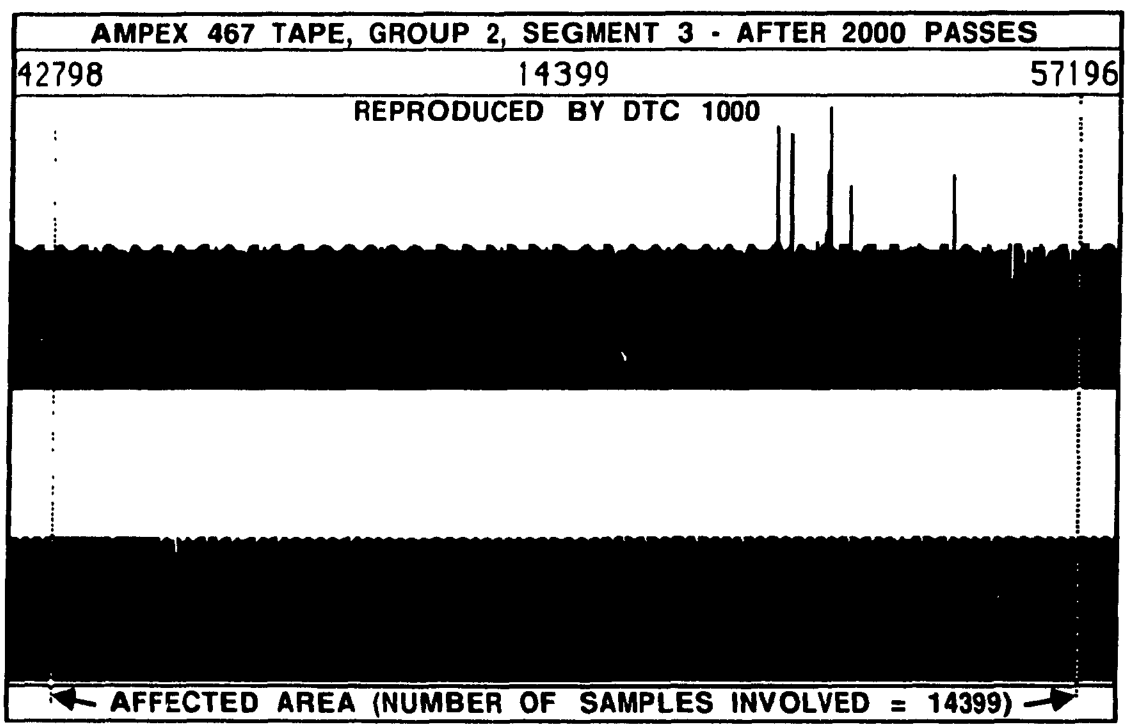


FIGURE 22

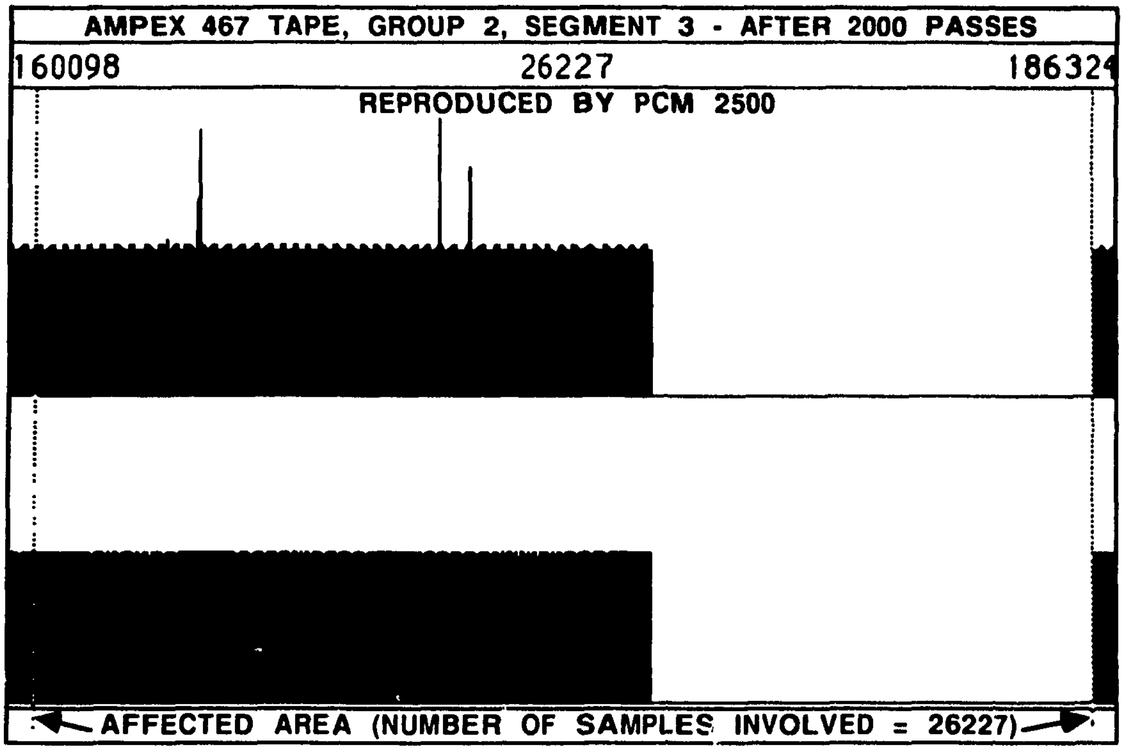


FIGURE 23

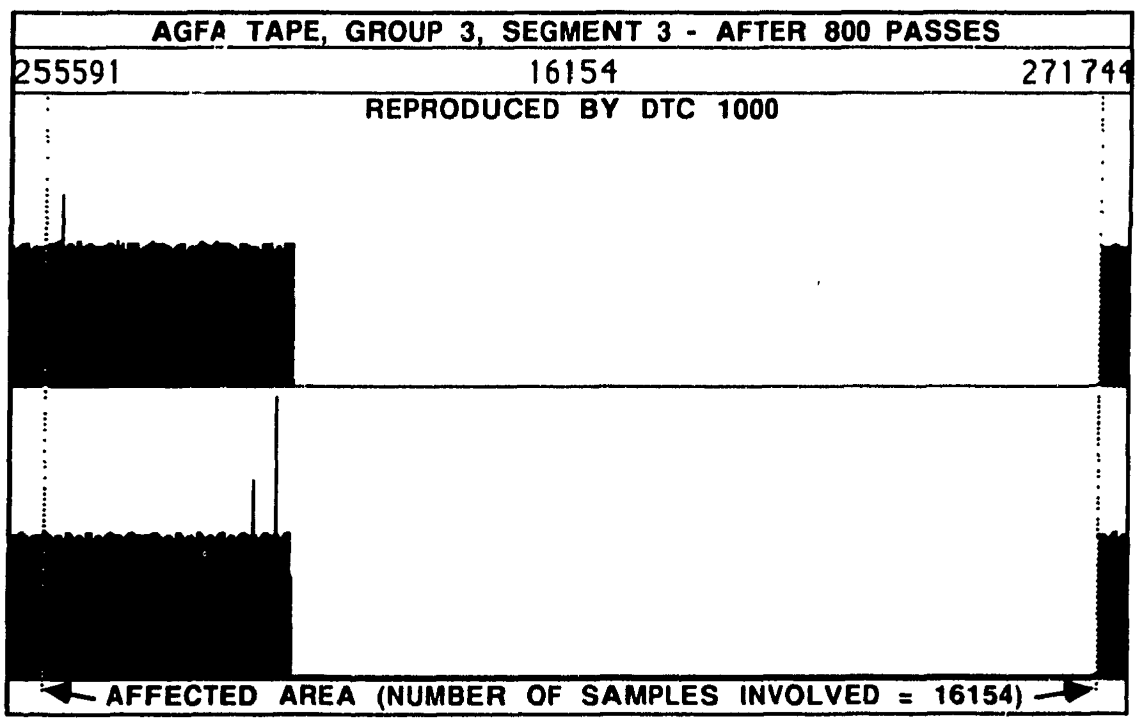


FIGURE 24

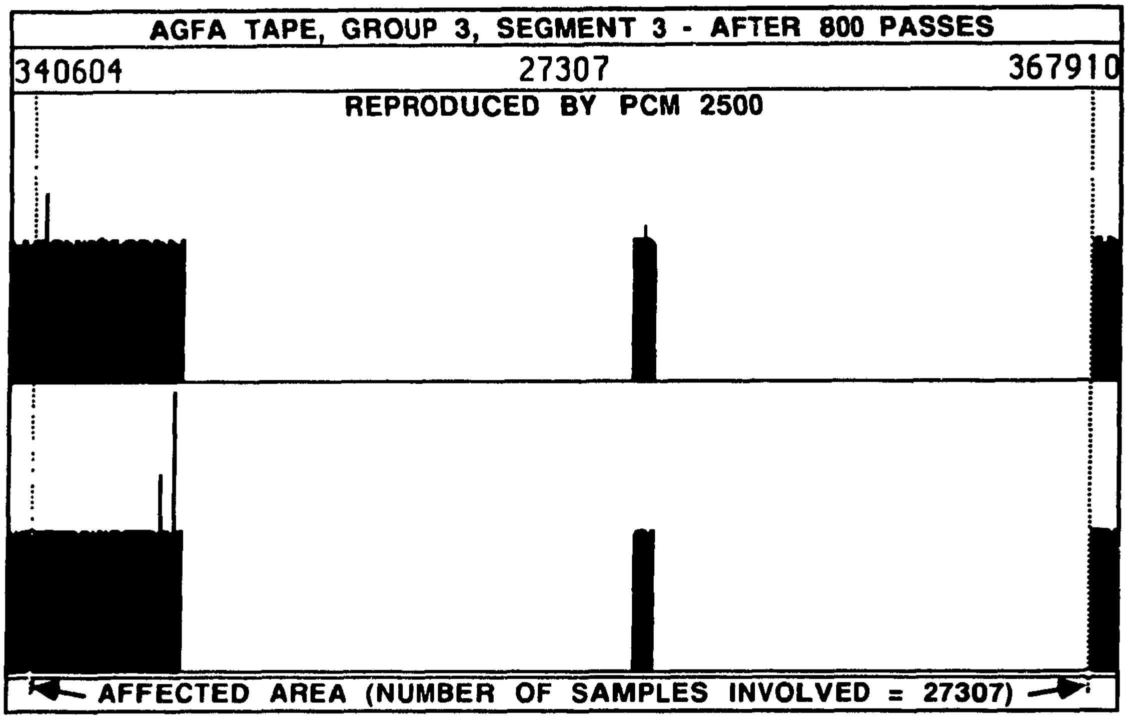


FIGURE 25

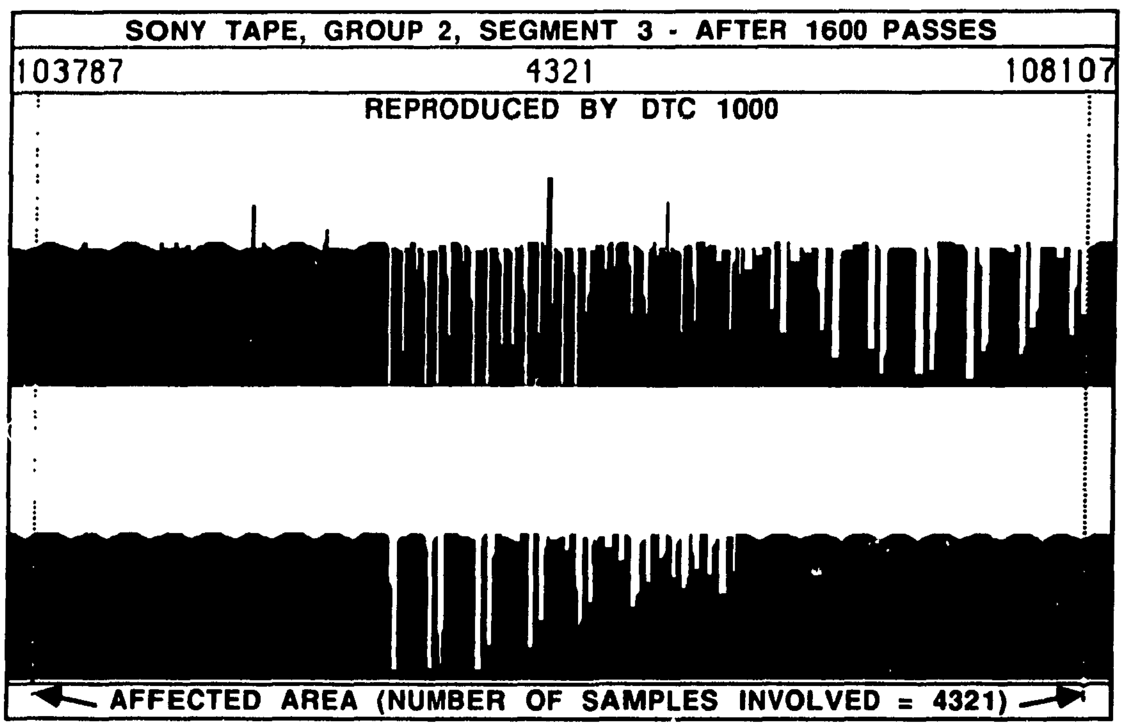


FIGURE 26

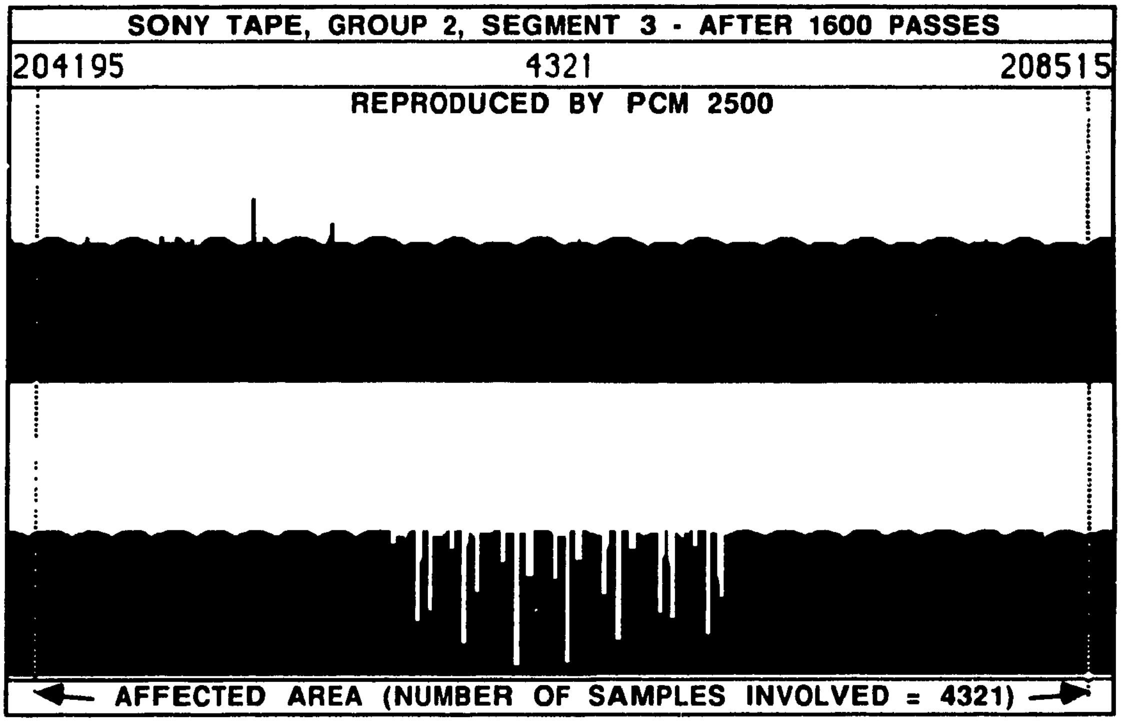


FIGURE 27

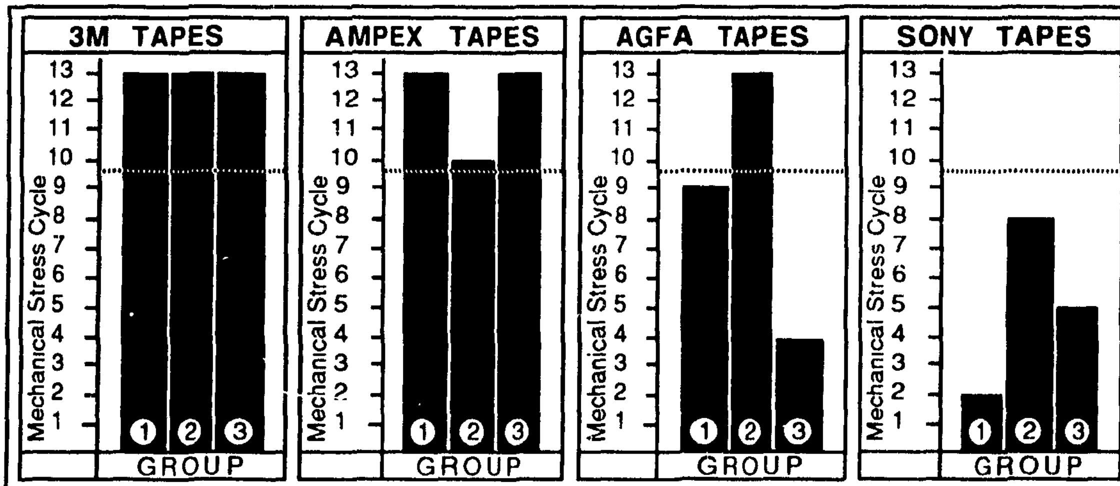
With the exception of the cases discussed above, the data obtained from the error correction indicators on PCM 2500 R-DAT recorder corroborate other objective data, as well as results of the subjective listening test for all remaining segments. The annotated data of the error correction display activity were assembled into charts and are shown in full in the Appendix C. A study of these charts did not give any evidence that dropouts could be anticipated through observation of the error correction activity, as no increase in error correction activity prior to the occurrence of apparent dropouts could be found. The subjective listening test results support these findings as progressive deterioration of data was not observed by subjects before an audible dropout could be detected. (See Table 9)

One striking feature in these charts is the significant difference in error correction activity between two segments (segments 5 and 6) appropriated to delve into overwrite function performance. Segment 6, which was not reproduced in between the data being overwritten, had almost three times as many correction indications as segment 5. This is believed to be caused by the following: The roughness of tape surface was basically unaffected in segment 6; but, in segment 5 the tape surface was made smoother as the heads kept polishing the surface during reproductions. Therefore, when the data was overwritten, better interface between the tape and the heads in segment 5 resulted in the lower error count.

Prior to the commencement of mechanical and environmental stress exposure, a possible increase in friction torque during tape running was investigated. All tapes were fast wound and rewound ten times and the duration of each operation was timed. No significant increases in time needed to wind the tapes were observed, even though small variations in time occurred from cycle to cycle. In general, the time needed to wind the tapes tended to decrease as the experiment progressed; thus, no increase in friction torque was encountered.

Dropouts apart, other reliability concerns ought to be mentioned. Some problems were encountered with loading of Ampex 467 tapes into R-DAT recorders, as these tended to be rejected by the loading mechanism. Occasionally, the loading had to be attempted more than twice before the cassette would be drawn in, lowered onto the transport mechanism, and the tape drawn out successfully. Both recorders that were used during the study experienced loading difficulties with this particular brand of tape. The cause of the problem was not investigated as a number of aspects, such as shell dimension tolerances, would have to be considered. In addition to the loading problem, one Ampex tape that was to be used for back up and was not involved in the study, broke up while being rewound.

A reliable performance of individual tapes throughout the study was achieved in only half of the tapes involved. All 3M tapes, two Ampex tapes, and one Agfa tape completed 2600 passes of mechanical stress without an apparent loss of data. The remaining tapes failed at various stages of the experiment. On average, a tape withstood 1933 passes before it would fail. This average tape failure point was calculated from the combined performances of all tapes and cannot be interpreted as an indicator of tape durability in general terms. It serves here only as a denominator of above and below average tape performance. (See Figure 28)



NOTE The dotted line shows the average tape performance, as derived from combined performances of all tapes in the experiment

FIGURE 28

As shown in the figure above, only two brands of tape, 3M and Ampex, performed above the average failure point while the performance of the other two brands of tape, Agfa and Sony, was well below the average. However, this data is relevant to this study only and cannot be used to evaluate the performance of these particular brands of tape in general terms The tapes in this study were exposed to amounts of stress unparalleled by any professional usage, and it may well be that all of these brands of tape will perform reliably in all professional applications. Therefore, it is just within the context of this study that it can be said that only 3M tapes are considered reliable, as they showed no apparent data loss at the conclusion of testing. As only one of three Ampex tapes failed the rigorous testing after it reliably completed 75% of the total mechanical stress test, the performance of Ampex tapes is considered adequate. Two out of three Agfa tapes and all three Sony tapes failed to withstand at least 75% of the mechanical stress exposure. Thus, both brands are herein considered unreliable.

The performance of individual groups, as related to various stress exposures, did not reveal any of the stresses or their combinations to be specifically detrimental to the media failure. In all three groups, 50% of tapes failed. Therefore, no conclusive evidence indicating that one particular kind of stress or their combinations is more harmful to the media can be presented here. Statistical analysis of the average failure point for each group shows that tapes in group 1 completed 1850 passes, tapes in group 2 completed 2200 passes, and tapes in group 3 completed 1750 passes before failing.

The fact that all but one of the apparent dropouts occurred in third segments, about 1 5 seconds from the beginning of this segment, is rather significant It seems that a single mechanical part within the transport assembly mechanism of the R-DAT recorder, or the cassette itself, is responsible for inflicting the damage. An attempt to investigate the problem was made, but the offending part could not be located as the tape path was obscured by the loading mechanism. Unfortunately, the tape path could be accessed only if parts of the loading and transport assemblies were removed. Although the search had to be abandoned, the suspicion that the excessive friction is caused by the rubbing of tape over a single edge or mechanical part remains. Should this be confirmed, it could imply that the quality of the transport assembly mechanism was the key factor in the reliability results of this study.

Finally, another aspect which may have influenced the outcome of this study was the rewind search mode of operation. Two speeds were found to be employed in the rewind search operation, one slower and one faster. The slower speed was activated automatically when the ID point being searched was within thirty seconds of the current tape position. As the recorded test sequence was 30 seconds long, it was the slower speed that was activated when the "search previous ID" button was pressed after a reproduction pass. Therefore, the tapes were not exposed to the maximum mechanical stress which could be exerted by the R-DAT recorders.

Conclusions and recommendations

This research was concerned with an examination of the reliability of R-DAT recording media in regard to professional and archival applications. Four brands of R-DAT tapes were subjected to mechanical stress, environmental stress, and a combination of both the mechanical and environmental stresses. Data generated from these tests was analyzed objectively, subjectively evaluated, and subsequently compared.

Only one brand of tape did not exhibit apparent deterioration of data after being subjected to mechanical and/or environmental stress. The other three brands of tapes failed at various points throughout the testing. Thus, only one brand of tape was ranked as being 100% reliable, this being 3M.

One failure per tape was found on: Ampex 467 tape in group 2, Agfa tapes in groups 1 and 3, and Sony tapes in groups 1 and 2. Sony tape in group 3 failed twice. As only one in three Ampex tapes failed after withstanding more than 75% of the mechanical stress, the performance of Ampex brand of tape was ranked as adequate Agfa and Sony brands of tape were ranked as unreliable. However, this ranking cannot be extended beyond this study, as the stress exposure in this experiment was well in excess of the stresses involved in standard professional applications

It was found that variations in durability exist not only among brands of tape, but also among tapes of the same brand. Although each tape in a brand was subjected to a different combination of stresses, the fact that all stress related groups of tapes had an equal number of tapes that failed is indicative of variations in quality among tapes of the same brand. It is therefore recommended that some meaningful standardized test procedure to alleviate these variations be undertaken by the tape manufacturers. It is understood that such testing would increase the retail price of the media, but it could be expected that users requiring a reliability certification would absorb the price increase in exchange for guaranteed quality.

As six out of seven apparent dropouts observed in this study were found to be at the same place on each tape, it was suggested that some part of the transport mechanism is responsible. Thus, the reliability of tapes is also closely linked to the state, the quality, or the design of transport mechanism in a particular R-DAT recorder. Should these implications be substantiated, the individual R-DAT hardware manufacturers and service would require a stepped up quality control of individual parts or, changes in the design of involved assemblies or parts that are destined for professional users.

Following the reliability testing, the tapes were stored in a room environment. The stability of data was verified after six months of storage No further deterioration of audio output was observed. Thus, longer storage periods are required in order to generate data indicative of media's archival suitability.

Comparisons of data generated by subjective and objective methods were made. It was shown that in the majority of cases, the subjective evaluation results corroborate the objective findings. In cases where inconsistencies in the data were apparent, explanations of possible causes were provided

The limitations of this study were threefold. First, the state of the equipment used in this research presented an uncontrolled variable in that it might have impacted upon results in either positive or negative ways Second, the existing body of literature pertaining to investigation of the thesis topic is small While this portends potential benefits to the production of hypothesis generating research, hypothesis testing research, such as this study, can be adversely affected by uninvestigated, unknown variables. The third limitation upon this research was that of financial constraints. While it would be preferable to use a variety of R-DAT recorders to mitigate the aforementioned uncontrollable equipment variable, this was not possible due to budgetary concerns.

In summation, it can be said that performance results of the tested media exceeded expectations and, in a majority of cases, the results were better than tape manufacturers' representatives anticipated. The final recommendation of this study is that further research is needed. This should focus on R-DAT media with the new and improved tape formulations and R-DAT recorders with confidence play back heads, available in today's market. The suitability of R-DAT media for archival applications must be examined on a long term basis in order to provide industry professionals with data that will facilitate the decision making process regarding R-DAT media's future role in audio and data storage industries

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I. ARTICLES

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4. INTERVIEWS

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Syracuse University

Wickstrom, David

Senior Audio Engineer

Belfer Audio Laboratory and Archive

Syracuse University

Appendixes

APPENDIX A

SUBJECTIVE LISTENING TEST

First name

Family name

Sex [M] [F] Age

Occupation

If student. Degree sought . year

Music training. [Yes] [No]

If Yes Specialty and/or instrument

Years of training

Professional music experience [Yes] [No]

If Yes: Years of experience

Sound engineering experience [Yes] [No]

If Yes Years of experience

Type of headphones used

TEST RUN

INSTRUCTIONS: In "2 BETTER" or "2 WORSE" below, the "2" refers to the second tone in the pair having a better or a worse sound quality. If there is no difference in sound quality between the first and second tones, they are "SAME". Please check the appropriate box.

1. Pair of tones are [SAME] [2 BETTER] [2 WORSE] **2.** Pair of tones are [SAME] [2 BETTER] [2 WORSE]

3. Pair of tones are [SAME] [2 BETTER] [2 WORSE] **4.** Pair of tones are [SAME] [2 BETTER] [2 WORSE]

Next page

PART 1

1. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
2. Pair of tones are. [SAME] [2 BETTER] [2 WORSE]
3. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
4. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
5. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
6. Pair of tones are. [SAME] [2 BETTER] [2 WORSE]
7. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
8. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
9. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
10. Pair of tones are: [SAME] [2 BETTER] [2 WORSE]
11. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
12. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
13. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
14. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
15. Pair of tones are [SAME] [2 BETTER] [2 WORSE]

PART 2

1. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
2. Pair of tones are. [SAME] [2 BETTER] [2 WORSE]
3. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
4. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
5. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
6. Pair of tones are: [SAME] [2 BETTER] [2 WORSE]
7. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
8. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
9. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
10. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
11. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
12. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
13. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
14. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
15. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
16. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
17. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
18. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
19. Pair of tones are [SAME] [2 BETTER] [2 WORSE]

PART 3

1. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
2. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
3. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
4. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
5. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
6. Pair of tones are. [SAME] [2 BETTER] [2 WORSE]
7. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
8. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
9. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
10. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
11. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
12. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
13. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
14. Pair of tones are. [SAME] [2 BETTER] [2 WORSE]
15. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
16. Pair of tones are [SAME] [2 BETTER] [2 WORSE]
17. Pair of tones are [SAME] [2 BETTER] [2 WORSE]

Next page

PART 4

1. Pair of excerpts are SAME 2 BETTER 2 WORSE
2. Pair of excerpts are SAME 2 BETTER 2 WORSE
3. Pair of excerpts are SAME 2 BETTER 2 WORSE
4. Pair of excerpts are SAME 2 BETTER 2 WORSE
5. Pair of excerpts are SAME 2 BETTER 2 WORSE
6. Pair of excerpts are SAME 2 BETTER 2 WORSE
7. Pair of excerpts are SAME 2 BETTER 2 WORSE
8. Pair of excerpts are SAME 2 BETTER 2 WORSE
9. Pair of excerpts are SAME 2 BETTER 2 WORSE
10. Pair of excerpts are SAME 2 BETTER 2 WORSE
11. Pair of excerpts are SAME 2 BETTER 2 WORSE
12. Pair of excerpts are SAME 2 BETTER 2 WORSE

PART 5

1. Pair of tones are SAME 2 BETTER 2 WORSE
2. Pair of tones are SAME 2 BETTER 2 WORSE
3. Pair of tones are SAME 2 BETTER 2 WORSE
4. Pair of tones are SAME 2 BETTER 2 WORSE
5. Pair of tones are SAME 2 BETTER 2 WORSE
6. Pair of tones are SAME 2 BETTER 2 WORSE
7. Pair of tones are SAME 2 BETTER 2 WORSE
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14. Pair of tones are SAME 2 BETTER 2 WORSE
15. Pair of tones are SAME 2 BETTER 2 WORSE
16. Pair of tones are SAME 2 BETTER 2 WORSE
17. Pair of tones are SAME 2 BETTER 2 WORSE
18. Pair of tones are SAME 2 BETTER 2 WORSE
19. Pair of tones are SAME 2 BETTER 2 WORSE
20. Pair of tones are SAME 2 BETTER 2 WORSE
21. Pair of tones are SAME 2 BETTER 2 WORSE
22. Pair of tones are SAME 2 BETTER 2 WORSE
23. Pair of tones are SAME 2 BETTER 2 WORSE
24. Pair of tones are SAME 2 BETTER 2 WORSE
25. Pair of tones are SAME 2 BETTER 2 WORSE
26. Pair of tones are SAME 2 BETTER 2 WORSE

PART 6

1. Pair of tones are SAME 2 BETTER 2 WORSE
2. Pair of tones are SAME 2 BETTER 2 WORSE
3. Pair of tones are SAME 2 BETTER 2 WORSE
4. Pair of excerpts are SAME 2 BETTER 2 WORSE
5. Pair of tones are SAME 2 BETTER 2 WORSE
6. Pair of tones are SAME 2 BETTER 2 WORSE
7. Pair of tones are SAME 2 BETTER 2 WORSE
8. Pair of tones are SAME 2 BETTER 2 WORSE
9. Pair of tones are SAME 2 BETTER 2 WORSE
10. Pair of excerpts are SAME 2 BETTER 2 WORSE
11. Pair of tones are SAME 2 BETTER 2 WORSE
12. Pair of tones are SAME 2 BETTER 2 WORSE

Next page

PART 7

1. Pair of tones are SAME 2 BETTER 2 WORSE
2. Pair of tones are: SAME 2 BETTER 2 WORSE
3. Pair of tones are SAME 2 BETTER 2 WORSE
4. Pair of excerpts are SAME 2 BETTER 2 WORSE
5. Pair of tones are SAME 2 BETTER 2 WORSE
6. Pair of tones are. SAME 2 BETTER 2 WORSE
7. Pair of tones are SAME 2 BETTER 2 WORSE
8. Pair of tones are. SAME 2 BETTER 2 WORSE
9. Pair of tones are SAME 2 BETTER 2 WORSE
10. Pair of excerpts are SAME 2 BETTER 2 WORSE
11. Pair of tones are SAME 2 BETTER 2 WORSE
12. Pair of tones are SAME 2 BETTER 2 WORSE

PART 8

1. Pair of tones are SAME 2 BETTER 2 WORSE
2. Pair of tones are SAME 2 BETTER 2 WORSE
3. Pair of tones are SAME 2 BETTER 2 WORSE
4. Pair of excerpts are SAME 2 BETTER 2 WORSE
5. Pair of tones are SAME 2 BETTER 2 WORSE
6. Pair of tones are SAME 2 BETTER 2 WORSE
7. Pair of tones are SAME 2 BETTER 2 WORSE
8. Pair of tones are SAME 2 BETTER 2 WORSE
9. Pair of tones are SAME 2 BETTER 2 WORSE
10. Pair of excerpts are SAME 2 BETTER 2 WORSE
11. Pair of tones are SAME 2 BETTER 2 WORSE
12. Pair of tones are SAME 2 BETTER 2 WORSE

PART 9

1. Pair of tones are SAME 2 BETTER 2 WORSE
2. Pair of tones are SAME 2 BETTER 2 WORSE
3. Pair of tones are SAME 2 BETTER 2 WORSE
4. Pair of excerpts are SAME 2 BETTER 2 WORSE
5. Pair of tones are SAME 2 BETTER 2 WORSE
6. Pair of tones are SAME 2 BETTER 2 WORSE
7. Pair of tones are SAME 2 BETTER 2 WORSE
8. Pair of tones are SAME 2 BETTER 2 WORSE
9. Pair of tones are SAME 2 BETTER 2 WORSE
10. Pair of excerpts are SAME 2 BETTER 2 WORSE
11. Pair of tones are SAME 2 BETTER 2 WORSE
12. Pair of tones are SAME 2 BETTER 2 WORSE

PART 10

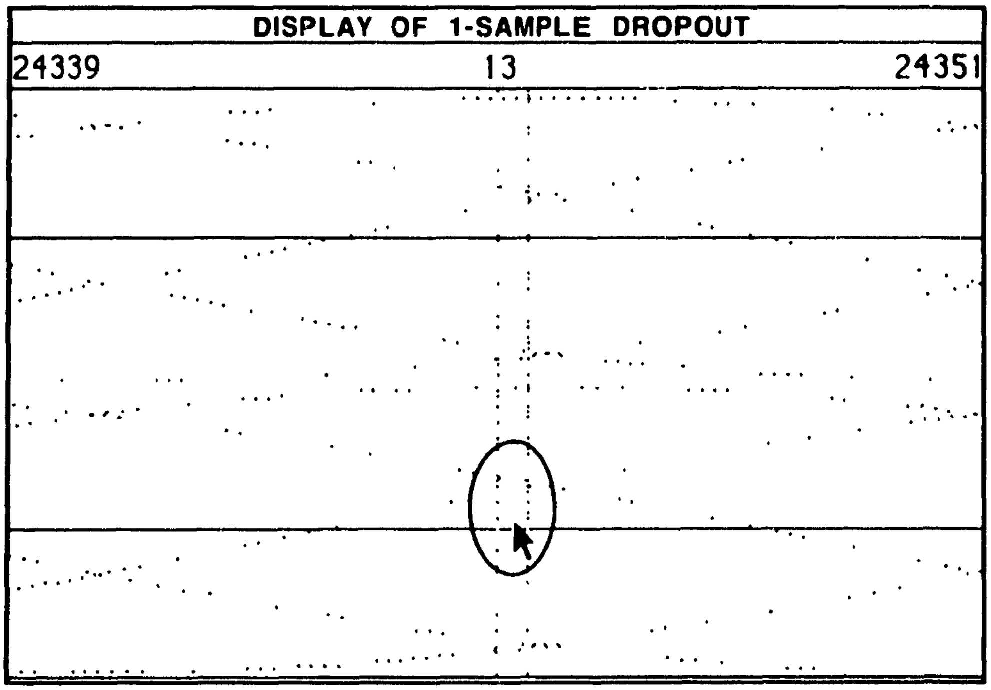
1. Pair of tones are SAME 2 BETTER 2 WORSE
2. Pair of tones are SAME 2 BETTER 2 WORSE
3. Pair of tones are SAME 2 BETTER 2 WORSE
4. Pair of excerpts are SAME 2 BETTER 2 WORSE
5. Pair of tones are SAME 2 BETTER 2 WORSE
6. Pair of tones are SAME 2 BETTER 2 WORSE
7. Pair of tones are SAME 2 BETTER 2 WORSE
8. Pair of tones are SAME 2 BETTER 2 WORSE
9. Pair of tones are SAME 2 BETTER 2 WORSE
10. Pair of excerpts are SAME 2 BETTER 2 WORSE
11. Pair of tones are SAME 2 BETTER 2 WORSE
12. Pair of tones are SAME 2 BETTER 2 WORSE

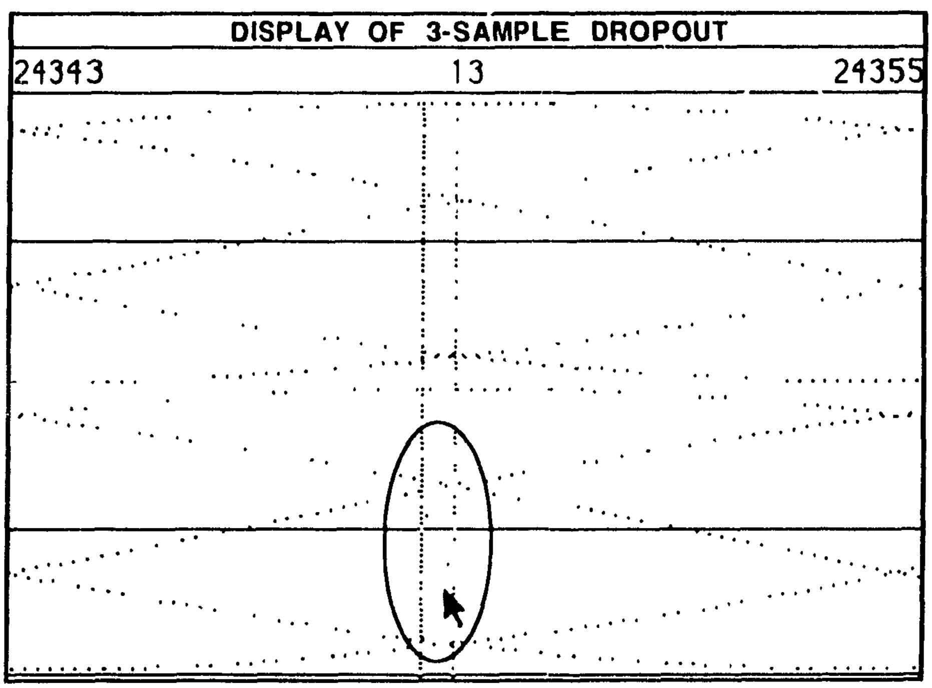
PART 11

1. Pair of tones are SAME 2 BETTER 2 WORSE
2. Pair of tones are SAME 2 BETTER 2 WORSE
3. Pair of tones are SAME 2 BETTER 2 WORSE
4. Pair of excerpts are SAME 2 BETTER 2 WORSE
5. Pair of tones are SAME 2 BETTER 2 WORSE
6. Pair of tones are SAME 2 BETTER 2 WORSE
7. Pair of tones are SAME 2 BETTER 2 WORSE
8. Pair of tones are SAME 2 BETTER 2 WORSE
9. Pair of tones are SAME 2 BETTER 2 WORSE
10. Pair of excerpts are SAME 2 BETTER 2 WORSE
11. Pair of tones are SAME 2 BETTER 2 E
12. Pair of tones are SAME 2 BETTER 2 WORSE

Thank you for your cooperation!

APPENDIX B

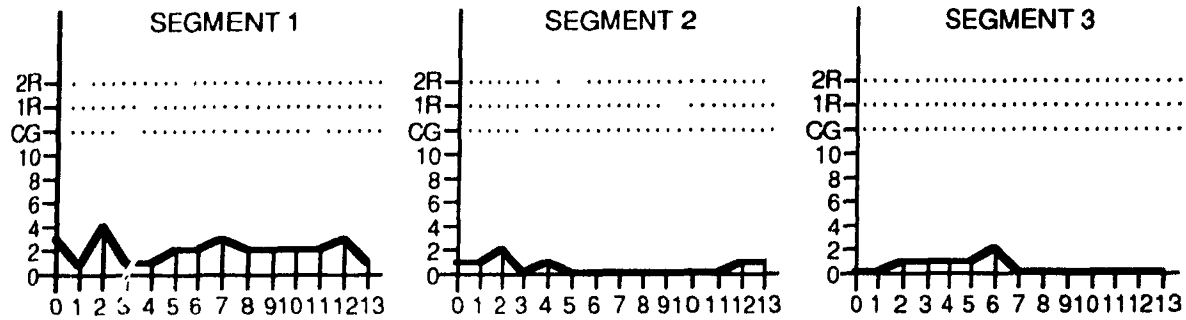

DISPLAY OF 1-SAMPLE DROPOUT
24339
13
24351


DISPLAY OF 3-SAMPLE DROPOUT
24343
13
24355

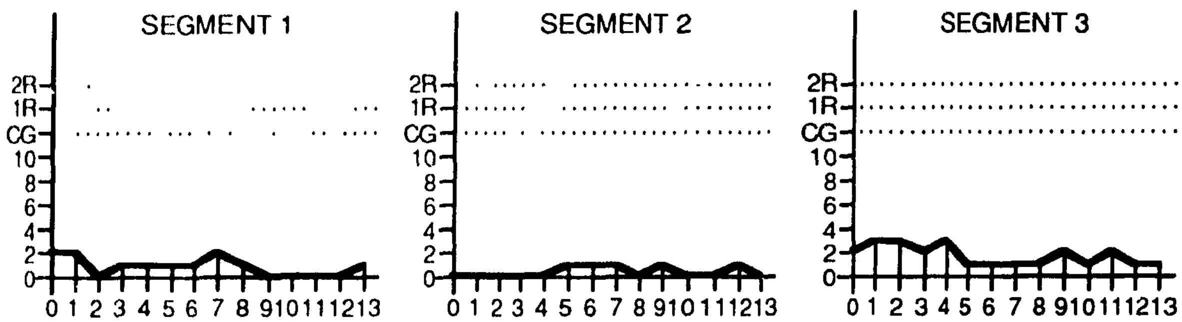
APPENDIX C

PCM 2500 ERROR CORRECTION DISPLAY CHART
3M TAPE: SEGMENT 1-3

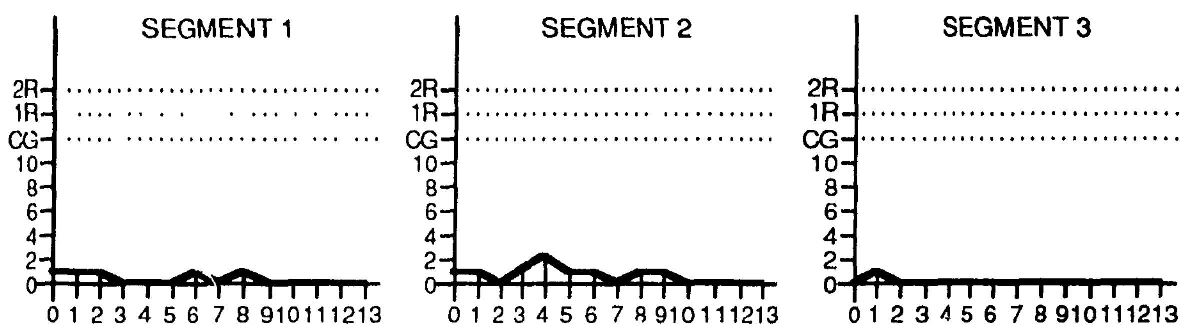
GROUP 1:



GROUP 2:



GROUP 3:



KEY:

2R = TWO RED - Red LED displays interpolation. Twice flashing red LED can indicate a mute outlined by interpolations

1R = ONE RED - Uncorrectable error is concealed by interpolation.

CG = CONTINUOUS GREEN - Green LED displays error correction The LED was continuosly lit from 1 to 2 seconds

Numbers 0-12 on the vertical axis - Number of individual green LED flashes (corrections).

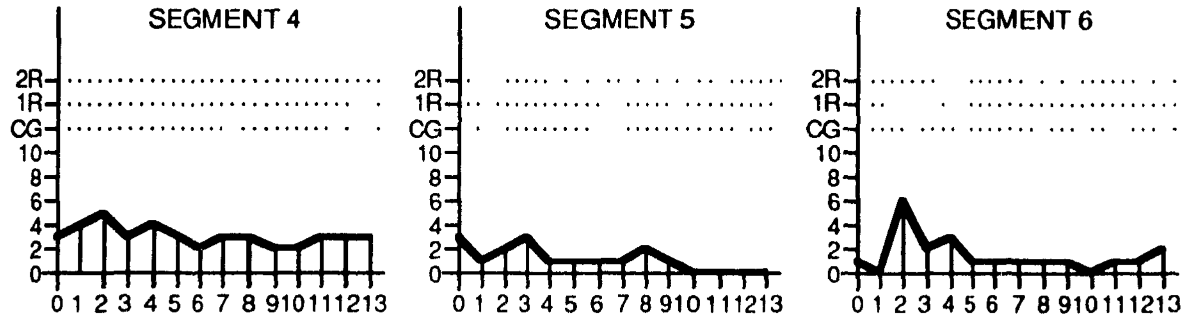
Number 0 on the horizontal axis - Activity of error display LEDs anotated before the tape was exposed to any stress

Numbers 1-13 on the horizontal axis = NUMBER OF MECHANICAL STRESS CYCLES - Activity of error display LEDs anotated after individual mechanical stress cycles

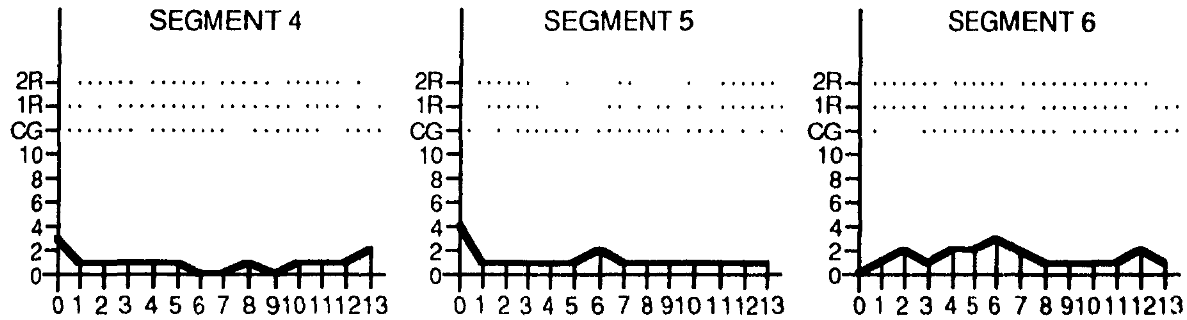
PCM 2500 ERROR CORRECTION DISPLAY CHART

3M TAPE: SEGMENT 4-6

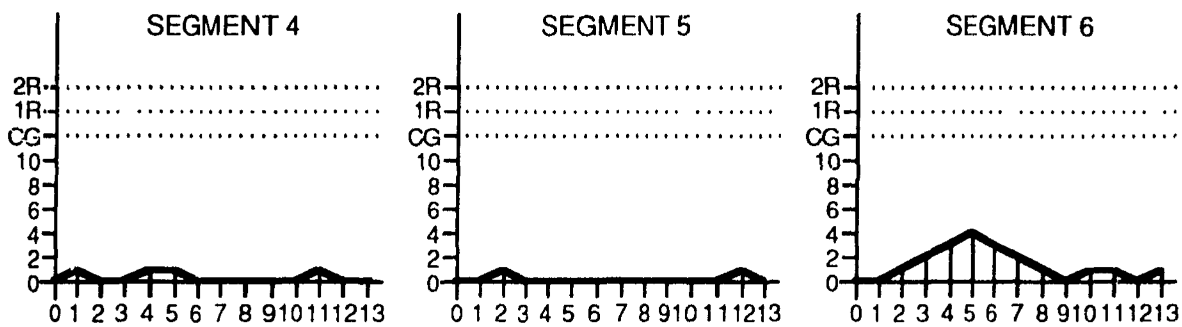
GROUP 1:



GROUP 2:



GROUP 3:



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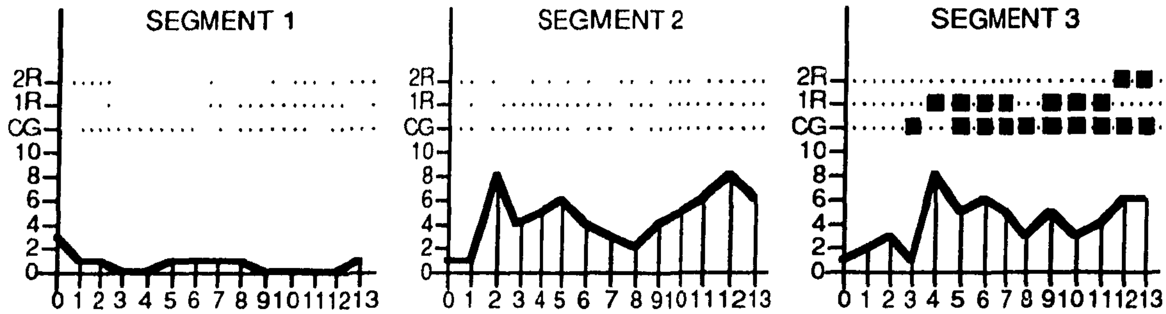
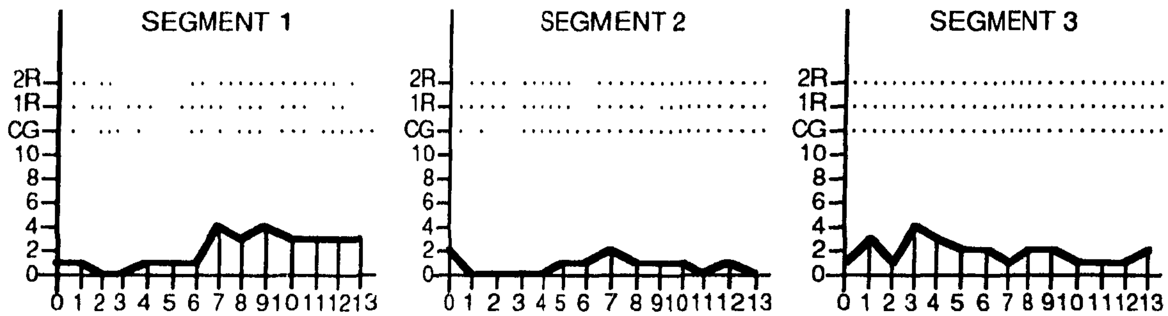
PCM 2500 ERROR CORRECTION DISPLAY CHART
AGFA TAPE: SEGMENT 1-3

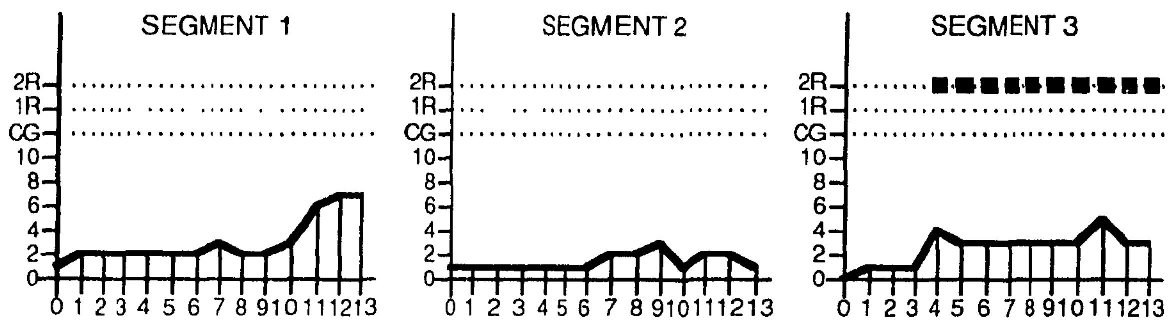
GROUP 1:



GROUP 2:



GROUP 3:



KEY:

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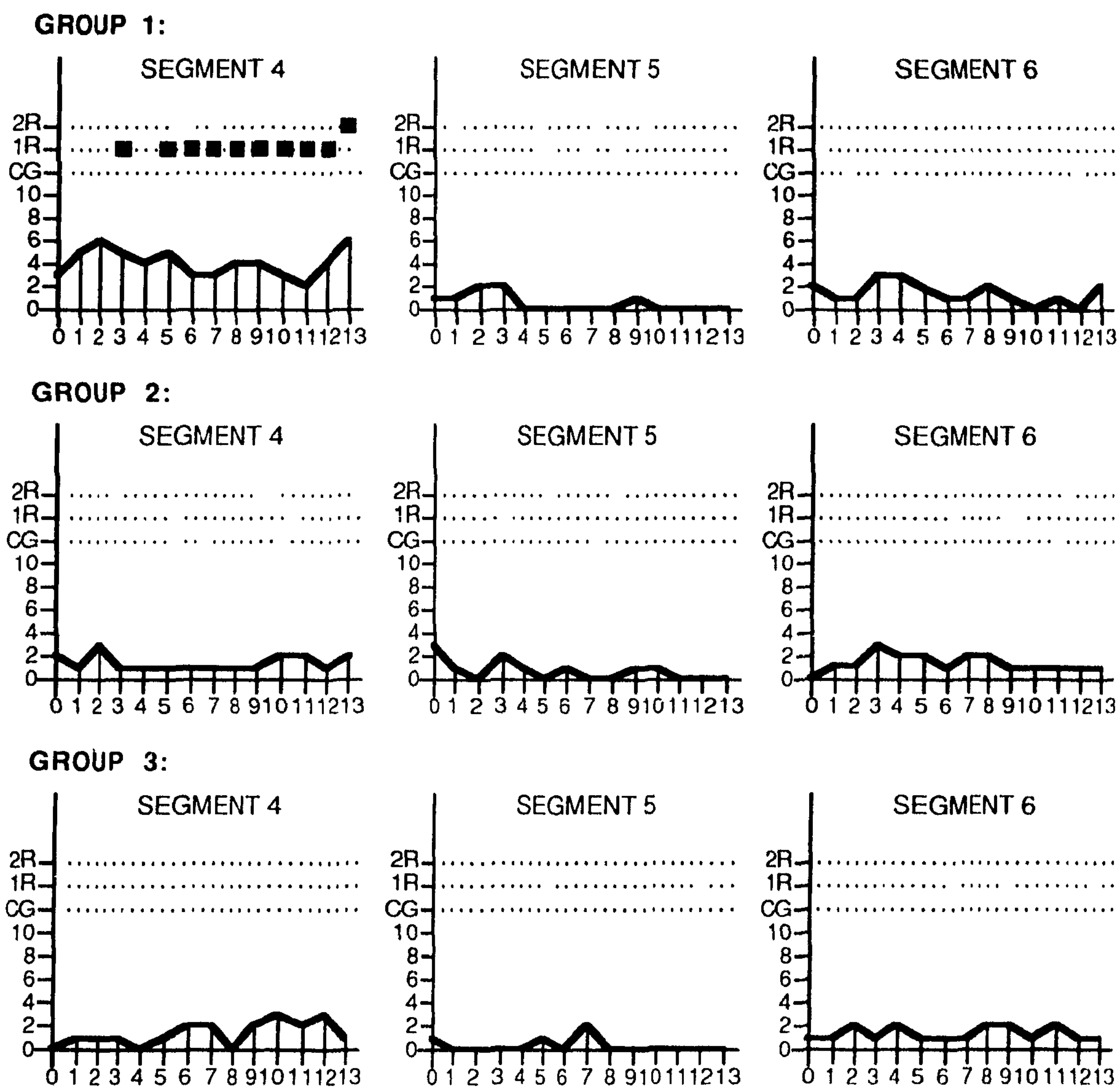
PCM 2500 ERROR CORRECTION DISPLAY CHART

AGFA TAPE: SEGMENT 4-6



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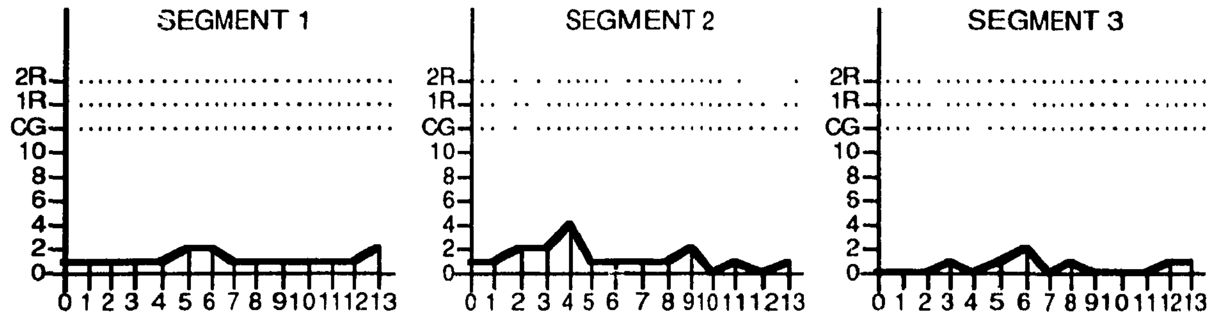
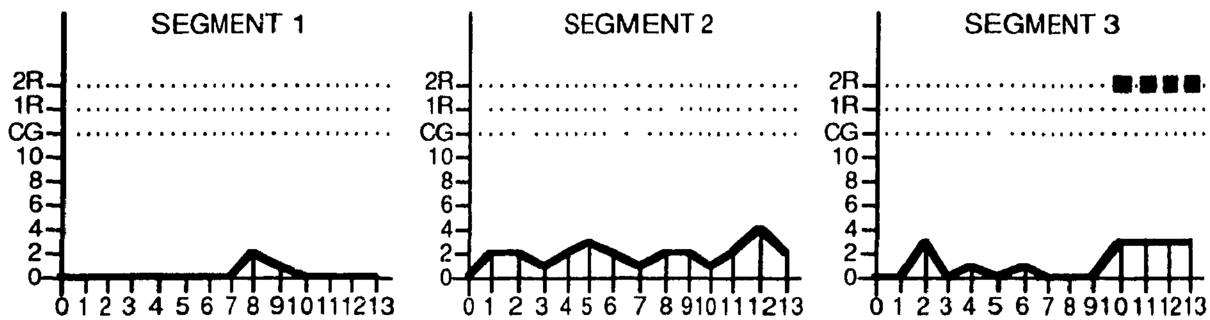
PCM 2500 ERROR CORRECTION DISPLAY CHART
AMPEX TAPE: SEGMENT 1-3

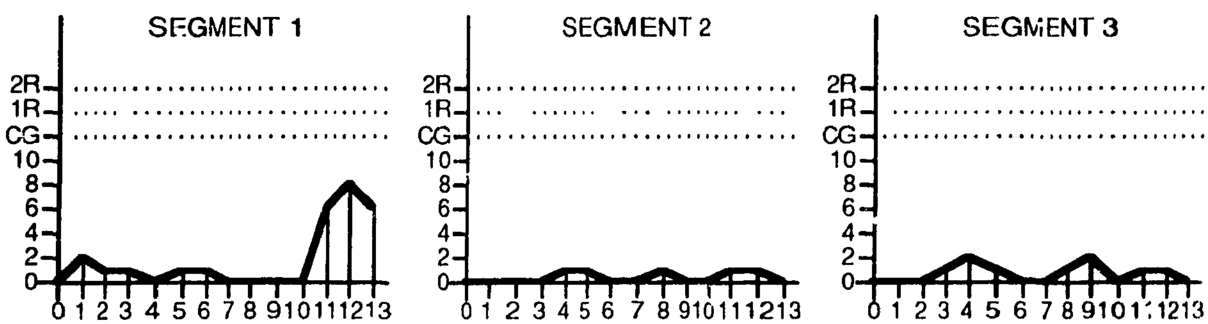
GROUP 1:



GROUP 2:



GROUP 3:



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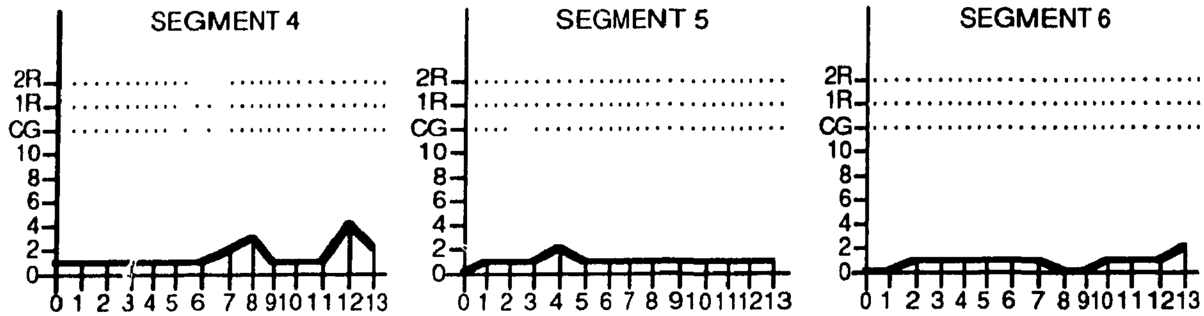
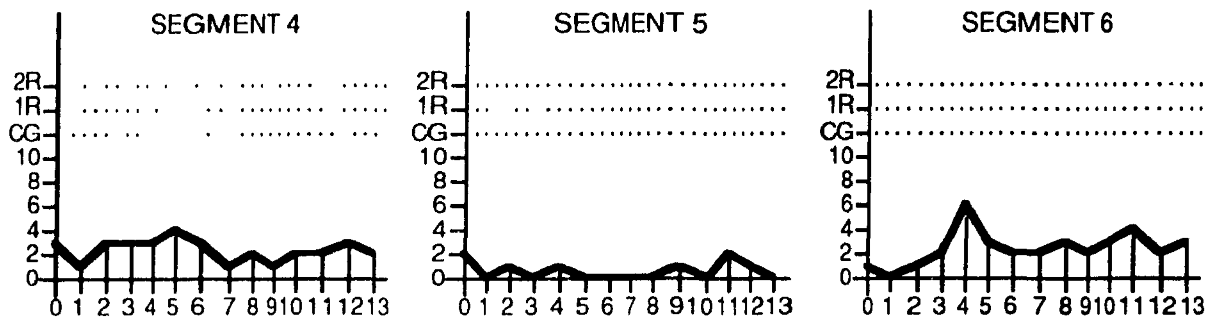
PCM 2500 ERROR CORRECTION DISPLAY CHART

AMPEX TAPE: SEGMENT 4-6

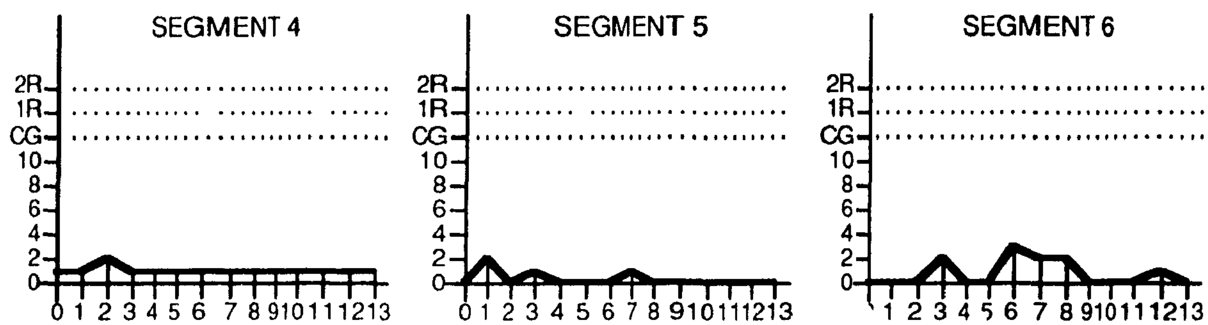
GROUP 1:



GROUP 2:



GROUP 3:



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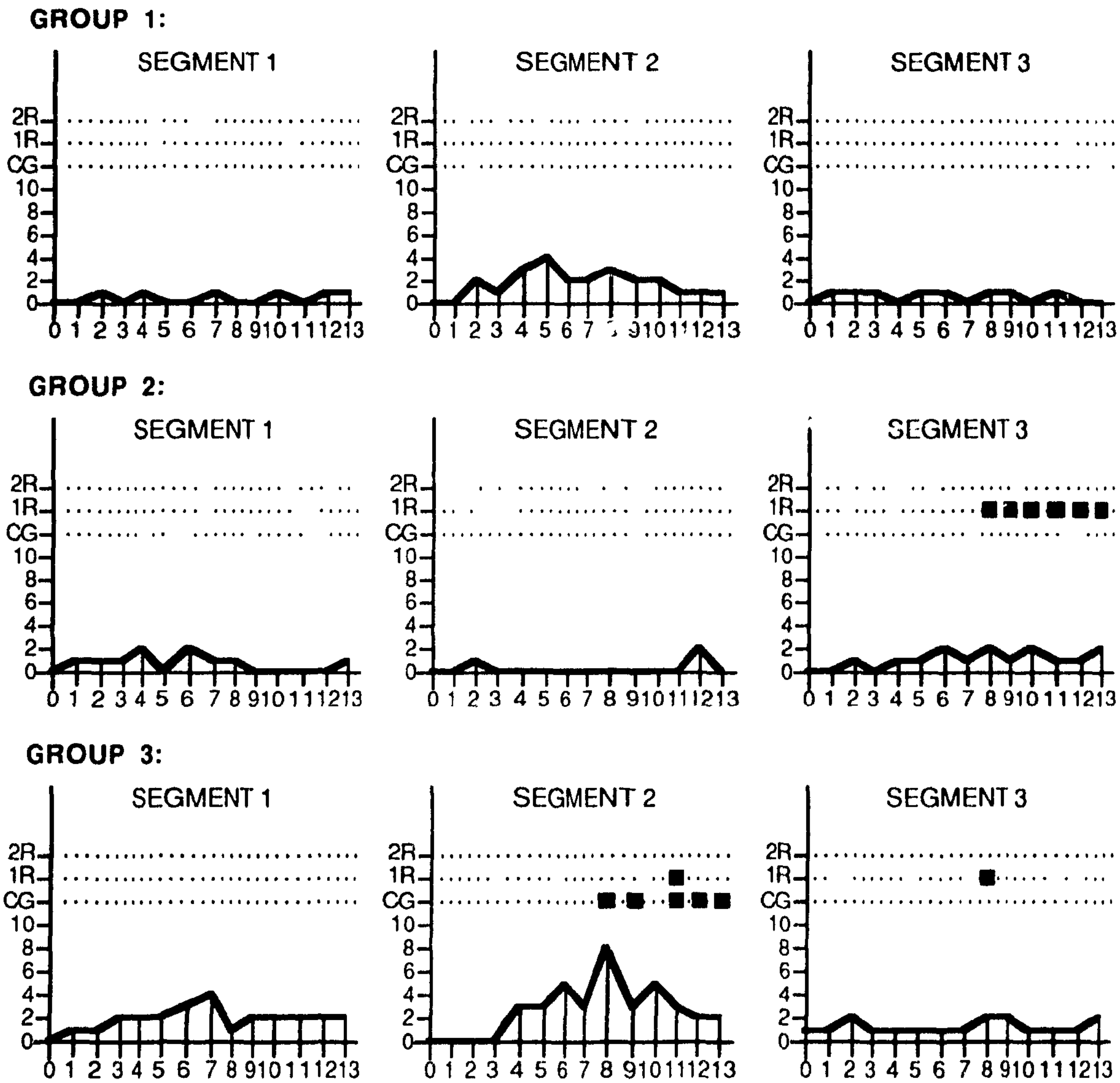
PCM 2500 ERROR CORRECTION DISPLAY CHART

SONY TAPE: SEGMENT 1-3



KEY:

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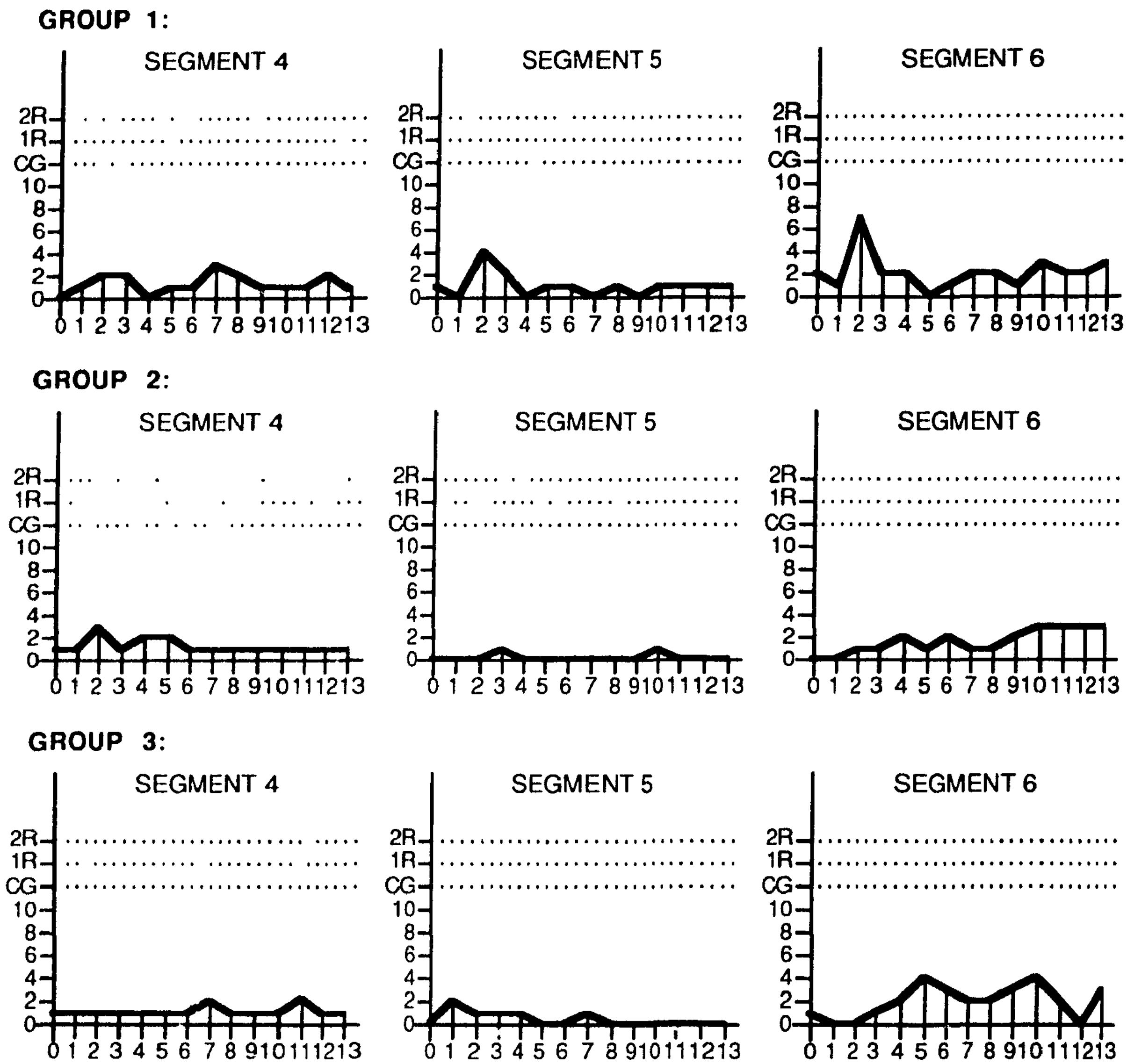
PCM 2500 ERROR CORRECTION DISPLAY CHART

SONY TAPE SEGMENT 4-6



KEY:

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