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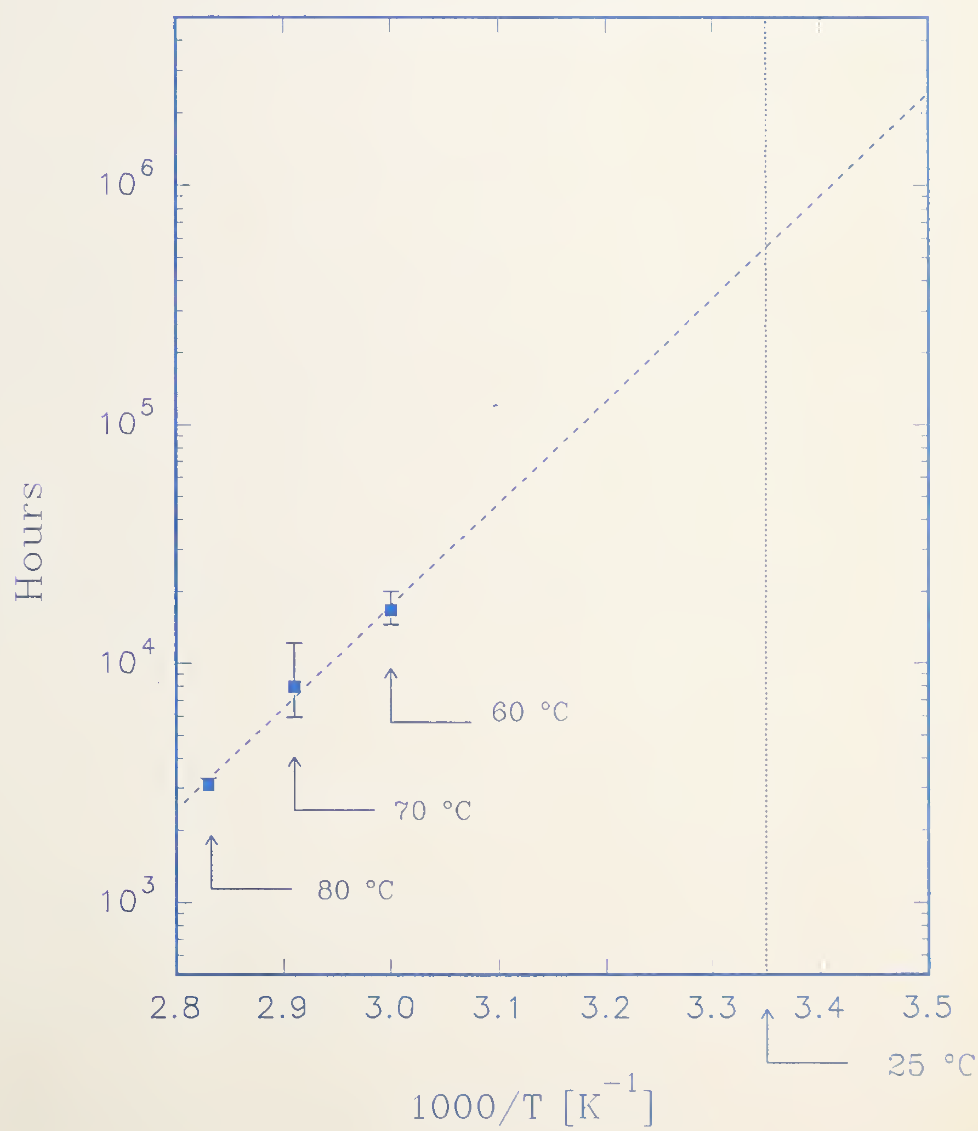
Development of a Testing Methodology to Predict Optical Disk Life Expectancy Values

Fernando L. Podio



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Reports on Computer Systems Technology

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Disclaimer

This publication illustrates the development of a testing methodology that can be applied to predict optical disk life expectancy values. The work was not aimed towards evaluating a particular type of optical disk. Commercially available optical disks have been used for the tests with the sole intent of illustrating the test procedures implemented. Values obtained showing changes in media parameters are included. Life expectancy values derived from the experiments are also shown to illustrate the testing approach rather than as an indication of the actual life expectancy of the type of disks used in the experiments. The reasons for this include the use of a very small number of samples with respect to the population of disks in existence, the presence of other degradation effects which do not correspond to the prediction model, and the use of stress environments with higher than normal relative humidity levels to permit aging disks in a reasonable length of time.

Because of the nature of this report, it is necessary to mention vendors and commercial products. The presence or absence of a particular trade name product does not imply criticism or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

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The technical support provided by teams of engineers from the Sony Company and ATG Gigadisc is very much appreciated. Also appreciated are the contributions in equipment to this program by these companies. Sony contributed to this program equipment equivalent to approximately $50,000. ATG has contributed equipment equivalent to $5,000.

Executive Summary

The National Institute of Standards and Technology (NIST), with the partial sponsorship of the U.S. National Archives and Records Administration (NARA), has set up an optical media measurement laboratory to test and analyze optical disk media characteristics and develop a testing methodology that can be used for deriving life expectancy values for optical disks.

The methodology included determining the characteristics that define the media end of life, a means of measuring the selected parameters, and a means of accelerating the media aging. Byte error rate (BER) was selected as the quality parameter and an end of life for the BER of 5×10^{-4} was also adopted. This value was a typical number used by the manufacturers at the time of the beginning of this program. The BER was measured over samples of three areas of the disks (inner, middle, and outer) and using three different patterns (high frequency, sequential, and random). Three environments were used for accelerating the aging of the media: 80 °C, 90% relative humidity (RH); 70 °C, 90% RH; and 60 °C, 90% RH. The reflectance of the blank areas and the carrier-to-noise ratio were also measured to monitor their behavior before and after the aging tests.

To illustrate the use of the testing methodology, the accelerated aging tests were run on a small set of polycarbonate substrate media. The particular type of media used was recommended by NARA. BER values were estimated from measurements in three areas of the disks and from sectors written with three different patterns. Extrapolated life expectancy values for room temperature and the same relative humidity used for the stress environments were then estimated from modified Arrhenius plots for each of the patterns and areas used for the BER measurements.

The results indicate that the methodology applied to a small sample of disks yields a range of extrapolated life expectancy values depending upon the patterns and areas used for the BER measurement. These results include data taken in areas of the disks where secondary effects took place. These secondary effects were due to causes such as damage to the sealing on the outer and inner edges of the disk due to the stress conditions that may have allowed moisture to seep in and the handling of the disks. These secondary effects cannot be accommodated by the mathematical model used for the extrapolations.

Another approach was also used to represent the results. This approach selected the data derived only from the middle area (assuming that these areas of the disks were the more isolated from the secondary effects) and from sectors written only with the high frequency pattern (worst case pattern for this implementation). Using these more representative data (high frequency pattern in the middle area) and median values of the BER, an extrapolated life expectancy of 121 years at room temperature and 90% RH was derived. Using the upper 95% confidence limit of the BER for the extrapolations, a more conservative extrapolated life expectancy value of 57 years at room temperature and 90% RH was obtained. However, assuming a maximum RH range for a storage environment of 40% to 50% RH, the projected life expectancy values using this method should be longer than the ones derived from our experiments.

These results are an approximation and should be used with caution because the experiments used a small number of samples and the presence of degradation effects which do not correspond to the prediction model. Furthermore, it should be noted that the higher than normal humidity levels used to permit aging disks in a reasonable length of time influences the results.

The most important conclusion of this work is that extrapolated life expectancy values may vary greatly because they depend, among other factors, on the test method used for calculating the quality parameter (e.g., BER), the measurement approach including data patterns used, areas measured (e.g., middle area), amount of data tested, mathematical model used, criteria for data analysis (including the statistical analysis used, confidence intervals, etc), and the stress conditions. Therefore, prospective users should be aware that claims of a life expectancy specification should be accompanied by specification of the above factors. The results derived in this research indicate that different testing methods have the potential for deriving different values of extrapolated life expectancy, all of which may be valid. The need for standard test methods for life expectancy is apparent. These standards would provide a commonly agreed upon basis for life expectancy testing so that vendor claims can be properly assessed by prospective users. Otherwise, comparisons between different products will not be possible.

New developments in both write-once read many times (WORM) and rewritable media technology warrant further research in accelerated life testing of these media. Additional research is needed to investigate on-line monitoring and reporting of error rate and error distribution. This would provide data managers with needed information on the status of their data. Research in the care and handling of these media and in test methods for media characteristics is also needed. Work on standardization of life expectancy methods, media interchange and test methods for media characteristics should continue.

This program of work also included active participation by NIST staff in standards committees which are developing test methods for predicting life expectancy and test methods for media characteristics. With NIST leadership, significant progress has been achieved in Technical Committee X3B11, Optical Digital Data Disks for standardizing test methods for media characteristics. The American National Standard Institute (ANSI) has approved a test methods standard (ANSI X3.199-1991) which documents test methods for media characteristics for 356 mm WORM media. Similar standards for other type of media are also being developed by TC X3B11. NIST is also working in the Joint Technical Commission on Data Permanence in the standardization of life expectancy for optical disk systems.

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Abstract

There are no standards for longevity of optical disks that can assist managers in the Federal government to select the right media for the storage of permanent records, and to know how long the information may be safely stored on those disks. This report focuses on research undertaken at the National Institute of Standards and Technology to develop a methodology to predict optical disk life expectancy values. In this research accelerated aging tests were run on small sets of disks and the quality parameter (the byte error rate) was periodically measured between aging cycles. These tests were used with a mathematical prediction model to develop a testing methodology.

This report presents the results obtained. The need for standard test methods for predicting life expectancy and for measuring media characteristics is apparent. Life expectancy extrapolations derived from the experiments produced a range of values depending upon the method used for deriving the quality parameter. Recommendations are made about the implementation of a testing methodology for life expectancy predictions, and what information to include in a life expectancy specification.

Key words: accelerated aging; Arrhenius model; byte error rate; media lifetime; optical disks, stress tests; optical disks, test methods.

Chapter 1

Program Overview

1.1 History of the Program

The National Institute of Standards and Technology (NIST) computer storage optical media research program began several years ago with the recognition that an investigation into the life expectancy properties of optical digital data disks was needed [1]. The current NIST research program includes optical media stability studies, an optical media testing laboratory, and studies related to the utilization of optical data storage. The U.S. National Archives and Records Administration (NARA) sponsored research under this program aimed at developing a testing methodology that can be used to predict optical disk life expectancy values. Participation in standardization efforts in methods for predicting life expectancy, recommended practices for data permanence, and test methods for media characteristics were also goals of the program.

Under this program, NIST developed a methodology for deriving optical disk life expectancy values. NIST also formed an optical media measurement laboratory able to test optical disk media characteristics and run accelerated aging tests on different types of optical disks representing different media technologies, recording layer structures and substrates. The results and conclusions of the program are being shared with the relevant standards committees.

Another direct consequence of the program is the significant progress achieved in the last two years in the development of standard test methods for media characteristics. With NIST leadership, Technical Committee (TC) X3B11 Optical Digital Data Disks, is developing standards for test methods for media characteristics. One standard was approved as an American National Standard [2]. This standard includes test methods for media characteristics for 356 mm write-once read many times (WORM) media. Other draft test methods standards under development include test methods for media characteristics for 130 mm and 90 mm rewritable magneto-optic media and 130 mm WORM media.

The expertise developed by NIST staff also contributes to alternative programs for better utilization of optical media by the Federal Government. NIST staff is chairing a NIST/NASA Working Group for the development of test methods and specifications for 14 inch rewritable ruggedized optical media (with the sponsorship of NASA). A NIST Special Publication documents these test methods [3]. NIST staff is working in a program partially sponsored by NARA to study the care and handling of optical media. NIST is also involved in a program to investigate the status of on-line monitoring techniques for error rates and error distributions on optical disk subsystems. Under this program the Computer Systems Laboratory of NIST organized a government/industry working group to build an industry consensus for a method(s) of reporting error rate information through an interface.

The future availability of devices to read current media depends on the existence of a sufficiently large market with multiple vendors. This requires industrial standards for media interchange. Otherwise, drives capable of reading the particular media and format may become unavailable before the end of life of the media. Requirements for media interchange standards based on only one format may be even more helpful in resolving that problem. NIST is also actively working in national and international standardization committees in the development of media interchange standards and it is also actively participating in the IT9/AES Joint Technical Commission (JTC) on Data Permanence. The work of the JTC will eventually lead to the standardization of methods to predict the life expectancy of optical computer storage media/systems. The expertise acquired by NIST staff during this research program has already been used by NIST to provide its technical advice to the JTC as well as other standardization committees.

1.2 The Methodology

A methodology for accelerated aging of optical media is needed to estimate media/systems life expectancy values. This methodology includes determining one or more media characteristics that define the end of life (EOL) for the media; a means of accelerating the aging of the media; and a means of measuring the selected parameters. Industry standards are needed to provide a commonly agreed upon basis for life expectancy testing so that vendor claims can be properly assessed by prospective users. These standards should include standard test methods for the selected media characteristics and a standard methodology for estimating life expectancy values.

The initial expectation was that the methodology would be substrate independent. Experiments were originally planned concurrently using polycarbonate and glass substrate media. Test procedures were implemented for several media characteristics, including the byte error rate (BER), the carrier-to-noise ratio (CNR) and blank area reflectance. For the preliminary tests of these media characteristics, two types of 300 mm Write Once Read Many (WORM) media were used: a glass substrate media and a polycarbonate substrate media. NIST worked with industry to obtain support and contributions for the program. These contributions consisted of equipment (including media) and technical support.

The polycarbonate substrate media used for the experiments was a type of Sony 300 mm WORM. This media was run in a Sony WDD-3000 drive and Sony WDC-2000-10A controller. The other media, was the ATG Gigadisc 300 mm WORM, which uses a glass substrate. This media was run using an ATG GC/GD 1001 drive/controller. Both controllers were connected to the host computer using a Small Computer System Interface (SCSI) interface [4].

We assumed that a media characteristic such as the bit or byte error rate would reflect better than other characteristics a general (average) degradation of the media under the planned stress conditions. Initial degradation tests were run and BER, CNR and blank area reflectance were measured. Data was gathered from these parameters before the initial aging tests and during the rest of the program to monitor the behavior of these characteristics. The time consuming nature of these measurements and aging tests soon became apparent. For this reason and budget limitations, we decided to concentrate efforts on only one media type. The media used for the tests was the media of particular interest to NARA, the 300 mm WORM polycarbonate substrate media [5, 6].

A measurement always involves errors which are inherent to the measurement system and they should be kept in mind when the results are compared. Ideally, media and drives from different manufacturers are used to correlate the results and separate causes and effects of errors. However, most of the 300 mm WORM media from different manufacturers are not interchangeable.

We initially intended to use the raw bit error rate as the quality parameter instead of the BER. Measuring the bit error rate for the particular type of media would have required building dedicated electronics to condition and acquire the proper analog signals in the read channel, since the particular polycarbonate media selected for the experiments uses an 8 of 10 modulation scheme. The advantage of acquiring data through dedicated electronics and high speed instrumentation is that it is possible to acquire the user data as well as the sync and address information as analog signals. This approach allows for studies of the analog signal degradation in different areas of the sectors. However, the disadvantage of this method is that it is necessary to develop software for each drive and, in some instances, dedicated hardware, as well. Another disadvantage is that, in general, the amount of data that it is necessary to acquire is large and the instrument's memory should be able to store this data. Measurements of error rates using a signal generator for writing signals on the disks were not considered adequate at that time. Dedicated testers or controllers were considered, but were not used because of cost, the lack of standard formats, and technology limitations. Therefore, we decided to use commercially available drives and controllers to acquire the data.

The disadvantage of this approach is that, in general, only user data can be accessed. This means that some sectors on both the inner and outer area outside the user data area can not be accessed and error data in other parts of the sector are not available. Another limitation of this approach is that it requires the use of the BER rather than the bit error rate as the quality parameter, since the bit stream is not available from the SCSI bus. Because of the problems cited with using raw bit error rate and the fact that the manufacturer's recommendation was to use the BER as the quality parameter, the BER was selected for the tests. A BER value of 5×10^{-4} for the end of life (EOL) was also adopted. This value is a typical number used by the manufacturers at the time of the beginning of this program.

For the BER measurement, the disks used in the experiments were divided into three areas: inner, middle and outer. Each area was divided into blocks with a length of 300 sectors. The same pattern was written on each sector of a block. The BER on each disk was calculated for the three different areas and for three different patterns (a high frequency, a sequential and a random pattern) for studying pattern and area sensitivity. This data was stored in computer files. After the media was subjected to the stress conditions, the data was periodically read back and compared with the pattern information to generate error information. This error information was stored in files to be processed later. Before running the BER tests on media that was being aged, BER tests were also run on a control group of disks. The purpose of using a control group of disks was to monitor the calibration of the drives used in the experiments.

Data was gathered at the beginning of the tests from the two surfaces of every disk under test. However, data from only one of the two surfaces was actually included in the calculations. A replacement policy was implemented in the event that a surface would suffer accidental damage and would have to be replaced. The replacement policy was that, if the surface used showed abnormal results because of an accident, the other surface would be used thereafter. It was assumed that the two surfaces would have been subjected to the same accelerating aging.

All the statistics used on the data assumed that if a byte is in error, the probability that the next consecutive byte is in error is very small. This initial assumption implies that the errors were expected to be independent. Linear burst errors in the media are not accommodated under that assumption. Therefore, if a media testing plan expects that the number of burst errors be high it would be necessary to design different mathematical tools to deal with them. The same is true for defects that are several tracks wide. For effects that may define the end of life prior to a general degradation of the media, methods other than defining the EOL as a value of BER should be applied. For example, the EOL can be defined as the time when the first uncorrectable read error occurs [7].

According to the statistical analysis done on initial BER data on a set of disks, the minimum amount of data that has to be tested per surface and per area to obtain a BER value within the range of $\pm$0.074 times the BER observed with 90% confidence limits is approximately 23 MBytes (in this case a point estimator of 76x300x1024). (This assumes an initial BER of at least .000021; smaller BERs not being significant.) If three areas are measured per surface, this represents approximately 70 MBytes of tested data per surface. The amount of bytes needed depends only on the estimated initial BER values and not on the total capacity of the disk. That is, for a 1 GByte surface, the tested bytes would only be 7% of the total capacity, while for a 3 1/2 80 MByte disks it would mean testing 87.5% of the total surface.

Normal operating or storage conditions do not effect the media characteristics in a short period of time. Therefore, tests of these parameters in a normal operational environment are not useful to predict the media life expectancy. Thus, it is necessary to accelerate the degradation in some way and apply a valid prediction theory. The Arrhenius model is frequently used with various kinds of materials for explaining aging effects at different temperatures [8, 9, 10, 11, 12, 13]. It is easy to use and requires a smaller number of stress conditions than other models. It can be used for optical media when the response of the quality parameter to the stress conditions is fairly linear and a plot of extrapolated EOL values (in hours) of the quality parameter versus an inverse value of the absolute temperature T also has a linear response. This assumption implies that the defect increase or the BER growth would respond to a first order rate equation, with the rate determined by a single activation energy. The Arrhenius model was assumed to be suitable for the media used in the experiments. It is desirable to use more stress conditions than the minimum required by the model used. But, because of time constraints and cost limitations, only three environments were chosen for the tests. Incorporating a fourth environment would have reduced the extrapolation error. Other models require more stress levels [9], [14]. For example, for the Erying model, the number of required stress conditions is higher than for the Arrhenius model.

Laboratory testing always involves some measurement error. Therefore, results obtained by applying this methodology may produce some deviations from a straight line. In addition, the degradation of a quality parameter such as the BER, which is a complex function of several physical phenomena, will not necessarily respond only to a first order rate equation. How much deviation from the straight line should be allowed and how good the approximation of using relative humidity levels other than those of normal use conditions is a task for the related standards committees.

The aforementioned assumptions are an approximation because it is not completely adequate to infer before testing that the degradation mechanism would precisely fit the Arrhenius model. Since the results are an approximation, it is also advisable to provide a way of deriving conservative life expectancy values.

Aging tests were run on selected sets of optical disks. The disks were supported vertically in holders and put into the stress environments. The three environments created to age the media were: 80 °C, 90% relative humidity (RH); 70 °C, 90% RH; and 60 °C, 90% RH. To achieve the proper levels of stress, the temperature and RH were ramped-up at a certain maximum rate after the media was placed in the chambers. Before removing media from the chamber, the temperature and relative humidity were also ramped-down at a certain maximum rate. The ramp-up and down conditions followed the manufacturer's recommendation for the type of media tested. More conservative rate values (smaller rates) can be used. Experiments were initially run on single pieces of media without following these slopes. In one experiment, an oven was properly ramped-up and a short aging cycle run in a single piece of media. But, before the media was removed from the oven, the oven was shut off to simulate a loss of electrical power. Tests run for BER on this sample showed an increase of BER that reached the EOL value of the parameter. This experiment showed that care should be used in running these type of experiments.

The media was removed from its protective cartridge before subjecting it to the stress conditions. The removal of the media from the cartridge introduces some handling problems because the media is exposed to dust, fingerprints, and the possibility of scratches. These problems can show up as systematic errors in the measurements. While a single damaged disk may be merely removed from the test, damage to several disks could jeopardize the significance of the data for the particular temperature and relative humidity. Only one disk was damaged during the NIST testing. (The data gathered from that surface was replaced in the calculations by the data gathered from the other surface of the same disk). Users ordinarily have no need to remove media from the cartridge and should not do so. If the risk of sudden abnormal behavior is high, it is advisable to incorporate more disks in the tests than the minimum required for the tests, gathering data from all of them. The drawback to this is that time increases, meaning that the disks will be out of the testing environment for a longer period of time. This may cause some error in the testing.

BER values were derived from the three set of disks aged at the three high temperature and humidity stress conditions. The median values were used instead of the mean as a more representative behavior of the three disks. The measured EOL values were produced with three disks per set. Using more disks would have produced more precise results, but would have cost considerably more. Plots of the quality parameter (BER) versus the aging time were generated for each set of disks. These plots have generally shown a straight line response. Modified Arrhenius plots were used with the data derived from BER tests to demonstrate how to extrapolate life expectancy values. These modified Arrhenius plots represent extrapolated life time values of the BER (in hours) versus an inverse value of the absolute temperature (T). Extrapolated life expectancy values for room temperature and the same relative humidity used for the stress environments were then estimated from these modified Arrhenius plots for each of the patterns and areas used for the BER measurements.

Other methods of life time predictions have been researched by NIST staff. For example, [7] describes a method based also on the bit/byte error rate (or block error rate) as the degradation parameter and in the determination of a kinetic model such as Arrhenius. However, the end of life under the accelerated aging conditions is defined as the occurrence of the first unrecoverable read error. Another method, included in the work of the NIST/NASA working group for the development of test methods for ruggedized rewritable media, includes a method which measures error rate derived from a signal previously written with an external generator. In this method, the assumptions are similar to the one used in the method used on this program [3]. There are instances where localized defect growth could conceivably cause an uncorrectable read error prior to the EOL value of BER. In those instances, prediction methods based on localized errors or uncorrectable read errors may be required. This is a subject of continued study in the relevant standards committees. The occurrence of such uncorrectable read errors depends heavily on the error correction strategy used. This varies considerably between manufacturers.

Chapter 2

Experimental Procedures

2.1 Introduction

An optical disk life expectancy methodology includes the selection of a set of media characteristics that represent the degradation behaviour of the media, a plan for accelerated aging tests, and the analysis, if possible, of failure mechanisms. Once the set of media degradation parameters is selected, the next step is to identify which of these parameters is critical for the definition of end of life of the media (EOL). This parameter is called the quality parameter. The approach used in accelerated aging is to measure the change of the quality parameter under stress conditions to predict its behavior in normal environments.

Media characteristics will not change significantly in a short period of time at normal operating conditions. Therefore, tests of these parameters in a normal operational environment are not useful to predict the media life expectancy. It is necessary to accelerate the degradation in some way and apply a valid prediction theory. That means being able to model the degradation of media characteristics at accelerated conditions using the end of life parameter.

As it was explained in Chapter 1, the Byte Error Rate (BER) was selected as the quality parameter. The frequency spectrum of the read signal was also tested to derive carrier-to-noise (CNR) values. In addition, the reflectance of the blank areas was also measured. These blank areas are located in the innermost and the outermost areas of the disks.

The optical disk drives were connected to the host computers using a SCSI interface as shown in figure 2.1. The software for the drives to communicate with the host computers was developed at NIST. This software is a SCSI command system that provides variable structures and a library of SCSI commands for software assisted device control. A NIST report describing the SCSI command system was published [4]. The following sections describe the test methods implemented for the selected media characteristcs.

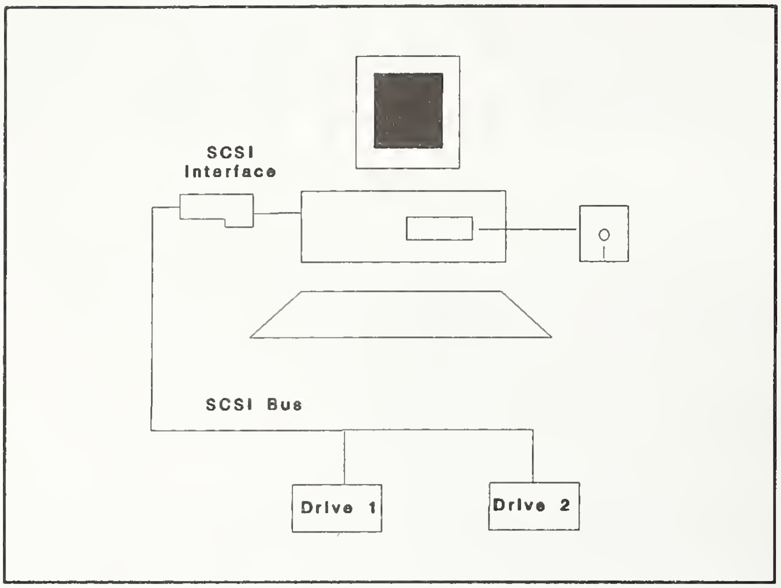


Figure 2.1. System interconnection.

2.2 BER Measurements

2.2.1 Introduction

BER is defined as the ratio of the number of bytes in error to the total number of tested bytes. Two approaches have been used to analyze the BER.

a.- BER Measured Over Three Areas on Each Surface

The first approach calculates BER using all three areas of the disk (inner, middle, and outer) without differentiation of the area, and using only one pattern at the time. This approach is being used by some manufacturers to report similar results. Three patterns were used in different calculations (high density, random, and sequential pattern).

b.- BER Measured Using a Statistical Analysis on Three Independent Areas

The second approach uses a statistical analysis by area on the disk (inner, middle, and outer) [15, 16, 17, 18, 19]. The data derived using this approach provides deviation values from the mean, using the "Student t" distribution with confidence limits of 90%. However, for some of the data sets analyzed, the deviation is high and does not show a good representation of the data in semi-log scale. The data was recalculated deriving information on median, maximum and minimum values versus aging time.

2.2.2 Measurement Procedure

The recording format of the polycarbonate media used for the experiments mixes the user data and the error correcting code (ECC) data within each sector of the disk. The glass substrate media has separate areas in each sector for the user data and for the ECC data. This difference has an effect on how the BER may be calculated for the two types of media.

The BER for the first media was calculated for the user data portion of the sector only, since the mixing of the user data and the ECC data makes it unlikely that the two would have different BERs. This situation does not apply to the glass media, because the BER might change from one value at the beginning of the sector to another value at the end of the sector. Therefore, ideally, for these type of media, it would be preferable to separately measure BER for both the user data and the ECC data areas. In the particular type of glass media used for the initial experiments, this would have necessitated a measurement technique that would have slowed the data acquisition by a factor of 25 times. For this reason, the BER was also measured for the user data only.

As was mentioned in Chapter 1, after the initial experiments using both types of media, experiments continued using only the polycarbonate substrate media. Different patterns were written in three areas on the disk to test for BER pattern sensitivity. The data were read into files. After the aging process started, the data were periodically read back with the ECC disabled and compared with the pattern information to generate BER information. This error information was stored in files for further processing. Table 2.2 lists the different phases of the BER measurement approach.

Table 2.2. BER measurement approach

Phase I	Write data on a selected group of disks
Phase II	Read the initial error data and identify a control group
Phase III	Age selected group of disks at different stress conditions
Phase IV	Read error data after every aging period
Phase V	Using a database management system, calculate BER
Phase VI	Print and plot results.

The disks were divided into three areas: inner, center and outer. Each area was divided into blocks of 300 sectors each (see fig. 2.2). The same pattern was written on each sector of a block.

Before running the BER test on media that had been aged, tests were run on a control group of disks. When the results were different from the values previously measured from the same control group, drive calibration problems were suspected and the drive was sent for calibration. This happened once during the experiments.

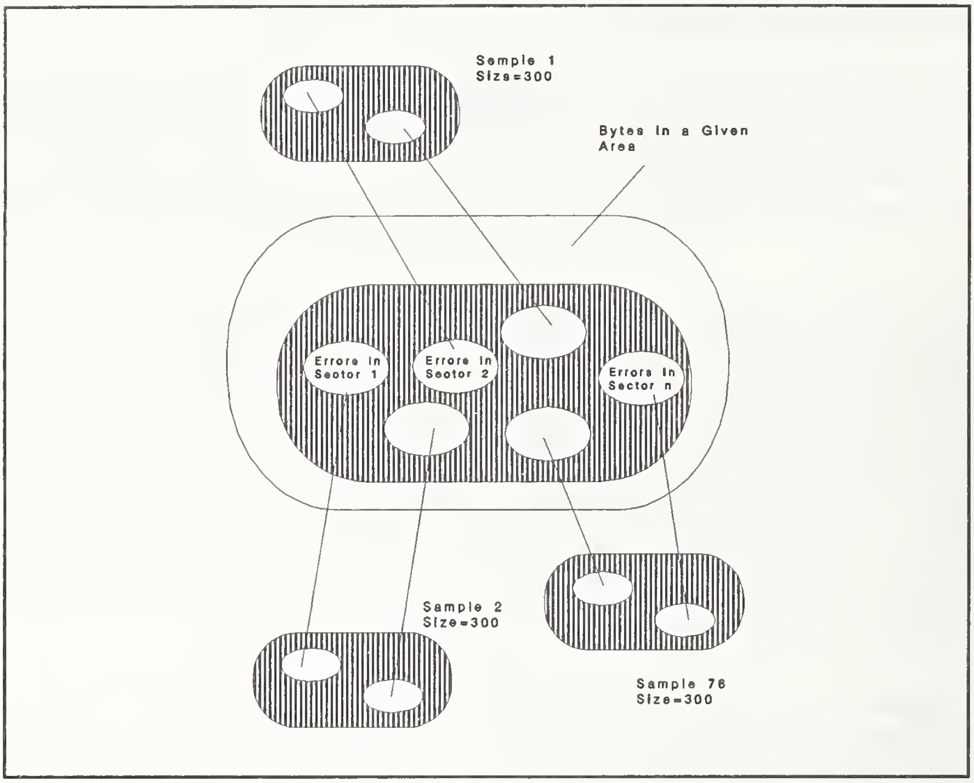


Figure 2.2. Grouping of sectors for the BER measurement.

2.2.3 Database Management

Since the volume of error information was high, a database management system and a database were used to handle the data. After the data was acquired, the database was updated and the data were selected in different arrangements in order to analyze the BER values for different patterns or areas.

2.2.4 Initial Tests to Determine the Statistical Analysis

In order to determine the statistical analysis to be used, and to have more understanding of the error distributions, tests were run using both types of media. Three different patterns were written three times each on the three different selected areas on these disks. This patterns were: the sequential pattern, a random pattern, and a high frequency pattern. In the sequential pattern, the bytes are in sequence from 00H to FFH. This pattern is repeated 4 times in the 1024 bytes of the sector. The random pattern is a succession of bytes generated by a random number generator. The high frequency pattern that does not have any significant meaning for the glass media but for the polycarbonate media with its 8 of 10 modulation it is the highest frequency that can be written on the media using the SCSI bus. BER values calculated from this test were used to estimate the mean of the BER for further statistical calculations. A statistical approach was used to determine the number of sectors to be written on the three different areas of the disk. The confidence interval and the confidence level were also calculated (see fig. 2.3).

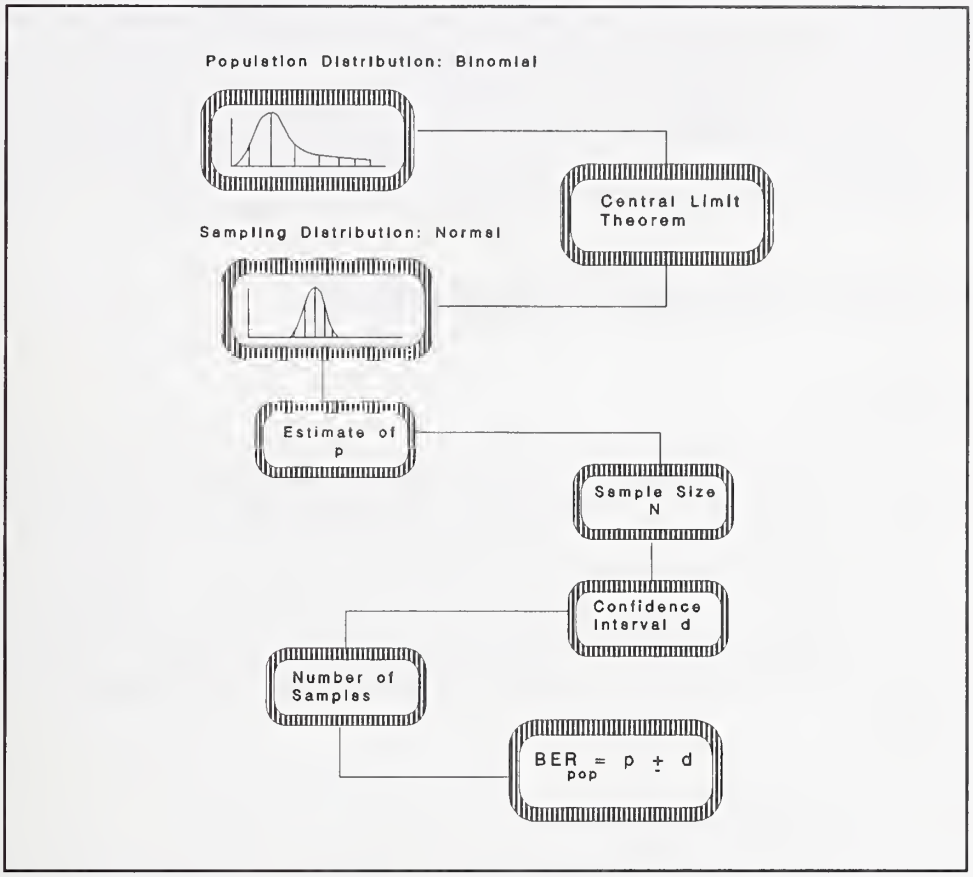


Figure 2.3. Statistical approach for the BER measurement.

2.2.5 Determination of the Number of Bytes to Be Used for the Test

Each area of the disk selected for the BER measurement (the inner, middle, and outer), was divided into 10 **sections**, which were numbered from 1 to 10. The sections were divided into 4 **partition tests**, numbered from 1 to 4. The partition tests are areas where only one type of test was allowed. The partition test 1 was designated for BER measurement, number 2 for Frequency Spectrum tests, and 3 and 4 were reserved for other tests.

According to the statistical method used, the number of bytes used for the initial BER measurement was 70 Mbytes per surface distributed in the three different areas. Hence, the minimum amount of data measured per area was approximately 23 Mbytes. The results were extracted from plots of BER versus aging time for the different conditions as will be shown in the next chapter.

2.2.6 Control Group of Disks

The control group was a set of disks which was stored in a normal operating environment. The control group was used to determine that the disk properties under the stress environments were varying solely due to the aging environments and not to other causes such as changes in the measurement systems (which included the drives). Before selecting the control group of disks, a large set of disks was tested for BER and the mean and standard deviation of the BER was determined. The BER values were normalized to Z scores and plotted. From this test, a control group was selected.

2.3 Blank Area Reflectance Measurement

2.3.1 Introduction

The objective of this measurement is to quantify the change in reflectance of the two blank areas of the disks. There are two areas per disk: the inner area, close to the center of the disk, and the outer area, close to the outer edge of the disk. For the set of disks subjected to the stress environments, blank refelctance values were determined between aging cycles. The control group was also measured periodically. The blank reflectance values were obtained by focusing a 830 nm GaAlAs solid state laser beam on the recording layer of the media and measuring the level of radiation reflected to a photodiode quadrature detector.

2.3.2 Measurement Procedure

The block diagram of figure 2.4 shows the interconnection of the hardware components used to measure the blank area reflectance. A laser power supply delivers an adjustable current to the laser diode. Quadrature photodetectors in the laser head assembly measure the light returning from the recording layer and proportional voltage signals are amplified in a servo amplifier driver. A focus voltage is returned to the laser head assembly by the servo amplifier driver to maintain focus on the recording layer. The quadrature photodetector outputs are summed by an external operational amplifier circuit and a chart recorder is used to record this voltage which represents the reflectance values.

The experiments were run using the polycarbonate substrate media mentioned above. It has two blank areas: approximately 5.9 to 6.7 cm from the center (inner blank area) and 14.2 to 14.7 cm from the center (outer blank area). The media was placed on a hub inserted into an micrometric movement stage. The hub fits snugly into the media spindle hole providing a media centering mechanism. The stage and media can be moved axially, rotationally, and radially with respect to the laser radiation axis using a triple stage controller. Reflectance values were recorded while rotating the media 360 degrees. The system was calibrated using a semiconductor wafer. Ten values were taken for each revolution and the mean, standard deviation and dispersion were calculated for each disk of each set. Blank reflectance values were plotted versus aging time for the three sets of disks.

These plots include the median values, the minimum, and the maximum for each set (see chapter 3).

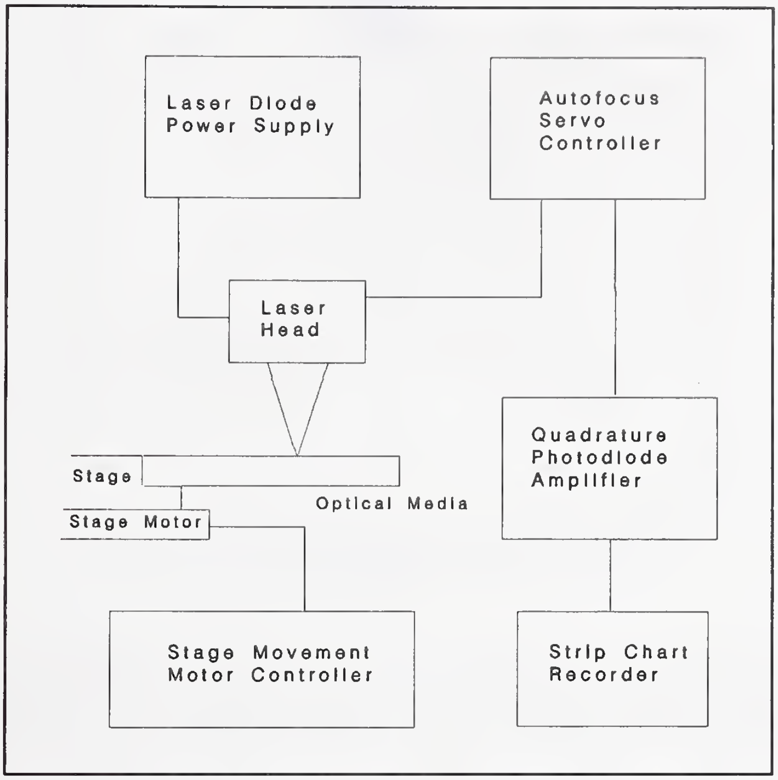


Figure 2.4. Reflectance measurement setup.

2.4 Carrier-to-Noise Ratio Measurement

2.4.1 Introduction

The measurement of the frequency spectrum allows derivation of characteristics such as the carrier-to-noise ratio (CNR). Initially CNR was measured for both types of optical media used for the experiments. As explained before, the experiments continued using only the polycarbonate based media.

2.4.2 Recording a Carrier on the Media

In the glass media used for the experiments, data can be written on the media in a pattern that produces a single frequency carrier. This carrier, when read back, is used to measure the CNR.

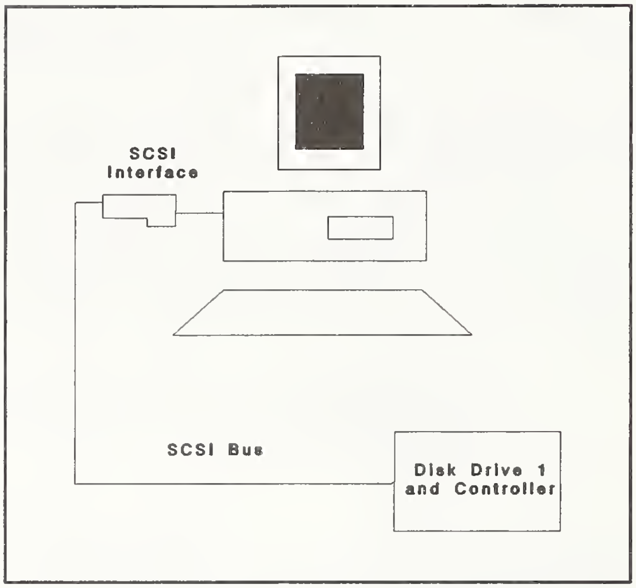


Figure 2.5. Generating a carrier on the media for disk drive 1.

In this media, user data is segmented into 85 bit pieces separated by 15 bits of sync information. Because the duration of a sync mark is an odd number of bits, the complement of the bit pattern must be used in alternate blocks of data to maintain constant carrier phase throughout the media. If this is not done, the fundamental is split into two parts by the phase modulation. The carrier frequency for the media is chosen to correspond to a repetitive "01" pattern. This is the highest frequency for which the particular media is designed, and is considered worst case from an information density standpoint. The pattern is written to the media using the diagnostic write SCSI command, and a coherent 2.5 MHz carrier results (see fig. 2.5 for drive 1, the drive that runs the glass media).

As explained before, the polycarbonate media controller, on the other hand, uses an 8 of 10 bit modulation of data and the resulting sequence of bits written to the media contains no alternating "01" patterns. As shown in figure 2.6, an external signal generator set to 2.6 MHz was used to drive the laser write circuit. To derive the CNR values, a SCSI write command for the desired amount of written sectors was used. The drive was allowed to control the address, blank area, tracking, servos and focusing, as it normally does.

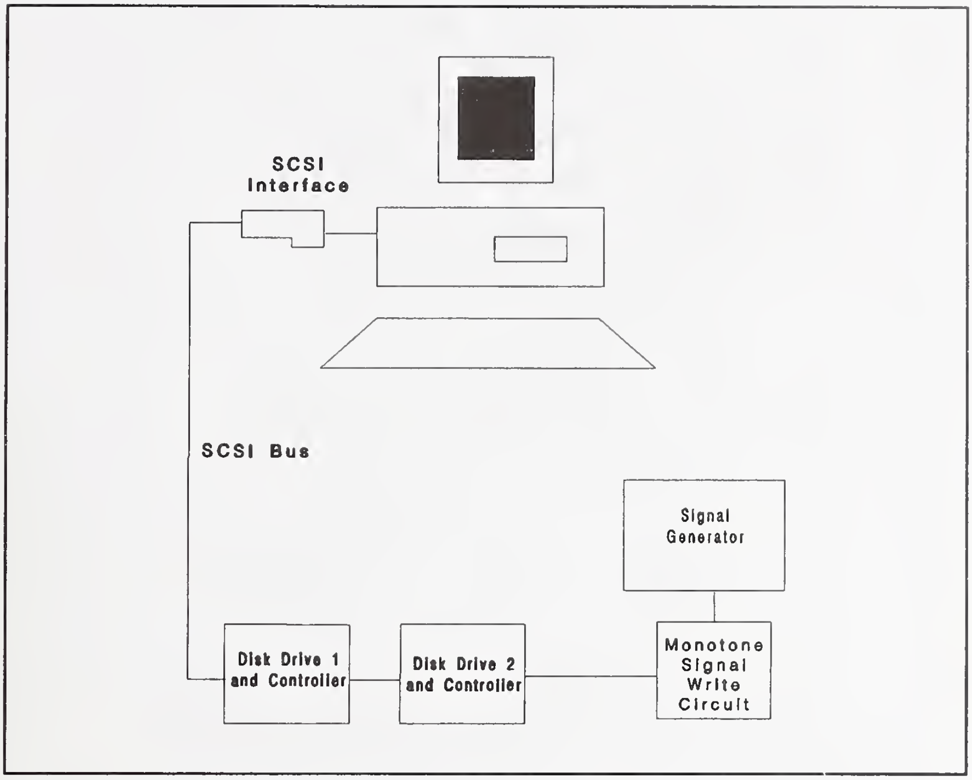


Figure 2.6. Generating a carrier on the media for disk drive 2.

2.4.3 Reading From the Media

A Hewlett-Packard 3585A spectrum analyzer was used to measure the frequency spectrum to derive the CNR values. The test track was read and the signal level measured using the spectrum analyzer with a center frequency equal to the maximum specified frequency f_c. The noise level was estimated by interpolating the average noise floor (see fig. 2.7). The spectrum analyzer correction factor (2.5 dB) was substracted from the difference between the signal level and the noise level. A program that acquires the data from the instrument and calculates the CNR values was developed. This program also plots the frequency spectrum of the read analog signal for a particular track. To position the head on the proper track to measure the analog read signal from the glass media, the "find first blank" SCSI command was used. This command tracks the media until a blank sector is found or the controller searches the requested number of sectors. Figure 2.8 shows the measurement setup for this media type.

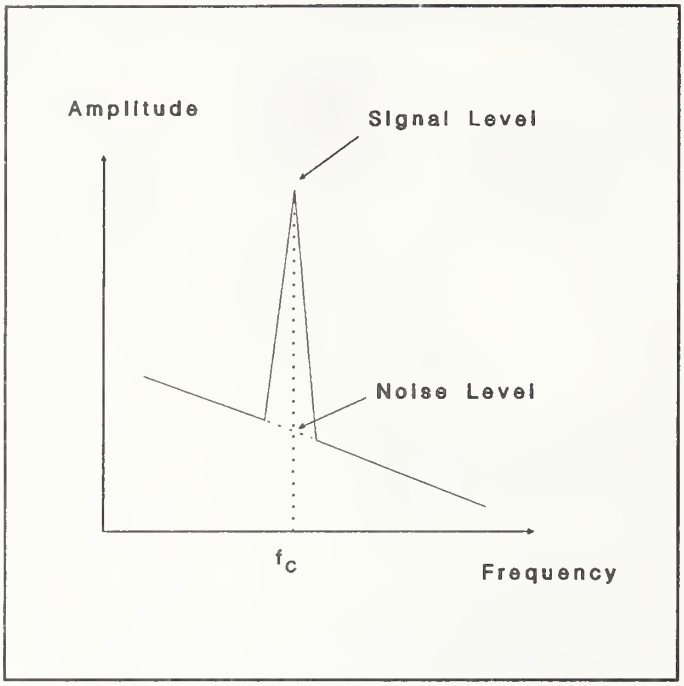


Figure 2.7. Amplitude versus frequency.

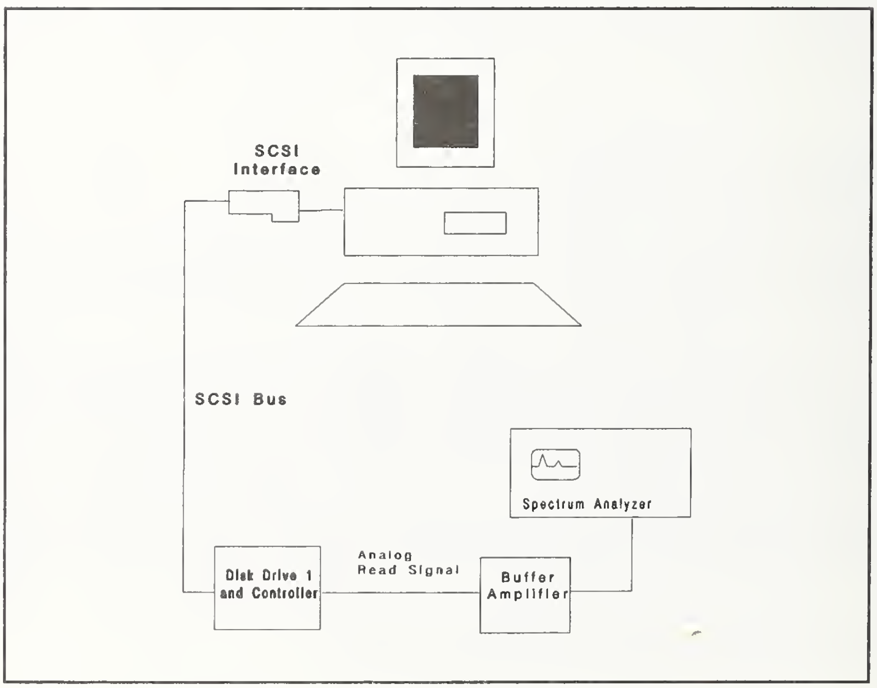


Figure 2.8. CNR measurement setup for disk drive 1.

For the polycarbonate media, the controller continuously tracks both the address and the user data when a SCSI command is issued. Therefore, only one written track was necessary to provide a signal for analysis (see fig. 2.9 for the measurement setup).

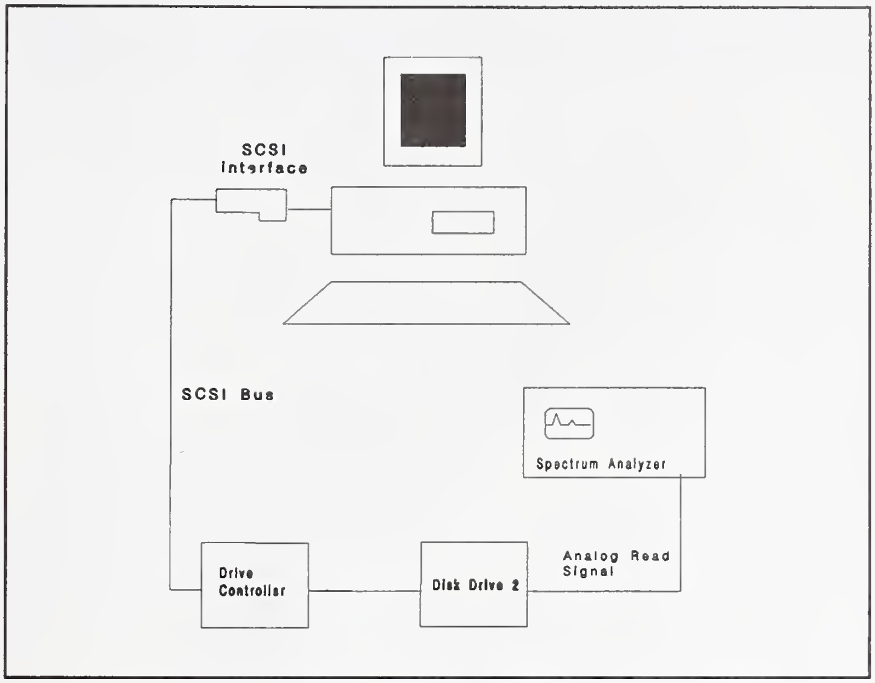


Figure 2.9 CNR measurement setup for disk drive 2.

2.5 Accelerated Aging Tests

As mentioned in Chapter 1, aging tests were run on three sets of optical disks. Each set consisted of three disks selected at random. Two ways were used to create the stress environmens (80 °C, 90% RH; 70 °C, 90% RH; and 60 °C, 90% RH). For the 80 °C, 90% RH enviroment, a temperature/humidity chamber was used. The T/H chamber is a temperature/humidity cabinet that includes a microprocessor-based controller. The other two stress environments were created using convection ovens containing desiccators in which saturated salt solutions were used to maintain constant relative humidity. Barium chloride was used to control the relative humidity [20]. The manual oven controllers were modified so that several ovens were controlled with a microcomputer through a multi-oven controller designed at NIST (see fig. 2.10).

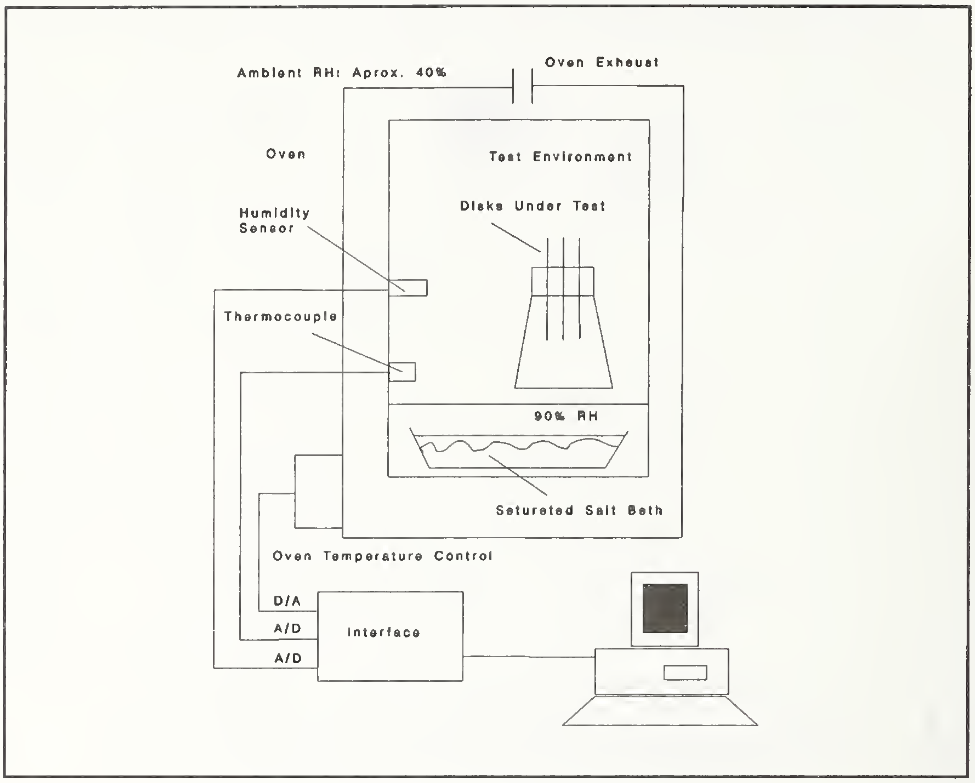


Figure 2.10. Multi-oven controller.

The media was cycled up and down according to temperature and RH gradients that did not exceed the manufacturer's recommendations. The set of disks were maintained at high temperature and relative humidity for periods of time. At the begining of the tests, the aging cycles were 140 hours. The aging cycles were later increased to 500 hours between tests.

Uninterruptible power supplies for the T/H chamber and the ovens were not available. However, tests have been run to account for unexpected interruption of power because of storms or other reasons. During a short interruption of power, the T/H chamber's microprocessor-based controller holds the cycle and continues with the programmed cycle after the power is restored. The multi-oven controller was designed so that upon an interruption of power on the computer and the oven, the computer reboots with a program that reads a file with information on which time and T/H have been recorded. The program regains operation at exactly the same point as before the power interruption.

2.6 Visual Inspection of the Media and Defects Localization

Visual inspection of media which exhibits localized abnormalities such as high BER or high reflectance aids in determining failure mechanisms. An optical bench equipped with a microscope, television camera, monitor and a hardware link to an image processing and storage system was used to explore defects in the optical path and at the recording layer. The measurement setup uses a polar coordinate system to return at a later time to an area on the media where a defect was found. This feature allows the tracking of defects after further aging. Figure 2.11 shows this optical image inspection system.

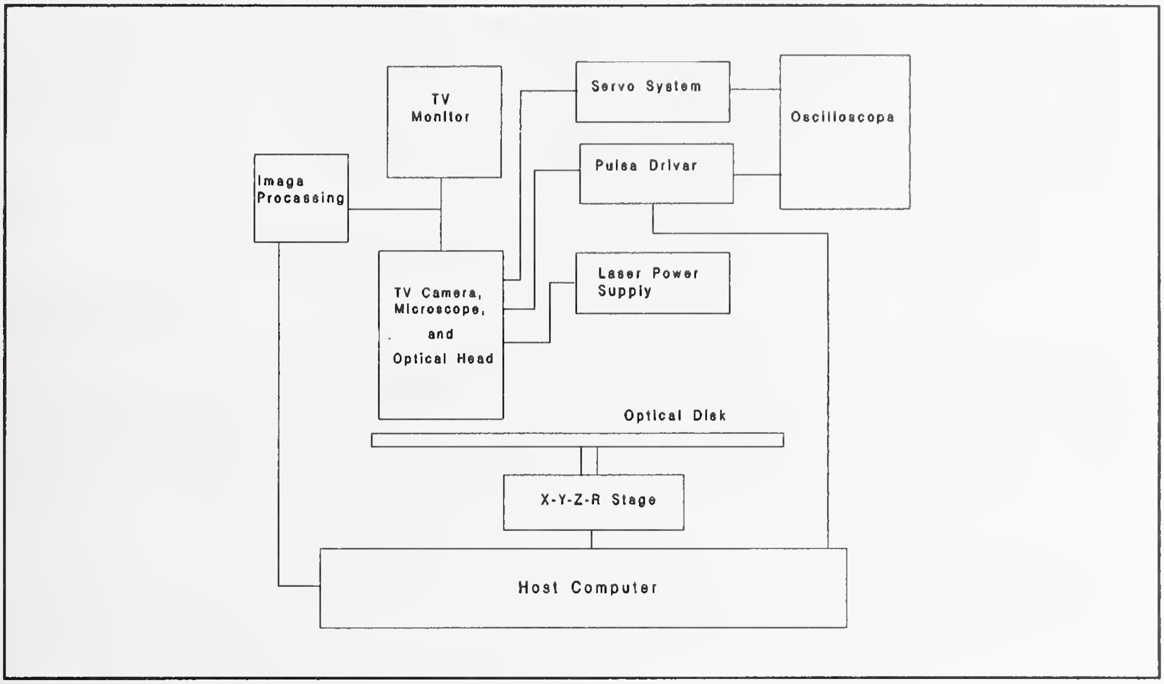


Figure 2.11. Optical inspection system setup.

Chapter 3

Results

3.1 Introduction

The results presented in this chapter were derived from the polycarbonate substrate media used for the experiments (see Chapter 1). The following data shows results of BER measurements and life time expectancy values derived from the three sets of disks that were aged at three different high temperature and humidity stress environments.

Table 3.1 summarizes the stress conditions for these sets of disks. The table also shows the total number of hours each disk set was aged. Data gathered on the sets that were aged were analyzed at periodic intervals. In addition, data was also gathered from the set of five disks that were used as the control group.

Table 3.1 Stress environments of high temperature and humidity.

Set #	Disks	Stress Environment	Total Aging Time
1	15, 22, 24	60 °C, 90% RH	5711 hr
2	26, 27, 28	70 °C, 90% RH	4120 hr
3	8, 14, 23	80 °C, 90% RH	4201 hr

3.2 BER Results

Figures 3.1 through 3.27 show the BER values versus aging time for the three stress conditions shown in table 3.1. Three similar sets of charts follow. These sets show BER values versus aging time in hours. The charts represent BER values calculated under different conditions (using different areas and patterns). The charts show median, maximum and minimum values of BER for sets of three disks where the data was read on only one surface (side) of each disk. The dashed line on each chart is the linear regression of the median values. The solid lines are the upper and lower 95% confidence limits of the median. The charts also show a horizontal dash line that reflects the end of life definition used to extract the EOL values (in hours). These EOL values are later used in modified Arrhenius plots.

Each set of BER charts are divided in three subsets for each of the stress conditions: 60 °C, 90% RH; 70 °C, 90% RH; and 80 °C, 90% RH.

(a) Four graphs showing the aging effect on the BER values over all three areas written on the disk using three different patterns (sequential, random, and high frequency). The fourth chart of this subset is a comparative graph that includes the three previous ones. This graph allows the reader to compare BER values extracted from blocks of sectors written with different patterns. Note that BER values derived from blocks written with the sequential or the random pattern show similar degradation tendencies. On the other hand, the slope is higher on the plots derived from reading blocks written with the high frequency pattern. This happens for the three stress conditions. However, the difference is more noticeable for the 60 °C, 90% RH and 70 °C, 90% RH environments.

(b) Four graphs showing the aging effect on the BER values for all three patterns using three different areas of the disk: the inner, middle, and outer area. The fourth chart of this subset is a comparative graph that includes the three previous ones. This graph allows the reader to compare BER values extracted from blocks of sectors written with all the different patterns, but in three independent areas of the disks, as explained before. The slopes are all similar for the 80 °C stress condition. For the other two stress conditions, the slopes on the inner and middle areas are similar, but the slope is higher in the case of the outer area. Therefore, as the graphs show, this outer area gives the smaller number of hours of extrapolated EOL.

(c) One graph showing the aging effect on the BER values on blocks of sectors in the middle area, written with the high frequency pattern only.

Sets 1 to 3 - Stress Conditions: 60 °C, 90% RH; 70 °C, 90% RH; and 80 °C, 90% RH.

Figures 3.1 to 3.4, figures 3.10 to 3.13, and figures 3.19 to 3.22 show the aging effect on the BER values over three areas of the disk using three different patterns. Figures 3.5 to 3.8, figures 3.14 to 3.17, and figures 3.23 to 3.26 show the aging effect on the BER values for all the three patterns on three independent areas, the inner, middle, and outer. In each of these areas, blocks of sectors have been written using three different patterns, the sequential (00 to FF Hexadecimal), a pseudo-random pattern, and a high frequency pattern, which is the hexadecimal value that produces the maximum linear density possible for the type of disks used in the experiments. Figures 3.9, 3.18, and 3.27 show the aging effect on BER on the middle area, selecting the blocks of sectors written only with the high density pattern. The choice of this combination of area/pattern becomes apparent later.

Table 3.2 summarizes the EOL values (in hours) for the different sets under the three different stress conditions. These values were extracted from the figures shown on the following pages.

Note that in some cases, the figures do not show the intersection of the regression line and the lower confidence limit with the BER end of life definition. The horizontal scale of the figures could have been expanded to show these intersections, but it would have been difficult for the reader to see the separate data points. Also, having the same scale for all figures makes visual comparisons easier.

Table 3.2 Extrapolated EOL values (in hours) for three sets of disks under three stress conditions

	60 °C, 90% RH			70 °C, 90% RH			80 °C, 90% RH		
	+95%	Median	-95%	+95%	Median	-95%	+95%	Median	-95%
Areas									
Inner	14,500	16,650	20,000	7,750	9,800	14,000	2,000	2,190	2,400
Middle	14,500	20,000	33,700	6,200	9,600	32,000	2,080	2,180	2,300
Outer	5,400	6,600	8,900	3,450	4,100	5,200	1,550	1,740	1,920
Patterns									
Sequential	9,950	11,700	14,000	6,800	9,000	14,500	1,890	2,110	2,250
Random	9,650	11,250	13,700	6,750	8,600	12,900	2,000	2,130	2,290
High Frequency	7,750	8,450	9,400	3,400	4,200	6,000	1,640	1,780	1,900

3.3 Application of the Arrhenius Model to the Data

3.3.1 Practical Considerations in the Application of the Arrhenius Model

The method of applying aging tests to optical disk media is relatively simple:

a) Stress environments are selected and the stress tests implemented. These tests include decisions, such as for how long the set of disks will be aged and which is the maximum temperature gradient to apply at the beginning and end of the stress cycles.

b) The quality parameter is selected or determined. Assuming that the quality parameter is the byte error rate (BER), a measurement of BER and a data analysis method are selected. Areas where the data is going to be written on the disks and which patterns to be used are also selected.

c) Data on the BER values versus aging time are maintained for each of the different environments selected. The slopes of these curves are then plotted versus an inverse function of the absolute temperature. An alternative to these Arrhenius plots is to plot extrapolated EOL values (in hours) derived from the BER plots versus an inverse function of the absolute temperature. (The latter is the approach used in this investigation). In either case, the life expectancy value is determined by extrapolation.

To use the Arrhenius model, the first requirement is that the plot of the quality parameter (BER) versus aging times should be a straight line. Deviations from a straight line reduce the accuracy of the predictions. In the case of major deviations from a straight line, the Arrhenius model may be not applicable for that parameter.

There are several important considerations to make in applying the Arrhenius model:

a) With limitations in testing time, some of the data on some of the disks do not reach the BER value defined as end of life within a reasonable time. Therefore, extrapolations are needed. This results in an approximation of the true EOL values for that data.

b) Data for the Arrhenius plots should be determined for three or more points to ensure that the EOL values actually do define a straight line.

c) If possible, the same drive should be used for all of the measurements with a given set of disks so that drive calibration does not become a factor in the accuracy of the results. If a drive must be replaced or calibrated during the testing of a set of disks, some means must be used to correct the data values. The approach used by NIST to correct data points generated with different drives, is described in a NIST publication [21].

3.3.2. Extrapolated Results From Modified Arrhenius Plots

Seven modified Arrhenius plots have been derived from the extrapolated EOL values shown on table 3.2 (see figs. 3.28 to 3.36). These plots use data points that are extrapolated end of life values (in hours) derived from the BER plots measured in three different areas, and using three different patterns as shown in each particular figure. The three points define a straigth line that is extrapolated to define the life expectancy values at ambient temperature. The charts also include error bars derived from the upper and lower 95% confidence limits of the BER median. Figures 3.28 to 3.30 show modified Arrhenius plots for the BER from data for all three areas, using only one pattern at the time. Figure 3.31 is a comparative graph which includes the three previous ones. Figures 3.32 to 3.34 show modified Arrhenius plots for the BER from data written in blocks of sector on three independent areas, for all three patterns. Figure 3.35 is a comparative graph which includes the three previous ones. Finally, Figure 3.36 shows a modified Arrhenius plot for the BER from data written using only the high frequency pattern in the middle area of the disk.

Table 3.3 summarizes the extrapolated life expectancy values (in years) derived from the modified Arrhenius plots on figures 3.28 to 3.30. These extrapolations were done at room temperature and at the same relative humidity used for the stress environments. The table shows that the extrapolated life expectancy values are similar using the sequential pattern or the random pattern. However, the areas written with the high frequency pattern show a shorter extrapolated life expectancy value. Note, as explained before, that the high frequency pattern used on these blocks of sectors is the hexadecimal value that produces the highest linear density possible in the disks used for the experiments.

Table 3.3 Extrapolated life expectancy values (in years) derived over the inner, middle, and outer areas using three different patterns.

Sequential	Random	High Frequency
51	45	24

Table 3.4 summarizes the extrapolated life expectancy values (in years) derived from the modified Arrhenius plots on figures 3.32, 3.33, and 3.34. These extrapolations were also done at room temperature and at the same relative humidity used for the stress environments. Note the dispersion in extrapolated life expectancy values derived from measurements of BER in different areas of the disk surface. Visual inspection of the disks showed damage effects produced by the stress conditions mainly in the outer areas, which explains the difference in BER values in the outer areas with respect to the inner and middle areas (see table 3.2).

Table 3.4 Extrapolated life expectancy values (in years) derived on three independent areas using three different patterns (high frequency, random, and sequential).

Inner area	Middle area	Outer area
140	242	12 (see text)

The Arrhenius model cannot accommodate secondary effects such as localized damages on the disks. These secondary effects are due to causes such as some damage of the sealing on the outer and inner edges of the disk due to the stress conditions that may have allowed moisture to seep in, and the handling of the disks. While these temperatures are normally used by some manufacturers, they may have been an excessive stress.

The difference between the BER values between the inner and outer areas may be explained by the amount of damage, the difference in the linear distance, and possible degradation of some of the mechanical characteristics in the outer area of the disks. A contributor to the difference in extrapolated life expectancy values between the inner and the outer areas may be the fact that in order to introduce the disks in the different stress environments, they were positioned in a small holder and separated by teflon washers from the center of the disks, which indirectly protected the inner area from secondary degradation effects. Note that the extrapolated life expectancy values on table 3.3 are also affected by these secondary effects. In this case these values reflect an average behavior that also include the damaged areas.

For the reasons just cited, the outer and inner areas are excluded in Figure 3.36, which shows a modified Arrhenius plot used to derive the extrapolated life expectancy value from BER data measured only in the middle area and on blocks of sector written only with the high frequency pattern (which gave the smaller life expectancy value in average of the three areas). Figure 3.37 shows a more conservative extrapolation. The figure shows the same modified Arrhenius plot of figure 3.36, but using an extrapolation of the upper 95% confidence limit of the BER. In both cases extrapolated life expectancy values are derived for room temperature and the same relative humidity used for the stress environments. Table 3.5 shows the extrapolated EOL values of the BER over the middle area. Table 3.6 shows the extrapolated life expectancy values for this particular combination of area/pattern.

Table 3.5 Extrapolated EOL values (in hours) over the middle area.

	60 °C, 90% RH	70 °C, 90% RH	80 °C, 90% RH
+95%	11,300	5,200	1,890
Median	15,200	8,000	1,970
-95%	24,750	34,300	2,050

Table 3.6 Extrapolated life expectancy values (in years) derived over the middle area using the high frequency pattern.

Extrapolation of the median values	Extrapolation of the upper 95% confidence limit of the BER
121	57

3.3.3 BER Control Charts for the Control Group

Figure 3.38 shows a control chart derived from BER values for the control group. These data are useful for supervising the measurement system, especially the drive behavior along the duration of the program. This was explained in Chapter 2. Periodic BER measurements of these disks show no degradation of this parameter, implying that the measurement was under statistical control. Note that the hours plotted range from 3000 hours from the beginning of the experiments to 10000 hours. These data were taken running BER measurements in the drive used for the experiments.

Before the tests shown in this figure, another drive was used for the experiments and these type of data were also taken. However, this drive went out of calibration because of the intensive tests run. This was detected using a control chart similar to the one shown in figure 3.38. After the first 2000 hours of tests, the data for the control group run in that drive went beyond $Z = 3$. These data were removed from the calculations of BER derived from that drive. After the drive was sent for recalibration, tests of BER for the control group showed again values of $Z < 3$. This approach is recommended to monitor the behavior of the measurement system when monitoring of absolute parameters is cumbersome, time consuming, or the resources for recalibrating the measuring system in-house are not available, as in this case. The assumption is that the control group of disks does not change characteristics rapidly (especially the BER values).

3.4. Optical Inspection of the Media

As mentioned in Chapter 2, an optical inspection system has been used to visually inspect the media between aging tests. The disks were periodically inspected between aging tests. Some defects were located and the images stored. The typical defect size was approximately equivalent to the width of four tracks, that is, a maximum value of 6.4 micrometers. Observations of the disks have also shown some spots, especially in the outer areas of both the blank and user data areas. It is reasonable to infer that water has penetrated the media through the outer seal. This effect was more severe for disks aged at 80 °C. From the results of BER, it is reasonable to infer that these spots are one of the reasons why the BER in the outer areas was usually higher than in the other two. These spots show in the results as systematic errors in the BER and EOL values.

3.5 CNR Results

Figures 3.39, 3.40, and 3.41 show the aging effect on the CNR values for three different tracks, located in the inner, middle, and outer areas. The response was fairly flat for both the disks aged at 60 °C, 90% RH and 70 °C, 90% RH. A decrease of CNR values can be observed for the set of disks aged at 80 °C and 90% RH. The plots in figure 3.41 show that the decrease is more significant in the outer area than in the inner area. The figure shows a worst case decrease of 10% of the CNR values on the outer track tested. Figure 3.42 shows CNR versus time (in hours) for the control group. The plots show that the response was fairly flat, denoting that variation of the CNR values in aged disks was due to the stress environments and not because of measurement errors. The flat response of the control group shows no variation in the measurement conditions.

3.6 Reflectance Measurement Results

Figures 3.43 through 3.48 show reflectance of the blank inner and outer bands of each surface for over 4000 hours of aging for the sets aged at 70 °C, 90% RH, and 80 °C, 90% RH, and for over 5000 hours for the set aged at 60 °C, 90% RH. The reflectance measurement method used allows testing only the approximate area tested before. However, the data collected is considered representative of the respective bands. The maximum increase observed in the values is approximately 5% of the blank reflectance values in both bands of the disks aged at 80 °C, 90% RH. Figures 3.49 and 3.50 show reflectance values versus time (in hours) for the control group for the inner and outer bands respectively. As in the case of the CNR experiments, the response for this group was fairly flat, denoting that variation of the reflectance values in aged disks was due to the stress environments and not because of measurements errors.

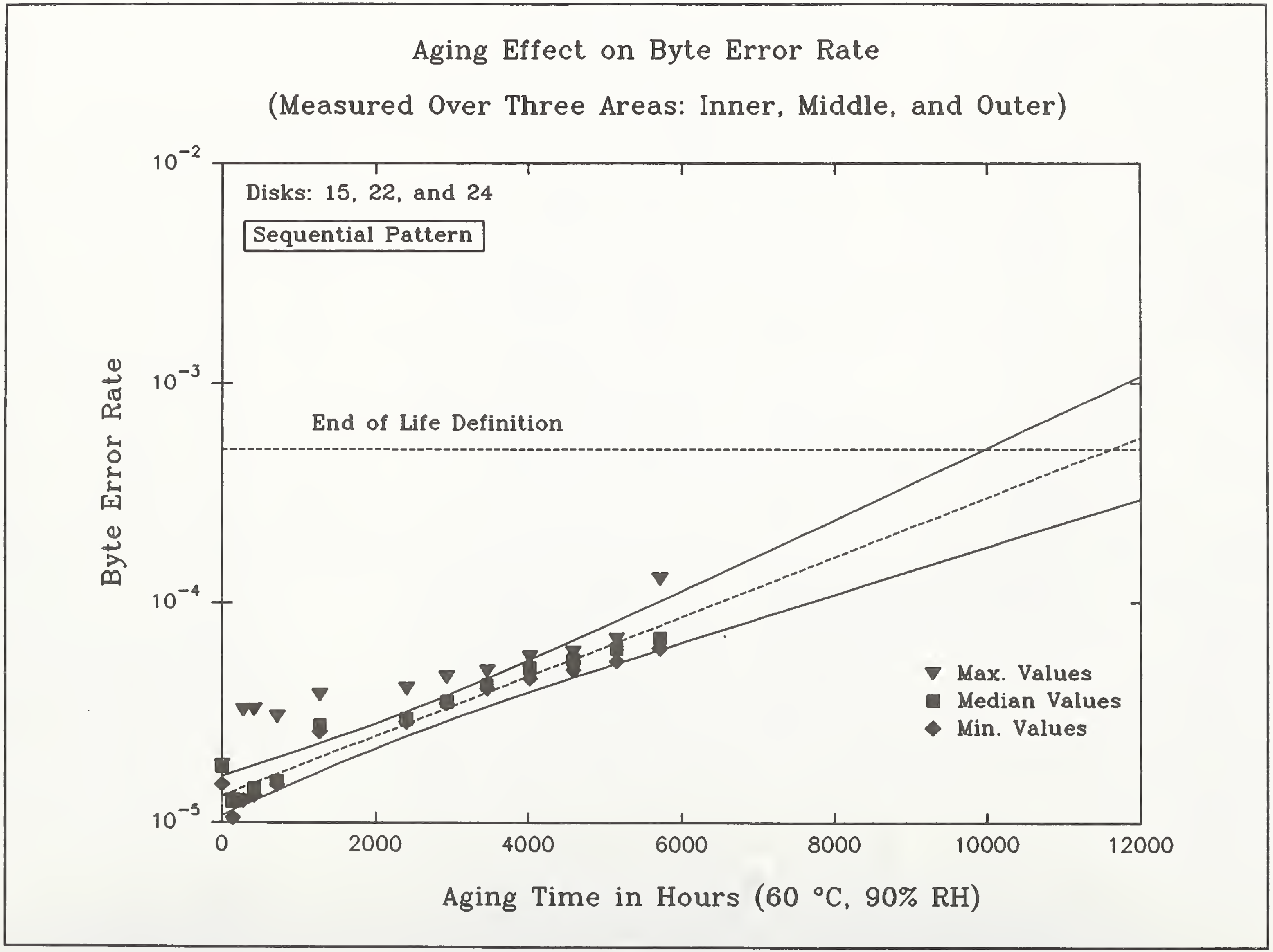


Figure 3.1. BER versus aging time (sequential pattern).

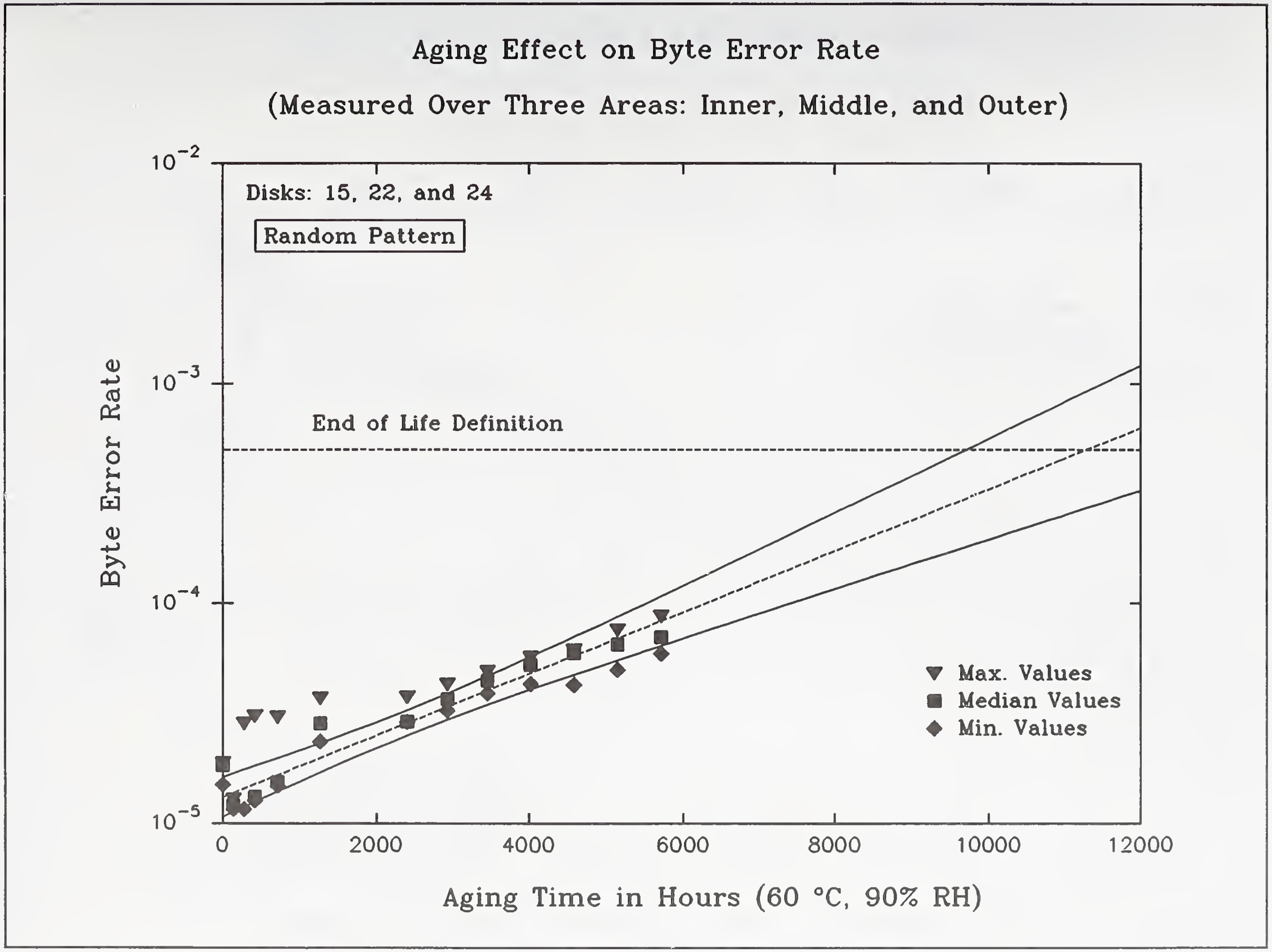


Figure 3.2. BER versus aging time (random pattern).

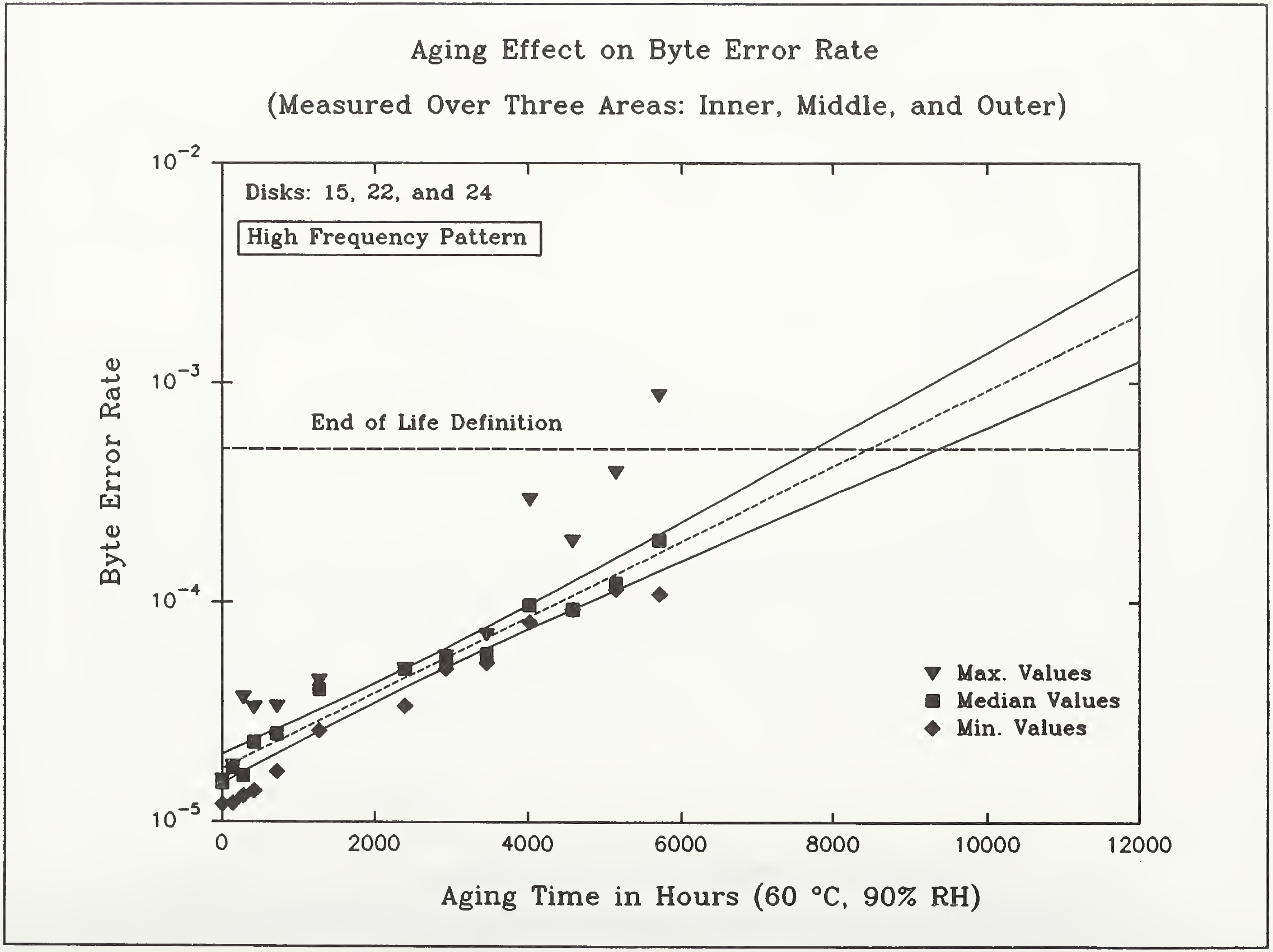
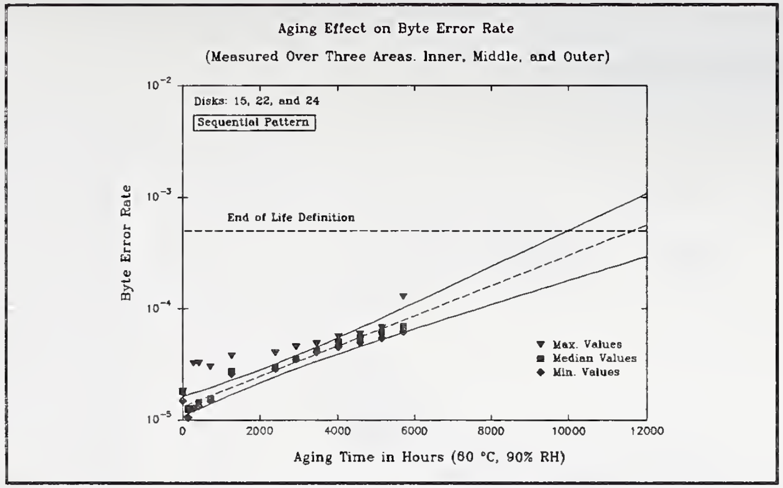
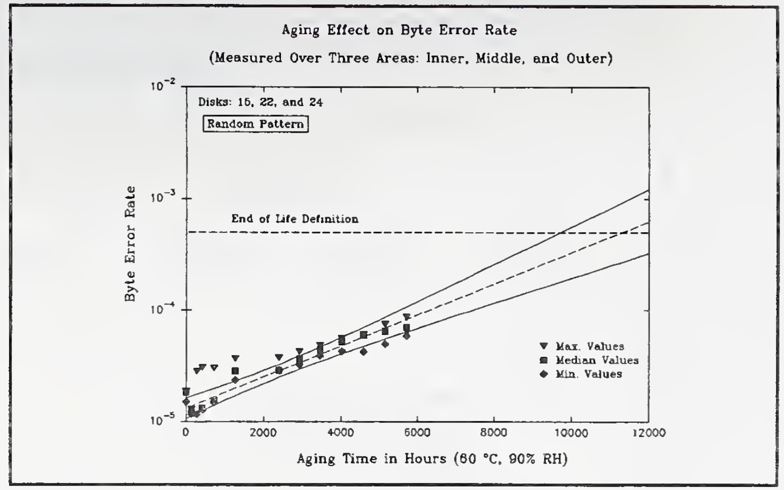


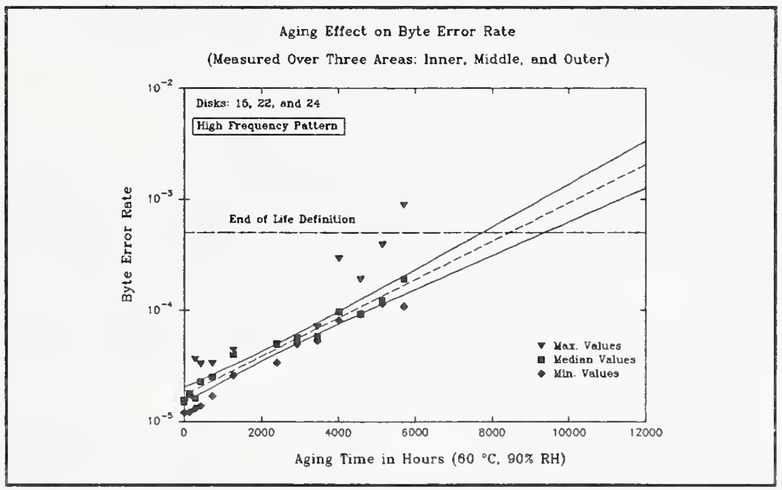
Figure 3.3. BER versus aging time (high frequency pattern).



(a)



(b)



(c)

Figure 3.4. BER versus aging time at 60 °C, 90% RH for three patterns.

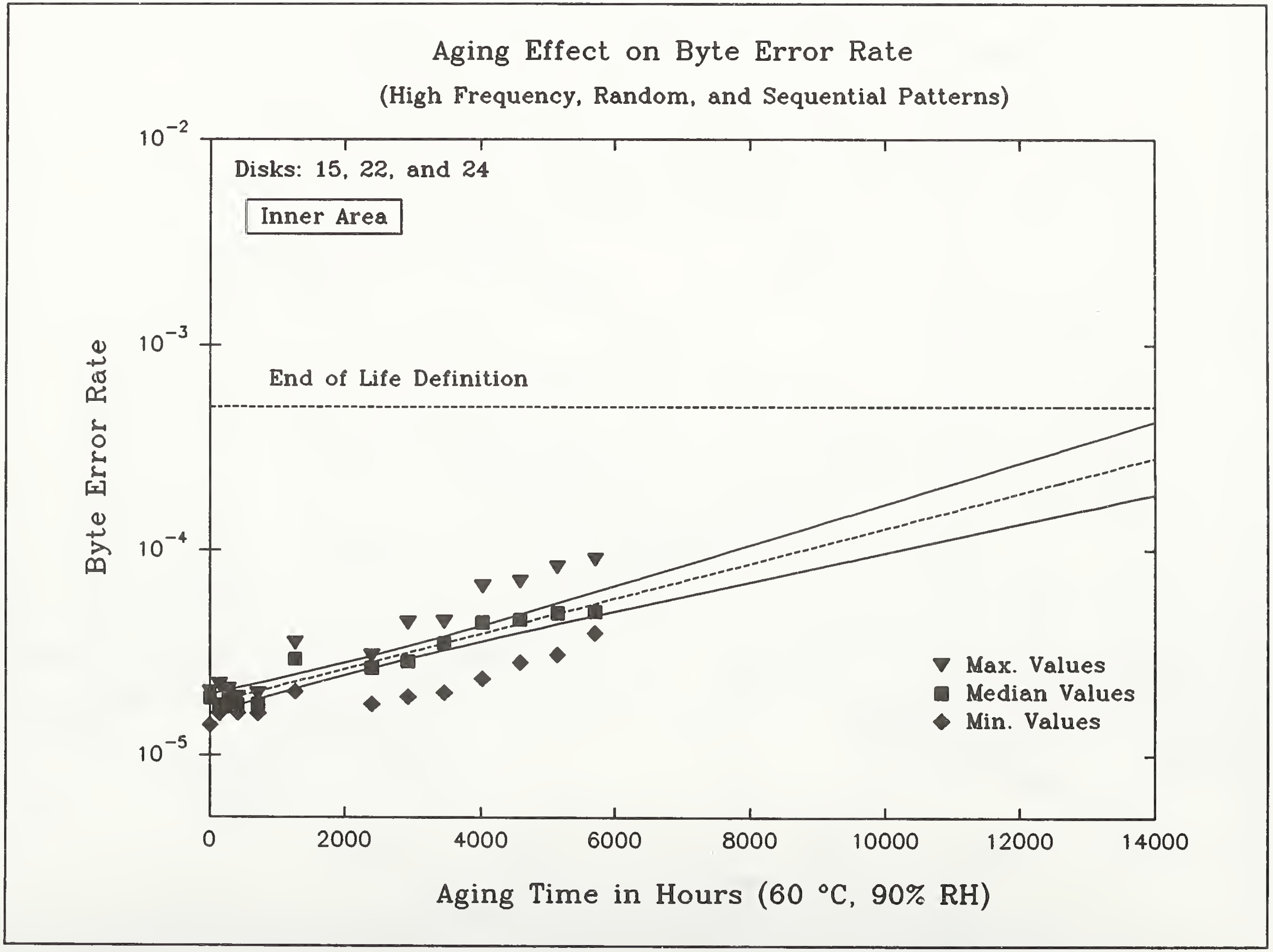


Figure 3.5. BER versus aging time (inner area).

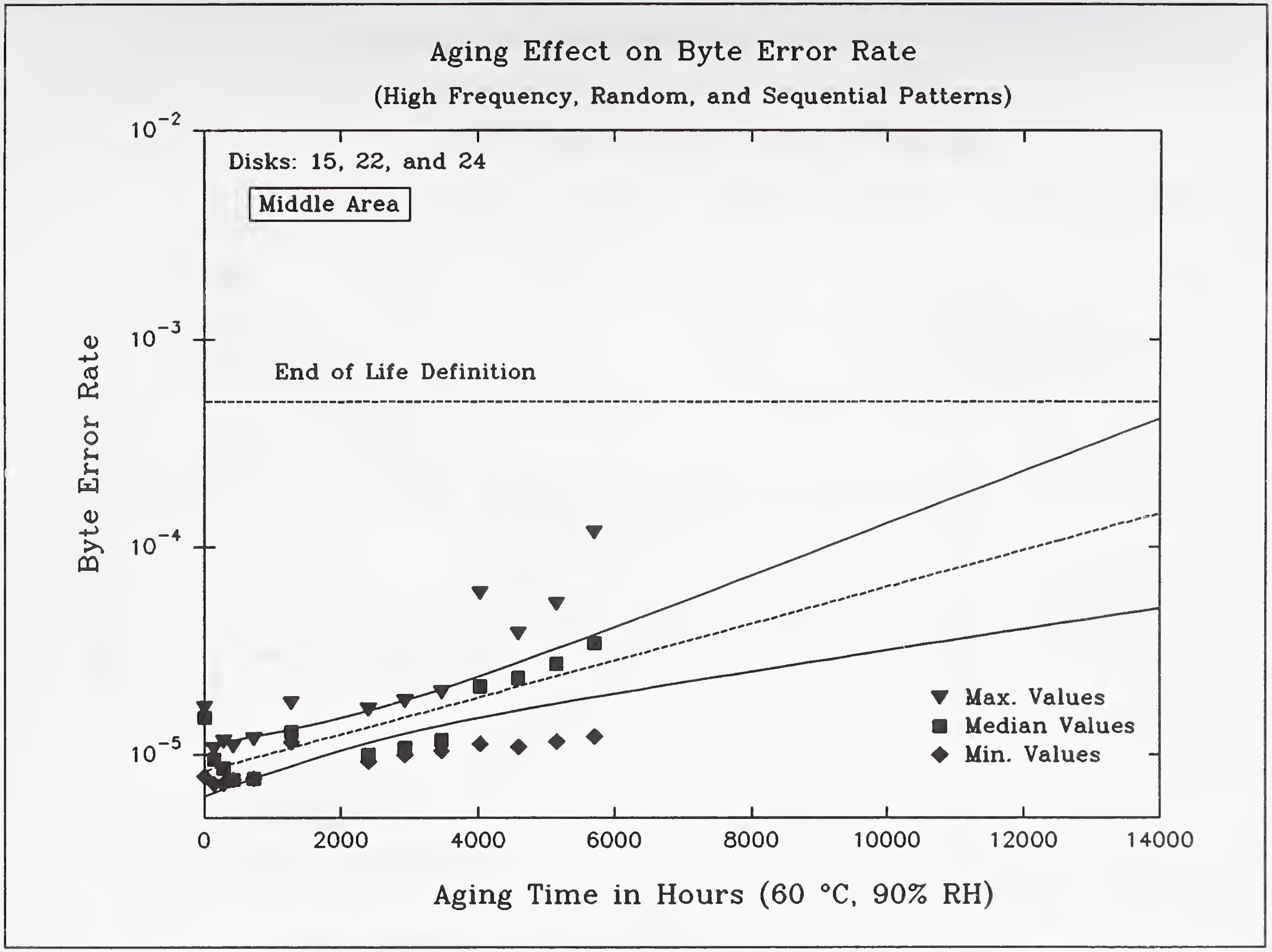


Figure 3.6. BER versus aging time (middle area).

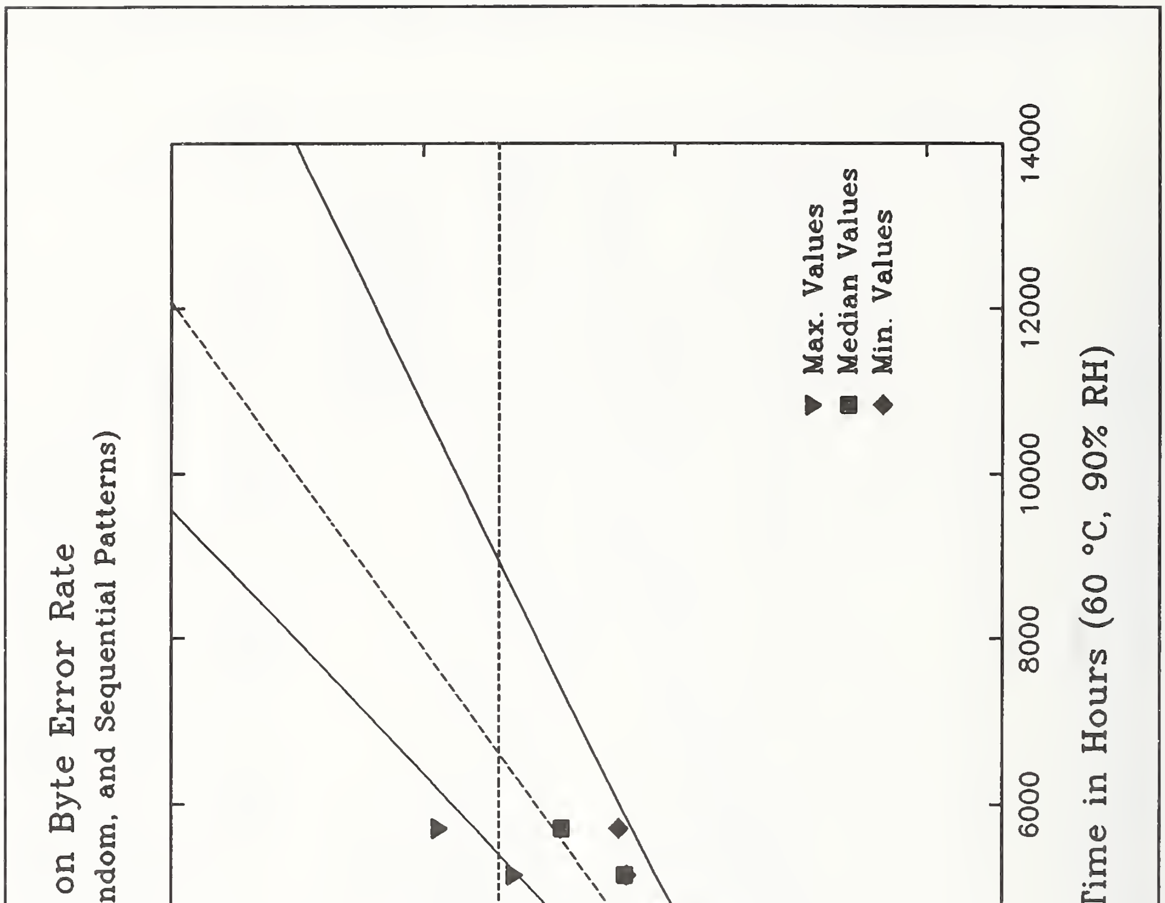
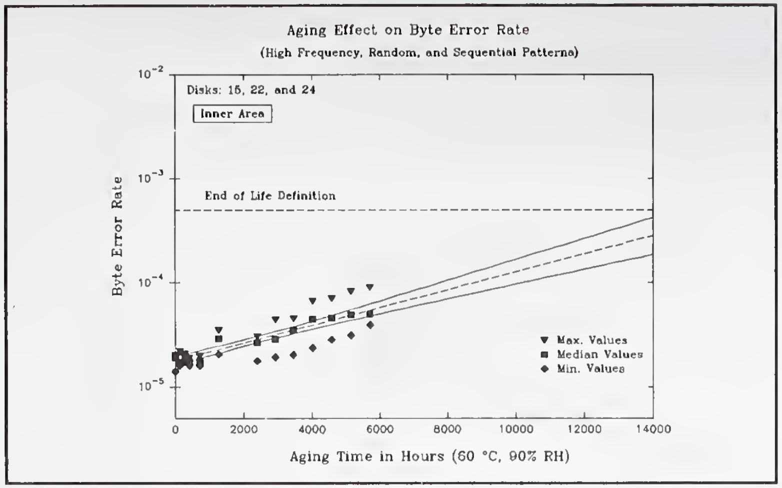
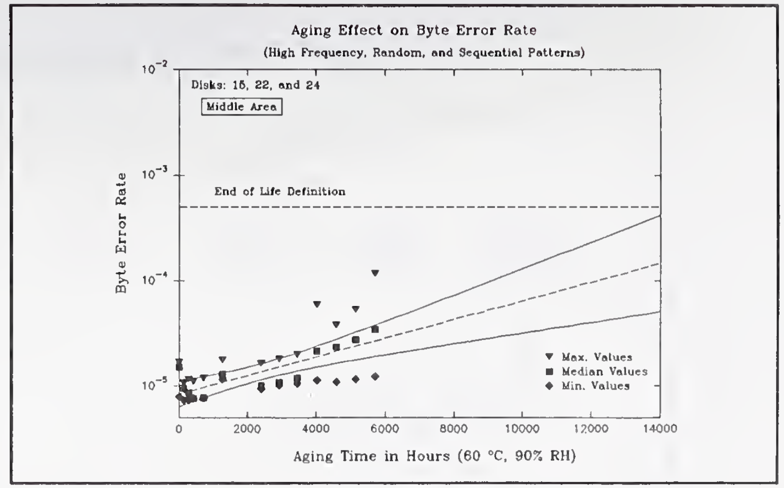


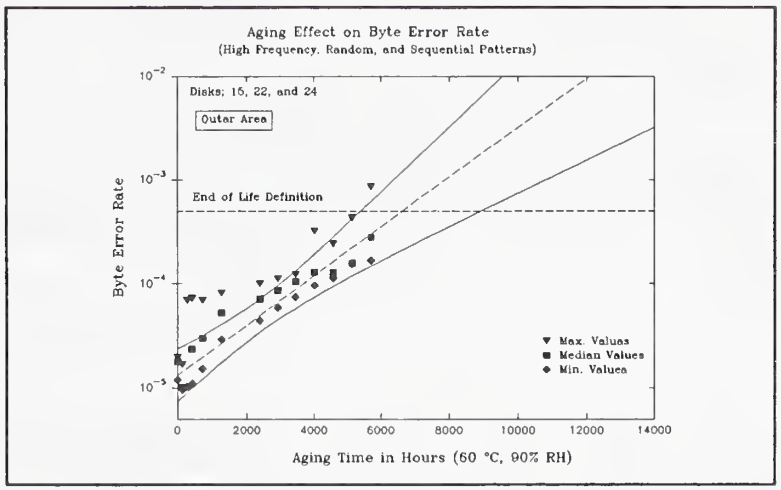
Figure 3.7. BER versus aging time (outer area).



(a)



(b)



(c)

Figure 3.8. BER versus aging time at 60 °C, 90% RH for three areas.

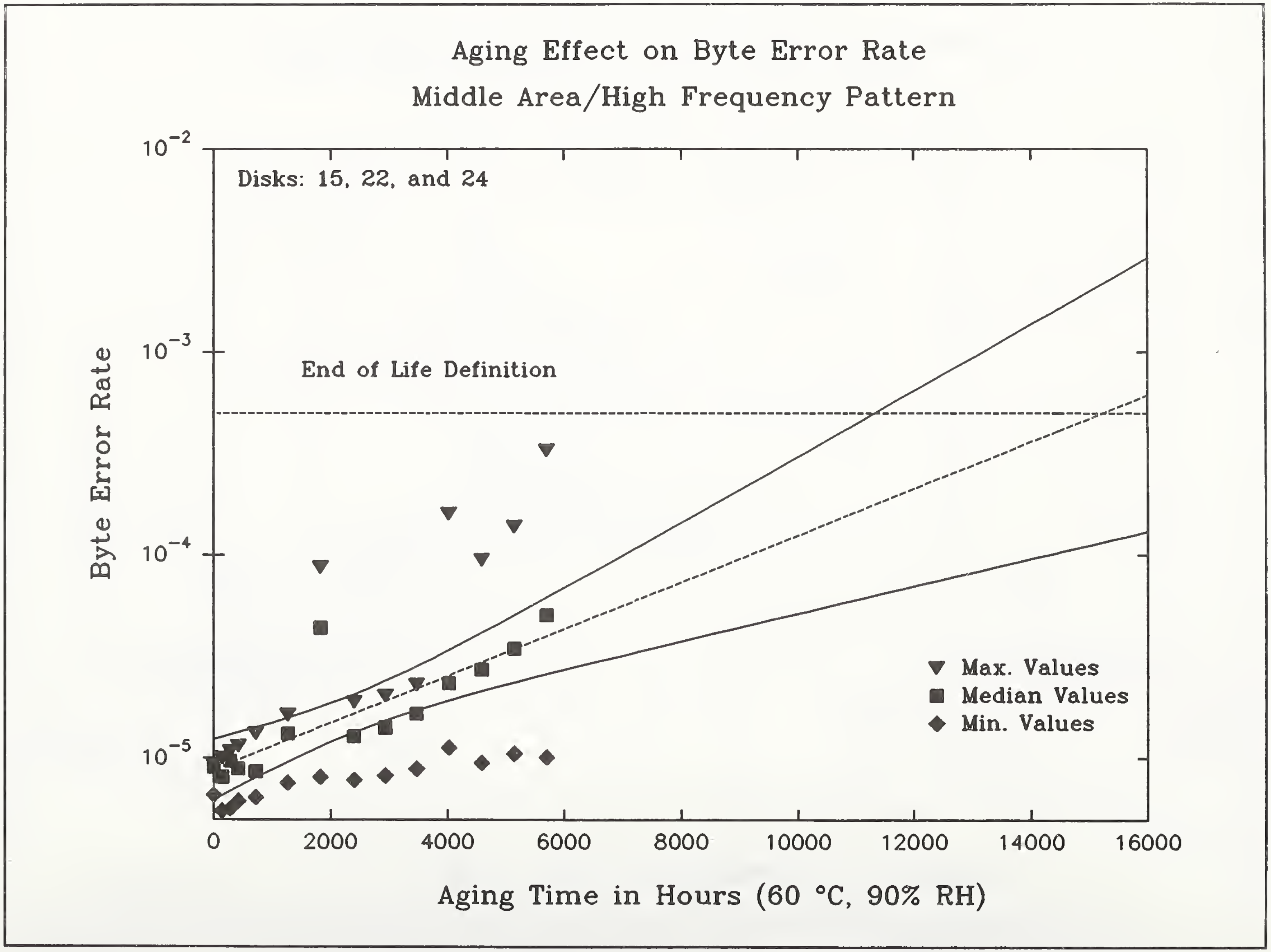


Figure 3.9. BER versus aging time (middle area/high frequency pattern).

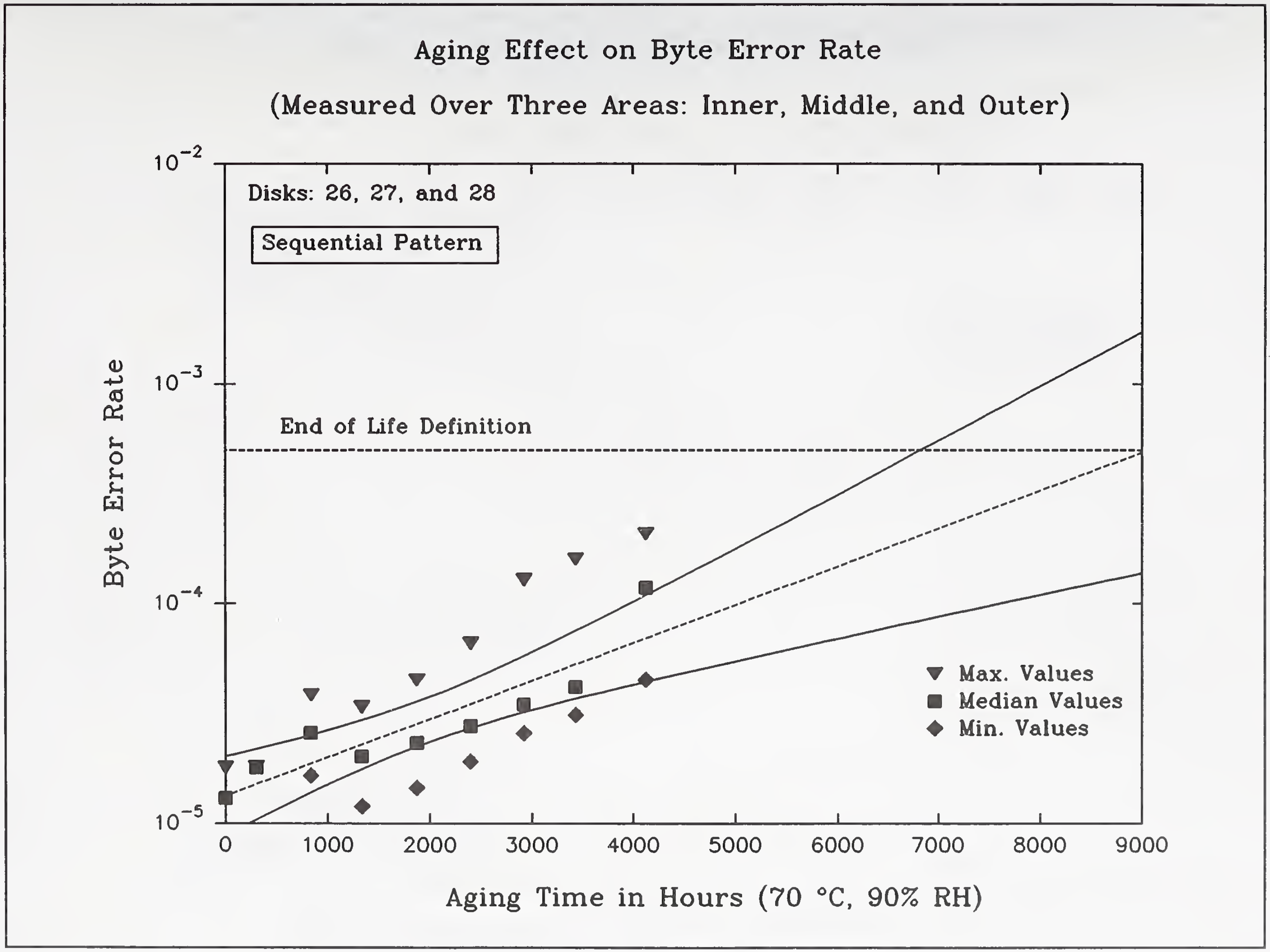


Figure 3.10. BER versus aging time (sequential pattern).

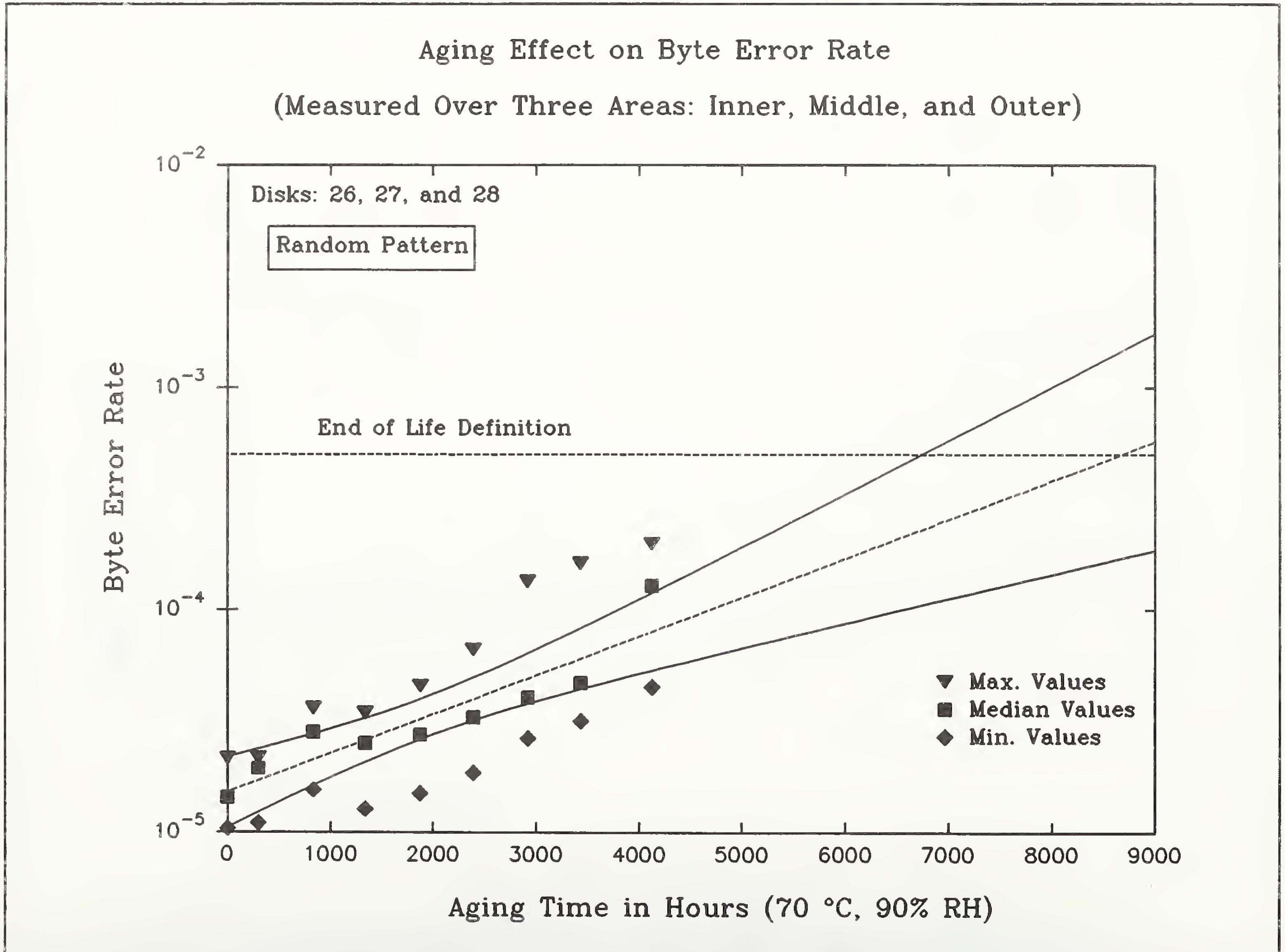


Figure 3.11. BER versus aging time (random pattern).

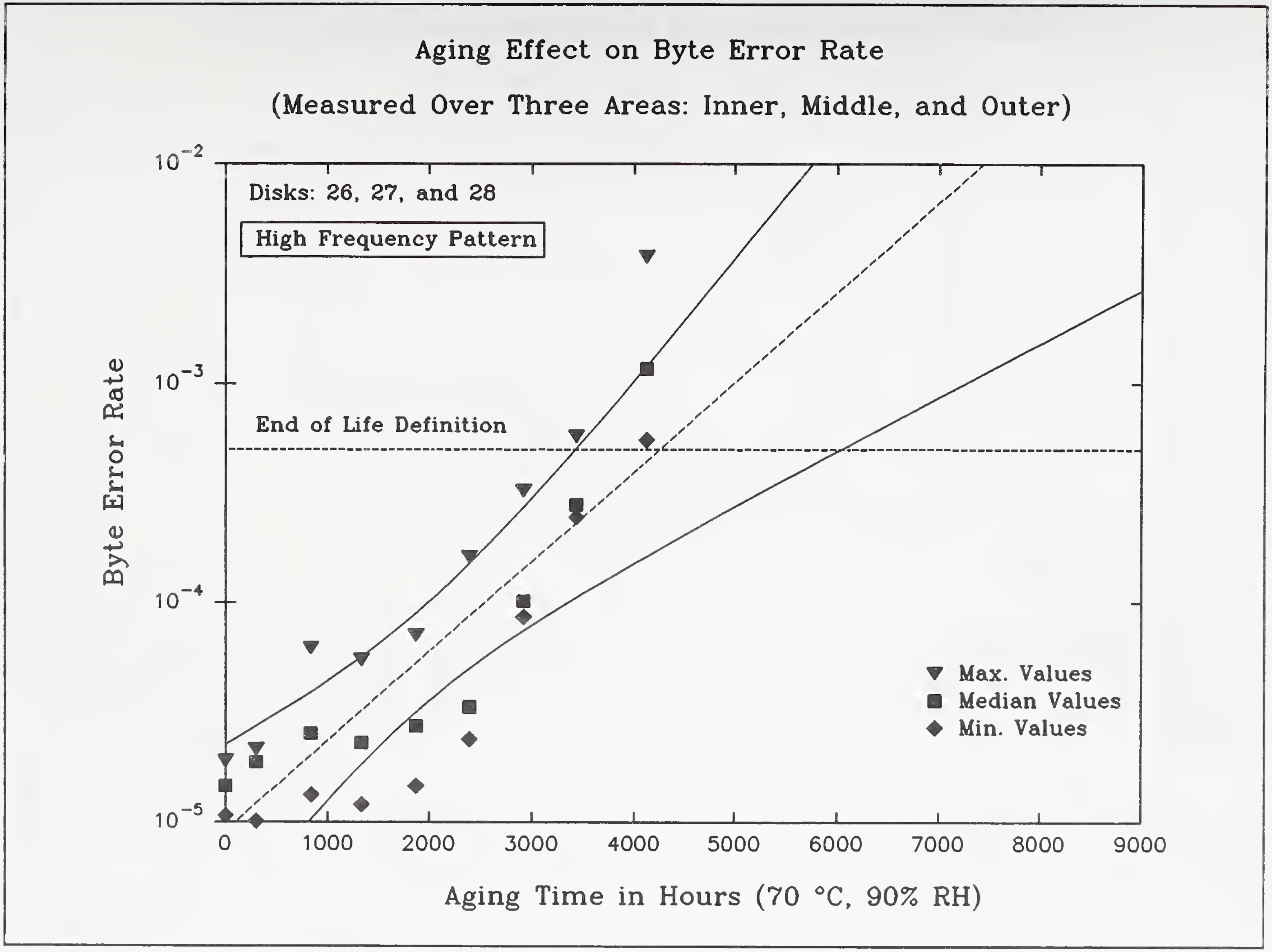
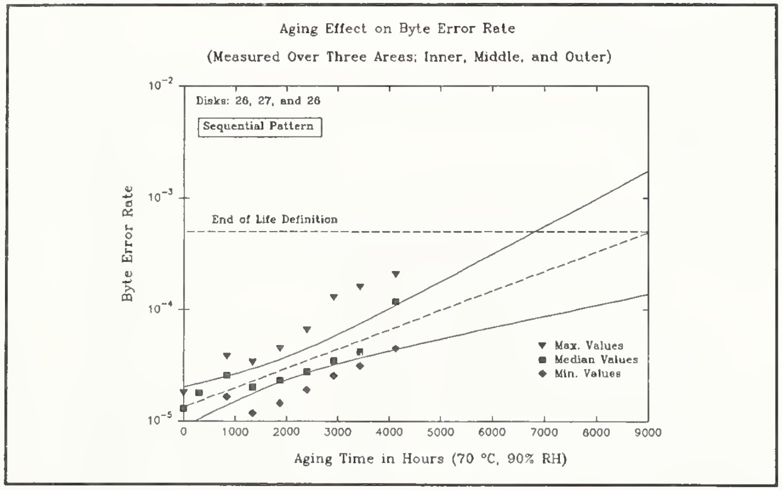
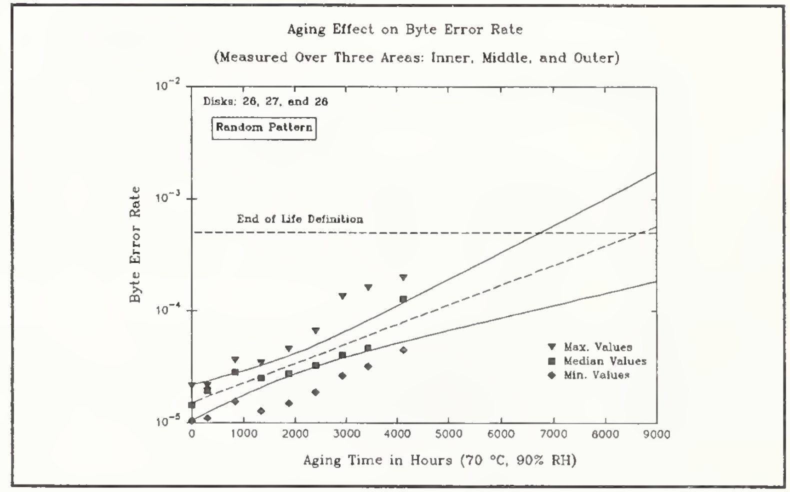


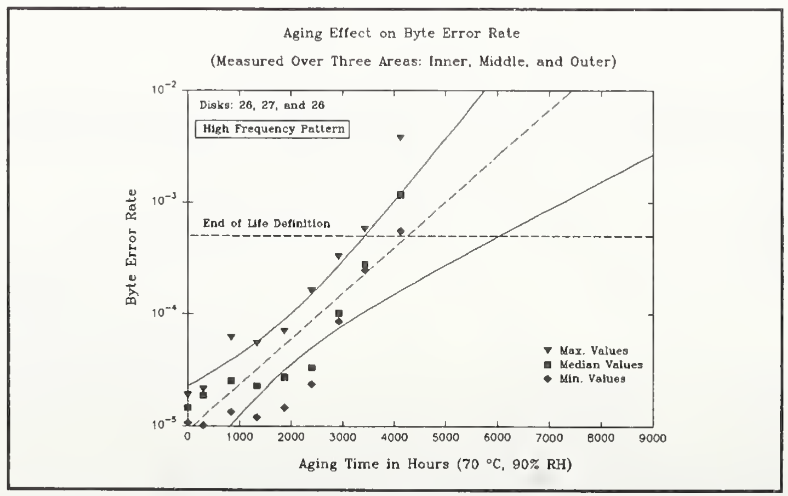
Figure 3.12. BER versus aging time (high frequency pattern).



(a)



(b)



(c)

Figure 3.13. BER versus aging time at 70 °C, 90% RH for three patterns.

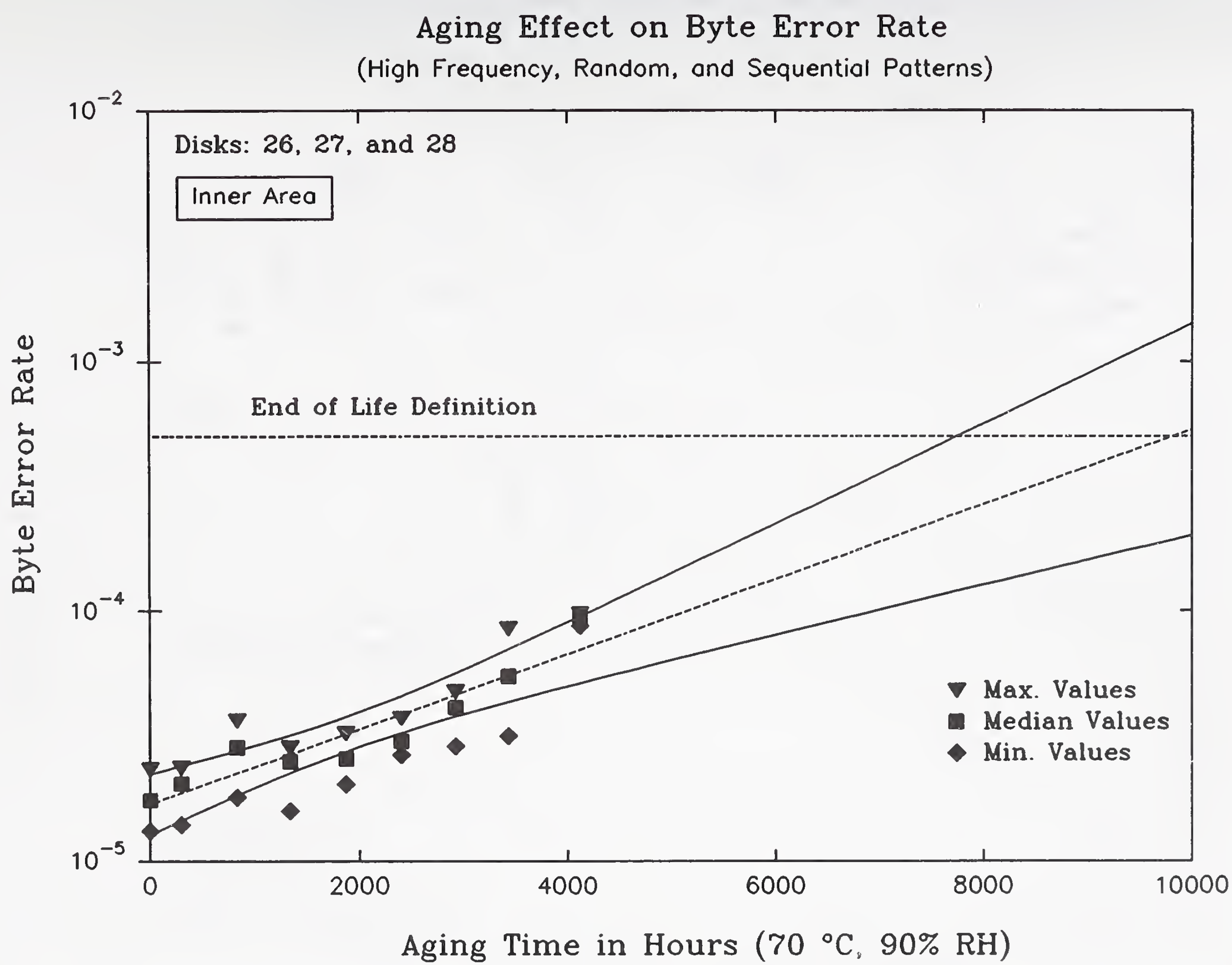


Figure 3.14. BER versus aging time (inner area).

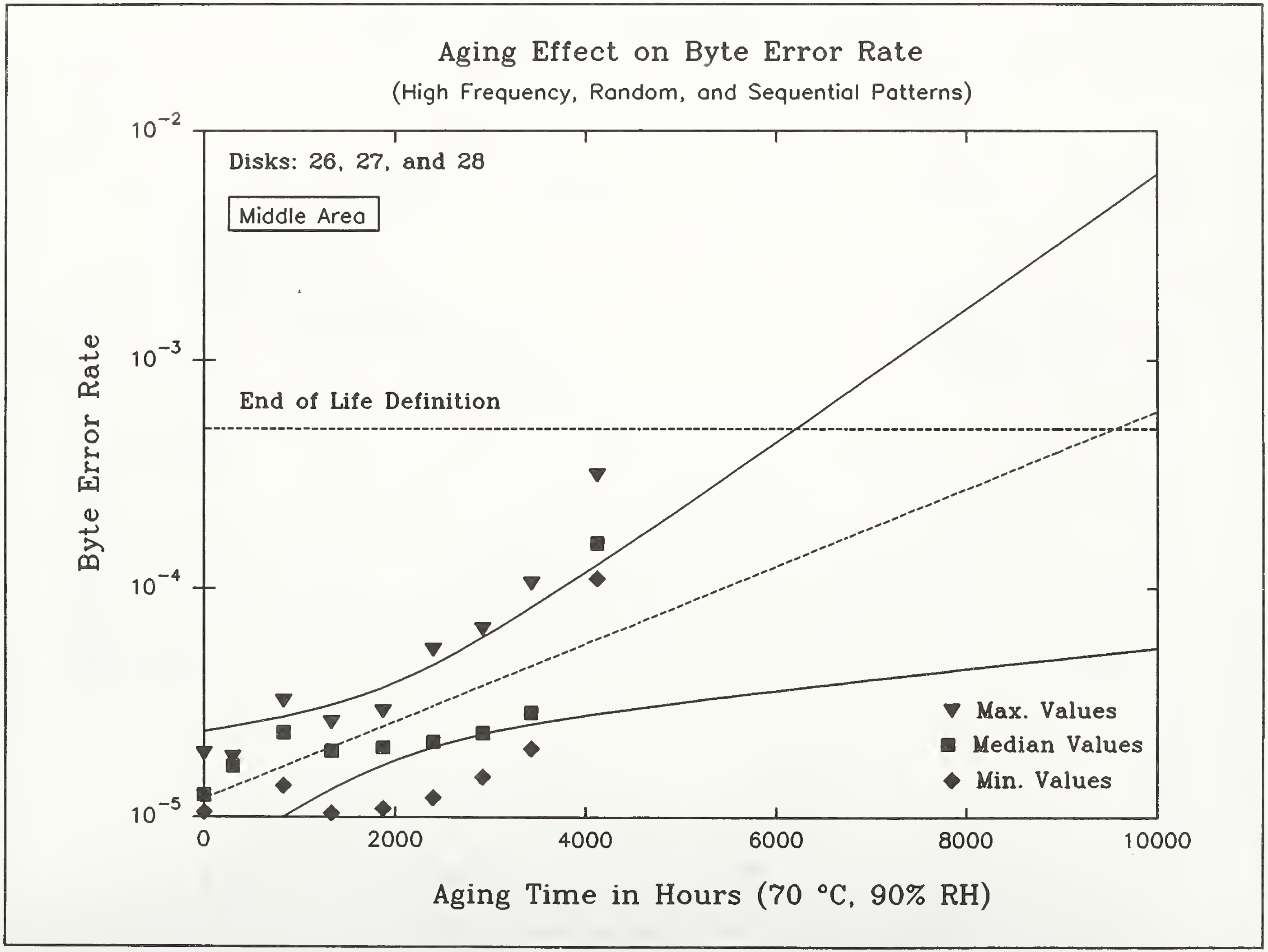


Figure 3.15. BER versus aging time (middle area).

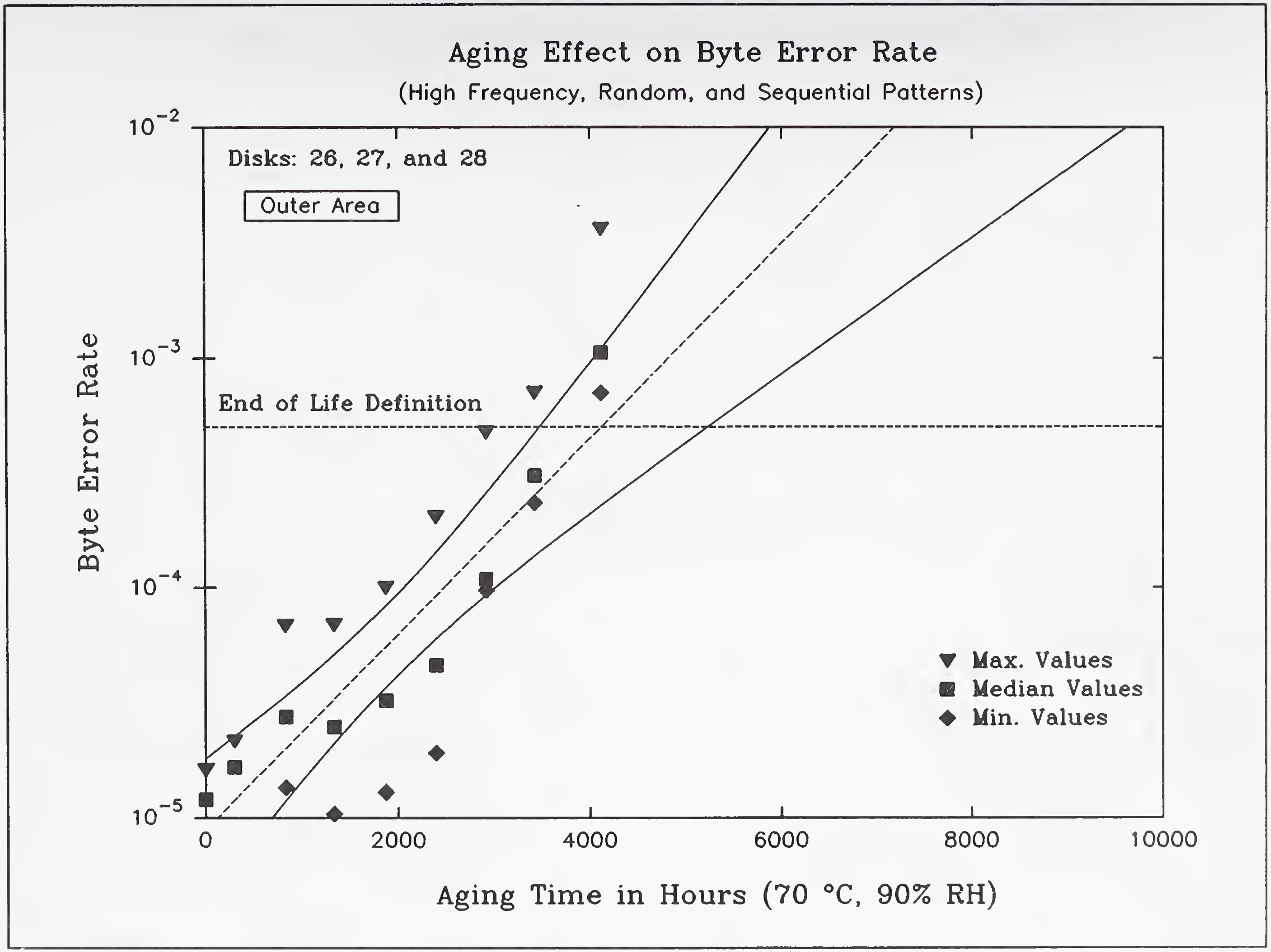
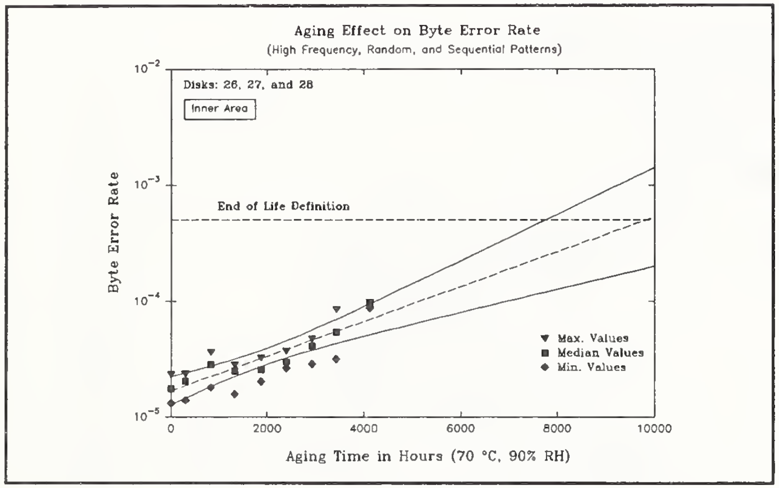
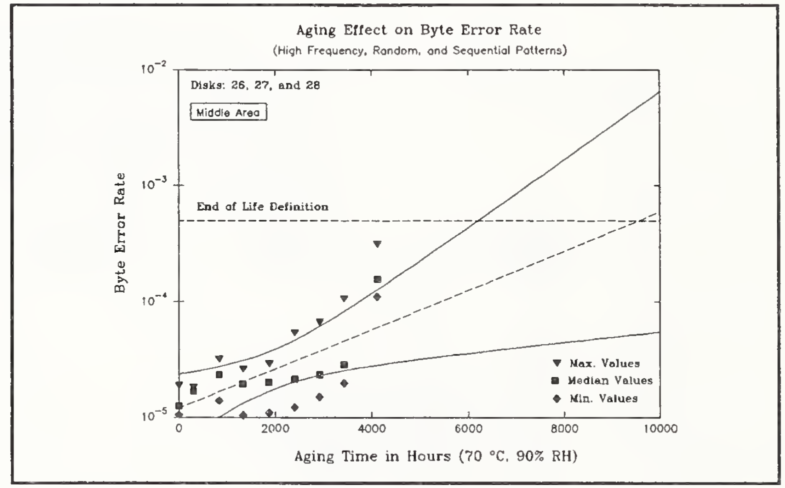


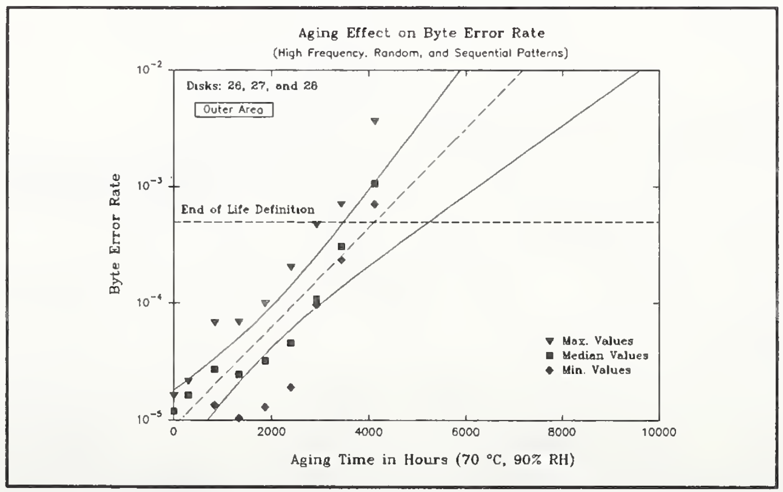
Figure 3.16. BER versus aging time (outer area).



(a)



(b)



(c)

Figure 3.17. BER versus aging time at 70 °C, 90% RH for three areas.

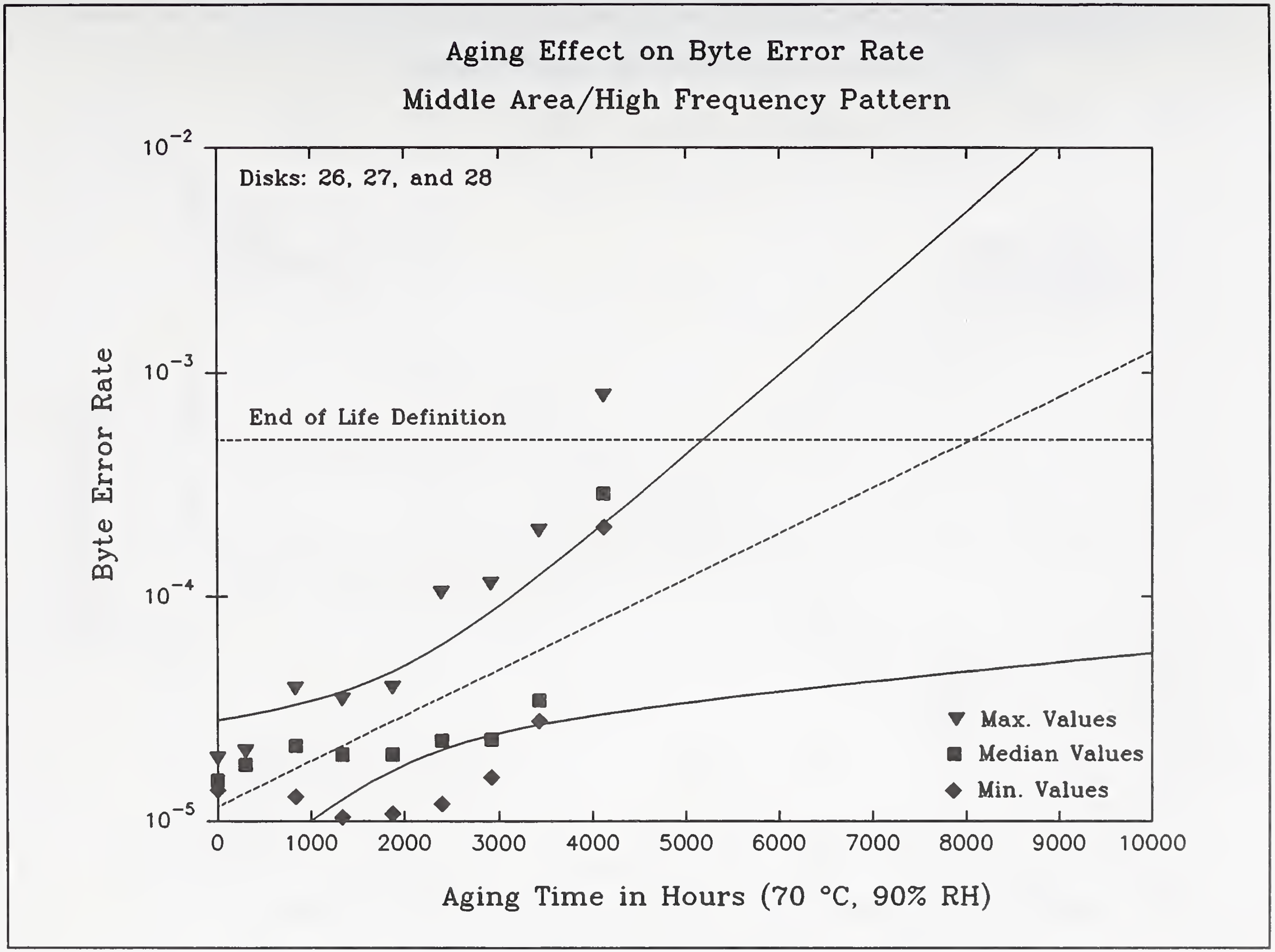


Figure 3.18. BER versus aging time (middle area/high frequency pattern).

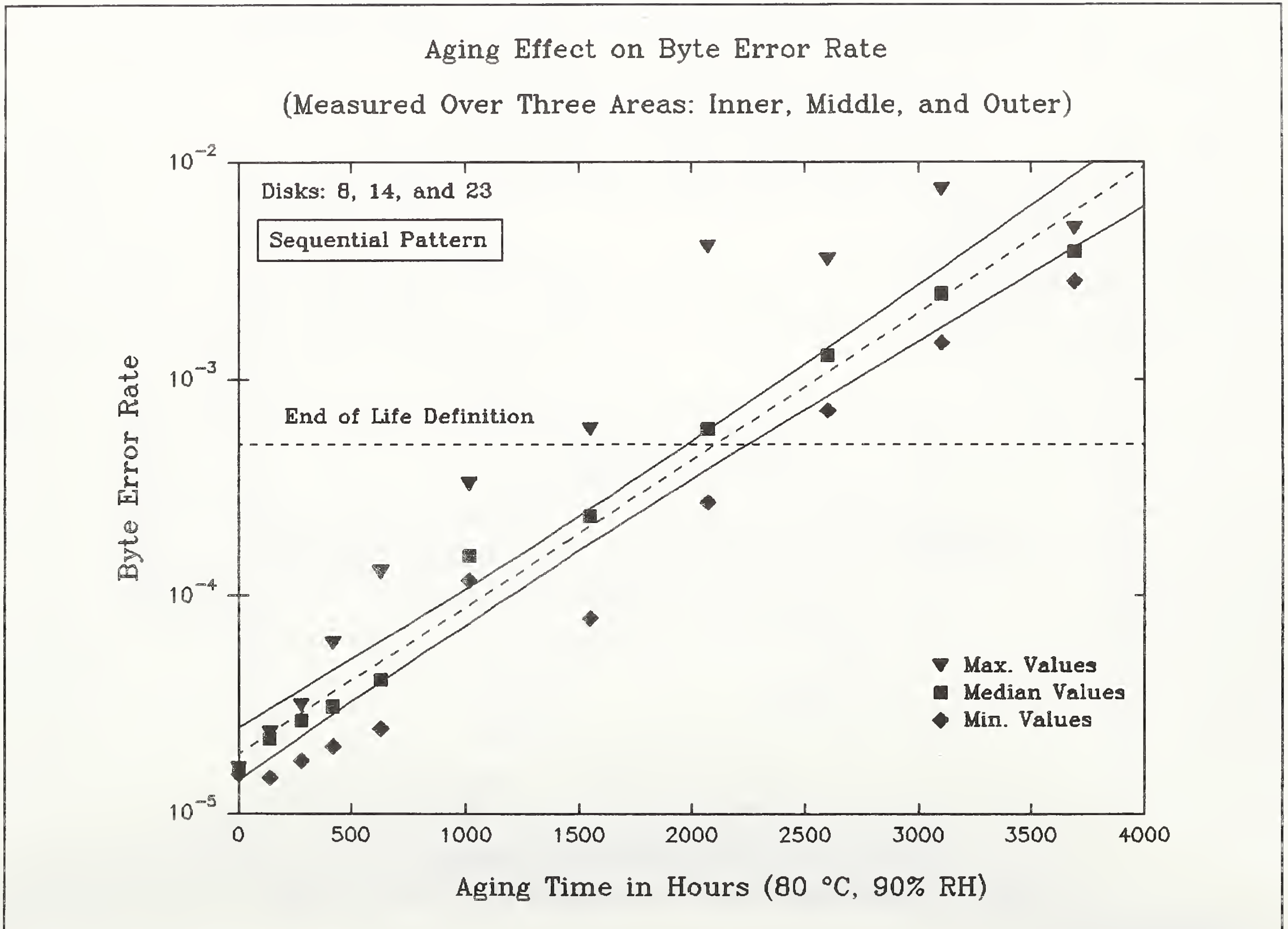


Figure 3.19. BER versus aging time (sequential pattern).

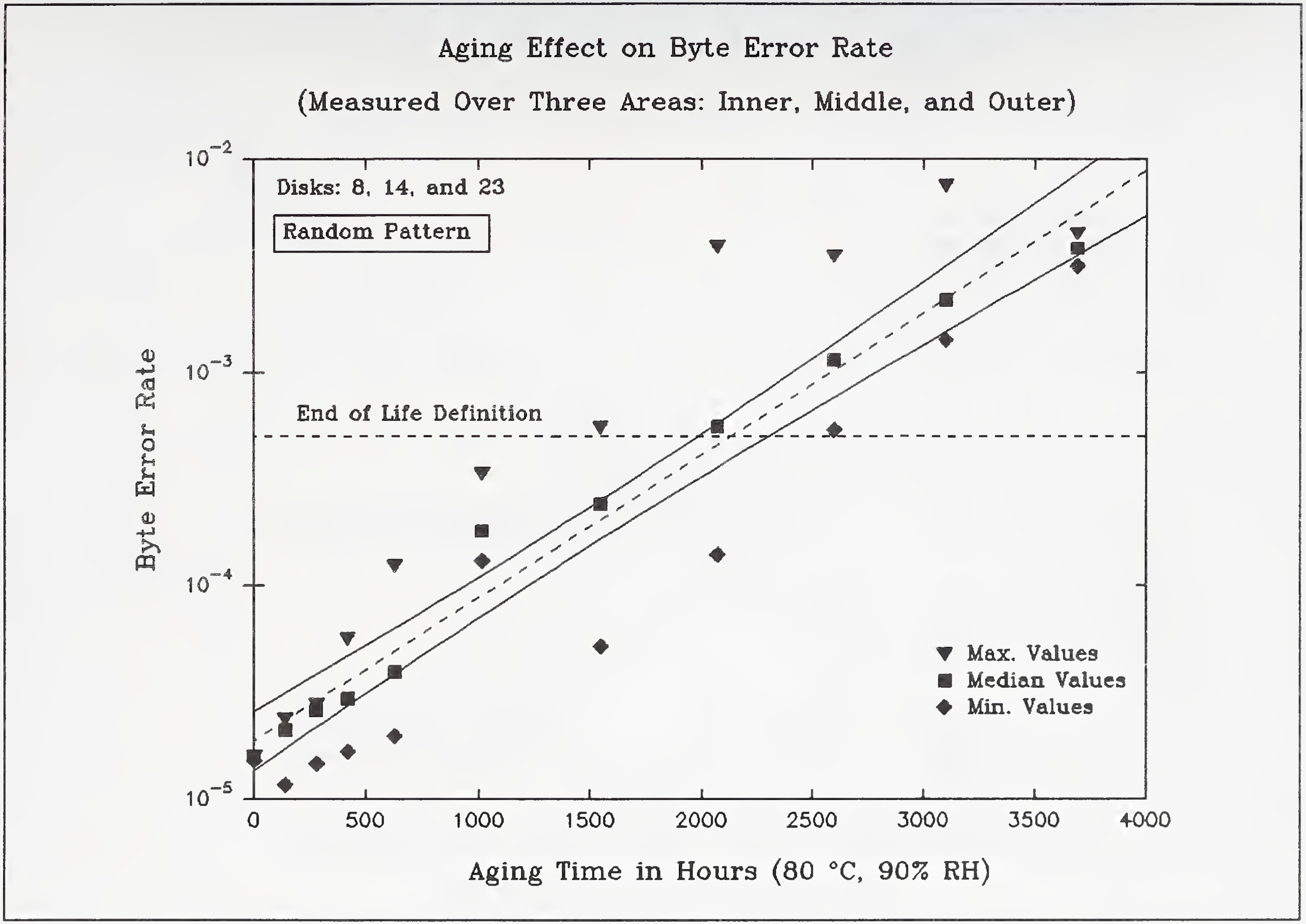


Figure 3.20. BER versus aging time (random pattern).

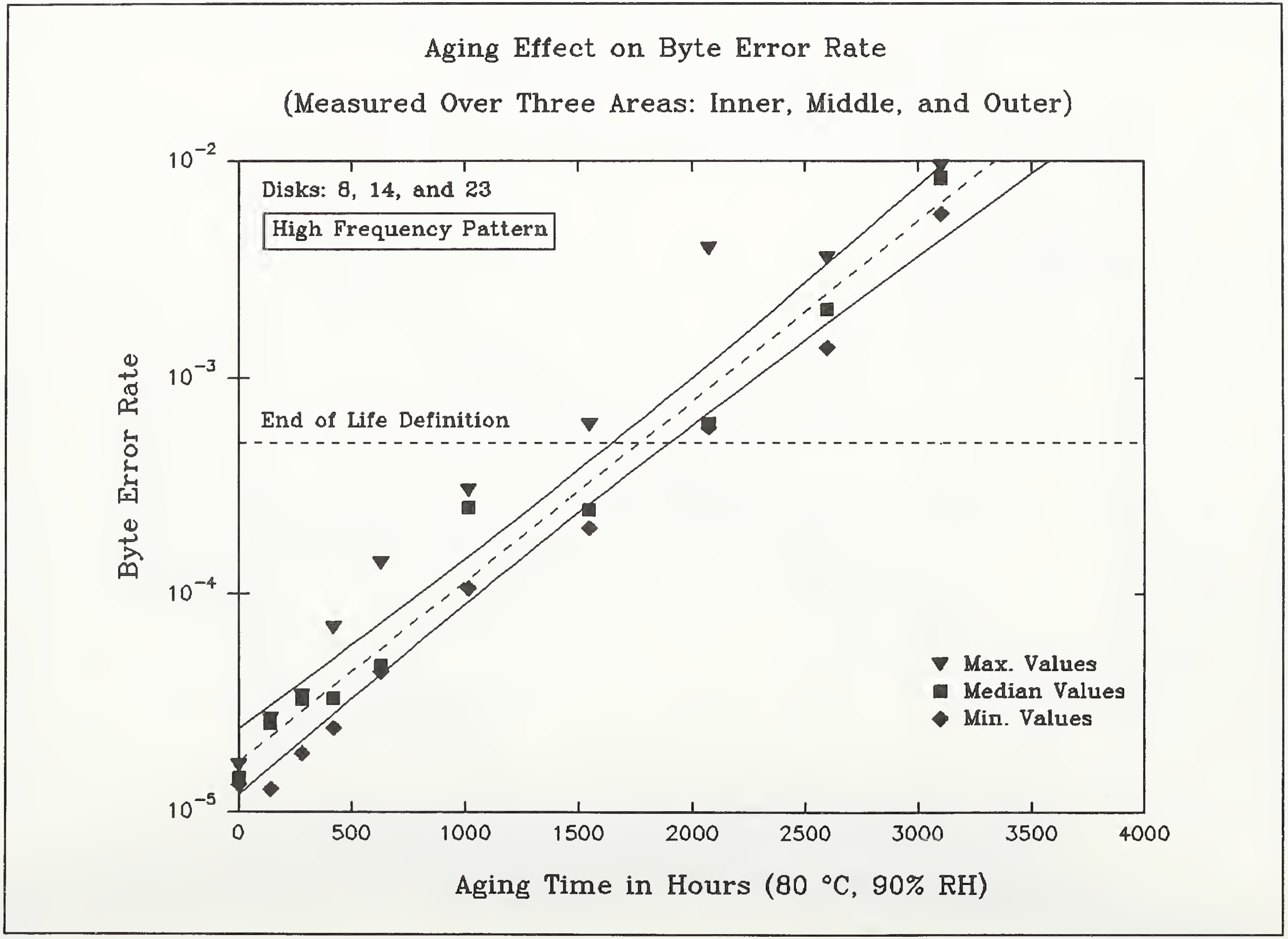
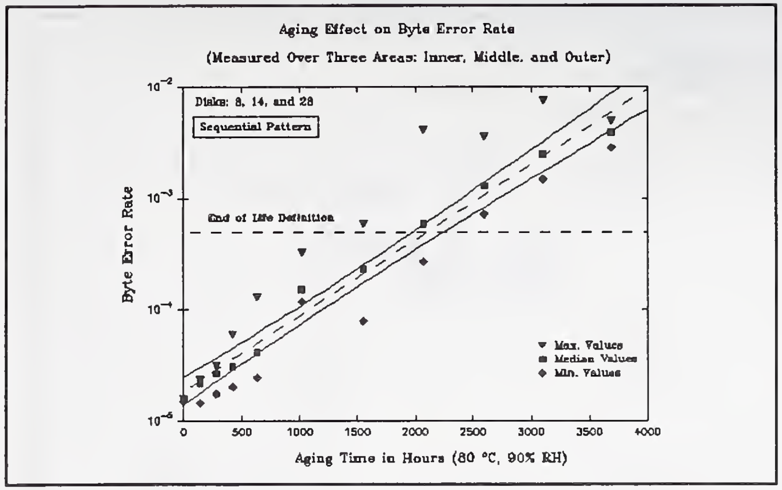
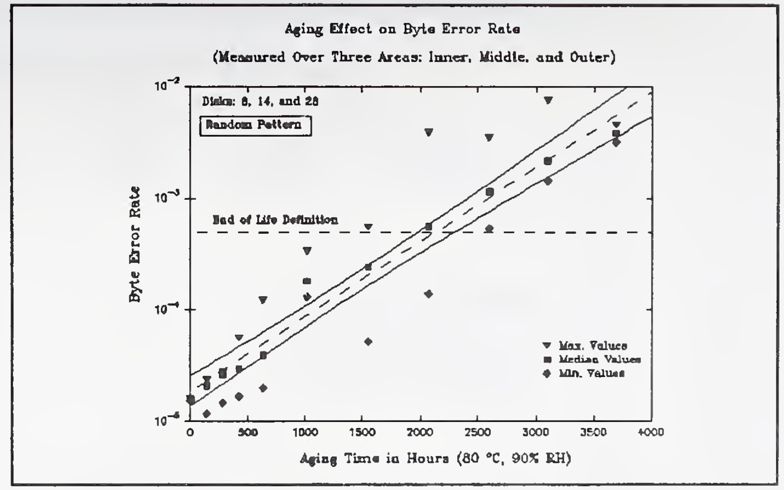


Figure 3.21. BER versus aging time (high frequency pattern).



(a)



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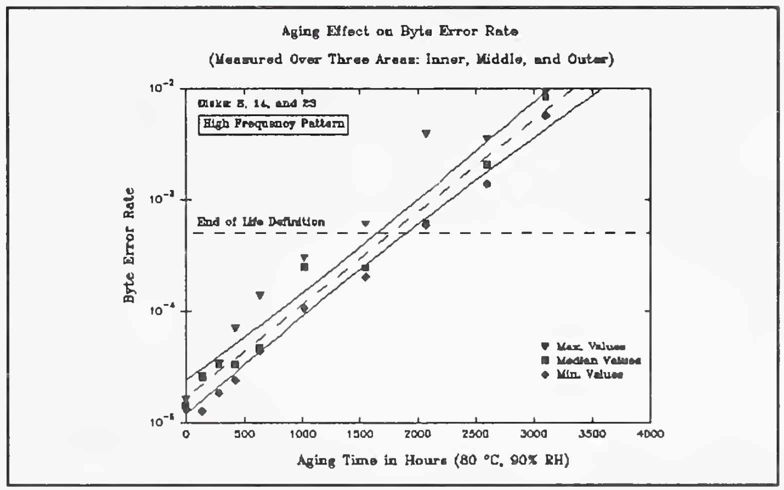


(c)

Figure 3.22. BER versus aging time at 80 °C, 90% RH for three patterns.

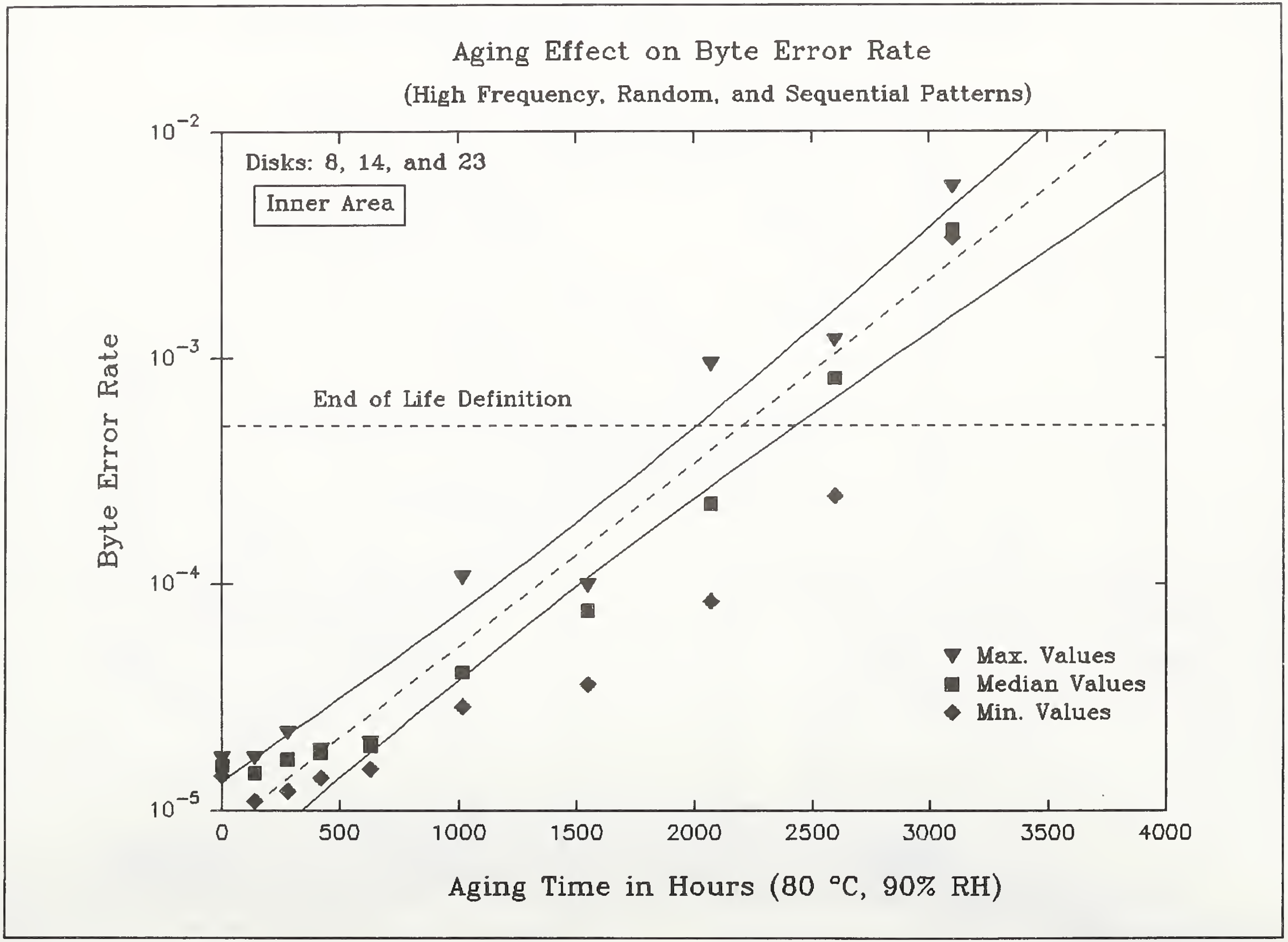


Figure 3.23. BER versus aging time (inner area).

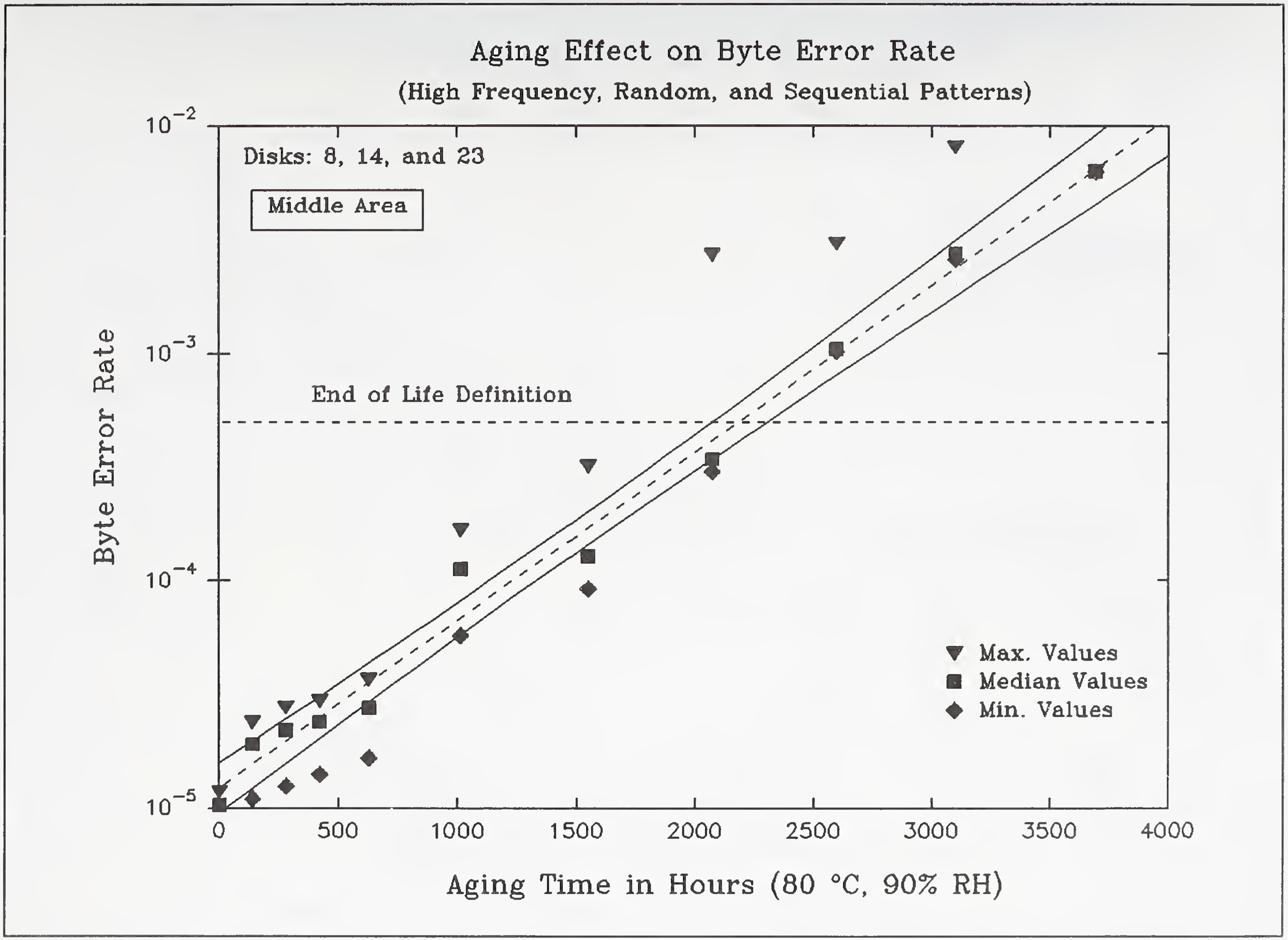


Figure 3.24. BER versus aging time (middle area).

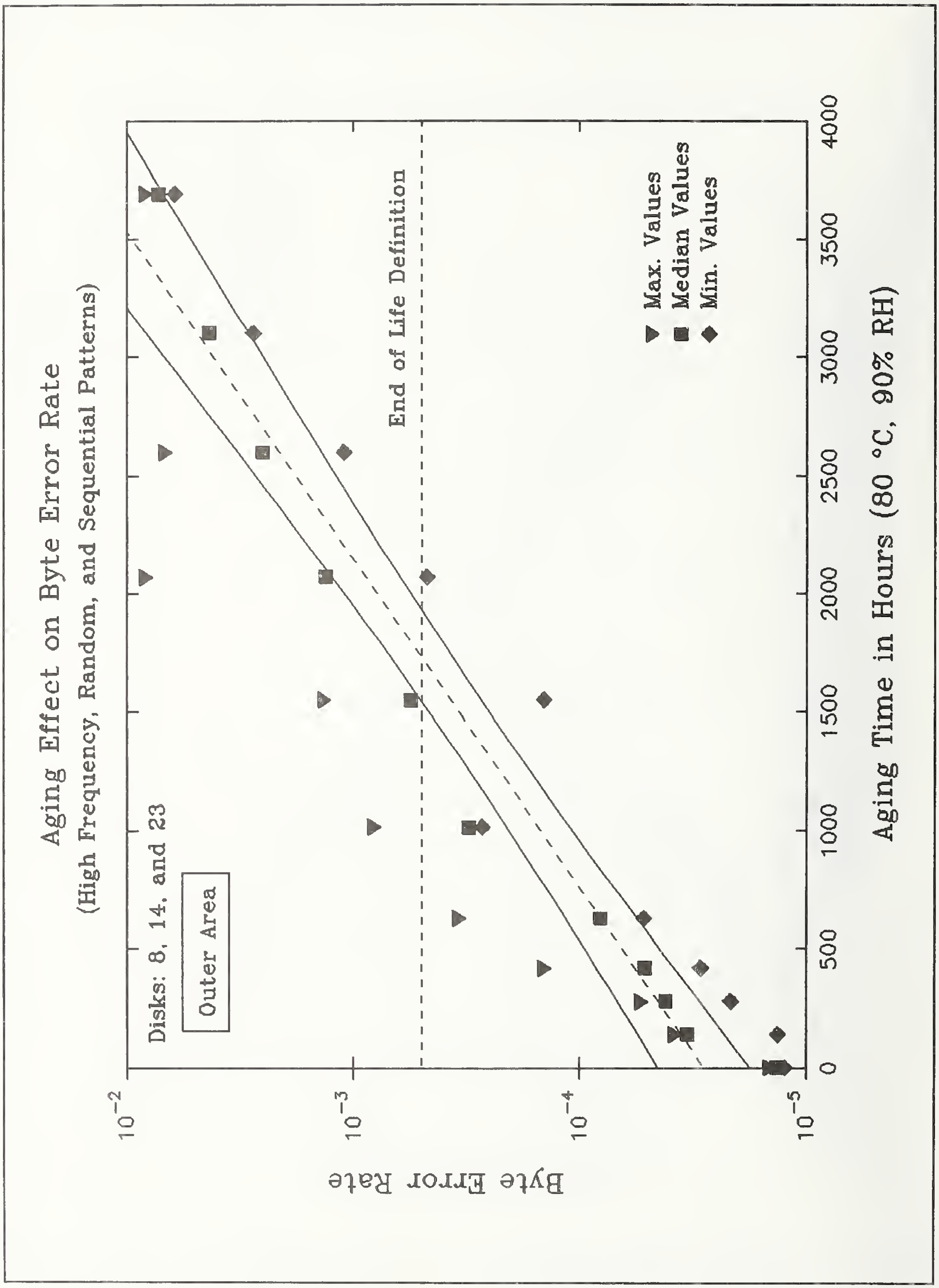
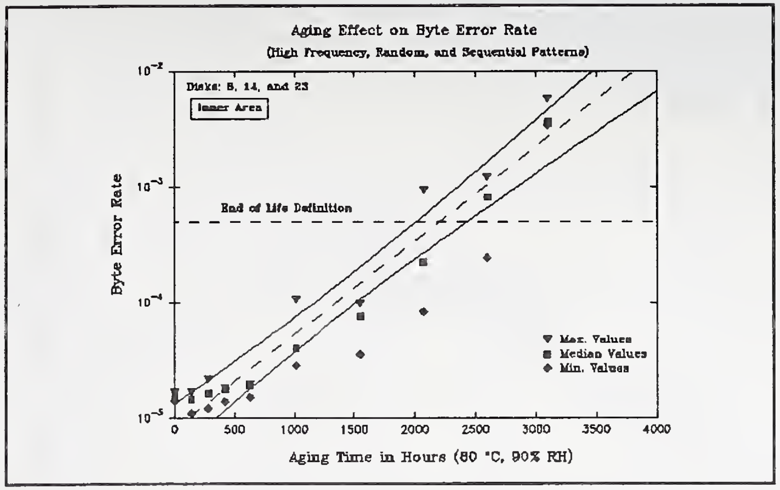
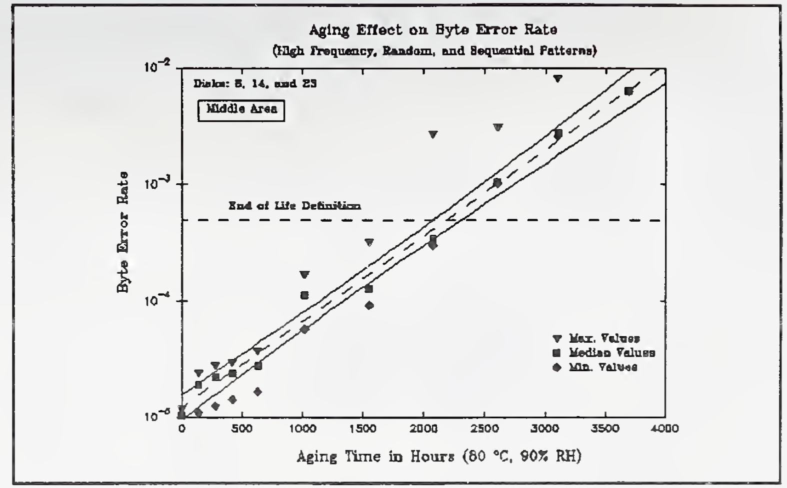


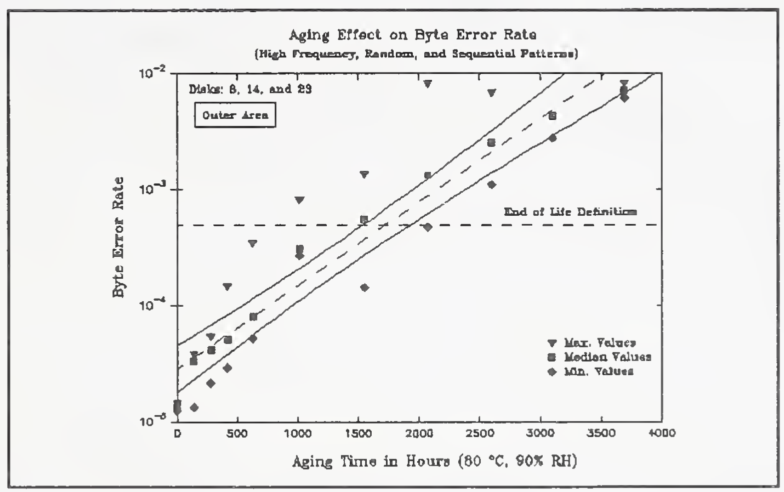
Figure 3.25. BER versus aging time (outer area).



(a)



(b)



(c)

Figure 3.26. BER versus aging time at 80 $^\circ$C, 90% RH for three areas.

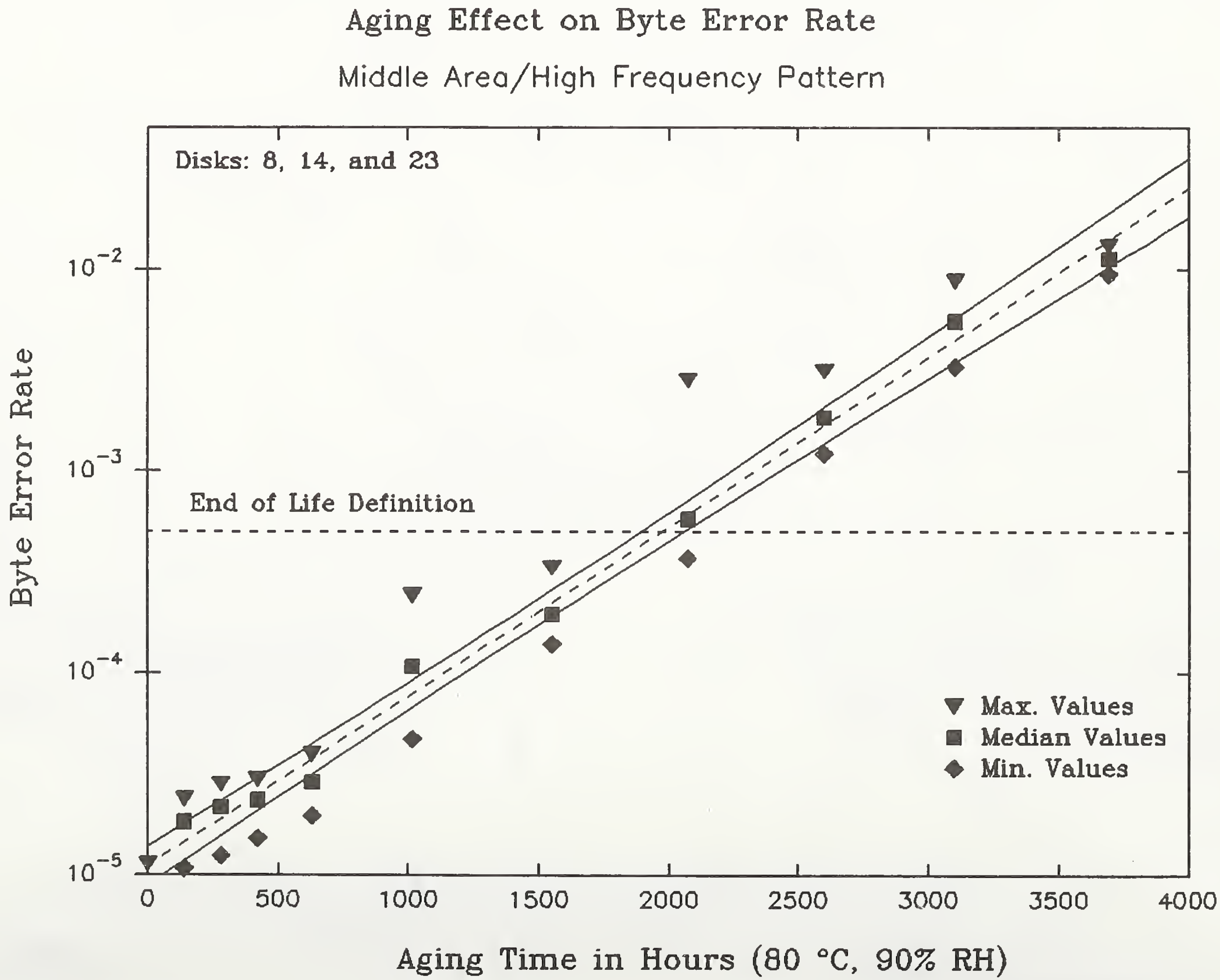


Figure 3.27. BER versus aging time (middle area/high frequency pattern).

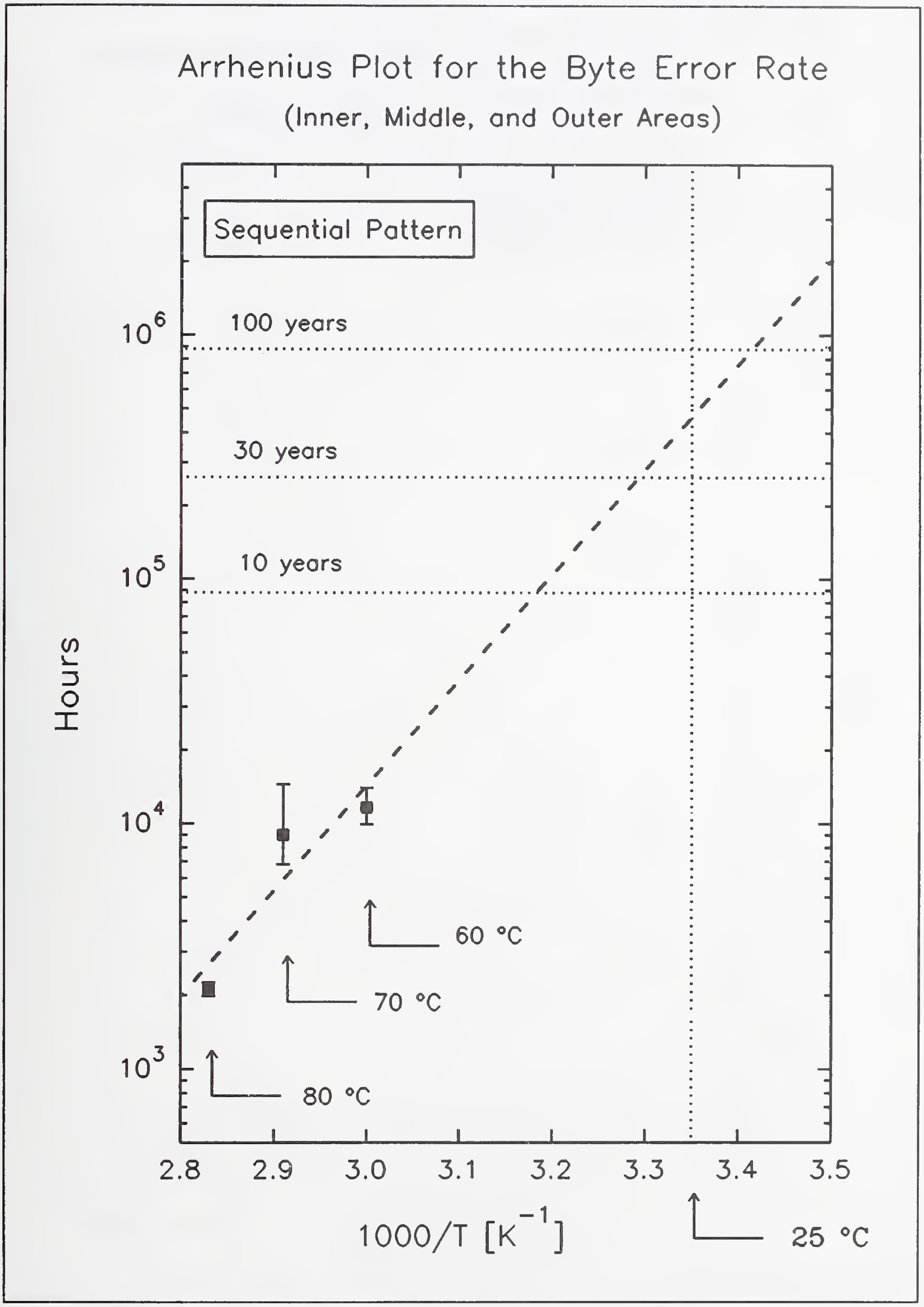


Figure 3.28. Arrhenius plot for the BER (sequential pattern).

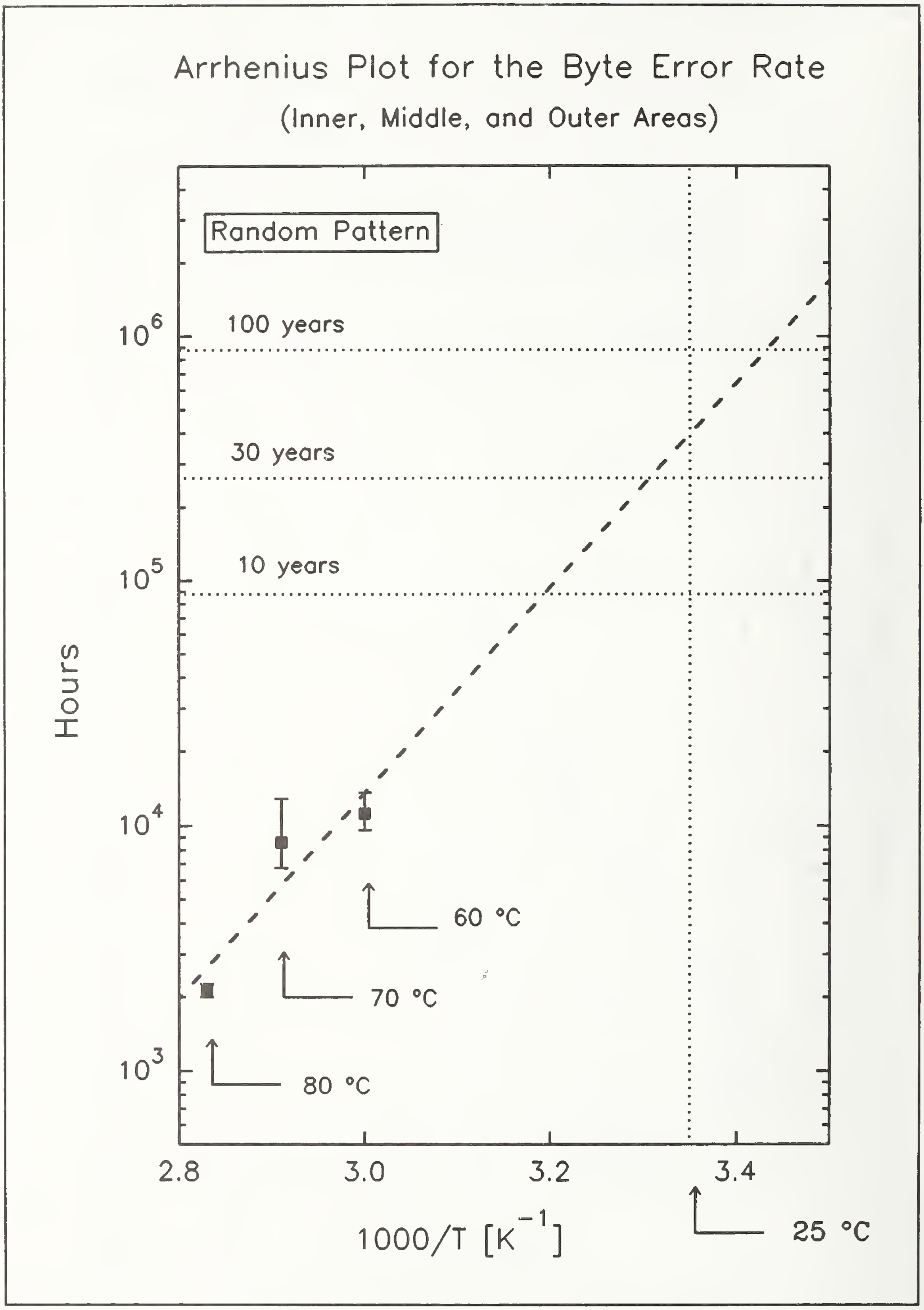


Figure 3.29. Arrhenius plot for the BER (random pattern).

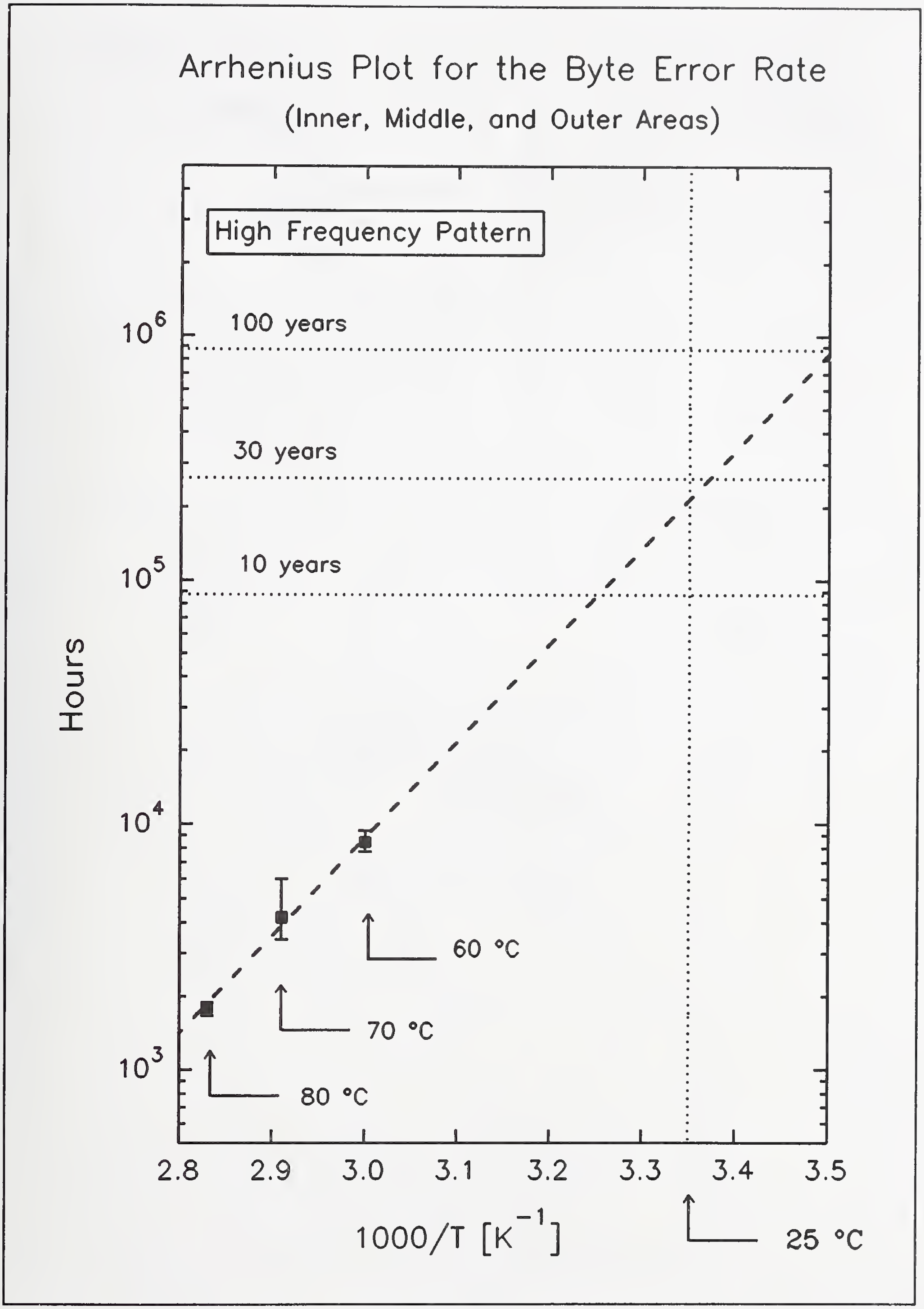
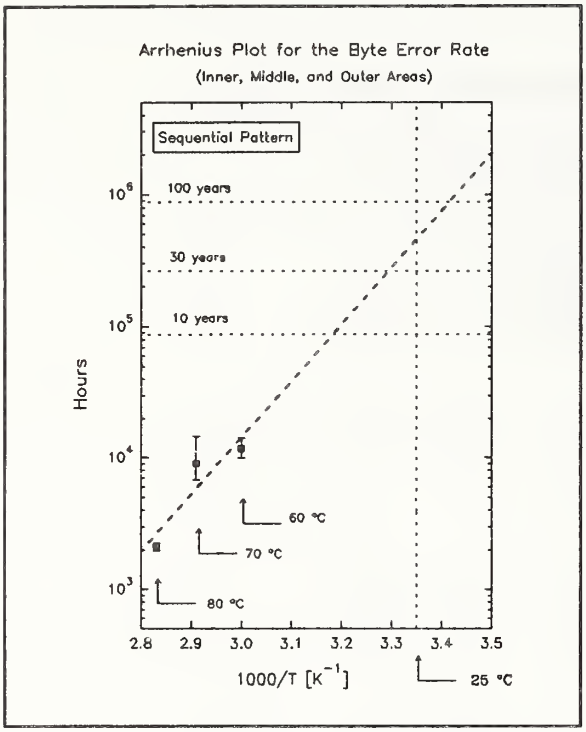
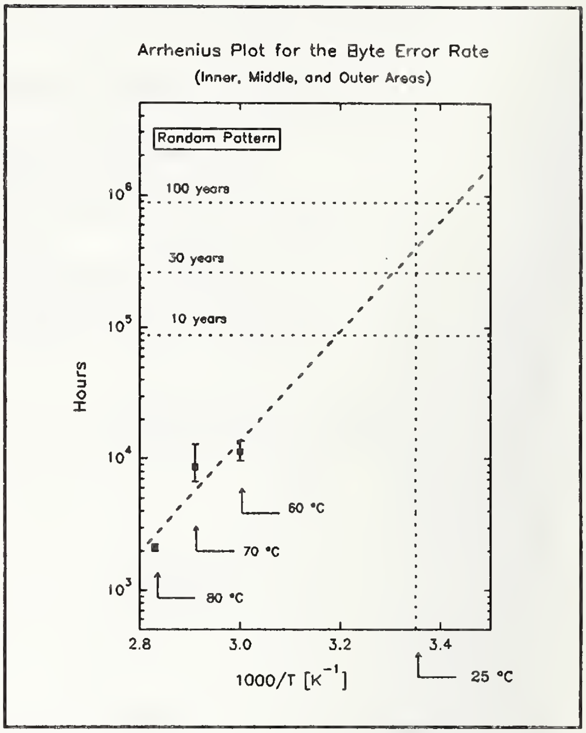


Figure 3.30. Arrhenius plot for the BER (high frequency pattern).



(a)



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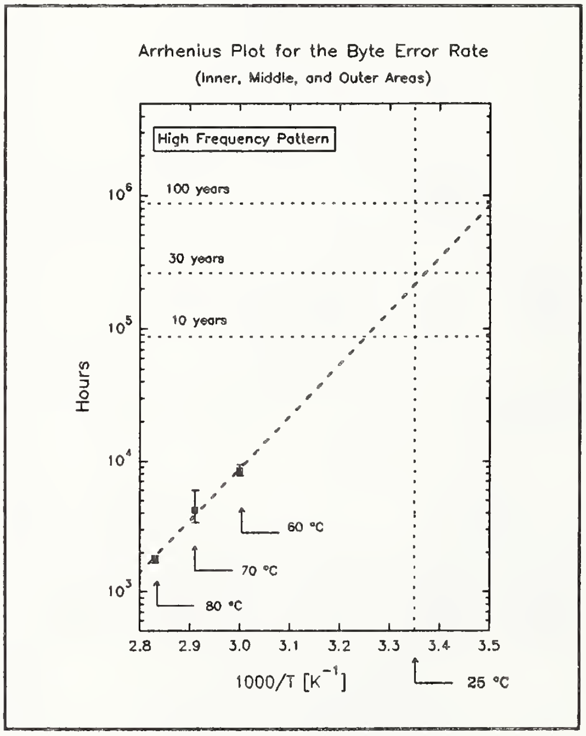


(c)

Figure 3.31. Arrhenius plots for the BER (three patterns).

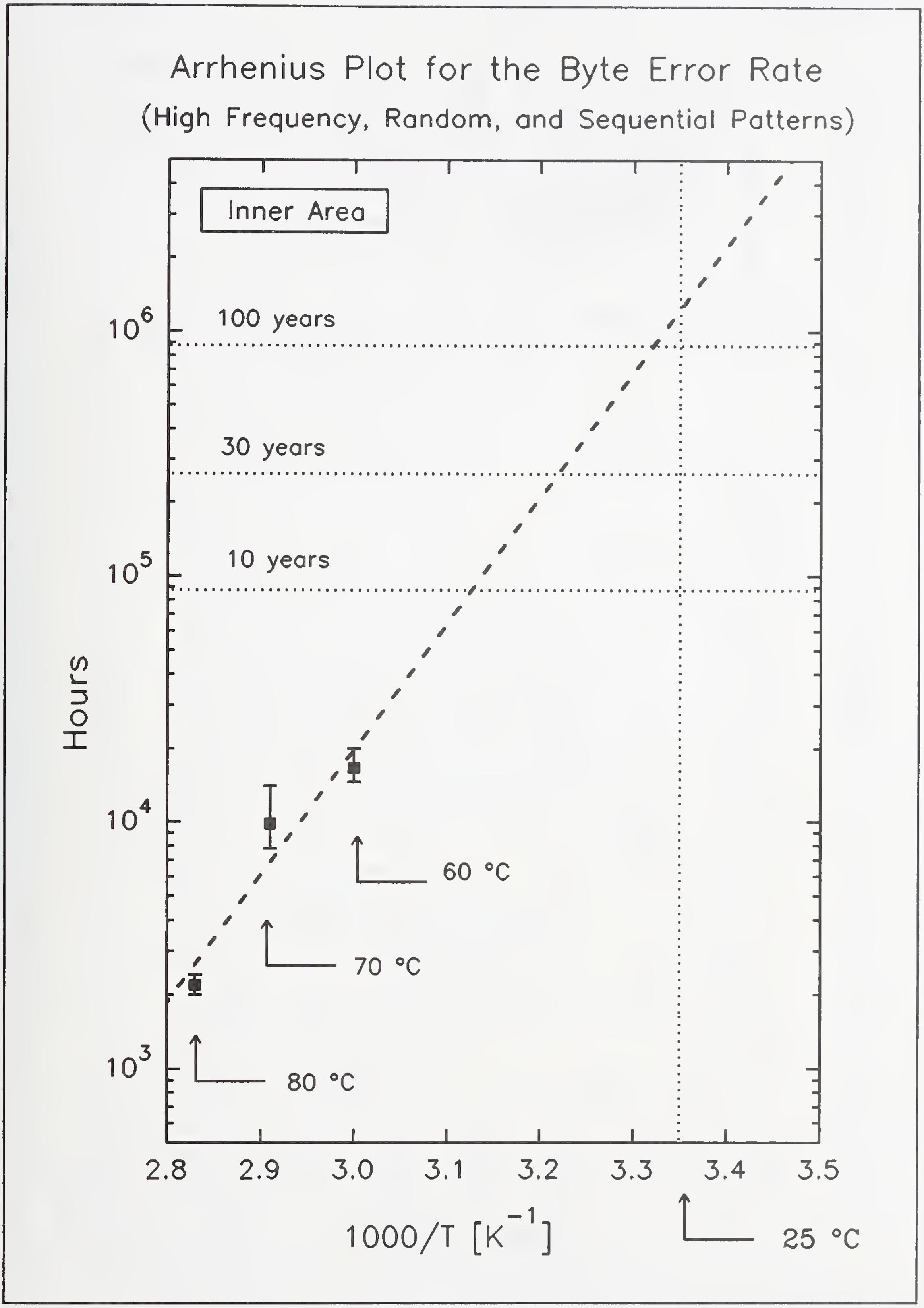


Figure 3.32. Arrhenius plot for the BER (inner area).

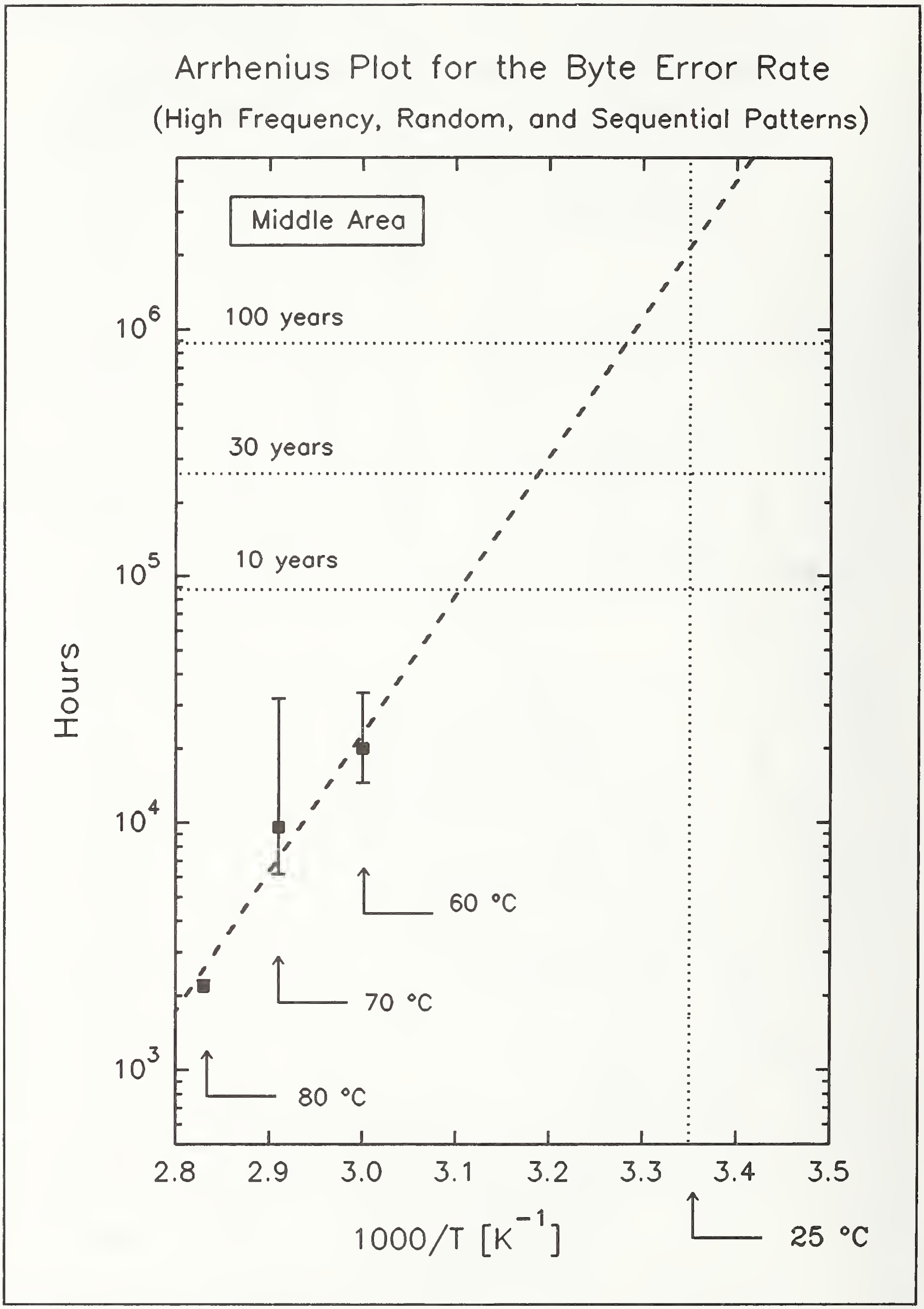


Figure 3.33. Arrhenius plot for the BER (middle area).

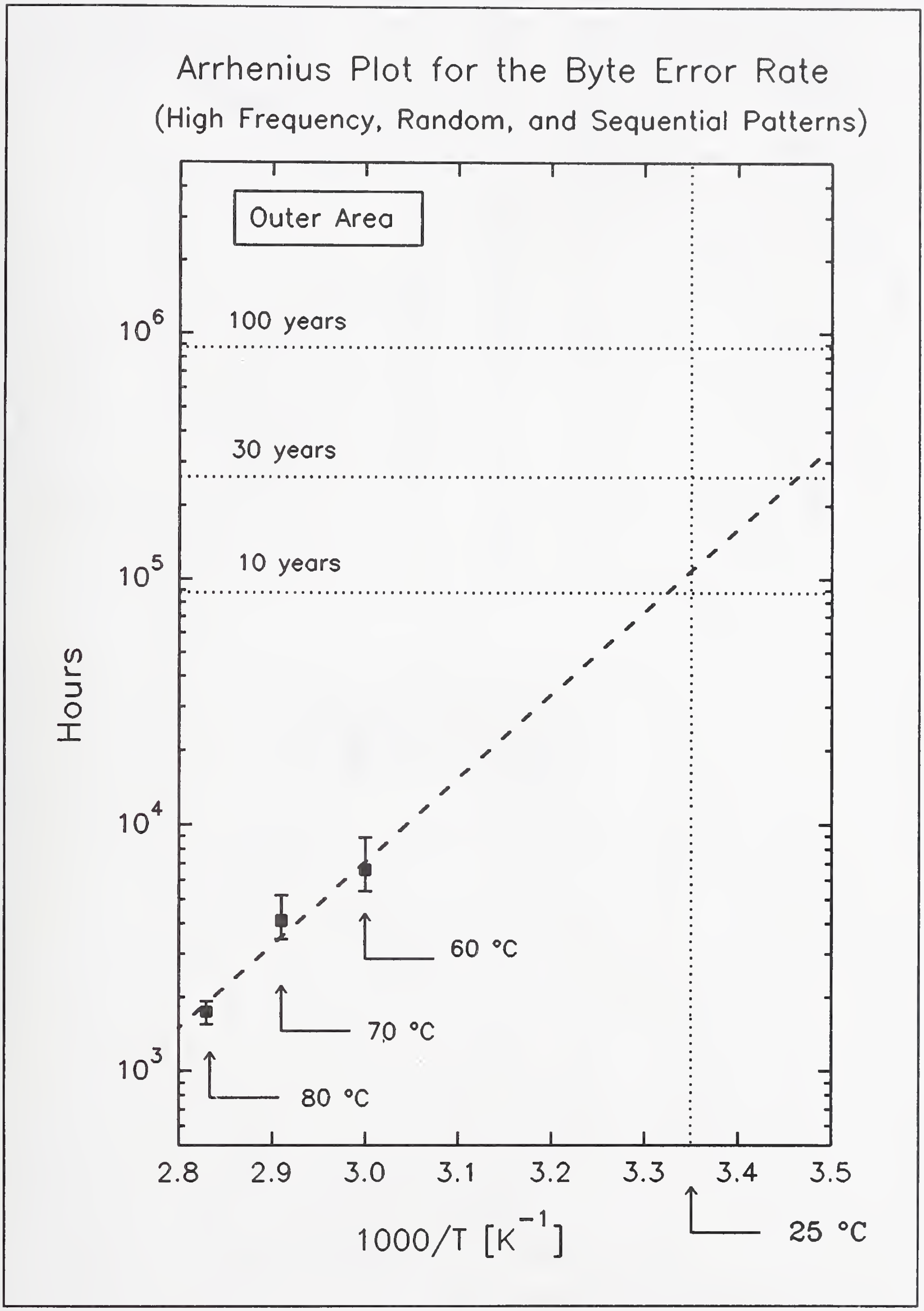


Figure 3.34. Arrhenius plot for the BER (outer area).

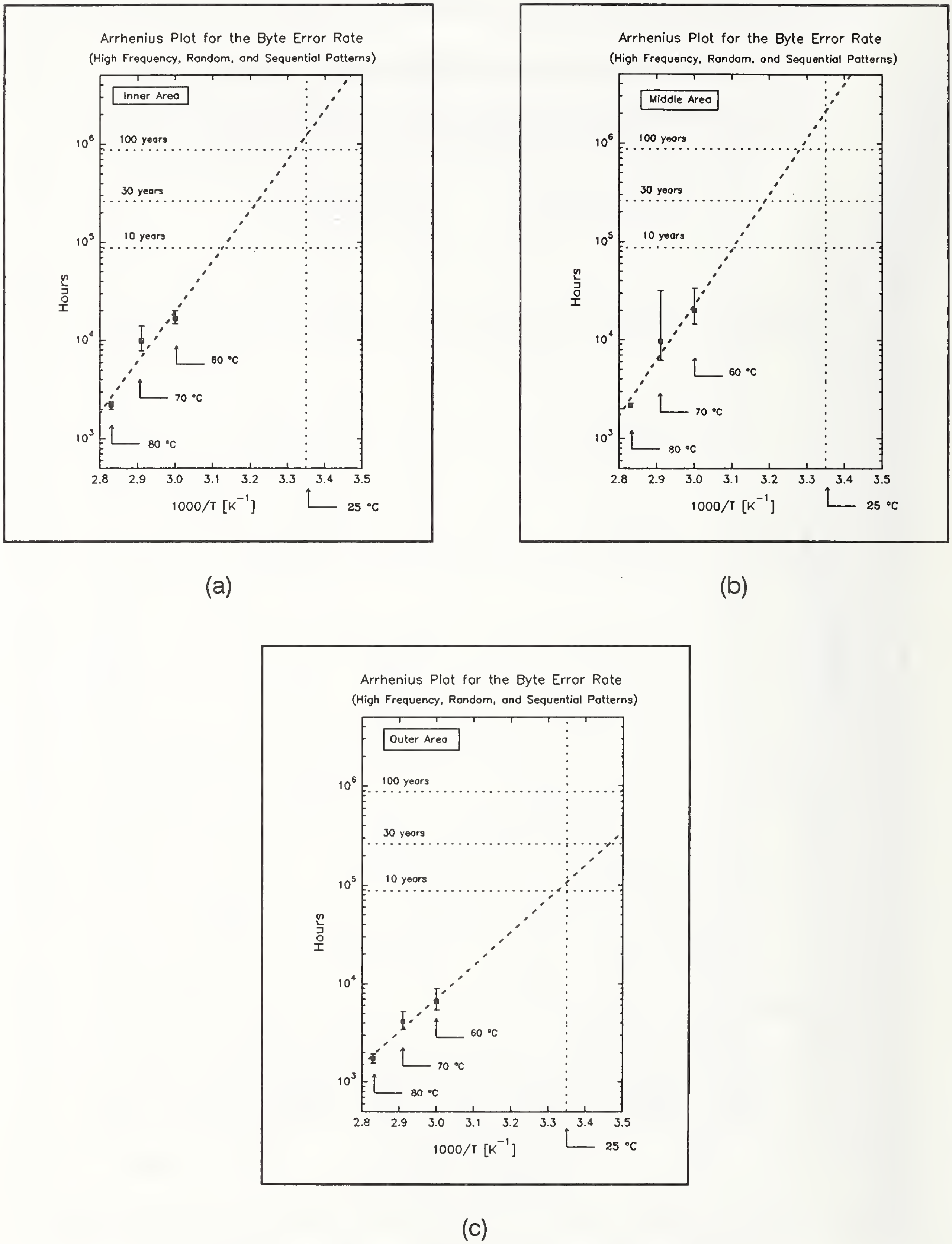


Figure 3.35. Arrhenius plots for the BER (three areas).

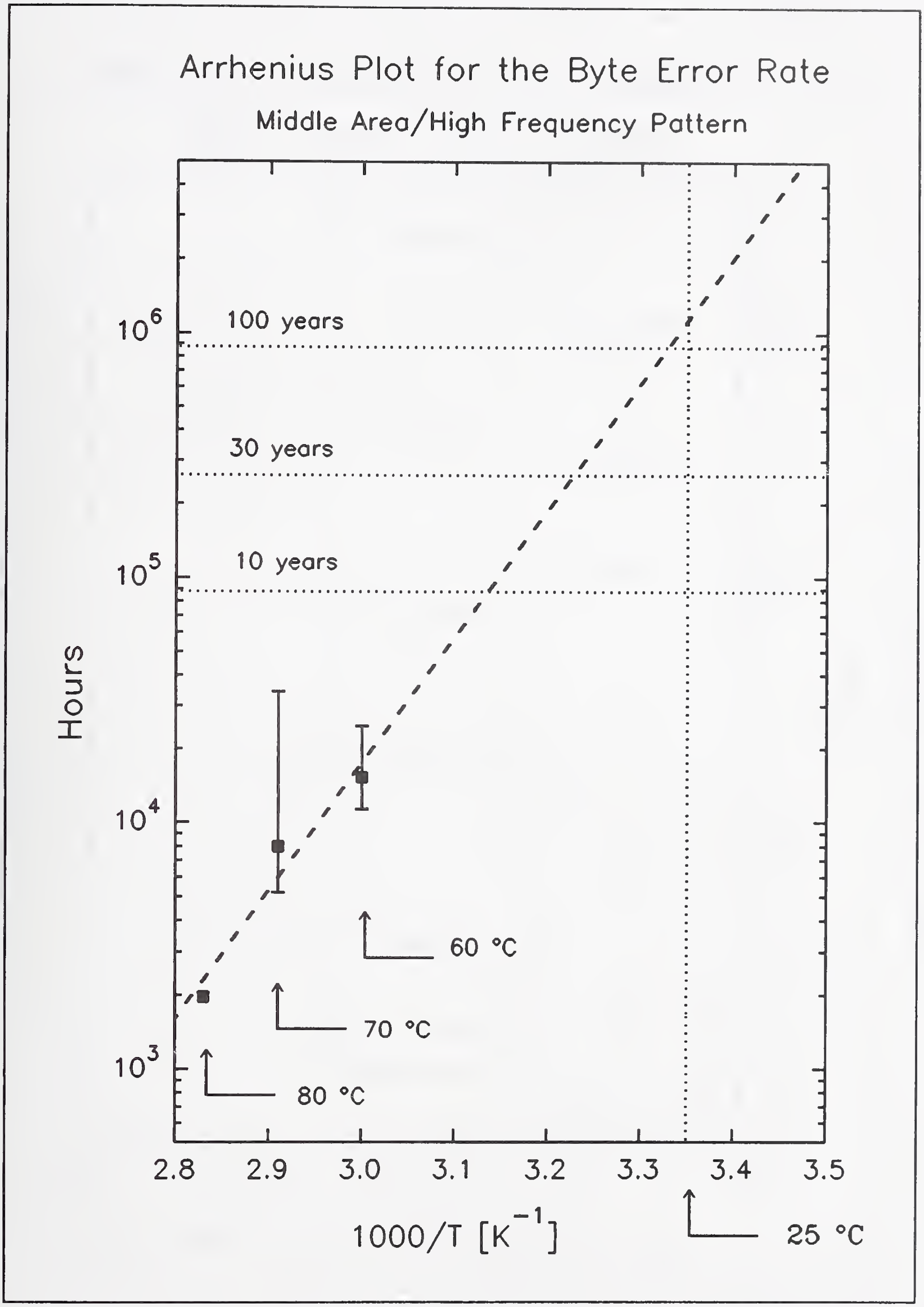


Figure 3.36. Arrhenius plot for the BER
(middle area/high frequency pattern).

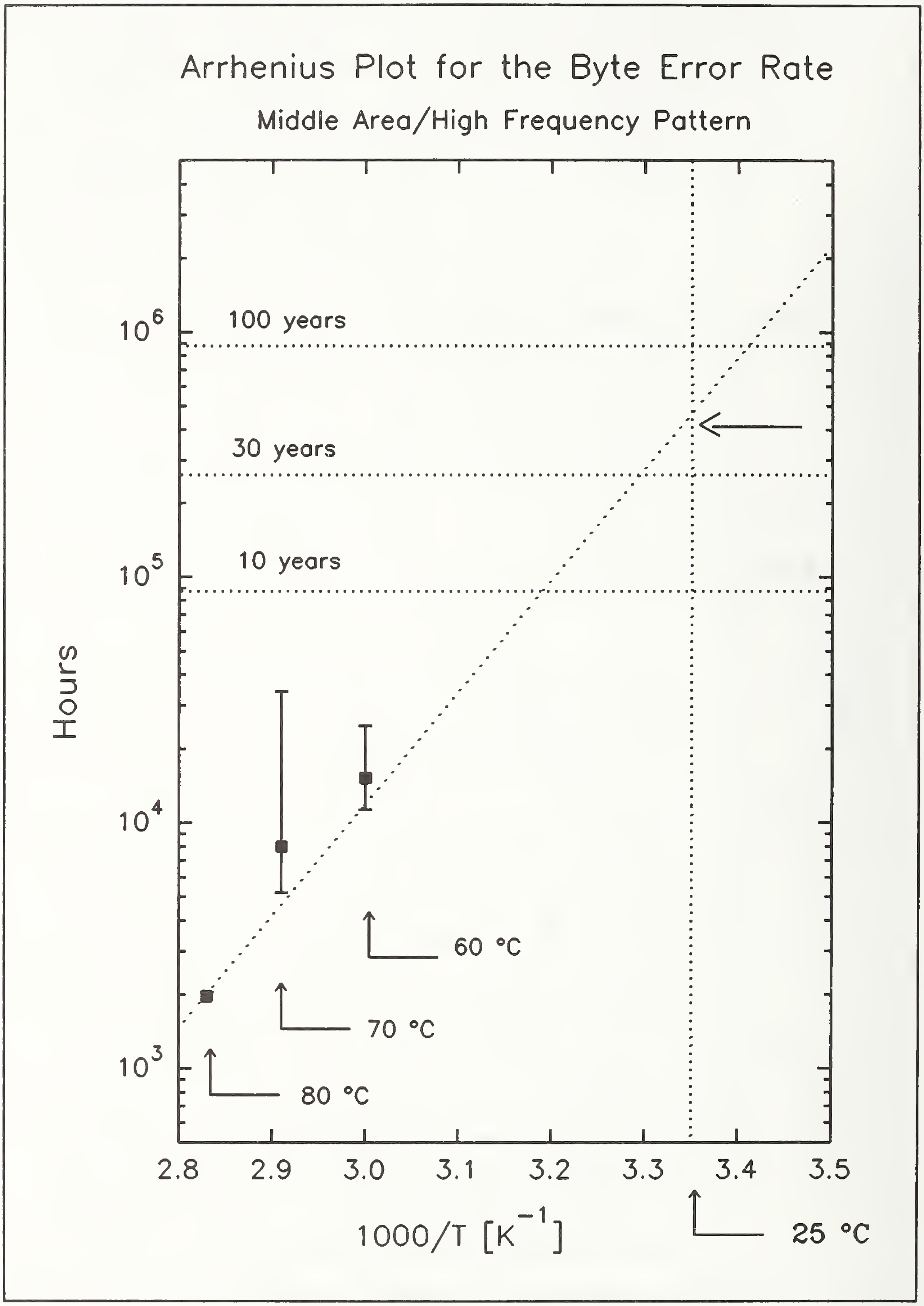


Figure 3.37. Arrhenius plot for the BER
(middle area/high frequency pattern, upper 95% confidence limit).

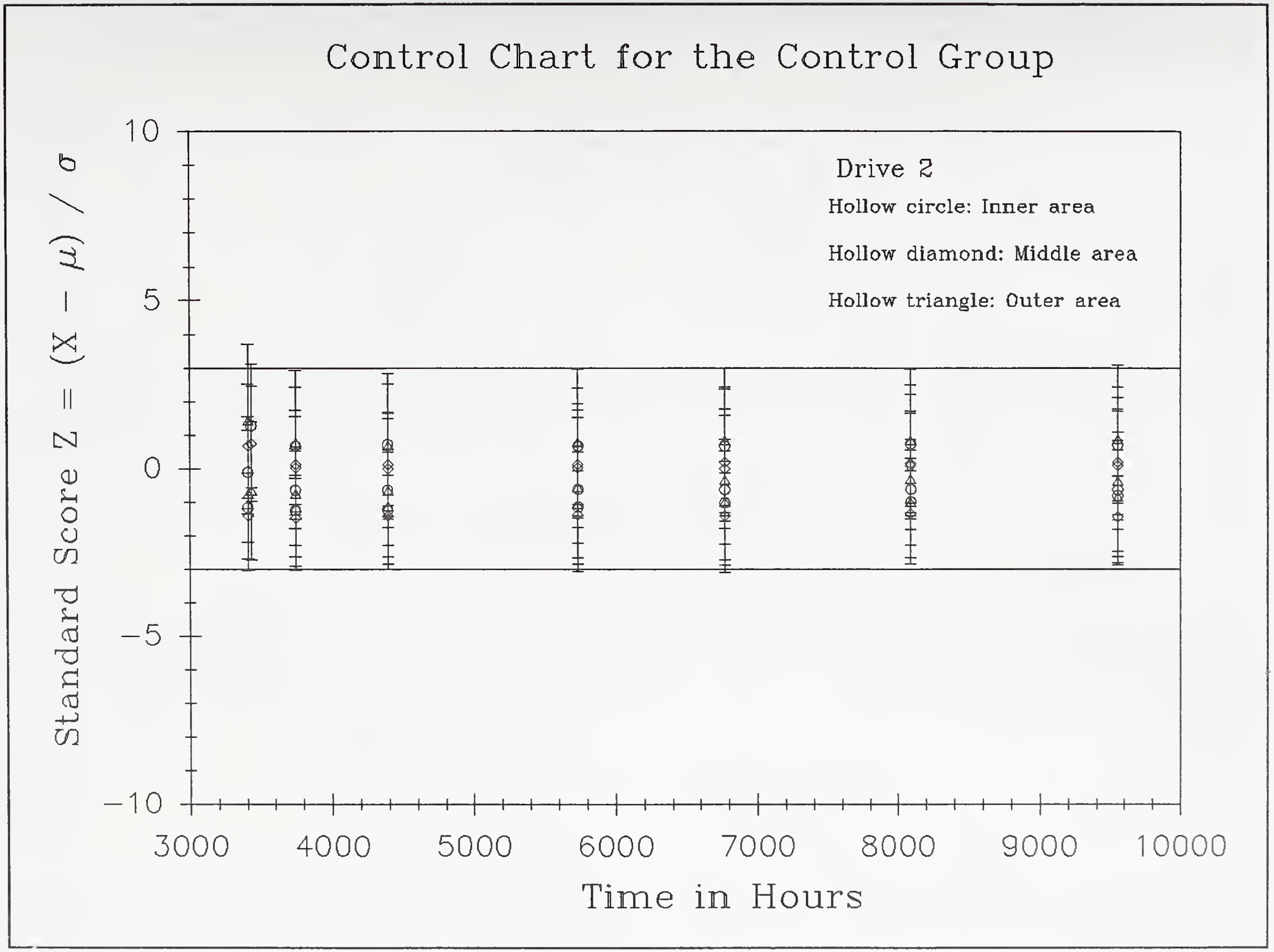
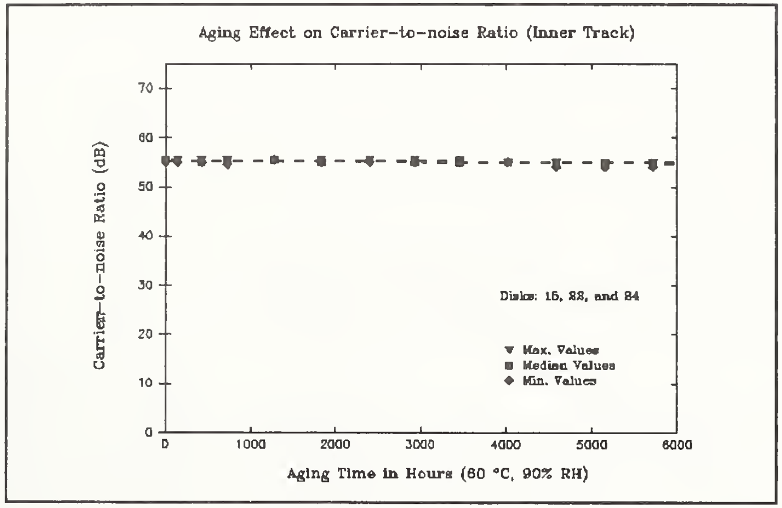
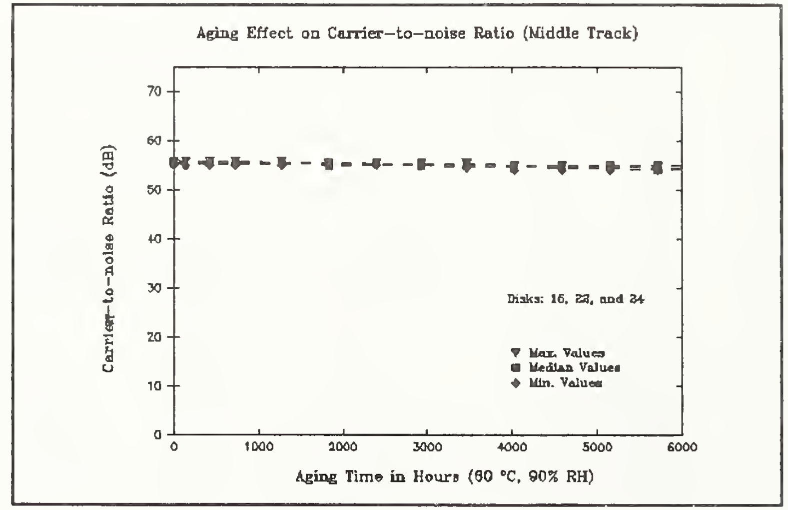


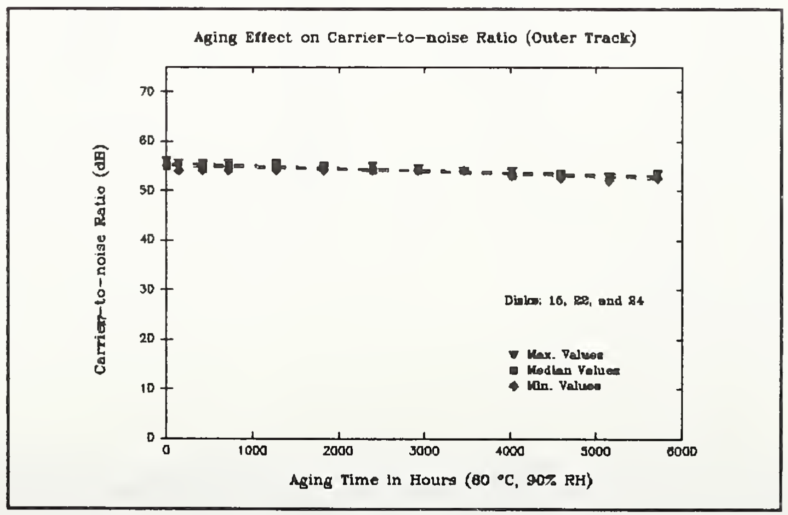
Figure 3.38. BER values for the control group.



(a)

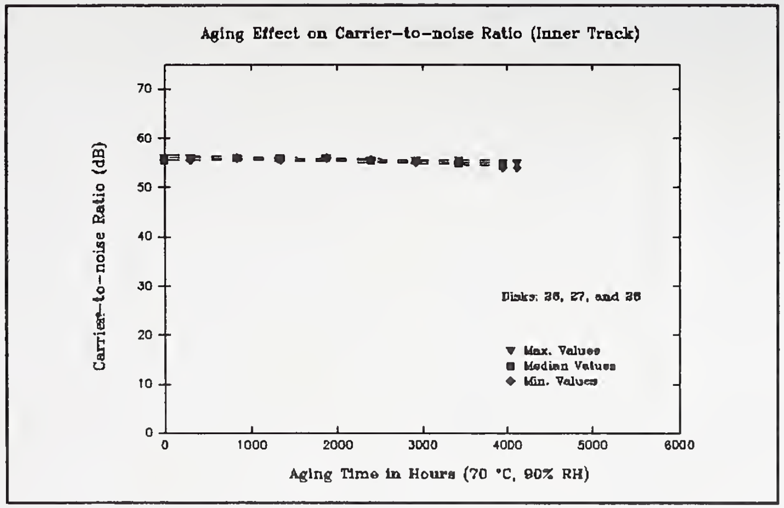


(b)

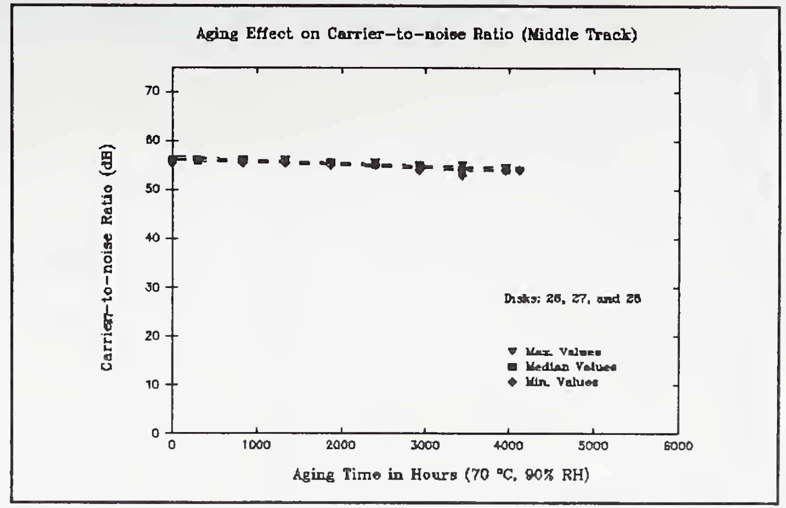


(c)

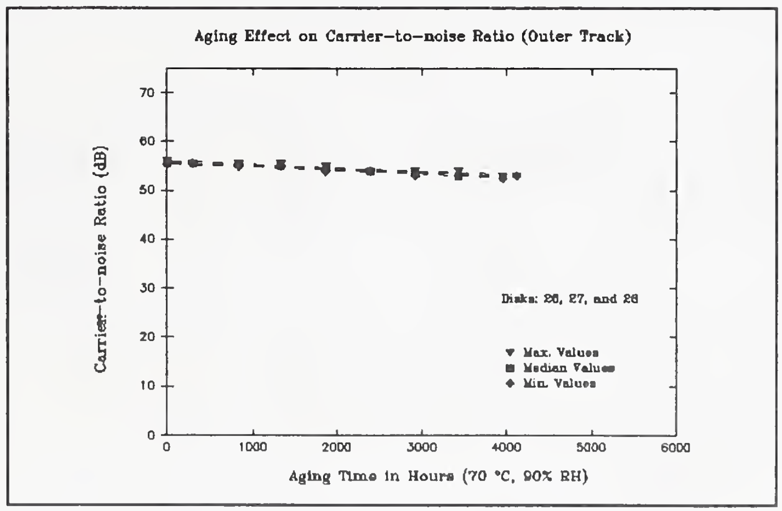
Figure 3.39. CNR versus aging time at 60 °C, 90% RH for three tracks.



(a)



(b)



(c)

Figure 3.40. CNR versus aging time at 70 °C, 90% RH for three tracks.

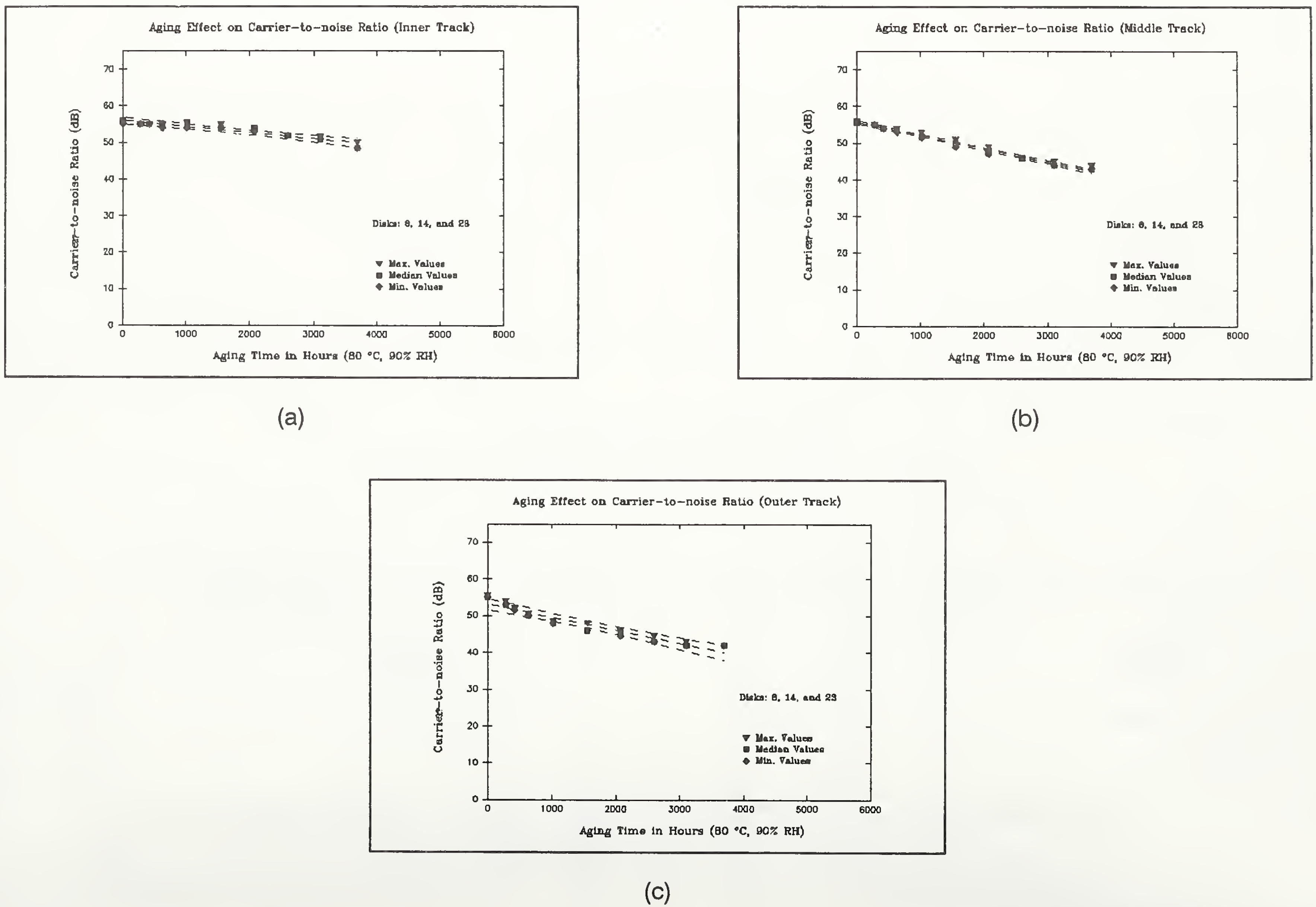


Figure 3.41. CNR versus aging time at 80 $^\circ$C, 90% RH for three tracks.

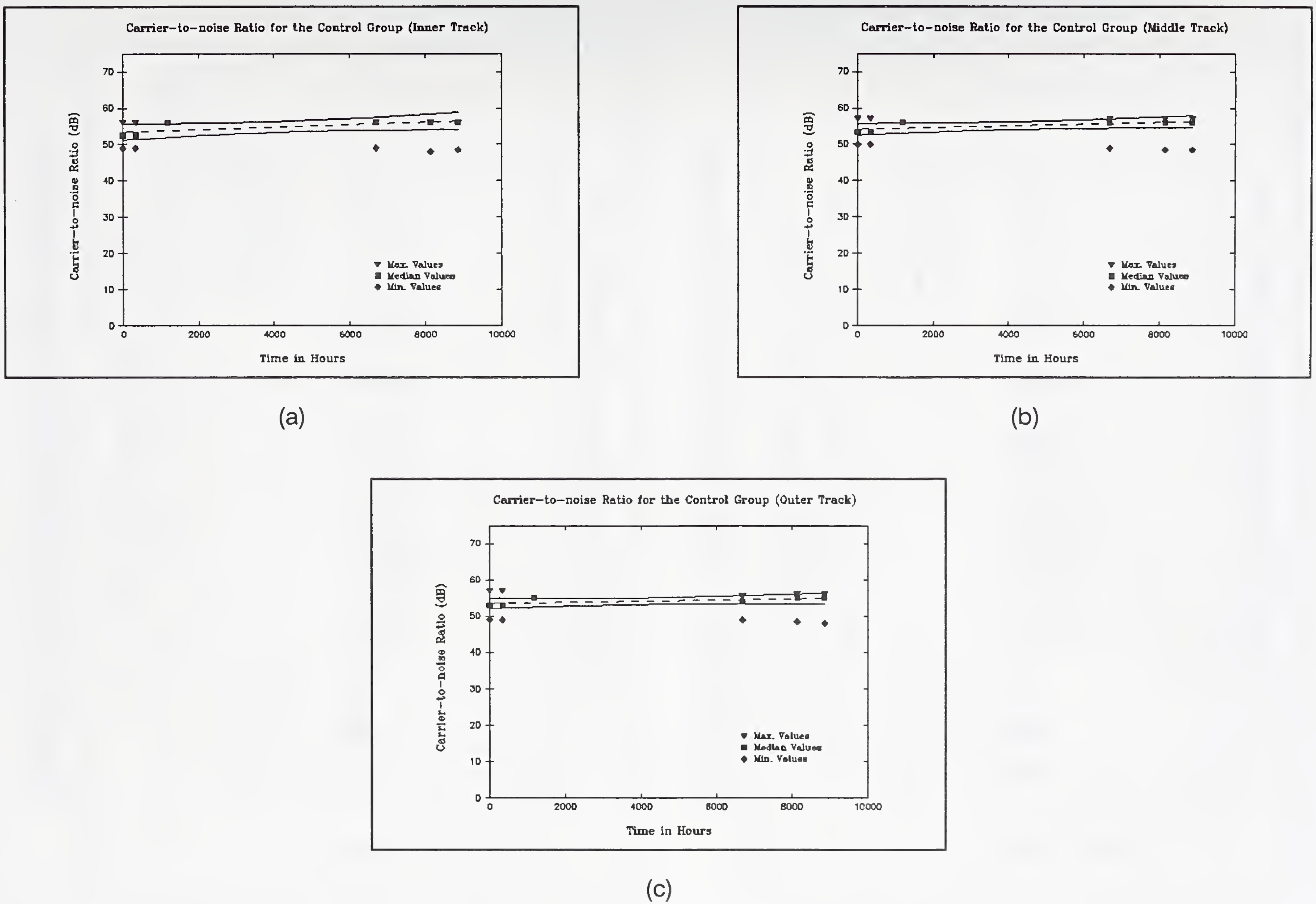


Figure 3.42. CNR values for the control group (three tracks).

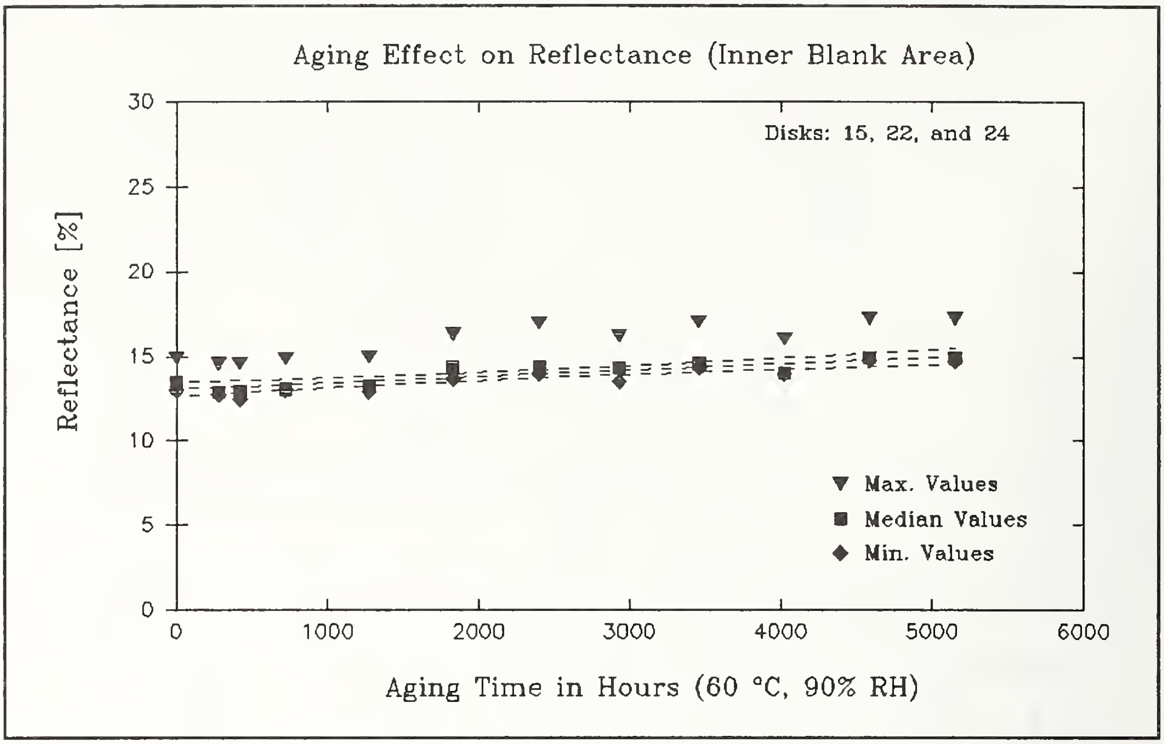


Figure 3.43. Reflectance versus aging time (inner blank area).

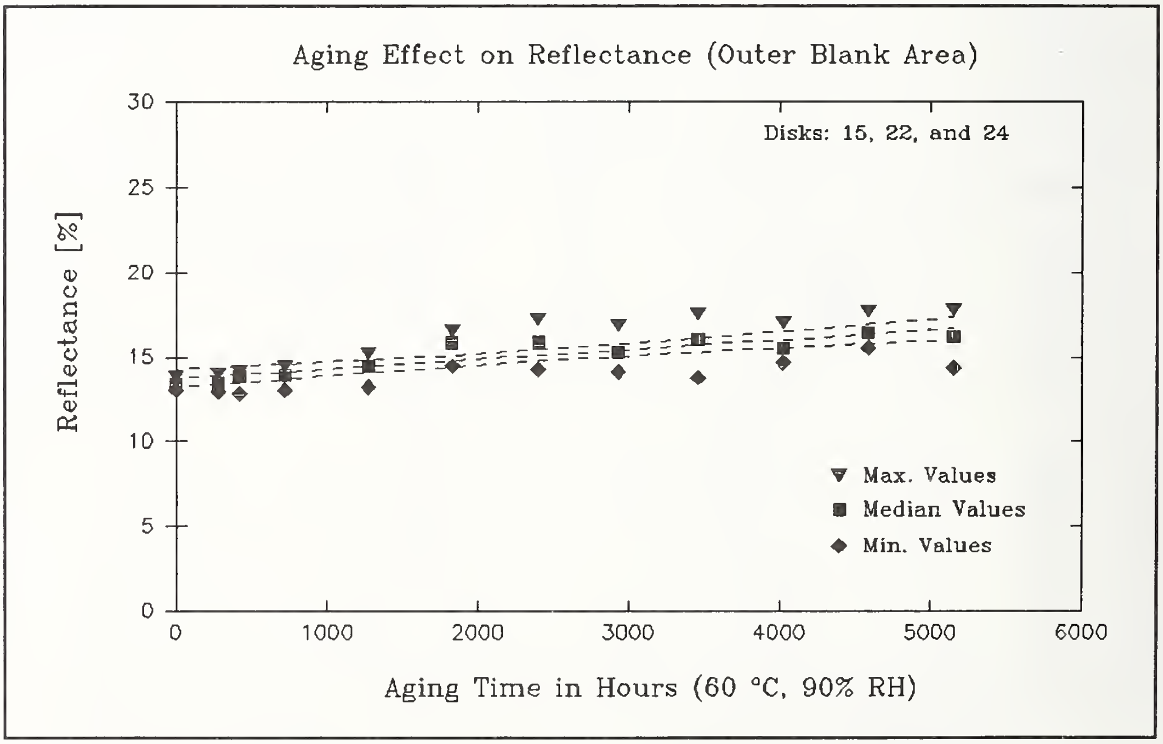


Figure 3.44. Reflectance versus aging time (outer blank area).

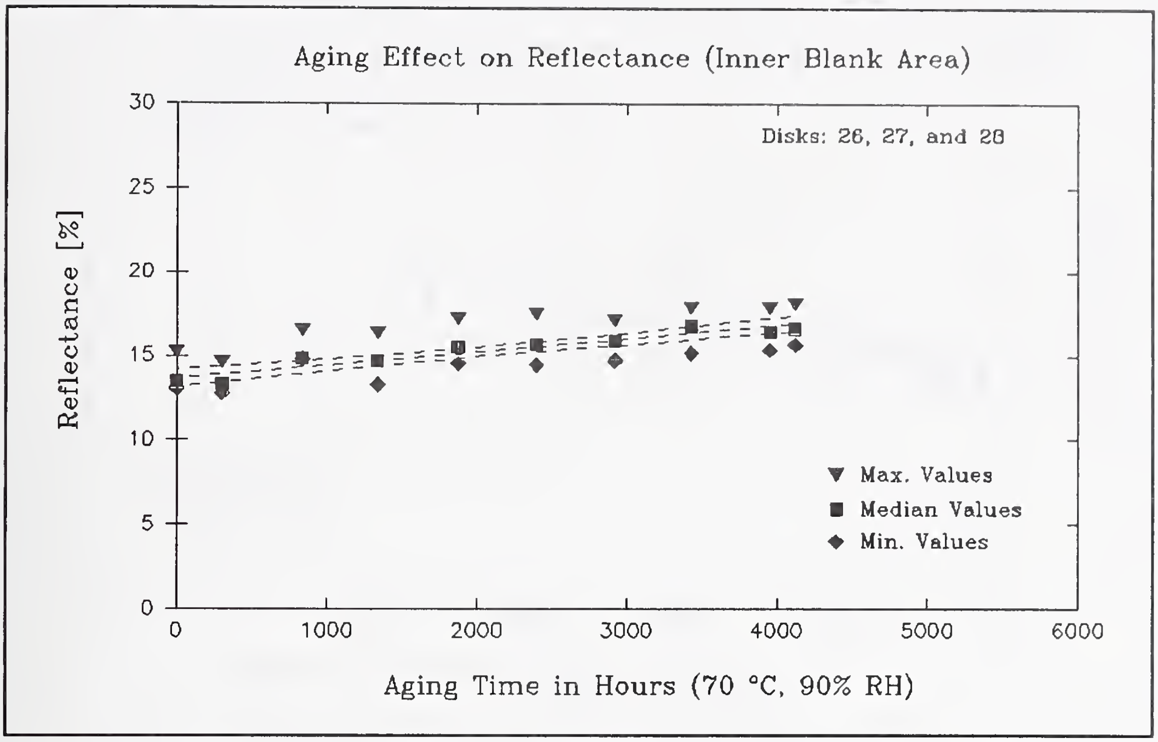


Figure 3.45. Reflectance versus aging time (inner blank area).

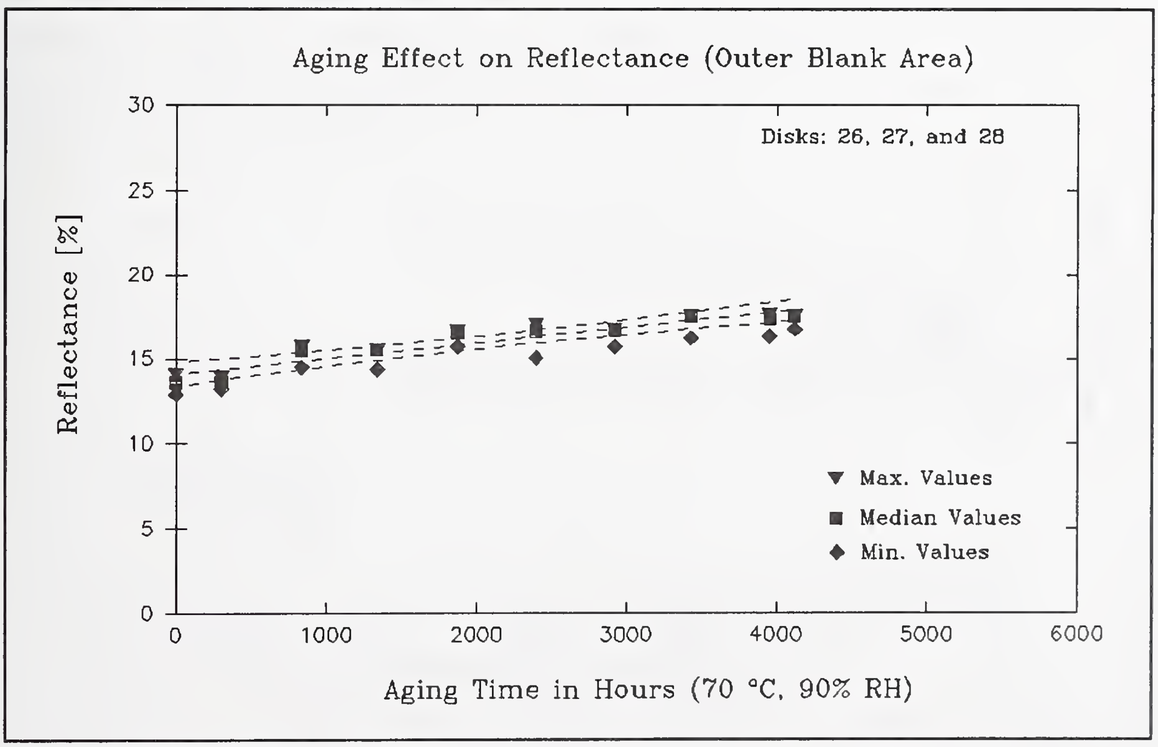


Figure 3.46. Reflectance versus aging time (outer blank area).

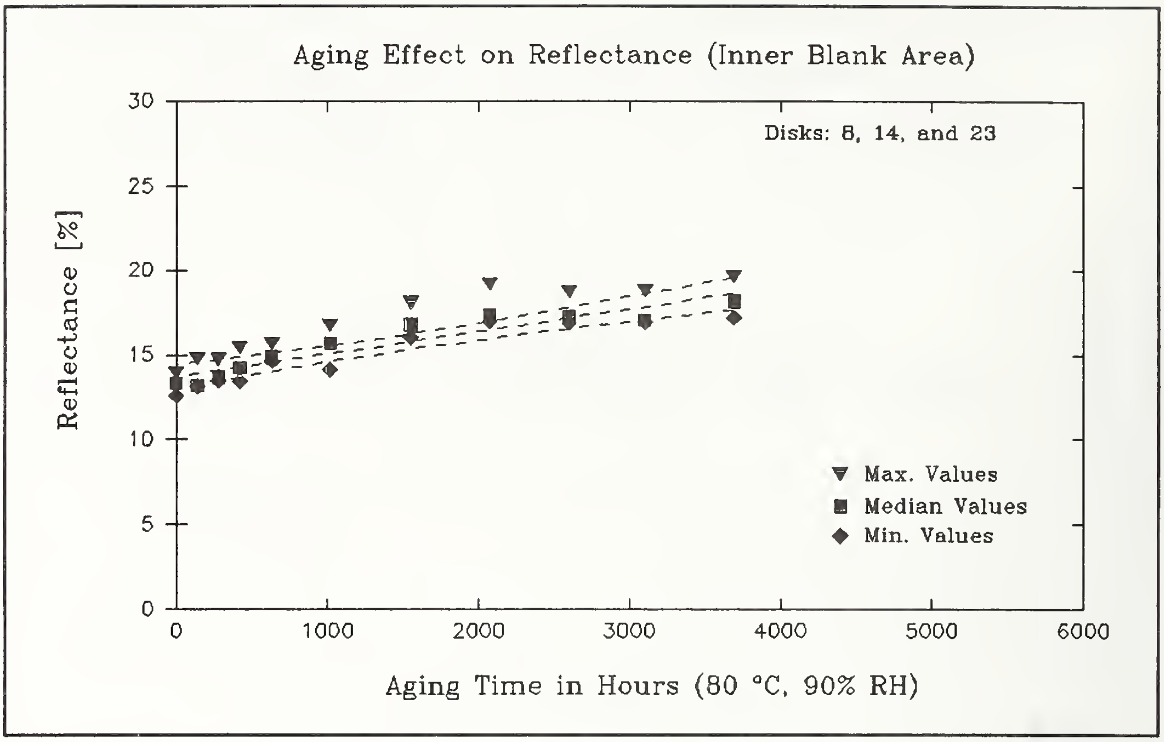


Figure 3.47. Reflectance versus aging time (inner blank area).

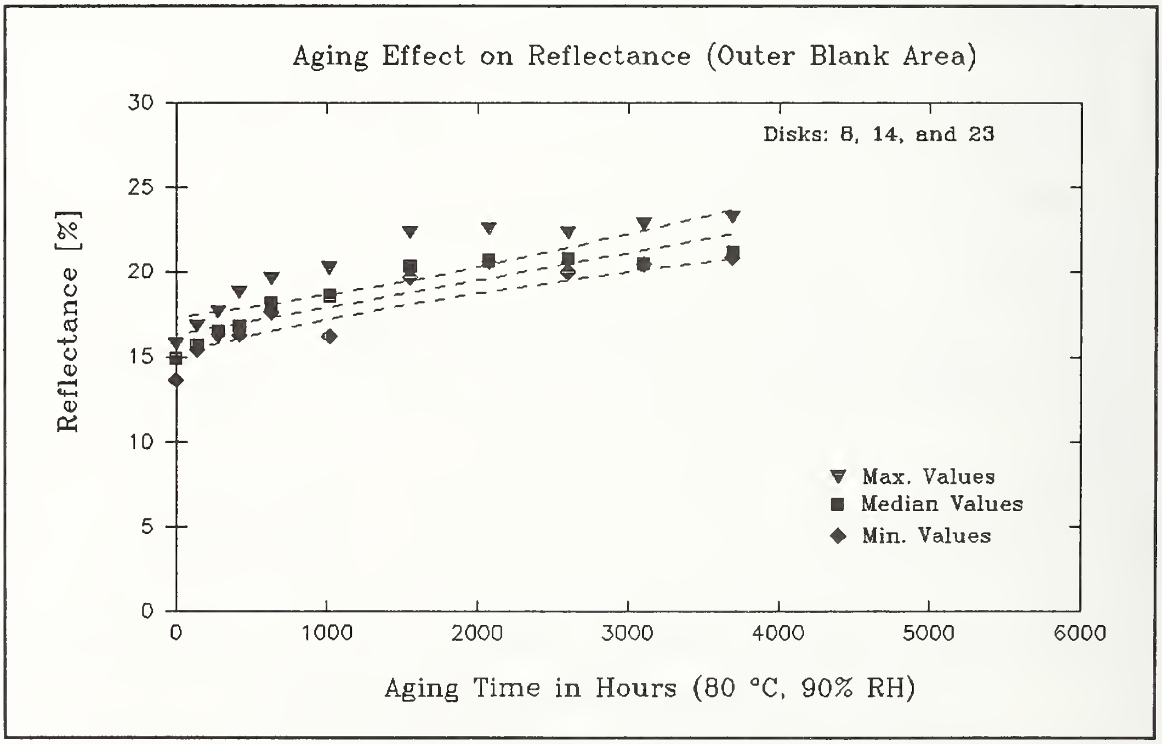


Figure 3.48. Reflectance versus aging time (outer blank area).

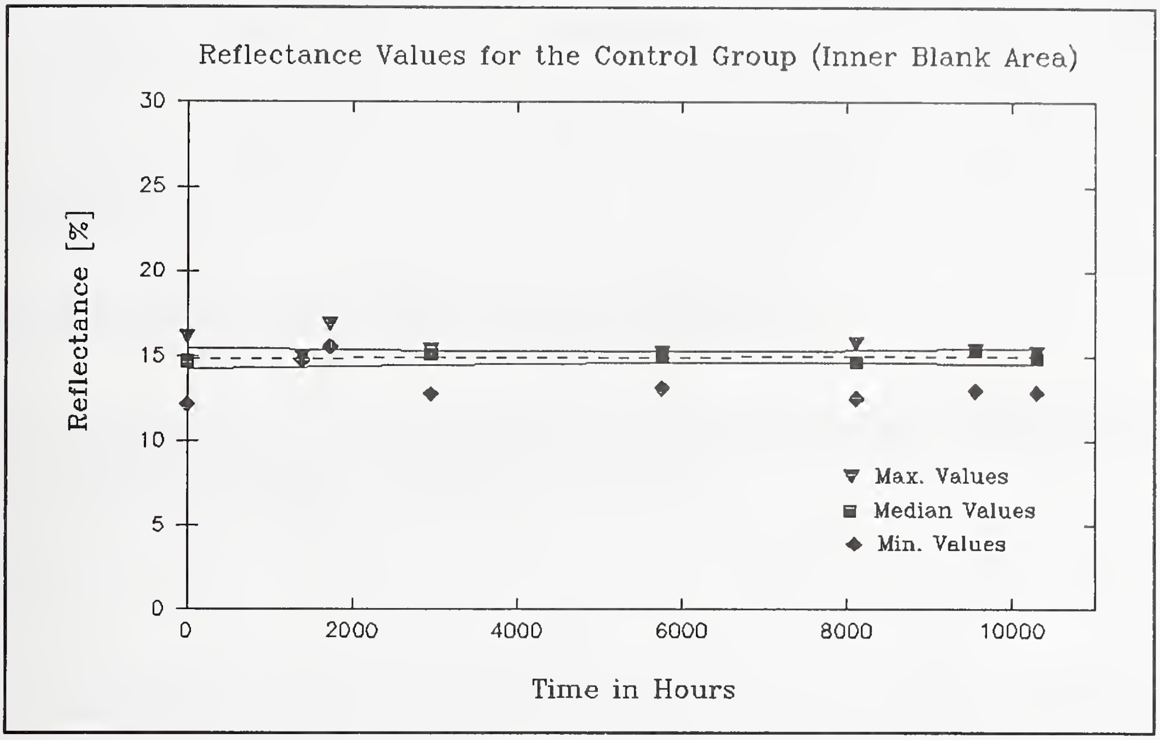


Figure 3.49. Reflectance values for the control group (inner blank area).

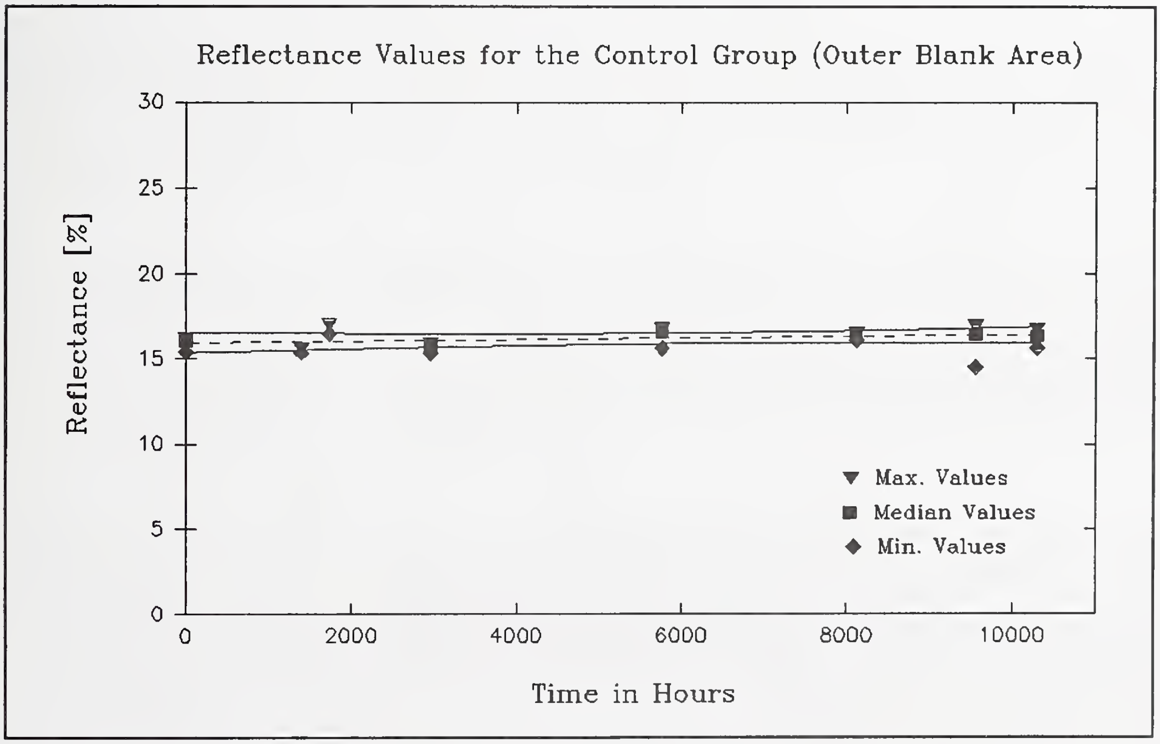


Figure 3.50. Reflectance values for the control group (outer blank area).

Chapter 4

Conclusions and Recommendations

4.1 Conclusions From the BER Results and the Extrapolations From the Modified Arrhenius Plots

The methodology as applied to one type of 300 mm WORM disks produced the following results:

a) When plotted on a semi-log chart versus aging time for the different environments, the BER values shows a generally linear response. In a few instances, there were some deviations from the straight line. How much deviation from the straight line should be allowed is a task of the standards committees. Possible causes of these deviations are due to experimental error, handling of the disks, degradation of some mechanical characteristics during aging, and effects of the high temperature and humidity stress conditions on the outer and inner seals which produced some localized defects on the disks. While these stress conditions are used by manufacturers for this type of media, in some cases they may have been an excessive stress. Users should note that media will never be used at the stress conditions used in these tests. Therefore, the secondary effects encountered during the aging procedures would not normally occur. These stress conditions are well beyond the storage or operating environment.

b) When BER values are calculated for three independent areas on each surface, the extrapolated end of life (EOL) values of the BER (in hours) are different for each area. The extrapolated EOL for the outer area gives the smallest (shortest time) values (see table 3.2). These differences are in part the result of secondary effects for which mathematical models such as the Arrhenius model do not apply. Section 3.3.2 discusses these secondary effects.

c) When BER values are calculated for three different patterns over the inner, middle, and outer areas on each surface, the extrapolated EOL values of the BER (in hours) are different for each pattern (see table 3.2). EOL values of BER derived using the high frequency pattern produced a shorter EOL estimate than the use of the other two patterns, which indicate no significant differences of extrapolated EOL values of the BER.

d) Modified Arrhenius plots derived from the extrapolated EOL values for the BER shown in table 3.2, indicate different extrapolated life expectancy values, depending upon the method used to derive the BER values as indicated in items (b) and (c) (see tables 3.3 and 3.4). For example, table 3.3 shows extrapolated life expectancy values derived from blocks of sectors written with three different patterns. Those values are: 51 years for the sequential pattern, 45 years for the random pattern, and 24 years for the high frequency pattern. The conclusion derived from the these results, according to the values in table 3.3, is that using different patterns for the experiments gives different results. The results show that different approaches for measuring the quality parameter (in this case the BER) can cause different extrapolated EOL values and consequently different extrapolated life expectancy values. In this experiment, these values reflect an average behavior that include the three areas mentioned above. Note that the extrapolated life expectancy values are for room temperature and the same relative humidity used for the stress environments.

e) Figure 3.36, shows a modified Arrhenius plot which represents the extrapolated life expectancy value from BER data measured only in the middle area (less susceptible to secondary effects) and on blocks of sectors written only with the high frequency pattern which gave the smaller life expectancy value (more conservative figure). Table 3.5 shows the extrapolated EOL values (in hours) over the middle area. Table 3.6 shows that the extrapolated life expectancy value for this particular combination of area/pattern is 121 years (for an extrapolation of the median values). Figure 3.37 shows a more conservative approach using the same set of data, but extrapolating the upper 95% confidence limit of the BER values. Table 3.6 shows that the extrapolated life expectancy value for this approach is 57 years. These extrapolated life expectancy values are also for room temperature and the same relative humidity used for the stress environments.

f) The results from the BER measurements are repeatable. While the measurement system used has its limitations because the tests were run in commercially available drives and there is no way to do an absolute calibration unless the drive is shipped back to the manufacturer's facilities, the data was sufficiently stable as shown in the figures. (Alternatives are very expensive; tests beds for BER and other media measurements range approximately from $100,000 to $500,000.)

g) Using a commercially available disk drive means that the drive may have to be recalibrated during the test period. This situation may be discovered by periodic testing of the control group of disks. If this occurs, the quality parameter data for that time period must be corrected or disregarded. This situation occurred on one occasion during the experiment. However, when the drive was returned from calibration by the manufacturer, data generated using that drive and the control group of disks showed that the drive was again correctly calibrated.

h) The EOL values derived from the BER plots were produced with three disks per set. Using more disks would produce more precise results, but would add considerably to the cost.

i) As pointed out above, a strict use of the Arrhenius model would require that plots of the quality parameter (in this case the BER) versus the aging time to be a straight line and plots of extrapolated EOL values (in hours) of the BER versus 1000/T also be a straight line.

j) The data shows that the extrapolated life expectancy values for the media strongly depend of the testing conditions, the patterns used, the areas measured, etc.

k) CNR decreased 10% for the set aged at the maximum temperature and 90% RH. However, the other two sets aged at smaller temperatures showed a fairly flat response. There were not sufficient changes in this parameter to be included in the definition of EOL. CNR tests run in a control group showed a flat response in over 9000 hours of testing.

l) Reflectance values increased no more than 5% in the sets aged at the three different stress environments. As in the case of CNR, there were not sufficient changes in this parameter to be included in the definition of EOL. Reflectance tests run in a control group showed a flat response during the testing period.

4.2 Discussion and Recommendations

The most important conclusion of our work is that extrapolated life expectancy values may vary greatly because they depend, among other factors, on the test method used for calculating the quality parameter (e.g., BER), the measurement approach including data patterns used, areas measured (e.g., middle area), amount of data tested, mathematical model used, criteria for data analysis (including the statistical analysis used, confidence intervals, etc), and the stress conditions. Therefore, users should be aware that claims of a life expectancy specification should be accompanied by specification of the above factors.

The results shown in Chapter 3 and in section 4.1 indicate that the methodology applied to a small sample of disks yields a range of extrapolated life expectancy values depending upon the patterns and areas used for the BER measurement. The range of extrapolated life expectancy values derived using three different patterns includes data taken in areas of the disks where secondary effects took place. These secondary effects cannot be accomodated by the mathematical model used for the extrapolations.

We also used another approach to analyze the data. In this approach we selected the data derived only from the middle area (assuming that these areas of the disks were the more isolated from the secondary effects) and from sectors written only with the high frequency pattern (worst case pattern for this implementation). Using these more representative data (high frequency pattern in the middle area) and median values of the BER, we derived an extrapolated life expectancy of 121 years at room temperature and 90% RH. Using for the extrapolations the upper 95% confidence limit of the BER, we obtained a more conservative extrapolated life expectancy value of 57 years at room temperature and 90% RH. However, assuming a typical RH range for a storage environment of 40% to 50% RH, the projected life expectancy values using this method should be longer than the ones derived from our experiments.

These results are an approximation and should be used with caution because the experiments used a small number of samples and the presence of degradation effects which do not correspond to the prediction model. Furthermore, it should be noted that the higher than normal humidity levels used to permit aging disks in a reasonable length of time influences the results.

Our results imply that different testing methods have the potential for deriving different values of extrapolated life expectancy, all of which may be valid. The need for standard test methods for life expectancy is apparent. Industry standards would provide a commonly agreed upon basis for life expectancy testing so that vendor claims can be properly assessed by prospective users. Otherwise, comparisons between different products will not be possible.

The method employed in the NIST experiments used the Byte Error Rate (BER) as the quality parameter. This method uses BER average values that give a general indication of the behavior of the media. For effects that may define the end of life previous to a general degradation of the media, other methods should be applied, such as defining the EOL as the first uncorrectable read error.

The Arrhenius model is easy to use and the required stress conditions are less than for the application of other models. For example, the number of stress conditions for the Erying model is higher than for the Arrhenius model. The Arrhenius model can be utilized for optical media when the response of the quality parameter to the stress conditions is fairly linear and the extrapolated EOL of the quality parameter versus an inverse value of the absolute temperature T also shows a linear response. How much deviation from the straight line should be allowed and how good the approximation of using relative humidity levels other than the use conditions is a task for the related standards committees. As long as the general response is similar, it would be possible to apply the same methodology to disks of other types.

Sets of disks were aged using high temperature and relative humidity as the stress conditions. Plots of the quality parameter (BER) versus the aging time have shown in general a straight line response and modified Arrhenius plots were used to show how extrapolated life expectancy values can be derived.

If the risk of sudden abnormal behavior is high, it is advisable to use more disks than the minimum required for the tests, gathering data from all of them. The drawback to this approach is that the disks will be out of the testing environment for a longer period of time. This may cause some error in the testing.

General conclusions on the extrapolated life expectancy values of other types of media will require implementing the methodology described to those types of media. It may be that the methodology might have to be adapted for some types of media (e.g., magneto-optic media might need different aging conditions, EOL definition, and model that fits the data, etc). Consequently, the methodology is applicable to other types of disks (perhaps with some modifications as stated above), but the results may vary considerably. This program provides the basis for such work. Candidate media include other types of WORM media and rewritable media, and media with different types of substrate, such as polycarbonate and glass. Tests run in different laboratories using the same general methodology should derive similar results as long as the chosen stress conditions are the same and the other testing conditions are followed.

There are instances where localized defect growth could conceivably cause an uncorrectable read error prior to the EOL value of BER. In those instances, prediction methods based on localized errors or uncorrectable read errors may be required. This is a subject of continued study in the relevant standards committees in which NIST is participating. The occasion of such uncorrectable read errors depends heavily on the error correction strategy used. This technique varies considerably between manufacturers.

During this program other methods of life time predictions have been studied by NIST. A recent submission to the JTC on Data Permanence is based on the bit/byte error rate (or block error rate) as the degradation parameter and in the determination of a kinetic model such as Arrhenius. However, in this submission, the life expectancy at the accelerated aging conditions is defined as the occurrence of the first unrecoverable read error.

4.3 Related Programs at NIST on Data Preservation

Currently NIST is involved in three programs related with issues of data preservation on optical media. These programs are:

(a) A program to investigate the status of on-line monitoring techniques for error rates and error distributions. Under this program a workshop was organized to identify on-line monitoring techniques in current products and suggested methodologies for on-line error rate monitoring. During the workshop a set of user requirements was identified and an government/industry working group was organized. This working group is sponsored by the Computer Systems Laboratory of NIST. The goals of the working group are to build an industry consensus for a method(s) of reporting error rate information through an interface as indicated by the results of the workshop. Included in this program is the implementation of a test/demonstration platform consisting of a workstation(s) and optical disk subsystem(s) that incorporate provisions for error rate reporting. The program also allows for participation in the relevant standards committees.

(b) A program sponsored by NASA to develop test methods and specifications for 356 mm ruggedized rewritable media. A working group with members of NIST, NASA and industry was formed. A set of test methods were developed and they are included in NIST Special Publication 500-191. The test methods document includes recommendations to test the life expectancy of the media.

(c) A care and handling study of optical media sponsored by NARA and NIST.

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There are no standards for longevity of optical disks that can assist managers in the Federal government to select the right media for the storage of permanent records, and to know how long the information may be safely stored on those disks. This report focuses on research undertaken at the National Institute of Standards and Technology to develop a methodology to predict optical disk life expectancy values. In this research accelerated aging tests were run on small sets of disks and the quality parameter (the byte error rate) was periodically measured between aging cycles. These tests were used with a mathematical prediction model to develop a testing methodology.

This report presents the results obtained. The need for standard test methods for predicting life expectancy and for measuring media characteristics is apparent. Life expectancy extrapolations derived from the experiments produced a range of values depending upon the method used for deriving the quality parameter. Recommendations are made about the implementation of a testing methodology for life expectancy predictions, and what information to include in a life expectancy specification.

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accelerated aging; Arrhenius model; byte error rate; media lifetime; optical disks, stress tests; optical disks, test methods.

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