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FINAL ENGINEERING REPORT

Design Study of Tradeoffs in Spacecraft Tape Recorder Development

JPL Subcontract 951937

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1.0 CONTRACT FULFILLMENT

This final engineering report is submitted in fulfillment of Jet Propulsion Laboratory subcontract number 951937 by Kinelogic Corporation.

2.0 INTRODUCTION AND SUMMARY

This study presents the development of information concerning various aspects of tape recorder systems. Its purpose is to permit an evaluation of the specifications for an Iso-Elastic tape recorder which would meet the requirements of a JPL mission. The desirable characteristics, independently feasible, are usually mutually exclusive. The problem is to arrive at a compromise between conflicting ideal requirements to produce a recorder which will most nearly satisfy all of the basic requirements.

Two approaches were employed in this study. The first was to study the design, and the resultant functional characteristics of a spectrum of Iso-Elastic tape recorders. This data would be presented in a series of correlation plots. These recorders were designed over a long period of time and for various types of missions. The plots would be useful only in defining trend lines or the limiting values that can be obtained with normal design effort. Naturally, any one characteristic can be emphasized without severe detriment to other characteristics if a major design effort is undertaken.

It would be expected that the trend line found, or the "normal" range shown by any one of the plots, would also be applicable to the extreme value of any one characteristic.

Several characteristics are not susceptible to treatment in this way.

For these characteristics, not amenable to treatment by study of existing designs, the second approach, theoretical analysis, was used.

While each topic is treated as a separate entity in the body of this report, there is always some inter-relationship between any two areas of interest. It will be necessary to temper any decision in one area by the corollary influence in all the other areas covered by this report, as well as a larger number of areas of interest which were not covered because the limited effort and short time span allotted to this study.

The characteristics treated by the first approach are the design parameters such as size, weight and length of tape and such functional results of these parameters as flutter, start/stop time, and skew. Several characteristics, which are basically systems decisions, such as the choice between analog and digital recording and between serial and parallel recording, are treated by analytical techniques. A short discussion of bearing life and a short analysis of the effects of changing tape thickness are also included.

Several of the correlation plots in this report show strong indications of utility and validity. It would be of value to compare these correlations to those obtained for machines of differing constructions. These correlations are shown, among others, on Figures 2, 3, 4, 6, 7, 8 and 18. In the area of topics which are susceptible to analytical treatment are those dealing with the effect of head-to-tape contact on signal to noise ratio and error rate of the signal channel, and also the effect of time degradation of components on signal to noise ratio for both analog and digital recording methods. Further, an attempt to put the analog versus digital selection on a numerical basis could be extremely valuable. This, however, is still probably not attainable with a practical level of effort.

This short study did not find any positive correlation between MTBF and any other design characteristic. It would be desirable to find such a relationship, should one exist, because MTBF is a prime requirement and such a pre-knowledge of incompatibility between the life and another requirement would save a large amount of design effort.

3.0 TECHNICAL ACTIVITY

3.1 Discussion of Tape Recorder Characteristics Analysis

3.1.1 Introduction

The analysis of the spectrum of existing machines proceded in six steps. The first step was the selection of characteristics to consider. The second step was to list all possible pairs of these characteristics which might show a valid relationship. Third, this list was reduced to a manageable number by selecting those relationships which could be of value in determining an optimum configuration. Fourth, the records were searched to unearth and collate the design and test information available. This information was placed on data sheets for later use and convenience. Fifth, the information was plotted to show the various relationships selected in the third step. Sixth, and last, the plots were examined and evaluated to determine whether a useful correlation was obtained from the data. Those plots which do show a useful relationship are analyzed and discussed briefly.

3.1.2 Characteristic Selection

The tape recorder characteristics which were selected for use in this study are in Table I. This list includes the physical characteristics of the design, functional characteristics of the resultant hardware, and several normalizing ratios of other characteristics which may serve as figures of merit.

TABLE I

Volume of Recorder

Weight of Recorder(not including record or playback electronics)

Length of Tape

Tape Speed

Tape Width

Tape Thickness

Track Width (also number of tracks)

Packing Density (linear)

Mean Time before Failure

Power

Flutter

Skew (both across tape and per inch)

Signal to Noise Ratio

Start/Stop Time

Dropout Rate

Area of Tape

Weight of Tape to Weight of Recorder Ratio (Wt/Wt Ratio)

Total Data Capacity to Weight of Recorder Ratio (Data/Wt Ratio)

Volume of Recorder to Weight of Recorder Ratio (Vol/Wt Ratio)

Tape Guidance

The last item in Table I is included to show the resultant skew obtained with the two guidance methods employed in the machines considered in this study.

3.1.2 Establishing Valid Related Pairs

Following the listing of characteristics shown in Table I, a nineteen by nineteen matrix was set up to show all the relationships possible between the characteristics selected. Since the matrix is symmetrical, it was only necessary to examine the row and column intersections of one half of the matrix. Each intersection was then examined to evaluate whether a valid relationship might exist between the characteristics for the corresponding row and column, e.g. the relationship between power and tape thickness should not have a valid relationship while power and tape speed should show some correlation. The intersections which were selected as showing a possible valid relationship were transferred to index cards. The listing of relationships was then sorted into four groups of decreasing value with regard to the aims of this study; possible value in the determination of the requirements of an optimum tape recorder configuration for a specific mission. There were approximately forty items in the first group. After the initial screening, this number was reduced slightly, upon review, so that thirty-eight relationships were selected for plotting. This list of relationships selected for plotting is shown in Table II. All MTBF plots were done at the design conditions and also with the tape speed normalized to 15 ips. The skew values were also plotted on the basis of measured skew and skew per inch.

TABLE II

MTBF - Power

MTBF - Volume

MTBF - Weight

MTBF - Tape Length

MTBF - Tape Speed

MTBF - Wt/Wt Ratio

MTBF - Data/Wt Ratio

MTBF - Skew

MTBF - Start/Stop Time

S/N Ratio - Packing Density

S/N Ratio - Tape Speed

S/N Ratio - Track Width

S/N Ratio - Dropout Rate

S/N Ratio - Flutter

Dropout Rate - Track Width

Dropout Rate - Packing Density

Dropout Rate - Tape Speed

Dropout Rate - Flutter

Flutter - Wt/Wt Ratio

Flutter - Power

Flutter - Start/Stop Time

Flutter - Packing Density

TABLE II

Flutter - Weight

Flutter - Volume

Start/Stop Time - Wt/Wt Ratio

Start/Stop Time - Power

Data/Wt Ratio - Packing Density

Wt/Wt Ratio - Tape Length

Wt/Wt Ratio - Tape Width

Wt/Wt Ratio - Power

Vol/Wt Ratio - Tape Width

Skew - Packing Density

Skew - Tape Width

Track Width - Packing Density

Power - Tape Speed

Power - Tape Width

Skew - Tape Guidance Method (to be tabulated)

This selection was made with the understanding that the data when plotted might not show any useful correlation and even that no correlation exists. Several items do not appear to be correlated but they are included because they may show the summation of a complex and obscure chain of relationships.

3.1.3 Collection of Design Data

The most laborious and time consuming phase of this study was the location of the design and test information for the eleven machines surveyed. These machines were designed and fabricated over a period of five years. This represents practically the entire history of the company. As a result, the records were difficult to locate. Further, there has been a continuous improvement in the documentation of the company. The data for the earlier machines had to be searched out from individual log books, and, in some cases, located where it was inserted in the body of various final reports. In a few instances, the information could only be obtained because an individual remembered that the data was recorded in a file not associated with the particular machine. It is thought that the compilation which resulted from this search is as complete as the original data sources permit.

A data sheet was prepared to record the original design and test data for a single machine and the derived criteria listed in Table I. These data sheets are included in 3.1.7. A brief description of the primary design requirements is included where applicable. Each machine data sheet carries an identifying symbol at its head. This symbol is used to identify the machine on all the individual plots and to relate the data sheet to the plots.

3.1.4 Data Plotting

The various plots of the design, test, and derived criteria are included in 3.1.6. Two criteria were plotted on the basis of design values and with a normalized value. These are the Mean Time Before Failure and Skew. The Mean Time Before Failure was normalized by multiplying by the speed ratio, to the value which would be obtained if the mechanism were run at a tape speed of 15 ips. This may introduce an error in the very low speed machines due to the additional speed reduction stages. However, the limited time and effort allotted to this study did not permit a detailed analysis of changes which might have been involved in changing the design speed of a particular unit. If these extra stages are eliminated the MTBF would be increased. The increase in MTBF could vary from 5% up to, possibly, 50% as a result of this elimination of parts which permit operation at an intermediate speed.

Where the existing machine did not have a previously prepared reliability analysis the MTBF was calculated for the belt drive system only. This was done to obtain a spectrum of MTBF's which could be used with a practical minimum effort. This procedure is valid because all other failure modes contribute less than 1 % to the total failure rate, at the MTBF point, in every reliability analysis of Iso-Elastic Drive recorders performed to date.

The skew was normalized to the skew per inch by dividing the skew by the track separation to obtain a measure of angular variation in tape position. Unfortunately, since the data was available for only four of the machines covered in this study, it was not possible to plot any of the relationships which involved dropout rate. A total of forty-two plots resulted from the available data due to the doubling of plots involving MTBF and Skew and dropping the plots involving dropout rate.

3.1.5 Review of Plotted Data and Estimate of Correlation Validity

After all the data points were plotted, the plots were reviewed to determine whether they revealed useable correlations between the variables. The plots were segregrated into three groups. The first group, Figures 1 through 18, are thought to show a real and useful correlation. The second group, Figures 19 through 27 indicate a real trend. However, the correlation is so poor that the value of the trend indicated is doubtful. Some of these plots may be worth the effort of obtaining more extensive data to establish whether a correlation does exist and the nature of any such correlation. The third group of plots revealed no correlation and, therefore, have not been included.

Based on the appearance of the distribution of data points, the correlation plots can be divided into two groups.

The first group shows the data points scattered within a band. The second group shows all the points scattered to one side of a line which marks the demarcation between the area in which the data points lie and the area in which there are no data points. This line, which marks the division between the two areas, is called a maximum limit trend line or a minimum limit trend line. If all the values of the dependent variable lie below the trend line, it is called a maximum limit trend line. Conversely, if all the values of the dependent variable fall above the trend line, it is called a minimum limit trend line. The maximum and minimum are used to define the limiting value of the dependent variable. The selection of the dependent variable, in many cases, is obvious because of mechanical reasons. In the remaining cases, where there is not an obvious dependence, the choice is arbitrary.

3.1.6 Data Plots

A brief discussion of the first 26 plots is given below. Because these graphs were arranged to place related trends closely together, the figure numbers bear no relation to the order in which the relations appeared in Table II. This was done to give some degree of ease in reviewing the data. Immediately following this discussion, the plots themselves are included.

3.1.6.1 First Group 1-18

Figure 1, S/N Ratio versus Packing Density shows that the minimum S/N ratio, which could be expected from a recorder, increases at the rate of about 3 db per 1,000 bpi. This result is not expected but is undoubtedly the result of greater overall attention to design details as the required packing density increases.

Figure 2, S/N Ratio versus Track Width shows that the S/N Ratio increases at the rate of 0.14 db per mil of track width. C. D. Mee in The Physics of Magnetic Recording, Interscience, 1964, page 242, Figure 7.3, indicates an overall relationship of 0.20 db per mil of track width over a larger range of track widths under lab conditions and, further, indicates that the S/N ratio varies as the square root of the track width. This match between empirical experience and a theoretical analysis is quite interesting.

Figure 3, Packing Density versus Track Width shows a minimum limit trend line. The track width is greater than a limiting value for a given packing density. This trend line slopes at about 0.006 inches per 1,000 bits per inch with a track width of 0.0085 inches at zero packing density (intercept). This curve can be used to determine the maximum number of tracks to specify for a given packing density.

Figure 4, Data/Wt Ratio versus Packing Density shows a trend of increasing bit storage capacity at about half the rate of the packing density increase. The one data point at 76 x 10 bits per pound is excluded because this machine utilized diphase recording with a single channel duplexed onto two adjacent tracks and with twelve serial passes. It could be expected that this scheme could result in a similar, but offset, trend. It would appear that packing density may nor be the most efficient way to increase storage capacity if weight is a limiting factor.

The terms skew (absolute) and skew (relative) are used to denote the actual measurement and normalized values of skew displacement in microinches. In all cases, the time displacement of simultaneously recorded bits is measured during reproduction. This measurement is customarily made between the outermost tracks in a head stack. However, in some cases, the measurement is made from the center track to the edge track in order to duplicate the application. This "time displacement" is then multiplied by the tape speed to obtain the skew in length dimensions. This value is called absolute skew, and is measured as indicated on the data sheet for the individual machine.

Since tape widths ranged from one quarter inch to one inch, it was thought that a normalized value might be more informative. The absolute is divided by the track separation to normalize the values of skew. This result is called skew (relative).

Figure 5, Skew (absolute) versus Packing Density shows a decreasing trend with increasing packing density. The data are widely scattered.

However, there does appear to be a maximum value of skew which would not be exceeded at a given packing density. The value of the maximum limit of skew decreases with increasing packing density. This is probably a consequence of the tighter skew requirements of higher packing densities .

Figure 6, Skew (relative) versus Packing Density shows exactly the same trend as Figure 5.

Figure 7, Flutter versus Transport Weight shows a sharp increase in flutter for transport weights less than 6 pounds. It appears that any system which has severe flutter and weight limitations will require an intensive design effort.

Figure 8, Flutter versus Transport Volume reveals a sharp increase in flutter for transport volumes less than 200 cubic inches. It appears that any system which has severe flutter and volume limitations will require an intensive design effort.

Figure 9, Flutter versus Wt/Wt Ratio shows a maximum limit trend line which indicates that the maximum expected flutter decreases with increasing Wt/Wt ratio. This result is contrary to what would have been expected. It was expected that the lower Wt/Wt ratios which would be representative of more ruggedly constructed machines would show lower flutter. It does not appear that the Wt/Wt ratio is a good measure of ruggedness. In addition, the high Wt/Wt ratio machines could be expected to show a lower reel torsional resonant frequency that the lower ratio machines. This lower resonant frequency results from a larger tape pack inertia and lower belt compliance as the tape pack diameter and the Wt/Wt ratio increases.

Figure 10, Flutter versus Packing Density shows a maximum limit trend line which indicates that the maximum expected flutter decreases with increasing packing density. Even if the two points at 7.5 and 12.4 percent flutter (light weight, low power machines) are excluded, the decreasing trend line is still found. This finding may be the result of measuring the flutter over a shorter period on machines with higher packing densities.

Figure 11, Flutter versus Start plus Stop Time indicates a rather diffuse trend line with the flutter decreasing with increasing start plus stop time. This effect is to be expected since rotary inertia and start plus stop time should be related by a direct proportionality. This result conflicts with the trend line found in Figure 9.

Figure 12, Flutter versus Power indicates that the maximum expected flutter decreases with increasing power. Even if the two points at 7.5 and 12.4 percent flutter (same points as in Figure 10) are excluded a similar trend is found.

Figure 13, Flutter versus Signal to Noise Ratio shows a maximum limit trend line with the maximum expected flutter decreasing as the S/N ratio increases. This plot may just reveal the signal degradation, caused by flutter; as a change in signal to noise ratio.

Figure 14, Start plus Stop Time versus Power shows a minimum limit trend line which indicates that the start plus stop time will exceed a value which increases as power increases. This result is not expected but is probably the consequence of severe weight limitations which usually accompany power limitations.

Figure 15, Skew (absolute) versus Tape Width shows a maximum limit trend line which indicates that the maximum expected skew decreases with increasing tape width. This excludes the one data point at 1750 microinches skew which is a measurement based on the skew between tracks 8 and 10 on one inch tape.

Figure 16, Power versus Tape Speed shows a maximum limit trend line which indicates that the power will be less than a value which increases with tape speed. This finding is contrary to expectations. It would have been more reasonable to have obtained a minimum limit trend line. However, since the Iso-Elastic Drive operates on a regenerative principle, the supply reel provides most of the power required by the take-up reel. The maximum limit trend line represents the least efficient designs.

Figure 17, Weight (of Transport) versus Tape Width. This plot replaces the planned plot of Wt/Wt ratio versus Tape Width. The original plot indicated a possible trend line except for two data points, one well above and the other well below the trend line. The data was replotted using weight of transport rather than wt/wt ratio to see whether an improved correlation would result. The second plot shows a maximum limit trend line indicating that the maximum expected weight increases with tape width. Naturally, a machine with a short tape length would fall below the limit line as evidenced by the data point at 4.2 pounds and 1 inch. This machine has 450 feet of tape.

Figure 18, Volume versus Weight. This plot indicates a band of values which can be expected in normal designs. If the volume and weight allotment for a given mission falls below the band great difficulty may be experienced in the design. If the point falls above the band two possible results may occur, one good and one bad. The unit may not actually require the entire alloted volume. On the other hand, and this will probably be the situation, it may be extremely difficult to meet the weight specification.

3.1.6.2 Second Group 19-27

Figure 19, MTBF (normalized to 15 ips) versus Data/WtRatio seems to indicate a band of expected values of MTBF which increases with increasing data/wt ratio. This requires that three data points be excluded. The first point at 0.63 hours is the oldest design covered in this study and predates the study of fatigue life of polyester film belts. The other two at 6560 and 17,000 hours are designs intended specifically for long mission lives. The latter two points might indicate an offset band that could be achieved with a design emphasis on long mission life. Without further information, it can only be assumed that a similar band exists at the higher level of MTBF.

Figure 20, MTBF versus Weight (of transport) the comment for Figure 18 applies with the substitution of weight for data weight.

Figure 21. MTBF versus Tape Speed seems to indicate that a maximum limit trend line exists with the maximum expected MTBF decreasing with

increasing tape speed. Since the fatigue life is dependent upon the number of stress cycles, this inverse relationship of life in hours and tape speed is to be expected.

Figure 22, Start plus Stop Time versus MTBF seems to indicate a band which shows that start plus stop time decreases with increasing MTBF. This relationship is probably fortuitous.

Figure 23, Skew (absolute) versus MTBF (normalized to 15 ips) seems to indicate a general decrease in skew with increasing MTBF. However, it is thought that this is probably fortuitous. No mechanism which could result in this correlation can be envisaged, nor do the other plots lend corralary support for this trend.

Figure 24, Power versus Tape Width does not seem to show any correlation. However, if the data points are separated into low, medium and high tape speeds, it appears that each group shows a trend of a gradual increase in power with increase in tape width. Both head and bearing frictions will vary in direct proportion to the tape width.

Figure 25, Power versus Wt/Wt Ratio shows the same relationship as Figure 24, except that wt/wt ratio is substituted for tape width.

Figure 26, Signal to Noise Ratio versus Tape Speed does not seem to show any correlation although it would be expected that a relationship would exist similar to the band indicated by the dashed lines. Unfortunately, only seven machines had S/N ratio data recorded. Of these, the one at the top edge of the band was designed with S/N ratio as an important criterion and the one at the bottom of the band is a machine with a low S/N ratio requirement. The remaining points are closely grouped about a line near the center of the band. This relation ship, if valid, could be of assistance in selecting a tape speed.

Figure 27, MTBF versus Data/Wt Ratio seems to indicate that there exists a minimum limit line such that it can be expected that the MTBF will exceed a value which increases as the data/wt ratio increases.

One interesting point is that MTBF does not show a positive correlation with any of the other tape recorder characteristics treated in this study. At best, there are only two characteristics (data /wt Ratio and Weight of Recorder) which may have a slight relationship to MTBF.

These plots can be used to screen the mission requirements for consistency and to identify tape recorder characteristics which may involve intensive design effort. The first step would be to identify the tape recorder characteristics which are determined by the mission objectives, and to rank these characteristics in order of decreasing importance. The various plots would then be examined to see whether the values of the characteristics fall in the areas which represent "realizable" values. If one or more points do not represent "realizable" values, it will be necessary to determine whether to modify the requirements slightly to move the points into easily attainable values or to require the more intensive effort involved in emphasizing the value of one characteristic. An example of conflicting requirements would be low flutter and short start plus stop time.

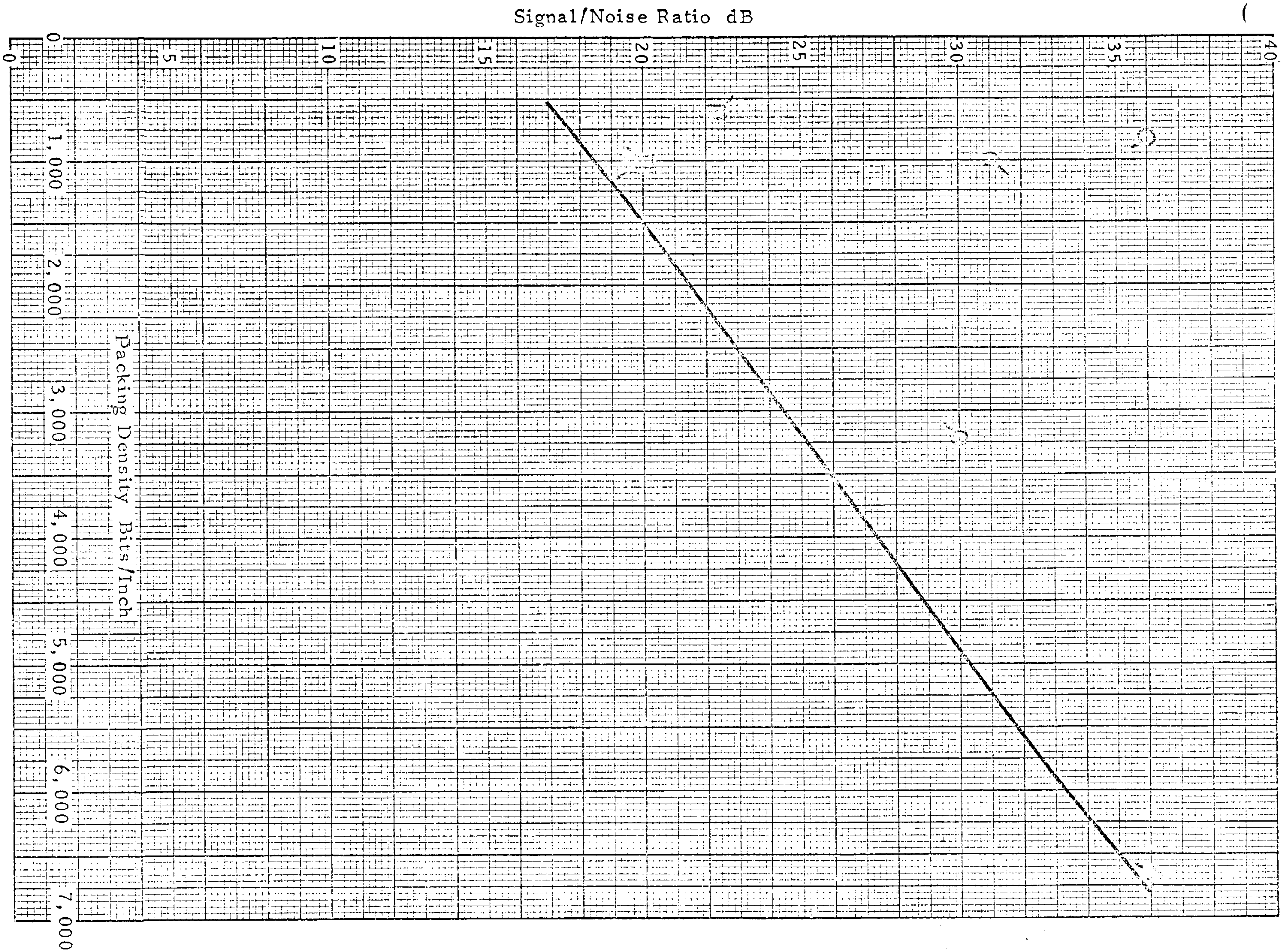

Signal/Noise Ratio dB
0
5
10
15
20
25
30
35
40
Packing Density Bits/Inch
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000

FIGURE 1

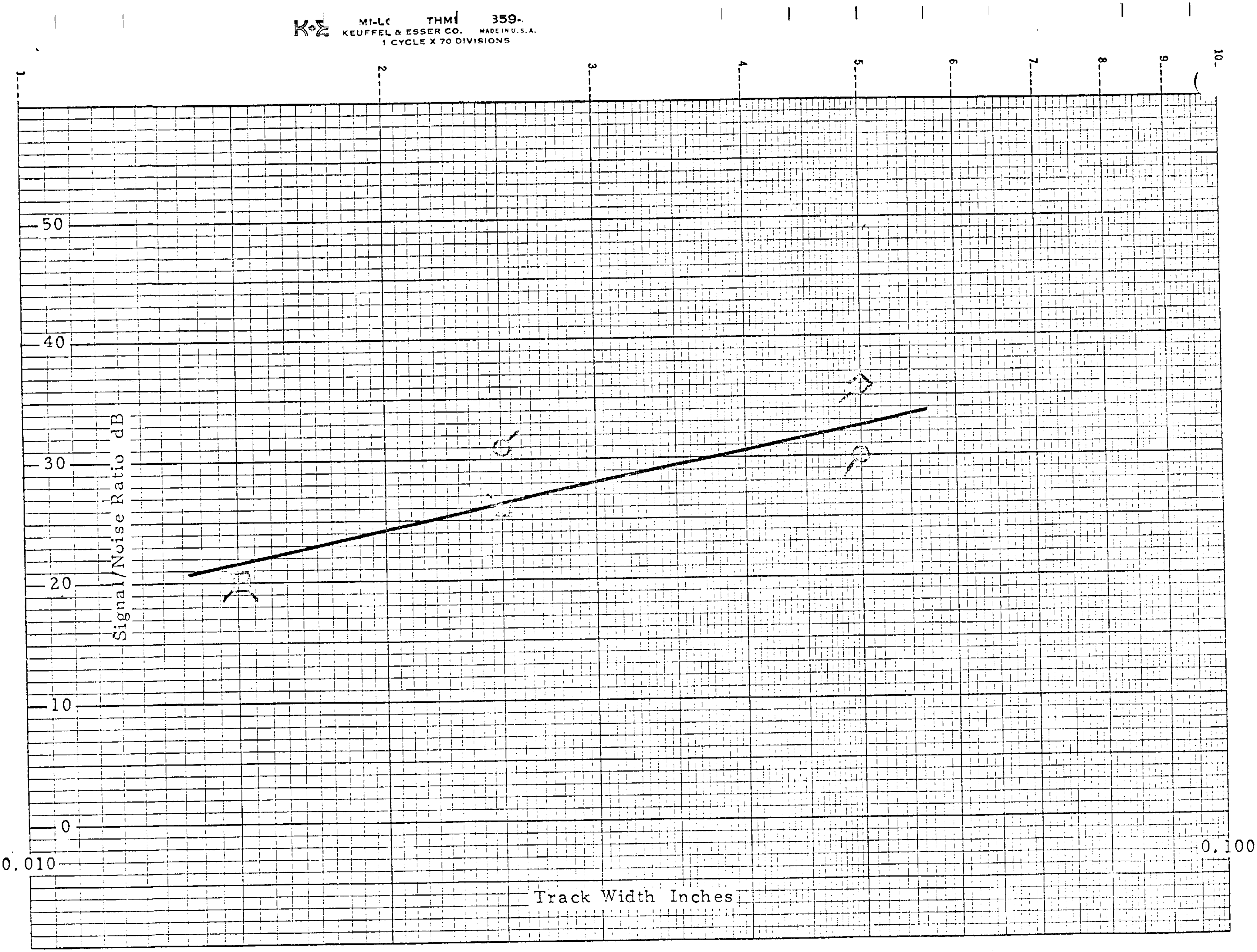
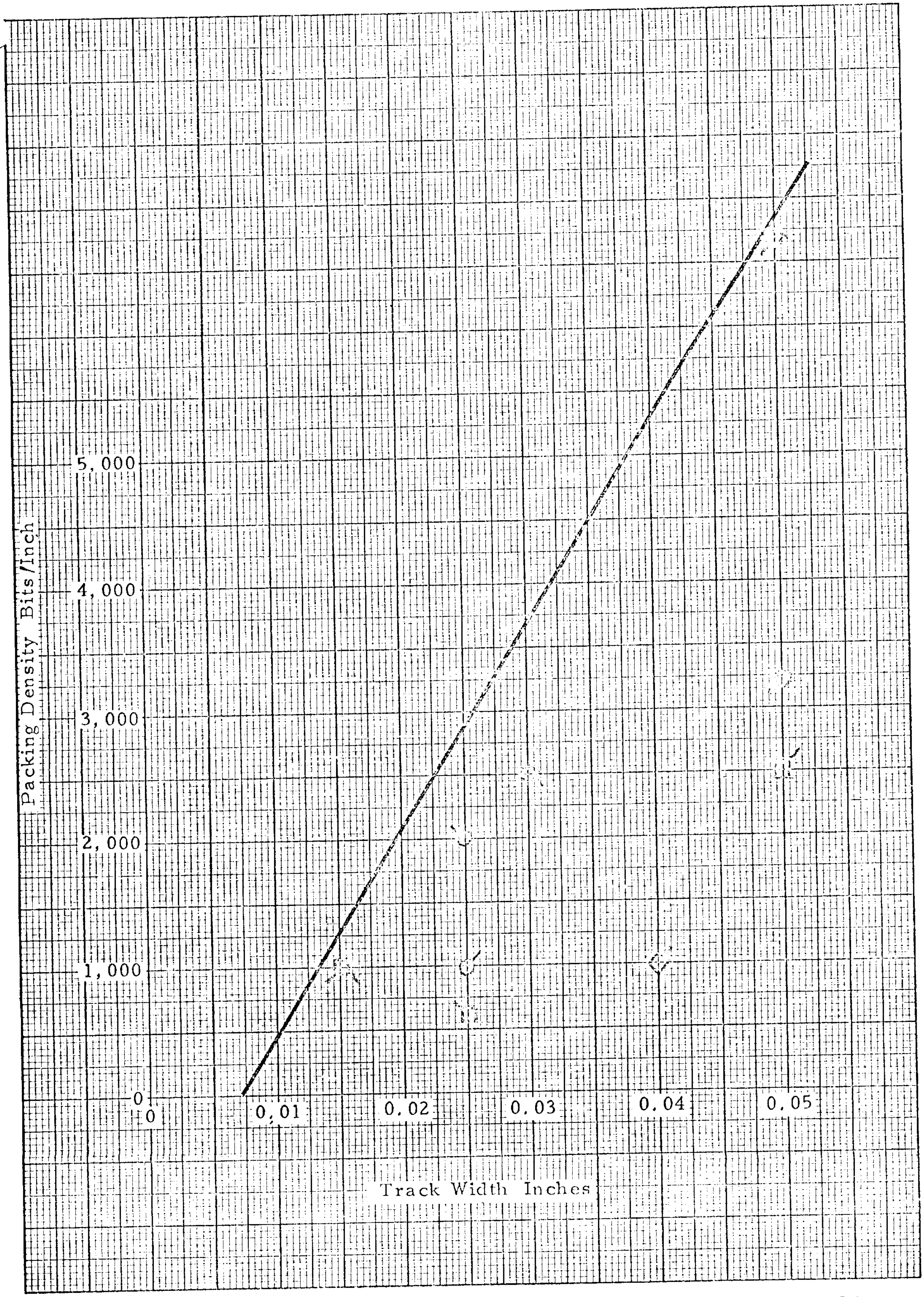

KEUFFEL & ESSER CO.
MADE IN U.S.A.
1 CYCLE X 70 DIVISIONS
50
40
30
20
10
0
0.010
0.100
Signal/Noise Ratio dB
Track Width Inches

FIGURE 2



Packing Density Bits/Inch
5,000
4,000
3,000
2,000
1,000
0
0
0.01
0.02
0.03
0.04
0.05
Track Width Inches

FIGURE 3

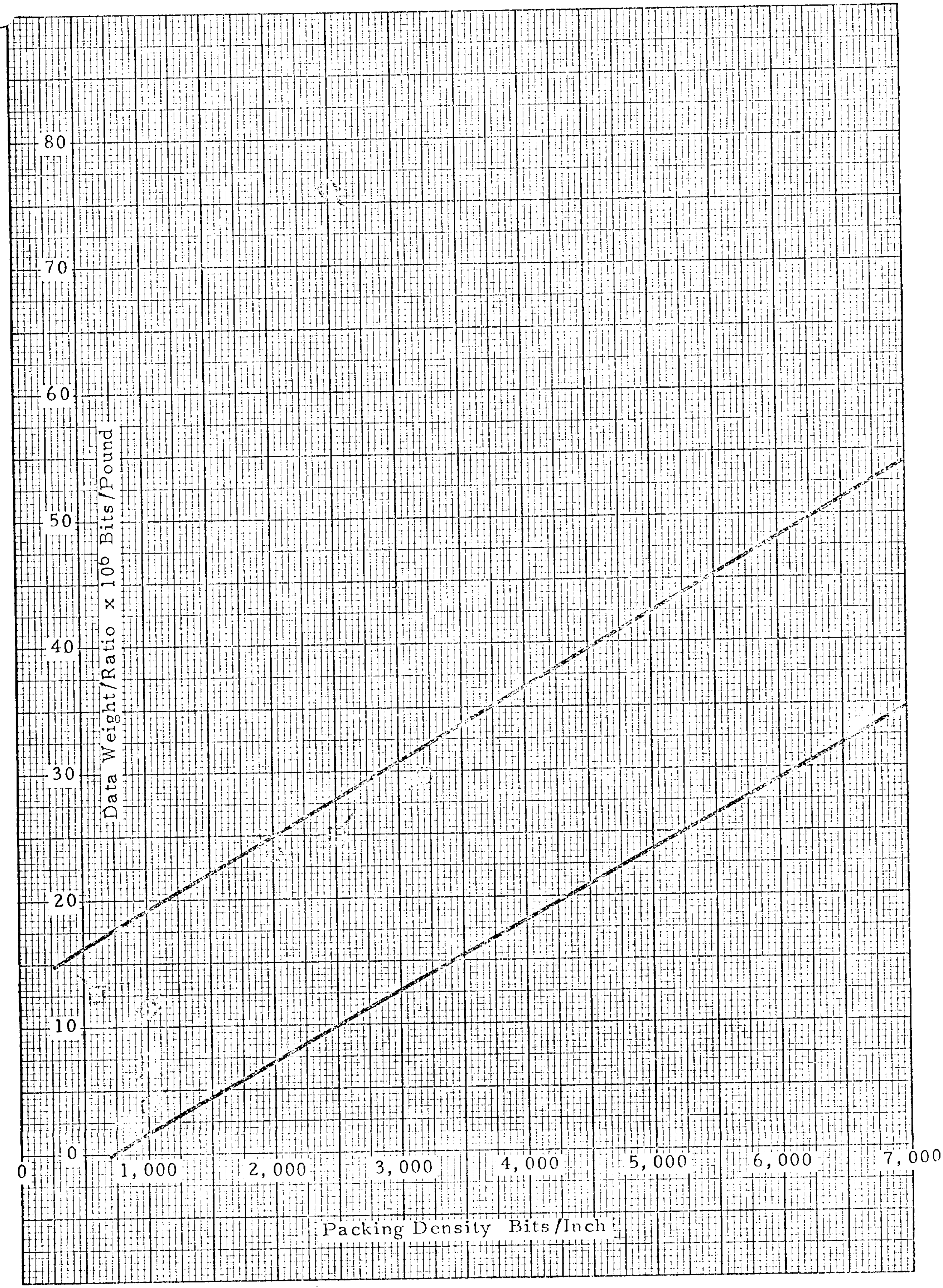
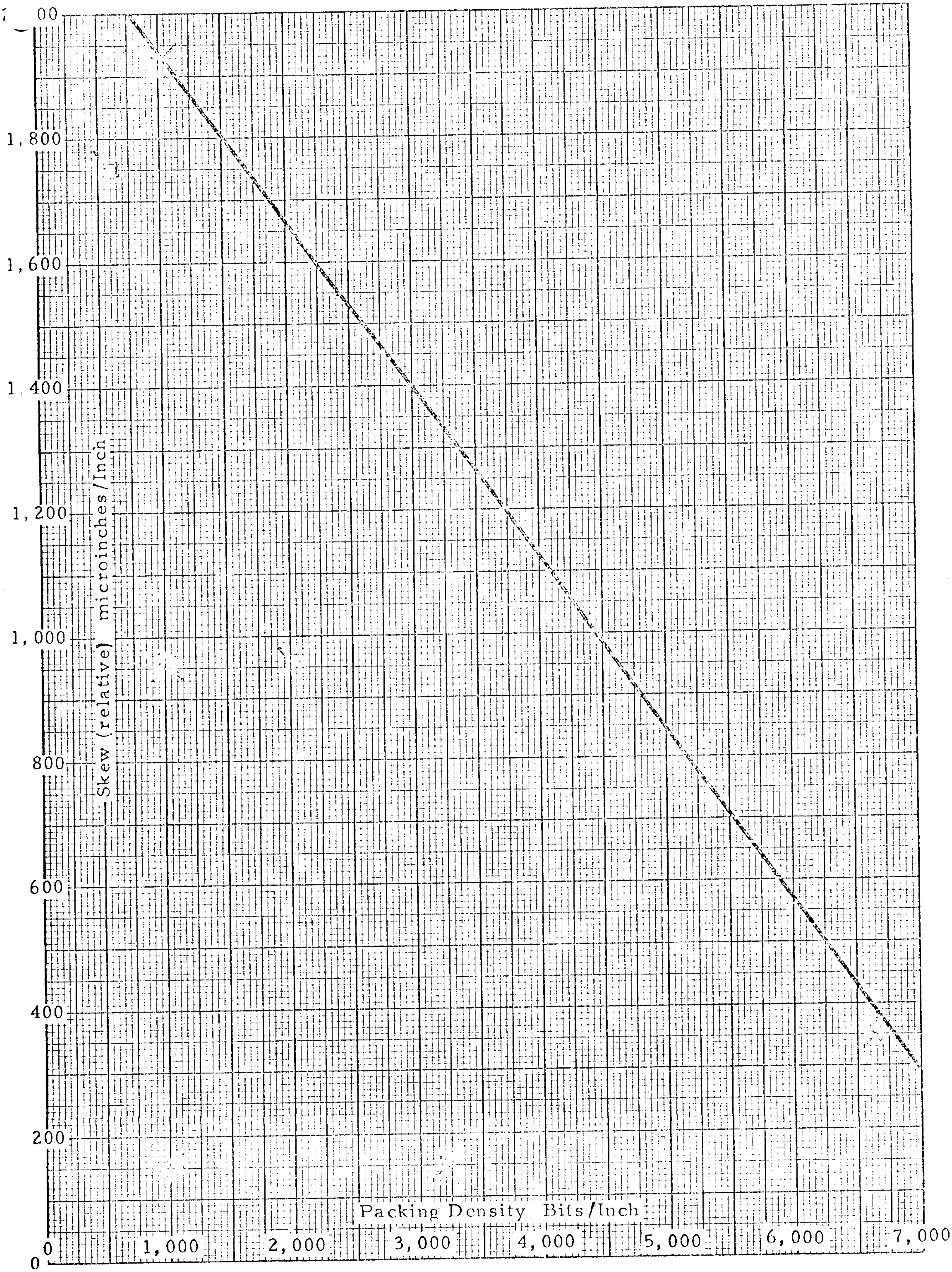
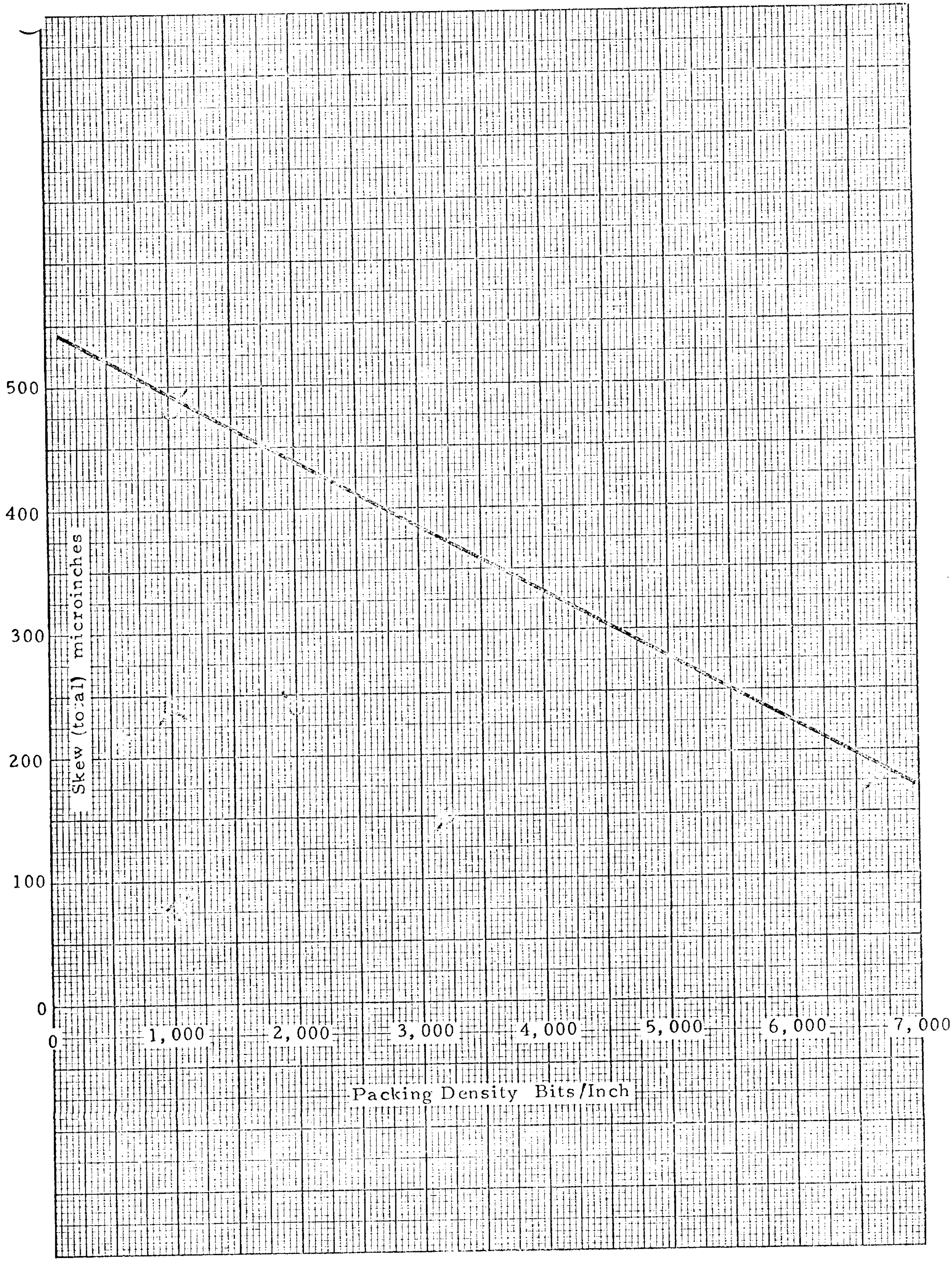

Data Weight/Ratio x 10^6 Bits/Pound
80
70
60
50
40
30
20
10
0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Packing Density Bits/Inch

FIGURE 4



Skew (relative) microinches/Inch
Packing Density Bits/Inch
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000

FIGURE 6



500
400
300
200
100
0
Skew (total) microinches
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Packing Density Bits/Inch

FIGURE 5

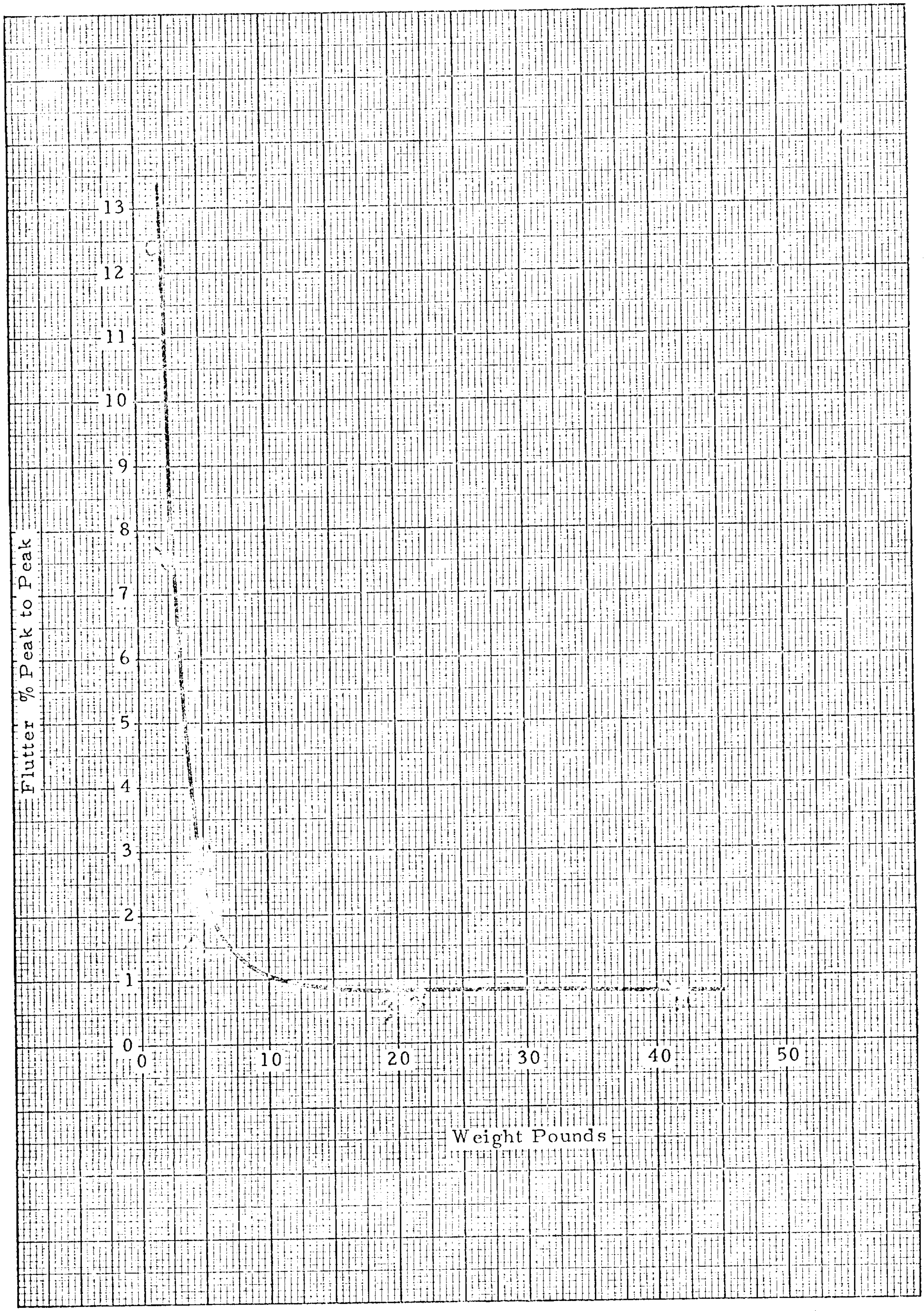

Flutter % Peak to Peak
0
1
2
3
4
5
6
7
8
9
10
11
12
13
0
10
20
30
40
50
Weight Pounds

FIGURE 7

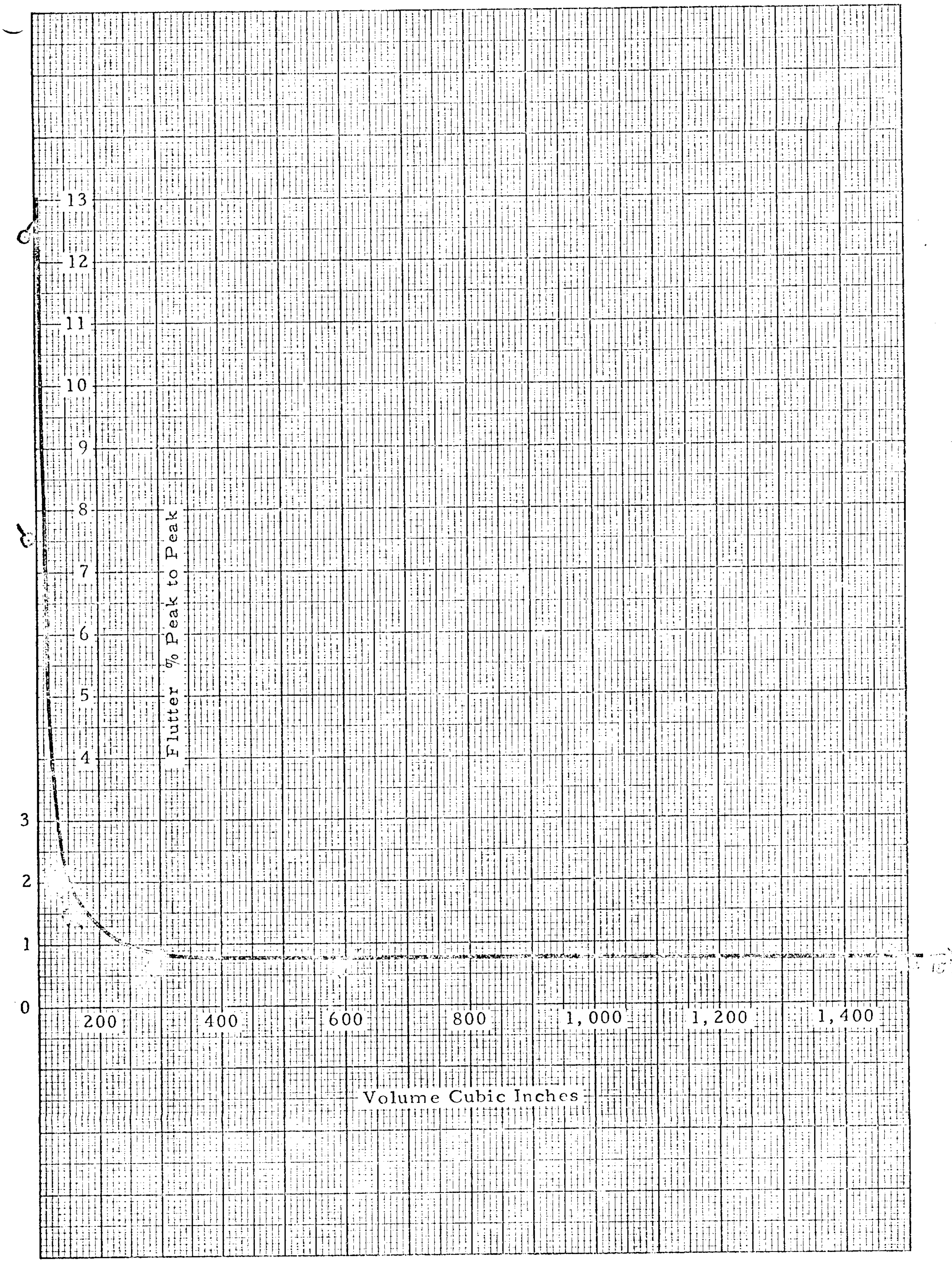

Flutter % Peak to Peak
Volume Cubic Inches
0
1
2
3
4
5
6
7
8
9
10
11
12
13
200
400
600
800
1,000
1,200
1,400

FIGURE 8

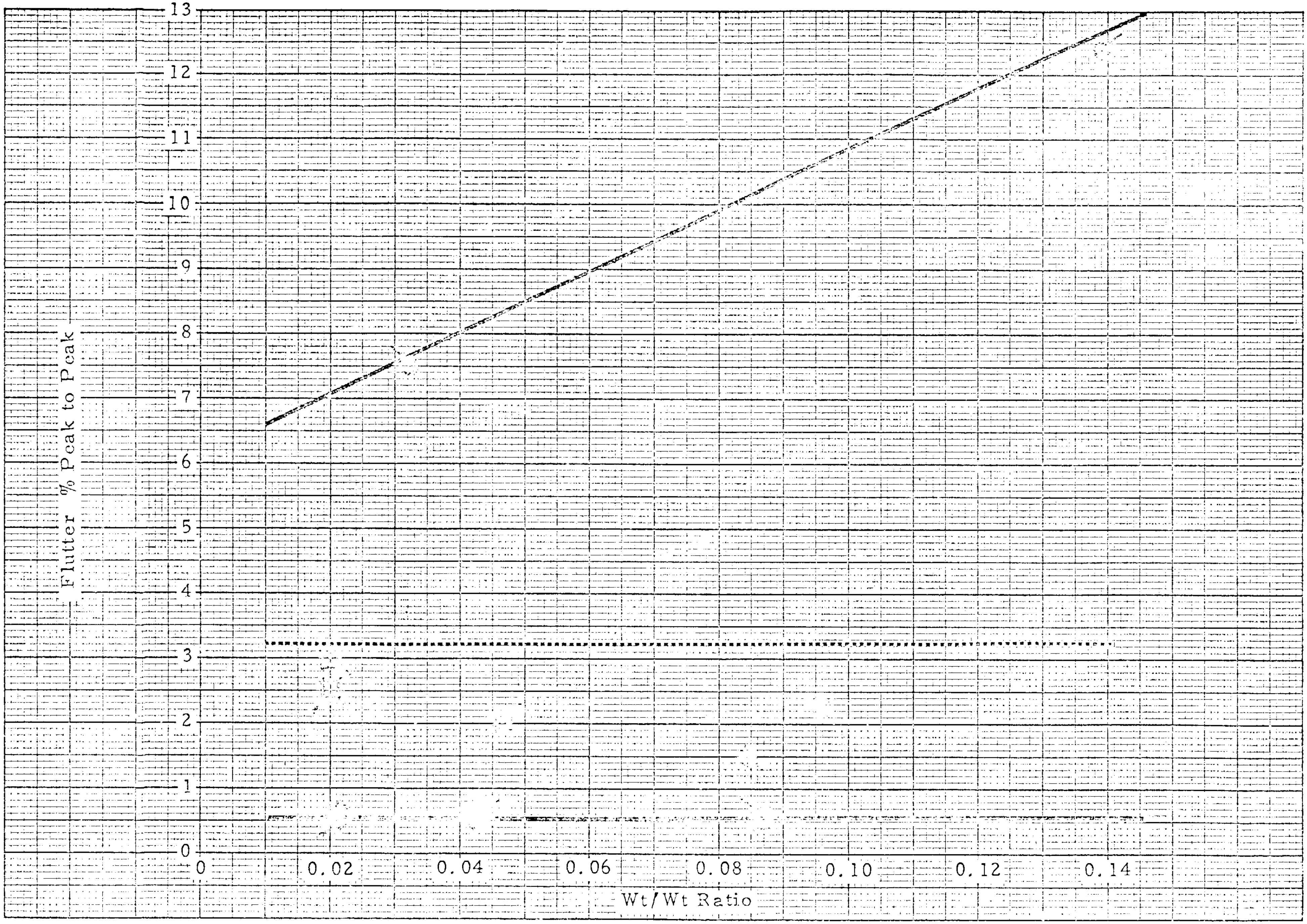
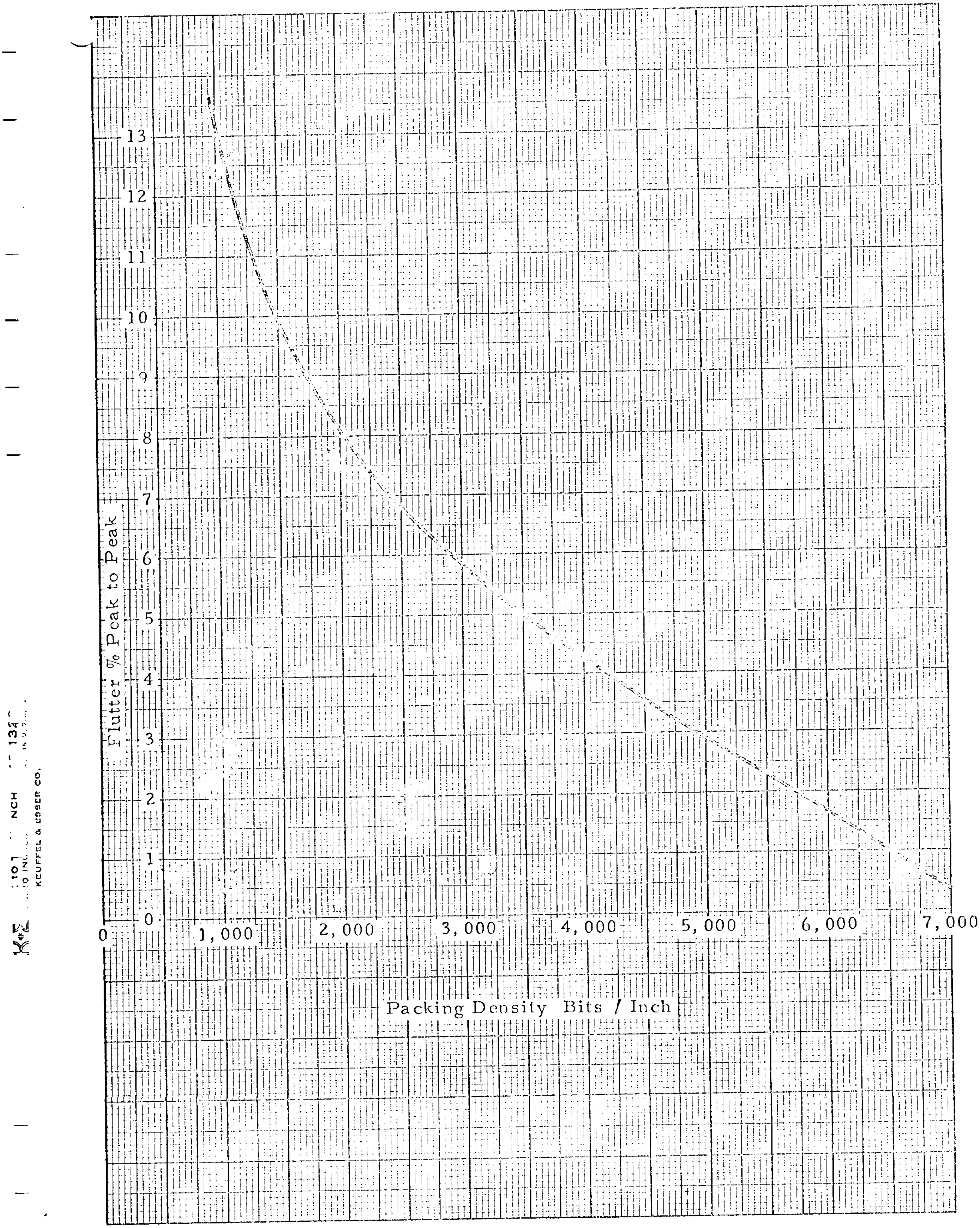
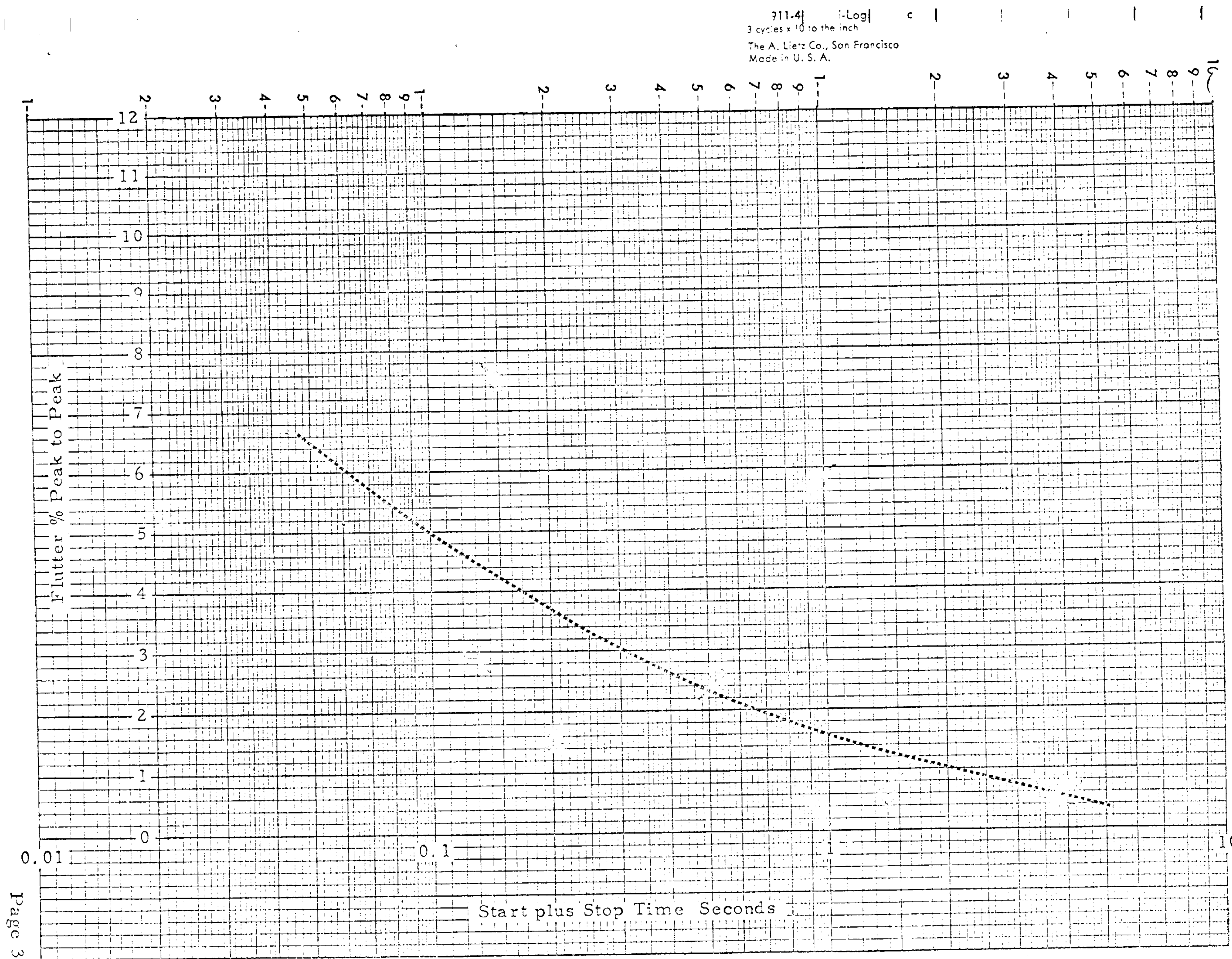

Flutter % Peak to Peak
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Wt/Wt Ratio

FIGURE 9



13
12
11
10
9
8
7
6
5
4
3
2
1
0
Flutter % Peak to Peak
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Packing Density Bits / Inch
KEUFFEL & ESSER CO.

FIGURE 10



911-4 Log
3 cycles x 10 to the inch
The A. Lietz Co., San Francisco
Made in U. S. A.
Flutter % Peak to Peak
12
11
10
9
8
7
6
5
4
3
2
1
0
0.01
0.1
1
10
Start plus Stop Time Seconds

FIGURE 11

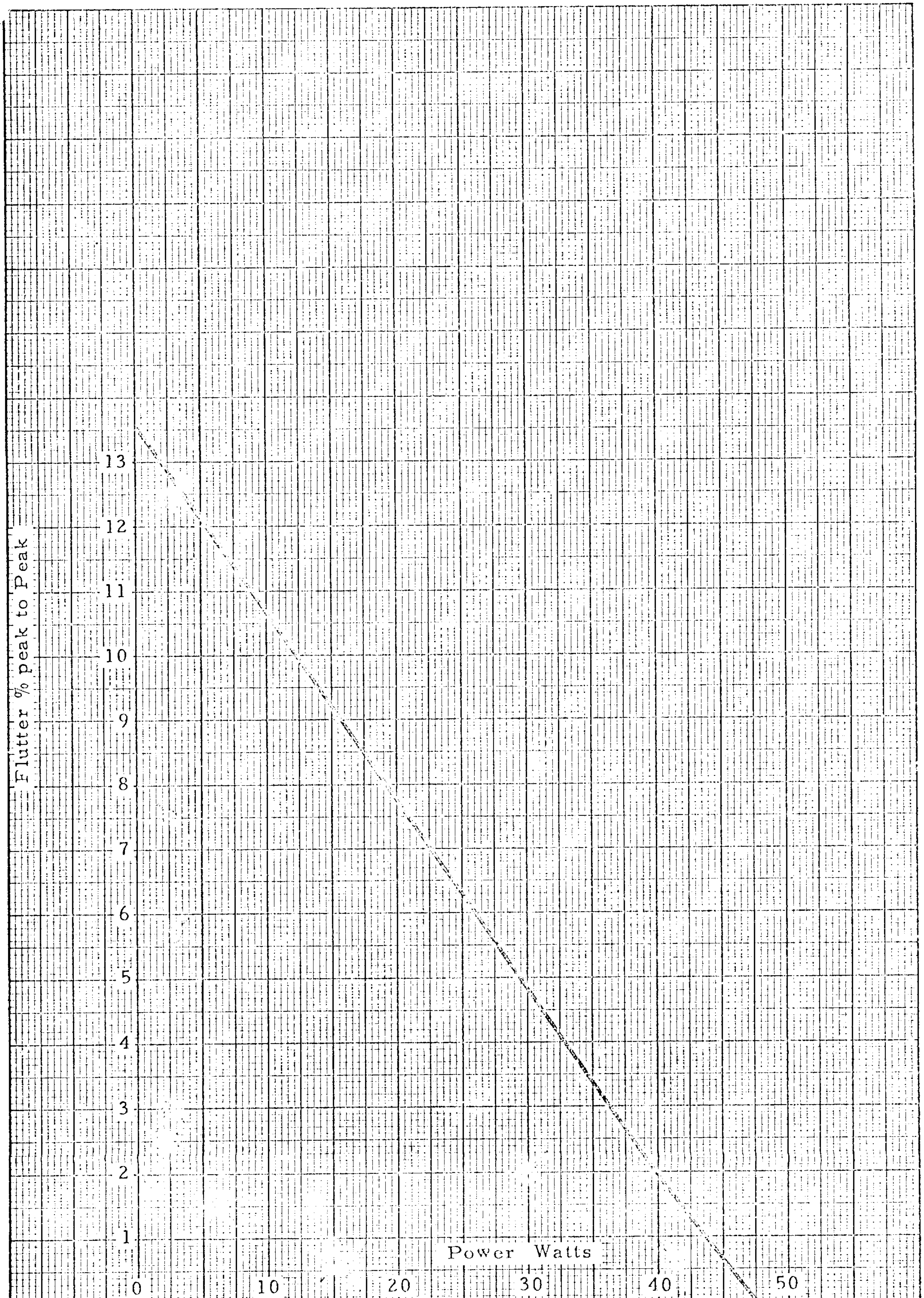
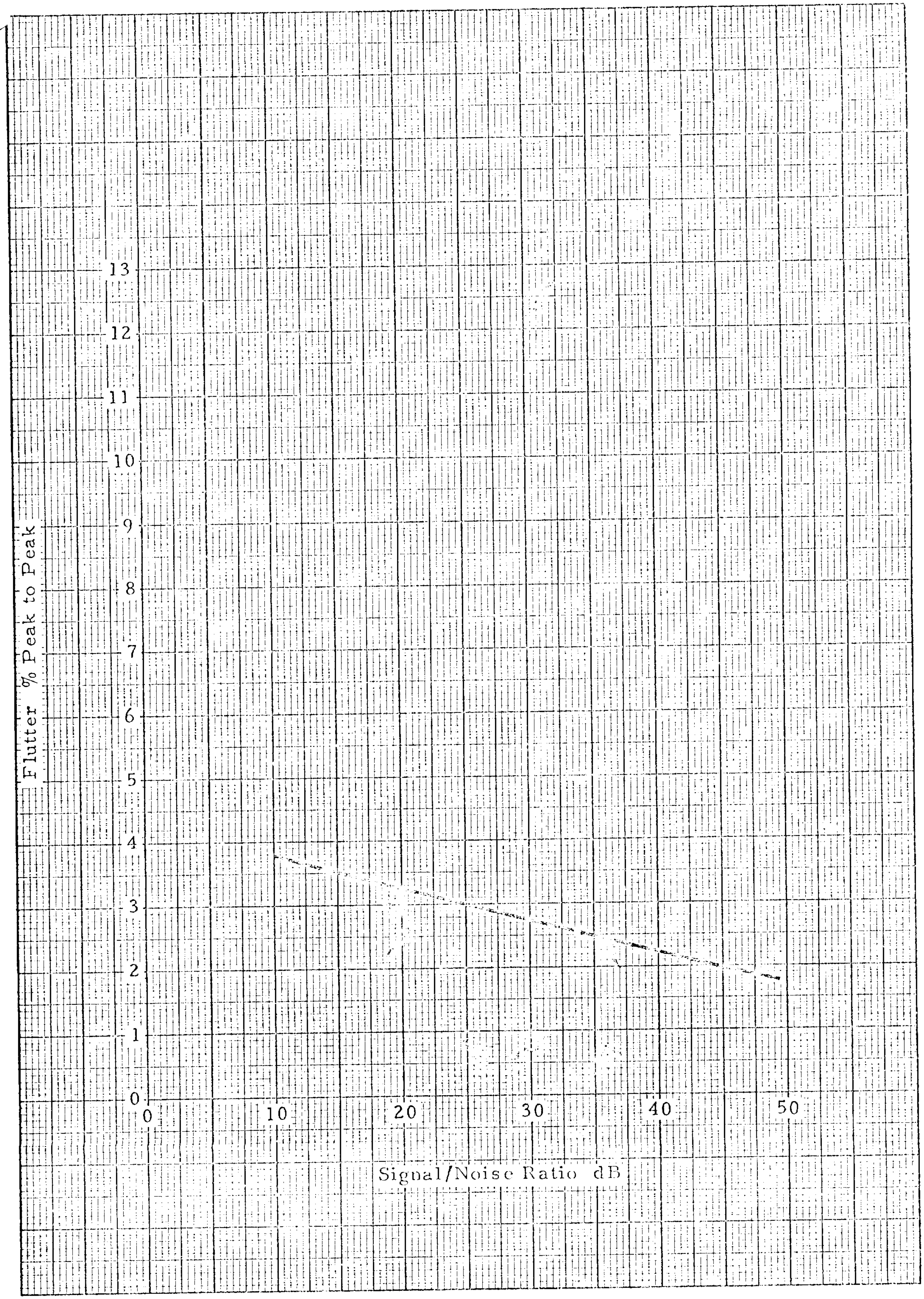
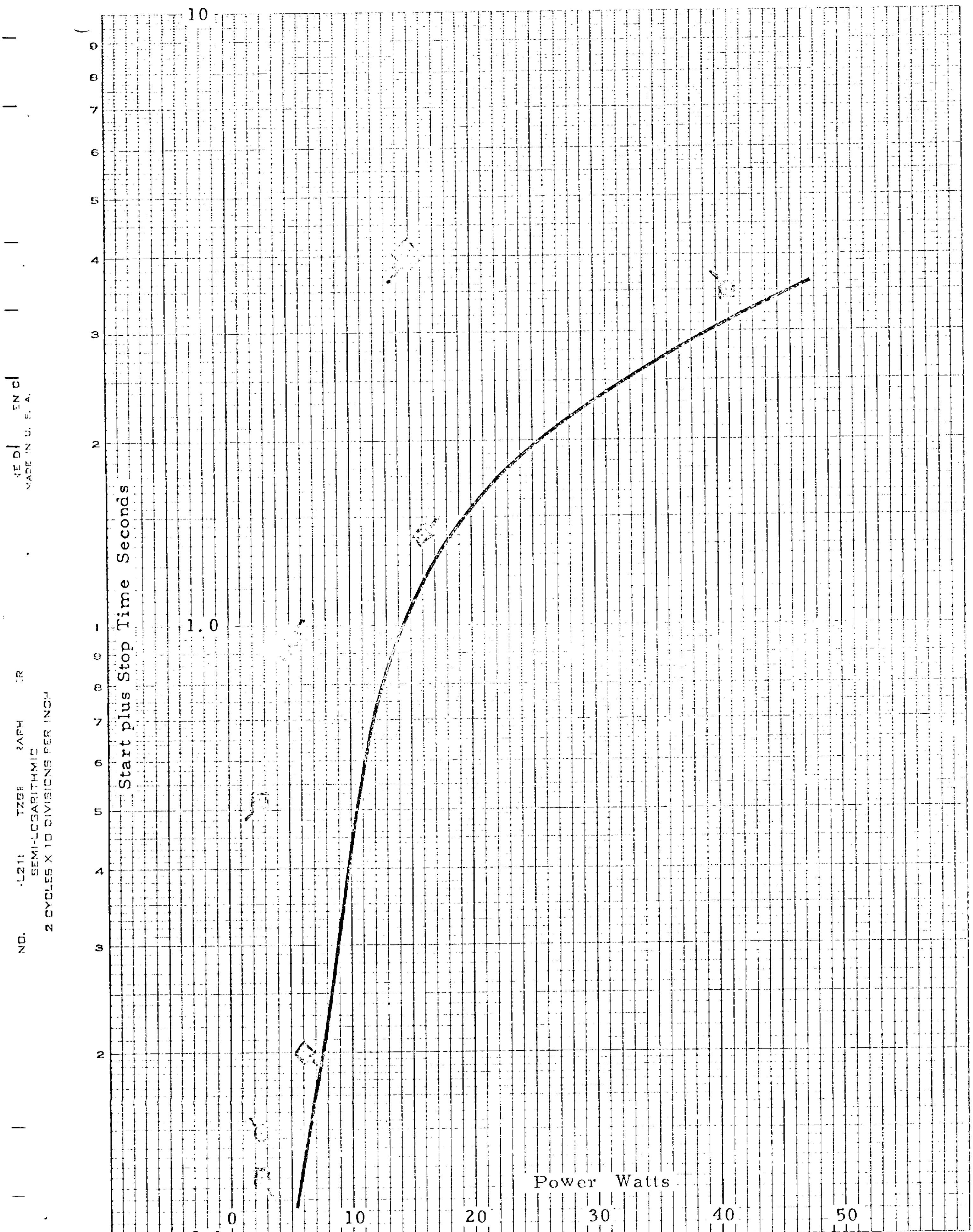

Flutter % peak to Peak
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Power Watts
0
10
20
30
40
50

FIGURE 12



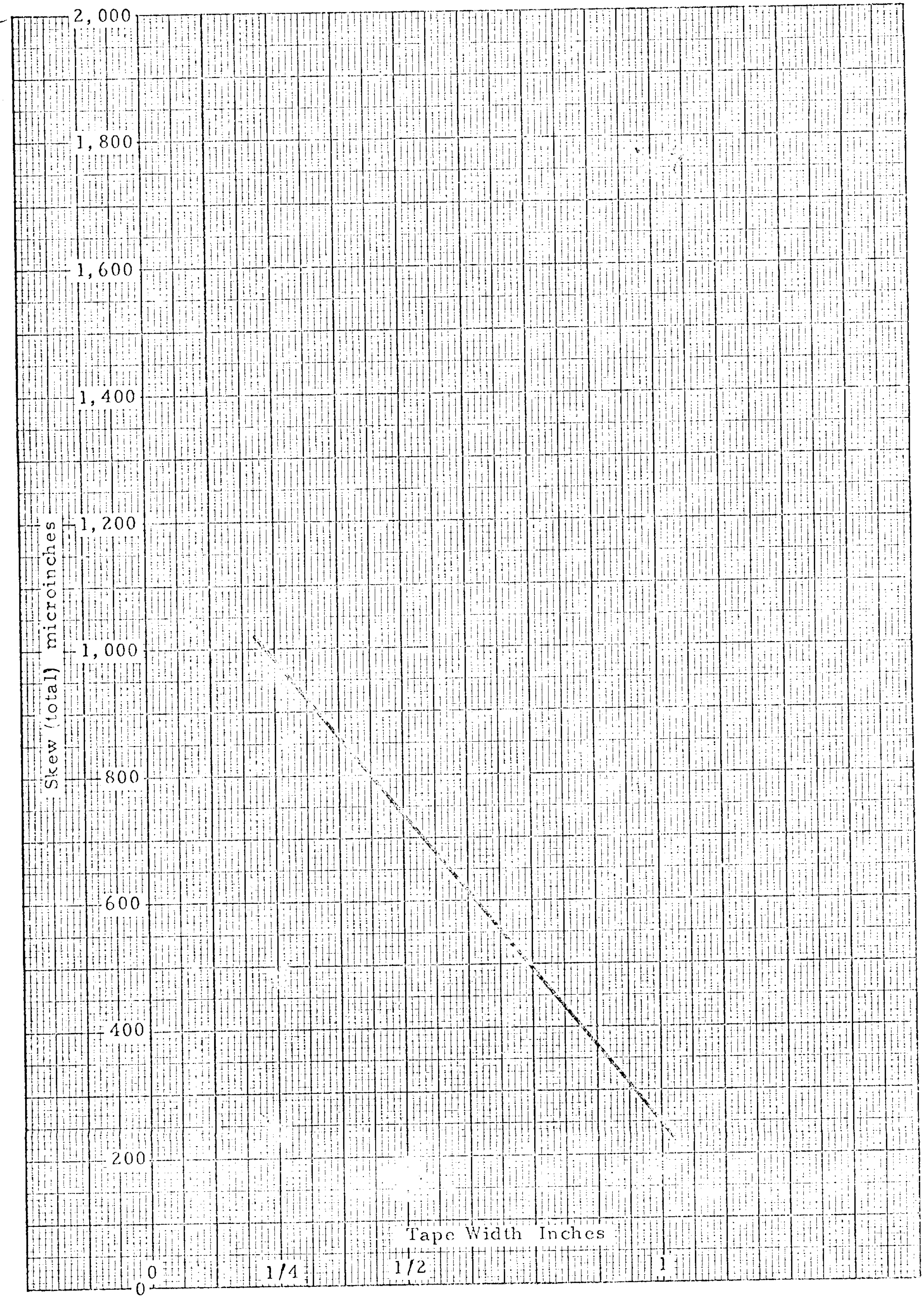
Flutter % Peak to Peak
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
Signal/Noise Ratio dB

FIGURE 13



Start plus Stop Time Seconds
Power Watts
10
1.0
0.1
0
10
20
30
40
50

FIGURE 14



2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Skew (total) microinches
0
1/4
1/2
1
Tape Width Inches

FIGURE 15

FIGURE 16

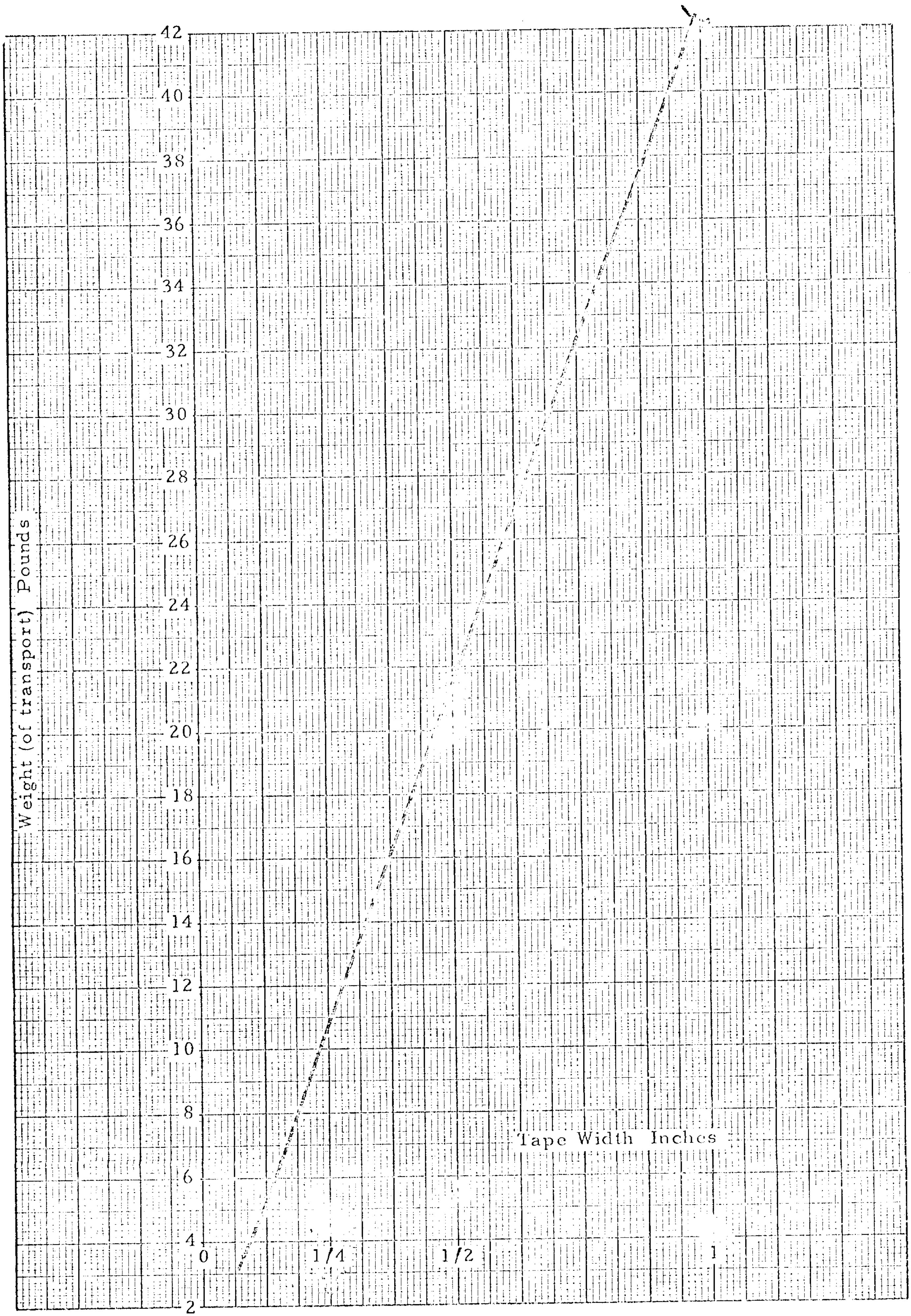
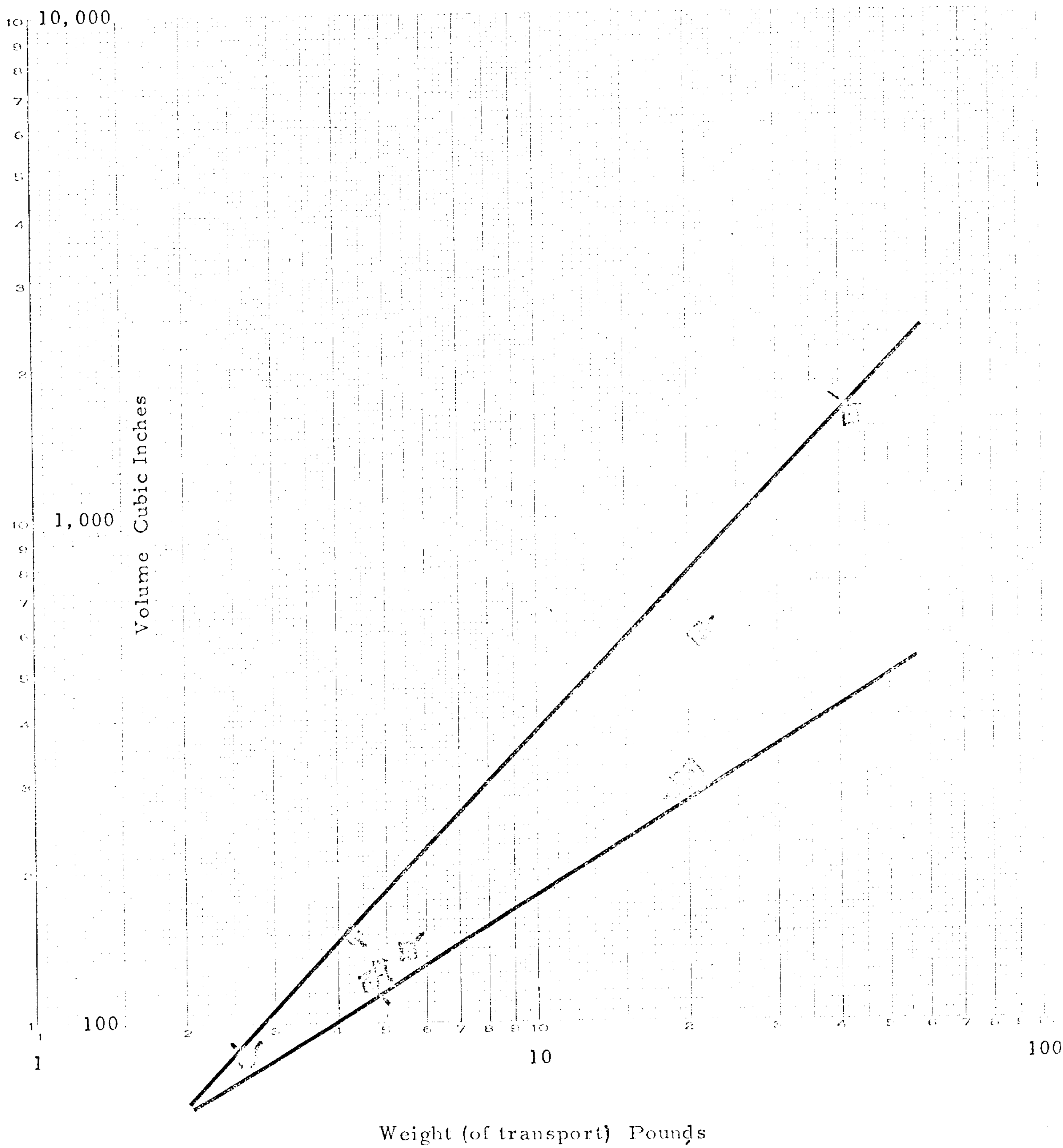

Weight (of transport) Pounds
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
Tape Width Inches
0
1/4
1/2
1

FIGURE 17



10,000
1,000
100
Volume Cubic Inches
1
10
100
Weight (of transport) Pounds

FIGURE 18

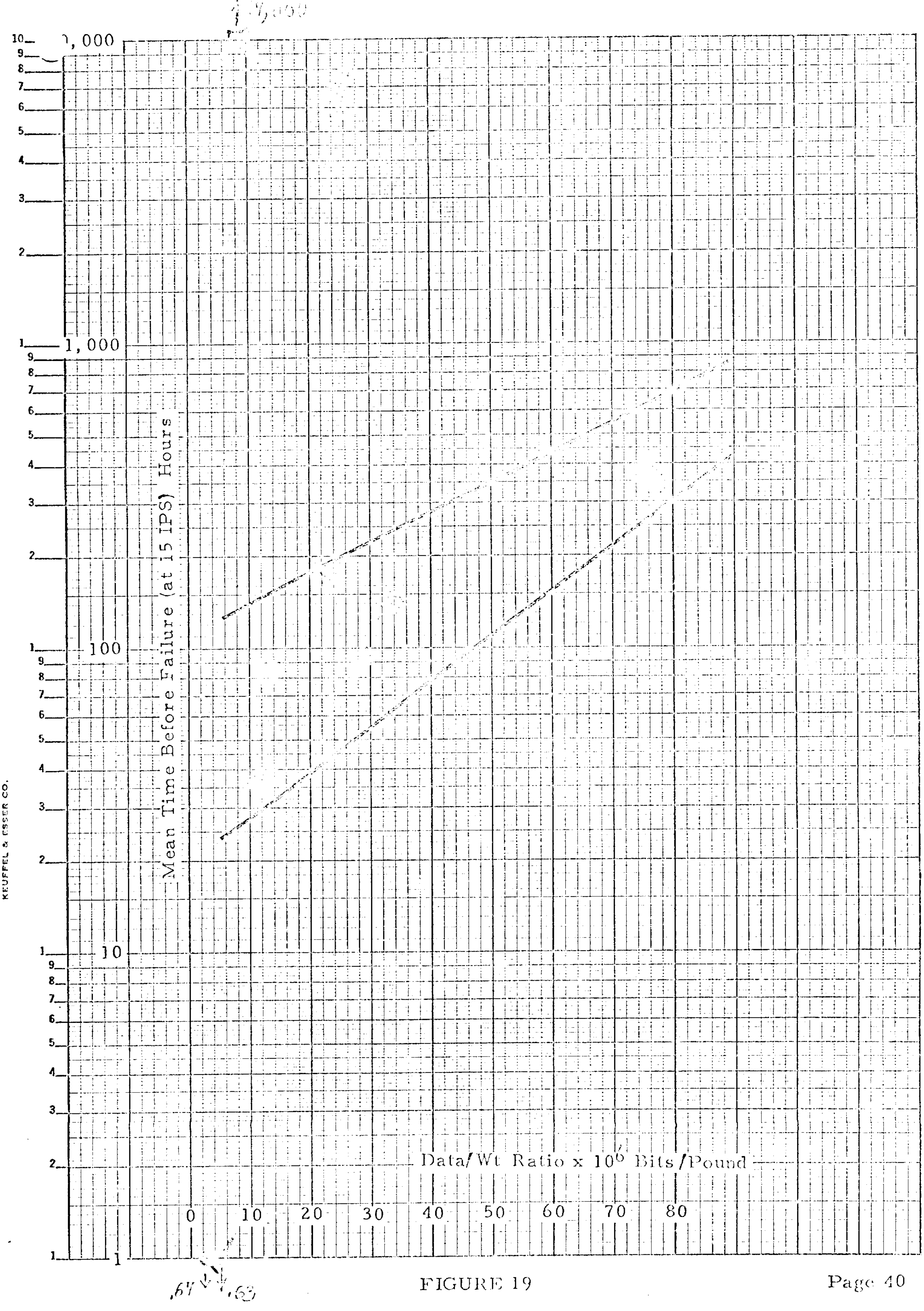
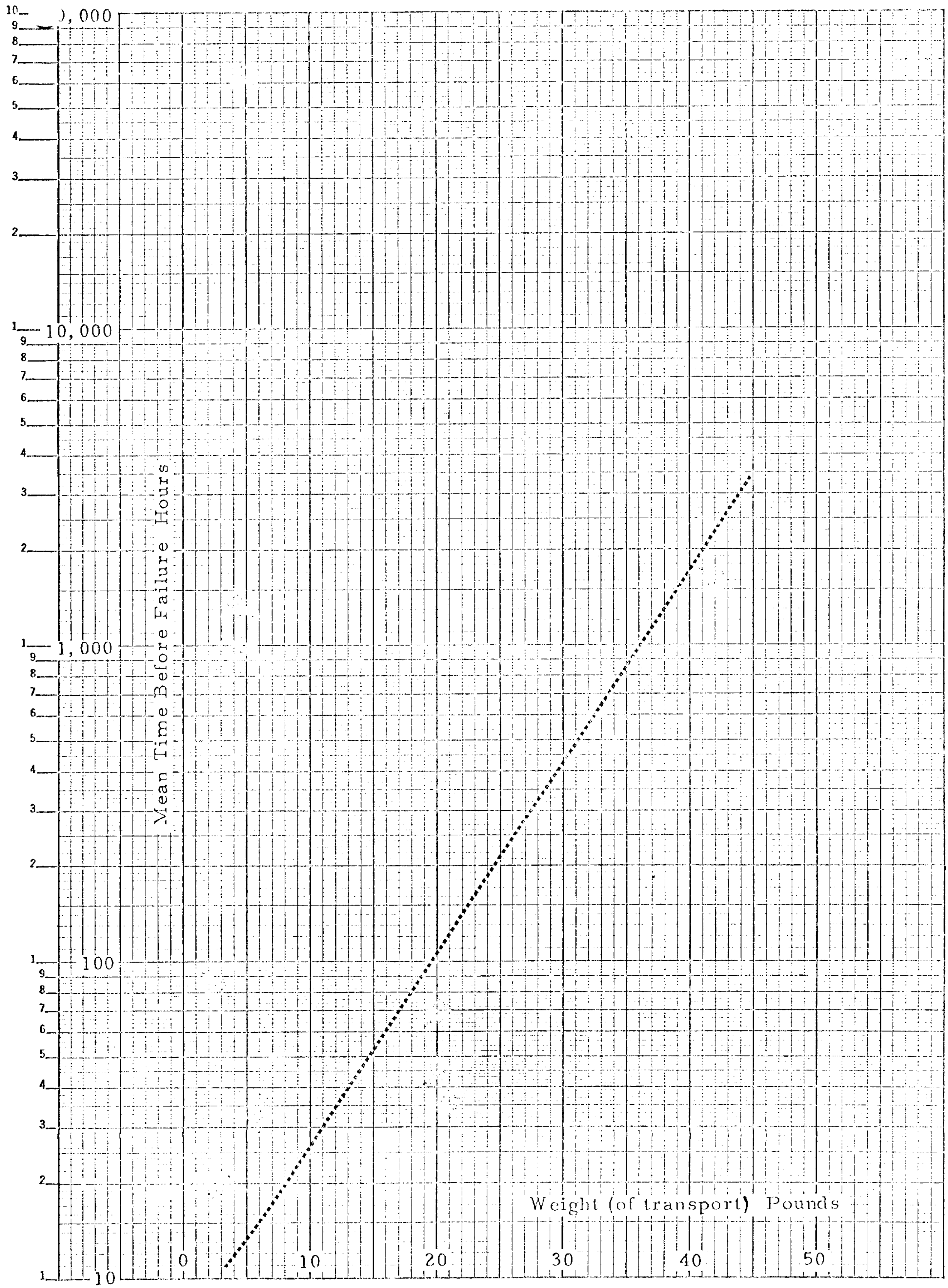

1,000
100
10
1
Mean Time Before Failure (at 15 IPS) Hours
Data/Wt Ratio x 10^6 Bits/Pound
0
10
20
30
40
50
60
70
80
KEUFFEL & ESSER CO.

FIGURE 19



Mean Time Before Failure Hours
Weight (of transport) Pounds
10
100
1,000
10,000
0
10
20
30
40
50

FIGURE 20

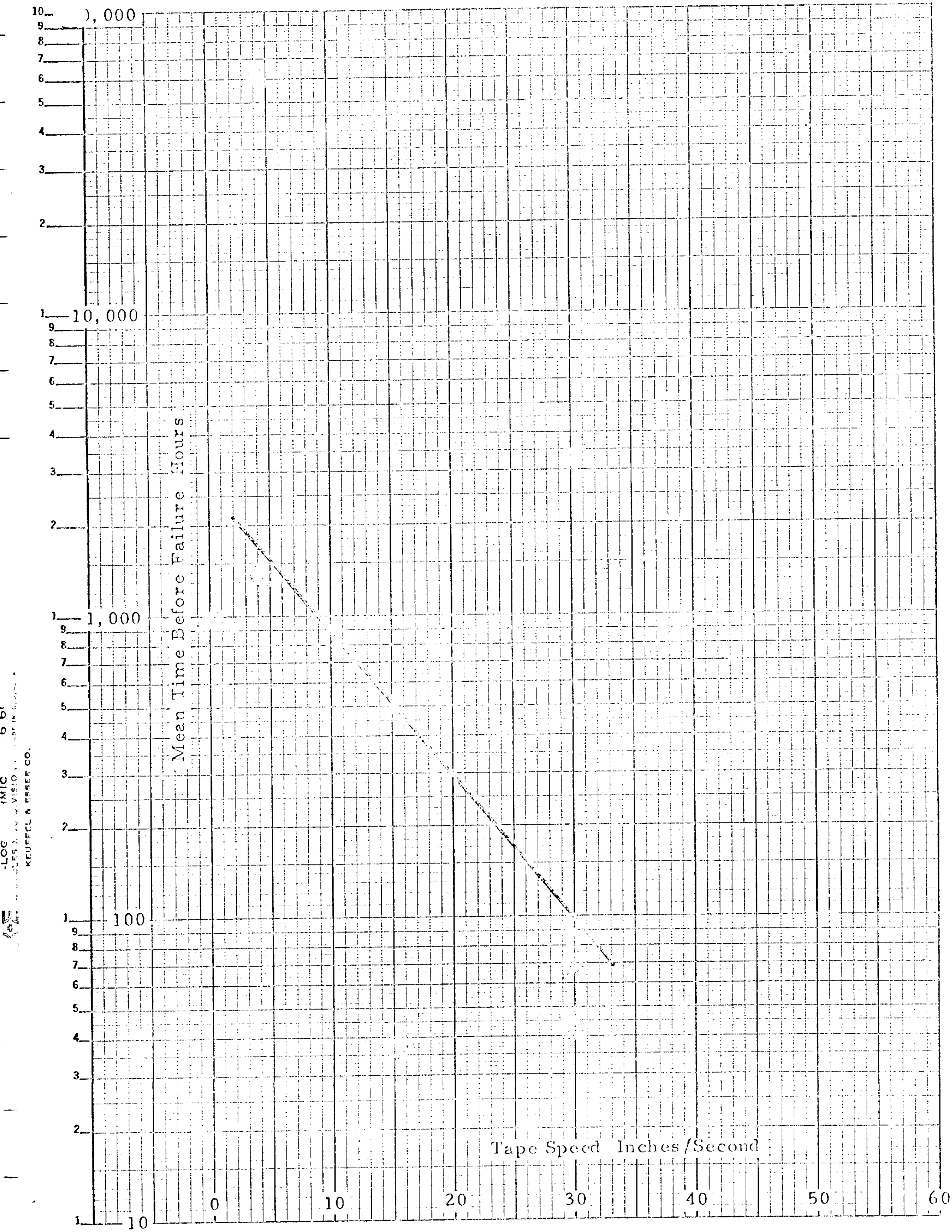

-LOG IMIC 6 6
KEUFFEL & ESSER CO.
10,000
10,000
1,000
100
10
Mean Time Before Failure Hours
Tape Speed Inches/Second
0
10
20
30
40
50
60

FIGURE 21

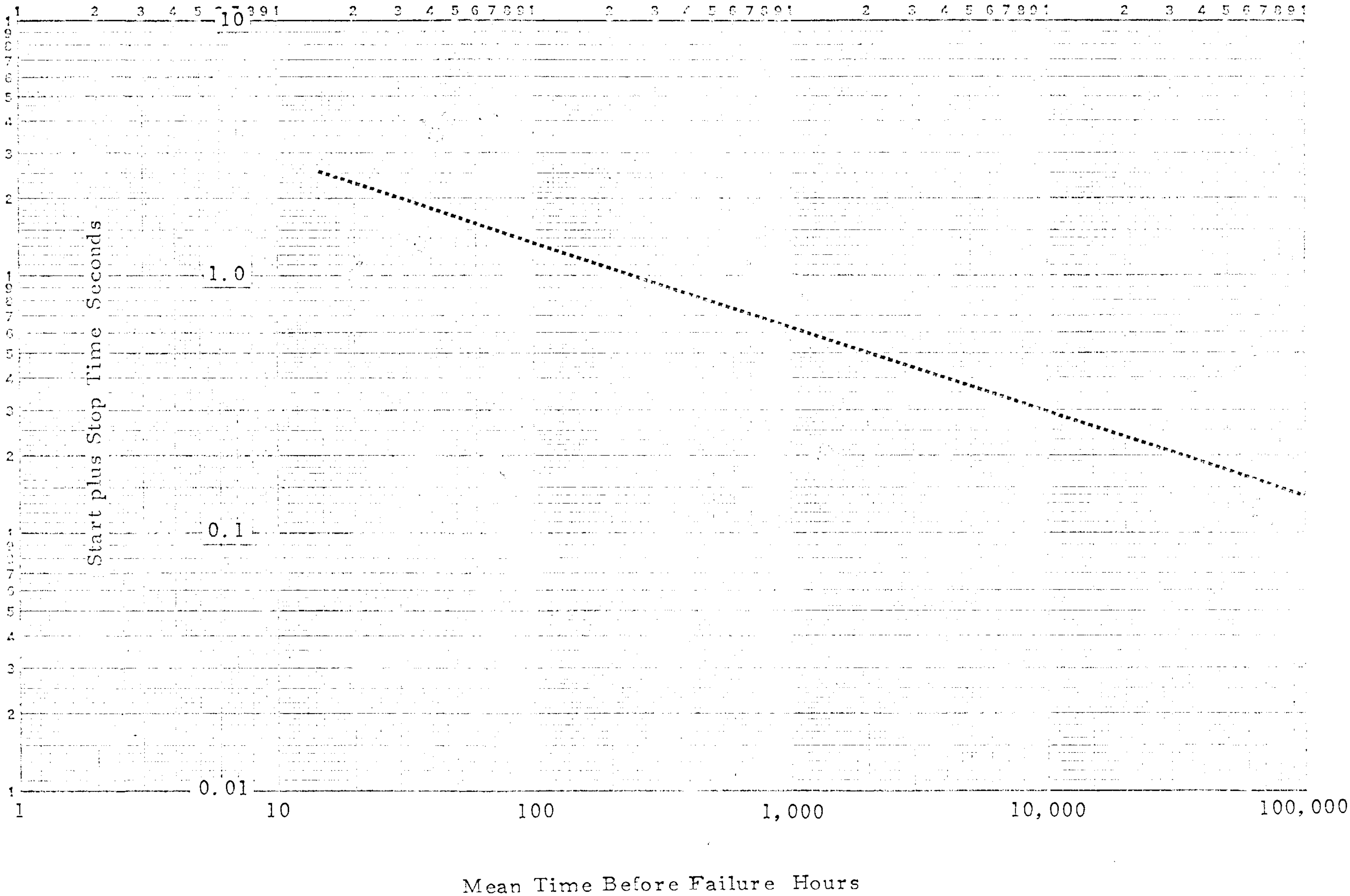
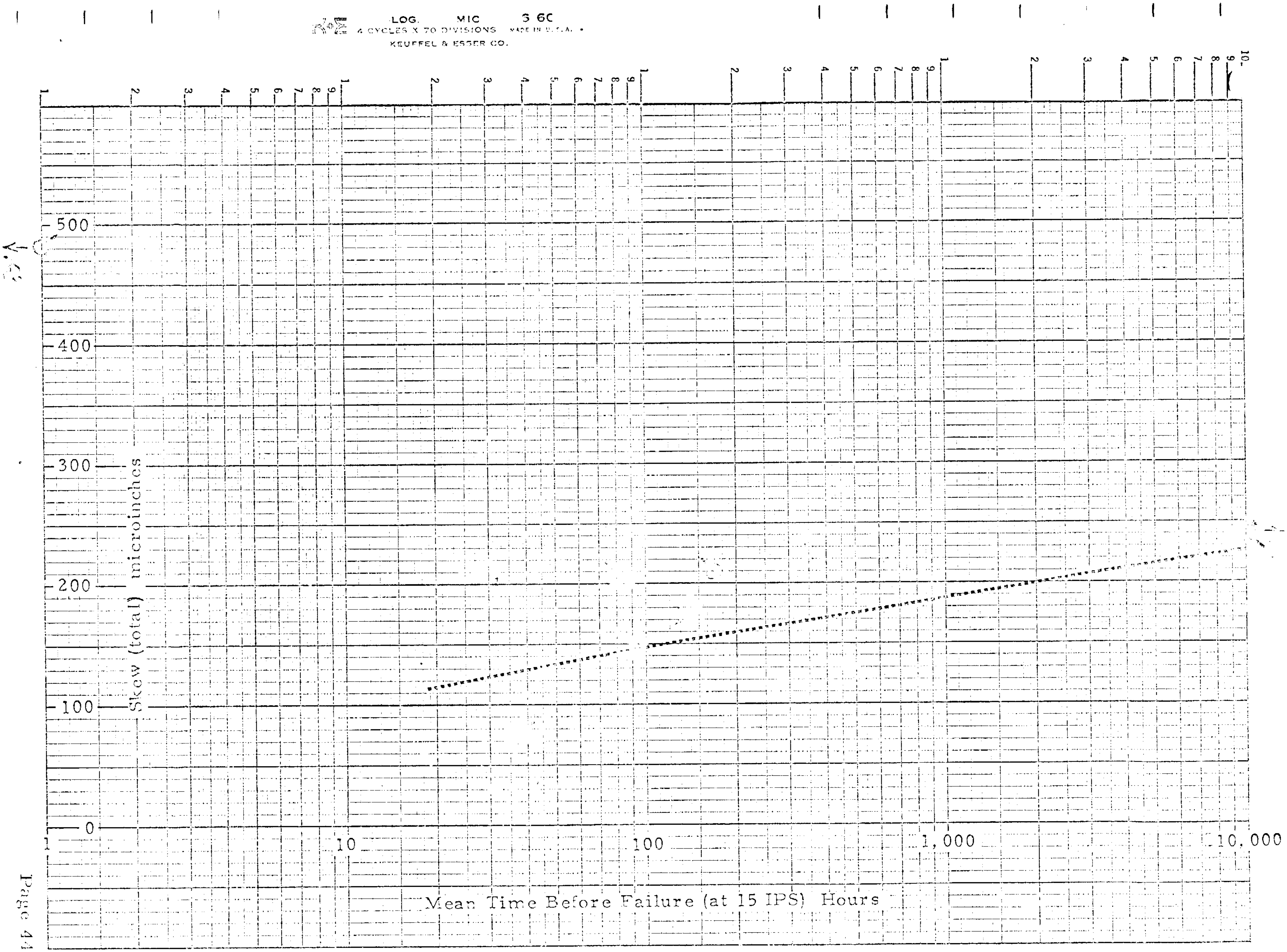
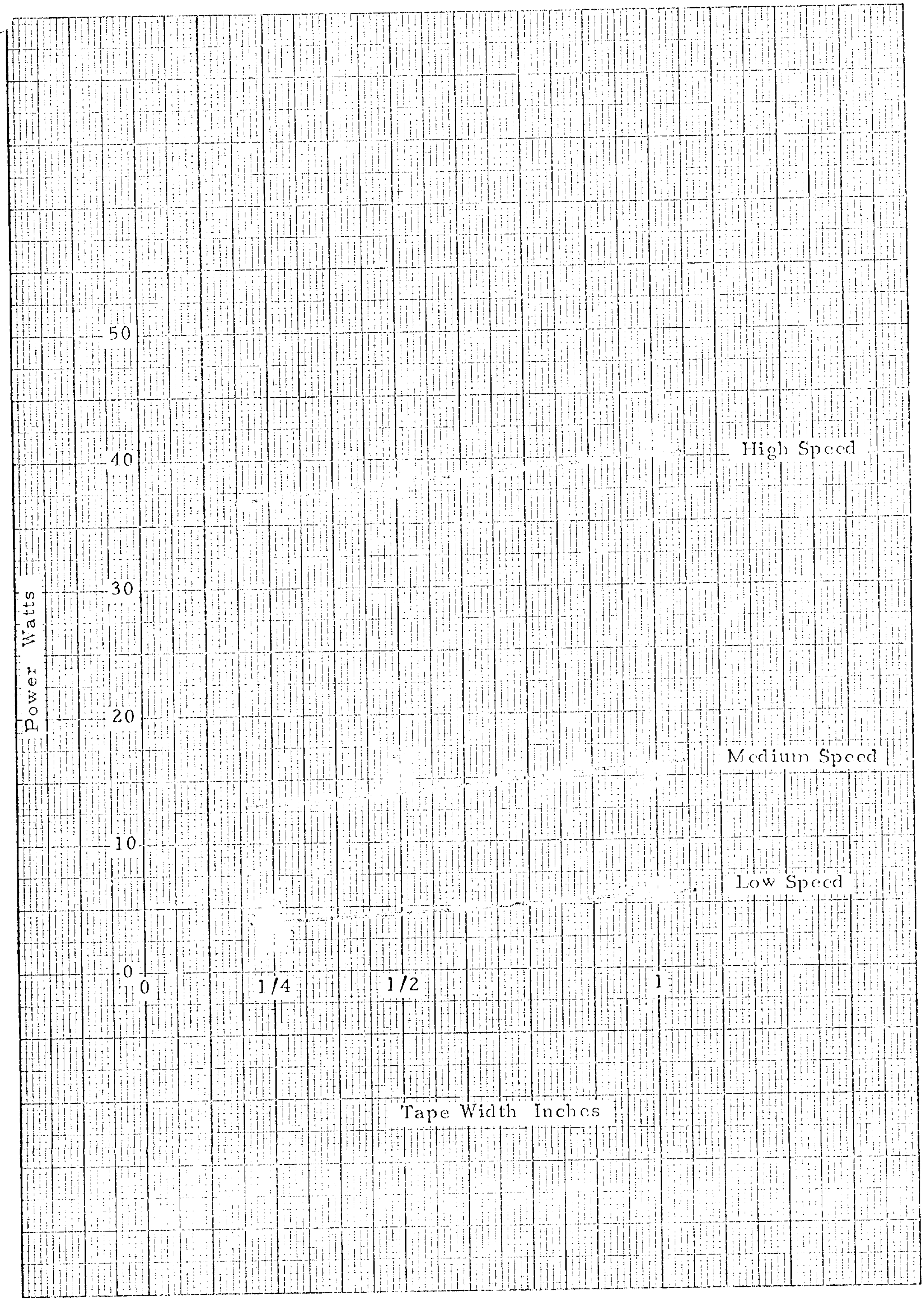

Start plus Stop Time Seconds
10
1.0
0.1
0.01
1
10
100
1,000
10,000
100,000
Mean Time Before Failure Hours

FIGURE 22



LOG. MIC 3 6C
4 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.
500
400
300
200
100
0
Skew (total) microinches
1
10
100
1,000
10,000
Mean Time Before Failure (at 15 IPS) Hours

FIGURE 23



High Speed
Medium Speed
Low Speed
Power Watts
50
40
30
20
10
0
0
1/4
1/2
1
Tape Width Inches

FIGURE 24

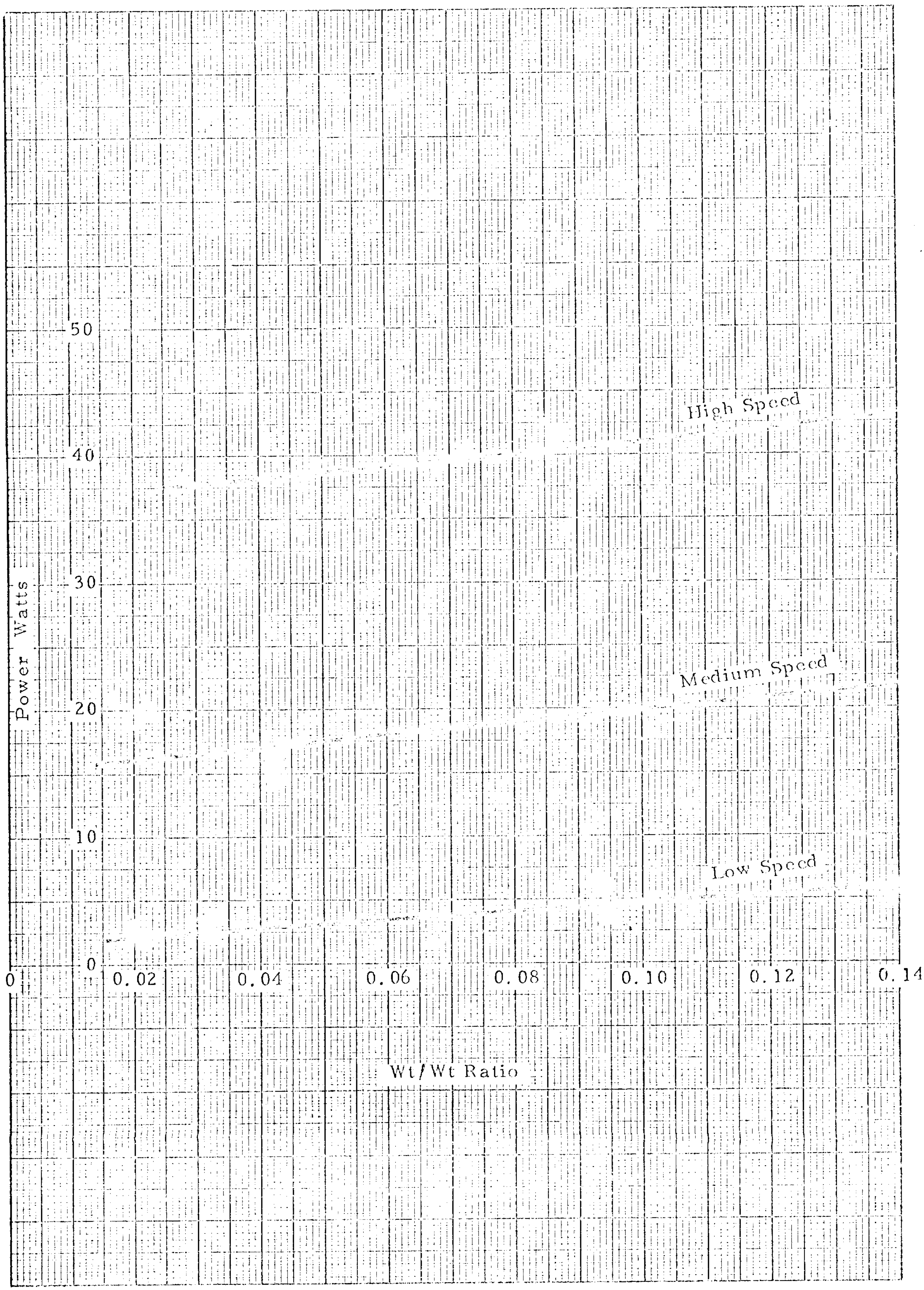

Power Watts
50
40
30
20
10
0
High Speed
Medium Speed
Low Speed
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Wt/Wt Ratio

FIGURE 25

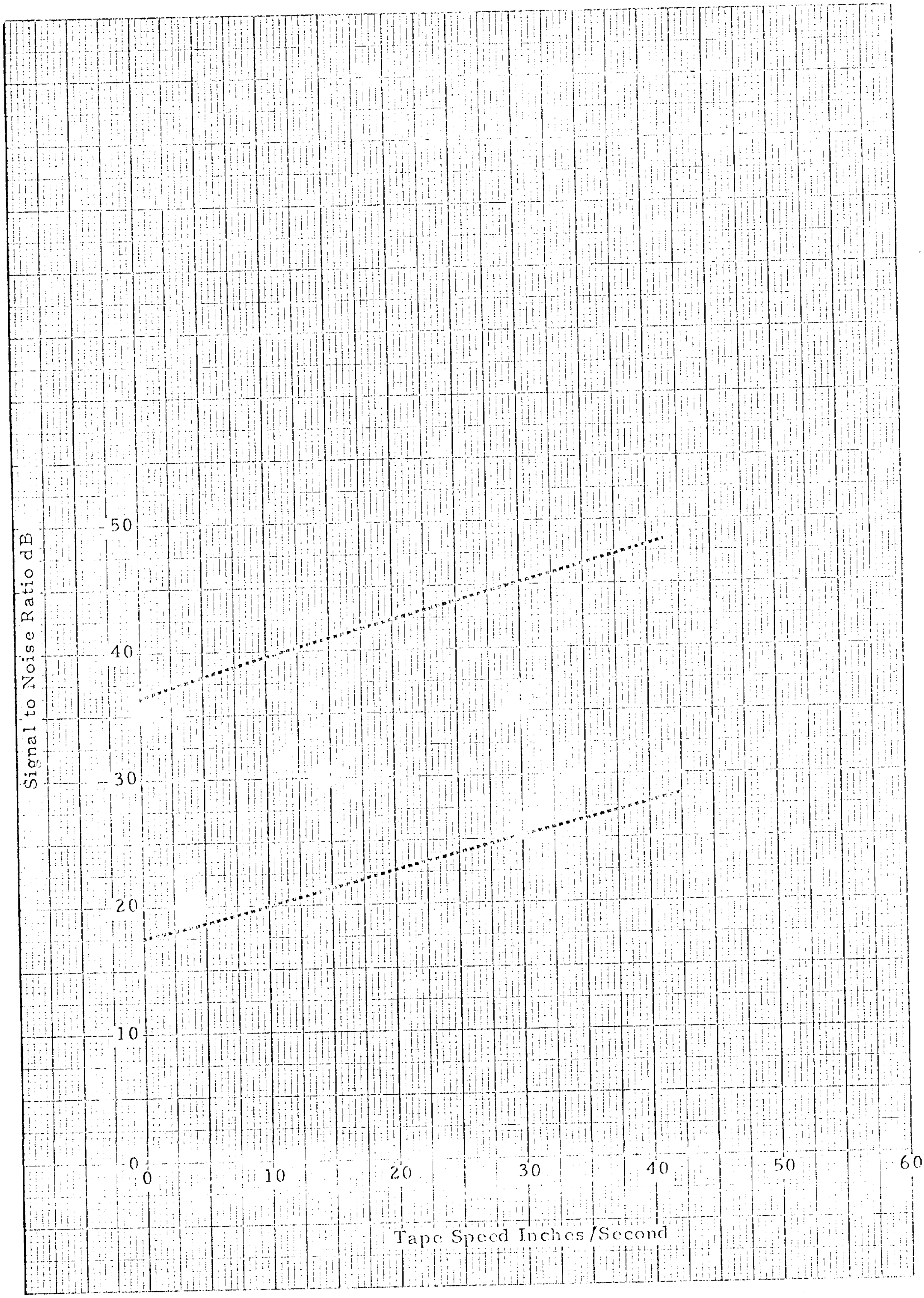

Signal to Noise Ratio dB
50
40
30
20
10
0
0
10
20
30
40
50
60
Tape Speed Inches /Second

FIGURE 26

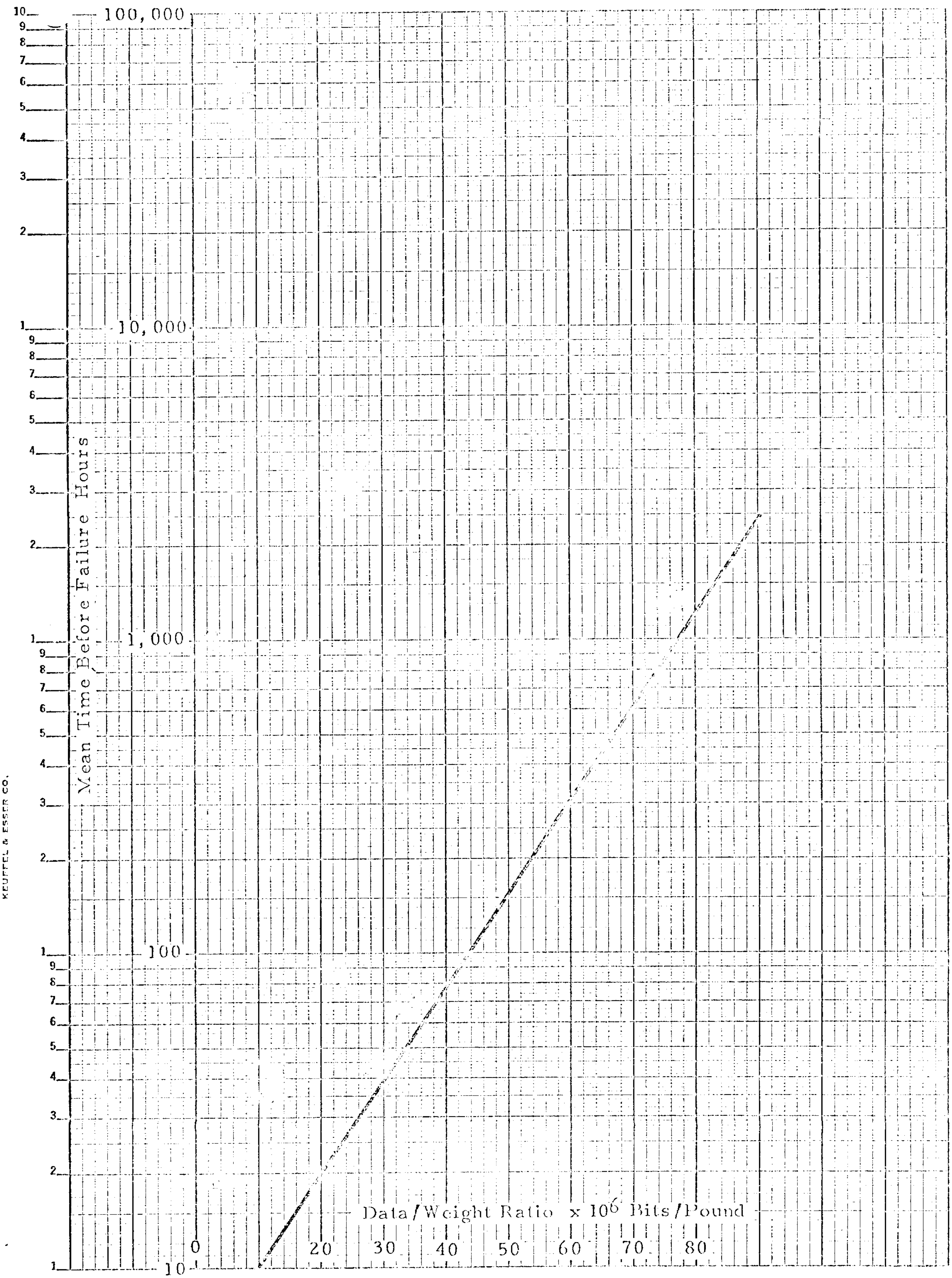

100,000
10,000
1,000
100
10
Mean Time Before Failure Hours
0
20
30
40
50
60
70
80
Data/Weight Ratio x 10^6 Bits/Pound

FIGURE 27

3.1.7 Data Sheets

The following pages contain the data which was compiled for preparation of the plots. As was stated earlier, each sheet has an identifying symbol which relates it to the symbols used in the plots.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol ♂

Description Low weight, low power Satellite recorder

Analog Recording: ________ Bandwidth ________

Digital Recording: X Packing Density (equiv. if Analog Mach) 1,000 bpi

Size: Length: 6 in. Weight 2.65 lb.

Width: 6 in.

Height: 2 3/8 in.

Tape Capacity: 468 ft. 1/4 wide

No. of Tracks 4 Track Width - in.

Power Required 5.2 watts Speed Control: ~~Servo~~/Synchronous

Tape Speed 12 (high) 1/2 (low)

Guidance: Fixed Flange Roller Other semi-trough

Test Data:

Speed 12 ips (high) 1/2 ips (low)

Flutter 5.7/20 (12.4) % P-P (RMS) at 12/ 1/2 ips

Bit-Bit Jitter ---

Skew 480 μ in (________ μ sec. at ________ ips

measured across 1/4 in (Track# ____ to# ____

Start Time 0.48 sec Stop Time 0.48 sec

S/N Ratio 31 db (P-P) (XXXXXXXXXXXXXXX)

Dropout Rate ----- bits in ------ bits

Derived Characteristics:

Data Capacity 10.1×10^6 bits

MTBF: 19 hr. Normalized to 15 ips 0.63 hr.

Vol. 86 in^3

Weight Ratio = Wt. Tape/System Wt = 0.139

Data Wt. Ratio = Data Capacity/System Wt. = 3.85×10^6 bits/ lb.

Vol/Wt. Ratio = 32.4

Skew/in. of tape width = 1920 μ in/in

Wt. of Tape 0.368 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol Q

Description Low power, extreme speed ratio. Designed with motor and control used on existing hardware.

Analog Recording: ______ Bandwidth ______

Digital Recording: X Packing Density (equiv. if Analog Mach) 833 bpi

Size: Length: 6 in. Weight 4.6 lb.

Width: 6 in.

Height: 3.325 in.

Tape Capacity: 550 (647 max.) ft. 1/4 wide

No. of Tracks 2 . Track Width ----- in.

Power Required 3.86 Speed Control: Servo/~~Synchronous~~

Tape Speed 12.8 (high) 0.01 (low)

Guidance: Fixed Flange Roller X Other --------

Test Data:

Speed 12.786 ips (high) 0.00995 ips (low)

Flutter 0.37/5.18 (use 2.27) % P-P (RMS) at 12.8/0.01 0-200Hz ips

Bit-Bit Jitter --------

Skew -------- μ in (----- μ sec. at ---- ips measured across --- in (Track# -- to# --

Start Time 125 m. Sec at 12.8 ips Stop Time 800 m. Sec at 12.8 ips

S/N Ratio 36 0-40 Hz. db (P-P) ~~(RMS)~~ ~~(RMS)(RMS)~~

Dropout Rate 1 bits in 10^4 bits

Derived Characteristics:

Data Capacity 11.7×10^6 bits

MTBF: 1,000 hr. Normalized to 15 ips 0.67 hr.

Vol. 120 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0955

Data Wt. Ratio = Data Capacity/System Wt. = 2.5×10^6 bits/ lb.

Vol/Wt. Ratio = 26

Skew/in. of tape width = ____ μ in/in

Wt. of Tape 0.44 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol ρ

Description

Analog Recording: X

Bandwidth 100 - 50 kHz

Digital Recording:

Packing Density (equiv. if Analog Mach) 3200 bpi

Size: Length: 9 1/2 in. Weight 20 lb.

Width: 7 1/2 in.

Height: 4 3/16 in.

Tape Capacity: 1100 ft. 1 wide

No. of Tracks 14

Track Width 0.050 in.

Power Required 15 watts

Speed Control: ~~Servo~~/Synchronous

Tape Speed 30 (high) 15 (low)

Guidance: Fixed Flange Roller ------ Other trough

Test Data:

Speed 30 ips (high) 15 ips (low)

Flutter 0.45 0-150Hz/0.8 0-1.2kHz % P-P ~~(RMS)~~ at ips

Bit-Bit Jitter -------

Skew 150 μ in (10 μ sec. at 15 ips measured across 1 in (Track# 1 to# 13

Start Time < 2 sec at 30 ips

Stop Time < 2 sec at 30 ips

S/N Ratio 30 db (P-P) ~~(RMS)xx(RMSxRMS)~~

Dropout Rate ------- bits in --------- bits

Derived Characteristics:

Data Capacity 590×10^6 bits

MTBF: 46 1/2 hr. Normalized to 15 ips 93 hr.

Vol. 298 in^3

Weight Ratio = Wt. Tape/System Wt = 0.043

Data Wt. Ratio = Data Capacity/System Wt. = 29.5×10^6 bits/ lb.

Vol/Wt. Ratio = 15

Skew/in. of tape width = 179 μ in/in

Wt. of Tape 0.87 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol ☐

Description ______

Analog Recording: ______ Bandwidth ______

Digital Recording: X Packing Density (equiv. if Analog Mach) 2500 bpi

Size: Length: 7 in. Weight 5.5 lb.

Width: 6 in.

Height: 3 5/16 in.

Tape Capacity: 650 ft. 1/2 wide

No. of Tracks 7 . Track Width 0.050 in.

Power Required 38 watts Speed Control: ~~XXXX~~/Synchronous

Tape Speed 30 (high) ------ (low)

Guidance: Fixed Flange Roller X Other ______

Test Data:

Speed 30 ips (high) ------ ips (low)

Flutter 2 % P-P (RMS) at 30 ips

Bit-Bit Jitter ----

Skew ------- μ in (------- μ sec. at ---- ips measured across ---- in (Track# -- to# --

Start Time -------- Stop Time ------

S/N Ratio ------ db (P-P) (RMS) (RMS-RMS)

Dropout Rate ----- bits in ______ bits

Derived Characteristics:

Data Capacity 137×10^6 bits

MTBF: 3280 hr. Normalized to 15 ips 6560 hr.

Vol. 1.39 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0465

Data Wt. Ratio = Data Capacity/System Wt. = 24.8×10^6 bits/ lb.

Vol/Wt. Ratio = 25.3

Skew/in. of tape width = ------ μ in/in

Wt. of Tape 0.256 lb.

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RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol ______

Description Low power, long mission life.

Analog Recording: ______ Bandwidth ______

Digital Recording: X Packing Density (equiv. if Analog Mach) 1000 bpi

Size: Length: 7 3/4 in. Weight 4.8 lb.

Width: 6 in.

Height: 2 3/4 in.

Tape Capacity: 489 ft. 1/4 wide

No. of Tracks 6 Track Width 0.019-Rec 0.016 P/B

Power Required 2.5 watts Speed Control: ~~XXXX~~/Synchronous

Tape Speed 4 (high) ------- (low)

Guidance: Fixed Flange Roller X Other ______

Test Data:

Speed 4.1 ips (high) ------ ips (low)

Flutter 3/0.1-10 kHz % P-P (RMS) at 4 ips

Bit-Bit Jitter -------

Skew 240 μ in (______ μ sec. at ______ ips measured across 1/4 in (Track# ___ to# ___)

Start Time 2.5 mSec Stop Time 100 m Sec

S/N Ratio 19.6 db (P-P) ~~(RMS) X (RMS-RMS)~~

Dropout Rate --------- bits in ------ bits

Derived Characteristics:

Data Capacity 35.2×10^6 bits

MTBF: 63,500 hr. Normalized to 15 ips 17,000 hr.

Vol. 128 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0202

Data Wt. Ratio = Data Capacity/System Wt. = 7.34×10^6 bits/ lb.

Vol/Wt. Ratio = 26.7

Skew/in. of tape width = 960 μ in/in

Wt. of Tape 0.0964 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol

Description: Second version of recorder, duplicate system except for one detail design change.

Analog Recording: ______ Bandwidth ______

Digital Recording: X Packing Density (equiv. if Analog Mach) 1000 bpi

Size: Length: 7 3/4 in. Weight 4.8 lb.

Width: 6 in.

Height: 2 3/4 in.

Tape Capacity: 489 ft. 1/4 wide

No. of Tracks 6 Track Width ______ in.

Power Required 2.5 watts Speed Control: ~~Servo~~/Synchronous

Tape Speed 4 (high) ------- (low)

Guidance: Fixed Flange Roller X Other ______

Test Data:

Speed 4.08 ips (high) ------- ips (low)

Flutter 2 1/2 (0-450 Hz) % P-P (RMS) at 4 ips

Bit-Bit Jitter -----

Skew 240 μ in (______ μ sec. at ______ ips measured across 1/4 in (Track# ___ to# ___)

Start Time 220 mSec Stop Time 300 mSec

S/N Ratio 20 db (P-P) ~~(RMS) XX (RMS-RMS)~~

Dropout Rate ------- bits in ------- bits

Derived Characteristics:

Data Capacity 35.2×10^6 bits

MTBF: 63,500 hr. Normalized to 15 ips 17,000 hr.

Vol. 128 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0202

Data Wt. Ratio = Data Capacity/System Wt. = 7.34×10^6 bits/ lb.

Vol/Wt. Ratio = 26.7

Skew/in. of tape width = 960 μ in/in

Wt. of Tape 0.0964 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol ◇̸

Description

Analog Recording: ______ Bandwidth ______

Digital Recording: X Packing Density (equiv. if Analog Mach) 1,000 bpi

Size: Length: 14.75 in. Weight 21 lb.

Width: 10.175 in.

Height: 3.950 in.

Tape Capacity: 2250 ft. 1/2 wide

No. of Tracks 9 Track Width 0.040 in.

Power Required 16 watts Speed Control: Servo/Synchronous

Tape Speed 15 (high) - (low)

Guidance: Fixed Flange Roller X Other ______

Test Data:

Speed 15.135 ips (high) - ips (low)

Flutter 0.6 (0-10KHz) % P-P (~~RMS~~) at 15 ips

Bit-Bit Jitter -

Skew 75 μ in (5 μ sec. at 15 ips measured across 1/2 in (Track# 1 to# 9)

Start Time 0.20 sec Stop Time 1.2 sec

S/N Ratio - db (P-P) (RMS) (RMS-RMS)

Dropout Rate 0.2 bits in 10^5 bits

Derived Characteristics:

Data Capacity 242×10^6 bits

MTBF: 36.5 hr. Normalized to 15 ips 36.5 hr.

Vol. 592 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0422

Data Wt. Ratio = Data Capacity/System Wt. = 11.5×10^6 bits/ lb.

Vol/Wt. Ratio = 28.3

Skew/in. of tape width = 150 μ in/in

Wt. of Tape 0.885 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol ☐

Description

Analog Recording: Bandwidth

Digital Recording: X Packing Density (equiv. if Analog Mach) 600 bpi

Size: Length: 21 in. Weight 42 lb.

Width: 15 in.

Height: 5 in.

Tape Capacity: 4600 ft. 1 wide

No. of Tracks 16 . Track Width 0.025 in.

Power Required 41.6 watts Speed Control: Servo/Synchronous

Tape Speed 60 (high) 30 (low)

Guidance: Fixed Flange Roller ---- Other trough

Test Data:

Speed 60.12 ips (high) 30.09 ips (low)

Flutter 0.60 at 0-10 kHz % P-P ~~(RMS)~~ at 30 ips

Bit-Bit Jitter ----

Skew 210 (doubtful) μ in (1.0 μ sec. at 30 ips measured across .12 in (Track# 8 to# 10

Start Time 1.6 Sec at 30 ips Stop Time 1.9 Sec at 30 ips.

S/N Ratio 26 at 30 ips db (P-P) ~~(RMS) (RMS RMS)~~

Dropout Rate 1 bits in 10^4 bits

Derived Characteristics:

Data Capacity 530×10^6 bits

MTBF: 41.5 hr. Normalized to 15 ips 83 hr.

Vol. 1575 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0865

Data Wt. Ratio = Data Capacity/System Wt. = 12.6×10^6 bits/ lb.

Vol/Wt. Ratio = 37.4

Skew/in. of tape width = 1750 μ in/in(doubtful)

Wt. of Tape 3.63 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol Q

Description Low volume, long mission recorder

Analog Recording: ________ Bandwidth ________

Digital Recording: X Packing Density (equiv. if Analog Mach) 2,500 bpi (diphase recording)

Size: Length: 6 in. Weight 4.25 lb.

Width: 5 in.

Height: 5 in.

Tape Capacity: 450 ft. 1 wide

No. of Tracks 24 Track Width 0.030 in.

Power Required 6 watts Speed Control: ~~Servo~~/Synchronous

Tape Speed 4 (high) - (low)

Guidance: Fixed Flange Roller - Other trough

Test Data:

Speed - ips (high) - ips (low)

Flutter 1.5 (0-2KHz) % P-P (RMS) at 4 ips

Bit-Bit Jitter -

Skew - μ in (- μ sec. at - ips measured across - in (Track# - to# -)

Start Time 100 m. sec Stop Time 100 m. sec

S/N Ratio - db (P-P) (RMS) (RMS-RMS)

Dropout Rate 1.0 bits in 10^5 bits

Derived Characteristics:

Data Capacity 324×10^6 bits

MTBF: 1361 hr. Normalized to 15 ips 364 hr.

Vol. 150 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0836

Data Wt. Ratio = Data Capacity/System Wt. = 7.6×10^6 bits/ lb.

Vol/Wt. Ratio = 27.3

Skew/in. of tape width = - μ in/in

Wt. of Tape 0.355 lb.

RECORDER CHARACTERISTICS SUMMARY SHEET

Identifying Symbol 

Description ______

Analog Recording: X   Bandwidth ______

Digital Recording: ______   Packing Density (equiv. if Analog Mach) 6,667 bpi

Size: Length: 10 in.   Weight 20 (est) lb.

Width: 7 3/4 in.

Height: 3 3/4 in.

Tape Capacity: 1,100 ft.   1/2 wide

No. of Tracks 7   Track Width 0.050 in.

Power Required 15 watts   Speed Control: Servo/Synchronous

Tape Speed 60 (high)   30 (low)

Guidance: Fixed Flange Roller X   Other ______

Test Data:

Speed 60.18 ips (high)   30.03 ips (low)

Flutter 0.6 % P-P (RMS) at 30 ips

Bit-Bit Jitter -

Skew 180 μ in ($\pm$ 3 μ sec. at 60 ips
measured across 1/2 in (Track# ___ to# ___

Start Time 1.0 sec   Stop Time 3.0 sec

S/N Ratio 36 db (P-P) (RMS) - - (RMS-RMS)

Dropout Rate - bits in - bits

Derived Characteristics:

Data Capacity 670×10^6 bits

MTBF: 70 hr.   Normalized to 15 ips 140 hr.

Vol. 292 in^3

Weight Ratio = Wt. Tape/System Wt = 0.0216

Data Wt. Ratio = Data Capacity/System Wt. = 33.5×10^6 bits/ lb.

Vol/Wt. Ratio = 14.6

Skew/in. of tape width = 360 μ in/in

Wt. of Tape 0.434 lb.

3.2 Discussion of Mean Time before Failure Analysis

The two classes of elements which contribute most to the failure rate in a reliability analysis of an Iso-Elastic Drive recorder are the polyester film belts in the drive train and the ball bearings. There are discrepancies in the life calculations of both these elements which act in opposite directions.

The data for the fatigue life calculation of polyester film belts is based upon the report "Final Report on the Fatigue Life of Polyester and Polyimide Film Belts," JPL Contract No. 950899. In that report, it was stated that where uncertainty existed, the conservative (leading to a shorter life projection) approach was used. Since the time that report was issued, a degree of field experience (unfortunately, not well documented) has been acquired which can be compared to the life calculations. It has been found that in many cases the life experienced in recorders has exceeded the calculated life by factors ranging from two to more than ten. The greatest discrepancy has appeared in two pulley drive systems with reasonably small drive pulley diameters. It is not known whether this discrepancy is the result of the low duty cycle in actual recorder operation, or is the result of a bias in the basis of the the method for life computation. In any case, it can reasonably be expected that the belt life will be longer, by a factor which is not known, than the life calculated on the basis of existing continuous running test data. It has also developed that test data, at least two orders of magnitude greater life than was performed in the above referenced document, is necessary to properly justify life calculations for the longer mission periods.

The life of ball bearings is calculated by the analysis methods adopted by the Anti-Friction Bearing Manufacturers Association (AFBMA). This method calculates the fatigue life of the bearings. It is a common opinion throughout the tape recorder field that bearing life is substantially lower than the life calculated in the above way. In tape recorders the operating speeds and loads are very low, compared to the normal operating conditions for these bearings. Other failure modes become much more significant relative to the fatigue failure modes. The major areas which appear to cause bearing failures are lubricant loss, lubricant failure and roughness of the bearings. There is no way to compute these effects. However, there must exist a considerable body of field experience which should be gathered and analyzed to obtain reliability data useful for tape recorder and similar application life analysis. This could only be done by one of the major government user agencies and would involve considerable effort to locate the existing use data and to examine this data, in detail, to unearth the information related to bearing lives. Once the basic field experience data was acquired, it should be possible, by existing mathematical techniques, to develop useful life prediction methods which take into account all the factors limiting life in this type of bearing application. This information would be of great utility to the various user agencies and the associated industries.

Within the limited experience of Kinelogic Corporation, every bearing failure which has been analyzed resulted in one of two diagnoses. The analysis was either loss of lubricant or lubricant failure. Unfortunately, Kinelogic Corporation has not been able, due to the nature of its work, to maintain contact with its equipment in the field. The feedback of information related to field failures has been extremely fragmentary and the knowledge of the use history has been even scantier. This condition probably applies to most of the suppliers of this class of equipment. Only the major users of this equipment are in a position to develop this information.

In summary, the belt lives are probably longer and the bearing lives shorter than indicated by standard reliability analysis techniques, with a net result that the analysis is probably conservative to some degree.

3.3 Discussion of the Effect of Varying Tape Thickness

When the requirements of a mission are such that existing hardware meets all the specifications except tape capacity, the temptation is to try to reduce the tape thickness in an effort to increase the capacity of a given machine. Alternatively, if the recording capacity is in excess of the requirements but insufficient tape durability has been experienced, an increase in tape thickness seems attractive. The effects on tape capacity and durability are not known, or are calculated only for the particular case under consideration. An attempt will be made to provide generalized solutions for the changes in capacity, and durability resulting from a change in tape thickness.

The length of tape in a tape pack with a given outside diameter and hub is inversely proportional to the overall thickness of the magnetic tape. Table III shows the calculations and the resultant multipliers to use when changing from one tape thickness to any other thickness. Each column under relative length or weight is used to change from one thickness to either of the other two.

TABLE III

Nominal Thickness (mils)	Overall Thickness (mils)	Relative Tape Length t_1/t_2			Relative Weight for Same Length t_2/t_1		
0.50	0.71	1.00	1.58	2.96	1.00	0.634	0.338
1.00	1.12	0.634	1.00	1.878	1.58	1.00	0.533
2.00	2.10	0.338	0.533	1.00	2.96	1.878	1.00

It is not possible to determine a generalized multiplier for tape pack diameter since the outside diameter is a function of the hub diameter as well as the length of tape. In general the outside diameter will change less than the square root of the change in thickness. The outside diameter can be calculated by:

$$D_1 = \sqrt{\left(\frac{48\,t\,L}{\pi} + D_2^2\right)}$$

Where D_1 = outside diameter in inches

D_2 = inside diameter in inches

t = overall tape thickness

L = tape length in feet

This formula can be used to calculate the diameter of the tape pack under any conditions. However, it should be noted that the inter-layer pressure increases as the number of outside turns increases. Because this can cause tape blocking, or buckling of the tape pack, it is desireable to keep the outside diameter of the tape pack less than twice the hub diameter, although 2.5 times does not cause much trouble and 3 times the hub diameter has been successfully used in some cases.

The durability of the tape is a more difficult property to evaluate because too many intangibles affect the life of the tape. If it is assumed that all the other factors affecting wear and degradation of the oxide coating are not changed when the tape thickness is changed, mechanical damage to the tape backing is the remaining variable. The resistance to mechanical damage can be measured by the resistance to damage to the edge of the tape. It is assumed that the resistance to edge damage can be measured by the resistance to edge buckling of the tape. It is further assumed that the oxide coating does not contribute any appreciable strength to the tape. The buckling strength of any particular span of tape is then:

$$P = \pi E t^3 / 3(1-v^2)b \text{ where } a/b > 2 \, *$$

a = span length in inches

b = tape width in inches

E = Young's Modulus in psi

t = tape backing thickness in inches

v = Poission's Ratio

P = critical buckling load in pounds

* Reference:

Formula 15, Table XVI, page 350, _Formulas for Stress and Strain_, fourth edition, Roark

Since all the variables except tape thickness are held constant, the above expression can be simplified to:

$$P = Kt^3$$

This states that the critical buckling load varies as the cube of the thickness. Therefore, the relative durability of the various tape thicknesses should vary as the cube of the thicknesses. Table IV shows the calculations and the resultant multipliers to use when changing from any one tape thickness to any other thickness.

TABLE IV

Nominal Thickness (mils)	Base Thickness (mils)	t^3	Relative Durability		
0.50	0.50	0.1250	1.00	0.161	0.0410
1.00	0.92	0.7787	6.22	1.00	0.255
2.00	1.45	3.049	24.4	3.92	1.00

One other consequence of changing tape thickness is the change in the life of the Iso-Elastic belt. This belt is usually the most critical element in the drive train, and its life is greatly affected by the change in tape thickness. The tensile stress in the tape should be maintained at 1000 psi and the cross-sectional area of the Iso-Elastic belt should be about equal to the cross-sectional area of the tape backing. The tensile force in the tape, and therefore, the required tensile force in the Iso-Elastic belt, will vary directly with the tape thickness. The net effect of the changes in belt tension and belt bending stresses, as reflected in belt life, are calculated for a typical small recorder. Table V illustrates the order of magnitude of the changes. It can be expected that the same kind of change will occur with any machine, but that the relative amount of change may be very different for another machine and would have to be checked in detail.

One serious consideration should be applied when considering a change in tape thickness. This is the problem of print through. The literature (C. D. Mee, ibid.) page 136, indicates that print through is a function of the wavelength to separation ratio with a maximum effect at a ratio of 10:1. The separation, in this case, is the tape thickness. It can, therefore, be expected that print through will become a more serious problem as the tape thickness is decreased.

In summary, it can be seen that a decrease in tape thickness will increase the capacity and the fatigue life of the system while decreasing the durability of the tape. The various multipliers from Tables III and IV can be used to adjust the scale factors when entering the plots, (Figures 1 through 27) For example, if it were desired to increase the capacity of a given design, the length multipliers would be used to check the effect upon characteristics which are affected by tape length. Unfortunately, there were no useful correlations with tape length found in the analysis of tape recorder characteristics. There are, however, the other factors, such as recording time, or packing density, which will vary in direct or inverse proportion to tape length. On the other hand, the relative weight of the same length of tape can be used to determine the change in Wt/Wt ratio or data/wt ratio. These new ratios can then be used to enter the plots which have the ratio as a variable to see the effect on the other characteristic plotted. This would be done when a change in tape thickness to obtain a different durability is contemplated.

TABLE V

Nominal Thickness (mils)	Base Thickness (mils)	Belt Thickness (mils)	Installed Stress (psi)	Bending Stress (psi)	Transmitted Torque Stress (psi)	Minimum Stress (psi)	Maximum Stress (psi)
0.50	0.50	0.00075	2,270	1410/1800	625	+235	+4,695
1.00	0.92	0.0015	2,140	2810/3600	575	-1,245	+6,315
2.00	1.45	0.002	2,540	3750/4800	680	-1,890	+8,020

Stress Range (psi)	Nominal Thickness (mils)	Endurance Limit Stress Range (psi)	Stress Ratio	Life Cycles of Stress	Relative Life		
4,460	0.50	2,550	1.75	3.3×10^6	1.00	2.20	8.46
6,560	1.00	2,900	2.26	1.5×10^6	0.455	1.00	3.84
9,910	2.00	3.150	3.15	0.39×10^6	0.118	0.260	1.00

3.4 Discussion of Serial and Parallel Methods of Recording Digital Data

Where digital data is to be recorded on magnetic tape, two methods are generally used. The first uses a number of amplifiers and multi-track heads across the width of the tape, with all of the tracks being recorded simultaneously. The other method uses only a single track at a time, and switches from track to track to utilize the complete width of the tape. Each method has its particular advantages, and its disadvantages. Perhaps, the principle advantage of the serial technique is that it is capable of about twice the packing density of the parallel case. Serial data will require a buffer for conversion of the data from a parallel to a serial format. This is somewhat complicated by the nature of the clock available with the parallel data. The serial clock need be a higher frequency, so there is the necessity of multiplying the input clock. The permitted packing density with the serial data may be higher than in the parallel case because there is no skew difficulty, and since a more sophisticated scheme (bi-phase) may be used for the coding. Packing density may be as much as twice as high when using bi-phase serial rather than parallel. Skew is critical in the case of parallel data, and may tend to be the limiting factor on packing density. In serial recording there is no way to measure skew using the data reproduced from the tape. Therefore, skew requirements are at a minimum but signal loss caused by azimuth errors could limit packing density. However azimuth losses are easier to control, by more than an order of magnitude, than are those due to skew.

Regarding dropouts, with respect to tape imperfections, the effect of a dropout would be to lose (assuming equal packing densities for both cases) an equal number of bits in both cases. If we assume 8 bit words, and assume that the dropout covered a period corresponding to 100 bits, the parallel recording would have 100 words with a possibility of an error in each. The serial would have 13 words with error possibility, where the error could be each bit of the word. The decision here seems to favor the serial case for no error correction, and the parallel case for complicated error correcting codes. It is unlikely that a tape imperfection on one track would have much influence on another track. The usual imperfection, in pretested tape, seems to have a circular form, usually less than 1/16 inch diameter.

The factors affecting the sensitivity to dropouts appear to be:

- Type of coding
- Signal-to-noise on playback
- Nature of the decoding used
- Track to track crosstalk in the head, and in the selection circuitry of the serial case.

Regarding the first of these, when the coding used is NRZ, the dropout sensitivity is relatively high. Experience has shown that the normally used coding schemes, listed in order of decreasing immunity to dropouts, are bi-phase, NRZ, and RZ.

Other factors being equal, a system that has a very good signal to noise ratio will be more immune to dropouts than one having a poor signal to noise ratio.

When the signal to noise ratio is poor, the sensitivity to the presence of a pulse must be sufficiently low that there is little chance of registering a pulse due to noise.

If, for retrieval of the recorded signal, a pure level detector is used, the system can be dropout sensitive. However, the use of a peak detection system will tend to reduce this sensitivity and a combination of the two methods can be expected to reduce the dropout sensitivity still further. The best immunity to dropouts may be obtained by the utilization of correlation techniques in detection.

Dropout sensitivity due to crosstalk occurs when the reproduce crosstalk is relatively high and there is a chance that pulse recorded on one channel will be reproduced on the adjacent channel to eliminate the crosstalk effects, a detection system must be employed which requires that the reproduced pulse exceed a minimum level before detection will occur. This level insensitivity can lead to problems if a dropout occurs which causes the amplitude of the reproduced pulse to be below this guard level.

A weakness of the serial method using track switching is that there is loss of data at each tape reversal. The corresponding difficulty with parallel recording is that although the data is continuous, there is the need for rewinding each time the tape comes to the end. When serial data has been recorded over the entire tape, the tape is once again at the beginning point (assuming an even number of tracks).

In the case of serial data, there is no particular natural restriction of the word length. In the case of parallel recording, the natural length of a word is set by the number of tracks. Tape speed will be higher in the case of serial data (by a factor of approximately half the number of tracks used) and the number of passes required for a fixed number of bits will increase by the same ratio. The winding required to reach a particular segment of data is shorter with multi-track serial recording, unless special provisions are made for fast search winding in a parallel machine. If the data is to be telemetered, there must, normally, be a conversion of the data to a serial format before transmission. This would mean that the parallel to serial converter at the input of the serial setup, would already exist in the system, and that the output of the serial format from the recorder would be in a form suitable for transmission. This would eliminate all of the serial reproduce electronics, with the exception of the selection matrix, the amplifier, the decoder, and the clock detector. If the already existing parallel to serial converter could be used in place of a parallel to serial converter at the input of the recorder, there is additional savings of electronics. Maximum bit rate will occur in the case of parallel data. A serial format will allow use of lower bit rates, if required. Other factors being equal, start-stop time will be much less for the parallel case. The efficiency of tape use may, or may not, be higher in the serial case depending upon factors not susceptible to determination without detailed system information. Tape use efficiency in rapid start/stop systems is extremely difficult to calculate. Some of the factors involved are as follows: How fast is the tape moving during operation? How much tape stretch occurs during acceleration? How close to the final velocity need the tape be before it is useful? How long does the tape continue to move?

When a comparison of efficiency of tape use is attempted between serial and parallel recording, complications enter since tape speeds differ, skew during acceleration is more of a problem with parallel data then with serial data, packing density differs (usually) between serial and parallel, because the serial normally can use biphase coding which is often difficult with parallel data etc.

Table V, on the following page, lists comparison points between the serial and parallel methods. Table VI lists the advantages and disadvantages of each.

Table V

Parallel	Serial
Input data must be in parallel form	Input data must be in serial form
Redundant coding is possible	Redundant coding is not possible
Tape speed is lower for same data rate	Tape speed is higher. The factor is $\frac{\text{Number of tracks in parallel case}}{2}$
Packing density is limited by skew	Packing density is about two times that possible with parallel case
There are no interruptions in recording of the data	The data is interrupted each time that the tape reverses direction
Unless there is a high speed available in the transport, rewind takes time.	No rewind is required, because, with an even number of tracks, the tape is returned to starting position after each complete record or reproduce cycle.
Parallel allows the greatest bit rate where highest speed is limited.	Serial allows use of low bit rate where lowest speed is limited

Table VI

Serial Method

Advantages	Disadvantages
Packing density not limited by skew.	Bit position not certain.
Uses one signal processing channel.	Complicated coder and decoder.
Rapid access.	More tape passes, higher speed.
More data per tape area.	Loss of data during tape reversal.
Possible to playback data while recording without loss of data	

Parallel Method

Advantages	Disadvantages
Error correcting coding possible	Skew limits packing density
Large amounts of data per second.	Requires extremely low speed
Relatively simple control logic.	For slow data rate output.

3.5 Reliability Considerations of Serial and Parallel Methods

3.5.1 Introduction

Some of the important performance and technical aspects of serial and parallel data recording have been discussed in the previous sections. This section presents some of the considerations that are important to achieve highly reliable long life - failure free recorder performance. Reliability estimates are presented for several typical multichannel recorder configurations having a range of complexity which will permit trade-offs to be made among such factors as serial and parallel, numbers of channels, operating time, and performance success criteria. In addition, some qualitative factors having a tangible effect on achievable recorder electronics reliability are discussed.

3.5.2 Serial Data Recording

The reliability block diagram for a typical multichannel serial recording data electronics subsystem is shown in Figure 28.* Each of the elements of this subsystem is essential to the successful performance of the recorder. Failure of any one or more of these major elements will cause significant loss of data or cause the recorder to fail completely. All of these major elements of the electronics subsystem are, therefore, functionally dependent and, for the purpose of reliability assessment, may be considered as part of a series system.

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* All referenced figures and tables are included at the end of this section.

The reliability values for the various elements in Figure 28 combine by the product rule as shown by the model below Figure 28. The reliability of each major element of the recorder data electronics is a function of the failure rate (λ) of the parts which comprise the assembly, and the time period (t) over which the subsystem is operated.

In estimating the reliability of the various elements of the recorder electronics, the failure rate of parts is assumed to be constant with time. This is considered valid and conservative for high quality parts which are adequately derated and applied in accordance with good engineering practices.

For a constant failure rate the reliability of a single part $R = e^{-\lambda t}$, and, for a group of N parts in a serial system, the reliability of the element formed by the N parts is $\exp^{-(\lambda_1 + \lambda_2 + \lambda_3 + --- \lambda_n)t}$.

Table VII contains a tabulation of the generic part failure tate values and derating values that have been used in estimating the reliability of the various recorder configurations.

Two typical multichannel serial recorder data electronics configurations have been evaluated. One configuration contains eight channels and the second contains 31 channels. The estimated parts count for each of the major elements required by these recorder configurations is summarized in Table VIII. The total failure rate for each generic part group and the total failure rate for the 8 and 31 channel configurations are also presented in Table VIII. It will be noted that the inverter power supply, inverter control, the data encoder and record amplifier, and the decoder and playback amplifier are identical in both configurations. The remaining elements vary in complexity as a function of the number of channels in the recorder configuration.

The estimated reliability of the 8 and 31 channel serial configurations as a function of operating time over the range of 100 to 5000 hours is tabulated in Table IX. These values are plotted in Figures 29 and 30 for the 8 and 31 channel configurations respectively.

3.5.3 Parallel Data Recording Configurations

For this method of recording 8 and 31 channel configurations will be evaluated to permit comparison with the serial configurations previously discussed. The multichannel parallel configuration is more complex and contains more parts than a serial recorder with the same number of data tracks. For this reason, the parallel recorder also has a higher total rate of failure than a corresponding serial recorder.

Despite these disadvantages, the multichannel parallel recorder has the very distinct advantage that the effect of a small number of channel failures on loss of data can be compensated, to a degree, by the use of parity checks and redundancy error codes as discussed in the previous section. This permits the loss of one or several channels without significantly reducing overall recorder performance.

A reliability block diagram for a typical multichannel parallel recorder data electronic subsystem is shown in Figure 31. To estimate the probability that the recorder will survive for an operating time "t" with no channel failures, the model in the lower part of Figure 31 may be used. For this case, it is assumed that all elements of the recorder must survive, and operate satisfactorily, for the mission period, and that the reliabilities of individual elements combine by the product rule as shown by the model. A more generalized model, which can be used when some fraction x/n of the channels may be permitted to fail, is given in Figure 32.

The estimated parts counts of the major elements required for the 8 and 31 channel parallel recorder configurations are summarized in Table X. Also presented in Table X are the total failure rate for each generic part group and the total failure rate for the 8 and 31 channel configurations. These parts associated with R_6, R_7, and R_8 are serial elements whose failure would result in complete failure of the recorder, regardless of how many failures can be permitted in the channels. The failure rate of the elements λ_6, λ_7, and λ_8 = 0.816%/1000 hours. For the 8 channel configuration the total failure rate for elements λ_1 to λ_5 inclusive = 5.5166%/1000 hours. For the 31 channel configuration the corresponding failure rate is 21.6855%/1000 hours.

The estimated reliability values for the 8 and 31 channel parallel configuration, as a function of operating time over the range 100 to 5000 hours, is tabulated in Table IX. For each configuration, reliability values were computed for zero channel failures and one channel failure. For the 31 channel configuration, the probability that not more than two channel failures would occur was also computed. These various values are plotted in Figures 24 and 30 to enable direct comparisons to be made with the 8 and 31 channel serial configurations.

3.5.4 Comparison of Reliability Potential of Serial and Parallel Configurations

The configurations, rated in order of decreasing reliability potential are:

CONFIGURATION

Rank	8 Channel	31 Channel
1	parallel, 1 channel failure allowed	parallel, 2 channel failures allowed
2	serial	parallel, 1 channel failure allowed
3	parallel, no channel failures allowed	serial
4	--	parallel, no channel failures allowed

For both the 8 and 31 channel configurations, parallel recording, in which one or more channel failures may be allowed, has a higher reliability than serial recording, while serial recording has a higher probability of survival than the parallel case in which no channel failures are allowed. It will be noted from Figure 30 that, for the 31 channel configurations, the probability of survival for parallel recording with 1 channel failure allowed has a lower probability of survival than the corresponding serial configuration for operating times greater than 3700 hours, although out to 5000 hours the differences are small. Because of its more desirable reliability profile for times <3700 hours, the parallel case with one channel failure allowed is preferable to the serial approach.

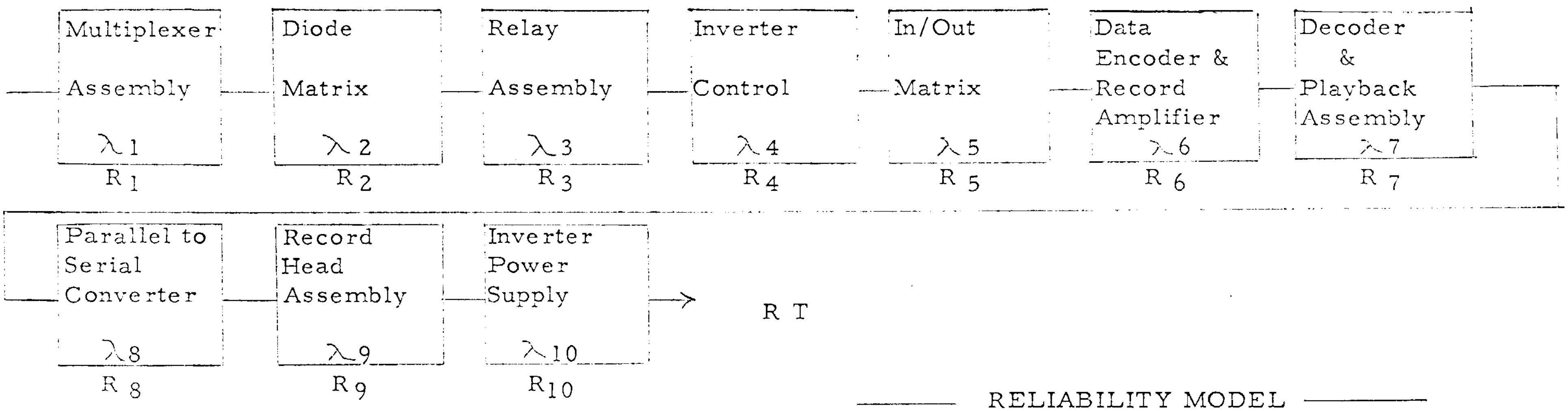
3.5.5 Other Considerations

The reliability estimates for the serial configurations of parallel and serial recording data electronics subsystems, given in the preceeding discussion, are predicated on the basis of high quality, commercially available parts having failure rates of the values shown in Table VII. It is possible to obtain parts having failure rates lower than the value shown in Table VII. These require special process controls, extensive screening tests and careful application control. These processes, while highly desirable, reflect themselves in increased part costs. The decision to specify that these processes be employed is an economic trade-off beyond the scope of this study. As a rule of thumb, if the overall failure rate is reduced by 1/2, the operating time axis in Figures 2 and 3 can be extended by a factor of two for the same reliability values on the Abscissa scales. This then permits comparisons to be made for any failure rate values that may be obtainable.

Part failure rates are also influenced by the environmental conditions to which the parts are subjected. Such conditions as in-flight temperatures, radiation effects, and pre-launch sterilization can have a significant effect on the failure rate. Efforts must be made to minimize temperature excursions during use, by adequate derating, heat sinking, and proper thermal design. Radiation damage must be minimized by using parts having a high degree of radiation resistance and by providing adequate shielding to minimize damage due to cumulative radiation dosage. All parts used should be of a type that have been qualified to withstand the various space environmental conditions to which they will be subjected, in addition to having demonstrated and ability to withstand sterilization without degradation of performance.

For long space missions, the problems of part parameter stability and the resultant effects on circuit performance become quite important. Digital circuits are inherently more tolerant of part parameter changes than are analog circuits. Hence, the part stability requirements for analog circuits may be more stringent than for applications of the same part in digital circuits. Since all parts have a tendency to vary over predictable ranges with time, it is highly desirable that all circuits, both analog and digital, be subject to worst case analyses to ensure that they will be capable of operating satisfactorily, with the variations in part parameters which may occur, in long time duration space flights.

RELIABILITY BLOCK DIAGRAM AND MODEL FOR MULTICHANNEL SERIAL RECORDING ELECTRONICS SYSTEM



RELIABILITY MODEL

$$R_T = R_1 \bullet R_2 \bullet R_3 \bullet R_4 \bullet R_5 \bullet R_6 \bullet R_7 \bullet R_8 \bullet R_9 \bullet R_{10}$$

$$R_T = \prod_{i=1}^{10} R_i$$

$$R_T = e^{-(\lambda 1 + \lambda 2 + \lambda 3 + \lambda 4 + \lambda 5 + \lambda 6 + \lambda 7 + \lambda 8 + \lambda 9 + \lambda 10)\, t}$$

$$R_T = \exp\left[-\left(\sum_{i=1}^{10} \lambda_i\right) t\right]$$

FIGURE 28

TABLE VII

ELECTRONIC PART FAILURE RATE VALUES AND APPLICATION DERATING CRITERIA

Generic Part Class	Derating (maximum operating conditions)	Failure Rate (%/1000 hours)
Resistors, Fixed Carbon	< 50% power	.00035
Capacitors, Ceramic	< 50% voltage	.00070
Capacitors, Tantalum	< 50% voltage	.030
Diodes, Signal	< 10% power	.001
Diodes, Zener	< 40% power	.010
Transistors, Signal Silicon	< 10% power	.010
Transistors, Power, Silicon	< 25% power	.010
Relays	< 25% rated contact current	.100
Transformers & Inductors	<100° C	.030
Potentiometers		.011
Connectors		.002/con + .001/pin
Transistors, Photo Sensitive		.050
Diodes, Ga. As.		.100
Thermistors		.03
Filter, Feedthrough		.005
Integrated Circuits (flip flop & gates)		.02
Crystals		.002
Record Head (per track)		.018/track

TABLE VIII

ESTIMATED PARTS COUNT AND FAILURE RATE VALUES FOR 8 AND 31 CHANNEL SERIAL RECORDING ELECTRONICS SUBSYSTEM

Element (8 Channel / 31 Channel)	Resistors Fixed Carbon	Capacitors Ceramic	Capacitors Paper	Diodes Signal	Diodes Zener	Transistors	Relays	Transformers & Inductors	Connectors Pins	Record Head	Integrated Circuit	Totals
Multiplier Assembly	100/400		1/1	64/244	1/1	40/160			20/45			
Diode Matrix				32/141								
Relay Assembly	20/78	8/20		32/84		8/20	2/4					
Inverter Control	12/13			22/30		3/3						
In/Out Matrix	8/32			14/56		3/12						
Data Encoder and Record Amplifier	30/30	8/8		22/22		10/10						
Decoder and Playback Amplifier	162/162	30/30	8/8	80/80	2/2	42/42						
Parallel to Serial Converter											20/75	
Record Head Assembly Tracks										8/31		
Power Supply Inverter	17/17	8/8	4/4	19/19	5/5	8/9	2/2	2/2	10/10			
Total Estimated Parts Count	350/[illegible]	54/[illegible]	13/[illegible]	281/[illegible]	8/[illegible]	114/[illegible]	4/4	7/7	30/55	8/31	20/[illegible]	884/[illegible]
Failure Rate – 8 Channels	[illegible]	[illegible]	[illegible]	[illegible]	.0800	[illegible]	.4000	.0600	[illegible]	[illegible]	.4000	3.0953 %/1000 hours
Failure Rate – 31 Channels	.2563	.0432	.3900	[illegible]	.0800	2.5500	.6000	.0600	.0650	.5580	1.5000	6.7243 %/1000 hours

TABLE IX

ESTIMATED PROBABILITY OF SURVIVAL VALUES FOR 8 AND 31 CHANNEL SERIAL & PARALLEL RECORDER ELECTRONICS

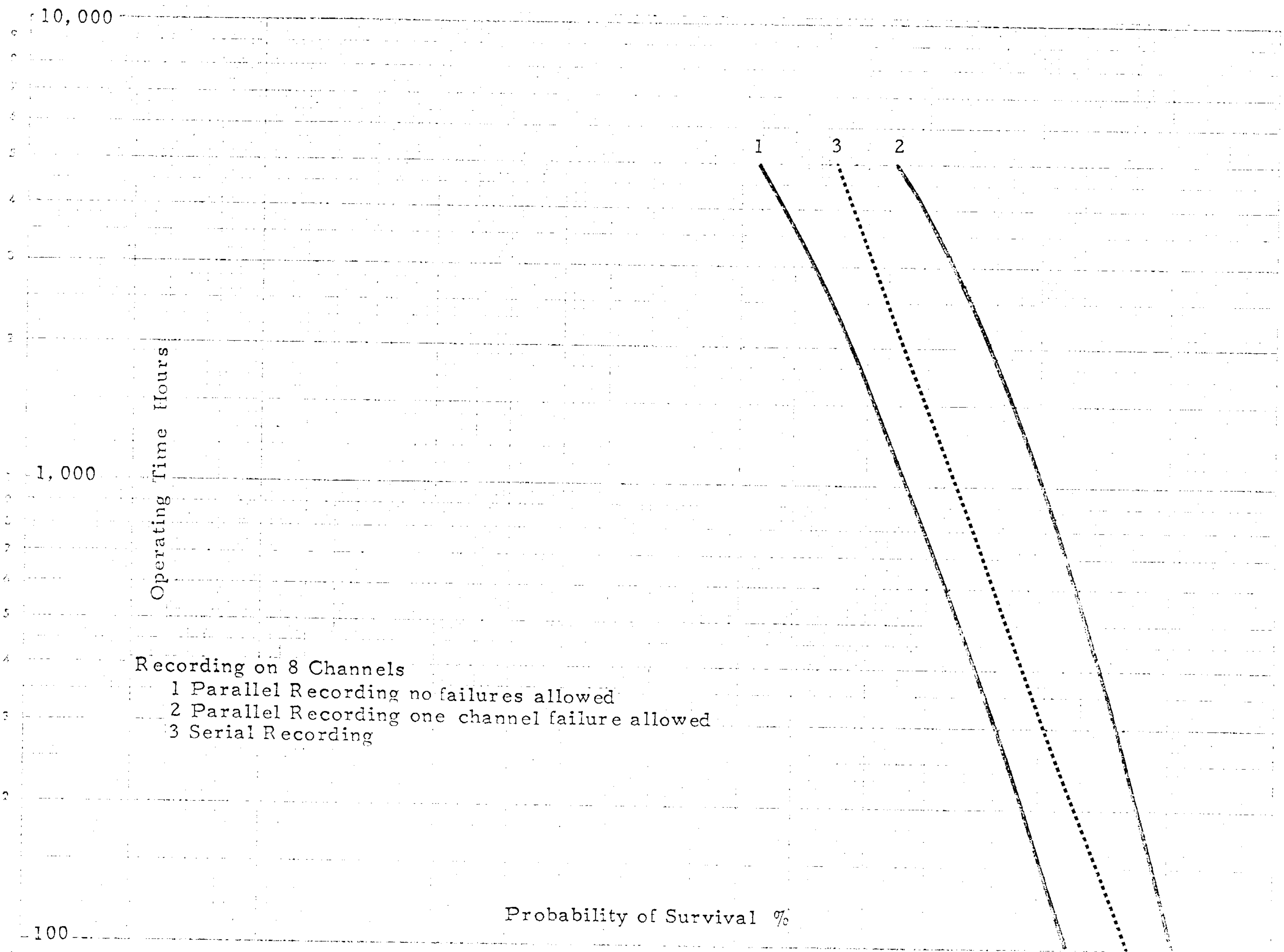
	Operating Time Hours	100	200	300	400	500	600	700	800	900	1000	2000	3000	4000	5000
8 Channels	Serial	.99691	.99382	.99075	.98770	.98462	.98160	.97858	.97555	.97253	.96950	.9400	.9115	.8833	.8571
	Parallel 0 Channel Failures	.99368	.98740	.98115	.97498	.96880	.96270	.95660	.95060	.94451	.93852	.8808	.8262	.7760	.7291
	Parallel 1 Channel Failure Maximum	.99916	.99830	.99742	.99650	.99554	.99458	.99359	.99256	.99150	.99042	.9760	.9648	.9460	.9250
31 Channels	Serial	.99325	.98655	.97990	.97330	.96670	.96020	.95370	.94725	.94090	.93450	.8735	.8161	.7625	.7130
	Parallel 0 Channel Failures	.97770	.95599	.93460	.91380	.89340	.87350	.85410	.83510	.81650	.79810	.6375	.5090	.4063	.3245
	Parallel 1 Channel Failure Maximum	.99855	.99745	.99554	.99321	.99045	.98735	.98392	.98016	.97610	.97163	.914	.840	.756	.672
	Parallel 2 Channel Failures Maximum	.99919	.99835	.99751	.99655	.99571	.99479	.99379	.99274	.99164	.99044	.975	.9475	.911	.864

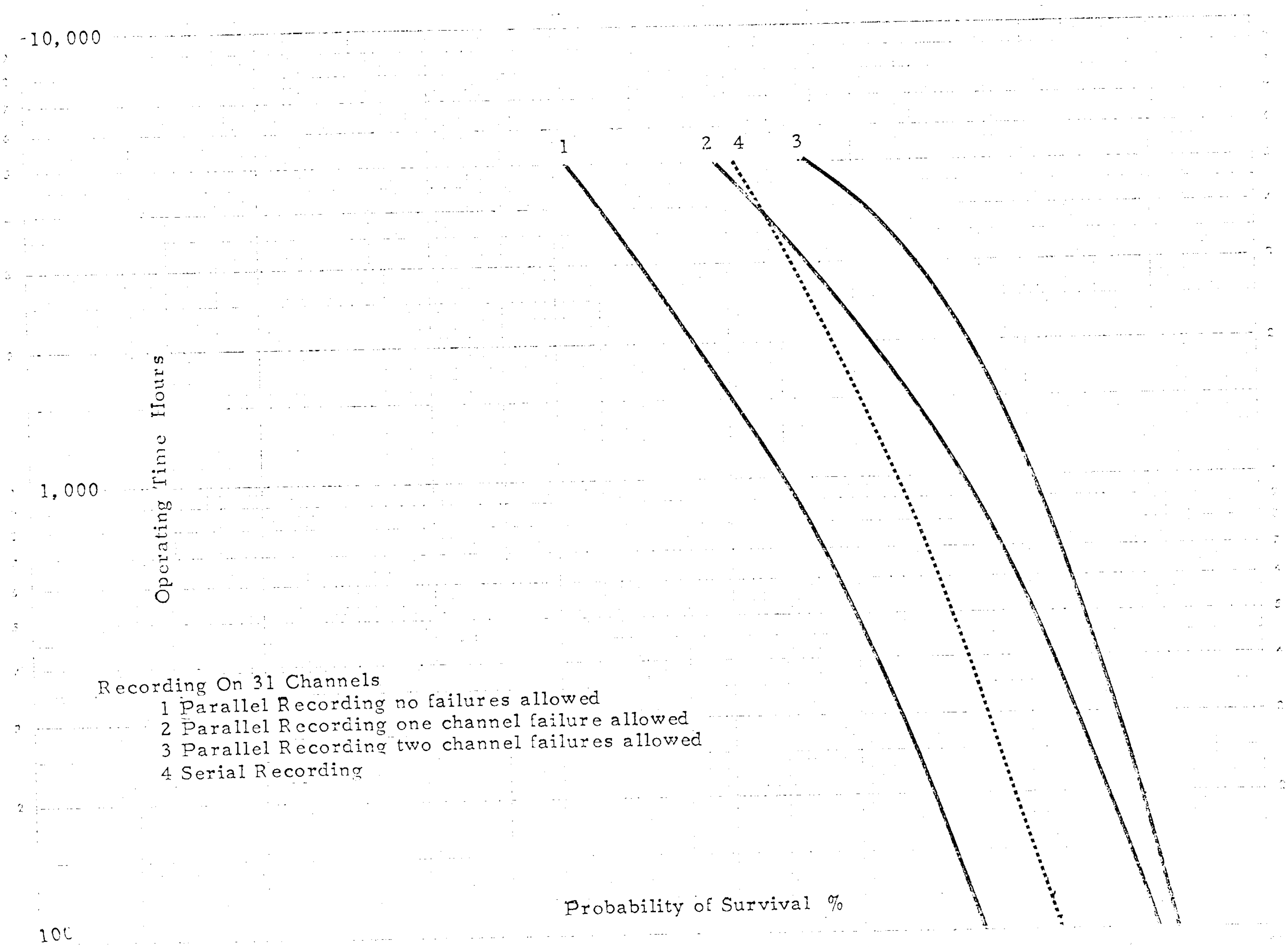
TABLE X

ESTIMATED PARTS COUNT AND FAILURE RATE VALUES FOR 8 AND 31 CHANNEL PARALLEL RECORDING ELECTRONICS SUBSYSTEM

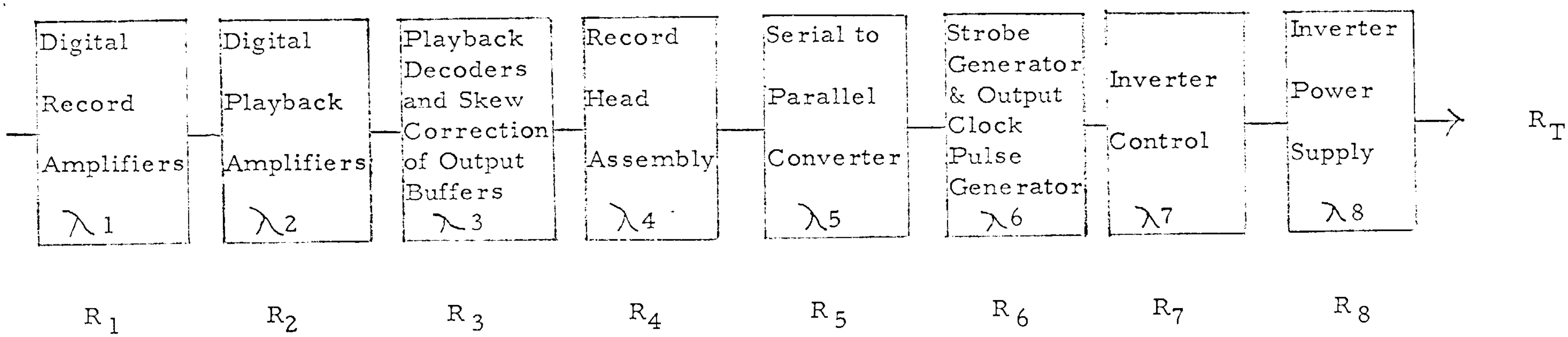
Element (8 Channels / 31 Channels)	Resistor Fixed Carbon	Capacitors Ceramic	Capacitors Tantalum	Diodes Silicon	Diodes Zener	Transistors	Relays	Transformers & Inductors	Connectors Active Pins	Record Heads	Integrated Circuits	Totals
Digital Record Amplifier	288/1116	40/155	24/93	136/527	8/31	120/465		16/62	20/45			
Digital Playback Amplifier	184/713	32/124	24/93			96/372			20/45			
Playback Decoder & Skew Correction of Output Buffer	176/682	16/62		88/341		40/155						
Strobe Generator & Output Clock Pulse Generator	16/16	2/2		14/39		4/4						
Serial to Parallel Converter											20/75	
Record Head Assembly Tracks										8/31		
Inverter Control	13/13			20/20		3/3						
Power Supply Inverter	17/17	8/8	4/4	19/19	5/5	8/8	2/2	2/2	10/10			
Total Estimated Parts Count	694/2557	98/351	52/190	277/944	13/36	271/1007	2/2	18/64	50/100	8/31	20/75	1503/5357
Failure Rate 8 Channels	.2430	.0686	1.5600	.2770	.1300	2.7100	.2000	.5400	.0600	.1440	.4000	6.3326
Failure Rate 31 Channels	.8940	.2455	5.7000	.9440	.3600	10.0700	.2000	1.9200	.1100	.5580	1.5000	22.5015

Total Failure Rate %/1000 Hours


10,000
1,000
100
Operating Time Hours
Probability of Survival %
1
3
2
Recording on 8 Channels
1 Parallel Recording no failures allowed
2 Parallel Recording one channel failure allowed
3 Serial Recording


10,000
1,000
100
Operating Time Hours
1
2
4
3
Recording On 31 Channels
1 Parallel Recording no failures allowed
2 Parallel Recording one channel failure allowed
3 Parallel Recording two channel failures allowed
4 Serial Recording
Probability of Survival %

RELIABILITY BLOCK DIAGRAM AND MODEL FOR MULTICHANNEL PARALLEL RECORDING ELECTRONICS SYSTEM



Reliability Model

(no channel failures permitted)

$$R_T = R_1 \circ R_2 \circ R_3 \circ R_4 \circ R_5 \circ R_6 \circ R_7 \circ R_8$$

$$R_T = \sum_{i=1}^{8} R_i$$

$$R_T = e^{-(\lambda 1 + \lambda 2 + \lambda 3 + \lambda 4 + \lambda 5)\,t} \circ e^{-(\lambda 6 + \lambda 7 + \lambda 8)\,t}$$

$$= \exp\left[-\left(\sum_{i=1}^{5} \lambda it\right)\right] \circ \exp\left[-\left(\sum_{i=6}^{8} \lambda it\right)\right]$$

$$= \exp\left[-\left(\sum_{i=1}^{8} \lambda it\right)\right]$$

FIGURE 31

FIGURE 32

RELIABILITY MODEL FOR MULTICHANNEL PARALLEL RECORDING ELECTRONICS SUBSYSTEM IN WHICH A LIMITED NUMBER OF CHANNEL FAILURES CAN BE PERMITTED

Let $R_A = \sqrt[N]{R_1 \circ R_2 \bullet R_3 \circ R_4 \bullet R_5}$ = composite reliability of a single channel

$R_B = R_6 \bullet R_7 \circ R_8$ composite reliability of all serial elements whose failure would result in complete failure of the recorder.

Where $R_1 \ldots R_8$ correspond to the elements shown in the Reliability Block Diagram in Figure 31.

Then $R_T = \sum_{R=0}^{x} \binom{N}{x} R_A^{N-R} (1-R_A)^R \bullet R_B$

Where N = Number of channels in recorder

x = Maximum number of channel failures permitted

R_T = Probability that the recorder will operate satisfactorily with friction $N-x/N$ of the recorder channels running for time T

R_A, R_B = Are as defined above

For the case where no channel failures are permitted:

$R_T = (R_A)^N \bullet R_B$ which reduces to the model shown in Figure 31.

3.6 Comparison of Analog and Digital Recording Techniques

There are areas where there is no choice which of the methods to use. Analog recording is characterized by the ability to handle large amounts of data, but not very well. Digital recording can handle only a relatively small amount of data, but can handle it very well.

For a given amount of data, analog recording will record the information on a much shorter length of tape. If we assume that the information bandwidth is from 100 Hz to 1000 Hz, a tape speed of 1 ips would be quite adequate for analog. For digital, assuming a resolution of 32 levels, this would require 15,000 bits per second. Using a packing density of 2000 bits/inch of tape, a tape speed of 7.5 ips would be needed. In actuality, the analog system could handle considerably more than the 1 kHz bandwidth. Since the amount of tape for a given amount of data is much greater for digital, one would expect the weight and size of a digital machine to be considerably greater than that of an analog machine having the same capacity. Argueing against this, is the fact that the use of analog recording usually requires lower flutter than does the digital. If the amount of data is large, the analog machine would definately have the advantage of lower weight and size.

Start time differences between analog and digital are caused by the following factors: For the same data, a digital machine will usually be operating at a higher speed. The analog machine, however, is more susceptible to the influence of flutter. In general, one would expect the low speed machine to reach speed sooner than the high speed mechanism. Since the analog machine requires more nearly constant speed than the digital machine, and will probably have greater inertia, and because the time to start a synchronous motor-driven machine tends to be dominated by the inertia of the motor, rather than the inertia of the rest of the system, the end result is that the two systems will start in about the same time. In fact, a little more time will be required for the analog machine to reach the required steady-state speed. However, if the drive used employs servo, the analog machine will usually have the advantage of lower start time because the inertia of the motor is not as limiting a factor with servo drive. In addition, with the servo drive, assuming the same data, there will be less tape in the analog case, and hence, the start time will be less due to the reduced mass.

Summarizing:

Synchronous Motor Drive	Analog start time slightly longer
Servo Drive	Analog start time appreciably shorter

The physical transport will be essentially the same in either analog or digital recording. In the case of the analog recording, there must be greater care in the design of the machine to avoid flutter, bounce of the tape, etc. Rotating components will be nearly the same, with some possibility of an additional speed reduction in the analog case, depending on the exact data to be recorded. In any case, the tape speed would be less by a large factor (10 or more) for the recording of analog data.

The required tape guidance accuracy in the two cases is similar, with the analog recording requiring the greater accuracy. With digital recording the only tape guidance problem that one expects to encounter is skew. In the case of serial recording of digital data, skew is not a problem. With analog, skew is usually a minor part of the guidance problem. In addition to skew, azimuth, scrape flutter, tape bounce, and weaving of the tape path all become serious problems. Where scrape flutter produces only very minor jitter with digital recording, it produces major frequency modulation on the data when analog recording is used. Weaving of the tape can cause amplitude error with analog recording and occasionally, in severe cases, can cause crosstalk between channels. Tape bounce can affect the high frequency response of a channel. This is particularly severe if the information recorded is the modulation of a high frequency signal. In summary, the guidance requirements in the case of analog recording are much more severe.

With regard to degradation of performance with time, analog recording becomes slightly degraded very quickly, and the degradation continues to increase rather gradually, until the time the head wears out, when there is a rapid loss of high frequency response.

Digital recording methods do not follow this pattern. They typically continue to operate at very near their new condition until a degradation threshold is reached, when the output rather rapidly fails and the error rate increases drastically. With optimum design, severe degradation of the analog signal will occur before the digital signal is appreciably affected.

Usually, flutter is not a severe problem in digital recording. The only instance where it becomes as significant a worry as analog is in the case of digital information that is to be reproduced and telemetered over a long distance link. In this application, there is some advantage to using a servo system to phase lock the reproduced data to a crystal oscillator, and reclock the data as it is reproduced. In this way all timing irregularities of the reproduced data may be removed. This is not possible with analog data because it cannot be reclocked. It is possible to use a phase lock servo in such a manner that the time delay error (or Time Base Error) of analog data can be held to a low value, but this still does not remove the high frequency flutter components. The effect of flutter can be severe on analog data.

Some of the factors which produce amplitude variations in analog reproduction are as follows: Variation of density of magnetic particles in the tape can cause variation of the output of the tape (This is usually termed clumping) as can variations of the thickness of the coating, roughness of the backing, and roughness of the surface of the tape. This last is a particularly severe problem with high frequency data. An effect similar to, but much more severe than, the effect of tape surface roughness results from accumulation of oxide or the presence of small particles on the tape. These produce a decrease in amplitude, particularly of the high frequencies. The magnitude of the effect is about $55 \frac{d}{\lambda}$ db, where d is the separation of the tape and the head produced, and λ is the wave-length of the signal in question, both expressed in the same units.

Digital recording is unaffected by this, until the signal loss is so severe that pulses are reproduced below the threshold of the electronics. When this happens, the reproduced digital data rapidly becomes unusable. This normally occurs with much more severe tape separation than that required to make the analog data quite unreliable.

It should be mentioned that there is the possibility of using coding to eliminate errors with digital data. When this is done, digital recording can be expected to result in data having a very high level of confidence that the data is correct. It is never possible to do this with analog recording; since analog errors are not quantized, error correcting codes are not possible. Analog data always has some error associated with it.

3.7 Discussion of Considerations in Selection of Servo Control or Synchronous Drive Systems

3.7.1 General Servo Considerations

There are a number of tape recorder drives possible using servo control of the capstan motor. There are systems using only a discriminator, and those employing phase detection. The systems using discriminator only (Figure 38)* provide, under the best of circumstances, fairly good control of tape speed with reasonable flutter. If such a system is implemented with tachometer to provide the feedback signal, the results are similar to those using a synchronous motor except that the motor speed cannot be held exactly over a period of time. If the feedback signal is taken from the tape (Figure 39), a discriminator type servo can give fairly good control of steady state speed, and good control of flutter.

If it is desired to control the speed of the tape rather well (so far as the steady state speed is concerned) a phase detector and a stable reference frequency must be used.

If the phase detecting servo obtains its feedback signal from a tachometer (Figure 40) attached to the motor shaft, results rather close to the use of synchronous motors may be obtained. The main difference while running is that the servo tends to be a "stiffer" drive than a synchronous motor because there are no belts needed between the motor and the capstan shaft.

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* All figures referenced in this section are included at the end of the section.

If highly accurate speed control is needed, or if preservation of time is required, this may be attained by using a phase lock servo, which obtains its feedback (Figure 6 and Figure 7) from the tape during reproduction. The usual case is that recording is done with the servo locking the output of a tachometer to a stable frequency. While the data is being recorded, a "clock track" is also recorded. The clock signal is typically derived from a crystal oscillator. Phase lock to the clock track occurs during playback. This type of servo is characterized by extremely low flutter at low rates, and by exact preservation of frequency. Time base error (TBE) is the usual criterion for the evaluation of operation of a phase lock to tape system. TBE is the time difference between the data reproduced on playback, and the output of the crystal oscillator to which the tape is phase locked. It is usually in terms of peak-to-peak, two sigma limit, or rms.

In common with any servo system, a servo controlled tape transport is sensitive to external disturbances and to imperfections (noise) in the means used to sense the output. The noises and disturbances, which will be considered here, are as shown in the diagram of the block s of the servo system (Figure 37).

Dl consists of all those disturbances which affect the motor speed. Some of the sources are torque ripple in the motor, bearing friction in the motor, or coupled to the motor, angular accelleration of the transport, reflected torque from reels, etc. D2 consists of all those disturbances which affect relative motion of the tape and playback head. The D2 component which causes the principal degradation in transport operation is varying friction of the tape against heads, guides, and so forth (giving rise to "scrape flutter"). Other D2 components are vibration of the head or the capstan or guides relative to the transport, variation in tape tension causing stretching of the tape between the capstan and the reproduce head, etc. It ought to be noted that as here defined, D1 and D2 are not completely independent. It is possible for a reel irregularity, for example, to cause variation in tape tension which will slightly change the speed of the motor. This same change in tension will cause stretching of the tape between the capstan and the head. During playback, the flutter recorded on the tape is included in D2.

N1 is the tachometer noise. The nature of this noise depends on the type tachometer used. When the tachometer uses the coincidence of teeth of two gears, one fixed to the transport and one fixed to the motor shaft, the errors are minimum because this type of tachometer can be designed to cause cancellation of almost all the error caused by gear imperfections. Unfortunately, it is difficult to use this type of tachometer for a high performance servo system because the number of samples during a revolution of the motor shaft is determined by the number of teeth on the gear.

The type of tachometer most often used is optical in nature. There are alternate clear and opaque regions near the edge of a disc. Light passes through the disc, through a stationary pattern which duplicates the light and dark regions on the disc, and then, to a light sensitive element. This type of tachometer allows a larger number of samples than the gear type (on the order of 5000 lines), but does not offer the error cancelling features of the gear tachometer. The only averaging that occurs is that which takes place at the graticule located between the tachometer disc and the light sensing element. This is caused by line to line spacing errors. Because the graticule is comprised of a number of lines, any error between two lines on the tachometer is averaged over the number of lines on the graticule. The extent of this averaging is limited by the number of possible lines that can be used on the graticule. This number is, in turn, limited by the nature of the optics associated with the light source and sensing element. The servo speed controls discussed here utilize optical tachometers.

The noise produced by an optical tachometer arises from two main sources. The first is the lack of concentricity of the pattern as it rotates because of the dimensional runout and mounting tolerances. This produces a noise which is almost purely sinusoidal in nature, with a frequency equal to the rotational rate of the shaft on which the tachometer is mounted. Reasonable care will hold the magnitude of this noise to a small fraction of a percent of flutter. Peak-to-peak, this is numerically equal to the percentage represented by the total indicated runout of the radius of the pattern.

The N1 noise of greatest concern is that which is produced by errors in the positions of the lines on the tachometer disc. Typically, (when the master tachometer disc is produced on a ruling machine) there are systematic errors in line location. These errors produce a flutter indication which is harmonically related to the speed of the shaft on which the tachometer is mounted. The systematic error may be repeated a large number of times around the disc. (In one case, such errors occurred 40 times around the disc) In addition, there are randomly distributed errors in line position. Discs which eliminate this noise are not commercially available.

It is possible to make a master tachometer disc which is fairly free of these imperfections by electro-mechanical means. A general process for producing a master tachometer disc is to mount a good ruled tachometer or a geartooth tachometer, a heavy flywheel, a motor and a photographically sensitive disc on a single shaft. The bearings must be as good as possible. The ruled tachometer or geartooth tachometer is phase locked to a crystal oscillator, and the crystal oscillator is used to trigger light pulses which strike the photographic plate through a narrow slit. If the nature of the servo is correct, and the process is continued for a time, when the plate is developed, the result will be a tachometer with extremely low error. In particular, the spacing of lines which are close together will be very nearly uniform. As will be seen later, this is particularly important.

N2 is the error involved in the process of phase detection from the tape. This can be caused by an instability of the reference oscillator. However, this stability is usually quite good. The main contributor to N2 is the electrical noise which is present in the clock channel output. Since the clock signal, as reproduced, is usually a sinusoid, Gaussian noise will produce a shift in the timing of the zero crossing of the clock signal. Because the zero crossing time is used to determine the phase difference between the clock signal and the reference signal, this shifting of the zero crossing will also produce errors when the discriminator is connected to the clock track. Means of minimizing this noise are; to maximize the slope of the reproduced clock signal in the region of the zero crossing (By increasing the clock frequency or amplitude) passing the clock signal through a filter which rejects frequencies which are far removed from the clock signal and using a good quality preamplifier at the head. (A similar noise can occur with the optical tachometer, but usually the signal to noise ratio at the output of the photoelectric transducer is very high.)

It should be noted that the noise, in both the case of N1 and N2, is in the form of Time Base Error. There is a relationship between TBE and flutter which involves a factor of ω between the two. For a component at radian frequency ω, TBE is proportional to ω times flutter. Thus, the predominant frequency injection experienced results in flutter at the high end of the servo frequency response. (As a first order approximation, random error generated TBE spectral density tends to be rather flat with frequency.)

Typical gain of a servo system (any servo system which is designed to provide the maximum benefit of feedback, without the possibility of instability) has a loop gain against frequency plot similar to Figure 43. The decrease of gain with increasing frequency averages about 30 db/decade. The flutter at very low frequencies is reduced to vanishingly low levels. The TBE is appreciable, because of the ω factor in the conversion of flutter spectral density to TBE spectral density. It is to be noted that the TBE of a system is equivalent to the position error of a servo system. The theorems for a position servo system apply.

The mechanical model that will be used for derivation of various servo control tape transports will be consistent with a Kinelogic recorder having a DC pancake torque motor, a photoelectric tachometer which has radial lines ruled around its edge, and design steps taken in regard to the tape and belt paths to avoid resonance problems.

Assumptions and derivations follow:

The data are, for the most part, transformed to flutter, or velocity form, rather than to position, or TBE form. Conversions back to TBE are made at the end of calculation.

3.7.1.1 Velocity Transfer

The transfer from motor voltage to motor velocity for the Kinelogic transport considered is:

$$\frac{10\,(2.5 \times 10^{-6}s^2 + .8 \times 10^{-3}s + 1)}{(.05s + 1)\,(1.5 \times 10^{-6}s^2 + .62 \times 10^{-3}s + 1)} \quad \text{radians}/\text{volts}$$

The transfer from capstan velocity to tape speed is assumed to be unity. While this is not strictly true, it is an assumption which is very nearly exact for the frequencies at which the servo is active.

Values for T_3 and T_4 for which stability exists are:

$$T_3 = -28\,\frac{(10^{-3}s + 1)\,(2.5 \times 10^{-4}s + 1)}{(2.8 \times 10^{-3}s + 1)\,(1.25 \times 10^{-4}s + 1)}$$

$$T_4 = -\frac{3 \times 10^3}{s}$$

3.7.1.2 Noise Factors in Optical Tachometers

Assume a tachometer which provides an output frequency of 10^4 Hz and assume that the RMS position error of the lines to be K times the separation of two adjacent lines. Under these conditions, what is the resultant noise?

If it is further assumed that the position errors are uncorrelated and Gaussian, the rms timing error will be:

$$10^{-4}\ k \text{ seconds rms}$$

If $\xi'_\phi(f)$ is constant over the band to 10kHz, then:

$$\xi'_\phi(f) = 10^{-12} \text{ X } k^2 \text{ (seconds)}^2/\text{cycle}$$

and $$\xi'_{fL}(f) = (2\pi f)^2 (10^{-12} \text{ X } k^2) \quad \text{(seconds)}^2/\text{cycle}$$

Unfortunately, the assumption that line position error is random and uncorrelated, is not normally correct. In practice, periodic errors occur. Once around errors, twice around, and even 40 times around have all been observed. This can give rise to appreciable flutter injection.

Consider: Capstan rotation of 10 rps 1000 lines on tachometer

k = .01 peak, 40 times around and sinusoidal.

This results in .5% p-p flutter. (The peak linear error of this tachometer assuming a 2 inch diameter pattern, is 63 μ inches in the above case. Errors of this size are difficult to avoid.

3.7.1.3 Noise Contributed to Tape Signal (N2)

The principal contributor to N2 is the electrical noise in the clock track playback.

Assume simple zero crossing detection of a sinusoid to which band limited Gaussian noise has been added. Assume a frequency of 10^4 Hz for the sinusoid. Also, assume noise which has constant spectral density over the frequencies of 5 kHz to 15 kHz, and a signal-to-noise ratio of 40 db rms/rms. This woudl produce an indicated TBE of 0.16×10^{-6} seconds rms. The spectral density of would be 5.12×10^{-18} sec^2/Hz. This would correspond to a flutter spectral density of

$$5.12 \times 10^{-18} (2\pi f)^2 = \text{cycle/sec}$$

and would also correspond to 0.026% rms flutter in the band 0 to 1000 Hz.

This noise source is usually not significant, though it is the limiting factor in the theoretical phase lock servo (See Develet, IEEE Transactions on Audio, May - June, 1964)

3.7.1.4 Capstan Rotation Irregularities due to Disturbance. (D1)

This noise is caused principally by the following factors:

1) Motor torque variations due to position change. (torque ripple)
2) Motor brush friction and bearing frictions.
3) Reel rate variations.

The largest factor is usually that due to motor torque variations.

Assuming the case of the Kinelogic recorder considered, the capstan speed is 12 rps and the torque ripple of the motor is 7% peak at 31 cycles/revolution. The value of D1 would be 0.105% rms flutter at 372 Hz. The corresponding TBE is 0.45 μ sec rms. at 30 ips tape speed.

3.7.1.5 Calculation of the effect of N2, D1 and D2 in the Case of Frequency and Phase Lock to Tape

The component of V_t (Figure 42) due to these factors is:

$$V_t = \frac{D_2 + T_2 D_1 + (T_3 + T_4)\, T_1 T_2 N_2}{1 + (T_3 + T_4)\, T_1 T_2}$$

where T_1, T_2, T_3 and T_4 are as previously defined (Figure 37)

Since T_2 is taken as a unity, we have:

$$\frac{D_1 + D_2}{1 + L} + \frac{L}{1 + L} N_2$$

As can be seen from the curves associated with the loop gain (Figure 42) the output due to a value of D1 of 0.1% rms at 370 cycles would be 0.13% rms flutter at the same frequency. It should be noted that this is the most severe kind of frequency for the injection of flutter from this source because the flutter is actually increased from the value which it would be if the system were open loop.

The rejection of the D1 and D2 disturbances fall off at about 30 db/decade, and there is unity transmission of these factors at high frequency. In the case of the N2 factor, this has a transmission of unity at low frequencies. At high frequencies, the transmission falls off at a rate determined by the high frequency poles of the transfer functions. The effect of low frequency noise is to perturb the output to the level of the noise. The effect of low frequency disturbance is very low, since this is attenuated by the open loop gain of the servo. At high frequencies, where the open loop gain is quite low, the transmission of these disturbances is nearly unity.

The disturbances resulting from reel rates are at a low frequency, perhaps 2 to 5 cycles per second, in the case of a machine operating at 30 ips. If we assume 1% rms flutter from reel rates, with the open loop system, closing the loop will cause this value to be reduced by the loop gain, which is in the vicinity of 40 or 50 db. This reduces the resulting flutter to something on the order of 0.01% rms. The main flutter from the D1 and D2 sources is the result of scrape flutter which has a spectral density that is approximately uniform with frequency. Most of this band is high frequency and outside the range of the servo. It should be noted that the only means, which allow control of scrape flutter, are to prevent its generation and to use a tape path which closely couples the capstan inertia.

Scaling to other tape speeds may be done by considering the resultant change in the frequency of the disturbance, the change in the amplitude of the disturbance, if any, caused by the change in the tape speed, and the change in the loop gain due to the change in the frequency of the disturbance. In addition, in the case where the tape speed is drastically changed, it is necessary to consider if the loop gain need be changed (In the case of low tape speed, the sampling associated with the phase detection becomes a factor, and the frequency at 0 db loop gain must be decreased.).

When this is done, for the system under discussion, the following factors result:

TABLE XI

Speed	D_1	D_2	N_2	Total Flutter rms summation	peak-to-peak*
63 ips	0.105%	0.01%	0.0025%	0.11%	0.39%
30 ips	0.13 %	0.01%	0.005 %	0.13%	0.45%
0.7 ips	0.34 %	0.34%	0.2 %	0.34%	1.19%
0.07 ips	14.0 %	0.1 %	2.0 %	14.3 %	50.0 %

* The flutter is composed of random and mixed frequencies of sine waves. The peak-to-peak value is, therefore, taken as 3.5 times the rms value to allow for the random mixture.

Part of the degradation in the 0.07 ips case is because of the need to reduce the frequency of the 0 db loop gain point due to the decrease in clock frequency.

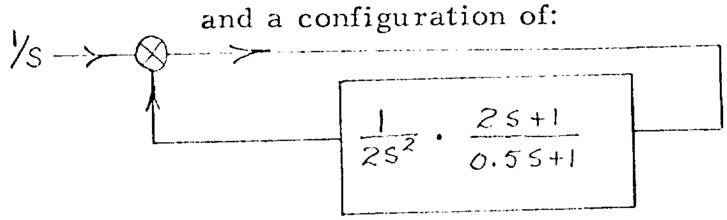
Ignored in the above is the scrape flutter component. The Kinelogic machine, which served as the prototype for the calculations had a flutter - when operated at 30 ips - of 0.18% rms. This was the value when using frequency lock and phase lock to the tachometer. When operated at the same speed, using frequency and phase lock to the tape, the flutter was 0.09%. Comparing this with the above table, it can be seen that the table is based on conservative assumptions.

3.7.1.6 Start Time

System start time has two main components. The first is the physical limitation on how fast the motor can drive the inertias of the system to the proper speed, considering the limitation on the torque available at the reels because of the finite friction of the tape and the belt on the capstan. After this time has passed, there is still the need to allow the rotation to come out of the transient state, etc. It is a reasonable approximation to our system to consider one with a loop gain of:

$$\frac{1}{2s^2} \quad \frac{2s+1}{0.5s+1}$$

and a configuration of:



The following approximations will be made:

The torque available to accellerate the tape does not exceed 3 oz-in. (This is the limit imposed by the design of the particular transport which is used in the servo part of this discussion.) The torque available at the motor is 10 oz-in. The inertia of the motor and the capstan is 0.002 oz. inches sec^2. The inertia reflected to the capstan of 550 feet of $\frac{1}{4}$ inch tape is 0.00044 oz-in-sec^2. The inertia of the tape reflected to the capstan is proportional to the length of tape. This is a conservative assumption, when the plot is started with the smallest reel.

This transfer is similar to the transfer of our system in the region of unity loop gain, and normalized to equals 1 when the open loop gain equals 1. When this system is derived by a step function, the Laplace transform of the output is:

$$\frac{1}{s} + \frac{1}{s+1} - \frac{2s+1}{s^2+s+1}$$

which, when converted back to time functions, is:

$$1 + \varepsilon^{-t} - 2\varepsilon^{-0.5t} \cos 0.866t$$

When this is evaluated for different t, we find that it is within 5% of its final value within 1 cycle of the frequency of unity loop gain, within 0.5% by two cycles, and when three cycles have passed, the value is within about 0.01% of final.

If we assume that the frequency at unity loop gain is 300 cycles, then it takes a little over 3 milliseconds to be within 5% of final speed, and about 7 milliseconds to be within 0.5% of final speed - after the electronics have come out of saturation. This is without respect to final tape speed. It will be assumed that the settling time is 7 milliseconds, for all speeds above 5 ips, and .30 milliseconds for very low speeds, reflecting the forced reduction of the servo bandwidth.

On this basis, the start time, doubled so as to include both start and stop time, is :

Final Tape Speed	550 ft of $\frac{1}{4}$ in tape	4600 ft of 1 in tape
0.07 inches per sec.	60 milliseconds	62 milliseconds
7.5 inches per sec.	24 milliseconds	210 milliseconds
30 inches per sec.	55 milliseconds	800 milliseconds
60 inches per sec.	92 milliseconds	1.58 seconds

3.7.1.7 Power Required by Transport

The type motor used in the servo controlled transports requires an amount of current which will develop 3 to 4 oz-in of torque. Assuming the use of a 28 volt supply, this can be assured with a low speed motor having a torque sensitivity of about 28 oz-in per amp, giving a power drain of 4.08 watts. For a high speed system, the motor used has to have a torque sensitivity of about 16 oz-in per amp. Using an available motor, this amounts to 6.8 watts.

3.7.2 Hysteresis Sychronous Drive System

The hysteresis synchronous motor drive system is straight forward and is primarily characterized by excellent speed repeatability. The major limitations on speed repeatability are the frequency stability of the power source and variations in torque. In the usual polyester film belt drive system, there is a difference between the speed ratio as determined by the geometry of the system and that which is actually obtained. This difference is proportional to the torque load and is designated as creep. The creep is an effect resulting from elastic deflection in the drive belts and occurs at all loads below the capacity of the belt system. There is a similar but smaller action called slip within the hysteresis synchronous motor near full load. Thus, variations in torque will cause similar variations in speed. The total creep is on the order of several tenths of a percent and the variations are, therefore, quite small. It is possible to compensate for the creep encountered in a drive system to bring the average speed as close as desired to the design speed by suitable identification of pulleys. In many machines, the recorded tape is played back on the same transport and absolute tape speed is only of academic interest.

The hysteresis synchronous motor must run at a high speed to develop sufficient power and efficiency. This high speed power source, in turn, requires a speed reduction drive train. When polyester film belts are used in the drive train, there is sufficient compliance in the belt system to cause the system to have torsional resonances with frequencies in the range of 20 Hz to, possibly, 500 Hz. Under normal conditions the torsional vibrations are sufficiently damped by friction so that this is not a problem. It is even better if some inertia is provided in the tape path. When the system is excited in a torsional mode, the tape flutter can build up to large values and even cause complete loss of tape tension.

The analytical treatment of the Iso-Elastic drive system with a hysteresis synchronous drive motor is extremely difficult. One attempt to analyze a particular system can be found in "Tape Recorder Reproducer Mechanism, Worst Case Analysis, Final Report; J. Lueder, I. Karsh, G. Barr, R Bruns; JPL Contract No. 950903." This report covers an analytical and a computer simulation treatment of the model. There was reasonable correspondence found between the two treatments and actual measurements of the equipment analyzed. However, the correspondence was not good enough to indicate that the model could be used directly in the design of similar systems.

For this reason, the data obtained from the spectrum of machines covered in the section on analysis of recorder characteristics will be used to compare the synchronous drive system to the computed values for the servo drive system.

Three characteristics are plotted (Figures 33, 34, and 35) as a function of tape speed. These characteristics are flutter, start plus stop time, and power. The servo drive system flutter shows a distinct advantage (Figure 34) in the intermediate speeds (from 0.2 to 2 ips) and a probable advantage at higher speeds, although the better synchronous drive systems are about equal to the calculated values for the servo drive system at these higher speeds. The start plus stop time (Figure 35) shows a distinct advantage for the servo drive systems at tape speeds above 7.5 ips, and no distinct difference at lower tape speeds. The synchronous drive system system shows a distinct advantage in the power required (Figure 33) at tape speeds below 4 ips. At the higher tape speeds the power required for a servo drive system would be about equal to the average value for synchronous drive systems. In these figures, computed values for the servo drive system are shown by a dashed line while the synchronous drive system data is shown by solid lines.

It can be seen that no clearcut superiority of one drive system exists and that the actual requirements of each mission must be determined before an optimum configuration can be established. If the mission requirements are set at unrealistic values, excessive costs in time and money may result.

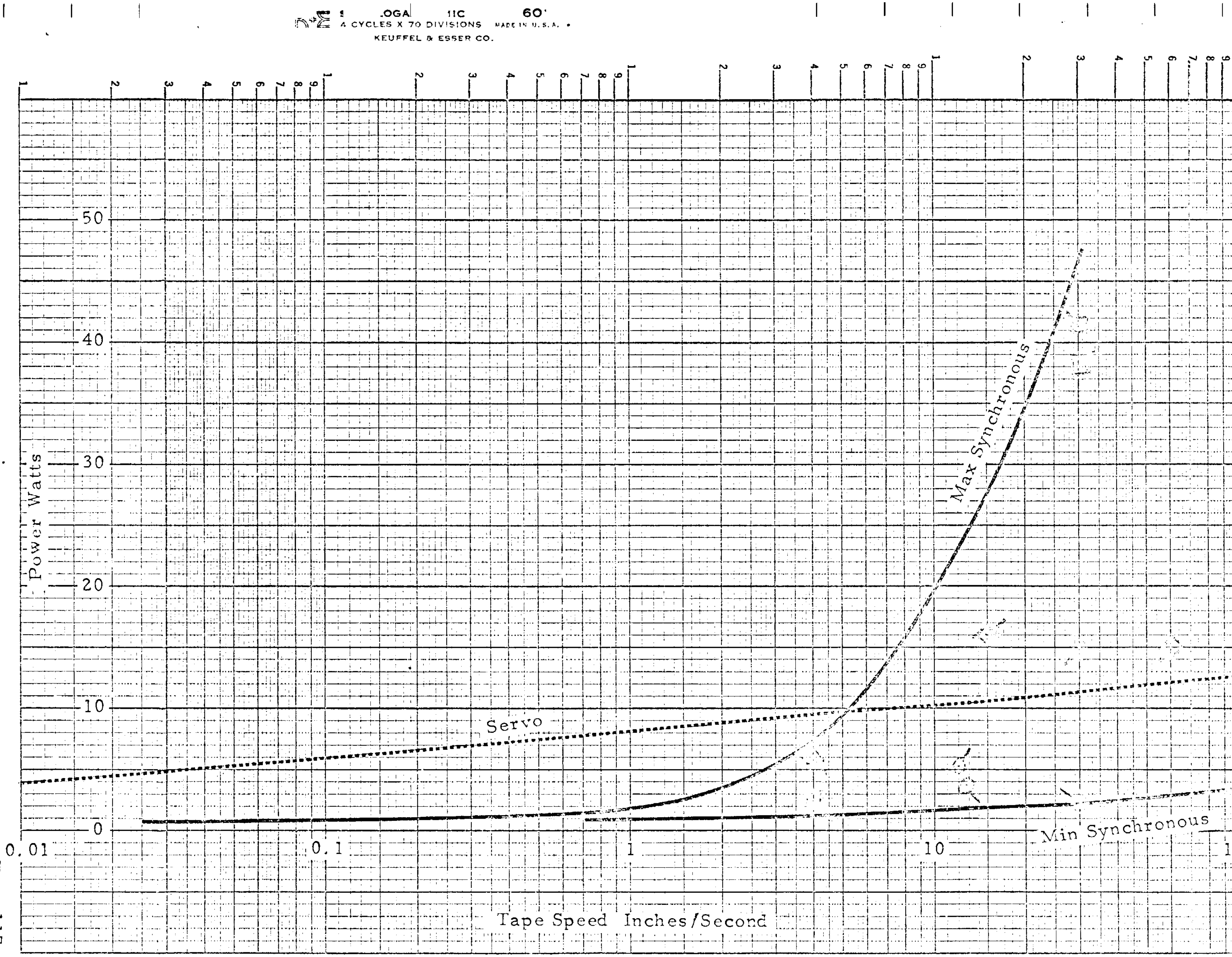
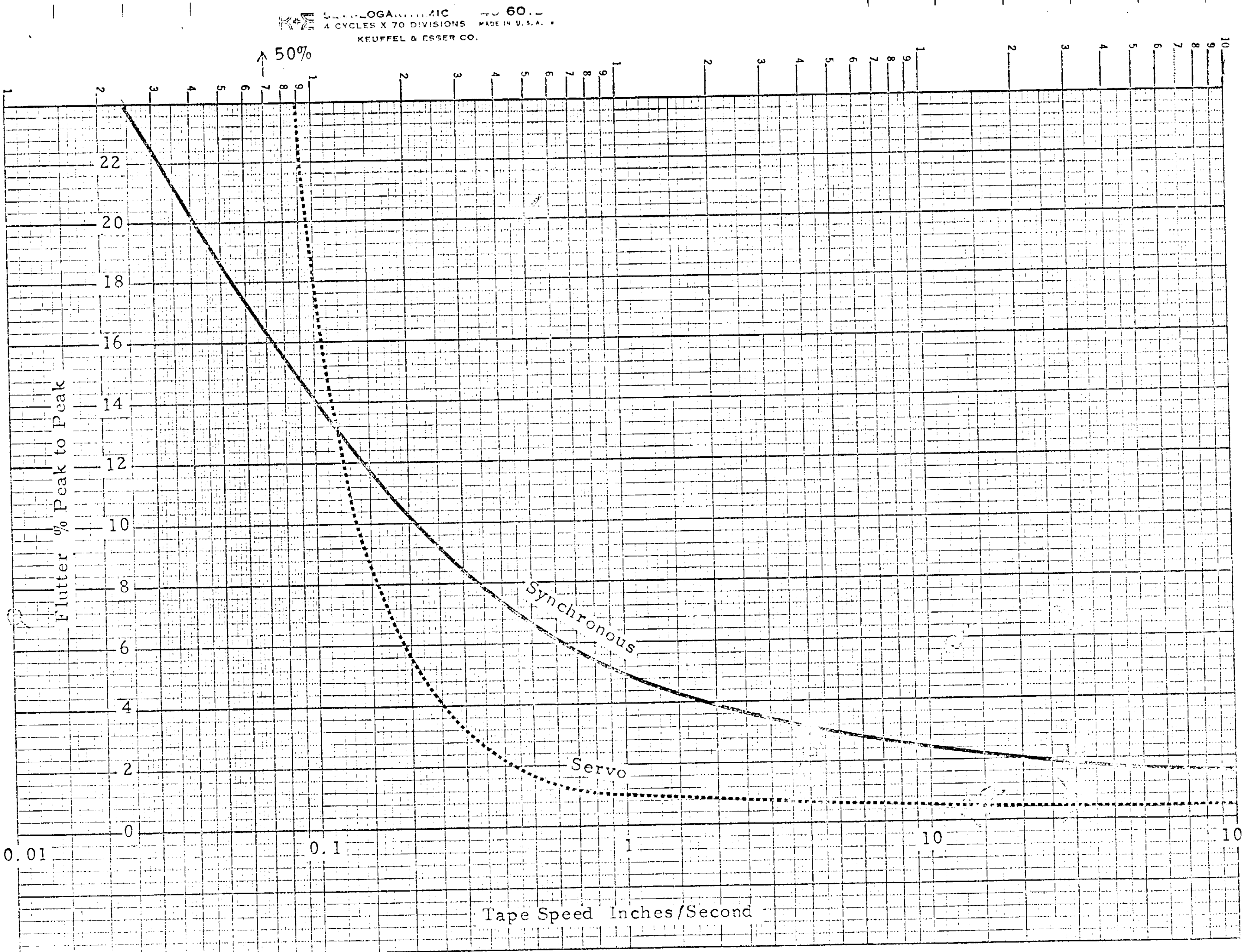

4 CYCLES X 70 DIVISIONS
MADE IN U.S.A.
KEUFFEL & ESSER CO.
Power Watts
50
40
30
20
10
0
0.01
0.1
1
10
100
Servo
Max Synchronous
Min Synchronous
Tape Speed Inches/Second

FIGURE 33



4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.
50%
Flutter % Peak to Peak
22
20
18
16
14
12
10
8
6
4
2
0
0.01
0.1
1
10
100
Synchronous
Servo
Tape Speed Inches/Second

FIGURE 34

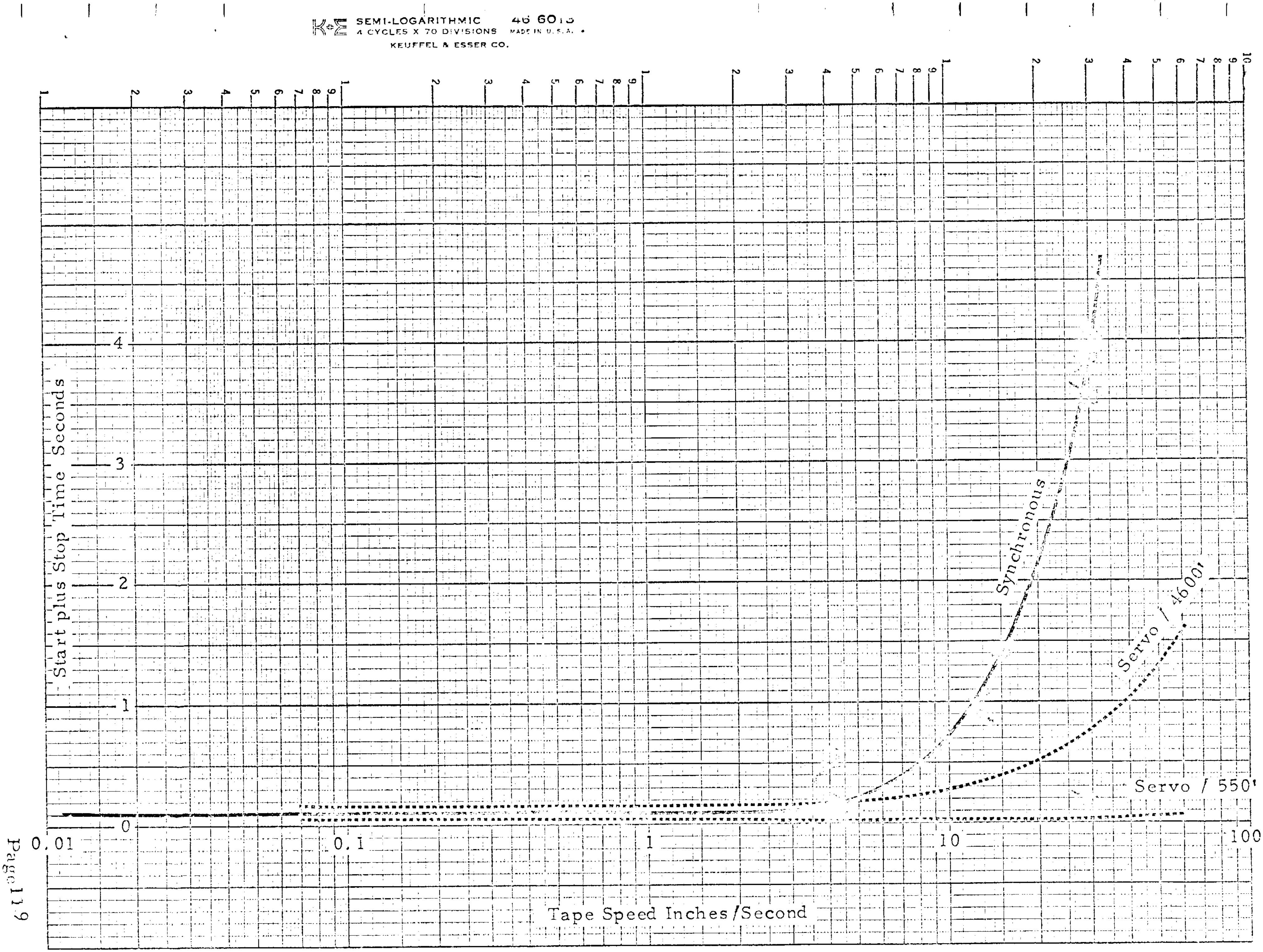
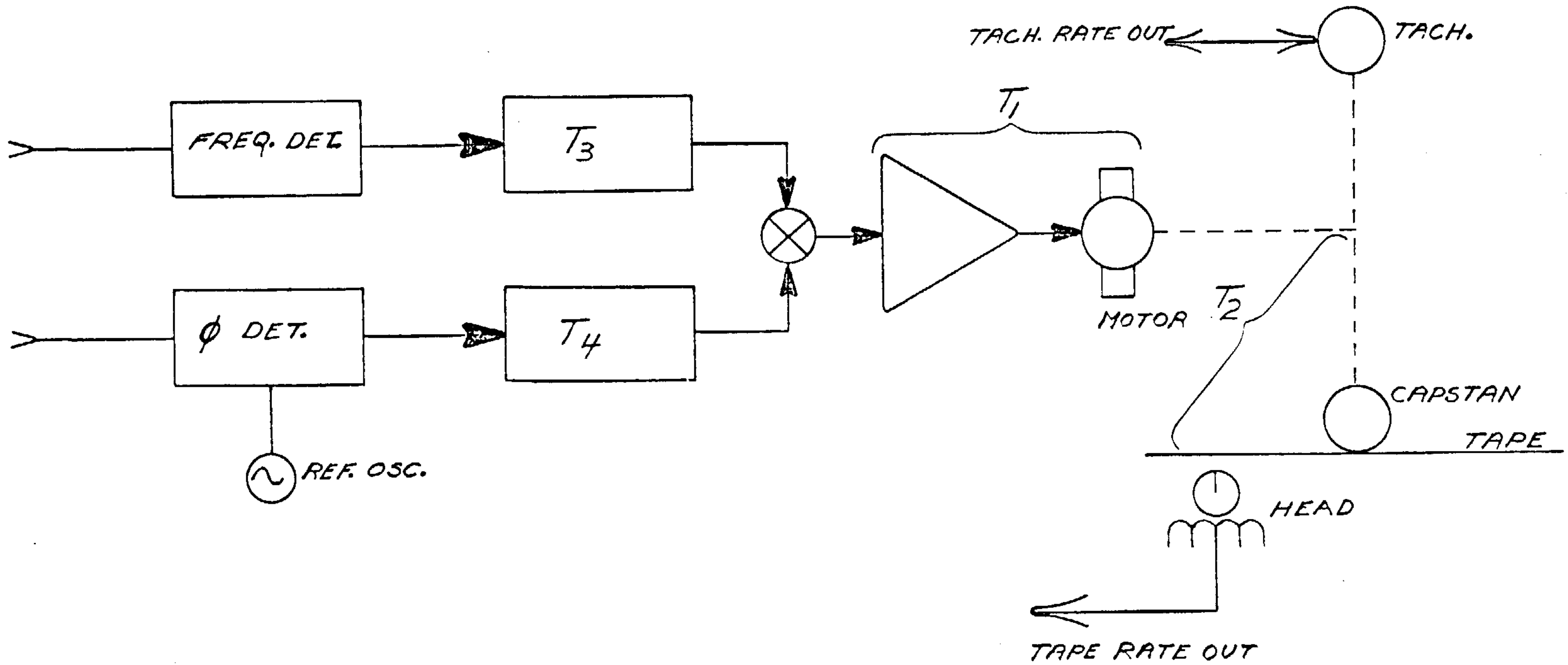

K+E SEMI-LOGARITHMIC 46 6013
4 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.
Start plus Stop Time Seconds
Tape Speed Inches/Second
Synchronous
Servo / 4600'
Servo / 550'

FIGURE 35

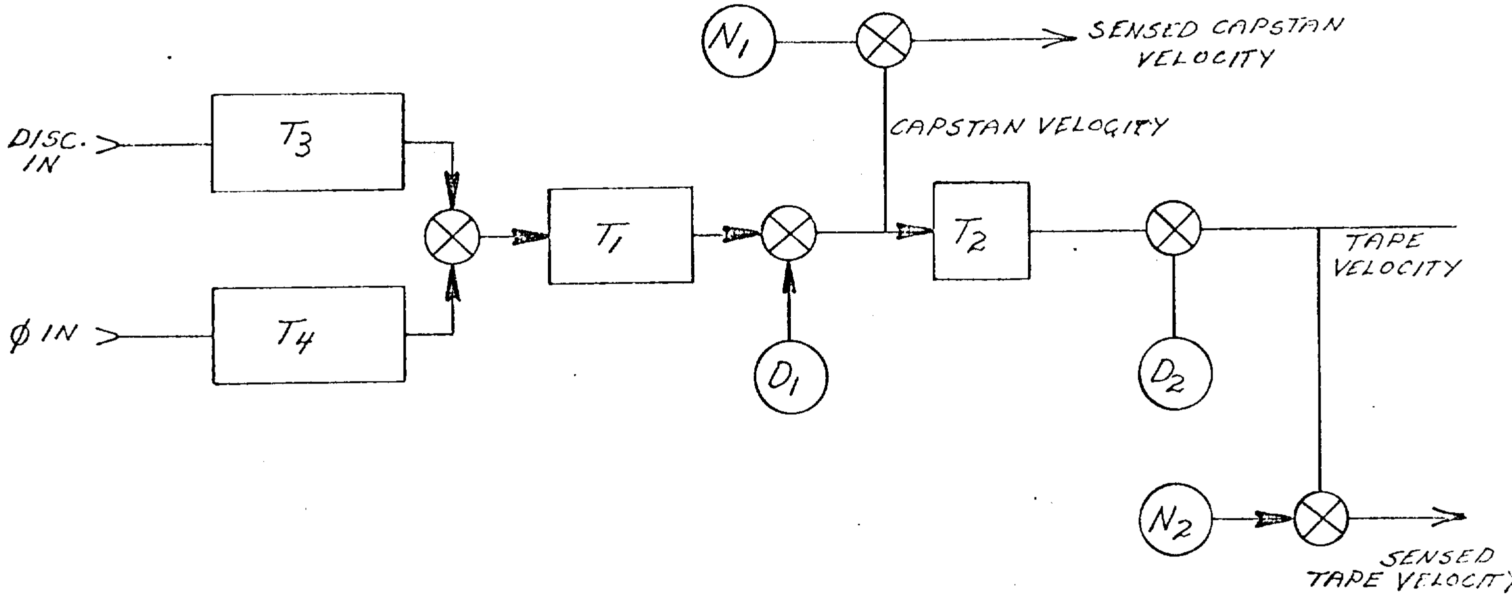


NOTE: $T_1 - T_4$ IDENTIFIED ON FIG. 37

FIGURE 36

Physical System Block Diagram

FIGURE 37



T_1 - Transfer from motor input to capstan velocity

T_2 - Transfer from capstan velocity to tape velocity

T_3 - Transfer from velocity of discriminator input to motor input

T_4 - Transfer from velocity of ϕ detector input to motor input

D_1 - Velocity disturbances to capstan motion

D_2 - Velocity disturbances to tape motion

N_1 - Noise added to capstan velocity signal

N_2 - Noise added to tape velocity signal

V_c - Velocity of capstan

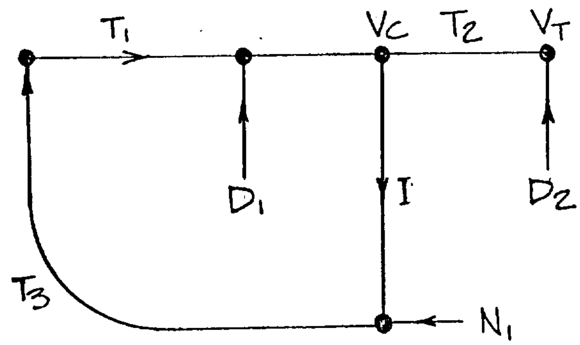
V_T - Velocity of tape

These symbols refer to Figures 36 through 44 and to text.

Physical System Block Diagram With Disturbance

And Noise Sources

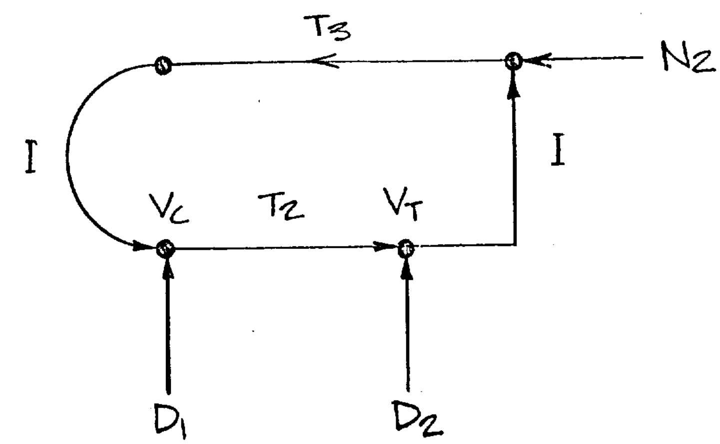
FIGURE 38



Signal Flow Graph Of System Connected For Tachometer,

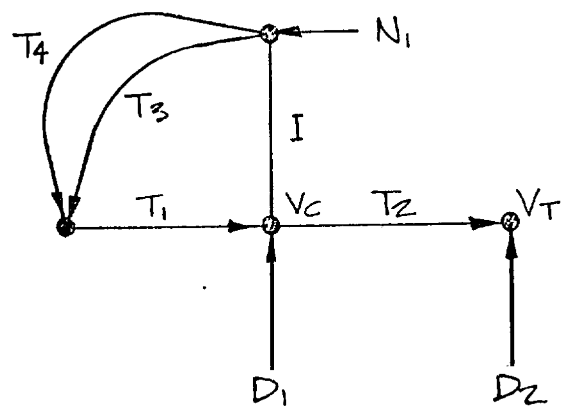
Frequency Lock Operation

FIGURE 39



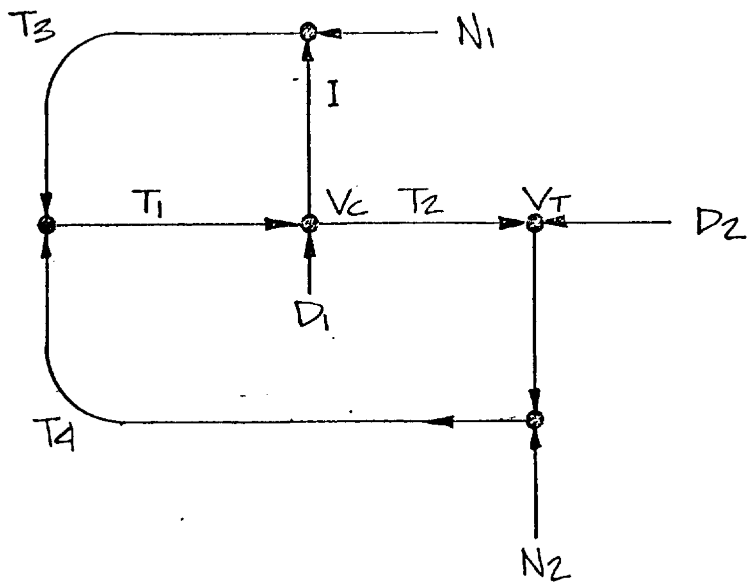
Signal Flow Graph Of System Connected For Frequency Lock To Tape

FIGURE 40



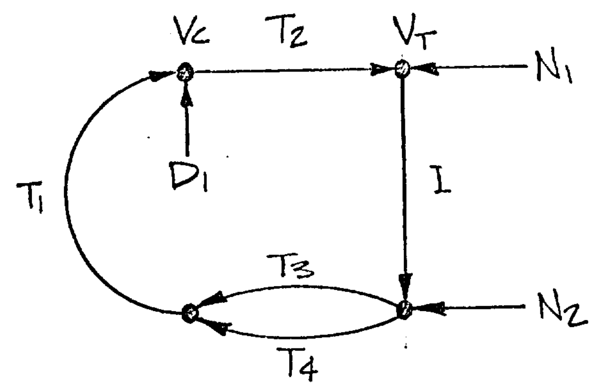
Signal Flow Graph Of System Connected For Ø Lock To Tachometer
And Frequency Lock To Tachometer

FIGURE 41



Signal Flow Graph Of System Connected For Ø To Tape
And Frequency Lock To Tachometer

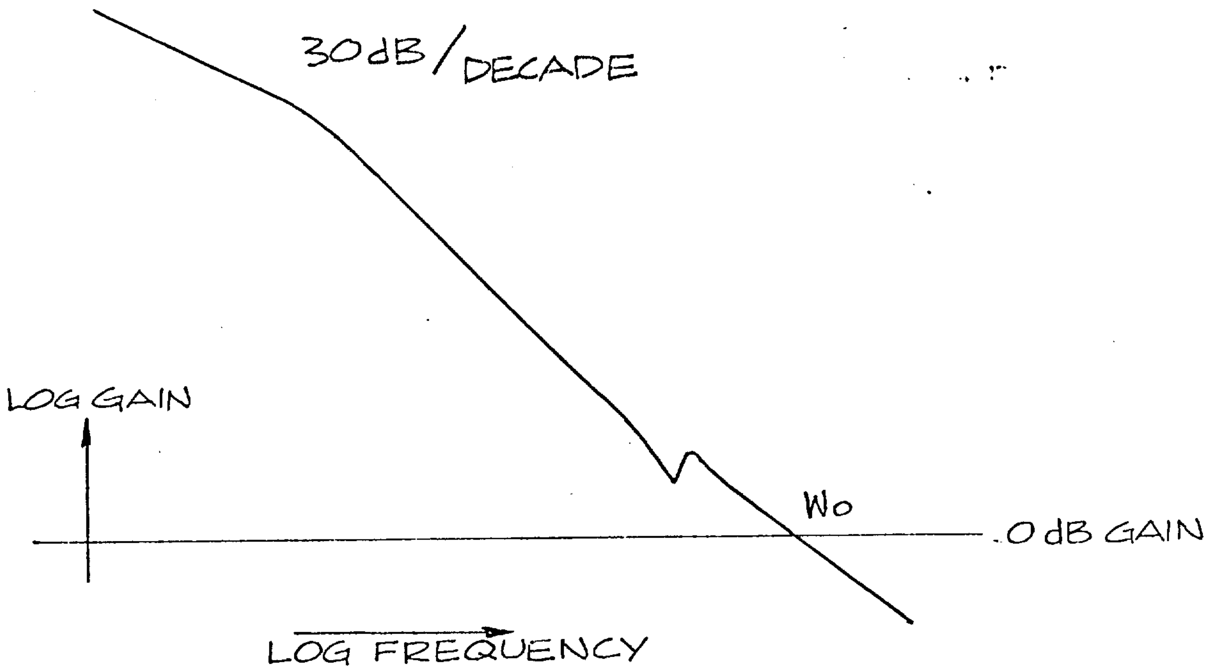
FIGURE 42

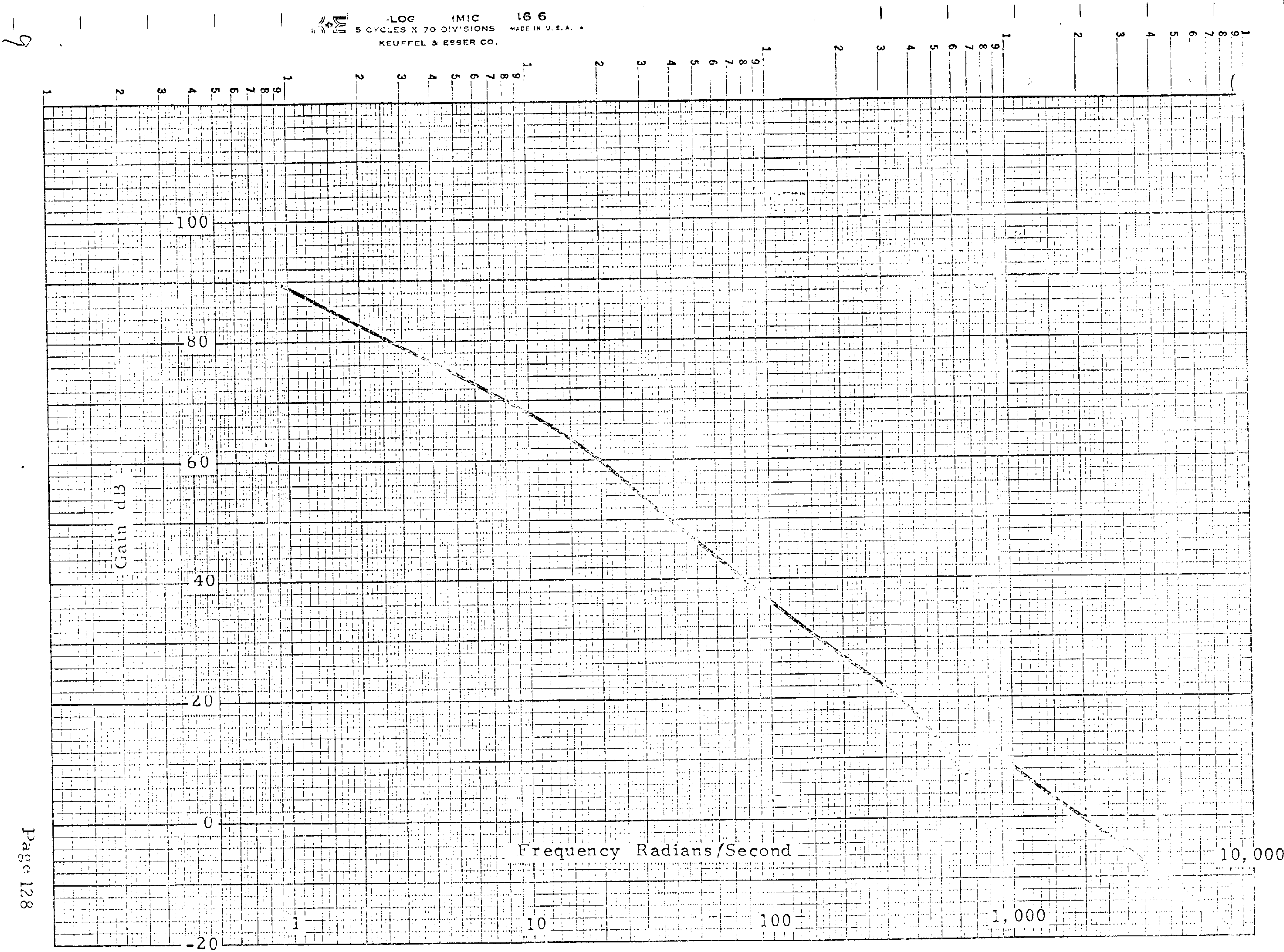


(This is the connection which holds flutter and TBE to a minimum)

Signal Flow Graph Of System Connected For Ø Lock To Tape, Frequency Lock To Tape

FIGURE 43





K&E
-LOGARITHMIC 46 6
5 CYCLES X 70 DIVISIONS
MADE IN U.S.A.
KEUFFEL & ESSER CO.
Gain dB
100
80
60
40
20
0
-20
Frequency Radians/Second
1
10
100
1,000
10,000

FIGURE 44

3.8 Reliability Consideration in Selection of Servo Control or Synchronous Drive Systems

3.8.1 Introduction

This section presents a comparison of the reliability potential of several typical tape transports using either a hysteresis synchronous motor or a torque (servo) motor as the power source. Reliability estimates are presented, which will permit tradeoffs to be made among such factors as: type of drive system (Servo or Hysteresis Synchronous) Record/Playback speed ratio, and operating time. In addition, some qualitative factors which have a tangible effect on achievable overall tape transport reliability are discussed.

3.8.2 Tape Transport Configuration Considered

Functional block diagrams of a typical servo driven tape transport and a comparable tape transport driven by a hysteresis synchronous motor are presented in Figures 45 and 46. Some of the important features and differences of the various transport configurations considered are summarized in Table XII.

Each of the elements of these systems is essential to the successful performance of the tape transport and the failure of any one or more of these major elements will cause the transport to either perform below its specified performance or to fail completely. Each of the major elements used in a tape transport are, therefore, functionally dependent and, for the purpose of reliability assessment, may be considered as part of a serial system. This is shown by the reliability block diagrams for the servo driven tape transport and the hysteresis motor driven tape transport in Figures 47 and 48 respectively. The reliability values of the various elements of the tape transports combine by the product rule as shown by the equation below Figures 47 and 48.

3.8.3 Failure Rate - Life Considerations

The reliability of each major element of the tape transports is a function of the failure rate (λ) of the parts which comprise the assembly and the time period (t) over which the tape transport is operated and, for some elements, the speed at which they are operated in the tape transport.

In estimating the reliability of each of the elements of the various tape transport configurations, the following assumptions have been made about their failure rates and life characteristics:

1. Electronic parts will have a failure rate which is constant with time, and will exhibit no wearout mechanisms or excessive drift that will affect performance of the tape transport. This is considered a valid and conservative assumption for high quality parts that are adequately derated and applied in accordance with good engineering practices. Table XIII shows the assumed derating levels and failure rate values used for the various generic classes of electronic parts.

2. Polyester film belts will have times to failure which are described by Weibull distribution. Belts will be derated in their application in the tape transport to stress ratios of 1.0 or less and as this stress level will have characteristic (mean) lives (α) of at least 10^9 cycles. For Iso-belt applications, the Weibull slope factor $\beta = 0.60$, and for all other belt applications, which do not involve reverse bending stresses, the slope factor $\beta = 1.4$. Belt life estimates are based on the data and methods of estimation given in Kinelogic Corporation Tape Recorder Belt Study Report, prepared for JPL.*

3. Bearing failure rates will be constant with time. Failure rates will be based on estimated bearing loads, speed, and load rating at operating speed, using the methods promulgated by the Anti-Friction Bearing Manufacturers Association (AFBMA). It is further assumed that bearing lubrication will be adequate for the intended operating life time, that the tape transport will be operated in a pressurized sealed container while operating in the space environment, and that the bearings will be applied in accordance with good design and workmanship practices; including adequate load derating.

---

*"Tape Recorder Belt Study, Final Report on Fatigue Life of Seamless Polyester and Polimide Film Belts", Kinelogic Corporation, Pasadena, California, 1965

4. The servo motor will have a life which is limited by the wear life of the brushes and commutator. The servo motor will have a characteristic life (α) of at least 10^8 cycles (does not include bearings) and the times to failure will be characterized by a Weibull distribution, with a slope $\beta = 1.5$; which denotes that the failure rate and, hence, the probability of failure increases with operating time. Achievement of the characteristic wear life is predicted on maintenance of a suitable environment in the pressurized recorder container during its useful life.

3.8.4 Servo Driven Tape Transports

The reliability of two, multi-speed, servo driven tape transports were evaluated for seven speed ratios in the range 900/1 to 7/1. One configuration utilized a complete phase lock speed control system and the other used a tachometer feedback, frequency discrimination speed control system. In all other aspects the tape transports were identical, as indicated by Table XII.

Table XIV contains a summary of the various electronic parts required for the phase lock and frequency discriminator servo systems. Table XX presents a summary of the failure rate of the servo electronics. The probability of failure of the electronic elements, as a function of operating time, is shown in Figure 49.

The servo motor has a characteristic life of 10^8 cycles as indicated in section 3.8.3. Table XXI presents a summary of the expected torque motor operating speeds and number of operating cycles per hour to achieve the indicated tape speed; assuming a $\frac{3}{4}$ inch tape capstan. Figure 50 shows the probability of servo motor failure as a function of cumulative operating cycles (revolutions) of the motor. As indicated in Table XXI, continuous operation of the torque motor for 6 months, at speeds above 200 rpm, will exceed the rated characteristic life of the motor brushes and will have a low probability of survival for this length of operation. Fortunately, the duration of the operating period at the higher operating speeds is short compared to the operating time at the lower operating speed. Table XXII presents the expected number of operating cycles in the high speed (record) and low speed (playback) mode for each of the 7 speed ratios considered. All speed combinations, except the 7/1 ratio (63/9 ips) have total operating cycles of 8 X 10^6 or less. The 7/1 ratio will accrue 1.35 X 10^8 cycles in 6 months which exceeds the characteristic life. The probability of survival for each speed combination is also shown in Table XXII. It will be noted that those speed combinations having 0.07 ips as the low speed have approximately the same number of total operating cycles and, hence, approximately the same probability of survival. This is also true of those speed combinations having a common 0.7 ips low speed. This results because the average speed of the machine is very close to twice the low speed used for playback. For the 63/9 ips (7/1 ratio) combination, the average speed is well above 9 ips and survival is low as a consequence.

The servo driven tape transport requires 26 ball bearings (this is similar to the Kinelogic ETM Recorder, less motor and speed reduction pulley, support bearings). The expected failure rate of the 28 bearings as a group adjusted for recorder tape speed, is summarized in Table XXIII. Figure 52 shows a plot of the overall probability of bearing failure, as a function of operating time, for the various tape transport operating speeds. Using the appropriate operating duration at each speed for the 7 speed ratios, the probability of failure, as a function of time, was developed for the various speed ratios as shown in Figure 52. Table XXIV shows the probability of survival of the bearings as a group for 6 months of operation for each of the 7 speed ratios.

The Servo driven tape transport used two polyester film belts, one to interconnect the two capstans to provide proper tape tension and the Iso-Elastic belt (Iso-belt) which turns at the same speed as the tape. The number of operating cycles per hour for each of these belts, at the six discrete record speeds considered, are tabulated in Table XXV. Based on the characteristic life and Weibull slope factors for each type belt application, Figure 53 and 54 were prepared which show the probability of belt failure, as a function of recorder tape speed and number of operating cycles. (The data in Figure 53 and 54 are also used for the hysteresis synchronous motor driven recorder to be discussed in a subsequent section). Using the appropriate operating duration at each speed for the 7 speed ratios, the probability of survival for 6 months for each belt type was determined and is summarized in Table XXVI. As with the bearings, the probabilities of survival associated with the 0.07 ips and 0.7 ips speed ratios each tend to be of approximately equal value. As indicated by Table XXVI the 63/9 ips combination has less than a 50% chance of survival for 6 months of operation.

Using the data developed for the various element groups of the servo driven tape transport, the overall probability of survival as a function of operating time, operating speed combinations, and type of speed control electronics is presented in Table XXVII. This data also shows that, at a given time, the probability values for all speed combinations having the same low speed value are nearly equal. Figure 55 presents a plot of a typical set of values for each speed range.

3.8.5 Hysteresis Synchronous Motor Driven Tape Transport

The reliability of three basic tape transport configurations using dual speed hysteresis shnchronous motors were evaluated for the seven speed ratios in the range 900/1 to 7/1 to provide a basis of comparison with the servo drive system discussed in Section 3.8.4. For speed combinations of 63/.07, 30/.07 and 15/.07 ips it was necessary to use three stages of speed reduction to achieve the 0.07 ips speed with reasonable pulley sizes. Likewise, for the 63/0.7, 30/0.7 and 15/0.7 ips speed combinations, it was necessary to use 2 stages of speed reductions to achieve the 0.7 ips speed. The 63/9 ips combinations were achieved in a single pass speed reduction for each speed. The belt diagrams and resulting motor, pulley and capstan speeds are shown below the tabulation in Table XXVIII.

As shown in Table XXVIII, motor speed combinations of 12000/1500 rpm (8/1 ratio) would be used for the 63/.07, 63/0.7, 63/9, 30/.74, 30/.07 ips speed combinations. For the 15/.07 and 15/.7 ips combinations, a dual wound motor of 6000/1500 rpm would be used. A duplex, magnetically activated clutch would be used in conjunction with each speed reduction system to couple the driven capstan to the proper speed reduction train. the dual speed motor (less bearings) has a failure rate of 0.60%/1000 hours. The duplex clutch has an assumed failure rate of 0.15%/1000 hours. Both of these numbers are consistant with data given in MIL Handbook 217 and also, the FARADA data on failure rates of mechanical and electromechanical devices. The probability of failure of the motor and clutch as a function of operating time is given in Figure 56.

Table XXIX contains a summary of the various electronic parts required for the hysteresis synchronous motor drive system. A summary of the failure rates for the electronic parts listed in Table XXIX are presented in Table XX. The probability of failure, as a function of operating time, of the electronics required for the Hysteresis Synchronous drive system is shown in Figure 49.

The Hysteresis Synchronous drive system requires 30 to 34 bearings depending on the speed ratio used. The expected failure rate, assuming for a worst case that 34 bearings would be used at each speed, is tabulated in Table XXI. Figure 57 shows a plot of the overall probability of bearing failure, as a function of operating time, for the various tape transport operating speeds. Using the appropriate operating duration for each speed for the speed ratios considered, the probability of failure as a function of operating time was developed for the various speed ratios and is shown in Figure 58. Table XXXI contains a tabulation of the probability of survival of the bearings for 6 months of operation for each of the speed combinations. The high reliability values indicated in Table XXXI justifies the simplifications that were achieved by assuming a worst case number of bearings at all speeds. As will be discussed in more detail under belts, all of the bearings are operating in both the high and low speed modes, and this has been considered in the probability of survival calculations.

3.8.6 Belts

The Hysteresis Synchronous drive system uses the same two type polyester film belts used in the servo motor previously discussed. In addition the H/S drive uses 3 to 5 additional belts, depending upon the speed ratios, to achieve the same dual speed operation as the servo driven tape transport. The belt diagram for each of the three basic configurations required is shown in Table XXVIII. Table XXXII identifies the configurations used for each speed combination and shows the number of operating cycles per hour for each of the 6 basic speeds. As indicated in Table XXXII, all belts are assumed to be 12 inches long to achieve long belt life. Figure 59 shows the probability of individual belt failure as a function of operating cycles. Using the belt cycle data on Table XXXII in conjunction with Figure 59, and the belt cycle data in Table XXV, in conjunction with the belt failure probability data in Figures 53 and 54 for the capstan and Iso-Elastic belt, which are identical to that used for the servo systems, Figure 60 was prepared. This shows the overall probability of failure as a function of speed range operating time for the Iso-Elastic belt, and all other belts combined that are used in the Hysteresis Synchronous motor driven tape transport. The probabilities of survival for 6 months of individual belts and for all belts combined that are used in the various configurations is tabulated in Table XXXIII. As was indicated by the belt and bearing results for the servo system previously, the probabilities of survival for all speed combinations having the same low speed value were essentially equal. This results from the fact that the average speed is approximately the same in each such case. It should be noted that all of the belts are rotating in both the high and low speed operating modes. When in the high speed mode the low speed belts are rotating at approximately 4 to 8 times the speed at which they operate at low speed. It has been assumed in estimating belt life that the belts will fatigue at the same rate whether they are transmitting normal operating torque or whether they are idling at high or low speed. Total operating cycles have been used in estimating the probability of failure of each type belt which are presented in Table XXXIII.

Using the data developed for the various element groups of the several Hysteresis Synchronous driven tape transport configurations that have been considered, the overall probability of survival as a function of operating time and operating speed combinations is presented in Table XXXIV. This data, like that for the servo system in Table XXVII, shows that, at a given time, the probability of survival values for all speed combinations having the same low speed value are nearly equal. The data in Table XXXIV has been plotted on Figure 55, to permit direct comparison with the servo drive systems considered in Section 3.8.4.

3.8.7 Comparison of the Servo and Hysteresis Synchronous Drive Systems

The reliability time profiles shown in Figure 55 for the servo and H/S drive systems show that for speed combinations having low speeds of .07 the Frequency Disc Servo-system is superior for the entire 6 month period, while the phase lock servo system out-performs the H/S for times up to 3000 hours. Beyond 3000 hours to 4400 hours there is no distinguishable difference between the phase lock servo and the H/S drive.

At 0.7 ips the H/S system is slightly superior to the phase lock servo system for times greater than 500 hours of operation. The H/S system is also slightly better than the Frequency Discriminator Servo System in the time interval 1000 to 3500 hours.

For the 63/9 ips combination the H/S system is clearly superior for all operating times greater than 250 hours. This occurs primarily because of the rapid accumulation of operating cycles on the servo motor at these speeds.

In utilizing the data in Figure 55 to make trade-off decisions, it should be observed that while the data would appear to indicate that one drive system is superior to another over the whole operating mission period, or over parts of the operating mission period, the resolution of the data that is used to make these estimates is in many cases too coarse to distinguish between the small differences that have been observed between the H/S and Servo Systems at 0.7 and 0.07 ips. For the 63/9 ips combination the differences are distinct and real and clearly indicate a superiority of the H/S system for the longer mission durations. Consideration of wear-out factors and failure rate trends, with time, would tend to favor the Servo System for short operating missions, while the Hysteresis Synchronous System appears to closely equal the Servo System as operating time approaches 6 months.

The data developed for both the Servo and H/S systems indicates that, for the speed combinations having a common low speed of 0.07 ips, the reliability of both systems is limited by the reliability of the electronics subsystem.

The electronic elements constitute the bulk of the effective failure rate for these combinations. For the 0.07 ips combinations the effective failure rate of both the belts for the H/S system and the Belt and Servo Motor for the Servo system constitute about 60% of the total failure rate.

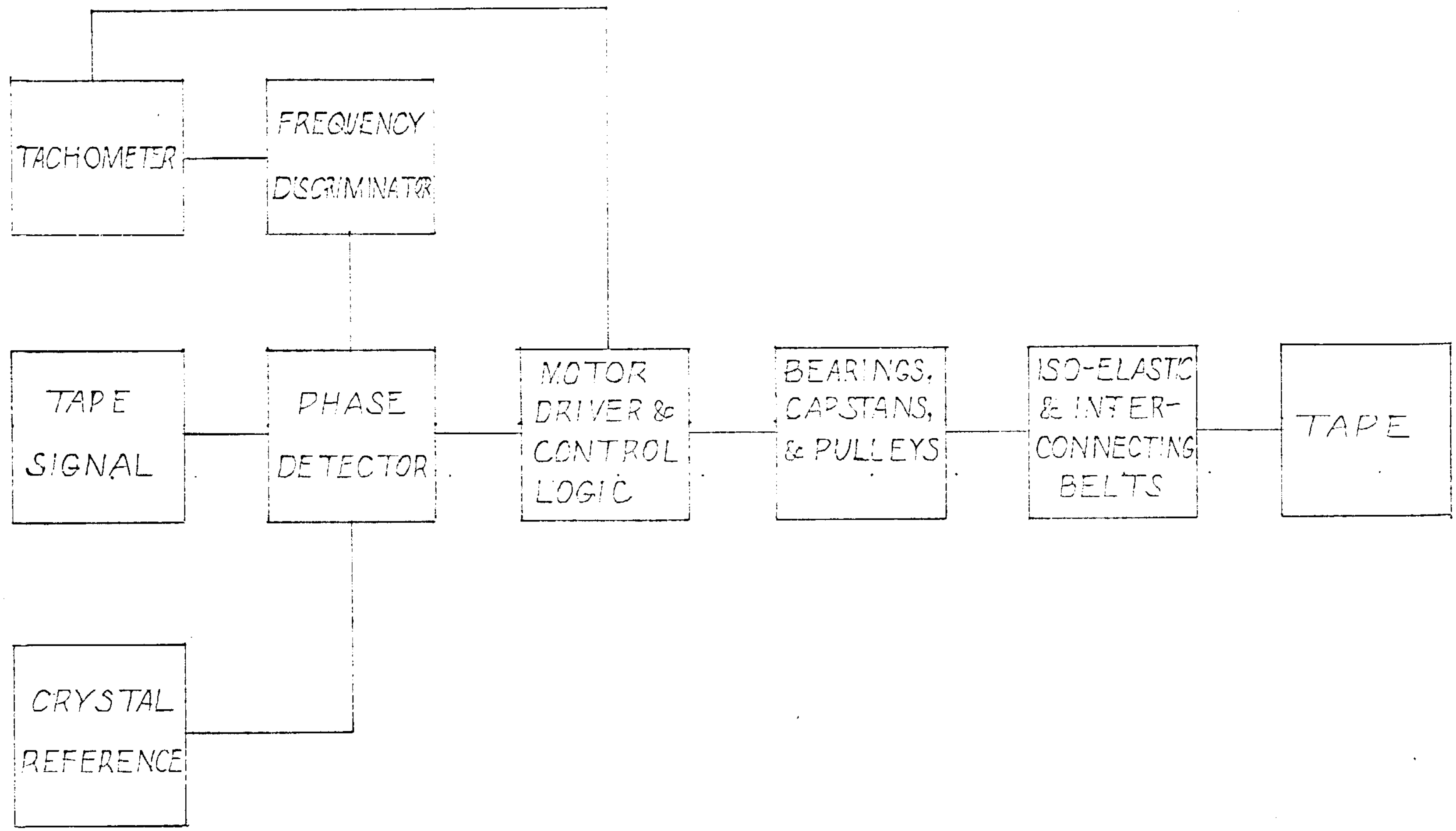
At 63/9 ips the effect of the electronics failure rate on the total reliability becomes insignificant as time increases.

This points up an area where the use of high reliability parts having failure rates lower than those given in Table XIII could make a significant improvement in the reliability that can be achieved for high speed ratio, low average speed tape recorders intended for long periods of operation in space environments.

3.8.8 Other Considerations

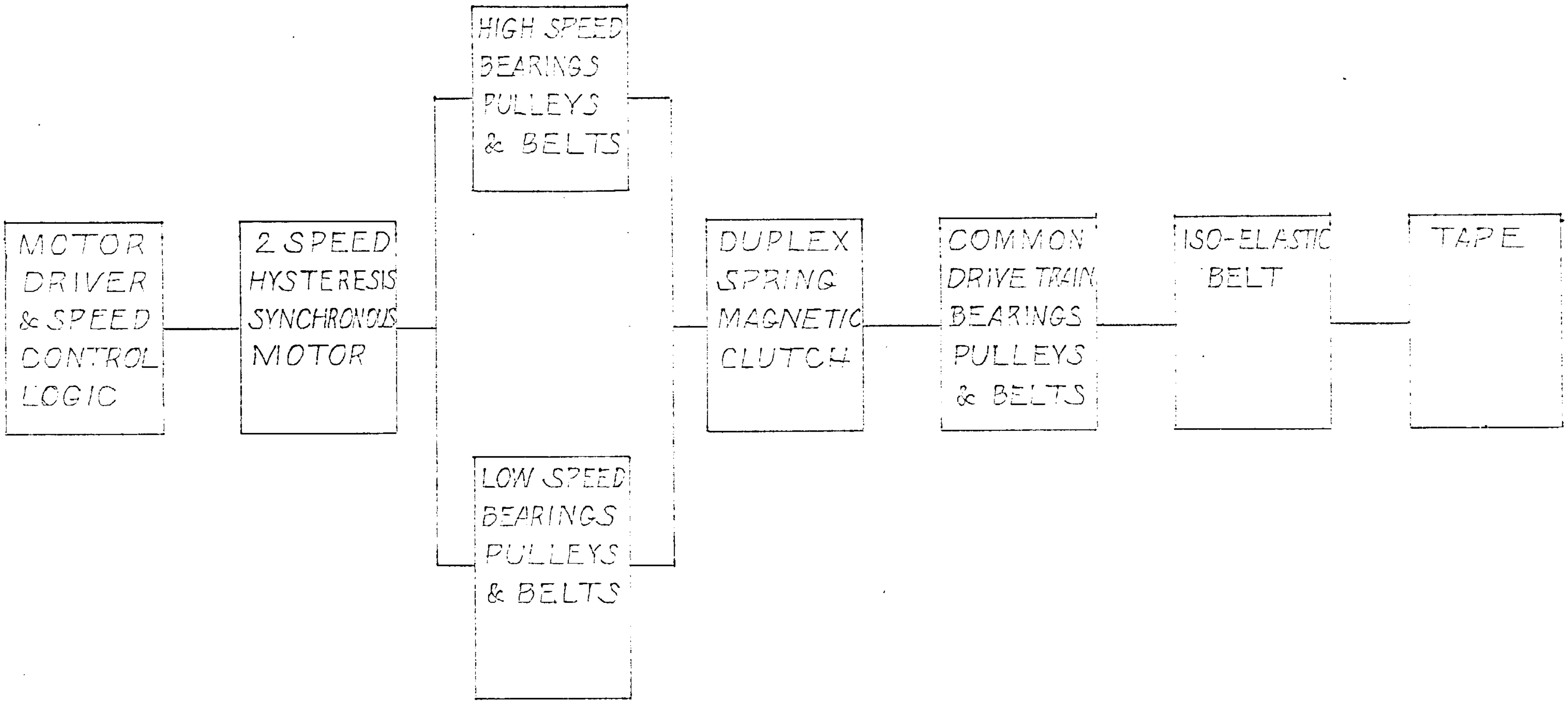
The factors which influence failure rates such as process controls, screening, application control, and environmental effects discussed in the earlier section on Data Electronics is also applicable here; although no general rule of thumb can be given for the improvement in reliability that results from a change in failure rate. For the .07 ips applications the reliability will increase by $(R)^{\frac{1}{2}}$ for a factor of two reductions in the overall failure rate of the electronics. For the higher speeds the change is less pronounced as the electronics constitute a smaller fraction of the total failure rate.

The lubricant used in most bearings of the type used in tape transports meets MIL-L-6085A. Kinelogic and others have successfully used this lubricant in a number of hermetically sealed space qualified recorders and other devices requiring low torque operations. MIL-L-6085A lubricants contain a rust inhibiting agent, which, in the presence of miosture, may cause an oxidation of the oil, resulting in the development of a gummy residue which may increase bearing torque loads to the point of failure. To prevent this oxidation from occurring, it would be desirable to completely dry the recorder of all moisture by an extensive purging of inert gas, heating or baking, or possibly, by degassing for a period of time at a low pressure sufficient to drive off the water vapor, but not low enough to affect the volatiles in the lubricant. From the viewpoint of lubrication longevity, it would be highly desirable to reduce moisture to the lowest possible value to minimize oxidation. Reduction of moisture to below 10% relative humidity, however, can produce an undesirable effect on overall recorder performance due to the generation of static electricity (Van De Graf effects). This may occur when the atmosphere is very dry and a charge develops on the polyester film belts. The optimum solution is a tradeoff among these two extremes.



TYPICAL PHASE LOCK CONTROLED SERVO DRIVEN MULTI-SPEED TAPE TRANSPORT

FIGURE 45



TYPICAL MULTI-SPEED TAPE TRANSPORT DRIVEN BY HYSTERESIS SYNCHRONOUS MOTOR

FIGURE 46

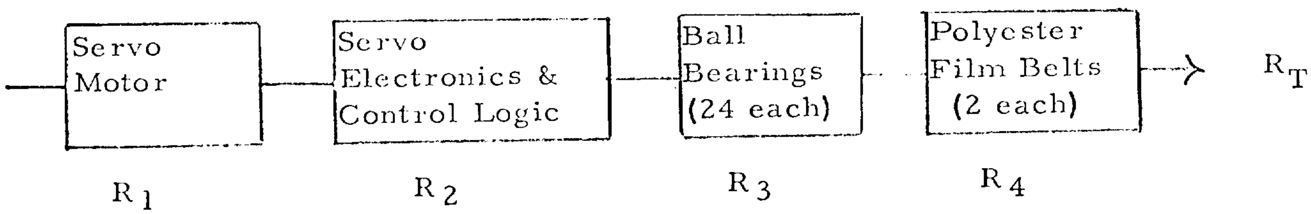
TABLE XII

COMPARISON OF IMPORTANT FEATURES OF SERVO DRIVEN AND HYSTERESIS SYNCHRONOUS DRIVEN TAPE TRANSPORTS

Feature	Servo Drive			Hysteresis Synchronous Drive		
Record/Playback Speed Ratio	63/.07 30/.07 15/.07	63/.7 30/.7 15/.7	63/9	63/.07 30/.07 15/.07	63/.7 30/.7 15/.7	63/9
Number of Polyester Film Belts	2 – 1 - Iso-Elastic Belt; 1 - Capstan Interconnect			7	6	5
Number of Ball Bearings	26			34	32	30
Type of Motor	Torque Motor with Brushes			2-speed Hysteresis Synchronous Motor		
Clutch	None Used			1 Magnetic Duplex Type		
Speed Control System	Crystal Controlled Phase Lock	Tachometer Feedback Frequency Discriminator System		R - C Controlled Frequency Inverter		
Number of Electronic Parts Used	458	311		477		

FIGURE 47

RELIABILITY BLOCK DIAGRAM OF TYPICAL SERVO DRIVEN MULTI-SPEED TAPE TRANSPORT

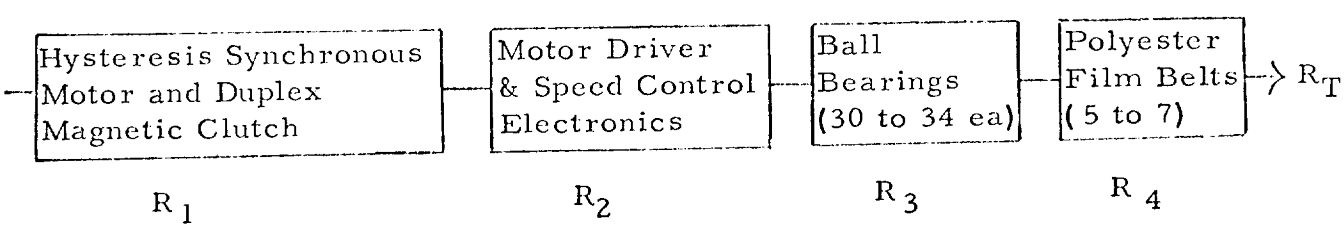


$$R_T = R_1 \bullet R_2 \bullet R_3 \bullet R_4$$

♦ ♦ ♦ ♦ ♦ ♦

FIGURE 48

RELIABILITY BLOCK DIAGRAM OF TYPICAL HYSTERESIS SYNCHRONOUS MOTOR DRIVEN MULTI-SPEED TAPE TRANSPORT



$$R_T = R_1 \bullet R_2 \bullet R_3 \bullet R_4$$

TABLE XIII

ELECTRONIC PART FAILURE RATE VALUES AND APPLICATION DERATING CRITERIA

Generic Part Class	Derating (maximum operating conditions)	Failure Rate (%/1000 hours)
Resistors, Fixed Carbon	< 50% Power	.00035
Capacitors, Ceramic	< 50% Voltage	.00070
Capacitors, Tantalum	< 50% Voltage	.030
Diodes, Signal	< 10% Power	.001
Diodes, Zener	< 40% Power	.010
Transistors, Signal Silicon	< 10% Power	.010
Transistors, Power, Silicon	< 25% Power	.100
Relays	< 25% Rated Contact Current	.100
Transformers & Inductors	< 100°C	.030
Potentiometers		.011
Connectors		.002/con + .001/pin
Transistors, Photo Sensitive		.050
Diodes, Ga. As.		.100
Thermistors		.03
Filter, Feedthrough		.005
Integrated Circuits (Flip Flop & Gates)		.02
Crystals		.002
Record Head (Per Track)		.018/Track

TABLE XIV

ELECTRONIC PARTS REQUIRED FOR SERVO DRIVE SYSTEM

	Resistors Carbon	Resistor Film	Capacitor Ceramic	Capacitor Tantalum	Diodes Signal	Diodes Zener	Transistors	Potentiometers	IC's	Crystals	Transformer	Connectors	Remarks
Motor Driver Assembly	46		3	2	6		17	1	5				
Frequency Disc Capstan Servo	22	9	6	2	2	1	10		1				
Phase Detector	29	10	11	3	3		16				1		Required only for Complete Phase Lock System
Crystal Reference	40		18		5		10			1			Required only for Complete Phase Lock System
EOT - BOT Sensor	14		2	2	8		4					50 pins	
EOT - BOT Flasher	12		2		4		5						
Command Logic	33		2	3	23	5	9						
Totals: Complete Phase Lock System	196	19	44	12	51	6	71	1	6	1	1	50	458
Totals: Frequency Discriminator System	127	9	15	9	43	6	45	1	6	0	0	50	311

TABLE XV

FAILURE RATE ESTIMATES FOR ELECTRONIC PARTS REQUIRED FOR VARIOUS DRIVE SYSTEMS

Part Type	Servo Drive System				Hysteresis Synchronous Drive	
	Phase Lock		Frequency Disc			
	Qty.	Failure Rate %/1000 hours	Qty.	Failure Rate %/1000 hours	Qty.	Failure Rate %/1000 hours
Resistor, Carbon	196	.0686	127	.0445	165	.0577
esistor, Film	19	.0190	9	.0090	7	.0070
apacitors, Ceramic	44	.0308	15	.0011	32	.0224
Capacitors, Tantalum	12	1.2000	9	.9000	7	.7000
iode, Signal	51	.0510	43	.0430	125	.1250
iode, Zener	6	.0600	6	.0600	7	.0700
Transistors	71	.7100	45	.4500	63	.6300
otentiometers	1	.0110	1	.0110	2	.0220
ntegrated Circuits	6	.1200	6	.1200		
Crystals	1	.0020				
ransformers	1	.0300			1	.0300
onnectors (pins)	50	.0600	50	.0600	50	.0600
EOT/BOT Sensors	(4)	.3000	(4)	.3000	(4)	.300
TOTAL		2.6624		1.9986		2.0241

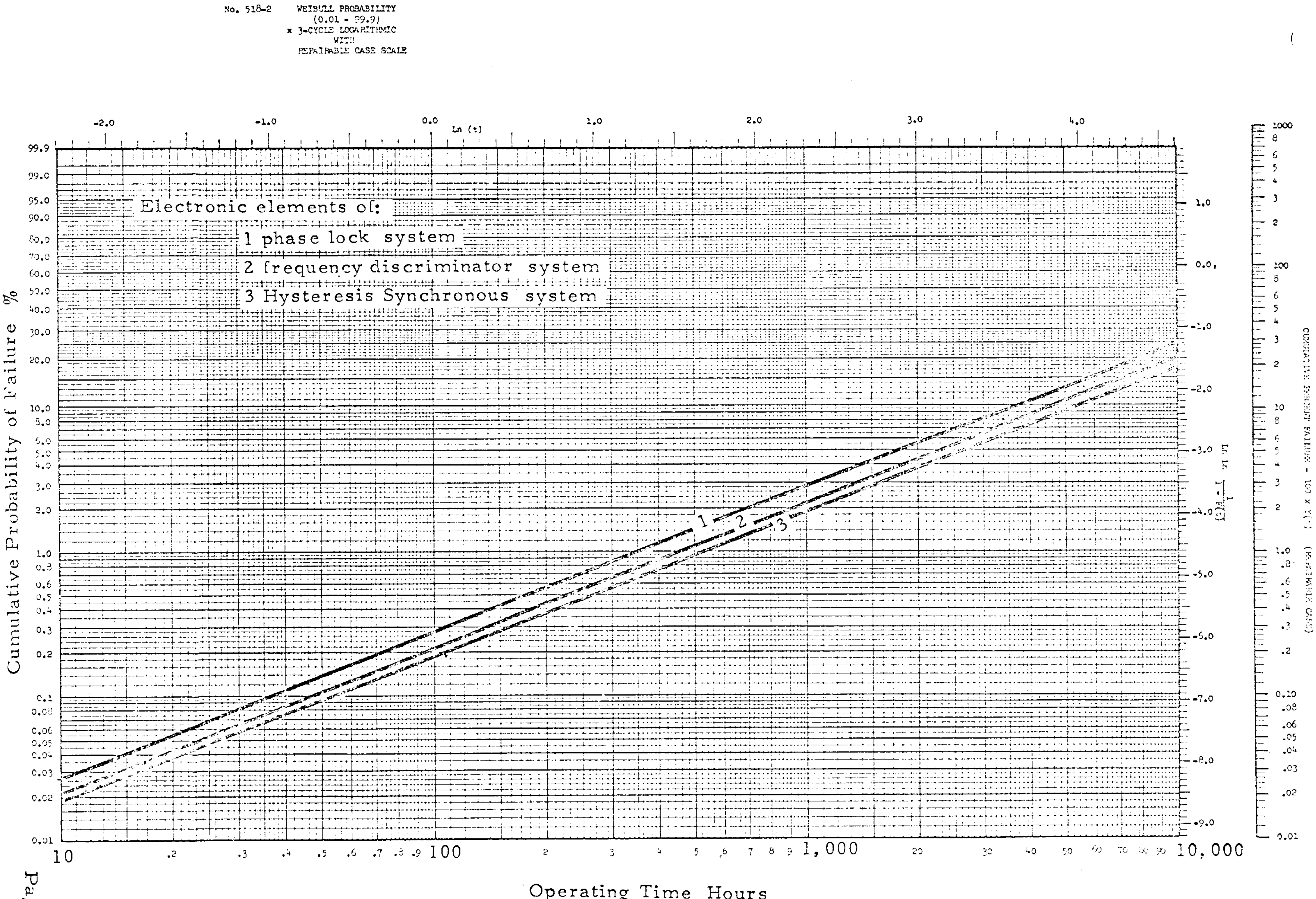

No. 518-2 WEIBULL PROBABILITY
(0.01 - 99.9)
x 3-CYCLE LOGARITHMIC
WITH
REPAIRABLE CASE SCALE
Ln (t)
Electronic elements of:
1 phase lock system
2 frequency discriminator system
3 Hysteresis Synchronous system
Cumulative Probability of Failure %
Operating Time Hours
1
2
3

FIGURE 49

TABLE XVI

SERVO MOTOR LIFE

Characteristic Life = 10^8 Cycles

Weibull Slope Factor = 1.5

WORST CASE OPERATING CYCLES

Tape Speed ips	Motor Speed rpm	Cycles per hour	Worst Case Number of Operating Cycles in 6 months of operation at indicated speed	Remarks
63	1410	84, 500	3.72×10^8 *	Continuous operation at any combination of these speeds exceeds rated life or will have low probability of survival.
30	670	40, 200	1.76×10^8 *	
15	335	20, 100	$.884 \times 10^8$ *	
9	200	12, 000	$.528 \times 10^8$ *	
.7	15.7	942	$.042 \times 10^8$	
.07	1.57	94.2	$.0042 \times 10^8$	

TABLE XVII

PROBABILITY OF SURVIVAL FOR EXPECTED NUMBER OF OPERATING CYCLES IN A TYPICAL SIX MONTH MISSION AT VARIOUS COMBINATIONS OF RECORD/PLAYBACK SPEEDS

Record/Playback Speed Combination ips	Expected Number of Operating Cycles in Six Months of Operation			Probability of Survival
	Record Mode	Playback Mode	Total	
63/.07	$.422 \times 10^6$	$.415 \times 10^6$	$.837 \times 10^6$	.99925
63/.7	4.22×10^6	4.11×10^6	8.33×10^6	.9770
63/9	59.8×10^6	75.3×10^6	135.1×10^6	**
30/.07	$.402 \times 10^6$	$.413 \times 10^6$	$.815 \times 10^6$	.99929
30/.7	4.02×10^6	4.06×10^6	8.08×10^6	.9775
15/.07	$.402 \times 10^6$	$.412 \times 10^6$	$.814 \times 10^6$	.99930
15/.7	4.02×10^6	3.97×10^6	7.99×10^6	.9780

**Exceeds characteristic life of motor.

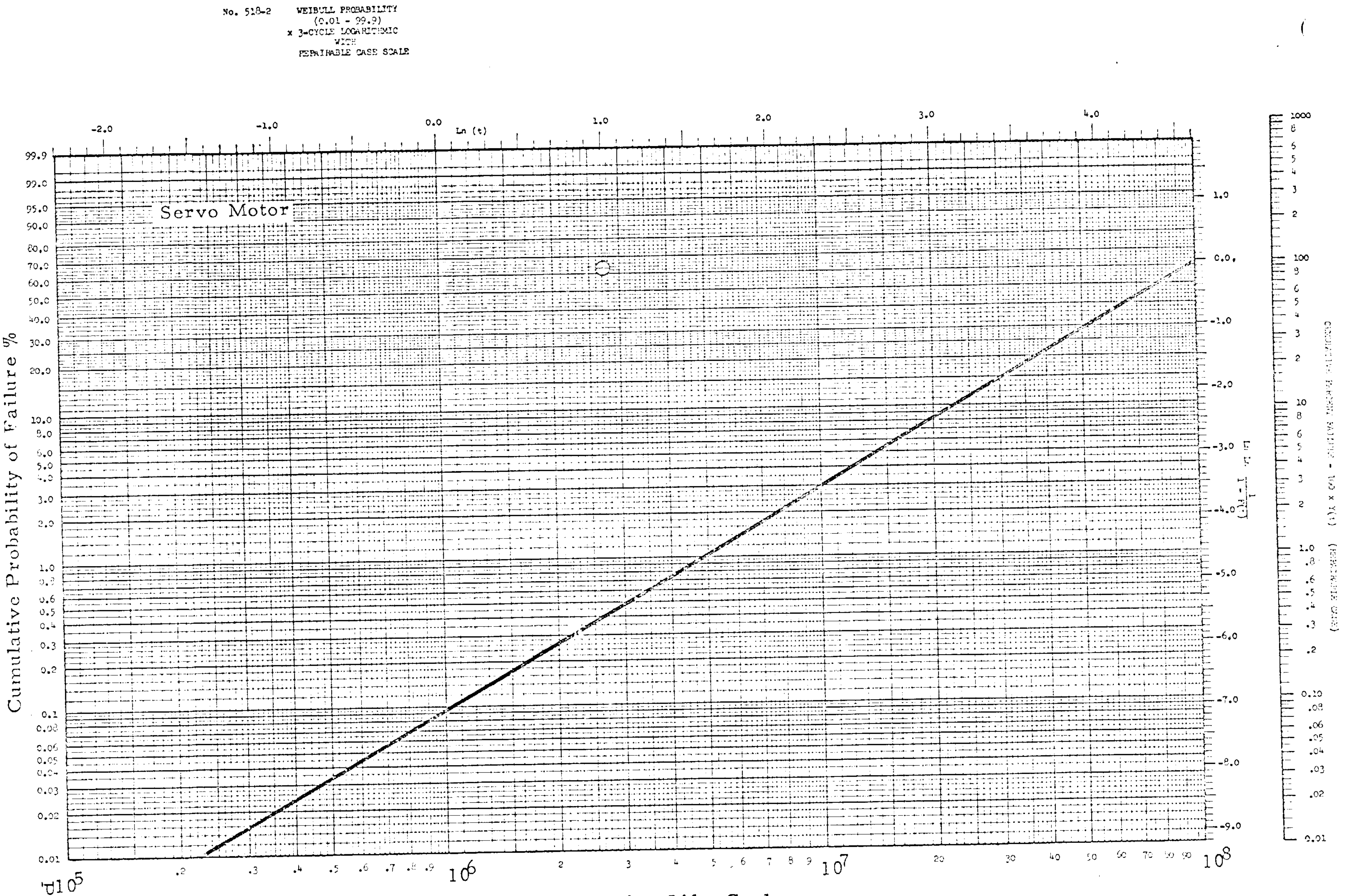

No. 518-2 WEIBULL PROBABILITY
(0.01 - 99.9)
x 3-CYCLE LOGARITHMIC
WITH
REPAIRABLE CASE SCALE
Servo Motor
Cumulative Probability of Failure %
Ln (t)
Operating Life Cycles

FIGURE 50

TABLE XVIII

DIRECT DRIVE SERVO SYSTEM

Bearing Failure Rates Adjusted for Recorder Speed

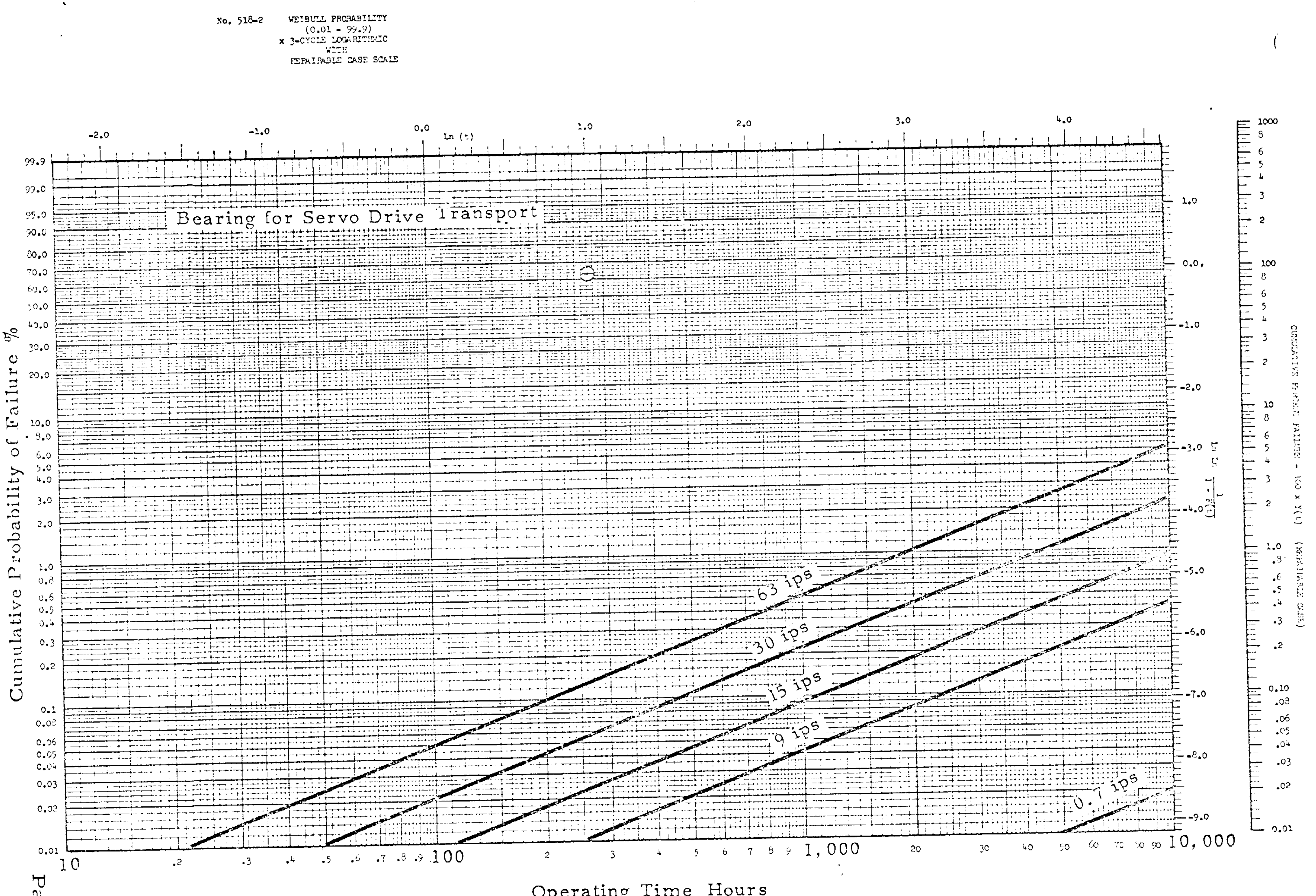
Recorder Speed (ips)	Qty. of Bearings	Total Failure Rate of 26 Bearings %/1000 hours
63	26	.500
30	26	.210
15	26	.091
9	26	.051
.7	26	.002
.07	26	.001

TABLE XIX

PROBABILITY OF BEARING SURVIVAL FOR SIX MONTHS OF OPERATION AT VARIOUS COMBINATIONS OF RECORD/PLAYBACK SPEEDS

Direct Drive Servo System

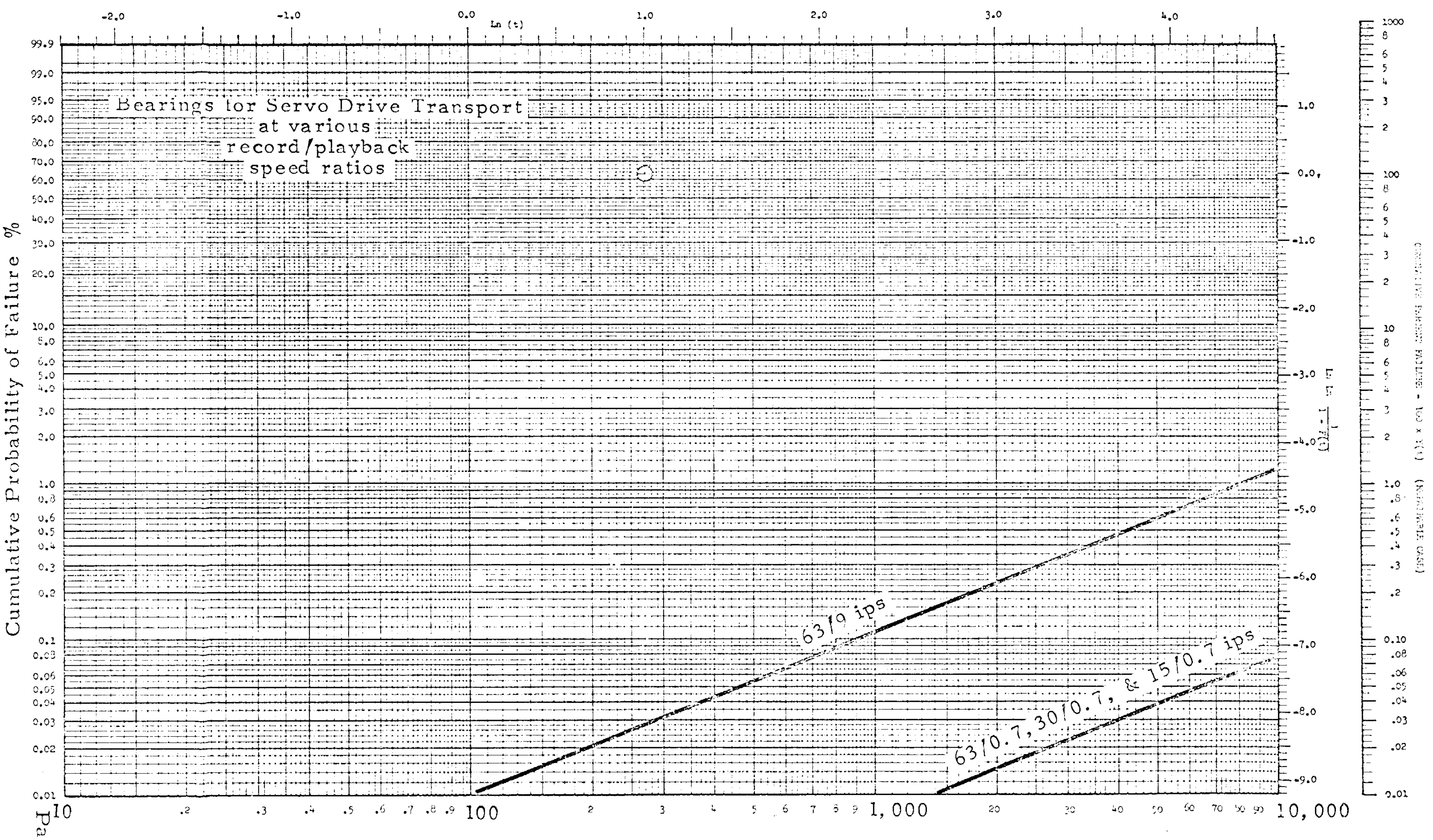
Record/Playback Speed Combination ips	Probability of Survival for 4400 hours.
63/.07	.999932
63/.7	.999663
63/9	.994840
30/.07	.999935
30/.7	.999704
15/.07	.999938
15/.7	.999734



No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE
Bearing for Servo Drive Transport
63 ips
30 ips
15 ips
9 ips
0.7 ips
Cumulative Probability of Failure %
Operating Time Hours
Ln (t)

FIGURE 51

No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE



63/0.07; 30/0.07 & 15/0.07 ips are all less than 0.01% at 10,000 hours

FIGURE 52

TABLE XX

DIRECT DRIVE SERVO SYSTEM

Belt Data

Tape Speed ips	Capstan & Torque Motor Speed rpm	No. of Belts	Belt Cycles Per Hour: Capstan Interconnect 6" Belt Length	Belt Cycles Per Hour: Iso-Elastic Belt 25" Belt Length	Remarks
63	1410	2	21,200	9000	Stress Ratios =
30	670	2	10,000	4300	1.0
15	335	2	5,000	2150	Median Life =
9	200	2	3,000	1300	$\sim 10^9$ cycles
.7	15.7	2	236	100	
.07	1.57	2	23.6	10	

TABLE XXI

DIRECT DRIVE SERVO SYSTEM

Probabilities of Belt Survival for Six Month Mission

Tape Speed Opn Mode Rec.	Tape Speed Opn Mode P/B	Rec/P/B Speed Ratio	Opn Time - Hours for Six Month Operating Mission Record	Opn Time - Hours for Six Month Operating Mission P/B	Probability of Belt Survival Record Mode Capstan Int.	Probability of Belt Survival Record Mode Iso-Belt	Probability of Belt Survival Playback Mode Capstan Int.	Probability of Belt Survival Playback Mode Iso-Belt	Total Probability of Belt Survival for 6 mos.
63	.07	900/1	5	4395	.9990	.988	.99983	.989	.97673
63	.7	90/1	50	4350	.9955	.950	.9956	.953	.8911
63	9	7/1	650	3750	.850	.780	.890	.790	.4665
30	.07	430/1	10	4390	.9992	.989	.99983	.989	.9780
30	.7	43/1	100	4300	.9956	.950	.9957	.954	.8995
15	.07	215/1	20	4380	.9992	.990	.99983	.989	.9781
15	.7	21.5/1	200	4200	.9960	.955	.9960	.955	.9050

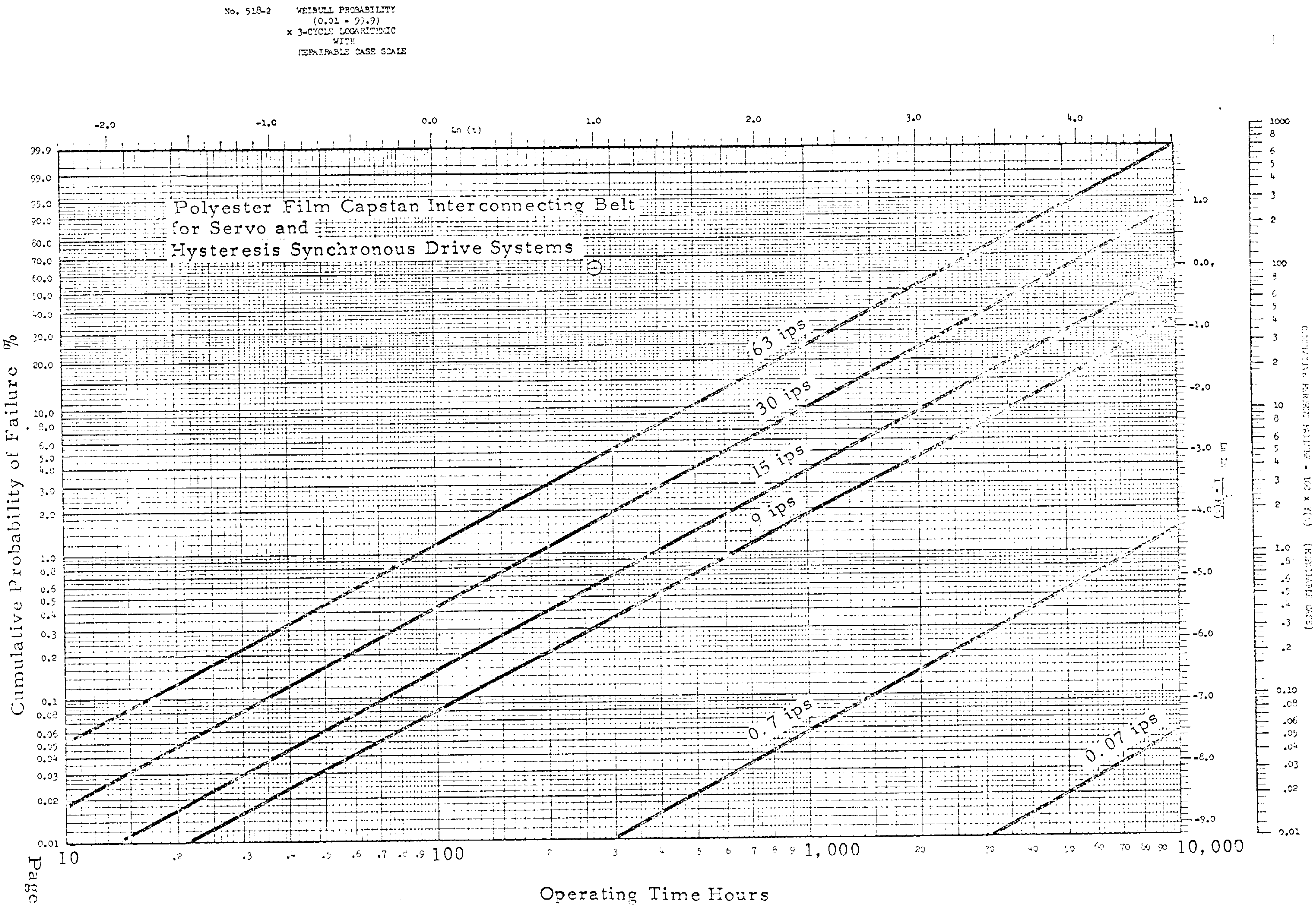

No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE
Polyester Film Capstan Interconnecting Belt
for Servo and
Hysteresis Synchronous Drive Systems
63 ips
30 ips
15 ips
9 ips
0.7 ips
0.07 ips
Cumulative Probability of Failure %
Operating Time Hours
Ln (t)

FIGURE 53

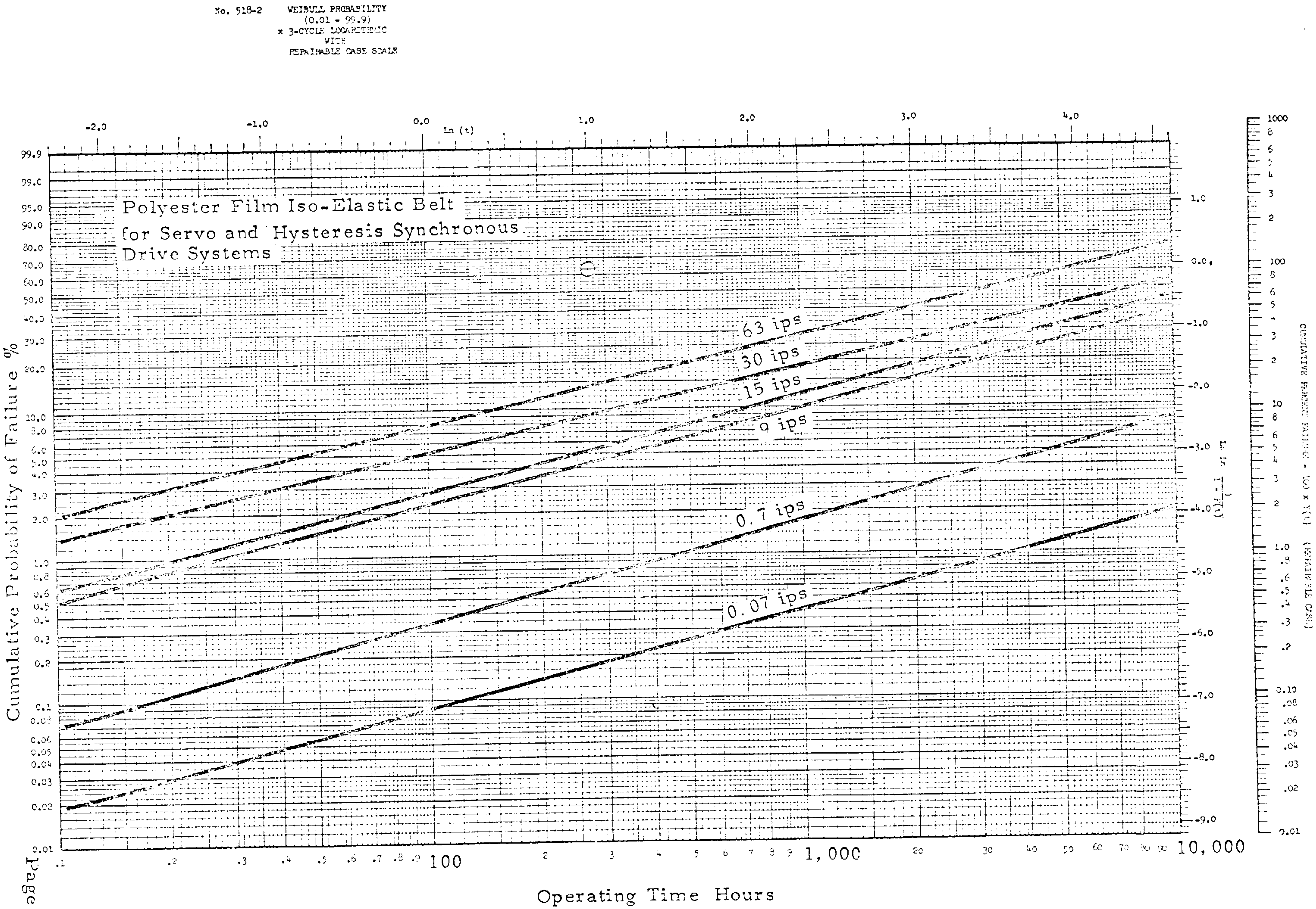

No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE
Polyester Film Iso-Elastic Belt
for Servo and Hysteresis Synchronous
Drive Systems
63 ips
30 ips
15 ips
9 ips
0.7 ips
0.07 ips
Ln (t)
Cumulative Probability of Failure %
Operating Time Hours
100
1,000
10,000

FIGURE 54

TABLE XXII

PROBABILITY OF SURVIVAL AS A FUNCTION OF OPERATING TIME FOR A TAPE TRANSPORT USING A DIRECT SERVO DRIVE HAVING VARIOUS RECORD/PLAYBACK SPEED RANGES

Record/Playback Speed Combination ips	Operating Time Hours 100	500	1000	2000	4000	
63/.07	.9975 (.998)	.987 (.990)	.9738 (.979)	.9380 (.956)	.8690 (.892)	Phase Cock Freq. Disc.
63/.7	.989 (.9895)	.958 (.961)	.9260 (.928)	.8310 (.839)	.7780 (.800)	
63/9	.953 (.953)	.800 (.803)	.6530 (.654)	.4510 (.4560)	.091 (.0925)	
30/.07	.9976 (.998)	.988 (.99)	.9738 (.979)	.9383 (.956)	.8692 (.892)	
30/.7	.990 (.991)	.960 (.963)	.9270 (.929)	.8340 (.8420)	.7820 (.804)	
15/.07	.9977 (.9981)	.989 (.99)	.9738 (.979)	.9390 (.957)	.8710 (.6893)	
15/.7	.992 (.9925)	.962 (.965)	.9286 (.930)	.8360 (.845)	.7880 (.810)	

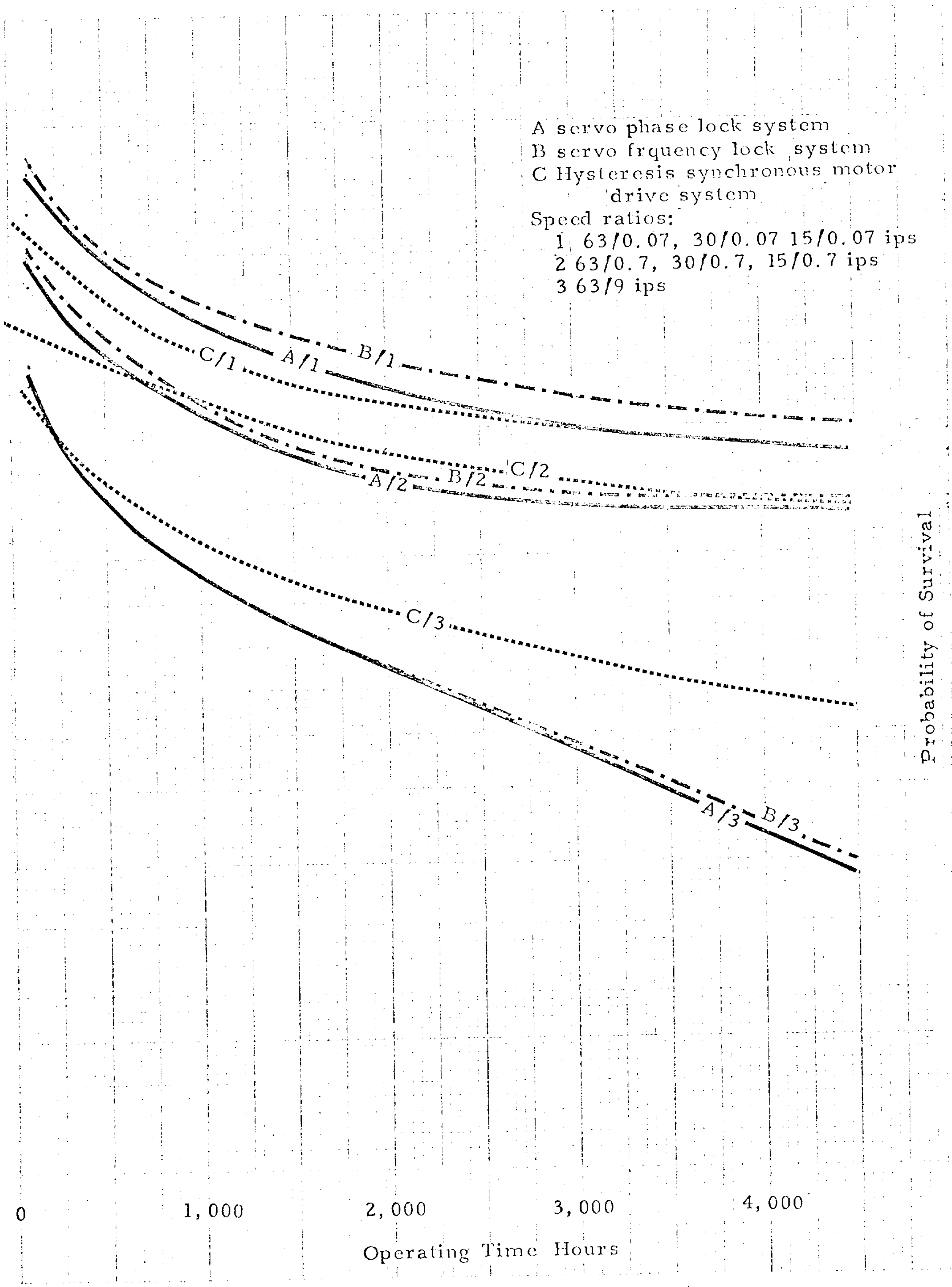

A servo phase lock system
B servo frquency lock system
C Hysteresis synchronous motor drive system
Speed ratios:
1 63/0.07, 30/0.07 15/0.07 ips
2 63/0.7, 30/0.7, 15/0.7 ips
3 63/9 ips
B/1
A/1
C/1
C/2
B/2
A/2
C/3
A/3
B/3
Probability of Survival
0
1,000
2,000
3,000
4,000
Operating Time Hours

FIGURE 55

TABLE XXIII

MOTOR, PULLEY & CAPSTAN BELT DIAGRAMS & SPEED DATA FOR HYSTERESIS SYNCHRONOUS DRIVE

Tape Speed ips	Motor Speed rpm*	Capstan Speed rpm	Diagram *	Bearing and Pulley Speeds rpm 1	2	3	4 (Capstan)
63	12000	1410	(1) (2) (3)			6000	1410
30	12000	670	(1) (2)			2860	670
15	6000	335	(1) (2)			1430	335
9	1500	200	(3)			850	200
.7	1500	15.7	(2)	317		67	15.7
.07	1500	1.57	(1)	247	40.7	6.7	1.57

* For speed combinations use diagrams below: Example for 63/.07 use Diagram (1); 63/.7 use Diagram (2); 30/.7 use Diagram (2)

Diagram (1)

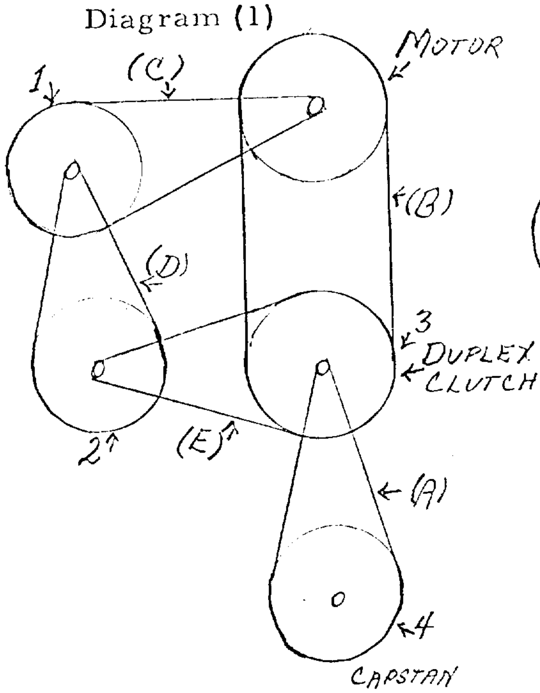


Diagram (2)

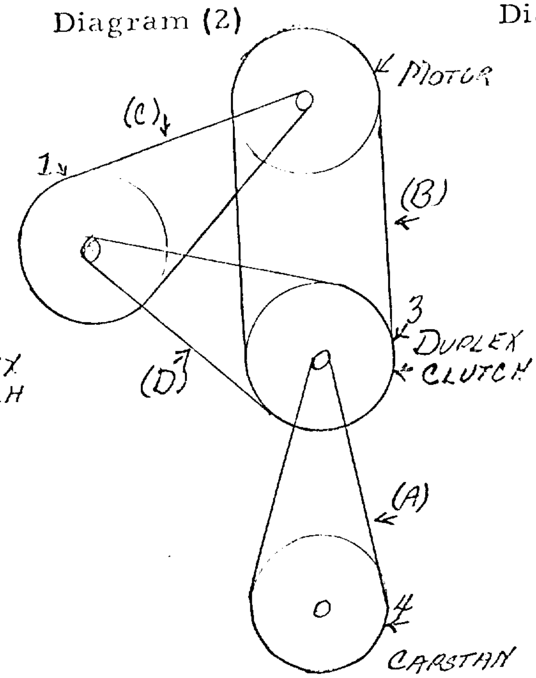
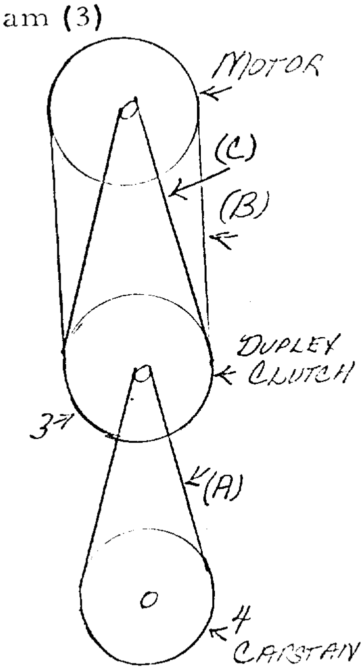
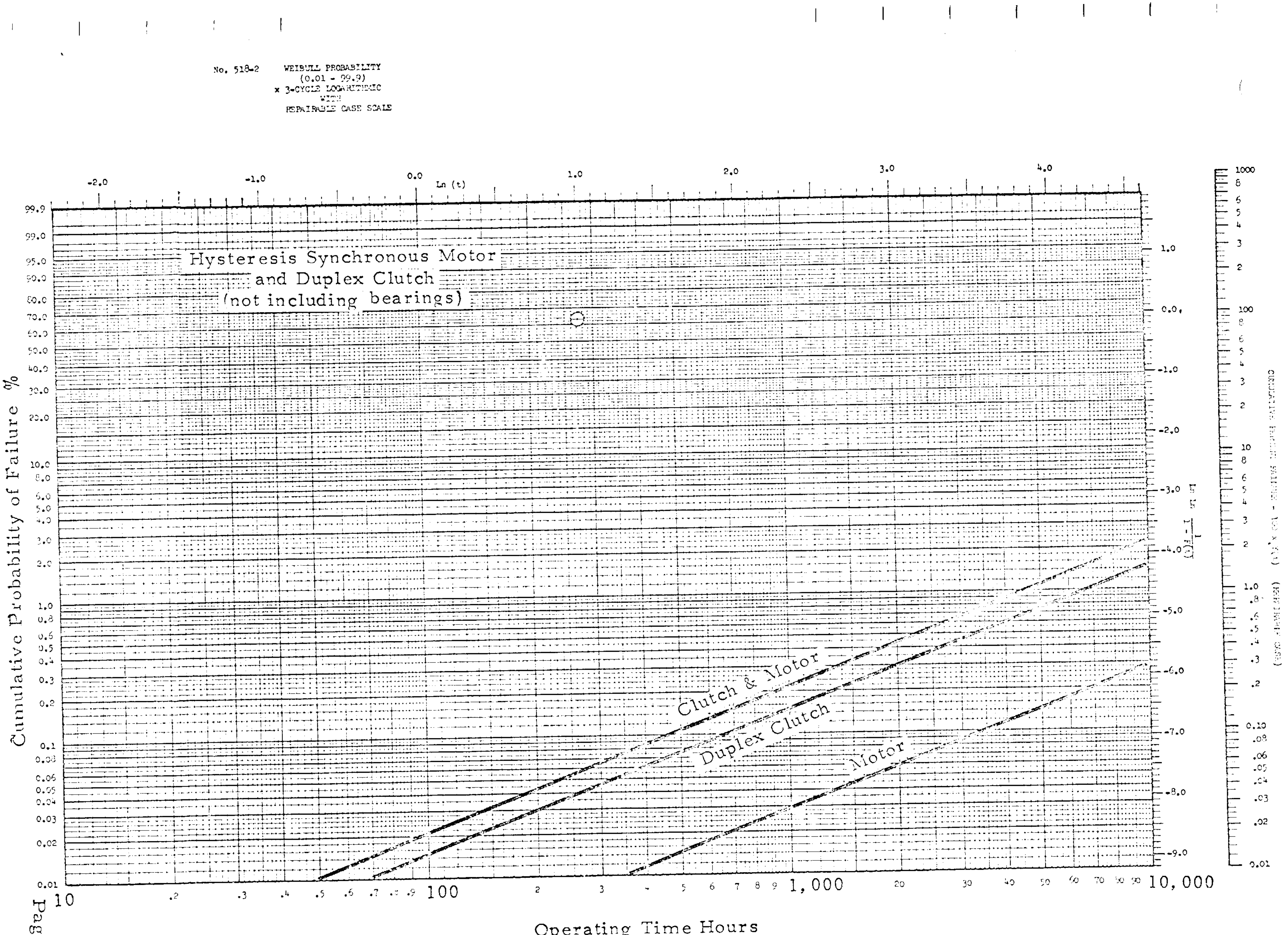


Diagram (3)



* Will be accomplished by varying frequency of power source and using dual wound motors.



No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE
Hysteresis Synchronous Motor and Duplex Clutch (not including bearings)
Clutch & Motor
Duplex Clutch
Motor
Cumulative Probability of Failure %
Ln (t)
Operating Time Hours

FIGURE 56

TABLE XXIV

ELECTRONIC PARTS REQUIRED FOR HYSTERESIS/SYNCHRONOUS DRIVE SYSTEM

	Resistor Carbon	Resistor Film	Capacitor Ceramic	Capacitor Tantalum	Diode Signal	Diode Zener	Transistors	Potentiometer	Connectors
Motor Driver Mother Board	1		2		2			2	50
EOT - BOT Monitor Assembly	14		2	2	8		4		
EOT - BOT Sensor Assembly	12		2		4		5		
Control Logic	33		2	3	23	5	9		
Inverter Clock	7	2		1	5	2	4		
Retard Module	16	1	6	1	11		5		
Phase Control Module	26		6		14		6		
Phase Power Regulator	20	4	4		14		10		
Inverter Driver	36		8		44		20		
Total	165	7	32	7	125	7	63	2	50

TABLE XXV

HYSTERESIS SYNCHRONOUS DRIVE SYSTEM

Bearing Failure Rate Adjusted for Recorder Speed

Recorder Speed ips	No. of Bearings	Total Failure Rate of 34 Bearings %/1000 hours
63	34 max.	.71
30	34 max.	.56
15	34 max.	.373
9	34 max.	.180
.7	34 max.	.0052
.07	34 max.	.0040

TABLE XXVI

PROBABILITY OF BEARING SURVIVAL FOR 6 MONTHS OF OPERATION AT VARIOUS COMBINATIONS OF RECORDER/PLAYBACK SPEEDS

Record/Playback Speed ips	Probability of Survival for 4400 hours
63/.07	.99979
63/.7	.99943
63/9	.9889
30/.07	.99977
30/.7	.99922
15/.07	.99975
15/.7	.99904

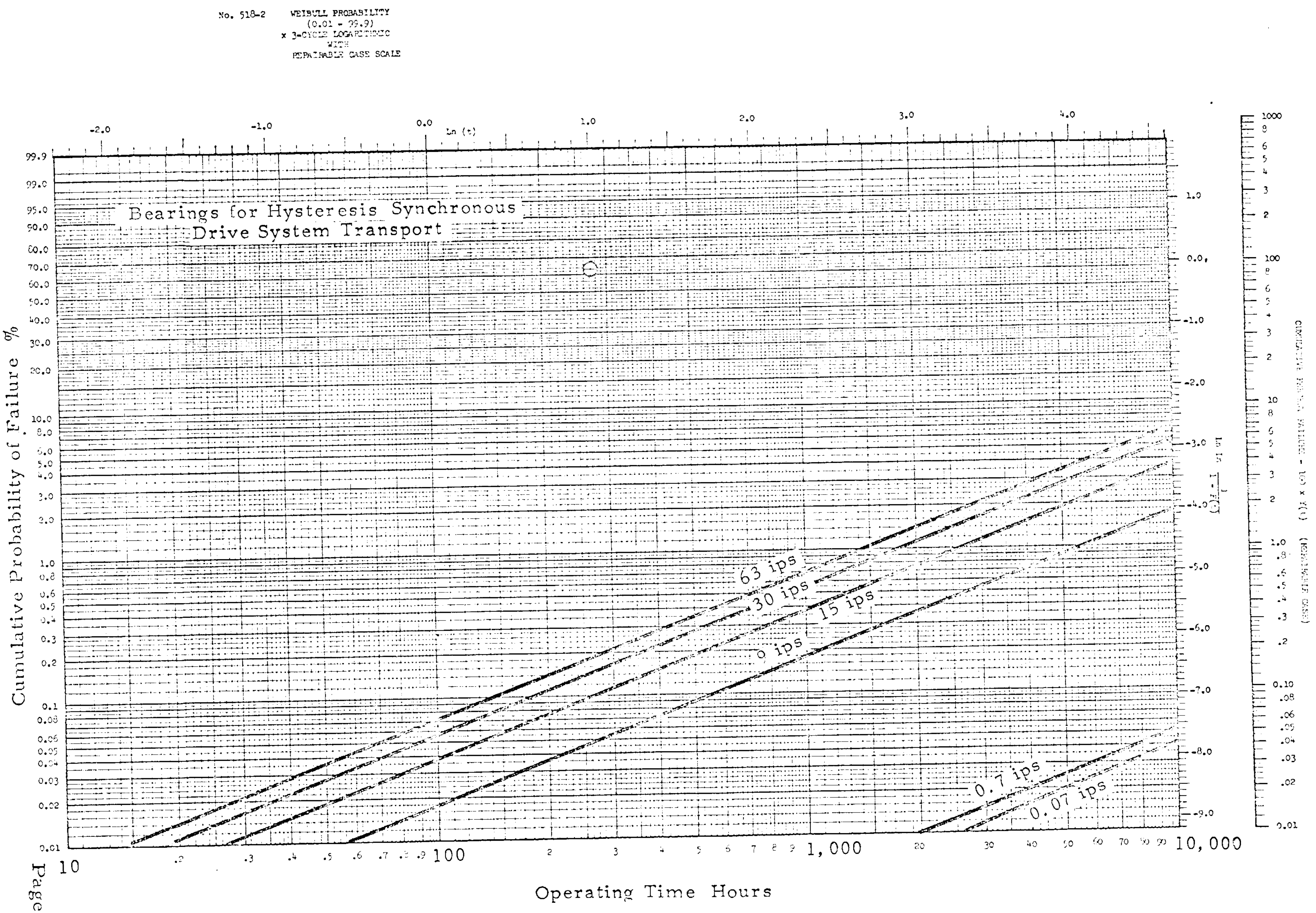

No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE
Bearings for Hysteresis Synchronous
Drive System Transport
63 ips
30 ips
15 ips
9 ips
0.7 ips
0.07 ips
Cumulative Probability of Failure %
Operating Time Hours
Ln (t)
10
100
1,000
10,000

FIGURE 57

No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE

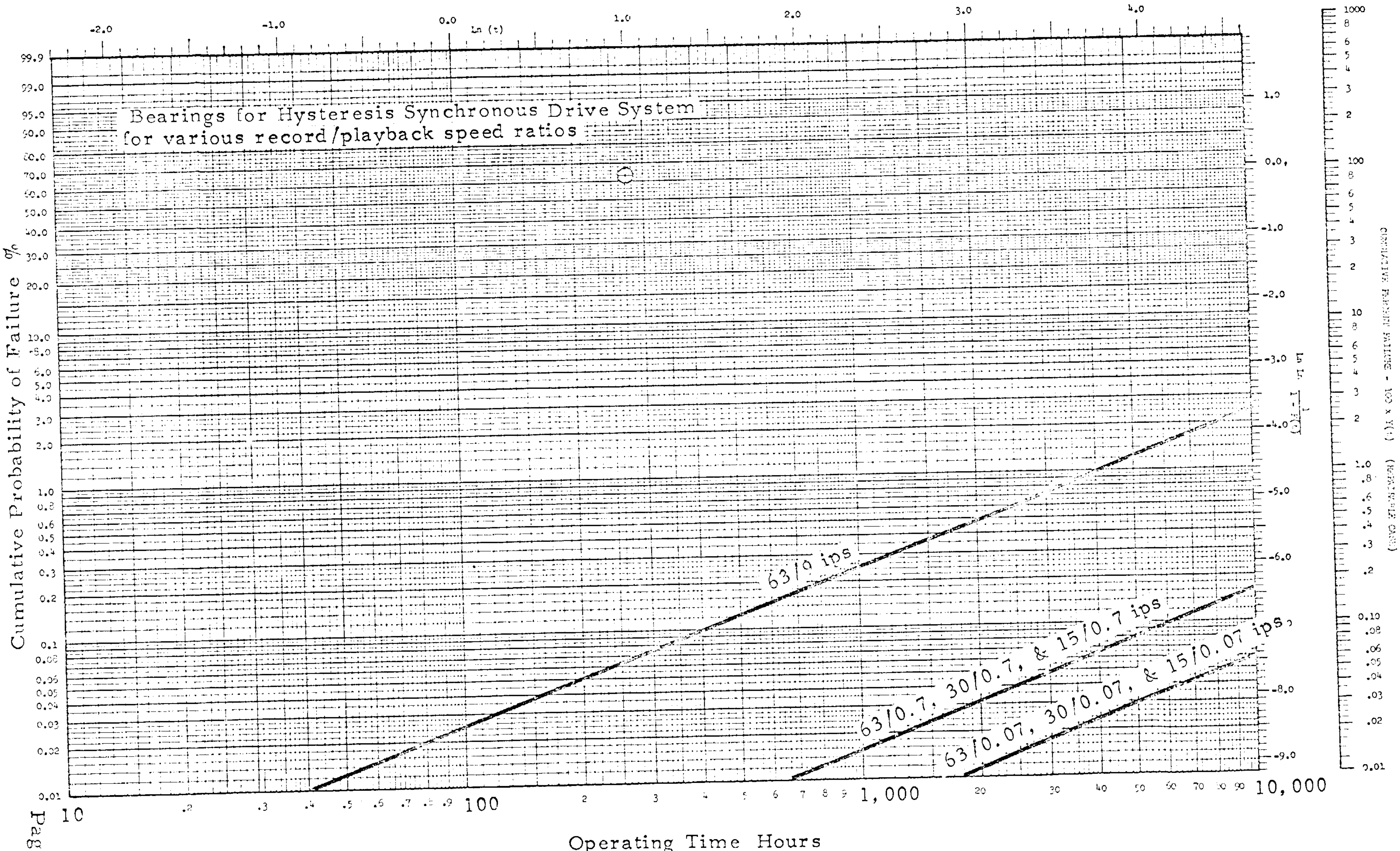


FIGURE 58

TABLE XXVII

HYSTERESIS SYNCHRONOUS DRIVE

Belt Cycles per Hour

ips	Belt A	Belt B	Belt C	Belt D	Belt E
63	21.2 K	45 K	45 K	7500	1250
30	10 K	45 K	45 K	7500	1250
15	5 K	22.5 K	22.5 K	3750	625
9	3 K	5.65 K	5.65 K		
.7	.236 K	5.65 K	5.65 K	950	
.07	.0236 K	5.65 K	5.65 K	950	150

Assume all belts 12 " long - stress ratio ≤ 1.0 median life = 1×10^9 cycles.

Belts Used for Different Speed Combinations

Speed Combination ips	Belts Used *
63/.07	A - B - C - D - E
63/.7	A - B - C - D
63/9	A - B - C
30/.07	A - B - C - D - E
30/.7	A - B - C - D
15/.07	A - B - C - D - E
15/.7	A - B - C - D

* Also uses the same Iso-Belt and Capstan Interconnect Belts used in Servo Drive

No. 518-2 WEIBULL PROBABILITY
(0.01 - 99.9)
x 3-CYCLE LOGARITHMIC
WITH
REPAIRABLE CASE SCALE

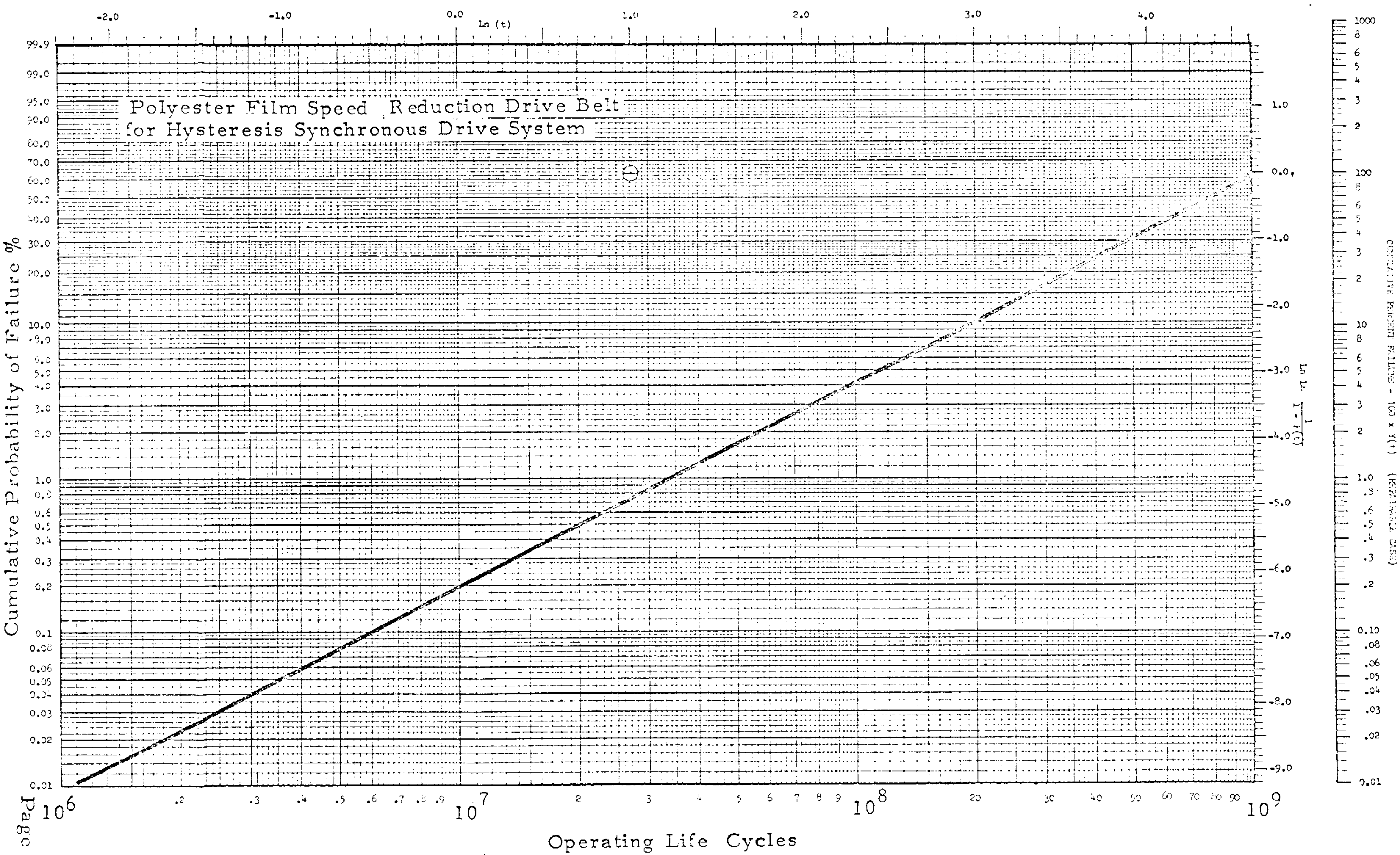


FIGURE 59

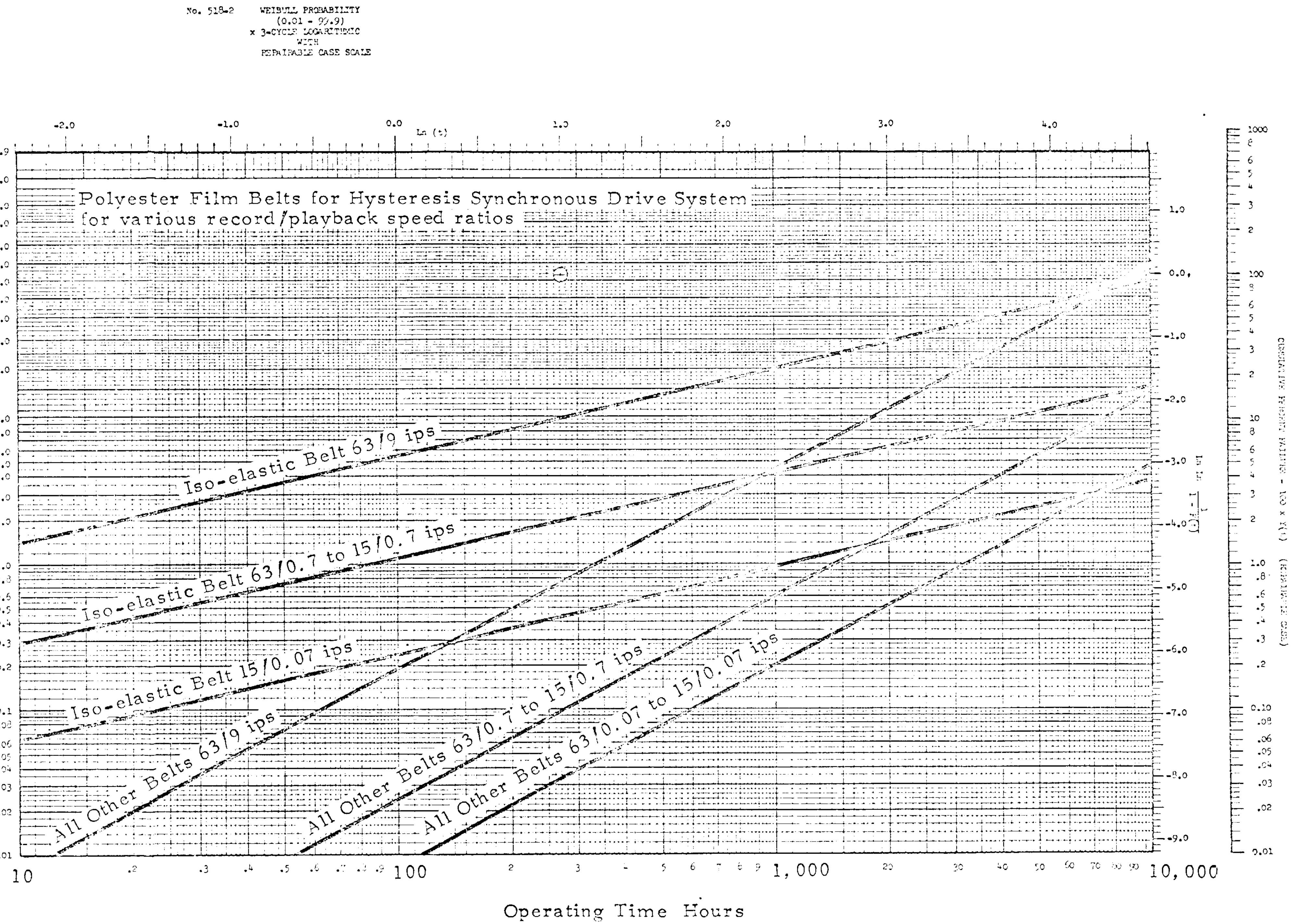

No. 518-2 WEIBULL PROBABILITY (0.01 - 99.9) x 3-CYCLE LOGARITHMIC WITH REPAIRABLE CASE SCALE
Polyester Film Belts for Hysteresis Synchronous Drive System
for various record/playback speed ratios
Iso-elastic Belt 63/9 ips
Iso-elastic Belt 63/0.7 to 15/0.7 ips
Iso-elastic Belt 15/0.07 ips
All Other Belts 63/9 ips
All Other Belts 63/0.7 to 15/0.7 ips
All Other Belts 63/0.07 to 15/0.07 ips
Cumulative Probability of Failure %
Operating Time Hours
Ln (t)
10
100
1,000
10,000

FIGURE 60

TABLE XXVIII

HYSTERESIS SYNCHRONOUS DRIVE SYSTEM PROBABILITIES OF BELT SURVIVAL FOR 6 MONTH MISSION

Tape Speed ips	Speed Ratio	Operating Time Hours for 6 month mission	Belts A	B	C	D	E	Capstan 1 & Iso-belt *	Total
63/.07	900/1	5 /4395	.9999+	.993	.993	.99935	.9999+	.9761	.961
63/.7	90/1	50/4350	.9999	.998	.993	.99935		.8961	.884
63/9	7/1	650/3750	.997	.993	.993			.4665	.4575
30/.07	430/1	10/4390	.9999+	.993	.993	.99935	.9999+	.9780	.963
30/.7	43/1	100/4300	.9999	.993	.993	.99935		.8998	.887
15/.07	215/1	20/4380	.9999+	.993	.993	.99935	.9999+	.9798	.965
15/.7	21.5/1	200/4200	.9999	.993	.993	.99935		.9050	.893

* Use same belt data used for Servo Drive

TABLE XXIX

PROBABILITY OF SURVIVAL AS A FUNCTION OF OPERATING TIME FOR A TAPE TRANSPORT WITH SYNCHRONOUS MOTOR DRIVE HAVING VARIOUS RECORD/PLAYBACK SPEED RANGES

Record/Playback Speed Combinations ips	Operating Time - Hours					
	100	500	1000	2000	3000	4400
63/.07	.9950	.9807	.9644	.9326	.905	.8640
63/.7	.9853	.9575	.9276	.8800	.8340	.7770
63/9	.9404	.8350	.7340	.5930	.4700	.3490
30/.07	.9950	.9807	.9644	.9326	.9050	.8640
30/.7	.9853	.9572	.9276	.8800	.8340	.7770
15/.07	.9950	.9807	.9644	.9326	.9050	.8640
15/.7	.9853	.9572	.9276	.8800	.8340	.7770