STUDY OF FAILURE AND RELIABILITY IN MICROELECTRONIC DEVICES

3rd QUARTERLY REPORT

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Electronic Research Center

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GENERAL PRECISION, INC.

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INDEX

1. INTRODUCTION

Space programs demand increased requirements of long-time maintenance-free operation and the complexity of electronics equipment further requires higher reliabilities of the electronic component parts. The reliability improvement indicates that failure rates are strongly determined by specific changes in physical mechanisms which cause degradation and catastrophic failures. An understanding of the dependence of processes on environmental and operational stresses makes possible the development of mathematical prediction of reliability on a scientific basis and of tests to screen potentially weak devices.

The program performed under this contract was started originally under contract NASW-973. It has the following objectives:

1. Predict basic failure mechanisms and determine methods of detection through accelerated testing.
2. Isolate predominant failure mechanisms through testing as a function of stress level and process control.
3. Develop techniques to identify and verify failure mechanisms with a view towards developing screening techniques for high reliability devices.

An initial study of collecting and analyzing existing data provided much of the supporting data in determining probable failure mechanisms. The major mechanisms were identified as surface reactions such as inversion layer formations, ionic migration at the silicon dioxide surface, ionic entrapment at oxide defects and bulk reactions such as selective diffusion along dislocation lines and increased leakage and metalization changes. The possibility of gold precipitation was also considered. A test plan was devised to test devices of one integrated circuit type (NAND/NOR gate) of each of five manufacturers. The test consists of temperature cycling from -55°C to +125°C, temperature step stress testing from +200°C non-operating until failure of

1. INTRODUCTION (Cont.)

units, and operating life tests at +125°C.

The results of the test program during the period of March through May are described in this report.

2.0 SUMMARY

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During the third quarterly period of this contract, testing of all devices continued. Eleven devices were taken into the laboratory for detailed failure analysis to determine the specific failure mechanism. This investigation is continuing. The performance of the five device types still under test can be summarized as follows:

Vendor A: Input diode leakage is erratic in the life test. Five units failed catastrophically (low output transistor breakdown voltage) at the 6000 hour point.

After 330°C of the Temperature Step Stress Test, all units began to fail for several reasons. No specific failure mechanisms have been determined, analysis of these failures is continuing.

Vendor B: The units appear to be quite stable during the life test and temperature cycle test. However, units were removed from the Temperature Step Stress Test because of excessive purple plague at 250°C.

Vendor C: The units under life test and temperature cycling appear to be very stable. Degradation of V_{SAT} was noticed under Temperature Step Stress Testing from 300°C on with catastrophic failures occurring at the limits of 350°C.

Vendor E: Life test units appear stable at the 2000 hour points. Two input diode failures occurred during Temperature Cycling. During the Temperature Step Stress Testing intermetallic growth is apparently occurring at 200°C

over

2.0 SUMMARY (Cont.)

Vendor E: (Cont.)

and above. This is the same manufacturer as Vendor B, although these units are an all aluminum system.

Table I shows a tabulation of the number of failures that occurred at the significant measuring points. Failures recorded are not necessarily catastrophic failures or units that are outside the manufacturer's specification limits. Failure criteria are based on changes from initial measurements and defined in the contract work statement.

AUTHOR

TABLE I
SUMMARY OF FAILURES

LIFE TEST

DATA POINT	VENDOR A		VENDOR B		VENDOR C		VENDOR E	
	Total Number of sample	Number of Failures						
100 Hours	40	0	40	0	40	0	20	0
250 Hours	40	0	40	0	40	0	20	1
500 Hours	40	0	40	0	40	0	19	0
1000 Hours	40	1	40	0	40	1	19	0
2000 Hours	39	0	40	0	39	0	19	0
3000 Hours	39	0	40	1*	39	0		
4000 Hours	39	2	40	0	39	0		
5000 Hours	37	2	40	0	39	0		
6000 Hours	35	5	40	1*	39	1*		

*Device returned to test

TEMPERATURE CYCLING

50 Cycles	20	0	20	0	20	0	30	1
100 Cycles	20	0	20	0	20	0	15 (Note)	1
150 Cycles	20	4	20	0	20	0	NA	NA

Note: Group III only sees 50 cycles

TEMPERATURE STEP STRESS

200°C	50	0	50	0	50	0	43	13
250°C	48	2	50	50	50	0	30	3
275°C	48	0			50	0		
300°C	48	0			50*	0	27	18
315°C	48	0			50	0		
325°C	-	-			-	-		
330°C	48	0			50	0		
340°C	48	8			50	0		
350°C	40*	40			50	8		

*All devices increasing in output transistor saturation voltage greater than 10% of initial value. Device not removed from test but indicated formation of intermetallic compound.

3.0 LIFE TEST

3.1 Summary of Results

Devices are continuing life test, Vendors A, B, and C will complete 7000 hours on 14 June 1966 and Vendor E will complete 3000 hours on 5 July 1966. The data has been reduced, reviewed and the results are summarized and analyzed in the following paragraphs.

The data collected from the operating life test on Vendors A, B, C and E are provided in the form of distribution plots located in the Appendix of this report. It should be noted that only those parameters that characterize the device's stability have been included in the graphs. The distributions are the minimum and maximum values, 10th, 50th and 90th percentiles. The percentile plot shows that percentage of the readings falling below the value shown on the graph.

A factor influencing the parameter distributions are those devices which are catastrophic failures or exceed the degradation criteria and which are not removed from test until after the data has been reduced and plotted.

3.2 Vendor A

A discrepancy has occurred in the presentation of the data at the 3000 and 4000 hour data points. The data from the Control Group, which has seen no environments other than shelf life are included in the computer reduced data calculations. However, this has not occurred at the 5000 or 6000 hour data points.

Saturation Voltage

Peaks of maximum values of the output transistor saturation voltage curve at the 4000 hour and 6000 hours were caused by device 16 and 38 respectively which exceeded the established failure criteria. Device #16 increased 43 millivolts from its initial value point and device #38 increased 200 millivolts from its initial value. Device 16 was removed at the 5000 hour point

3.2 Vendor A (Cont.)

Saturation Voltage (Cont.)

and device 38 at the 6000 hours data point for failure analysis.

The parameter distribution for the remaining devices on life test indicate little variations.

Leakage Current

The input diode leakage current characteristics of the life test for the 10 and 50 percentiles have been remaining relatively stable. However, the 90 percentile shows some erratic response from one data point to the next. This is attributed to the nine device failures occurring at the 4000 hour, 5000 hour and 6000 hour data points. These devices were removed from test.

3.3 Vendor B

The data from the Control Group was used in the calculations of the 4000 hour percentiles.

Saturation Voltage

The output transistor saturation voltage characteristics of the life test exhibited a relatively stable parameter distribution. The peakedness of the maximum curve was caused by device #7 increasing 300 millivolts from its initial value to 577 millivolts. However, at the 6000 hour data point device #7 returned to a value of 258 millivolts.

Leakage Current

The input diode leakage current characteristics of the life test indicate a relatively stable parameter distribution, with a general trend of decreasing leakage current.

3.4 Vendor C

The Data from the Control Group was used in the calculations of the 4000 hour percentiles. Both the output transistor saturation voltage and the input diode leakage current are exhibiting stable and tight parameter distributions.

3.5 Vendor E

The percentile distributions plotted for the two output transistor parameters, Threshold Voltage and Output Leakage Current (I_{CEX}) exhibited a very tight and stable distribution. There appears to be an increasing trend on threshold voltage; however, the dispersion between the minimum and maximum values amounts only to approximately 40 millivolts.

The input diode leakage current has not shown any particular trend but the over all magnitude of leakage is very small.

Failures that occurred during life are summarized as shown in Table 2 for Vendors A, B, C and E.

TABLE 2

SUMMARY OF FAILURES - Vendor A

LIFE TEST

DATA POINT	Total Number of Samples	Number of Failures	Device Numbers	Remarks
1000 Hour Life	40	1	43	I_8 increased from 157.0 na to 2.19 ua.
4000 Hour Life	39	2	21	I_3 increased from 11.00 na to 61.96 ma.
			27	I_3 increased from 13.20 na to 15.94 ua.
5000 Hour Life	37	2	9	I_2 increased from 29.10 na to 434.4 na.
			16	I_3 leakage increased from 16.2 na to 27.00 ua.
6000 Hour Life	35	5	20	BV_9 decreased from 5.657 volts to .182 volts.
			22	BV_9 decreased from 5.649 volts to 2.786 volts.
			30	BV_8 decreased from 5.416 volts to .002 volts. I_8 reading of .5764 ma.
			38	BV_9 decreased from 5.737 volts to 2.200 volts.
			39	BV_9 decreased from 5.830 volts to 3.388 volts
7000 Hour Life	30			

TABLE 2 (Cont.)

SUMMARY OF FAILURES - Vendor B

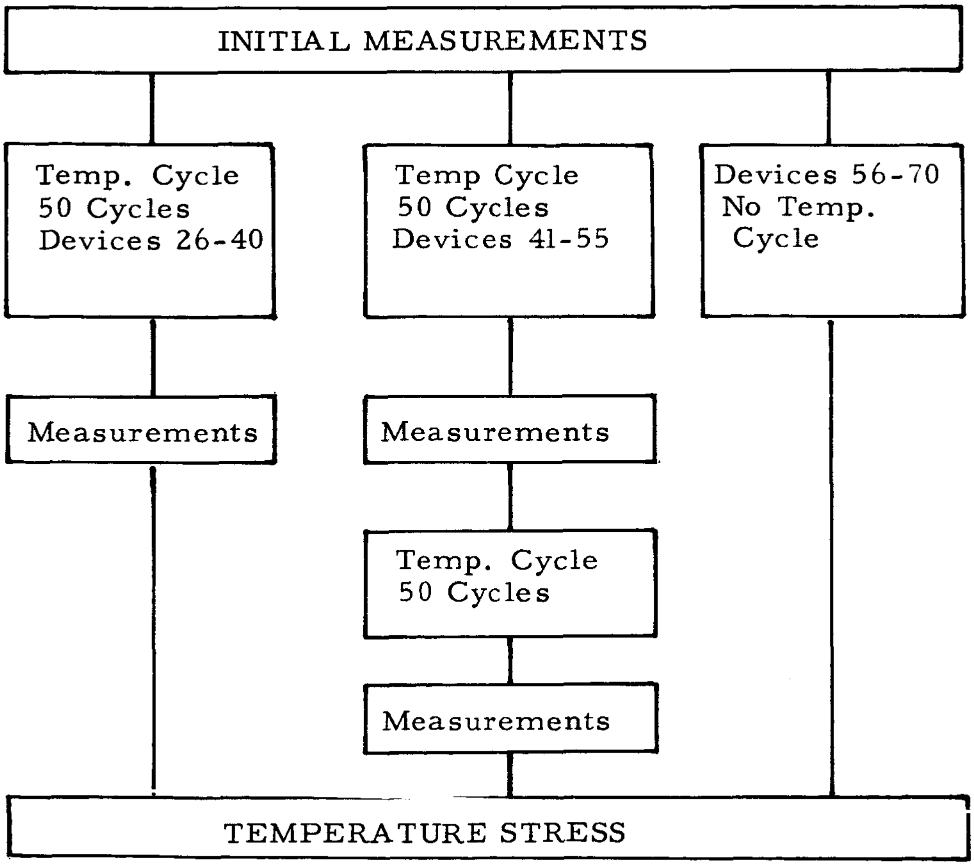
DATA POINT	Total number of Failures	Number of Failures	Device Number	Remarks
3000 Hour Life	40	1	19	I_3 increased from 4.80 na to 492.6 na. Device annealed and returned to test.
6000 Hour Life	40	1	30	BV_9 decreased from 31.30 volts to 13.59 volts. No failure analysis performed. Device returned to test.
SUMMARY OF FAILURES - Vendor C				
1000 Hour Life	40	1	31	I_7 increased from 2.7 na to 109.5 ua.
6000 Hour Life	39	1	24	V_{SAT} decreased from .265 volts to .2354 volts. Device returned to test.
SUMMARY OF FAILURES - Vendor E				
250 Hour Life	20	1	24	Output transistor leakage current increased from 750-800 na to 2 ma.
500 Hour Life	19	0		
1000 Hour Life	19	0		
2000 Hour Life	19	0		

4.0 Temperature Cycling

4.1 Status

The test results of temperature cycling for Vendor A, B and C were discussed in the 2nd Quarterly Report dated, February 1966.

It might be worthwhile to review the test sequence for Temperature Cycling for Vendor E.



Vendor E devices completed temperature cycling 10 March 1966. Device 26E exhibited shorts on Input Diodes #1 and #2 at the completion of 50 cycles. Device 54E exhibited a short on Input Diode #12 at the completion of 100 cycles. The remaining devices showed little change in the parameter values.

Failures that occurred during Temperature Cycling are summarized in Table 3 for Vendors A, B, C and E.

TABLE 3

TEMPERATURE CYCLING - SUMMARY OF FAILURES - Vendor A

DATA POINT	Total Number of Samples	Number of Failures	Device Number	Remarks
150 Cycles Temp. Cycling	20	4	48	BV_1 open circuit. Initial value was 5.760 volts.
			51	BV_1 and BV_2 open circuit. Initial values were 5.960 and 6.100 volts.
			61	V_{SAT_4} and V_{SAT_6} increased greater than 10% from initial value.
			63	V_{SAT_4} and V_{SAT_6} increased greater than 10% from initial value.
SUMMARY OF FAILURES - Vendor B				
150 Cycles Temp. Cycling	20	0	-	No Failures
SUMMARY OF FAILURES - Vendor C				
150 Cycles Temp. Cycling	20	0	-	No Failures
SUMMARY OF FAILURES - Vendor E				
50 Cycles Temp. Cycling	30	1	26	Input diode #1 and #2 shorted
100 Cycles Temp. Cycling	15	1	54	Input diode #12 Shorted.

TABLE 4

TEMPERATURE STEP STRESS - SUMMARY OF FAILURES- Vendor A

DATA POINT	Total Number of Samples	Number of Failures	Device Number	Remarks
250°C Temp Step Stress	50	2	100	I_1 increased from 2.6 na to 1.4 ua
			113	BV_9 open circuit. Initial value 9.82 volts.
340°C Temp Step Stress	48	8	67	BV_1 and BV_2 open circuit
			82	I_T increased from 11.0 na to 73.05 ma
			83	BV_1, BV_2 and BV_8 Open Circuit
			93	$V_{SAT}6$ increased from .275 volts to .604 volts.
			96	BV_8 and BV_9 open circuit
			104	I_2 increased from 19.0 ma to 21.19 ua
			111	BV_8 open circuit
			113	BV_9 open circuit
350°C Temp Step Stress	40	40	All re-maining	Most units had one or more failed para-meters. Open input diodes or increased output transistor saturation voltage.
SUMMARY OF FAILURES - Vendor B				
250°C Temp-Step Stress	50	50	60-115	Increase in output transistor saturation voltage and extensive broken bonds.

TABLE 4 (Cont.)

SUMMARY OF FAILURES - Vendor C

DATA POINT	Total Number of Samples	Number of Failures	Device Number	Remarks
300°C Temp. Step Stress	50	*50	All Units	All units show increase in Saturation voltage of greater than 10% of initial value. No catastrophic failures.
350°C Temp Step Stress	50	8	66	BV_8 Open Circuit
			68	Output transistor open
			73	Output transistor open
			77	Output transistor open
			82	Output transistor open
			83	BV_9 open circuit
			107	Output transistor open
			110	BV_7, BV_8 and BV_9 open circuit

*units were continued under test

TABLE 1 (Cont)

SUMMARY OF FAILURES - Vendor E

DATA POINT	Total Number of Samples	Number of Failures	Device Number	Remarks
200°C Temp Step Stress	43	13	32	I_{CEX1} and I_{CEX2} increased greater than X10
			35	BV_2 indicates a shorted diode
			36	BV_{12} indicates a shorted diode
			48	BV_{13} indicates a shorted diode
			51	BV_{13} indicates a shorted diode
			53	BV_{13} indicates a shorted diode
			56	BV_{12} indicates a shorted diode
			58	BV_{12} indicates a shorted diode
			60	BV_{13} indicates a shorted diode
			61	I_{CEX1} and I_{CEX2} increased greater than X10.
			63	BV_{13} indicates a shorted diode
			67	I_{CEX1} and I_{CEX2} increased greater than X10
			70	I_{CEX1} and I_{CEX2} increased greater than X10
250° Temp Step Stress	30	3	31	Input diode leakage current I_{T1} increased greater than X10.
			45	Input diode #13 shorted, Input diode leakage current I_{T1} and I_{T2} increased greater than X10.
			55	Increase in Threshold voltage greater than 10%.

TABLE 4 (Cont.)

SUMMARY OF FAILURES - Vendor E (Cont.)

DATA POINT	Total Number of Samples	Number of Failures	Device Number	Remarks
300°C Temp Step Stress	27	18	29	Input diode leakage current I_{T_1} increased greater than X10.
			30	Input diode leakage currents I_{T_1} and I_{T_2} increased greater than X10.
			33	Same as #30
			34	Input diode leakage current I_{T_2} increased greater than X10.
			39	Same as #30
			41	Input diode leakage current I_{T_1} and I_{T_2} increased greater than X10.
			42	Catastrophic failure
			43	Catastrophic failure
			44	Same as #41
			46	Same as #41
			47	Same as #30
			52	Same as #30
			55	Same as #41
			57	Same as #34
			59	Same as #41
			65	Same as #30
			66	Same as #41
			68	Catastrophic failure

5.0 Temperature Step Stress

5.1 Status

Vendors A and C completed the final post 350°C measurements. The data collected from temperature stress testing on Vendors A and C revealed that all the devices eventually failed at 350°C.

The data collected from temperature stress testing on Vendor E revealed the devices started failing at 200°C. The failures were localized to one of the input diodes thus leaving still a functional device. It was decided to leave the devices on test for further data.

Table 4 summarizes the failures that occurred as a result of temperature stress testing on Vendors A, B, C and E.

6.0 Failure Analysis

6.1 Introduction

Since the last quarterly report, one failed flat-pack device has been investigated in great detail. In addition, eleven failed devices have been opened and their upper surfaces examined.

This report will first describe the new data obtained and will then discuss the tentative conclusion drawn from the data, that a process investigation study is required to separate two possible sources of failure: (1) inadequate photoresist removal in areas of the microcircuit which have a high density of crevices in the oxide coating for direct aluminum coating to the silicon or (2) excessive chemical interaction between thin film aluminum electrodes and the oxide layer.

6.2 Experimental Data

A. Procedure for Opening Devices

The TO-5 cans were held in a 21/64ths collet in a lathe. The cans were opened with a needle-point tool. Subsequently, the base with chip and leads was potted in a small plastic cup. The potting compound used was Buehler catalog no. 20-3554 liquid, in a ratio of 1-1/2 to 1 per Buehler instruction label.

6.2 Experimental Data (Cont.)

A. Procedure for Opening Devices (Cont.)

The two flat packs were potted in the same compound, lid up, flush with surface. Then subsequently, the lid was lapped off on a cast iron lap charged with no. 600 Norbide, followed by methyl alcohol rinse.

B. Device No. 26E

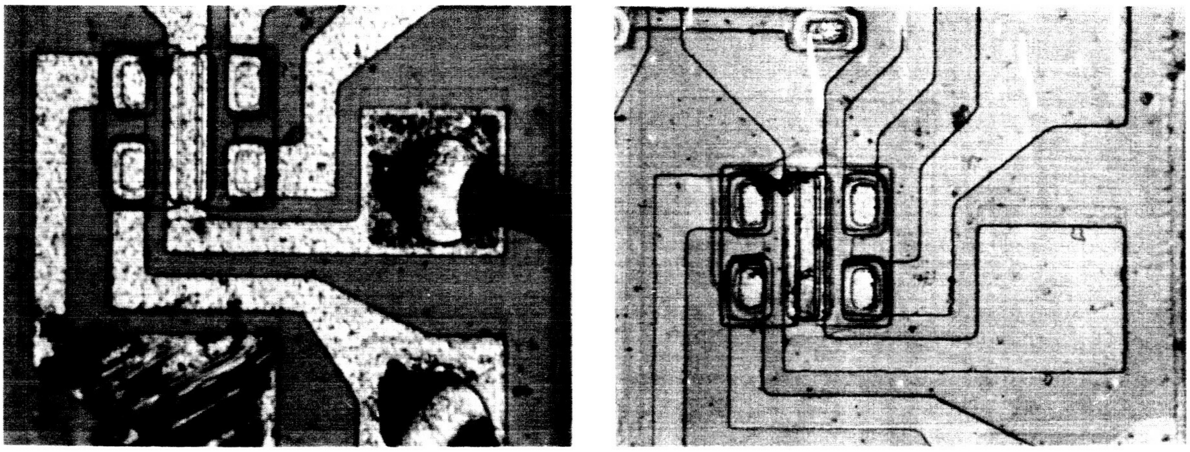
This device was reported to have a shorted diode. Figure 1 shows the shorted diode region both before and after removal of the thin film aluminum electrodes. It is readily apparent that the insulating layer between the diode and the common expander region is defective.

It should also be noted that the thin film electrode was very tenaciously bound to the insulating layer. Aqua regia was required to remove the aluminum. Hydrochloric acid which readily removed aluminum from other devices did not remove aluminum from this device. This extensive interaction can also be noted in the fact that the former position of the aluminum is clearly evident even after its removal, Figure lb.

There are at least two reasons for the defective region. One reason can be attributed to excessive interaction between the aluminum and the dielectric leading to a cratering action on the dielectric.

An alternative explanation may be inadequate photoresist removal in this region of rapid topographical changes. The photoresist would eventually carbonize yielding a conductive path and excessive current would yield the permanent cratering type defect evident in the device.

A suggested program to distinguish between the two alternatives is recommended in the discussion section of this report.



a. Before metallization removal   b. After metallization removal

FIGURE 1

Device 26E Before and After Thin Film Aluminum Electrode Removal. Note defective dielectric between diode and expander. Magnification 328X

6.2 Experimental Data (Cont.)

C. Diagnosis of Failure by Solid State Chemical Reaction Studies - A Comparative Study of Failed Devices.

At this stage in the program, the following devices were made available for study:

Vendor A

Sample No.	Test Condition	Remarks
16, 20	6,000 Hr. Operating Life	Reverse leakage current
54, 59	150 Temperature cycles +125°C to -65°C	Increase in output transistor saturation voltage
66, 85, 113	Temperature Step Stress Through 350°C	Breakdown voltage open or short

Vendor C

68, 107	Temperature Step Stress Through 350°C	Saturation Voltage Open

Vendor E

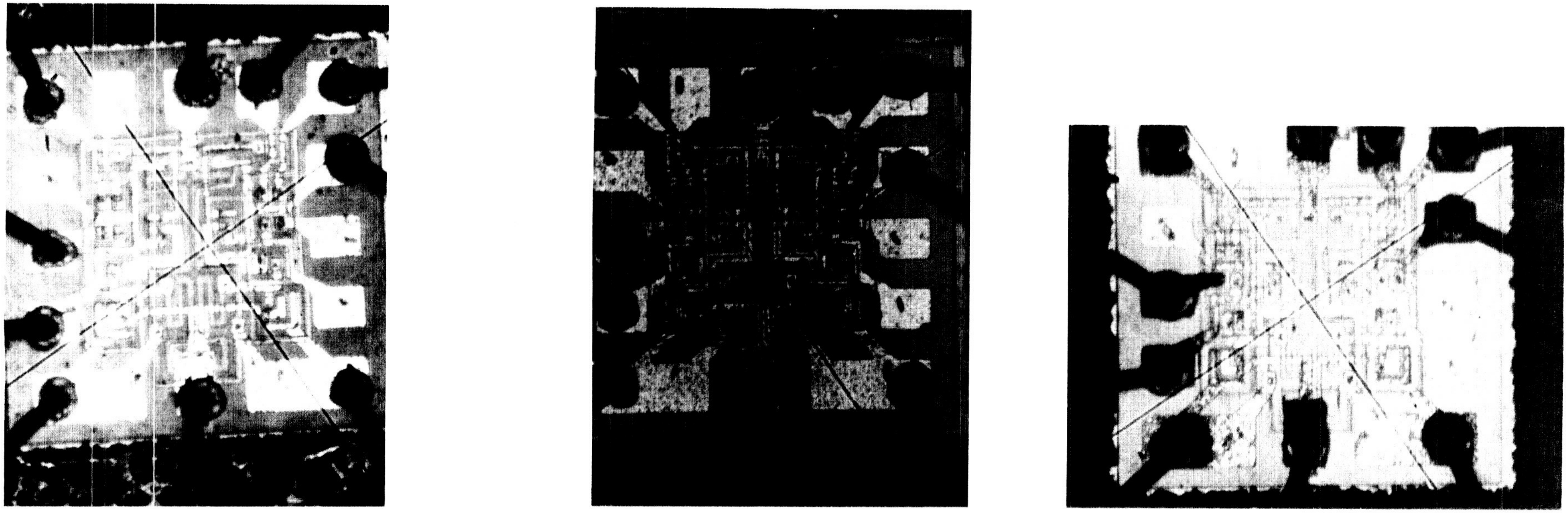
51, 58	Temperature Step Stress Through 200°C	Short in breakdown voltage measurement

Rather than studying each failure in a serial fashion, these failures will be studied in parallel. Thus far the surfaces have been microscopically examined and the following observations made.

1. Erratic Growth of Purple Plague

   It is well known that the growth of purple plague is temperature dependent. This is verified by examination of the pictures in Figure 2 which shows the progressive growth of purple plague as a consequence of the three types of tests used.

   What is not so well known is that purple plague growth is erratic from circuit to circuit. This is illustrated in



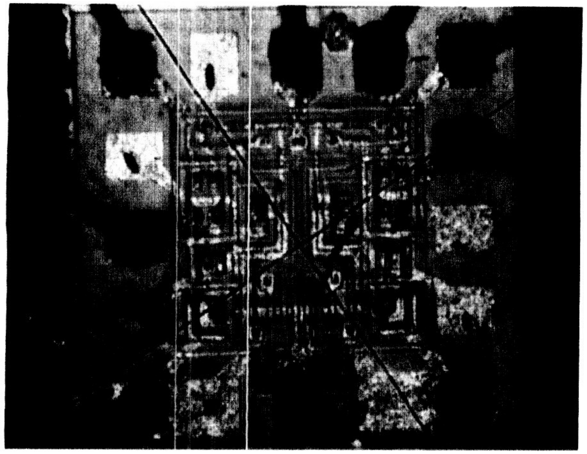
a. (#16 after)
6, 000 Hr. Life

b. (#54)
After Cycling

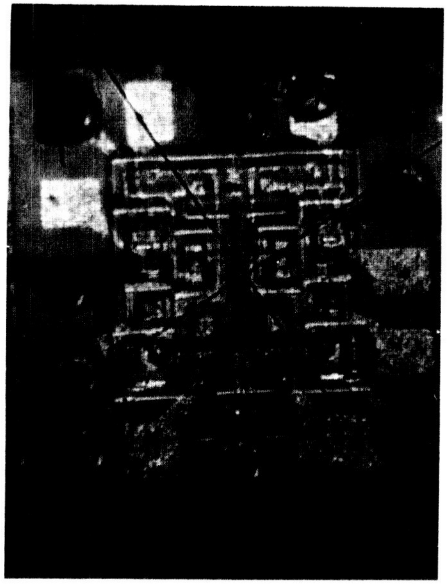
c. (#85)
After 350°C

FIGURE 2

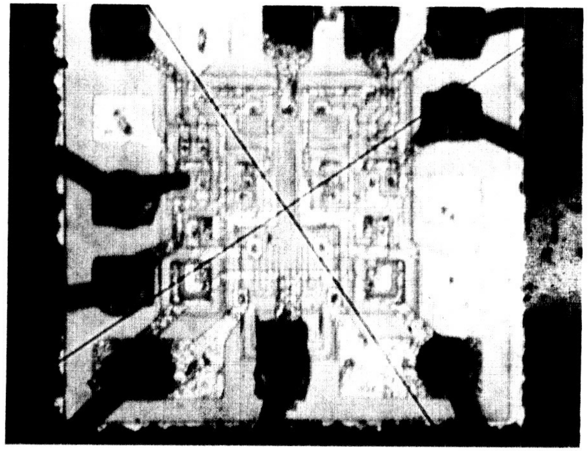
Progress Growth of Purple Plague. Mag. 40X



a. (#66)



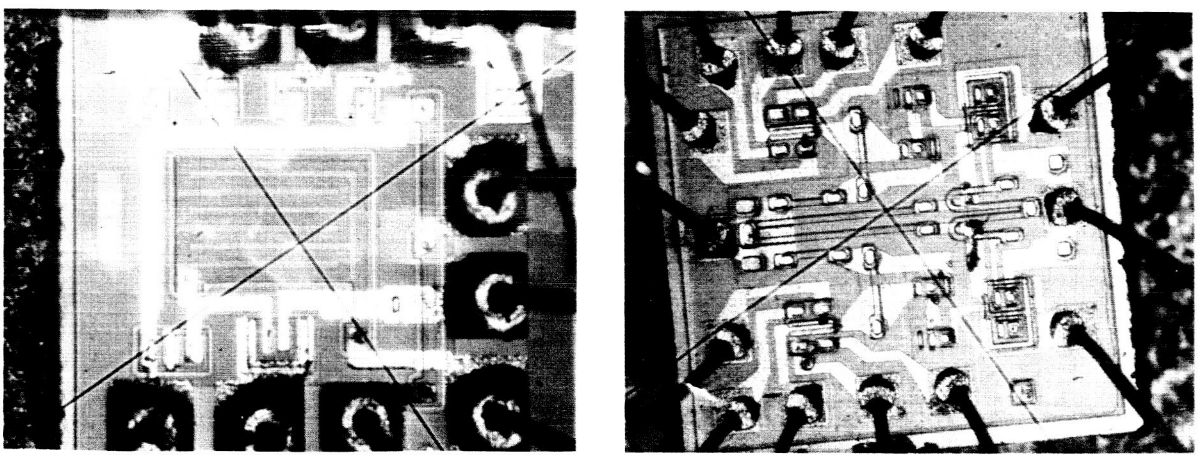
b. (#113)



c. (#85)

FIGURE 3

Erratic Growth of Purple Plague. Mag 40X
All devices were subjected to temperature stress test through 350°C. Note also the speckled appearance of the thin film aluminium contact areas.



a. (#68) Vendor C after 350°C   b. (#51) Vendor E After 200°C

FIGURE 4

Variability in Lead Connection Density

6.2 Experimental Data (Cont.)

1. Erratic Growth of Purple Plague (Cont.)
   Figure 3. All circuits were subjected to the same test conditions, yet there is considerable variation in the growth of the plague from the lead pads into the circuit.

2. Progressive Aluminum Electrode-Insulator Interaction. During the temperature stress tests the thin film aluminum leads interact with the underlying insulator. This is evidenced by a loss in the reflective properties of the aluminum and the growth of a speckled appearance in the lead pad areas. Close examination of the lead pad areas of Figure 2a and the corresponding areas of Figure 3 illustrate this change.

3. Imperfections in Dense Lead Connection Areas, Failures tend to occur in regions of high density of thin film lead connections. The wide range of densities in lead connections is shown in Figure 4. There were no failures in the devices represented by Figure 4a through the 340°C stress test while there is a high incidence of failures in the device represented by Figure 4b even after only 200°C stress testing.

6.3 Discussion

The total experimental data accumulated to date verify the fundamental conclusion that the bulk of the failures in microelectronic devices at the present time are process failures and not random failures.

Thus during the first year's program, Vendor B had to be eliminated from further study because of early incidence of purple plague. During this year's study, Vendor D had to be rejected completely because of a fundamental fabrication problem while Vendor E is exhibiting a high incidence of failures in a given region of the device.

The three processes which do not appear to be under adequate control at the present time are: (1) minimization of the rate of

6.3 growth of purple plague, (2) minimization of the rate and extent of interaction between thin film aluminum and underlying dielectric and possibly (3) incomplete removal of photoresist in regions of the device which have "windows" in the dielectric for thin film electrode connections.

This latter point requires amplification. The devices of Vendor E are exhibiting failure in a region where four diodes are densely clustered. The failure most intensively studied to date demonstrated an imperfection in the dielectric. This can be attributed either to: (1) excessive interaction between aluminum electrodes and the underlying dielectric leading to cavitation of the dielectric, or (2) inadequate removal of photoresist which carbonized on the passage of current, created a short and "blew" a hole in the dielectric.

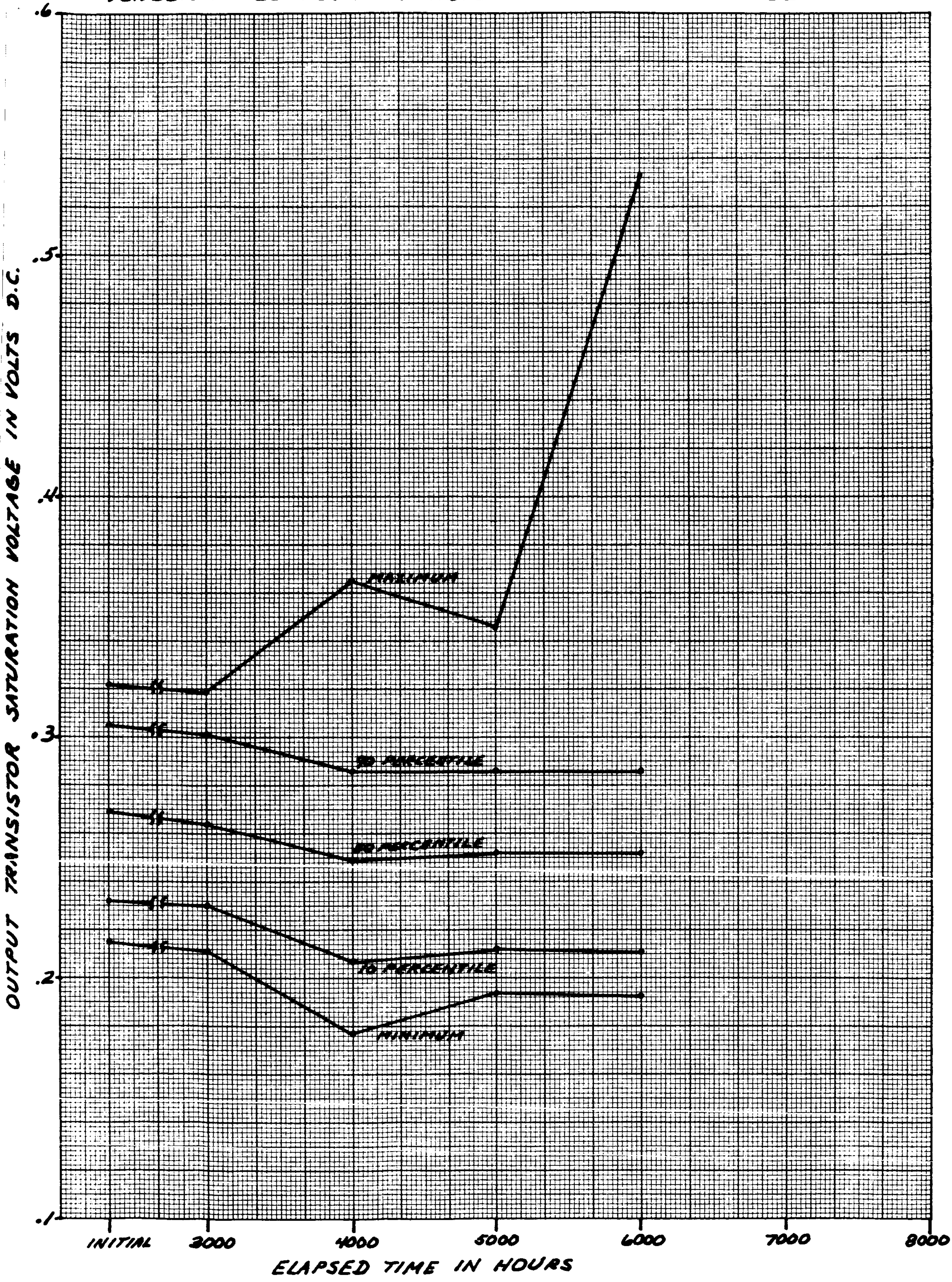
It is hightly recommended also that a program be authorized to systematically study the interaction between thin film aluminum and the underlying dielectrics currently in use, silicon dioxide and silicon nitride. Such a study will be a major step toward the goal of making the superstructure of microelectronic devices as reliable as the foundation, the silicon, appears to be.

APPENDIX I

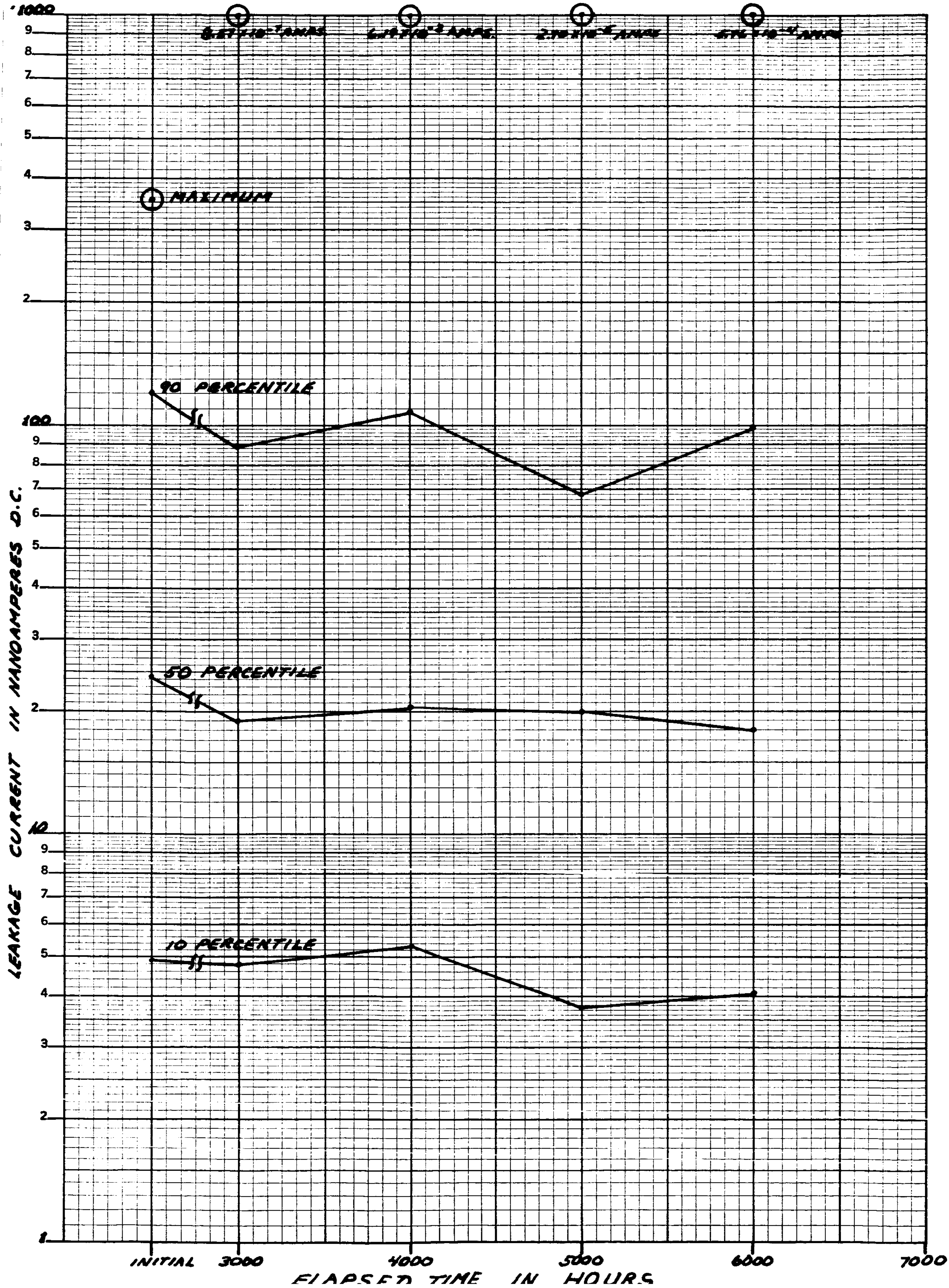
Percentile Graphs of Parameter Distribution of the Life Tests.

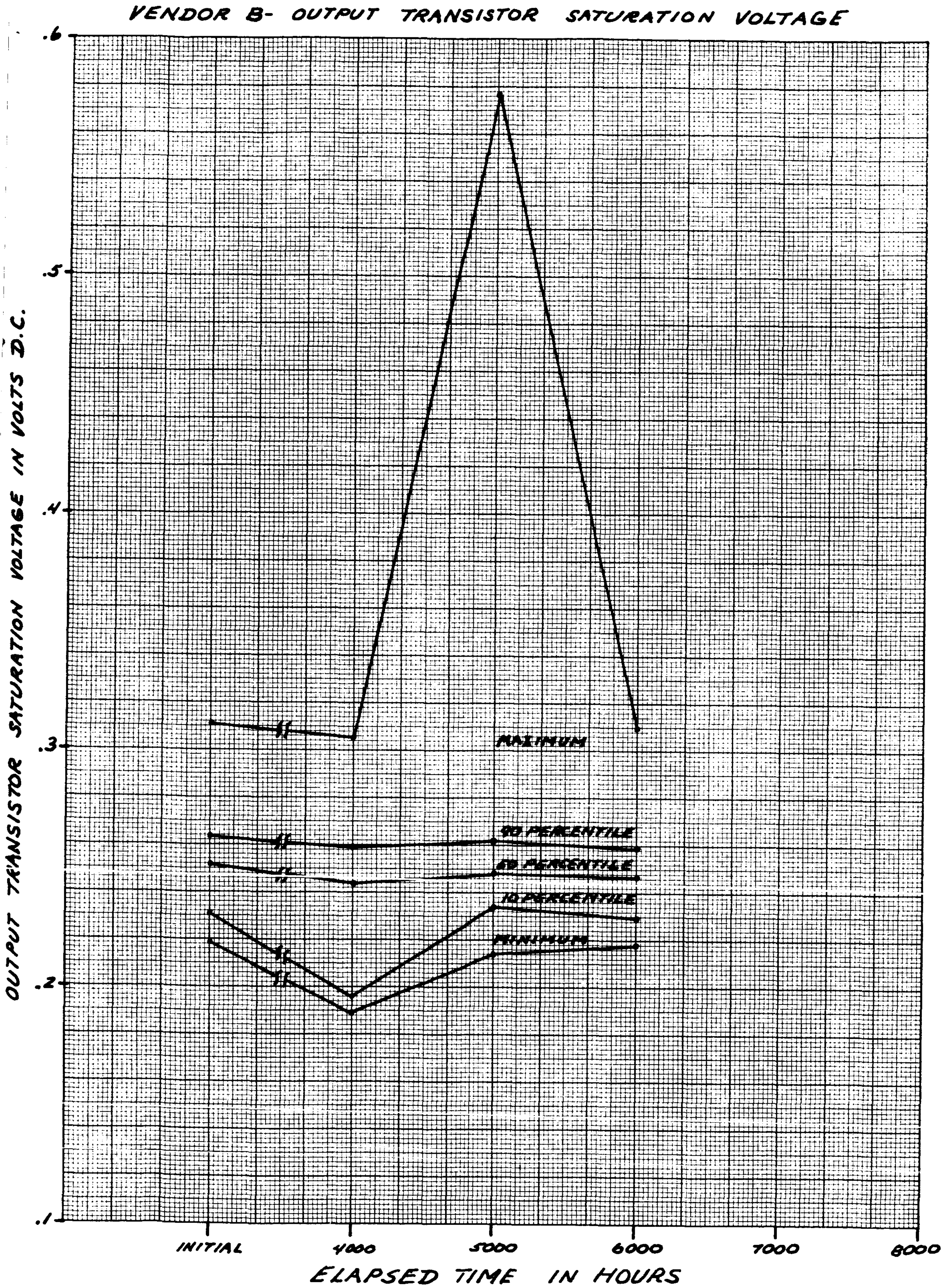
Vendor A
Vendor B
Vendor C
Vendor E

VENDOR A - OUTPUT TRANSISTOR SATURATION VOLTAGE

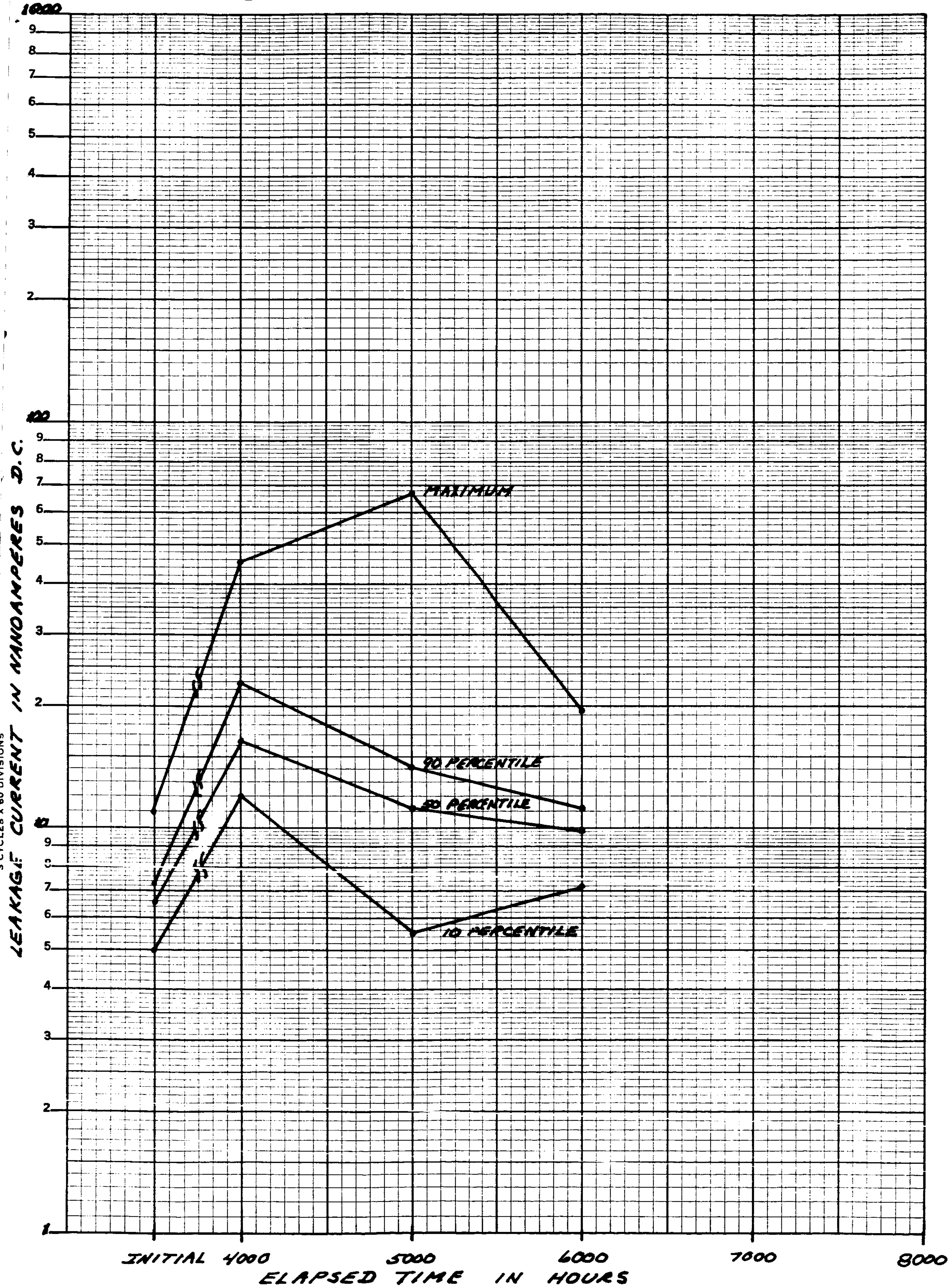


VENDOR A- INPUT DIODE LEAKAGE CURRENT

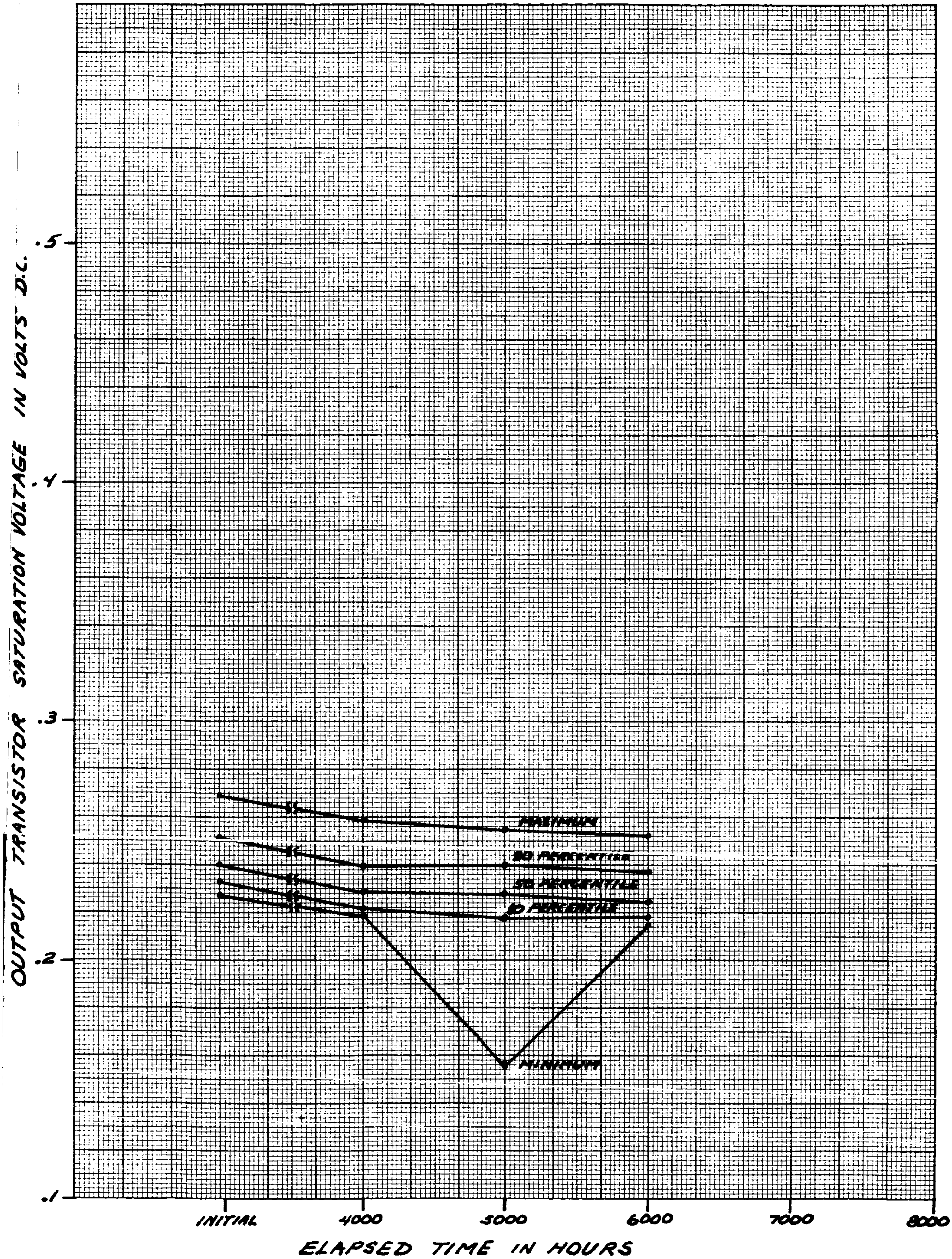



VENDOR B- OUTPUT TRANSISTOR SATURATION VOLTAGE
OUTPUT TRANSISTOR SATURATION VOLTAGE IN VOLTS D.C.
.6
.5
.4
.3
.2
.1
MAXIMUM
90 PERCENTILE
50 PERCENTILE
10 PERCENTILE
MINIMUM
INITIAL
4000
5000
6000
7000
8000
ELAPSED TIME IN HOURS

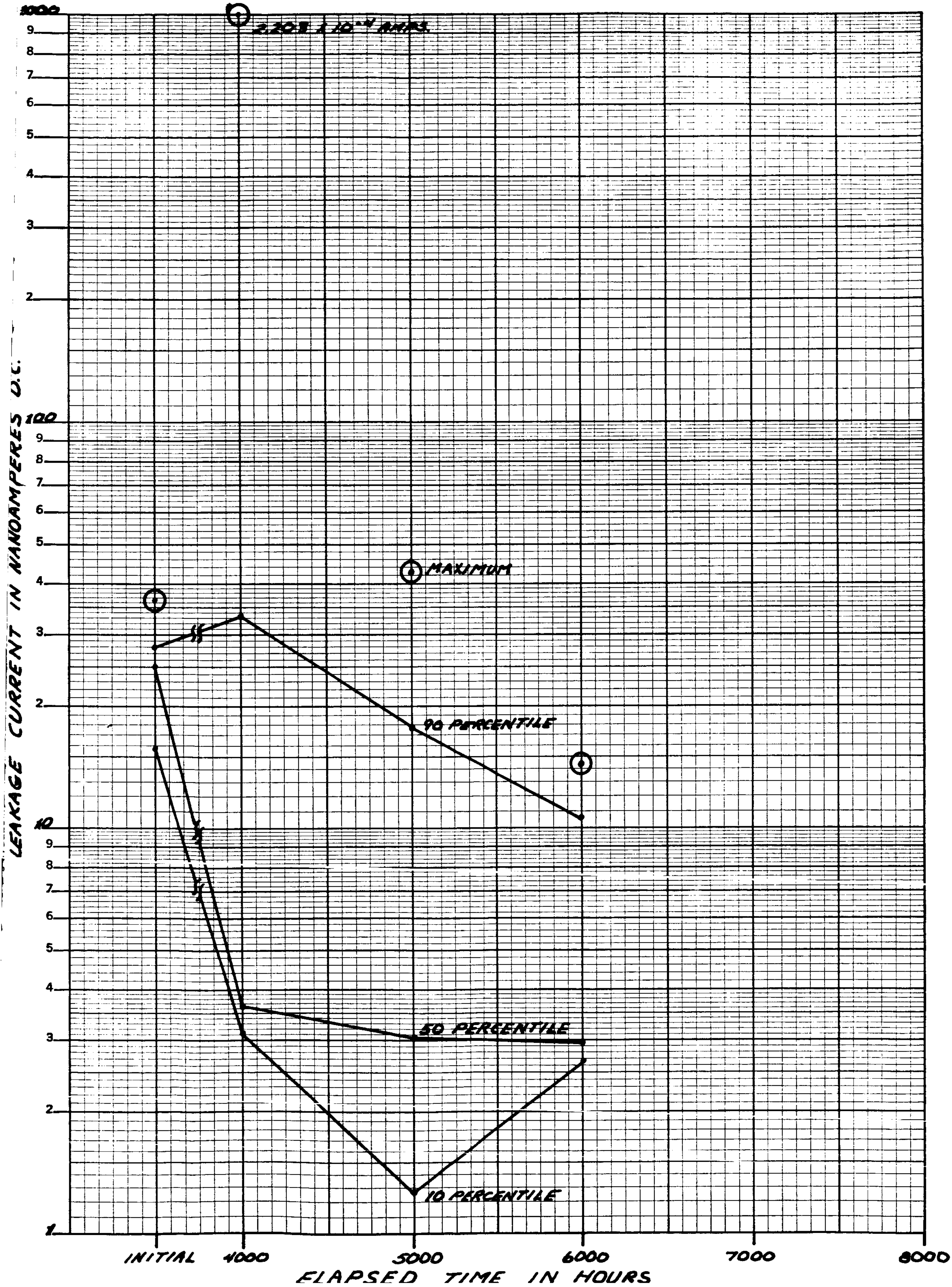
VENDOR B- TOTAL INPUT DIODE LEAKAGE CURRENT



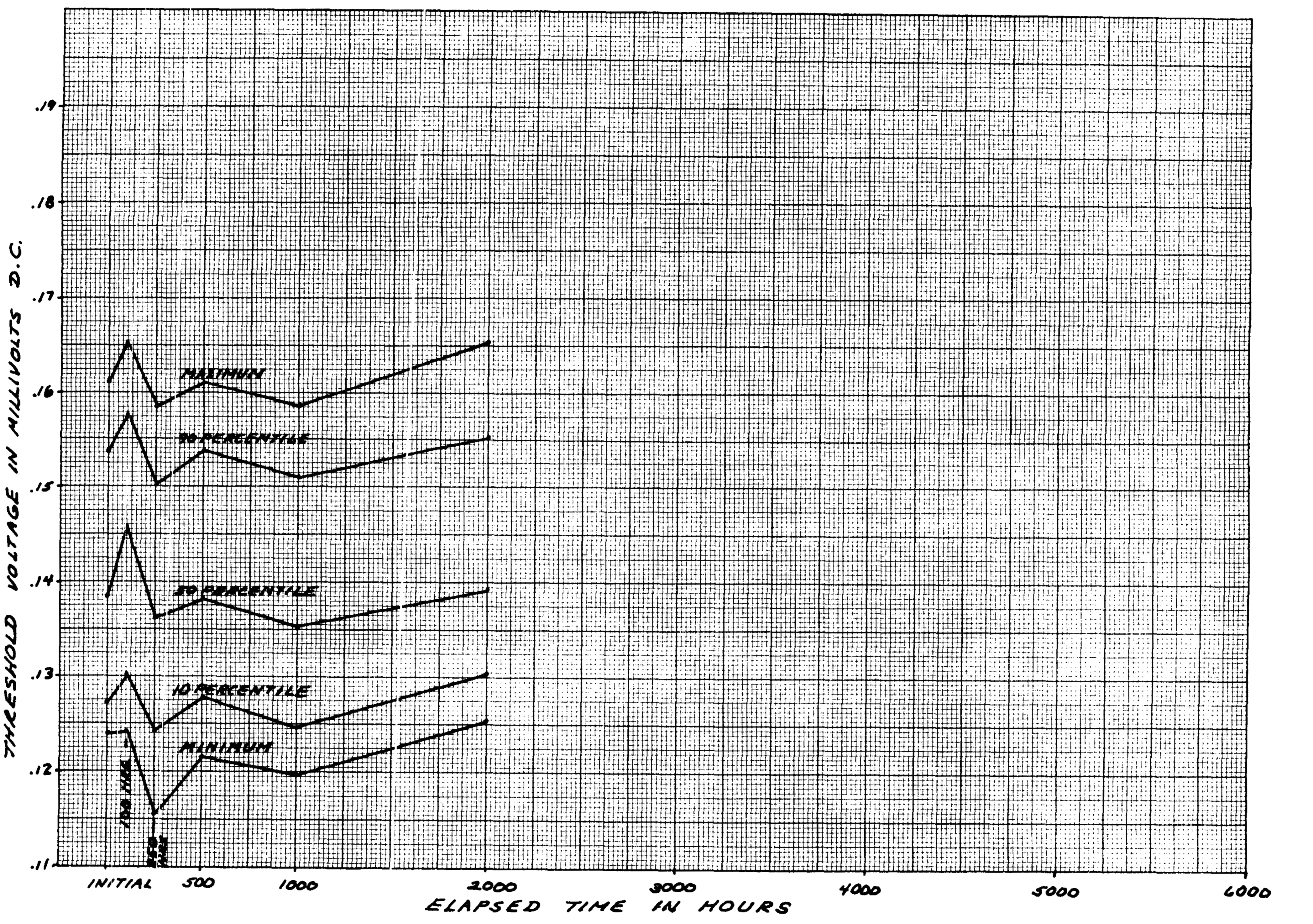
VENDOR C- OUTPUT TRANSISTOR SATURATION VOLTAGE



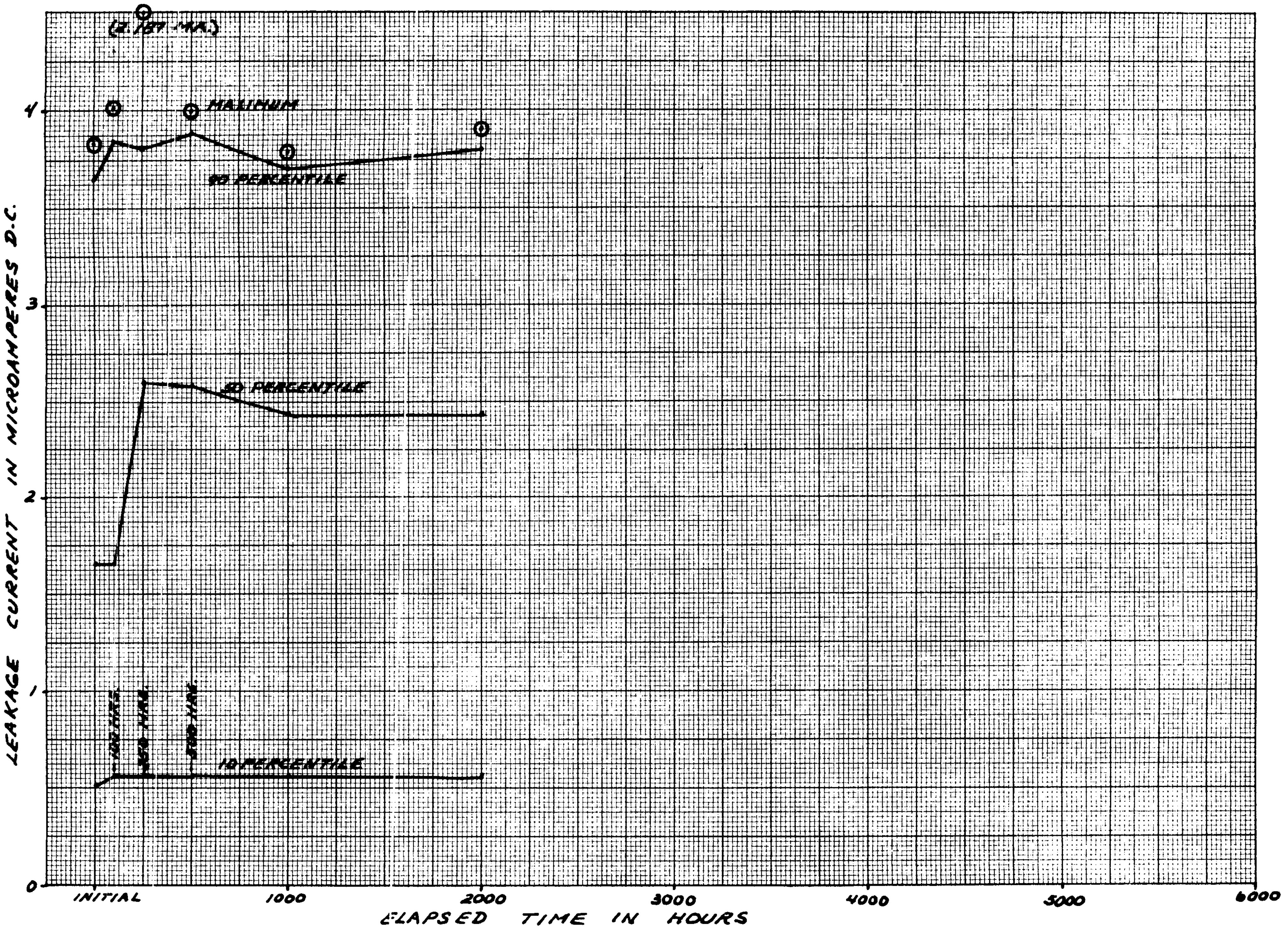
VENDOR C - INPUT DIODE LEAKAGE CURRENT



VENDOR E - THRESHOLD VOLTAGE



VENDOR E- OUTPUT TRANSISTOR LEAKAGE CURRENT (ICEX)



VENDOR E- INPUT DIODE LEAKAGE CURRENT