REPORT NO. P70-467

FINAL REPORT

MULTI-ENVIRONMENT MODEL VERIFICATION TEST

Contract No. NAS 5-21027

Prepared by
Hughes Aircraft Company
Culver City, Calif.

for Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland

OCTOBER 1970

AEROSPACE GROUP
HUGHES
HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

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DESCRIBING RESULTS OF 4000 HOURS
OF
MULTI ENVIRONMENT MODEL VERIFICATION TEST

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SUMMARY

The prior contracts NAS5-9638 and NAS5-10325 took a fresh look at the categorization and formulation of stress and strength factors for semiconductor diodes so as to provide an improved rationale for prediction based on realistic mathematical models. A general model for the failure rate of diodes was first developed and then the values of all the specific constants and parameter values were determined for the 1N3600 general purpose diode. A final report describing the validated model was dated 31 January 1968,(Contract NAS5-10325).

As a result of the above studies a multi-environment model test program was undertaken. This test envolved 4,000 hours on 700 diodes under combined stresses. This is the final project report describing the interpreted results.

At the conclusion of the 4,000 hours of test at maximum rated load and 100°C, with a total cumulative gamma radiation of 1.6×10^8 Rads(Si) and programmed vibration of 10g there resulted: only one catastrophic (intermittent open) diode failure; 5 degradation failures for recovery time out of specification; and 31 degradation failures for reverse current (leakage) beyond specification of 100 namp.

These results can be interpreted as complete verification of the mathematical model for failure rate prediction from stresses applied in actual service use when the type of circuit application and its sensitivity to failure mode are considered. Since the model was developed to fit data of actual failure events, the definition of failure must be considered in interpreting the result. For example, the model predicted a total of 11 failures for the 700 diodes tested for 4,000 hours in the combined environment with radiation and maximum rated load. The factor not defined was whether these failures would have occurred in a digital or analog application circuit.

When the shift in performance characteristics caused by the combined stress with time is considered, only eight of these diodes would have failed in a typical digital logic circuit that is insensitive to reverse leakage less than 10μ amp but critical of recovery time. However, if the diodes had been used in linear amplifiers which typically are insensitive to recovery time but critical to leakage currents greater than 1.0μ amp, the total number of diodes degrading beyond this failure limit (thus indicating that they would have failed in this service) is 15. From this it can be seen that the

model predicted very closely the number of failures that would have occurred in a typical system application of 700 diodes used in a variety of circuit types including both linear and digital.

If conservative application of the model is desired the results of this verification project can be summarized in the recommendation "For digital high speed circuits use the model results directly. For sensitive linear circuits multiply the model results by a factor of two." For general mixed circuit applications intermediate adjustments to the results predicted by the model can be deduced from knowledge of the circuit applications and from failure mode and mechanism studies.

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I INTRODUCTION

In review, a total of 700 diodes, type 1N3600 manufactured by Fairchild Semiconductor and selected at random from among large incoming stocks and without any screening or special testing were irradiated for 4,000 hours at a constant gamma flux of 40,000 R per hour from a 600 curie cobalt 60 source. The diodes were temperature controlled at 100°C ± 5°C and alternately loaded (60Hz) at 150 ma, forward current and at 50 volts inverse bias, (maximum rating). The vibration tables on which the test fixtures were mounted were adjusted to give 10g at a programmed 93 minutes out of each 8 hours. At these test conditions the model predicted a total of 11 failures as is explained in the next section. The following sections describe the data resulting and explain how these data closely verify the previously developed and validated model.

Following a discussion of the verification, other sections of this final report describe the experimental method and the data analysis procedures. Two appendices contain the data analysis computer program and histograms of the DC parameter measurements.

II VERIFICATION OF THE MODEL

Using the model and its related π factor curves as described in the Final Report for Diode Reliability Prediction Technique (Contract NAS 5-10325) dated 31 January 1968 the following prediction applies for the conditions of test as performed.

A. Summary of Test Design

1. Test diodes - Quantity 700 JAN 1N3600
   Manufacture - Fairchild Semiconductor Corporation
2. Test Time - 4000 hours (2.8×10^6 part hours)
3. Test Environment and Stress
   - a. Operating temperature - 100° ± 5°C
   - b. Vibration - 10 g's peak, 60 Hz 93 minutes every 8 hours
     (19.4% duty cycle)
   - c. Electrical stress - 60 Hz rectification
     power dissipation = 225 mw
     average forward current Io = 150 mA
     peak reverse V_R = 50 volts
     (junction temperature Tj = 150°C)
   - d. Radiation (Cobalt 60) - 40,000 Rad(Si) per hour
     (total radiation 1.6×10^8 Rad(Si))
   - e. Shock - none

B. Failures Predicted by Model

1. Math Model

$$\lambda_p = \lambda_a (\pi_{TM} \pi_S \pi_{VT} \pi_{Qa}) + \lambda_b (\pi_{TE} \pi_U \pi_{VT} \pi_{Qb})$$

where:

λ_a is a base mechanical failure rate dependent upon the part type

π_{TM} is an adjustment factor dependent upon the body temperature and which works in conjunction with λ_a.

π_S is an adjustment factor dependent upon shock level and number of shocks which works in conjunction with λ_a and π_{TM}.

π_{VT} is an adjustment factor dependent upon vibration level and temperature; it works in conjunction with all other factors in the equation.

π_{Qa} is a vendor quality factor. It depends upon his control of the mechanical parameters of the device during production and works in conjunction with λ_a.

λ_b is a base electrical failure rate dependent upon the part type.

π_{TE} is an adjustment factor dependent upon electrical stress and temperature and act on λ_b.

π_U is an adjustment factor dependent upon rate of radiation exposure (low levels of radiation only) and acts in conjunction with λ_b and π_{TE}.

π_{Qb} is a vendor quality factor; it depends upon his control of the electrical parameters of the device during production and works in conjunction with λ_b.

2. Prediction Factors for Diodes in Test

a. Mechanical factors

π_{TM} = 4 for 100°C test temperature
π_S = 1 for no shock
π_{Qa} = 1 for Fairchild
π_{VT} = 40 for 10 g's at 100°C
π_{VT} = 1 for zero g's
λ_a = .0007 for base mechanical failure rate

b. Electrical Factors

π_{TE} = 12 for Tj = 150°C

π_{VT} = 40 for 10g's at 100°C

π_{VT} = 1 for 0 g's

π_U = 18 for 4×10^7 Rad/1000 hours

π_{Qb} = 1 for Fairchild

λ_b = .0002 base electrical failure rate (in %/1000 hours)

c. Composite π_{VT} factor - The vibration factor for the prediction of failure rate is a combination of the π_{VT} for zero g and 10 g vibration. They are combined by weighting them by their duty cycle and adding them together as follows:

$\pi_{VT(10)}$ = 40 at 10 g's for 93 minutes every 8 hours

$\pi_{VT(0)}$ = 1 at 0 g's for 387 minutes out of every 8 hours

The composite $\pi_{VT(c)}$ is then:

$$\pi_{VT(c)} = \pi_{VT(10)} \times \frac{93}{8 \times 60} + \pi_{VT(o)} \frac{387}{8 \times 60}$$

$$= \frac{40 . 93}{480} + \frac{1 . 387}{480}$$

or $\pi_{VT(c)}$ = 8.55

3. Predicted Failure Rate - Combining the values from 2 (a,b and c) above into the prediction equation as follows:

$$\lambda_p = \lambda_a (\pi_{TM} \pi_S \pi_{VT(c)} \pi_{QA}) + \lambda_b (\pi_{TE} \pi_C \pi_{VT(c)} \pi_{Qb})$$

$$= .0007 (4 \times 1 \times 8.55 \times 1) + .0002 (12 \times 18 \times 8.55 \times 1)$$

= .024 (mechanical) + .360 (electrical)

λ_p = .384%/1000 hours or 0.384×10^{-5} failures per hour

4. Number of predicted failures - Seven hundred diodes on test for a duration of 4000 hours gives a total of 2.8 million part hours. Using the failure rate of 3 above the number of predicted failures is 11 computed as follows.

Number of Mechanical Failures = $.024 \times 10^{-5} \times 2.8 \times 10^6$

= 0.67 mechanical failures

This checks remarkably well with one intermittent mechanical open diode.

$$\text{Number of Electrical Failures} = 0.360 \times 10^{-5} \times 2.8 \times 10^{6}$$
$$= 10.1 \text{ electrical failures}$$
$$\text{Total predicted number of failures} = 10.10 + 0.67 = 10.77$$
$$\text{or} \approx 11 \text{ failures}$$

C. Interpretation of Test Results

The conditions used in the prediction of 11 failures were experimentally reproduced in this test experiment. The later section herein on data analysis describes the detailed test results. These are believed to closely confirm the model when the types of failure observed are interpreted in terms of probable failure in typical application circuits.

The final test results as described in section IV "Data Analysis" can be summarized as follows:

A total of 37 diodes were found out of specification at the end of the test. The specification limits are general procurement requirements and depending on the circuit application do not define probable failures in actual circuit applications. Many minor variations outside the specification limits will not cause failure in specific circuit applications.

A total of 20 diodes of the 37 out-of-specification are believed degraded to the point that they would be classed as real failures in some sort of circuit. For this purpose two basic classes of circuits are considered. These are those in digital service where the circuitry is critical of recovery time but generally insensitive to leakage, and those in linear or analog service where the circuitry is usually insensitive to diode recovery time but more critical of leakage.

A total of 15 out of the 20 probable application failures are judged to be probable failures in analog circuitry and 8 of the 20 are probable failures in digital circuitry. This means that 3 of the 20 would be failures in either type of circuit application.

If it is assumed that the model predicted the probable failures in digital circuitry the 11 predicted is pessimistic compared to the 8 actual. On the other hand if the prediction is assumed to apply only to analog circuitry the 11 predicted is optimistic compared to the 15 actual failures. If there is a general mix of circuitry in a system containing both analog and digital circuitry the predicted 11 failures is probably a more accurate prediction than could logically be expected.

From this it is believed that the model is verified as a reliable predictor of probable failure of the 1N3600 diodes when used in typical known applications. A future improvement in the model would be to include a term which takes into consideration the requirements for a specific application. This application factor (π_A), would be a function of the definition of failure in each application. Inclusion of this term would make possible a more precise prediction of failure rate where specific circuit requirements are known.

III EXPERIMENTAL METHODS

A. Electrical Parameter Measurements

The electrical parameters of the diodes tested and their specification limits are as follows:

Parameter	Limits
Forward voltage at 10 ma	0.66V to 0.74V
Reverse current at 50V	0.1 microampere maximum
Reverse recovery time	4 nanosecond maximum

The forward voltage was measured with a digital voltmeter, Hewlett-Packard, Model 3400 with accuracy of ±0.05% ± 1 digit. Reading four places the uncertainty is between 0.06% and 0.15%. The reverse current was measured with a microammeter, Hewlett-Packard, Model 425A with a 11021A probe with accuracy of ±2%. The reverse recovery time was measured with a sampling oscilloscope, Hewlett-Packard, Model 175A with a switching time tester plug-in unit, Hewlett-Packard Model 176A with a rise time measurement capability of 1 nanosecond.

The reverse recovery time measurements were made in accordance with the test plan described in MIL-STD-750B, Method 4031, test condition B. By this method each diode is loaded at a 20 ma forward current through a 100 ohm load. A 2 volt reverse pulse is then applied and the recovery time t_{rr} is the measured time from the zero crossing to the time that the current reduces to 10% of the peak reverse current.

The initial recovery measurements were made on all the diodes prior to their mounting on the test modules. The final recovery measurements were made after the 4000 hours of irradiation and the diodes had been removed from the modules. It was not possible to measure the recovery time with the diodes on the modules because of the large shunt wiring capacitance of the fixtures.

The initial, final, and intermediate measurements of forward voltage and reverse current were all made with the diodes mounted on the test modules and wired to the electrical power cables. For diode test these cables were plugged into a test set up with a diode selection switch. This allowed rapid measurement of the d-c parameters. During the course of the 4000 hour combined environment some of the diodes' external solder attachments failed and some of the wires to the modules failed. In these cases d-c measurements were made via manual probes. Failed solder connections at the diodes were repaired before restart of the environmental exposure.

B. Multi-Environment Facility

The facility to provide the multi-environment consisted of four primary control systems and three monitoring systems all intercoupled for remote operation. The test installation is illustrated in the block diagram of Figure 1. The four major control systems are:

1. Radiation Control System
2. Vibration Control System
3. Thermal Control System
4. Electrical Loading System

The two monitoring systems providing information concerning the operation within the sealed concrete cave are:

1. Radiation Monitoring
2. Intercom and Audible Noise Monitoring

1. Radiation Control System - This system consists of a mechanical actuator equipped with a remote controlled safety release that withdraws the cobalt source up from its lead pig (shield) into the active radiation position. In the event of a power failure the source is dropped by gravity into the safe position. If for any other reason an emergency occurs, the source can be safely lowered into the pig from the remote control station.

2. Vibration Control System - The diodes being tested were mounted on cantilever base plates attached to two mechanical (balanced eccentric weights) vibration tables. The installation is shown in the photograph of Figures 2, 3 and 4. The cantilever mounts were dynamically balanced with the solid extended plate to apply a 10 g sine wave vibration on the diodes. The on-off cycles of the vibration tables were programmed from the remote control station. Here a set of motor driven cams actuated appropriate control switches.

3. Thermal Control System - The diodes under test were mounted at a fixed radius from the radiation source on a set of 14 thermally controlled plates. The photograph of Figure 3 shows seven of the fourteen thermal control mounting plates. Visible on the near plate are two 25 watt (740 ohm) heater resistors, two thermal sensors (Bonded Platinum Wire Thermistors) and a safety thermal cutout at the center. The position of the heaters and sensors was later changed as shown in Figure 5 in order to achieve minimum temperature gradient across each mounting plate. The fifty diodes mounted to the radiation front of the plates were connected individually at the rear to a printed circuit wiring board as shown in Figures 5 and 6.

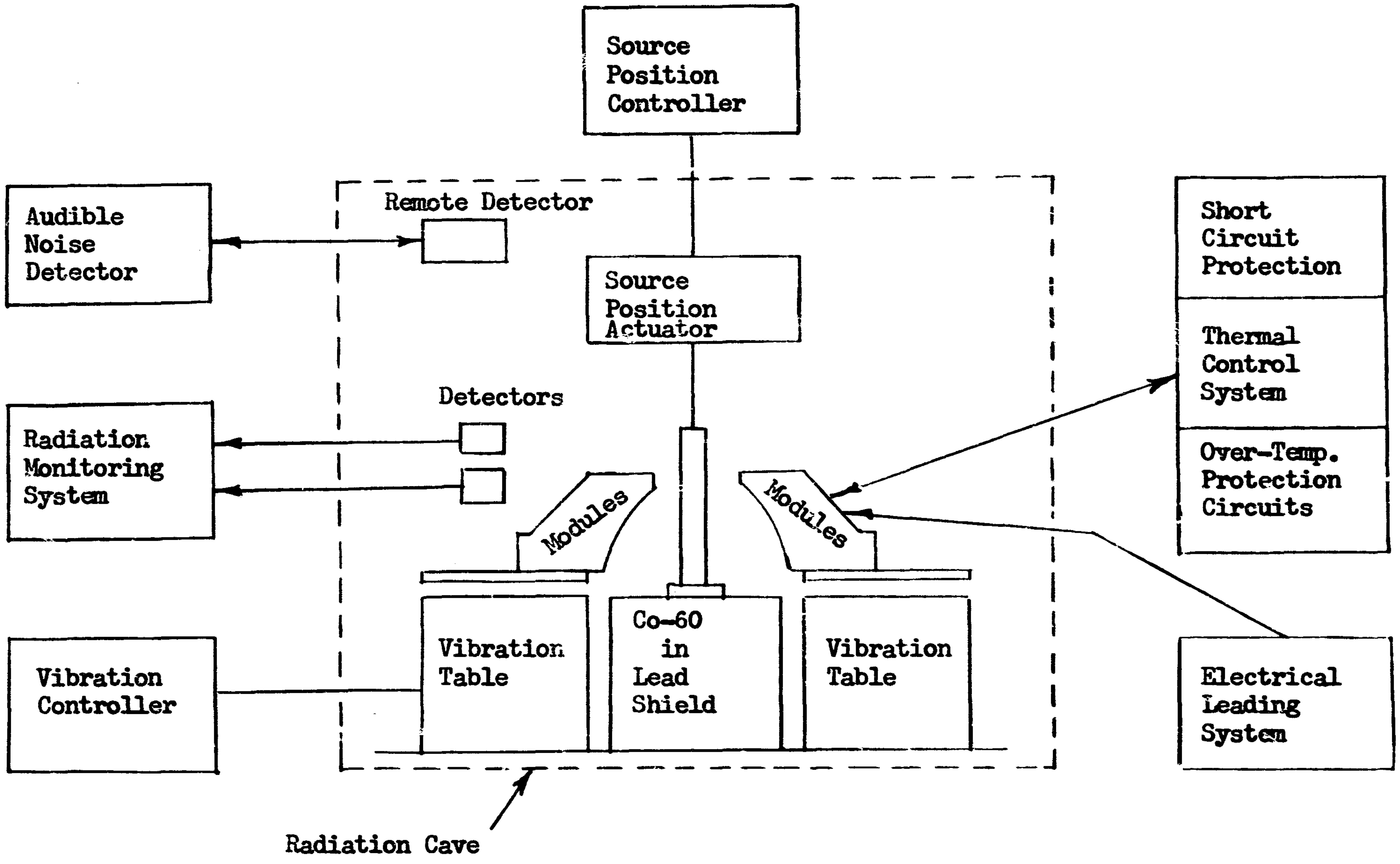


Figure 1. Hybrid Block Diagram: Diode Radiation Test Installation

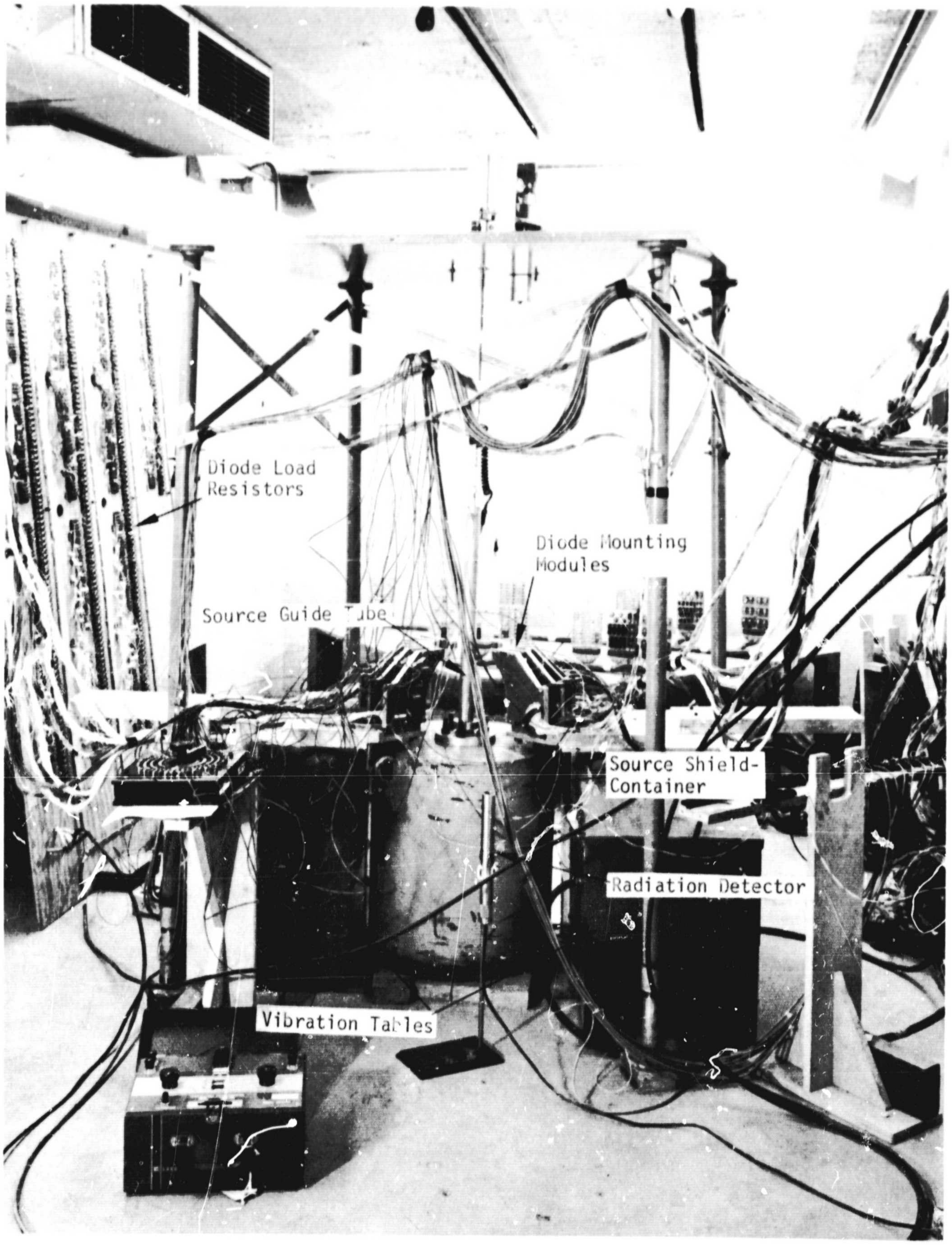


Figure 2. Vibration Mounting Installation

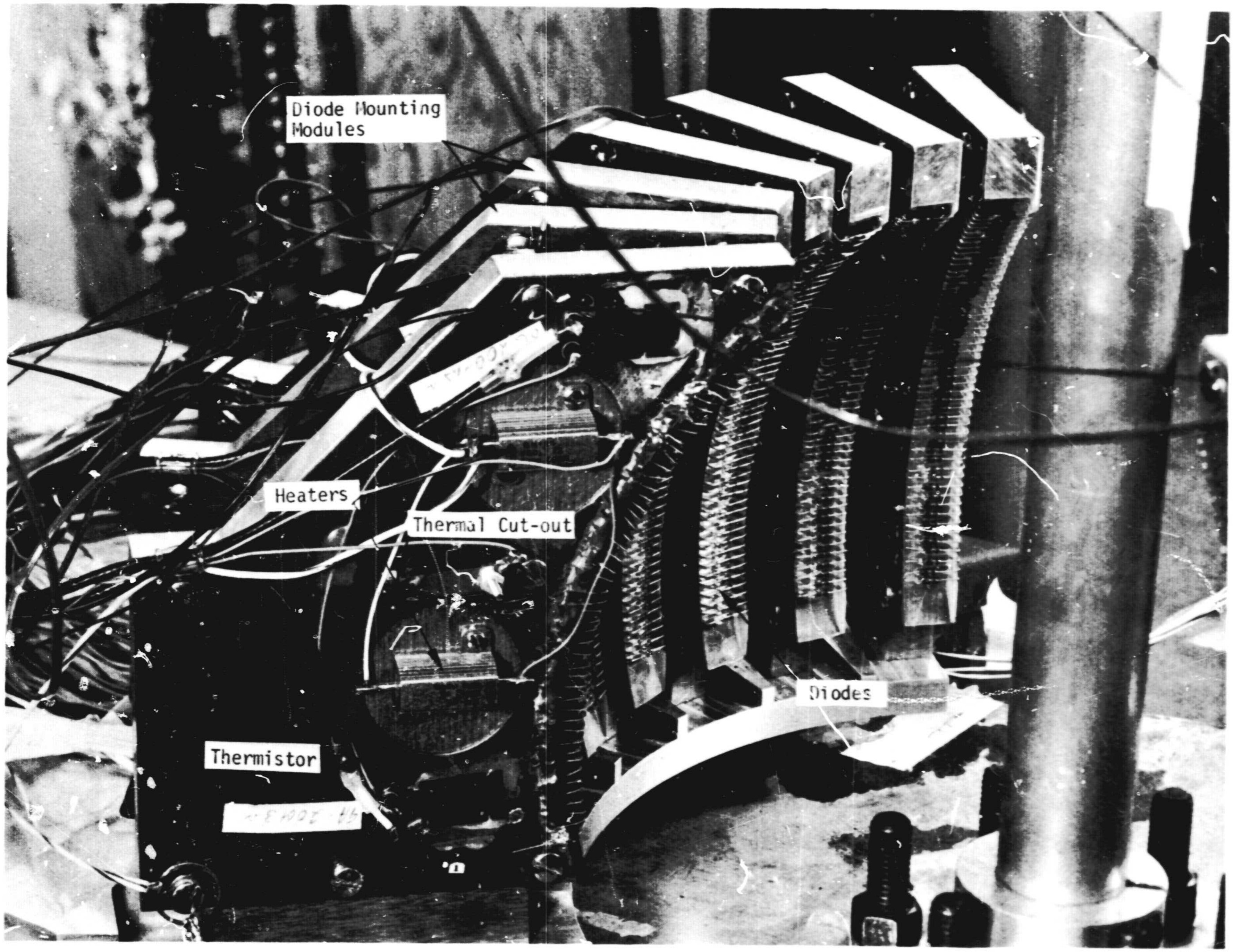


Figure 3. Thermal Control Mounting

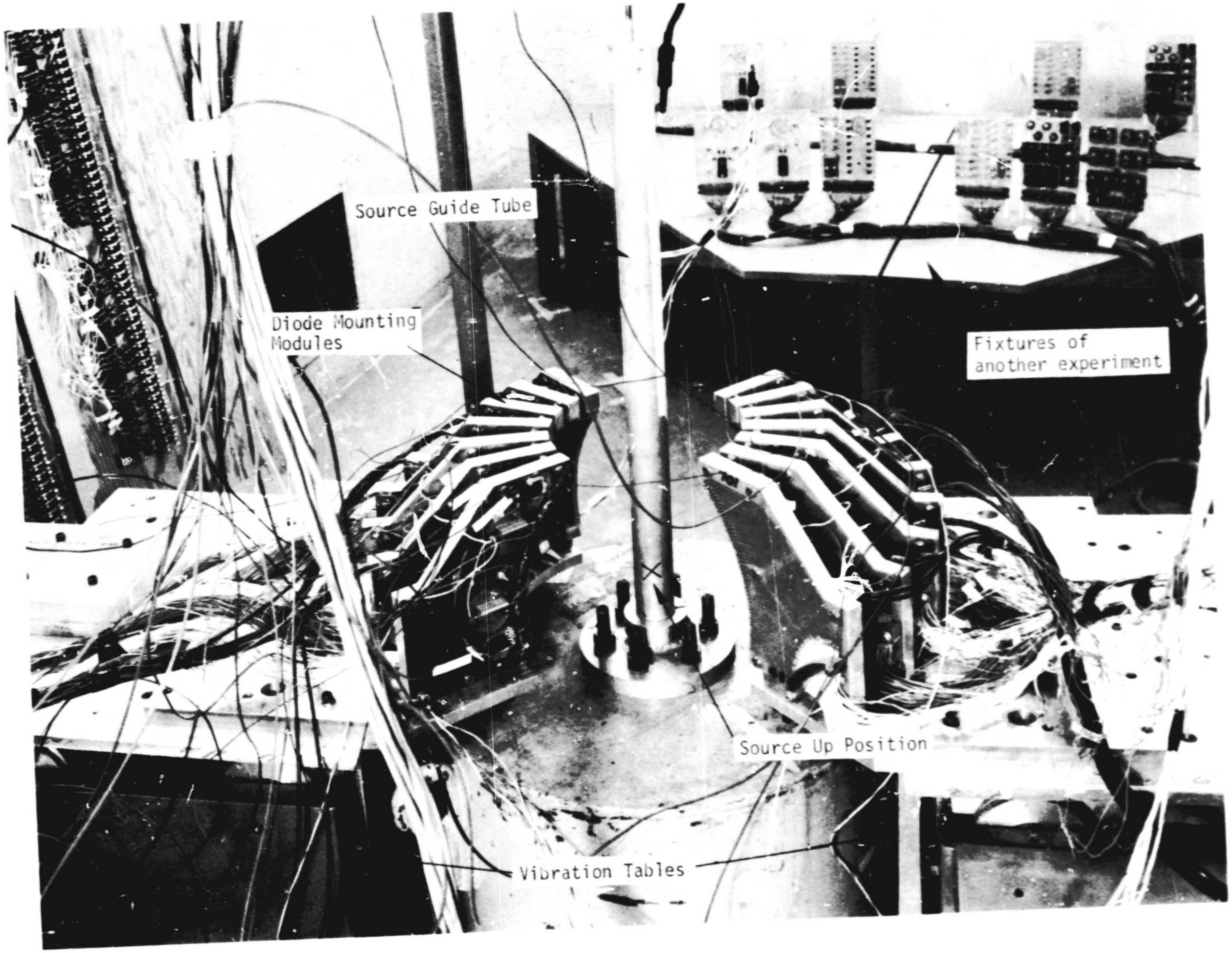


Figure 4. Complete Thermal and Vibration Assembly

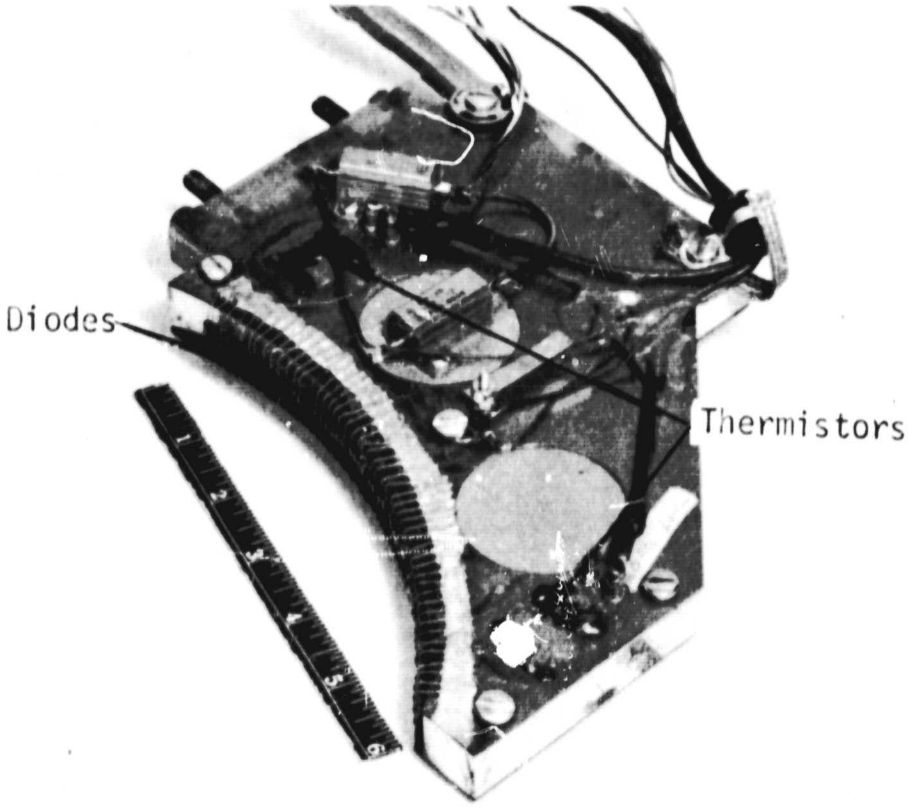


Figure 5. Diode Mounting Module: Heat Control Side View

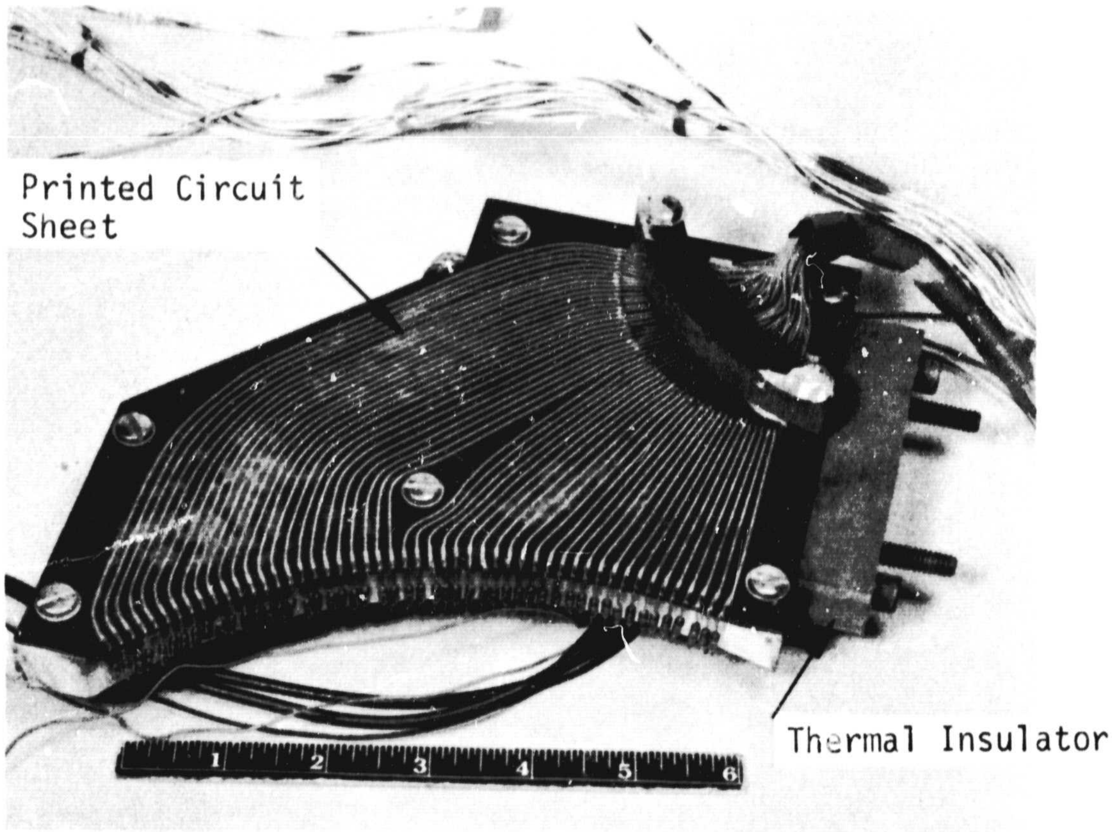


Figure 6. Diode Mounting Module: Diode Mounting Side View

Thermal isolation between the plates and the mounting base was achieved by means of the 1" thick phenolic insulating block shown beneath each plate. Insulation of the assembly from the ambient room air was provided by a fiberglass mat and an encompassing balsa wood box (not shown).

The photograph of Figure 4 shows the complete thermal and vibration assembly without the insulating covers. This photo reveals the printed circuit wiring board and the spherical radiation position profile achieved by the cantilevered vibration mounts.

4. Electrical Loading System - Electrical loading of the diodes was achieved by a solid state synchronous switch which alternately coupled a low power inverse voltage supply and a high current low forward voltage supply to the two halves of the system. This system maintained a constant high current load on the power supply.

5. Independent Monitoring System - A radiation monitoring system and an audible noise monitoring system were included in the facility instrumentation.

The Radiation Monitoring System contained a basic radiation sensor, ionization chamber, Victoreen Model 605, and Victoreen Model 575 Radocon meter. Also there was a back up detector consisting of an air-ionization chamber and a Keithley electrometer.

These devices were used to assure that the proper radiation existed during the radiation periods and that the radiation level was safe to entry into the cave during maintenance and equipment test periods. These basic devices were augmented for safety requirements by a hand operated counter (Model 440 manufactured by Victoreen).

The audible noise remote monitoring system was in effect, a special intercom which allowed the test operator to listen to the vibrator action from outside the closed radiation area. Any unusual sounds could be detected without removing the heavy concrete blocks which sealed the entrance to the cave.

C. DIODE HANDLING

A quantity of 750 JAN 1N3600 diodes manufactured by Fairchild Semiconductor Corp. (date Code 6848) were drawn from Hughes electronic stores, serialized and tested for recovery time. After the initial measurements 700 diodes were then soldered to the modules with the anodes connected to the common ground terminal and the cathodes to a printed circuit wiring board to which the electrical power cables were attached. The diodes were soldered in place before the excess lead length was clipped off to prevent shock to the diodes. During the solder process, the leads adjacent to the diodes were heat-sinked to preclude thermal damage. Four diodes damaged during installation were replaced and not included in the failure data. Following the 4000 hours environmental test and final d-c electrical test the diodes were removed for reverse recovery time test. Each cathode lead was unsoldered and the diode then removed by peeling back the anode lead out of the solder connection to the ground return plate. This avoided thermal damage and mechanical damage to the diode.

D. ENVIRONMENTAL EFFECTS AND MAINTENANCE

The test fixtures were adversely affected by the multi-environment. Occasional failures required maintenance where practicable. Several electrical power wires to the printed circuit boards on the modules opened at the point of attachment to the modules. The elevated temperature and gamma radiation both accelerate chemical processes which stiffen the polyvinyl chloride insulation on the wire. Figure 6 shows the insulations darkening which accompanies physical degradation, which is significant at about 10^8 rad.

The initial or zero hour data taken after the diodes were mounted on the test modules showed that 22 devices had leakage currents exceeding the 100 nA specification limit. The leakage current histogram for zero hours in Appendix B shows these devices as the upper tail of the distribution. During the first 1000 hours of operation the leakage current on all 22 devices decreased to less than 100 nA and remained within the specification limit throughout the test program. The most probable cause of these initial high readings was the effects of soldering heat and possible external contamination from the soldering flux used during the assembly of the diode test modules. The subsequent high temperature operation cleaned up the contamination and improved the ability to make accurate readings of the actual diode leakage currents. Since the high leakage readings were attributed to assembly and measuring problems and not to device defects the diodes were not counted as failures and their data was included in the final failure rate calculations.

During the second 1000 hour exposure interval several of the wires to the diodes on two modules failed open. The apparent failure mechanisms were loss of resilience of the insulation under the phenolic clamp with resultant motion and abrasion with ultimate failure of the wires. These wires were not repaired because to do so would have required disturbing many wires considered to be at incipient failure. This resulted in the loss of less than 20,000 part hours of electrical loading. The diodes were still subjected to the vibration temperature and radiation. Since the equivalent loss of diode test hours was negligible compared to the total test program of 2.8 million part hours it was neglected in the final failure rate calculations. The cable on one module was repaired where the break in the wire was before the phenolic clamps.

Figure 6 also shows the nylon spiral wrapping for the cable is discolored at the end nearest the source of radiation. Cable clamps of this same material used to clamp instrumentation cables to the rear edge of the modules broke as a result of the degradation due to heat and radiation and stress due to cable vibration. These nylon clamps were replaced by metal clamps with rubber linings.

Short lengths of cables mounted on the modules were subject to resonant vibration and were attached to the modules with epoxy. Several of these attachments parted after 1000 and 2000 hours of environment and required reattachment with fresh epoxy. The epoxy noticeably darkened after 4000 hours of the environment as may be seen by comparing the fresh epoxy in Figure 5 with aged epoxy in Figure 6. Colored photographs are used in order to make this discoloration visible.

IV DATA ANALYSIS

A. Data Handling

A large quantity of test data resulted from the test program. For each diode there were five time sequential readings of forward voltage drop (V_f), five values of the reverse leakage (I_r), and two of the reverse recovery time (t_{rr}). For the 700 diodes on test a total of 8,400 parameter readings were obtained.

To simplify the problem of accurately examining this large quantity of data for out-of-specification condition or unusual diode behavior, use was made of a GE265 time-sharing computer. The 7000 readings of V_f and I_r were punched on paper tape and loaded into the computer memory files for further processing.

A computer program was written in "X Basic" language for processing the data. This data analysis computer program is attached as appendix A of this report. The program computed the mean,standard deviation, skewness and kurtosis for each of the sets of parameter readings and time delta change of the parameter readings. The computer then printed out a frequency distribution histogram of the data. Provisions were made for removing extreme values from the histogram and listing their values separately.

B. Specific Analyses

The first analyses made using the computer were to prepare histograms of each of the zero hour, 1000 hour, 2000 hour, 3000 hour and final 4000 hour reading of the V_f and I_r measurements. These computer histograms were transferred to graph paper and are presented in appendix B of this report.

The V_f histograms are plotted using a linear scale for the parameter values and it can be seen that distributions are non-normal due to upper and lower extreme values. The shift of the mean value of V_f with test time is statistically significant. However the mean downward shift of less than 10 millivolts over the test period is within the variation which could be accounted for in the measurement test conditions of changing temperature of the room and in the accuracy of test measurement. Thus no significance is attached to the apparent downward trend in the forward voltage drop. An increase with time of the apparent quantity of outliers was at first thought significant but later discredited when the diodes were removed from their connections and tested individually. It was found that the apparent increase of forward voltage drop was generally caused by degradation of the connections and the test circuitry rather than by changes in the diodes themselves. Thus the test result can be interpreted that forward voltage drop is not a critical parameter and does not seriously degrade even after 4000 hours at maximum rated load and with the total radiation dose of 1.6×10^8 Rads.

For all practical purposes the analysis of degradation hinges about the values of reverse leakage (I_r) and recovery time (t_{rr}). Since the recovery time could not be measured while the diodes were mounted in the test circuit, the major indication of degradation with time and stress was the shift of values of the reverse leakage.

The computer was programmed to indicate those sets of data which appeared anomalous to the normal. These were then given closer scrutiny in order to verify the anomaly as a real failure or as an indication of instrumental error.

C. Anomalous Parameter Measurements

A total of 64 diodes were related to data which appeared to be anomalous in some respect. Many of these showed measurement of a forward voltage drop which was increasing with a definite trend in time. As shown in the conclusion column of Table I all of these V_f trends were traced to the connection network and no failure could be confirmed to the diodes from increased voltage drop.

The asterisks on Table I indicate the parameter measurements which were anomalous and which required further investigation before failure of the diode in question could be affirmed. The Table I Conclusion Comments describe the decisions reached by these further investigations. In most cases these investigations consisted of careful remeasurement of the diode characteristics after the individual items had been removed from the test setup and returned to the laboratory for careful analysis.

D. Diode Failures

Of the 64 diodes listed in Table I a total of 20 were confirmed as potential application failures. These are shown in Table II together with information concerning the failure mode and an interpretation of the type of application in which failure would have been likely. From Table II it can be seen that a total of 8 diodes would have been likely to fail in a digital application and 15 of the 20 in a linear circuit application as explained in section II C. This is based on a leakage current of 10 times the specification value for analog circuits and 1 microampere or a recovery time exceeding the 4 nanosecond specification limit for fast digital circuits.

E. Specification Limit Failures

Although the specification limits are generally artificial in regard to failure of devices because of design safety factors, it is important to see how many diodes degraded out of specification during the 4000 hours of combined stress. This information is summarized in Table III.

Table I. ANOMALOUS DIODES PARAMETER MEASUREMENTS

								Conclusion			
										Application Failure	
Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	OK	Out of Spec	Analog Circuit	Digital Circuit
007	V_f - mv	707	711	707	856 *	700	695	x			
	I_r - nA	13	12.5	13	13.2	15.9	-	x			
	t_{rr} - nsec	2.7	-	-	-	3.2	-	x			
010	V_f - mv	707	710	730	766 *	691	-	x			
	I_r - nA	16	15.2	15.6	.68μA *	19.5	17 nA	x			
	t_{rr} - nsec	2.8	-	-	-	2.6	-	x			
011	V_f - mv	706	711	705	727	688	-	x			
	I_r - nA	14	1.38μA*	0.72μA*	17	0.49μA	-		x		
	t_{rr} - nsec	2.7	-	-	-	2.7	-	x			
013	V_f - mv	707	711	705	845 *	782*	697	x			
	I_r - nA	15	14	14	12	20.6	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.6	0	x			
028	V_f - mv	708	711	705	706	702	-	x			
	I_r - nA	15	1.6μA*	1.2μA*	3.8μA*	2.35μA*	2.5μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	2.7	-	x			
039	V_f - mv	704	709	704	745	852 *	688	x			
	I_r - nA	17	16	16	14.8	21	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.6	-	x			
050	V_f - mv	708	710	705	706	703	-	x			
	I_r - nA	27	3μA*	1μA*	50μA*	105μA*	18 nA	x			
	t_{rr} - nsec	2.8	-	-	-	2.6	-	x			
088	V_f - mv	709	725	716	727	721 *	712	x			
	I_r - nA	30	14	12.4	12.5	15.1	-	x			
	t_{rr} - nsec	2.7	-	-	-	3.7	-	x			
096	V_f - mv	704	707	702	703	698	-	x			
	I_r - nA	26	150 *	440 *	780 *	228 *	215*nA		x		
	t_{rr} - nsec	2.8	-	-	-	2.8	-	x			

TABLE I. ANOMALOUS DIODES PARAMETER MEASUREMENTS (Continued)

Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	Conclusion			
								OK	Out of Spec	Application Failure	
										Analog Circuit	Digital Circuit
124	V_f - mv	704	706	714	707	718 *	692	x			
	I_r - nA	4.1μA*	17nA	15.2 nA	15.2 nA	19.6 nA	-	x			
	t_{rr} - nsec	2.9	-	-	-	2.7	-	x			
130	V_f - mv	709	711	707	706	695	-	x			
	I_r - nA	13	13	12	14	15.2	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
142	V_f - mv	705	710	706	710	693	-	x			
	I_r - nA	13	13	12	12	15	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
145	V_f - mv	706	708	704	705	703	-	x			
	I_r - nA	15	570 *	460 *	560 *	1.2μA*	810 nA*		x		
	t_{rr} - nsec	2.8	-	-	-	3.8	-	x			
147	V_f - mv	709	708	705	705	699	-	x			
	I_r - nA	21	0.31μA*	55	65	0.52μA*	-		x		
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			
158	V_f - mv	704	706	703	703	698	-	x			
	I_r - nA	17 nA	4.2μA*	140 nA*	130 nA*	2.2 μA*	140 nA*		x		
	t_{rr} - nsec	2.8	-	-	-	2.9	-	x			
160	V_f - mv	702	705	702	702	704	-	x			
	I_r - nA	24	2.3μA*	1.1μA*	1.8μA*	1.37μA*	920nA*		x		
	t_{rr} - nsec	2.8	-	-	-	2.9	-	x			
161	V_f - mv	705	708	705	705	700	-	x			
	I_r - nA	19	17.8	16.2	15	17.7	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.1 *	-		x		x
166	V_f - mv	708	709	706	706	701	-	x			
	I_r - nA	12	12	11	11.2	14.4	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			

TABLE I. ANOMALOUS DIODES PARAMETER MEASUREMENTS (Continued)

Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	Conclusion			
								OK	Out of Spec	Application Failure	
										Analog Circuit	Digital Circuit
179	V_f - mv	706	706	703	703	697	-	x			
	I_r - nA	15	2.8μA*	1.6μA*	3.4μA*	3.4μA*	3.8μA*		x	x	
	t_{rr} - nsec	2.9	-	-	-	3.4	-	x			
185	V_f - mv	704	707	705	705	699	-	x			
	I_r - nA	13	2μA*	1.3μA*	5.5μA*	3.5μA*	4.3μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.8	-	x			
209	V_f - mv	707	709	706	707	698	-	x			
	I_r - nA	14	3.4μA*	0.45μA*	0.62μA*	2.3 μA*	590 nA*		x		
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
224	V_f - mv	708	710	705	721	754 *	691	x			
	I_r - nA	16	1.35μA*	0.68μA*	0.4μA*	1.1 μA*	295 nA*		x		
	t_{rr} - nsec	2.8	-	-	-	3.1	-	x			
233	V_f - mv	709	715	709	723 *	721 *	711	x			
	I_r - nA	19	17.8	17	17	21	-	x			
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			
235	V_f - mv	710	716	708	673	664	-	x			
	I_r - nA	14	13	12	26.2	34.0	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
255	V_f - mv	702	772 *	OPEN *	694	691	693		x	x	x
	I_r - nA	15	14.4	14.2	16.2	17.4	-	x			
	t_{rr} - nsec	2.8	-	-	-	3.6	-	x			
274	V_f - mv	700	704	703	711	721 *	690	x			
	I_r - nA	17	16.2	19	16	19.8	-	x			
	t_{rr} - nsec	2.8	-	-	-	3.3	-	x			
284	V_f - mv	705	708	705	706	699	-	x			
	I_r - nA	15	1.5μA*	.98μA*	.7 μA*	1.7μA*	.86μA*		x		
	t_{rr} - nsec	2.8	-	-	-	3.8	-	x			

TABLE I. ANOMALOUS DIODES PARAMETER MEASUREMENTS (Continued)

Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	Conclusion			
								OK	Out of Spec	Application Failure	
										Analog Circuit	Digital Circuit
288	V_f - mv	708	709	706	706	700	-	x			
	I_r - nA	24	2.6μA*	1.3μA*	1.1μA*	1.9μA*	1.15μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			
318	V_f - mv	709	712	708	709	702	-	x			
	I_r - nA	10	11	11.5	10.5	13.2	-	x			
	t_{rr} - nsec	2.8	-	-	-	5.5 *	-		x		x
332	V_f - mv	702	707	704	704	697	-	x			
	I_r - nA	85	72	28	0.76μA*	0.3μA*	-		x		
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			
362	V_f - mv	707	712	712	710	705	-	x			
	I_r - nA	15	.72μA*	.44μA*	.25μA*	1.6μA*	.46μA*		x		
	t_{rr} - nsec	2.8	-	-	-	3.8	-	x			
363	V_f - mv	706	708	709	707	764 *	695	x			
	I_r - nA	14	13.8	14	12.5	16.8	-	x			
	t_{rr} - nsec	2.8	-	-	-	3.5	-	x			
367	V_f - mv	703	704	705	703	697	-	x			
	I_r - nA	20	17.4	20	2.2μA*	1.0 μA*	.84μA*		x		
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			
379	V_f - mv	705	675 *	705	704	668 *	691	x			
	I_r - nA	17	52	51	46	62	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.8	-	x			
380	V_f - mv	709	654 *	710	709	669 *	694	x			
	I_r - nA	22	52	50	46	62	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.7	0	x			
381	V_f - mv	708	654 *	709	707	702	695	x			
	I_r - nA	17	52	50	46	62	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.9	-	x			

TABLE I. ANOMALOUS DIODES PARAMETER MEASUREMENTS (Continued)

Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	Conclusion			
								OK	Out of Spec	Application Failure	
										Analog Circuit	Digital Circuit
424	V_f - mv	711	706	707	705	695	-	x			
	I_r - nA	14	.64μA*	.42μA*	1.4 μA*	1.29μA*	1.15μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	2.9	-	x			
425	V_f - mv	711	706	707	705	698	-	x			
	I_r - nA	14 nA	32μA*	240μA*	122μA*	44 μA*	18.0μA*		x	x	x
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			
443	V_f - mv	709	708	708	707	701	-	x			
	I_r - nA	14	3.5μA*	1.15μA*	2.8 μA*	1.8 μA*	1.65μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.6	-	x			
447	V_f - mv	712	710	710	709	704	-	x			
	I_r - nA	14	2.1μA*	1.3μA*	2.5 μA*	2.7 μA*	2.75μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.8	-	x			
449	V_f - mv	707	708	709	706	702	-	x			
	I_r - nA	15	2.33μA*	20.2	17	0.34 μA*	-		x		
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
463	V_f - mv	715	707	709	707	701	-	x			
	I_r - nA	13	12.4	11	11.8	14	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
466	V_f - mv	711	707	708	706	799	-	x			
	I_r - nA	32	14.5	.37μA*	20	.44μA*	-		x		
	t_{rr} - nsec	2.8	-	-	-	2.9	-	x			
501	V_f - mv	702	704	705	703	696	-	x			
	I_r - nA	16	.7μA*	24μA*	10 μA*	96 μA*	16 μA*		x	x	x
	t_{rr} - nsec	2,7	-	-	-	3.0	-	x			
504	V_f - mv	709	722	704	695	OPEN * wiring	692	x			
	I_r - nA	16	25	25.2	16.2	20.3	-	x			
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			

TABLE I. ANOMALOUS DIODES PARAMETER MEASUREMENTS (Continued)

								Conclusion			
										Application Failure	
Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	OK	Out of Spec	Analog Circuit	Digital Circuit
505	V_f - mv	709	713	715	704	OPEN * wiring	697	x			
	I_r - nA	12	14.5	22	12	14	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
518	V_f - mv	711	706	712	711	705	-	x			
	I_r - nA	11	11	9	10	12	-	x			
	t_{rr} - nsec	2.9	-	-	-	4.0 *	-	x			
524	V_f - mv	716	699	704	713	748 *	690	x			
	I_r - nA	22	21.8	17.2	18.5	22	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.6	-	x			
548	V_f - mv	716	700	706	703	697	-	x			
	I_r - nA	15	1.9μA*	1.1μA*	2.3μA*	2.55μA*	2.15μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.4	-	x			
565	V_f - mv	703	708	711	710	705	-	x			
	I_r - nA	42	16	11.2	12.5	30	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.1 *	-		x		x
571	V_f - mv	703	707	711	709	704	-	x			
	I_r - nA	14	13	37	.38μA*	0.16 μA*	-		x		
	t_{rr} - nsec	2.8	-	-	-	3.3	-	x			
582	V_f - mv	703	673 *	707	705	699	690	x			
	I_r - nA	13	28	26	27	32	-	x			
	t_{rr} - nsec	2.8	-	-	-	3.2	-	x			
583	V_f - mv	705	673 *	707	705	700	691	x			
	I_r - nA	19	28	26.2	27	32	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.9	-	x			
588	V_f - mv	709	707	710	708	702	-	x			
	I_r - nA	13	1.9μA*	1.5μA*	2.4 μA*	3.3 μA*	2.8μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.8	-	x			

TABLE I. ANOMALOUS DIODES PARAMETER MEASUREMENTS (Continued)

Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	Conclusion			
								OK	Out of Spec	Application Failure	
										Analog Circuit	Digital Circuit
624	V_f - mv	704	703	707	714	699	-	x			
	I_r - nA	16	10μA*	2μA*	4μA*	36 μA*	7.6μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.3	-	x			
633	V_f - mv	704	703	707	705	700	-	x			
	I_r - nA	14	13	12	13	14.4	-	x			
	t_{rr} - nsec	2.8	-	-	-	4.0 *	-	x			
656	V_f - mv	704	703	706	705	700	-	x			
	I_r - nA	16	1μA*	.86μA*	1.8μA*	1.9μA*	1.85μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			
665	V_f - mv	706	704	707	706	701	-	x			
	I_r - nA	18	.65μA*	1.0μA*	0.9μA*	40 μA*	3.3μA*		x	x	
	t_{rr} - nsec	2.8	-	-	-	2.8	-	x			
676	V_f - mv	701	700	704	702	697	-	x			
	I_r - nA	16	17.2	28	32	0.36 μA*	-		x		
	t_{rr} - nsec	2.8	-	-	-	2.8	-	x			
689	V_f - mv	707 *	723 *	726	731	725	716	x			
	I_r - nA	24	66	33	0.32μA*	82 nA	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.9	-	x			
700	V_f - mv	707	708	711	710	704	699	x			
	I_r - nA	12	11.8	11.0	11.2	13.3	-	x			
	t_{rr} - nsec	2.8	-	-	-	5.6 *	-		x		x
704	V_f - mv	712	715	722	734	764 *	699	x			
	I_r - nA	19	16	14.2	13.2	20	-	x			
	t_{rr} - nsec	2.8	-	-	-	2.6	-	x			
709	V_f - mv	701	708	704	705	701	-	x			
	I_r - nA	17	72.2μA*	48	44	160*	-		x		
	t_{rr} - nsec	2.8	-	-	-	3.0	-	x			

TABLE I. ANOMALOUS DIODES PARAMETER MEASUREMENTS (Continued)

Serial Number	Parameter and Units	0 Hours	1000 Hours	2000 Hours	3000 Hours	4000 Hours	Confirm Final	Conclusion			
								OK	Out of Spec	Application Failure	
										Analog Circuit	Digital Circuit
711	V_f - mv	708	714	711	714	710	-	x			
	I_r - nA	16	10.5	11	15	100	-	x			
	t_{rr} - nsec	2.8	-	-	-	5.5 *	-		x		x

TOTAL NUMBER OF DEVICE FAILURES

	Out of Spec	Analog Circuit	Digital Circuit
Number of Devices Out of Specification	37**		
Number of Devices Considered Analog Circuit Failures		15	
Number of Devices Considered Digital Circuit Failures			8
Total Number of Devices Considered Application Failure		20	

* Anomalous Readings: Note that several of the leakage readings marked anomalous and not counted as true failures were caused by leakage in the test fixtures. The final determination of the diode condition being out of specification or outside defined application failure limits was made based on measurements of the diodes after their removal from the test fixtures.

** The number of devices out of specification (37) includes one intermittent diode.

Table II: Critical Diode Failures (20 Devices)

SERIAL NUMBER	FAILURE MODE		APPLICATION - FAILURE	
	PARAMETER	MEASUREMENT	DIGITAL	LINEAR
28	I_r	2.5 μA		X
161	t_{rr}	4.1 n sec	X	
179	I_r	3.8 μA		X
185	I_r	4.3 μA		X
255	All	Open Intermittent	X	X
288	I_r	1.15 μA		X
318	t_{rr}	5.5 nsec	X	
424	I_r	1.15 μA		X
425	I_r	18 μA	X	X
443	I_r	1.65 μA		X
447	I_r	2.75 μA		X
501	I_r	16 μA	X	X
548	I_r	2.15 μA		X
565	t_{rr}	4.1 n sec	X	
588	I_r	2.8 μA		X
624	I_r	7.6 μA		X
656	I_r	1.85 μA		X
665	I_r	3.3 μA		X
700	t_{rr}	5.6 n sec	X	
711	t_{rr}	5.5 n sec	X	
		Number of failures	8	15

Table III shows that no diode failed by degradation of the forward voltage drop outside of the specification limits of 660 mv to 740 mv. This fact suggests that the various combined stresses may have been beneficial in counteracting any single stress tendency to change the forward conductance.

Reverse leakage current increased beyond the 100 namp specification limit on 31 diodes. This fact could lead to the conclusion that the combined stresses tend to decrease the inverse impedance of the weaker devices. This is confirmation that this phenomena can be used as a valuable screening test using accelerated combined environments for relatively short times and checking the change of reverse leakage. Unfortunately there is no correlation between changes of recovery time and changes of reverse leakage. These apparently are independent degradation mechanisms and must be measured separately.

As Table III shows there are a total of 37 diodes which degraded out of specification including the intermittent open.

F. Failure Rate Determination

Because the model was derived to predict the probable failure rate of devices while in specific stress service it is interesting to compare the predicted with measured failure rates. The predicted failure rate from the model relating to the 11 predicted failures for 2.8 million part hours is .39% per thousand hours. This relates roughly to a computed statistical "best estimate" which can be compared to the figures computed from the actual measurements as shown in Table IV.

V. CONCLUSION

The models for predicting failure rate and the quantity of failures to be expected in a given environment was developed under NASA-Hughes Contract NAS 5-9638, validated for values of the constants under Contract NAS 5-10325 and now verified by an independent combined environment life test under this Contract NAS 5-21027. The Hughes Aircraft Company believes that the successful accomplishement of this project represents the completion of a major milestone in the progress of Reliability Engineering. For the first time in history it is now possible to predict from a verified mathematical model, and in advance of tests, what the failure rate and quantity of failures will be under given conditions of environment and loading.

It is recommended that this same approach be applied now to the development and verification of a similar model for predicting the reliability of microcircuits. It is believed that this can be accomplished much more easily now that this and other modeling projects have been completed.

The failure rate prediction model used in this study was intended to predict the failure rate of the device in typical circuit application. On these devices where the predominant mode of failure is parameter or performance degradation the actual number of failures is dependent on the degree of degradation that is allowable before circuit failure occurs. In some applications an extremely large degradation may be tolerated and for other applications extreme stability may be necessary. The definition of failure becomes dependent on the specific requirements of each application.

A further improvement in the failure rate prediction model would be the inclusion of an application factor (π_A). Inclusion of this term would make possible a more precise prediction of failure rate and would further improve the ability to predict system failure rates. Further study and experimentation is recommended to establish how the π_A factor should be included in the model and what is its specific functional relationship with the circuit application requirements.

TABLE III: Specification Limit Diode Failures

Parameters and Test Conditions	Limits Min.	Max	Number of Failures
Forward Voltage, V_f at $I_f = 10$ mA	660 mV	740 mV	1 (intermittent open)
Reverse Current, I_r at $V_r = 50$ V	- -	100 nA	31
Reverse Recovery Time, t_{rr} at $I_f = 20$ nA $V_r = 2$ V $R_L = 100$ ohms	- -	4.0 ns	5

Table IV: Failure Rates Experienced

(Percent Per 1000, hours)

(Best Estimate, 60% and 90% confidence limits based on chi - square distribution)

Failure Definition		Spec Limit	Linear Circuit Application	Digital Circuit Application	Catastrophic
Number of Failures		37	15	8	1
Failure Rate Percent/1000 hrs.	Measured	1.32%/ 1000 hrs.	0.54%	0.29%	.036%
	Best Estimate	1.35%/ 1000 hrs.	0.56%	0.34%	.060%
	60% Conf.	1.40%/ 1000 hrs.	0.59%	0.46%	.072%
	90% Conf.	1.54%/ 1000 hrs.	0.76%	0.52%	.14%

APPENDIX A

DATA ANALYSIS COMPUTER PROGRAM

(PLUS PORTION OF AN ACTUAL
COMPUTER RUN HISTOGRAM)

```
MMF


01 FILE JEK2,JEK3,JEK4,JEK5,JEK6,JEK7,JEK8
4 PRINT "DELTA X=T(B)-T(A), WHAT VALUES FOR A AND B";
7 INPUT A,B
10  LET T(0)=0
13 DIM C(150)
16 DIM X(150)
25 DIM A(725)
28 LET S1=0
31 LET S2=0
34 LET S3=0
37 LET S4=0
40 LET N=1
41 LET I=1
43 LET L1=1.0E50
46 LET L2=-1.0E50
49 LET E1=0
52 PRINT
55 PRINT"ARE EXTREME VALUES OF THE DATA TO BE ELEMINATED?"
58 PRINT  "TYPE (0) FOR NO AND (1) FOR YES.";
61 INPUT L3
64 IF L3=0 THEN 82
67 PRINT"WHAT ARE THE UPPER AND LOWER LIMITS OF THE DATA"
70 PRINT"TO BE INCLUDED------";
73 INPUT L1,L2
80 PRINT "THE EXCLUDED DATA IS-- "
82 READ FILE D,T(1),T(2),T(3),T(4),T(5)
85 LET X(1)=T(B)-T(A)
88 IF X(1)>L1 THEN 97
91 IF X(1)<L2 THEN 97
94 GO TO 103
97 LET E1=E1+1
98 PRINT X(1)
100 GO TO 82
103 LET M1=X(1)
106 LET M2=X(1)
109 GO TO 157
110 IF ENDFILE 7 THEN 172\LET D=D+1
111 PRINT "D="D
112 IF ENDFILE D THEN 110
113 LET N=N+1
115 READ FILE D,T(1),T(2),T(3),T(4),T(5)
118 LET X(N)=T(B)-T(A)
124 IF X(N)>L1 THEN 133
127 IF X(N)<L2 THEN 133
130 GO TO 139
133 LET E1=E1+1
134 PRINT X(N)
136 GO TO 115
139 IF X(N)>M1 THEN 148
142 IF X(N)<M2 THEN 154
```

NME   CONTINUED

```
145 GO TO 157
148 LET M1=X(N)
151 GO TO 157
154 LET M2=X(N)
157 LET S1=S1+X(N)
160 LET S2=S2+X(N)↑2
163 LETS3=S3+X(N)↑3
166 LET S4=S4+X(N)↑4
169 GO TO 112
172 PRINT
175 LET M=S1/N
178 LET S=SQR((S2-S1↑2/N)/(N-1))
181 LET Z=(S3/N-3*S1*S2/(N↑2)+2*(S1/N)↑3)/(2*S↑3)
184 LET P1=(S4/N-4*S1*S3/N↑2+6*S1↑2*S2/N↑3-3*(S1/N)↑4)
187 LET P=(P1/(S2/N-S1↑2/N↑2)↑2-3)/2
190 PRINT
193 PRINT"THE FOLLOWING STATISTICS DESCRIBE THE DATA SUBMITTED"
196 PRINT
199 PRINT
202 PRINT "THE NUMBER OF PIECES OF DATA IS "I
205 PRINT
208 PRINT "THE MAXIMUM VALUE IS ---------- "M1
211 PRINT "THE MINIMUM VALUE IS ---------- "M2
214 PRINT
217 PRINT "THE MEAN VALUE IS ------------- "M
223 PRINT "THE STANDARD DEVIATION IS ----- "S
226 PRINT
229 PRINT "THE SKEWNESS IS --------------- "Z
232 PRINT
235 PRINT "THE KURTOSIS IS --------------- "P
236 PRINT
238 PRINT"THE NUMBER OF EXTREME VALUES ARE"
241 PRINT"WHICH IS EXCLUDED FROM THE DATA IS---"E1
242 PRINT
243 PRINT
244 FOR K=1 TO 150
247 LET C(K)=0
250 NEXT K
253 PRINT "                 DISTRIBUTION HISTOGRAM"
256 PRINT
259 PRINT
262 PRINT"CELL COUNT=H, UPPER LIMIT=M3, LOWER LIMIT=M4"
265 PRINT"WHAT VALUES FOR H,M3,M4";
268 INPUT H,M3,M4
271 LET R=(M3-M4)/H
274 LET C(1)=M4+R
277 FOR L=2 TO H
280 LET C(L)=C(L-1)+R
283 NEXT L
286 FOR I= 1 TO N
```

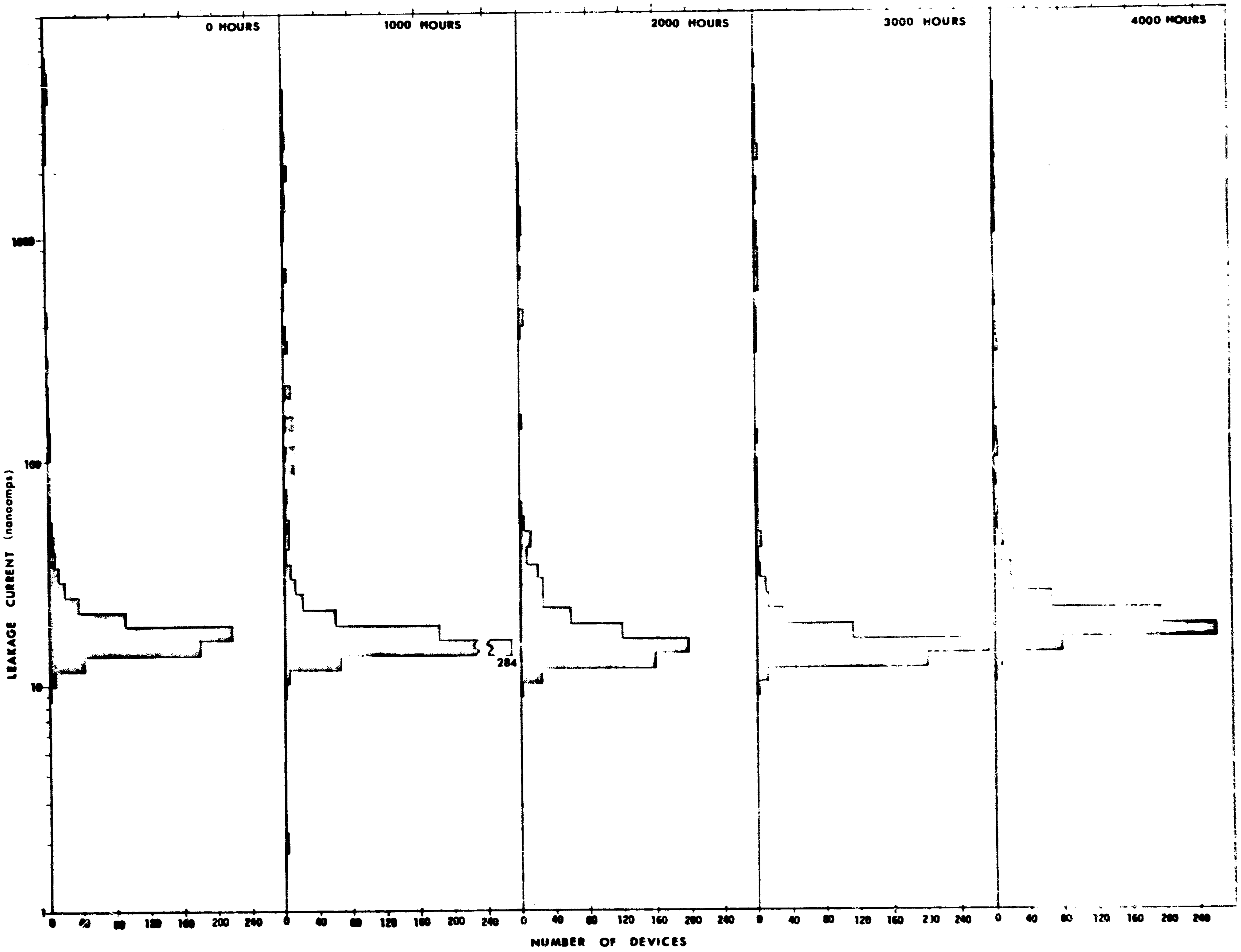
```
MMF      CONTINUED


287 IF X(I)>M3 THEN 304
289 LET K=0
292 LET K=K+1
295 IF X(I)<=C(K) THEN 301
298 GO TO 292
301 LET G(K)=G(K)+1
304 NEXT I
307 FOR J=H TO 1 STEP -1
310 LET G=G(J)
313 PRINT C(J)
316 LET C=G(J)
319 PRINT"  ";G(J);
322 IF G(J)<32 THEN 334
325 LET G(J)=G(J)-32
328 PRINT TAB(7);"XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX";
331 IF G(J)>=32 THEN 325
334 IF G(J)<16 THEN 343
337 LET G(J)=G(J)-16
340 PRINT TAB(7);"XXXXXXXXXXXXXXXX";
343 IF G(J)<8 THEN 352
346 LET G(J)=G(J)-8
349 PRINT TAB(8);"XXXXXXXX";
352 IF G(J)<4 THEN 361
355 LET G(J)=G(J)-4
358 PRINT TAB(8);"XXXX";
361 IF G(J)<2 THEN 370
364 LET G(J)=G(J)-2
367 PRINT TAB(8);"XX";
370 IF G(J)<1 THEN 376
373 PRINT TAB(8);"X";
376 PRINT
379 NEXT J
382 PRINT M4
385 PRINT
388 PRINT
391 PRINT "1 TO REDO HISTOGRAM, 2 TO RERUN, 0 TO END"
394 INPUT Z
397 PRINT
400 IF Z=0 THEN 415
403 IF  Z=1 THEN 244
406 PRINT"------------------------------------"
409 RESTORE FILE D
410 LET Z=0
412 GO TO 4
415 END
```

```
  726
    1     X
  725
    2     XX
  724
    0
  723
    3     XXX
  722
    2     XX
  721
    1     X
  720
    1     X
  719
    0
  718
    4     XXXX
  717
    2     XX
  716
    5     XXXXX
  715
    8     XXXXXXXX
  714
    6     XXXXXX
  713
   12     XXXXXXXXXXXX
  712
   35     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  711
   33     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  710
   49     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  709
   71     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXX      XXX
  708
   82     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXX
  707
   88     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXX
  706
   70     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXX      XX
  705
   48     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  704
   49     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  703
   47     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  702
   33     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  701
   19     XXXXXXXXXXXXXXXXXXX
  700
   13     XXXXXXXXXXXXX
  699
    4     XXXX
  698
    1     X
```

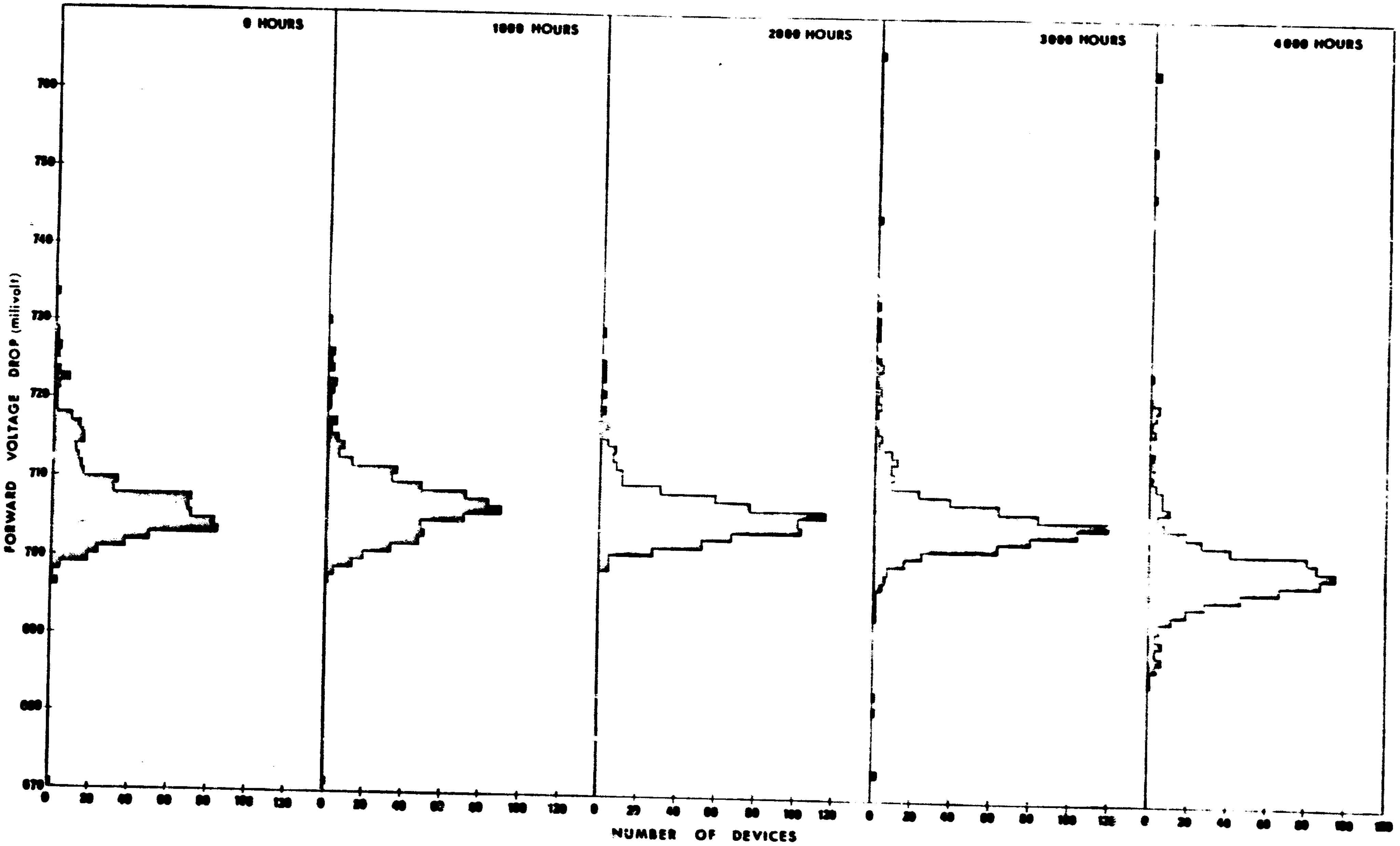
APPENDIX B

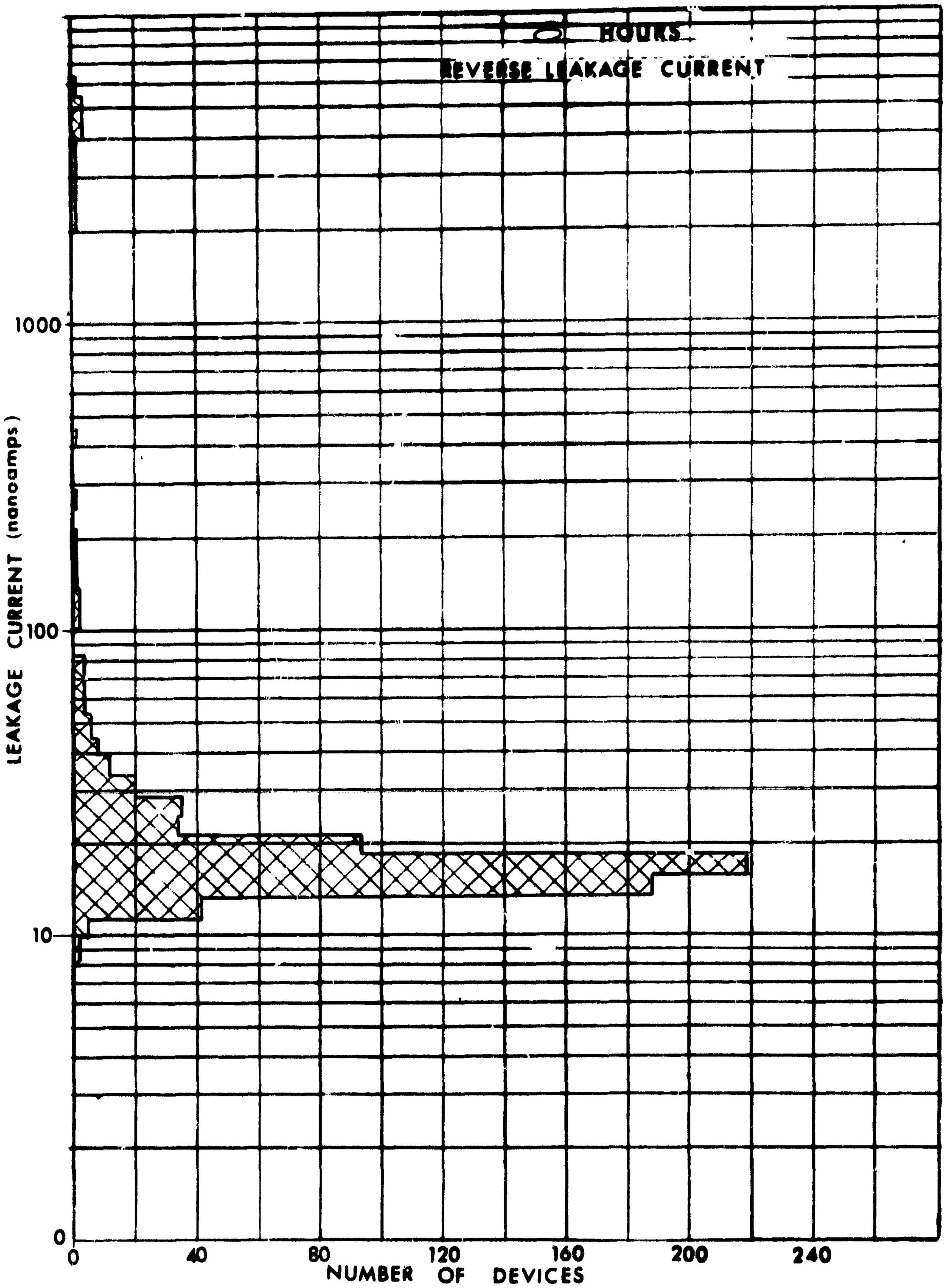
D.C. PARAMETER HISTOGRAMS

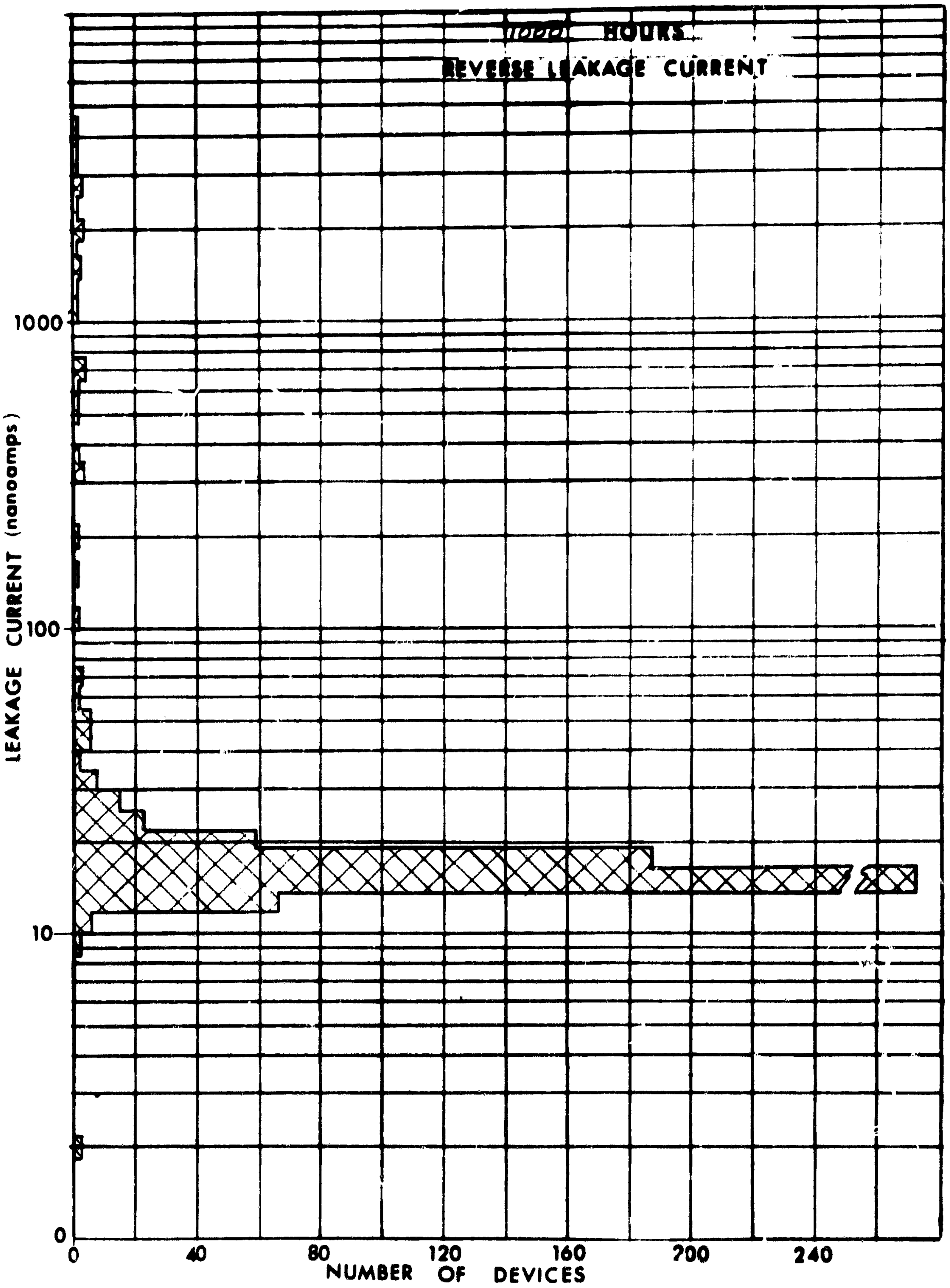
REVERSE LEAKAGE CURRENT DISTRIBUTION VERSUS TIME

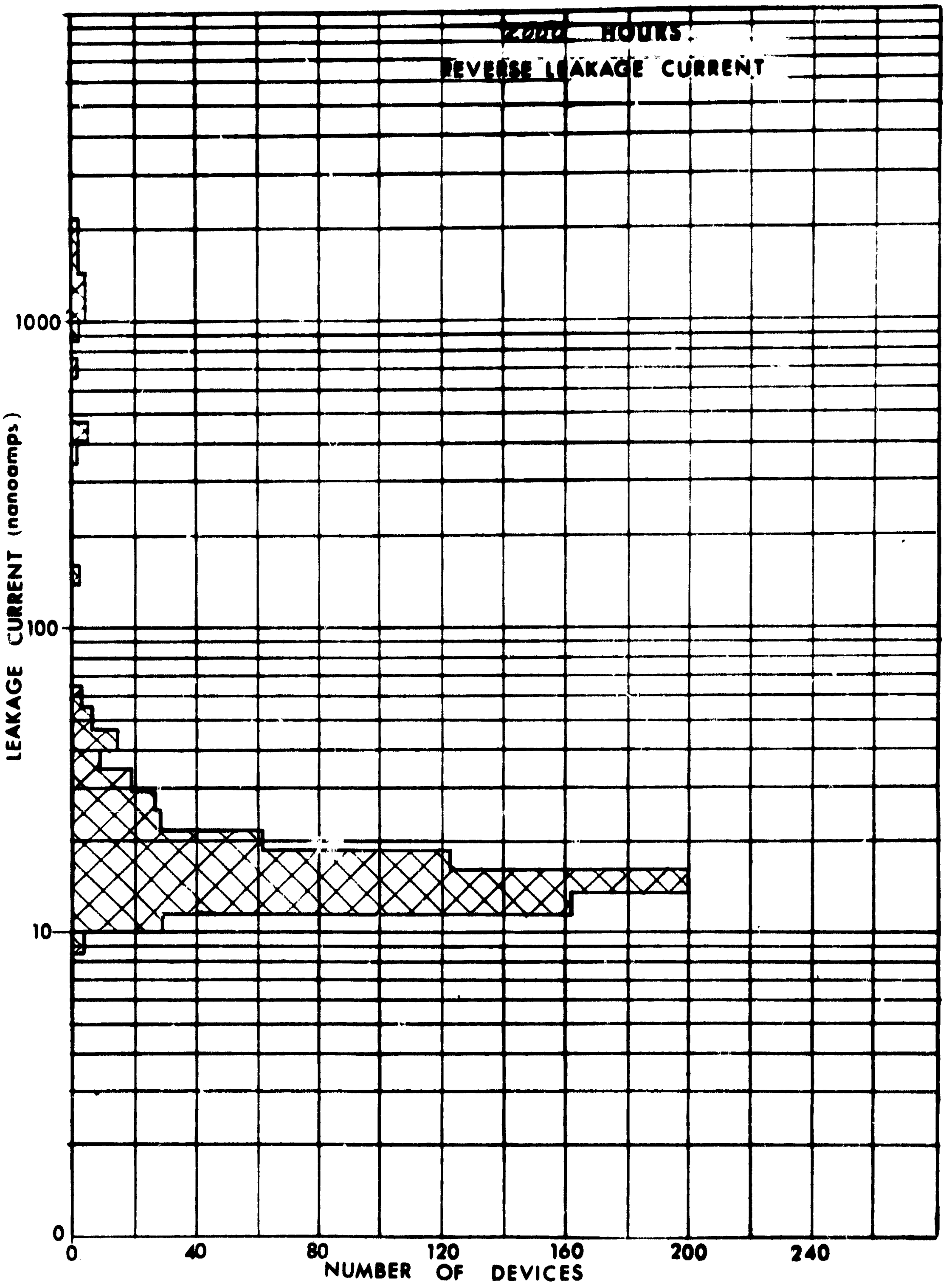


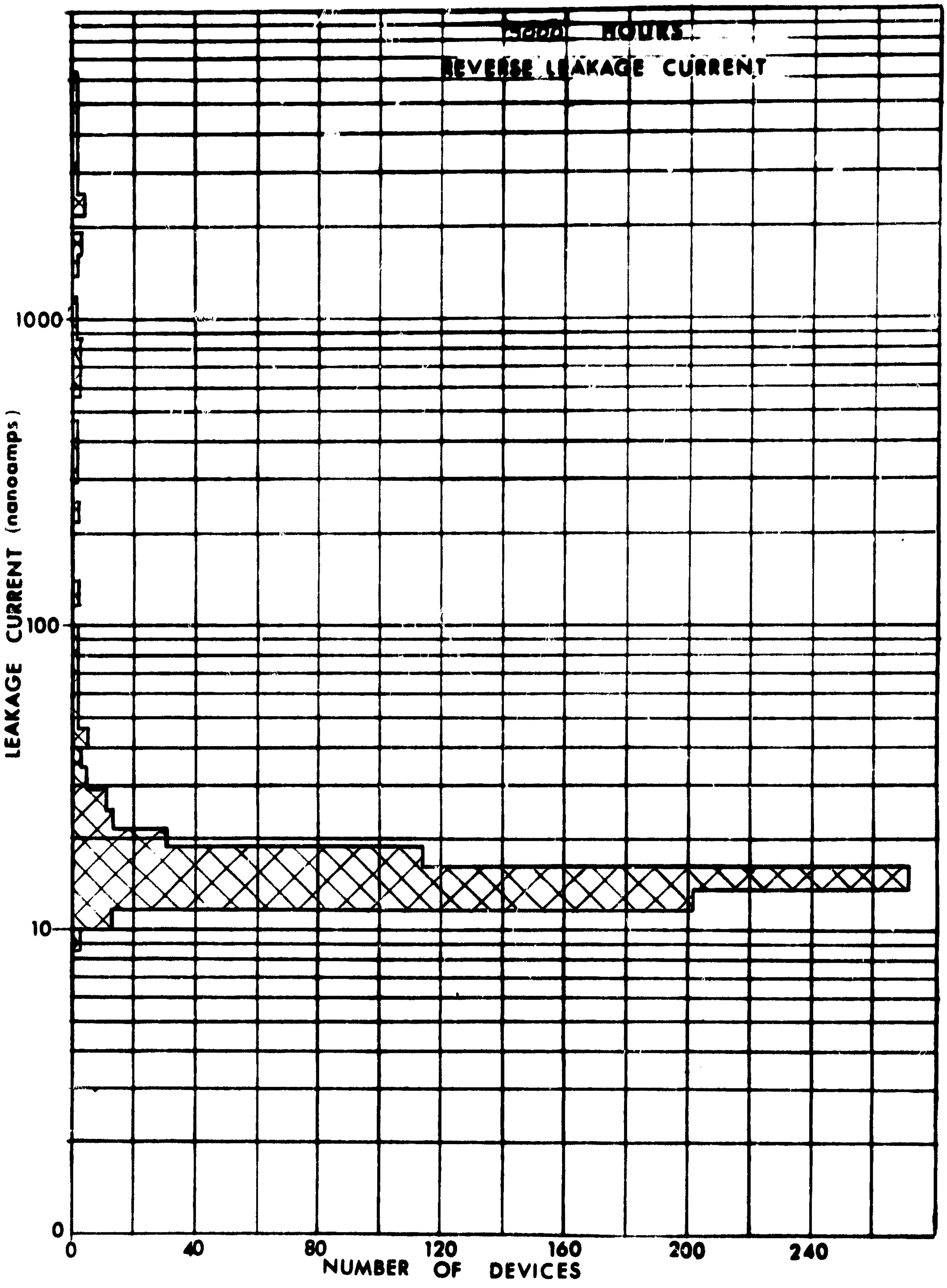
FORWARD VOLTAGE DROP DISTRIBUTION VERSUS TIME

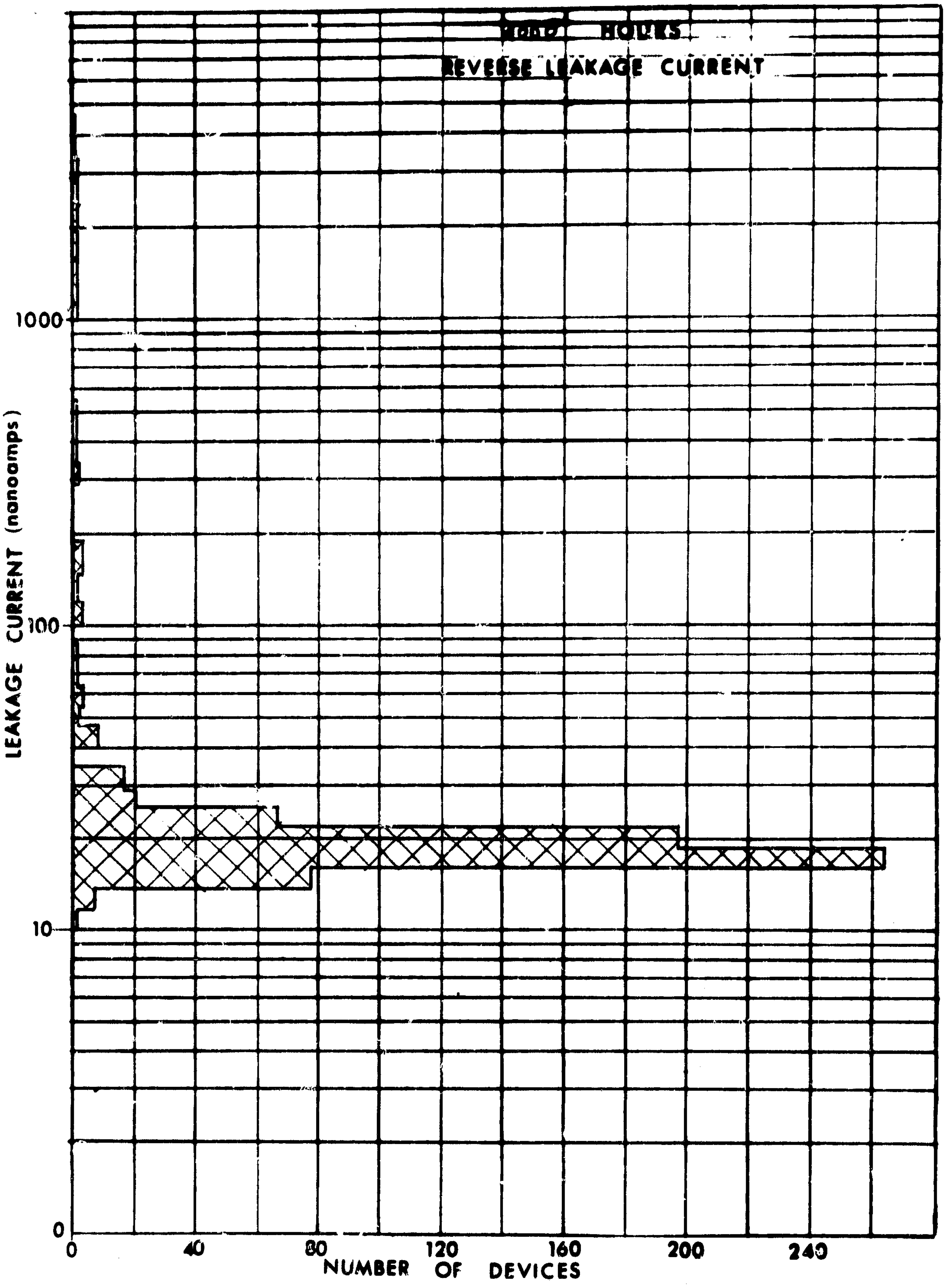


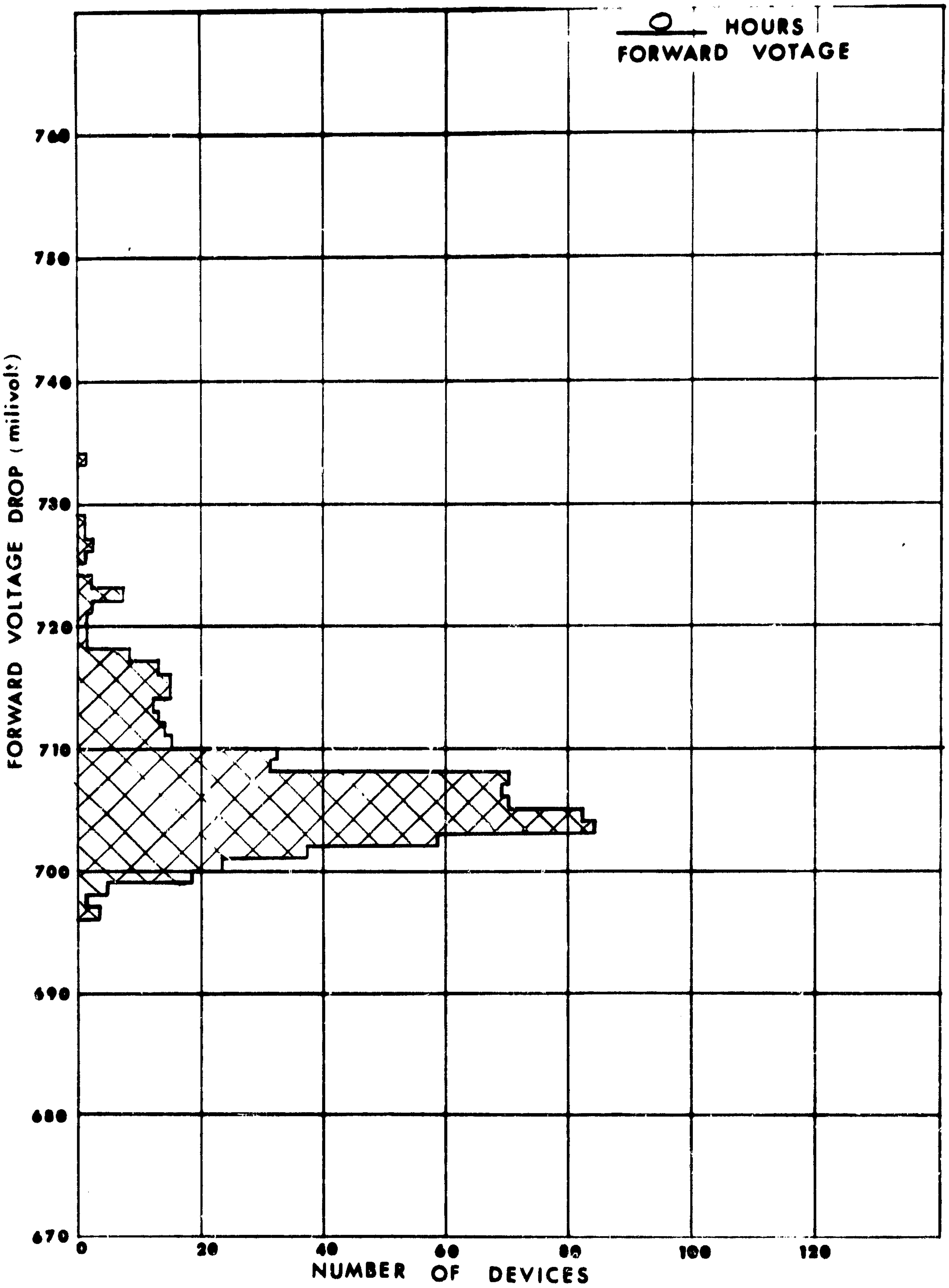

0 HOURS
REVERSE LEAKAGE CURRENT
LEAKAGE CURRENT (nanoamps)
1000
100
10
0
0
40
80
120
160
200
240
NUMBER OF DEVICES

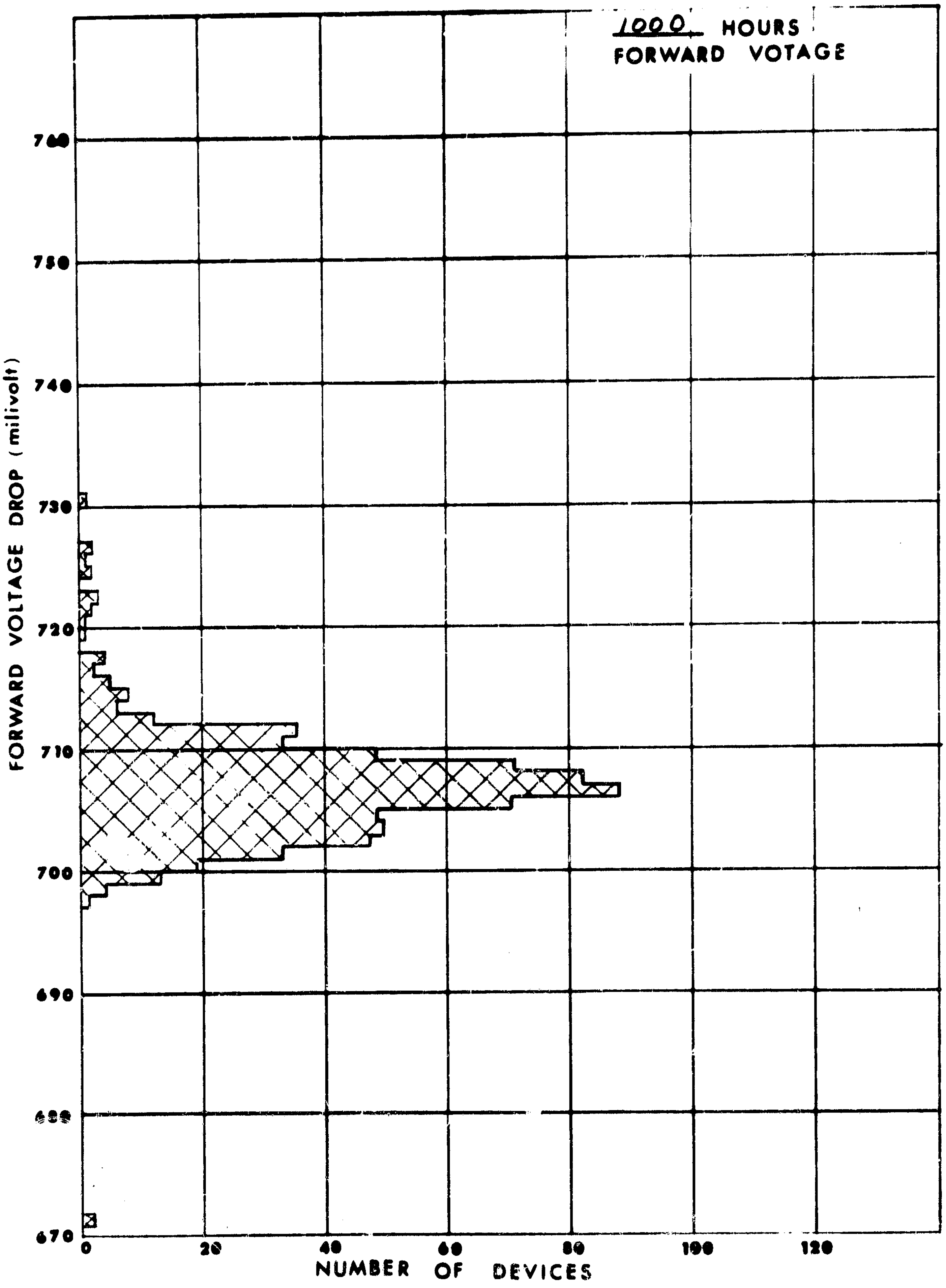

1000 HOURS
REVERSE LEAKAGE CURRENT
1000
100
10
0
LEAKAGE CURRENT (nanoamps)
0
40
80
120
160
200
240
NUMBER OF DEVICES

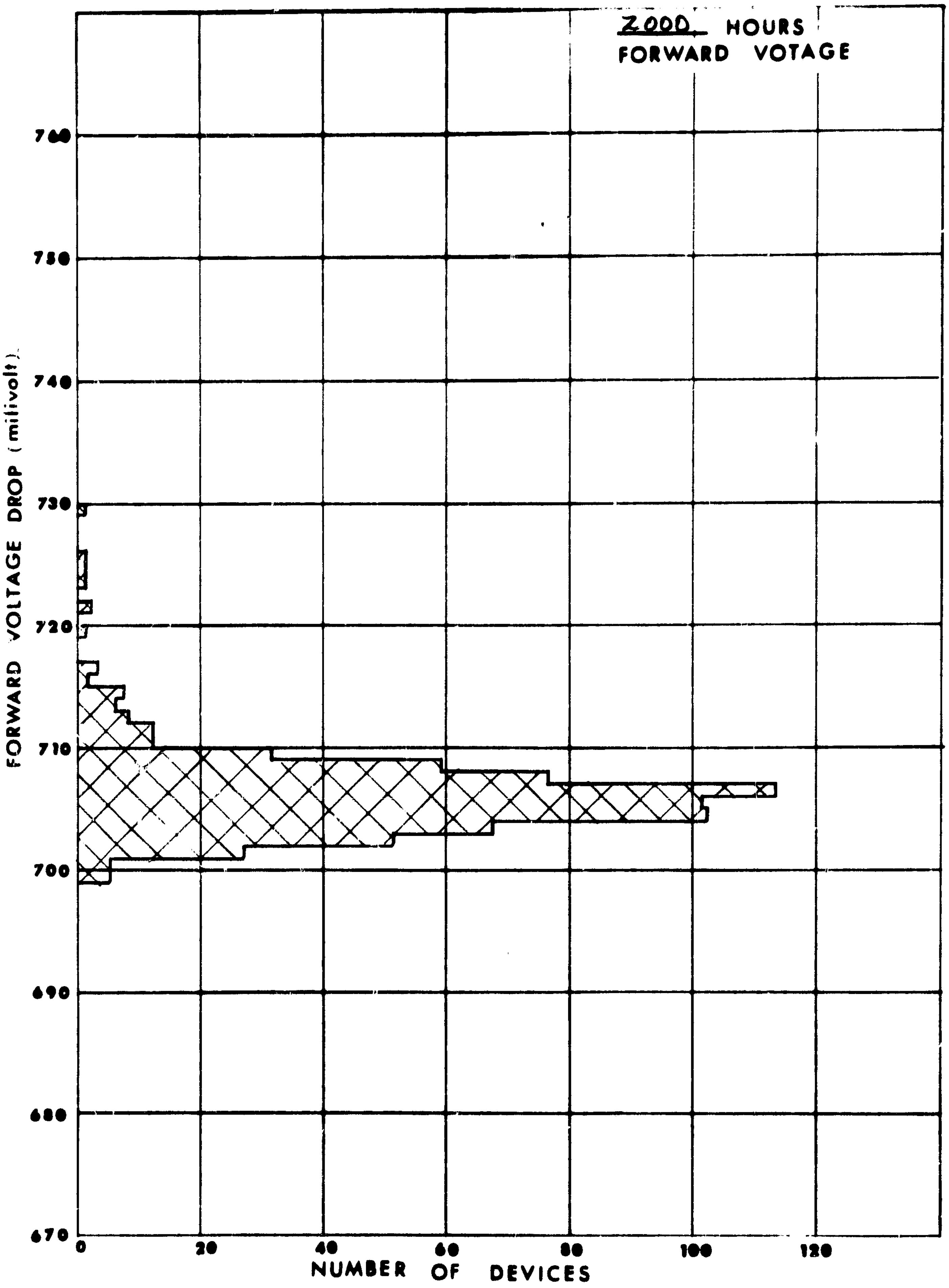

2000 HOURS
REVERSE LEAKAGE CURRENT
LEAKAGE CURRENT (nanoamps)
1000
100
10
0
0
40
80
120
160
200
240
NUMBER OF DEVICES

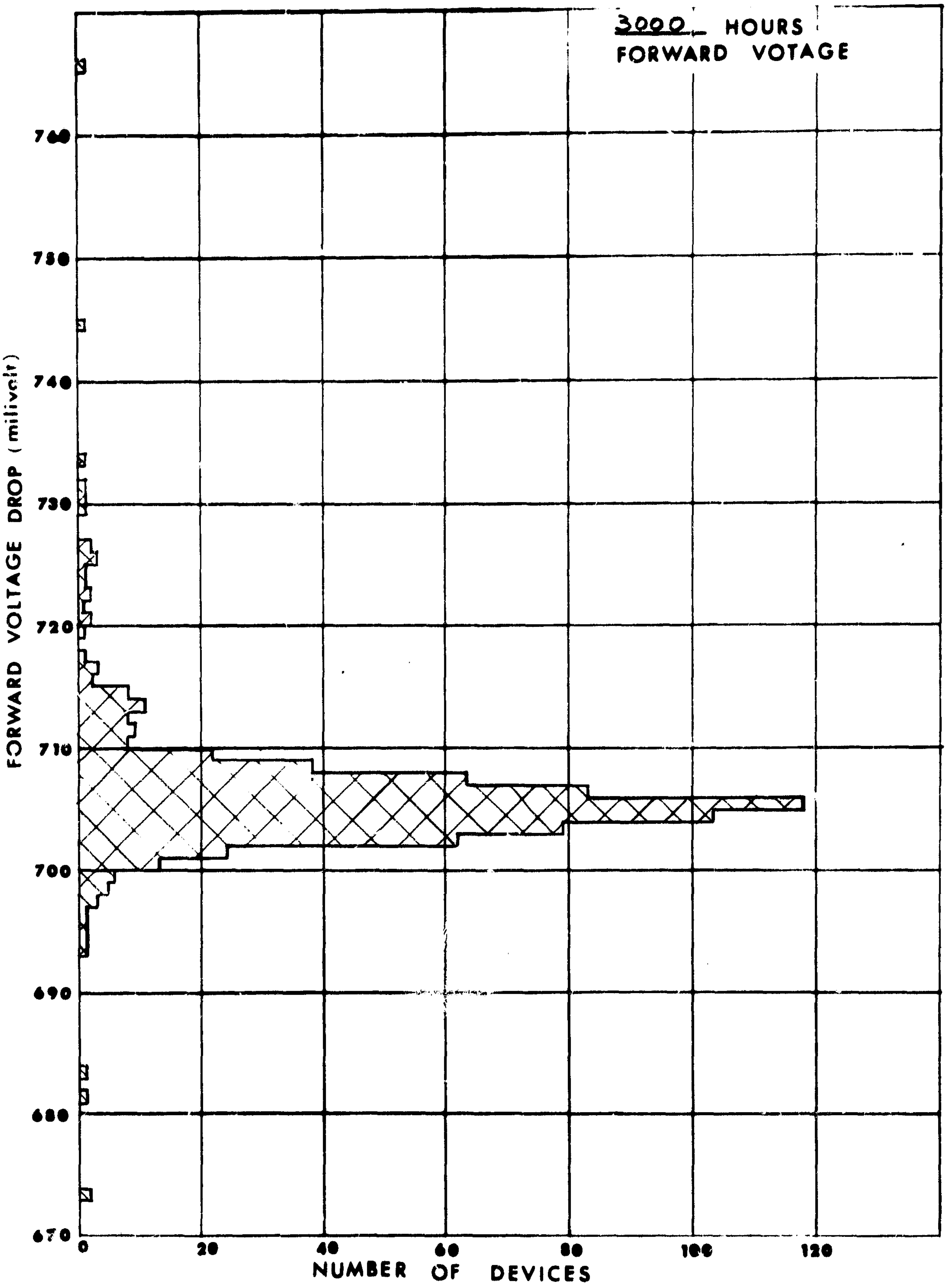

5000 HOURS
REVERSE LEAKAGE CURRENT
LEAKAGE CURRENT (nanoamps)
1000
100
10
0
0
40
80
120
160
200
240
NUMBER OF DEVICES

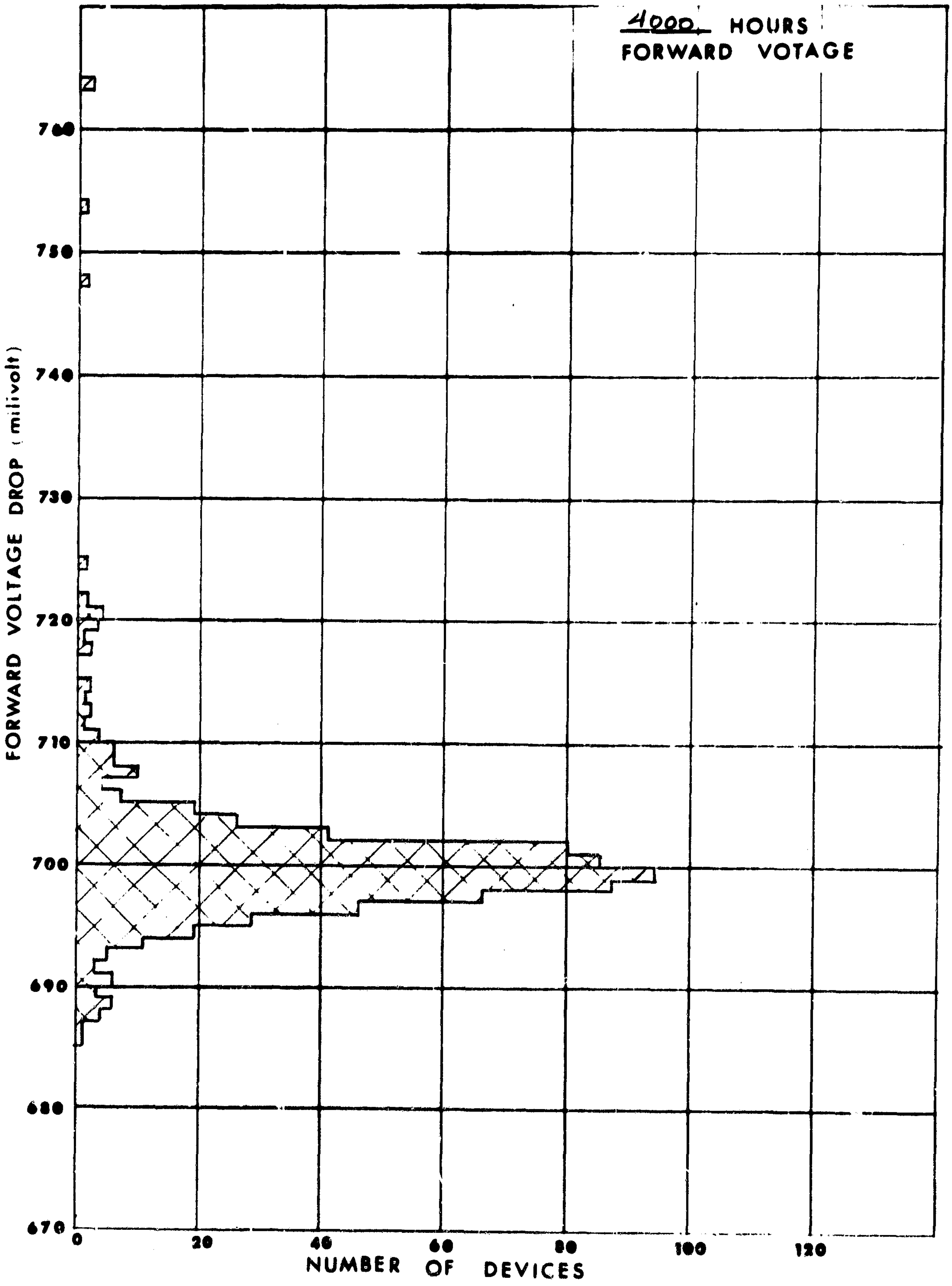

[illegible] HOURS
REVERSE LEAKAGE CURRENT
LEAKAGE CURRENT (nanoamps)
1000
100
10
0
0
40
80
120
160
200
240
NUMBER OF DEVICES


0 HOURS
FORWARD VOTAGE
FORWARD VOLTAGE DROP (milivolts)
760
750
740
730
720
710
700
690
680
670
0
20
40
60
80
100
120
NUMBER OF DEVICES


1000 HOURS
FORWARD VOTAGE
FORWARD VOLTAGE DROP (milivolt)
760
750
740
730
720
710
700
690
680
670
0
20
40
60
80
100
120
NUMBER OF DEVICES


2000 HOURS
FORWARD VOTAGE
FORWARD VOLTAGE DROP (milivolt)
760
750
740
730
720
710
700
690
680
670
0
20
40
60
80
100
120
NUMBER OF DEVICES


3000 HOURS
FORWARD VOTAGE
FORWARD VOLTAGE DROP (milivolt)
760
750
740
730
720
710
700
690
680
670
0
20
40
60
80
100
120
NUMBER OF DEVICES

4000 HOURS
FORWARD VOTAGE
FORWARD VOLTAGE DROP (milivolt)
760
750
740
730
720
710
700
690
680
670
0
20
40
60
80
100
120
NUMBER OF DEVICES