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AN EVALUATION OF THE EFFECTS OF NUCLEAR RADIATION ON DIELECTRIC MATERIALS BEING CONSIDERED FOR USE IN THE XMC-1256 HIGH-VOLTAGE SAFING SWITCH

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ABSTRACT

Irradiation tests were performed on liquid- and gas-insulated gaps in the Materials Testing Reactor near Idaho Falls, Idaho, and in Sandia Corporation's Cobalt-60 Source at Albuquerque, New Mexico. The object of these preliminary tests was to determine the relative values of the insulations which are being considered for use in the XMC-1256.

The comparison of leakage currents produced by a 3-kv potential, before, during, and after exposure is graphically shown for nitrogen, vacuum, sulphur hexafluoride, "Pyranol 1481," "Fluorolube FS-5," and "Coolanol 45."

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AN EVALUATION OF THE EFFECTS OF NUCLEAR RADIATION ON DIELECTRIC MATERIALS BEING CONSIDERED FOR USE IN THE XMC-1256 HIGH-VOLTAGE SAFING SWITCH

INTRODUCTION

The purpose of this series of tests was to make a preliminary evaluation of some selected electrical insulations which were being considered by Section 1432-4 for use in the XMC-1256 High-Voltage Safing Switch.

Because specific information concerning radiation effects on their insulating properties was not readily available, it was necessary to test samples of the insulations (nitrogen, sulphur hexafluoride, vacuum, "Fluorolube FS-5,"[1] "Coolanol 45,"[2] and "Pyranol 1481"[2]) in order to determine whether or not a dielectric selected to insulate a 2.5-kv switching circuit could sustain its insulating properties reasonably well during and after the following irradiations.

Radiation	Integrated Flux (500 hrs.)	Neutron Energies	Percentage of Neutron > 4 kev
Neutrons	1.3×10^{15} n/cm^2	> 2.5 mev	19
	2.1×10^{15} n/cm^2	> 1.5 mev	31
	3.3×10^{15} n/cm^2	> 0.7 mev	49
	6.8×10^{15} n/cm^2	> 4.0 kev	100
Gamma	6×10^5 rads (H_2O)		

The actual radiation levels encountered during exposure to the Materials Test Reactor (MTR) are shown in Table 1. These levels are near or slightly more than the levels shown above.

Certain other requirements for the XMC-1256 were not specifically pertinent to our tests, but they had to be considered because they influenced our actual testing procedures:

1. The leakage currents between the normally closed or normally open terminals of the 2.5-kv Form C (SPDT) contacts in the closed position and the terminals of the opposite throw-open position should not exceed approximately 10 microamperes at 2.5 kv.
2. The XMC-1256 may be epoxy-encapsulated in the next assembly.

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[1] Hooker Chemical Corporation

[2] Monsanto Chemical Company

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3. The 2.5-kv contacts will conduct a 2500-ampere nonrepetitive pulse of three microseconds duration.

4. Because the contacts of the XMC-1256 should not transfer under a 3000-g shock of from 1/2- to 1-millisecond duration, liquid dielectrics are considered for their dual use as a damping medium.

Samples of the insulations were contained in individual coaxial gap tubes (see Figure 1).

Up to 3 kv DC (the nominal breakdown voltage limit of air-filled gaps) was impressed across the terminals of the tubes, and the resulting leakage currents were measured before, during, and after irradiation. The recorded currents are the summation of currents both through and about the tubes. A commercial vacuum switch (see Figure 1) was used to evaluate vacuum, Kovar-to-glass seals, and the effects of radiation upon the carrying characteristics of molybdenum contacts.

The number of samples was restricted by the limited time, which precluded repeating the test several times, and by the limited number of test leads which could be accommodated in the one-inch conduit in the VG-9 beam hole plug at the Materials Testing Reactor where the reactor phase of the test series was conducted.

CONCLUSIONS

Upon analysis of the test data, it can be concluded that of the various gas and liquid dielectrics subjected to the irradiation of the MTR facility, the type least affected was dry nitrogen. It can be seen on the test data graphs that leakage currents of the nitrogen filled sample remained lower and more stable than leakage currents of the other types of gases and liquids subjected to the same facility. Although none of the samples exhibited leakage characteristics of an excessive amount (maximum encountered was 23 microamperes at 3000 v DC on the Pyranol filled sample) during the experiment, the nitrogen filled sample maintained the least amount of leakage throughout the irradiation procedure.

The liquid samples were somewhat less resistant electrically to the radiation intensities involved, but could warrant consideration for the design of a switching component of high mechanical shock capability utilizing the liquid as a damping medium. Measurements before and after the irradiation procedure revealed an increase of viscosity in the liquids used.

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TEST PROCEDURES

The electrical tests described below were performed before, during, and after the insulations were subjected to the following environments:

1. Materials Testing Reactor, Phillips Petroleum Company, Scoville, Idaho

   A 72-hour irradiation to an integrated fast neutron flux on the order of 10^{15} NVT, and a gamma ray dose of 7×10^8 rads at 110°F (see Table I).

2. Cobalt-60 Source, Sandia Corporation, Albuquerque, New Mexico

   Gamma ray dose on the order of 10^5 rads (H_2O).

3. Thermal, Sandia Corporation, Albuquerque, New Mexico

   Six-hour exposure at 110°F in an air-filled oven (see Figures 8, 9, 12, 16, 19, 20, and 23).

Electrical Tests

The following electrical tests were performed using the test equipment shown in Figure 2. The test circuit is shown in Figure 3.

Current vs. Potential

As indicated in Figure 4, leakage currents across the terminals of gaps and vacuum switches were measured through 30-foot cables. These 30-foot leads were necessary to provide the required space between the MTR radiation chamber and the test equipment. The same lengths were used for all the environments. The cables were shielded, and the shields were connected together to minimize coupling between the leads. The current measured was primarily the sum of conduction current across the gap through the dielectric being tested and leakage currents on the outside of the gap tubes. The metal gap tubes with their lead-through terminals simulated some designs of the XMC-1256.

High-Current Pulse Capabilities of a Vacuum-Insulated Switch

Current-Carrying Capacity -- As shown in Figure 3, a 12,000-ampere, 2500-volt DC pulse generator was periodically connected to the normally closed contacts of the unpotted vacuum switch during the MTR experiment. Measurements made during the pulse indicated that the pulse was attenuated by the cable connections to approximately 2000 amperes. Duration of the pulse was one microsecond.

Normally Closed (NC) Circuit Resistance -- The loop resistance of the normally closed circuit was measured with an ohmmeter.

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Physical Tests

Infrared and chromatographic analyses were performed on "Coolanol," "Fluorolube," and "Pyranol" samples. Fluid viscosities were also measured before and after irradiation. Results of these tests are included in the detailed test results (see pages 10 and 11).

Two vacuum switches were examined visually and polarimetrically before and after irradiation.

A pressure transducer was connected to the "Fluorolube FS-5" gap for the MTR experiment. However, an inaccessible wire broke loose on the transducer at the beginning of the experiment, and the pressure was therefore not monitored.

Ambient temperatures were measured during the tests.

Preparation of Insulation Samples

Gaps

Mild steel tubes were machined to fit 5-kv ceramic- and glass-insulated lead-through terminals. The terminals were soft-soldered to the ends of the tubes. Annealed OFHC* copper tubes were soldered to the tube walls to provide for flush-cleaning of the tubes after soldering operations and also for filling the tubes with insulations. Gases were filled at 15 psig and sealed by crimping and soldering the copper tubing. Liquids were filled under slight hydraulic pressure and the tubes crimped and soldered. A pressure transducer was connected to the gap tube containing "Fluorolube FS-5."

Vacuum Switches

The vacuum switches were rated for 60-cycle 10-kv (rms) duty. The switching lever, which is also the common terminal, was fastened in one throw position.

One switch was encapsulated in epoxy after its leads were attached. This switch failed dielectrically after encapsulation, but because of time scales, it was decided to make use of it anyway at a much lower voltage.

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*Oxygen free high conductivity.

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Wiring

Thirty-foot long polyethylene insulated, coaxially-shielded cables were soldered to the terminals of the gaps and switches.

All exposed metal at the terminal connections to the samples and on the samples was coated with "Krylon" after ultrasonic cleaning.

Mounting

For the MTR experiment, the samples were mounted on boards separated by stand-off insulators (see Figure 5). Bottles of "Pyranol," "Fluorolube FS-5," and "Coolanol 45" were attached to the top deck. Dosimeters were located on each deck. The assembly was inserted into a "Boral" box to shield against thermal neutrons from the reactor.

The samples were handled individually for the Co^{60} and $110^{o}F$ environments.

TEST RESULTS

The test results are summarized below in tabular and graphical form. The data used is included in the Appendix. Table VI shows the maximum leakage currents at 3 kv DC, measured for each environment.

Gases

There were certain characteristics which were common to the gas and vacuum insulated samples:

1. Irradiation had only a temporary effect on the resistivity. After removal from the radiation environment the resistivity substantially recovered within a few minutes to pre-irradiation levels.

2. The maximum effect occurred shortly after the start of irradiation at a time when equilibrium of ionization and temperature had been reached. This maximum effect was then maintained at a constant level until the irradiation ceased.

3. The MTR caused the greatest effect—leakage current readings were between 50 and 100 times as high as similar gaps irradiated in the Co^{60} gamma ray facility. When consideration is given to the fact that the dose rate in the MTR was 71 times greater than the dose rate in the Co^{60} facility, this result should be expected.

4. Thermal effects were insignificant except for the epoxy-encapsulated gaps. The potted gaps exhibited lower insulation levels.

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Each of the insulations did present certain individual characteristics:

Nitrogen (see Figures 6, 7, 8 and 9)

Unit No. 27, which was irradiated in the MTR, exhibited an increase in leakage current by a factor of 3000. The units irradiated in the gamma ray facility, with two exceptions, exhibited an increase in leakage current averaging a factor of 564. The spread was from 430 to 700. The first exception was the epoxy encapsulated units which seem to be temperature sensitive more than radiation sensitive. Data from these units was not considered with the unencapsulated units. The second exception was the unit No. 30 second polarity. The leakage current for the second polarity was almost two orders of magnitude higher than readings from all the other units, while the current for the first polarity was at the same level as the other units. Although it cannot be proved at this time, it is believed that this anomaly was due to some nonuniformity of the electrodes. The X-rays of unit No. 30 tend to confirm this as one electrode was badly bent.

Thermal exposure at 110°F caused the leakage currents of the encapsulated gap to be of the same order as an unencapsulated gap in the MTR.

Sulphur Hexafluoride (see Figures 10, 11 and 12)

Figure 11 shows that after irradiation the current increased rapidly between 2 and 3 kv. Apparently the gap was near breakdown. It was not possible to analyze the gap to determine what had caused the phenomenon. Rather than make unsupported conjectures at this time about the possible causes for the effect, in the event that SF_6 alone or in mixtures is considered for use in the XMC-1256, further experiments will be designed to determine the cause of any similar recurrent observations.

Vacuum (see Figures 13, 14, 15 and 16)

In general, the vacuum switches were more sensitive to the changing of polarity of the test potential.

Figures 13 and 15 include the epoxy-encapsulated switch which had partially failed after encapsulation. Time scales did not permit substitution of another potted switch.

The glass envelope of the unpotted switch darkened considerably after MTR exposure. As a result of gamma ray exposure another sample darkened slightly.

The resistance of the Kovar switch terminals had a greater effect than any other during thermal environment and it thereby reduced the net leakage current.

Liquids

There were certain characteristics common to all of the liquid-insulated gaps:

1. Infrared analysis of the samples before and after irradiation showed no significant differences in the region of 2 to 15 microns.

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2. Chromatograms indicated that the greatest changes had taken place in the Fluorolube FS-5; also that all the liquids were more affected by neutron and gamma ray exposure than by gamma rays alone, due to the much higher total dose obtained in the reactor.

Results of comparisons of gas chromatograms and fluid viscosities are noted under the specified fluid tests.

Fluorolube FS-5 (see Figures 17, 18 and 19)

Figures 17 and 18 show that the current increased by a factor of 2300 within the first five hours of MTR irradiation and decreased to a factor of approximately 316 thereafter.

Gamma ray irradiation caused an increase in current of a factor of about 2.5, or a little more than two orders of magnitude below the stabilized level in the MTR.

Recovery after MTR exposure was within one order of magnitude with reference to one test potential polarity and practically complete with reference to the opposite polarity.

Chromatograms indicated that the greatest change had taken place due to the MTR exposure.

Viscosity increased 42.9 percent after MTR compared to 2.4 percent after gamma ray irradiation.

Coolanol 45 (see Figure 20)

A terminal on the sample gap was broken at the start of the MTR test. The damage was beyond repair.

Leakage currents increased by a factor of 37 during gamma ray irradiation. Post-exposure currents were of the same order of magnitude as pre-exposure currents.

Viscosity increased 26.2 percent after MTR compared to 3.6 percent after gamma ray exposure.

Pyranol 1481 (see Figures 21, 22 and 23)

Figures 21 and 22 show that the MTR had caused the current to increase progressively to an average factor of 215. The effect was permanent with only slight annealing 23 hours after stopping the irradiation.

Only a sample bottle of the liquid was subjected to the Cobalt 60 source.

Viscosity increased 63.2 percent after MTR exposure compared to 6.9 percent after gamma.

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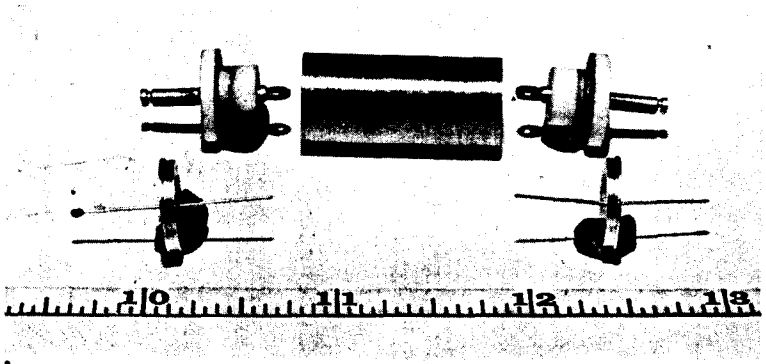
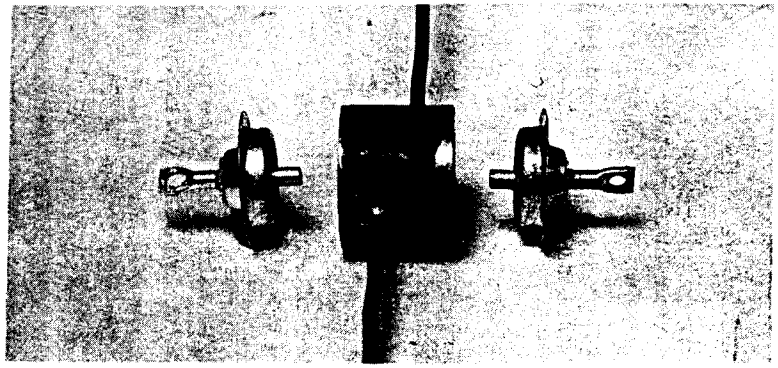
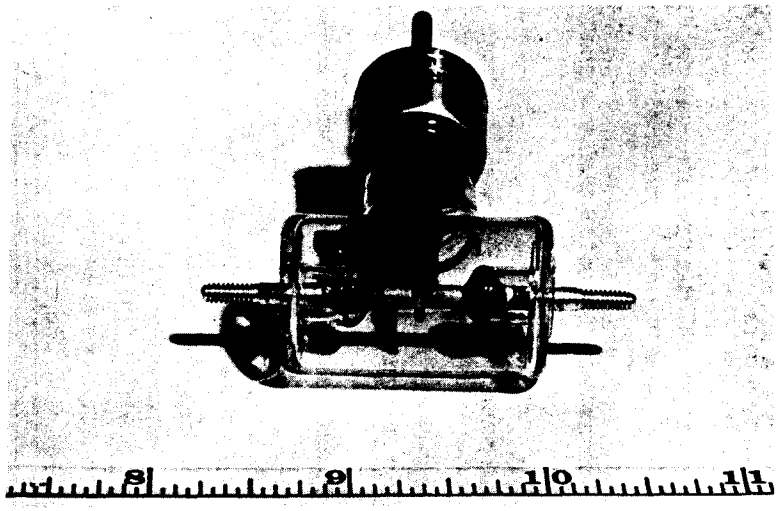


Type A gap tube--unassembled
Ceramic insulated terminals at top
Glass insulated terminals lower



Type B gap tube--unassembled
Glass insulated terminals



Vacuum switch--Form C contacts

Figure 1. Test Units

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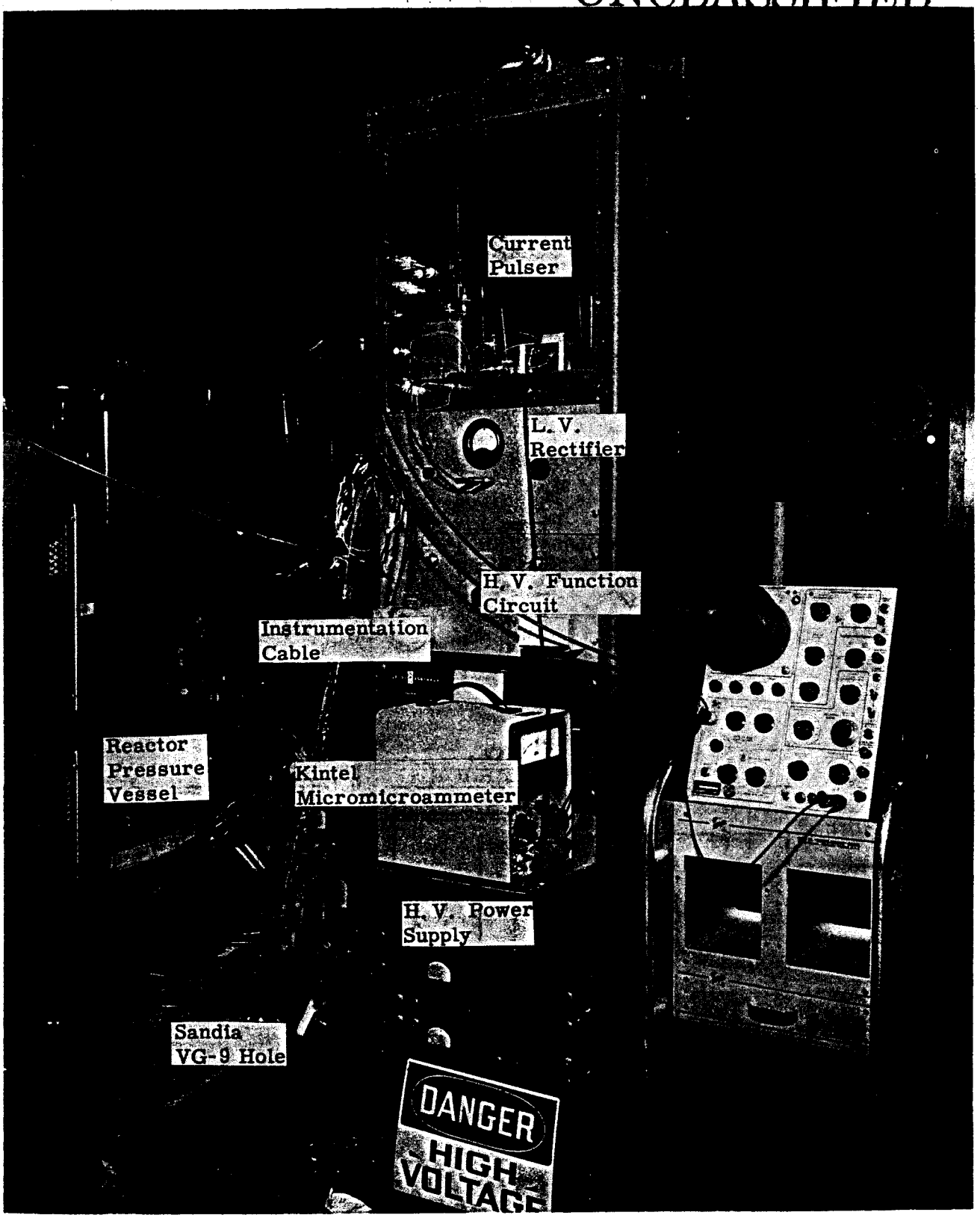

Figure 2. Test Equipment

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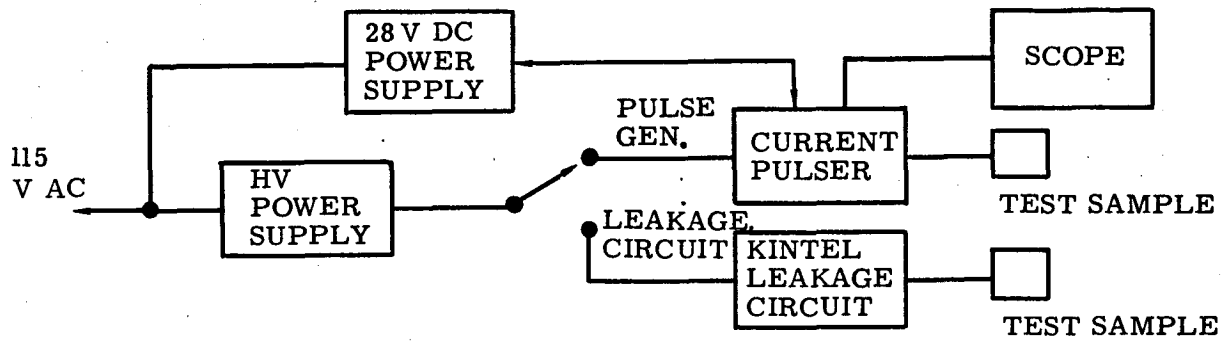
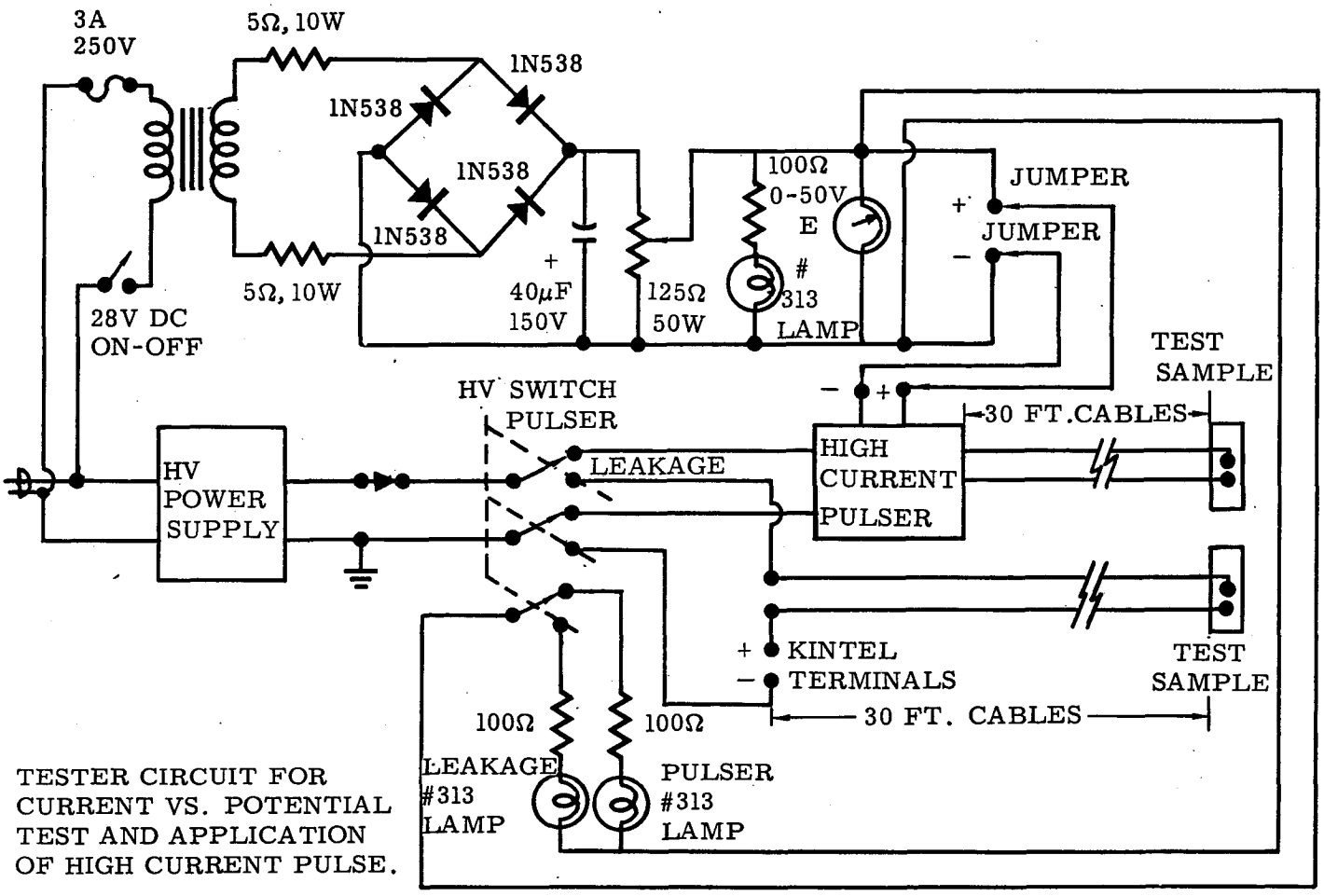


TESTER BLOCK DIAGRAM



TESTER CIRCUIT FOR CURRENT VS. POTENTIAL TEST AND APPLICATION OF HIGH CURRENT PULSE.

Figure 3. Test Circuit

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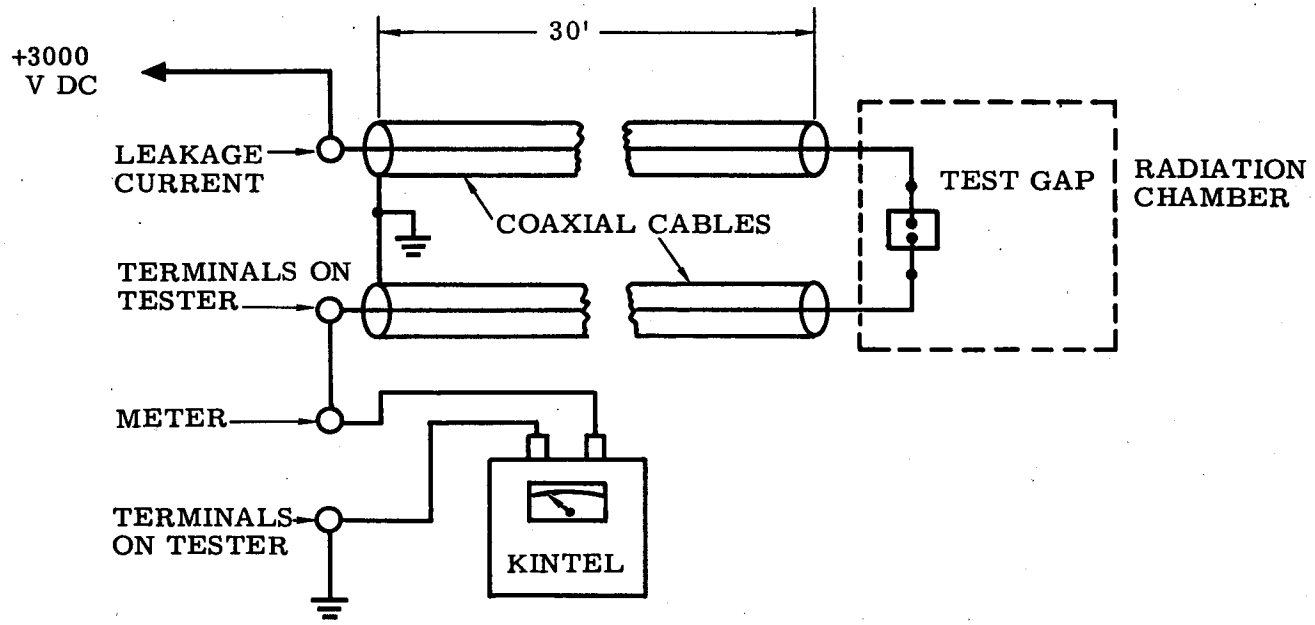

Figure 4. Leakage Current Measurement Circuit

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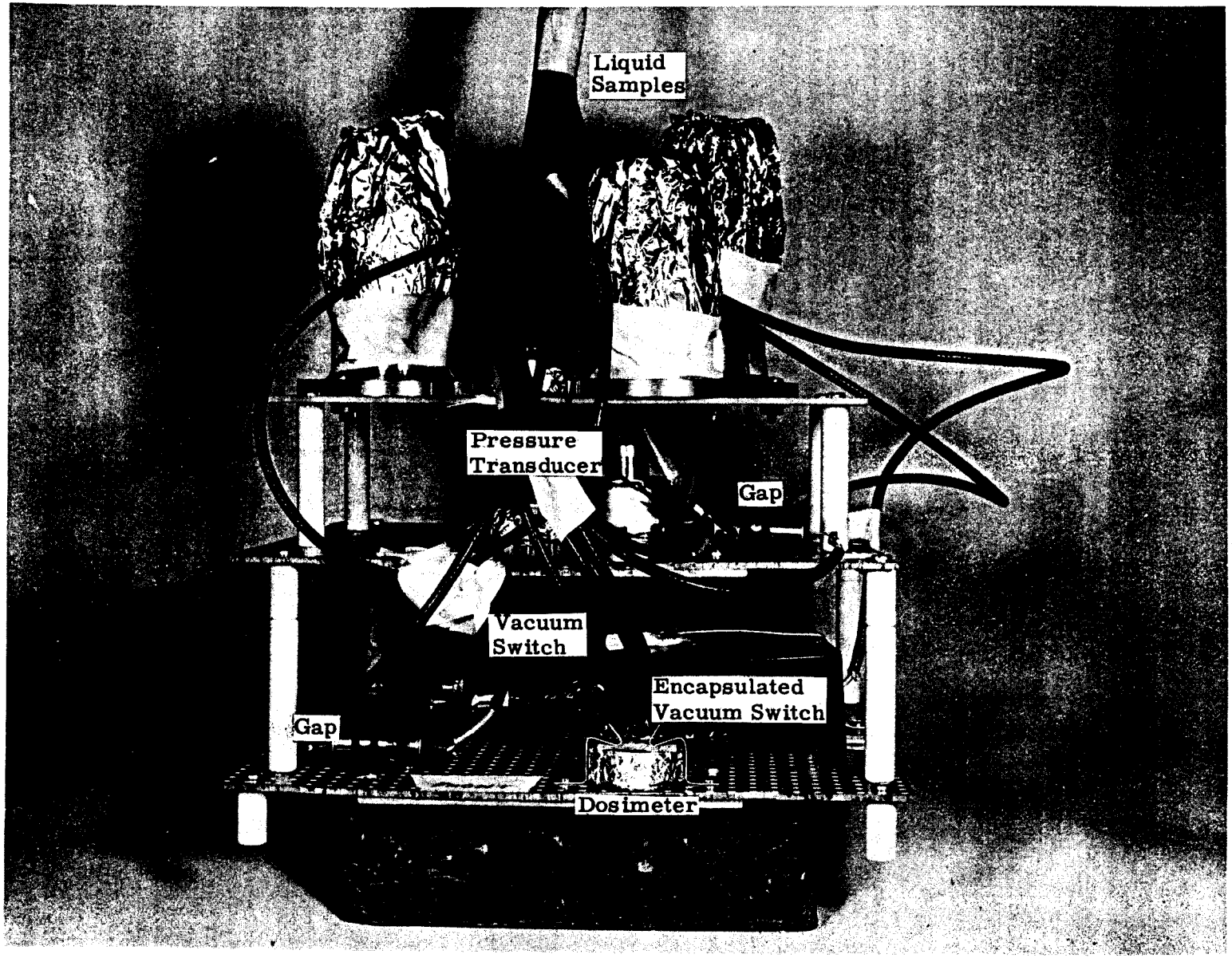

Figure 5. Test Unit Mounting Method

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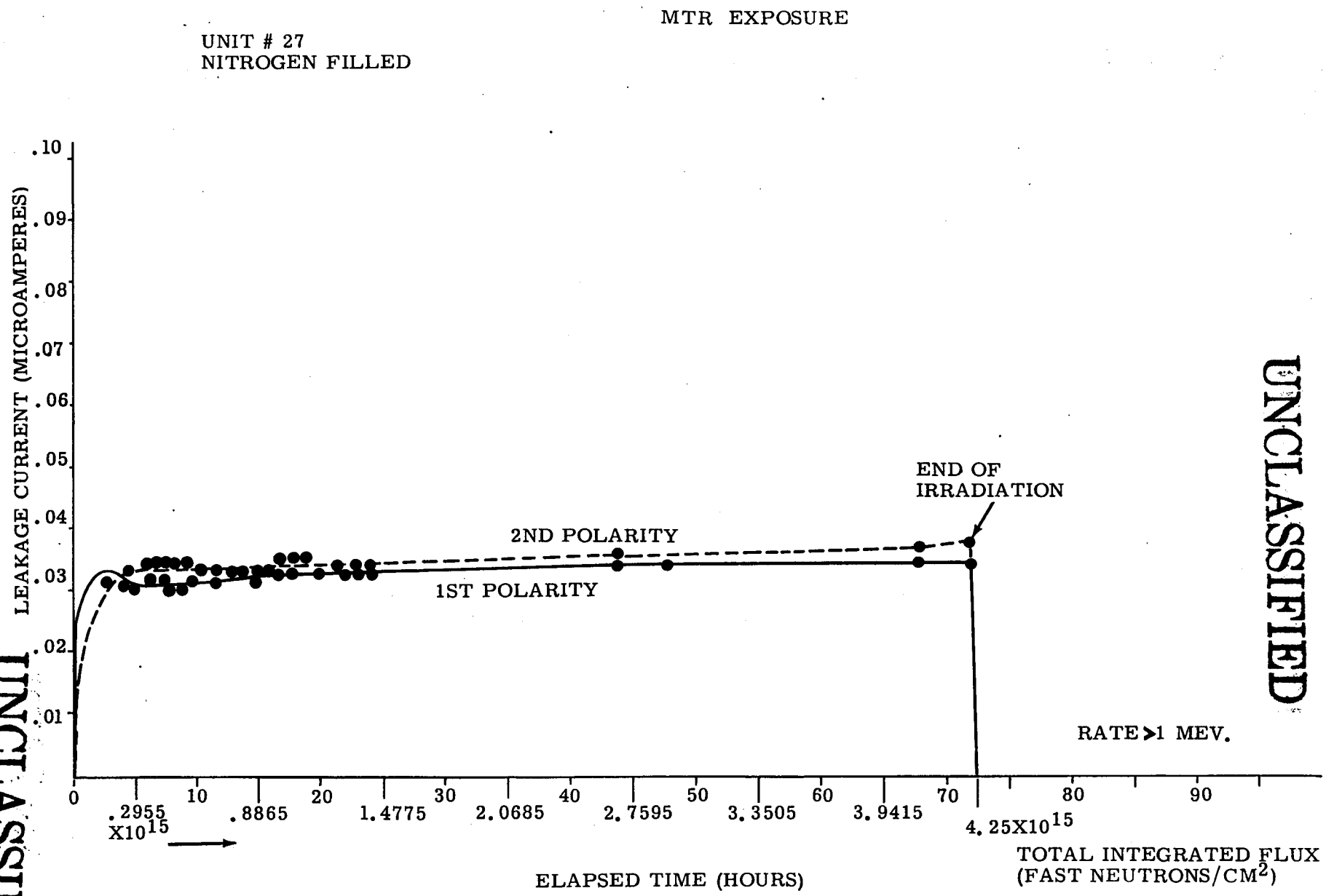

Figure 6. Test Data Graph

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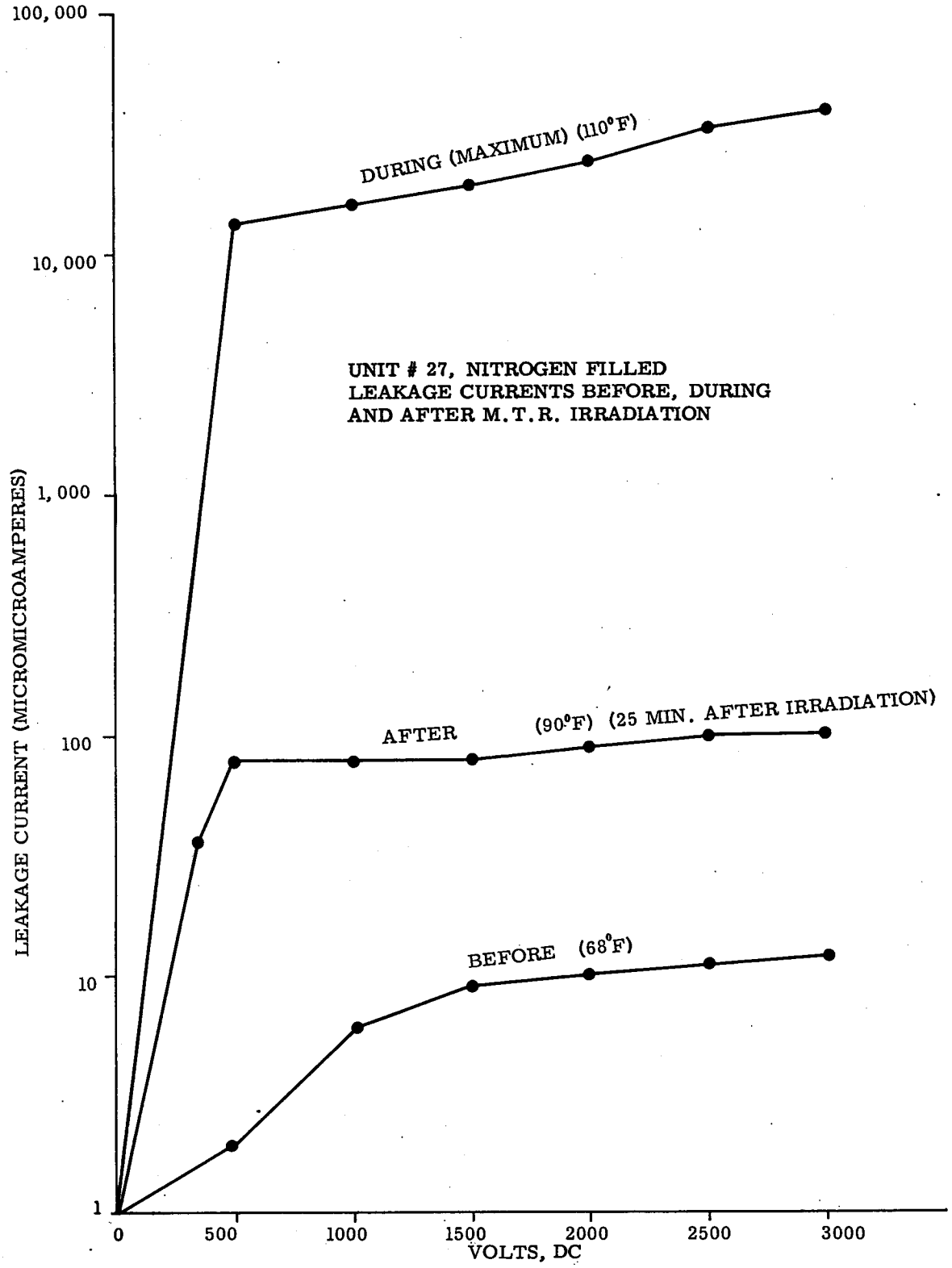

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Figure 7. Test Data Graph

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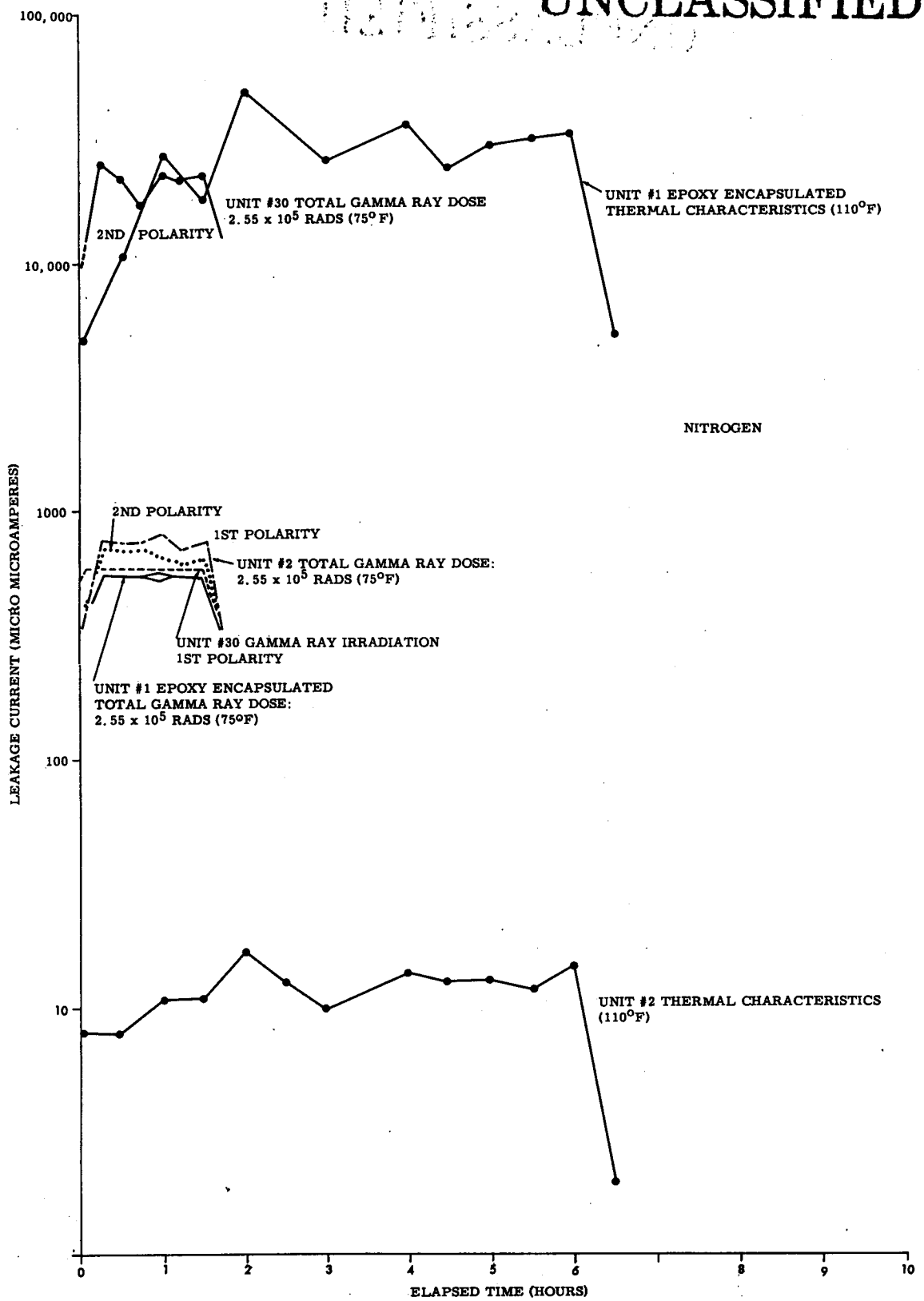

Figure 8. Test Data Graph

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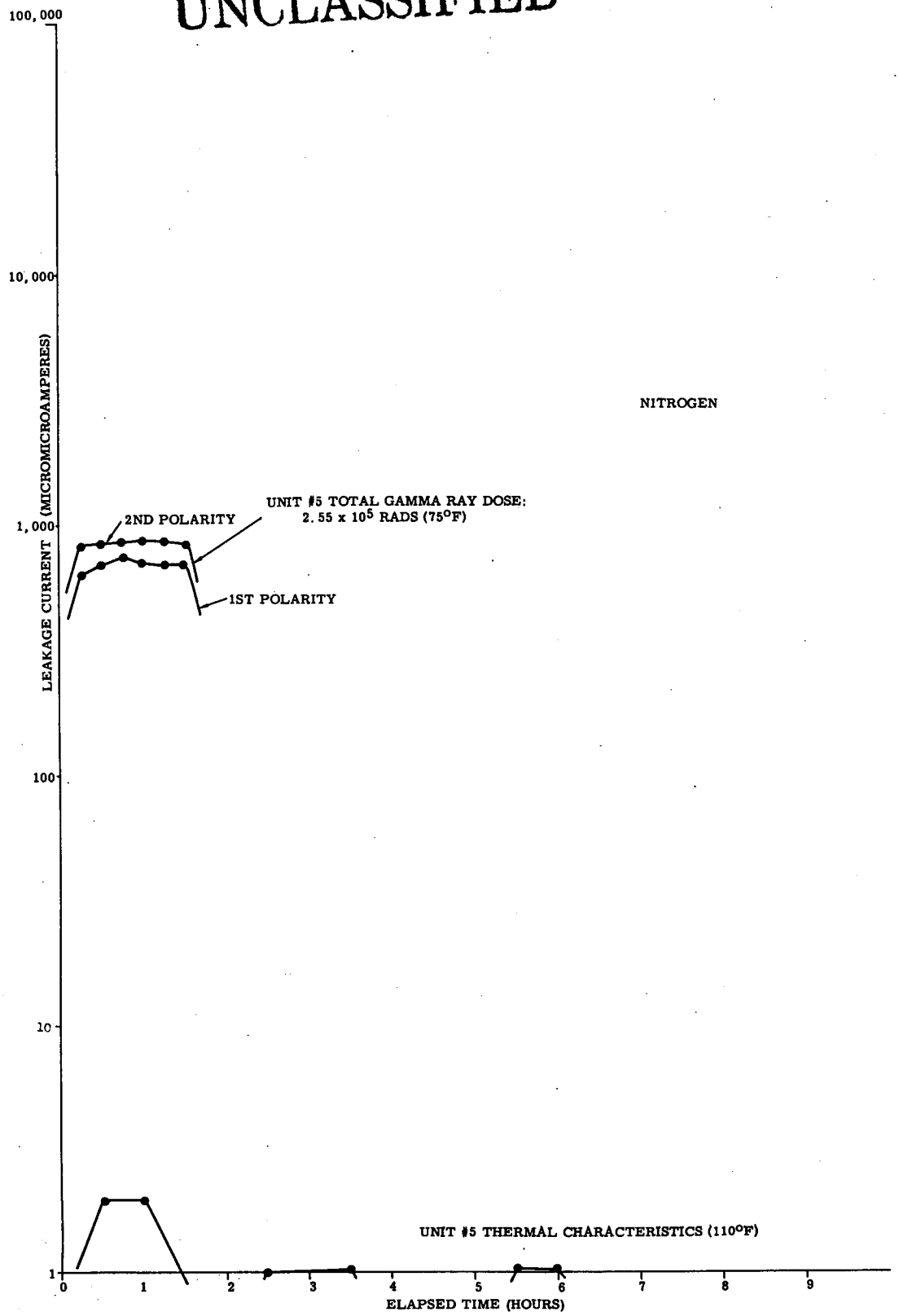

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Figure 9. Test Data Graph

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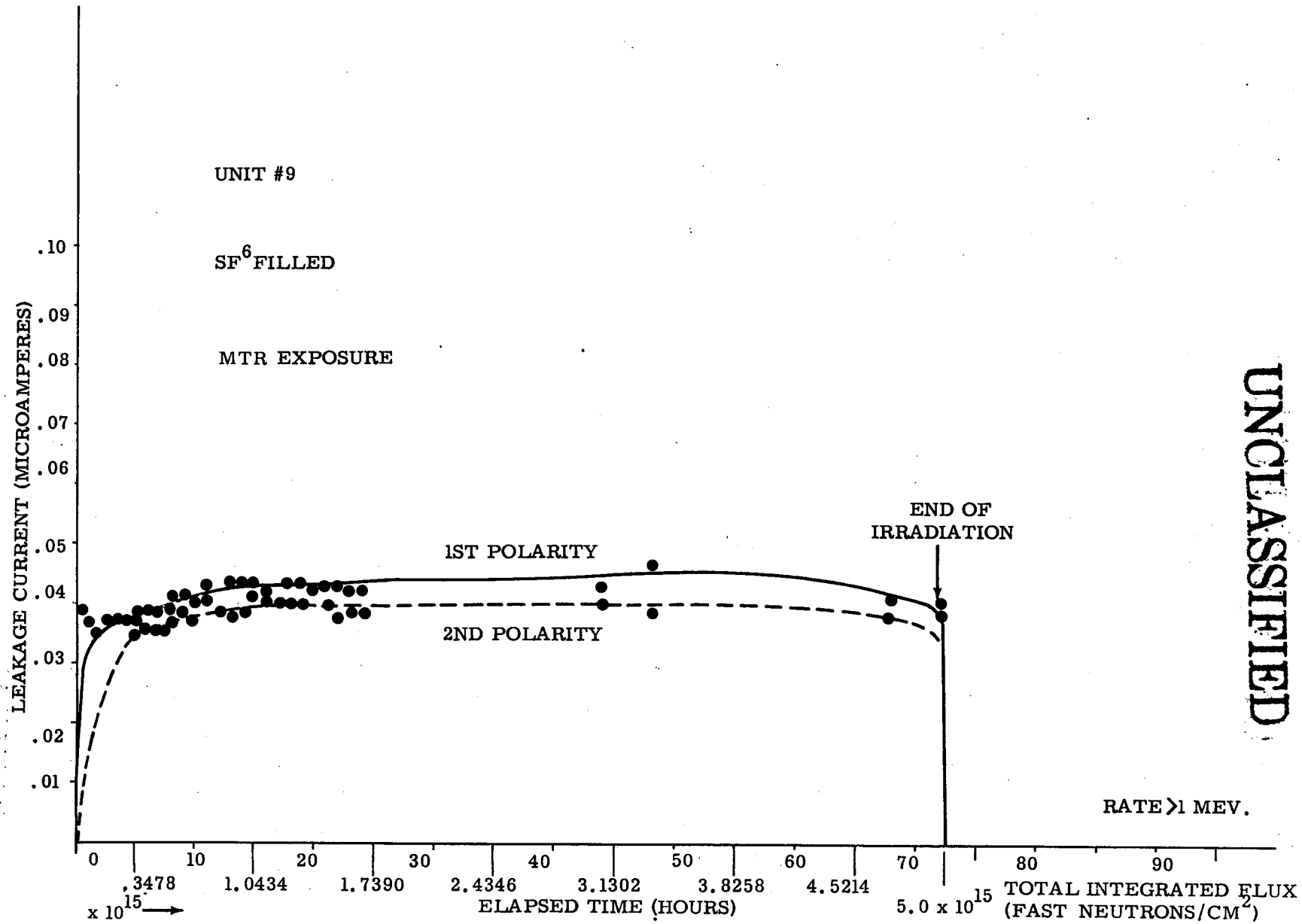

Figure 10. Test Data Graph

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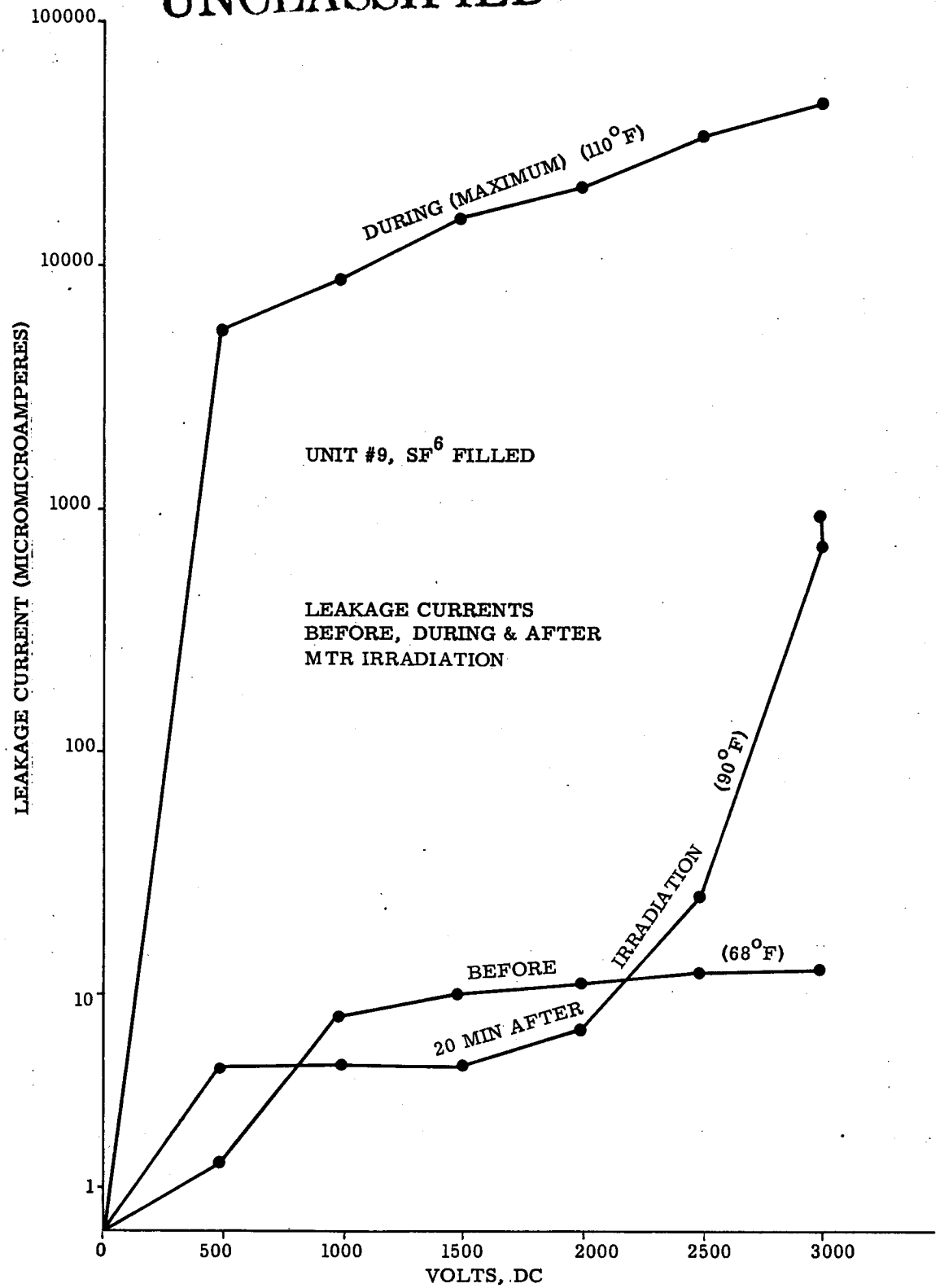

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Figure 11. Test Data Graph

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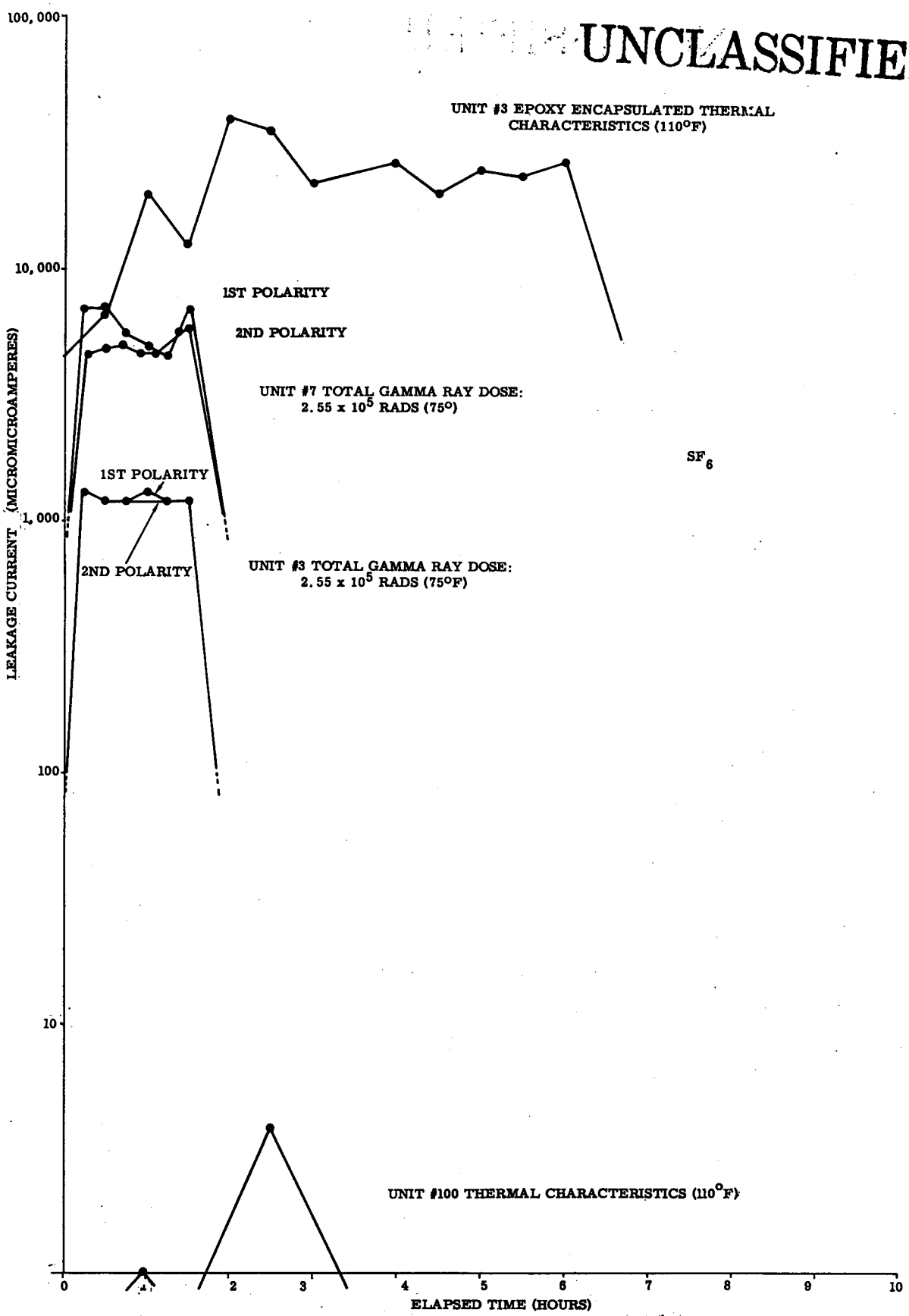

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Figure 12. Test Data Graph

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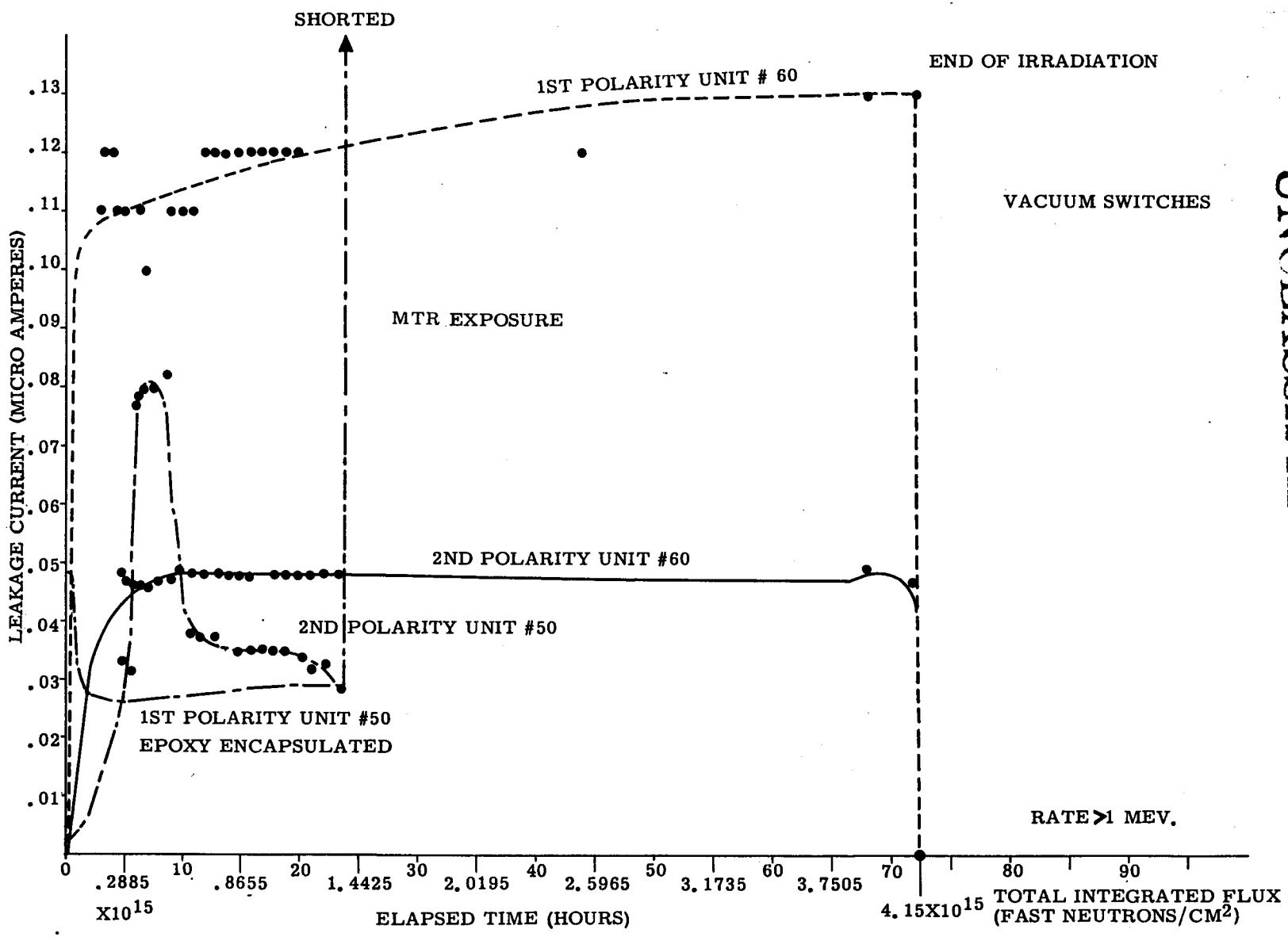

Figure 13. Test Data Graph

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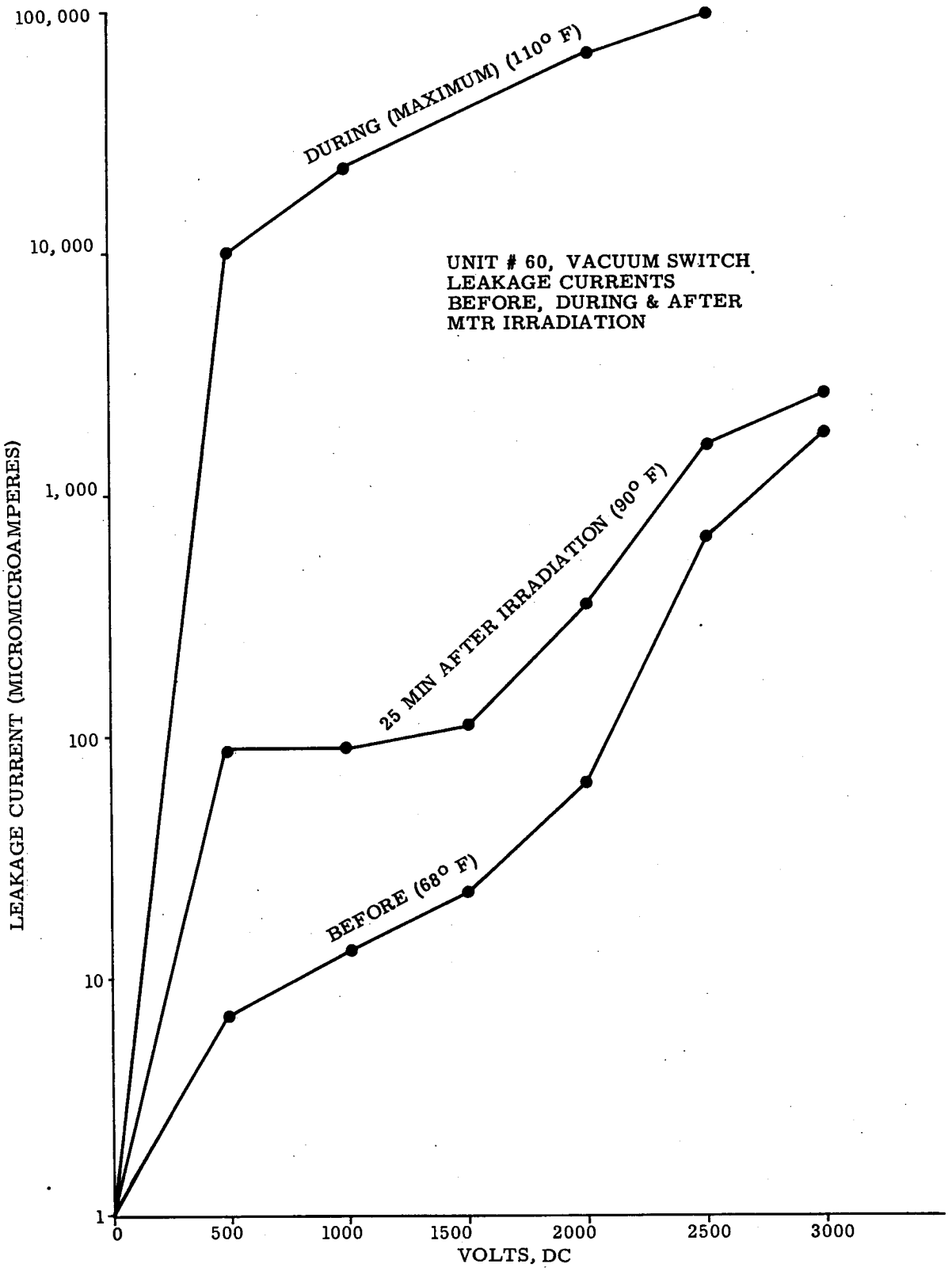

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Figure 14. Test Data Graph

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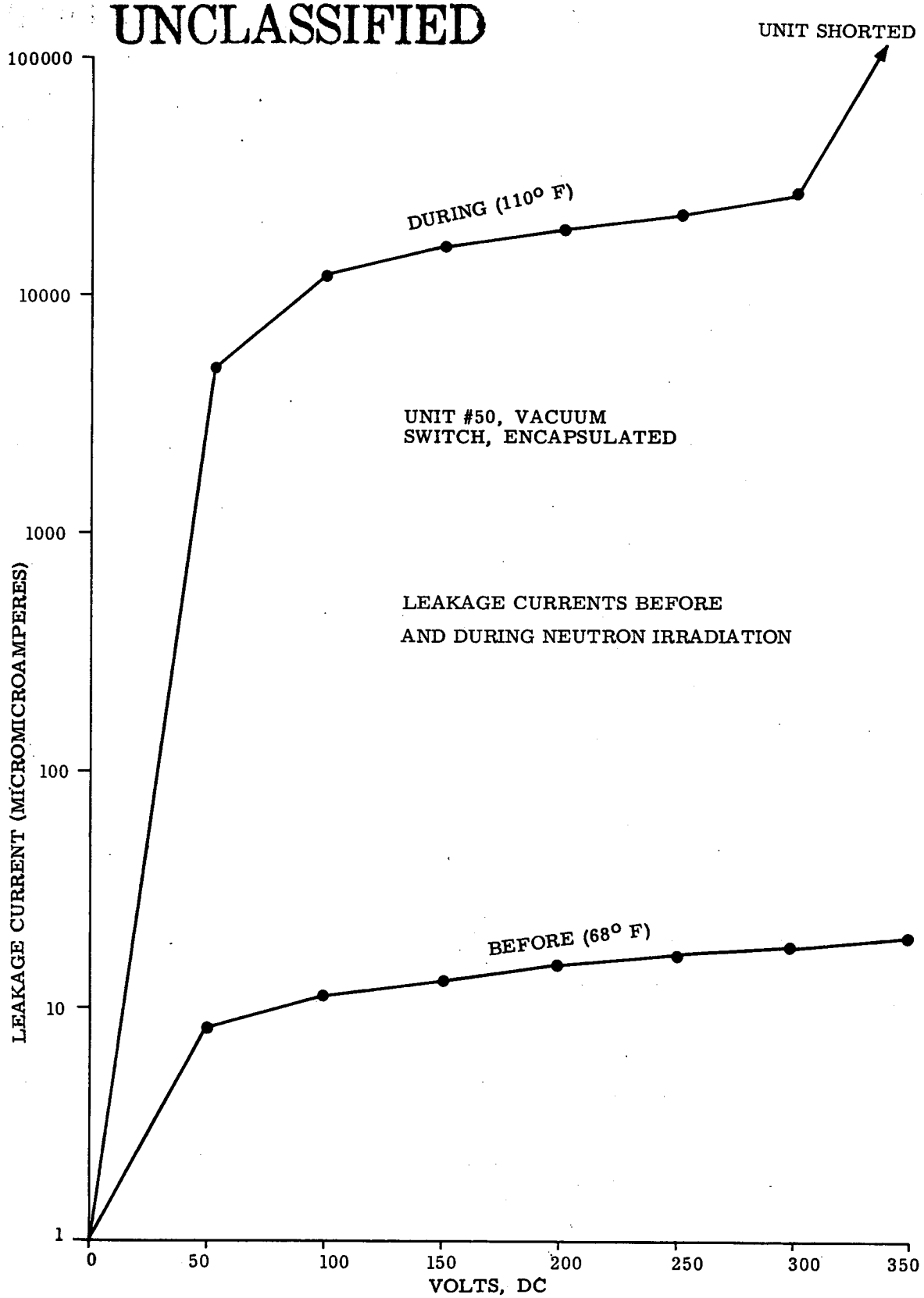

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Figure 15. Test Data Graph

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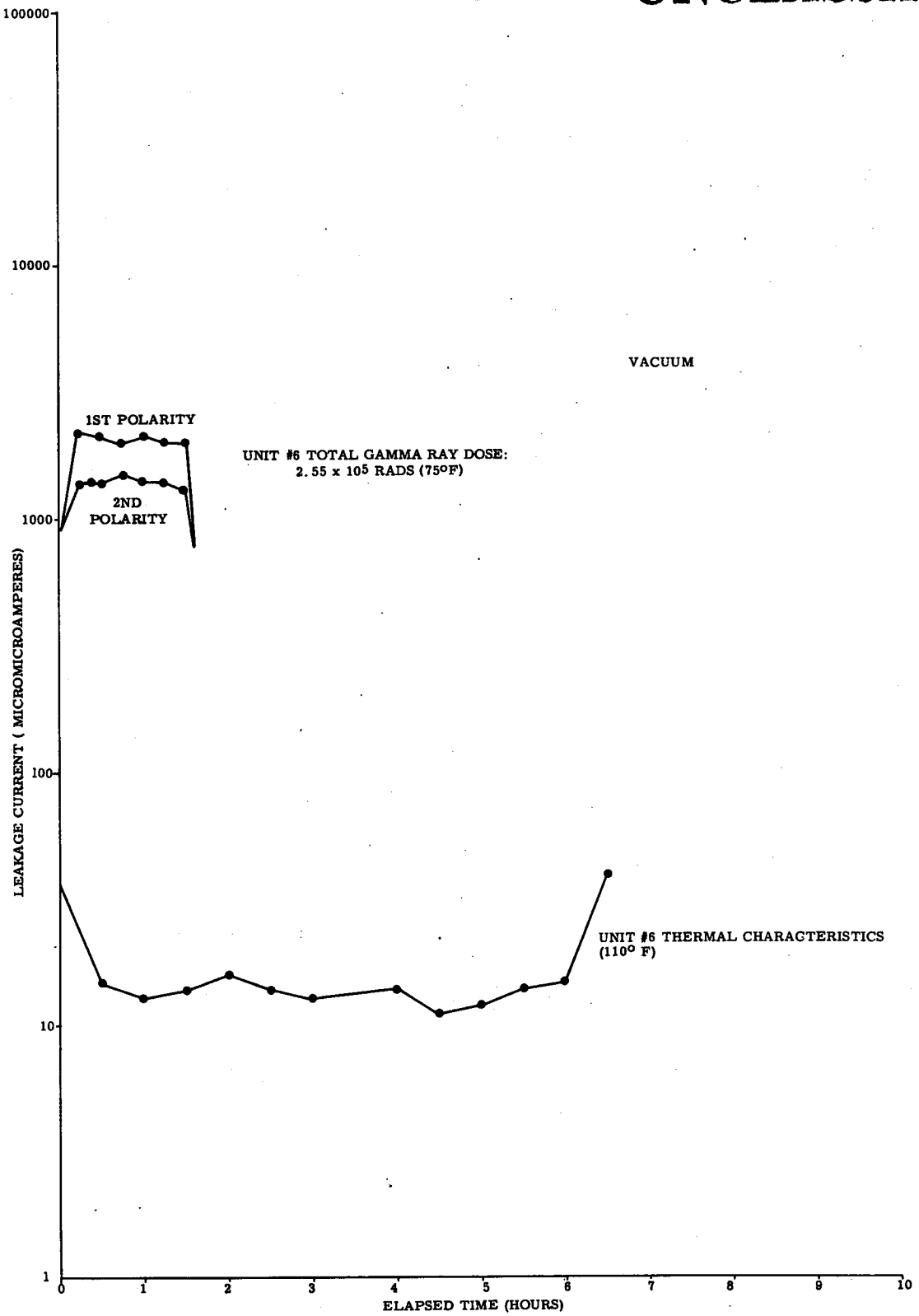

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Figure 16. Test Data Graph

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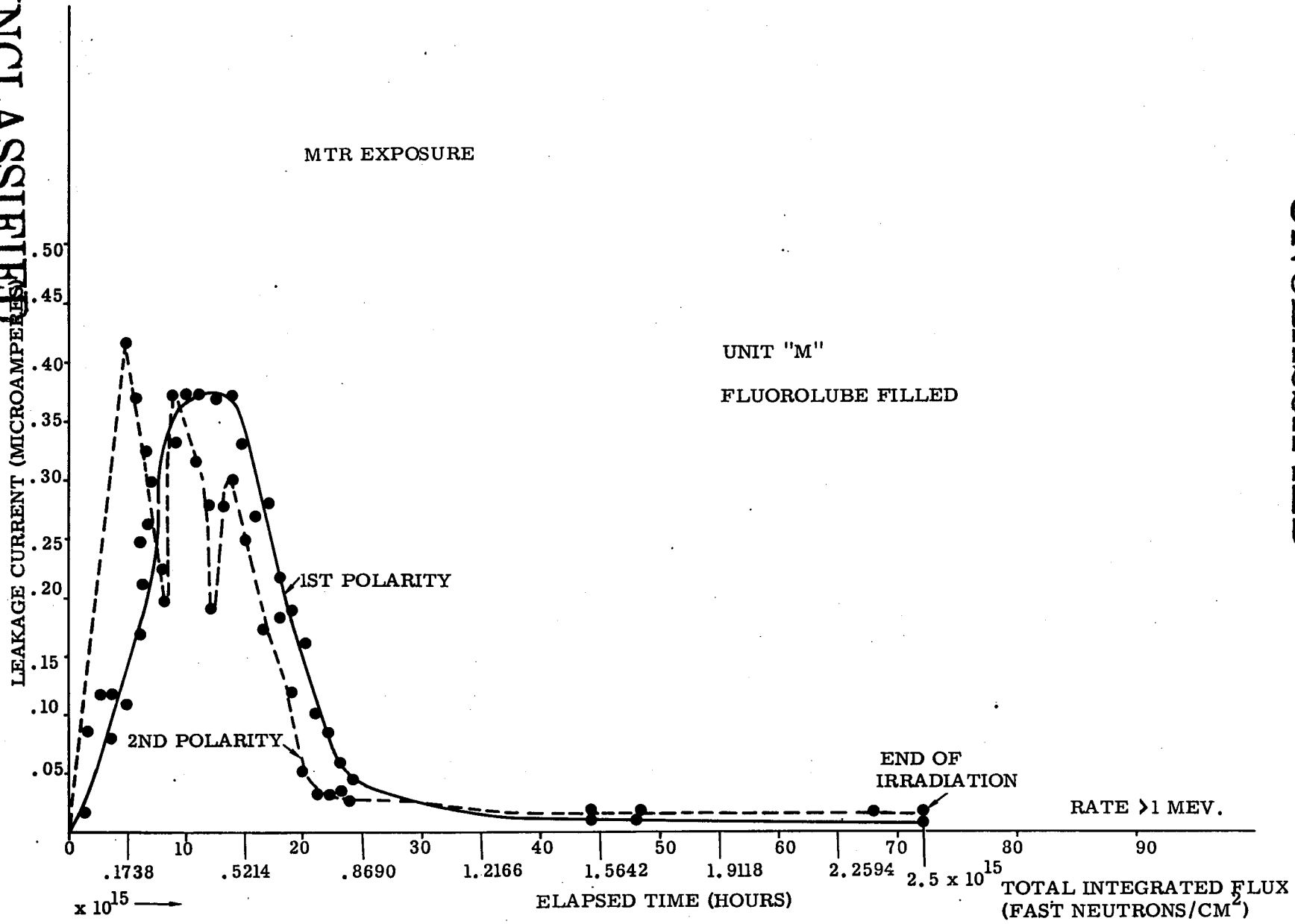

Figure 17. Test Data Graph

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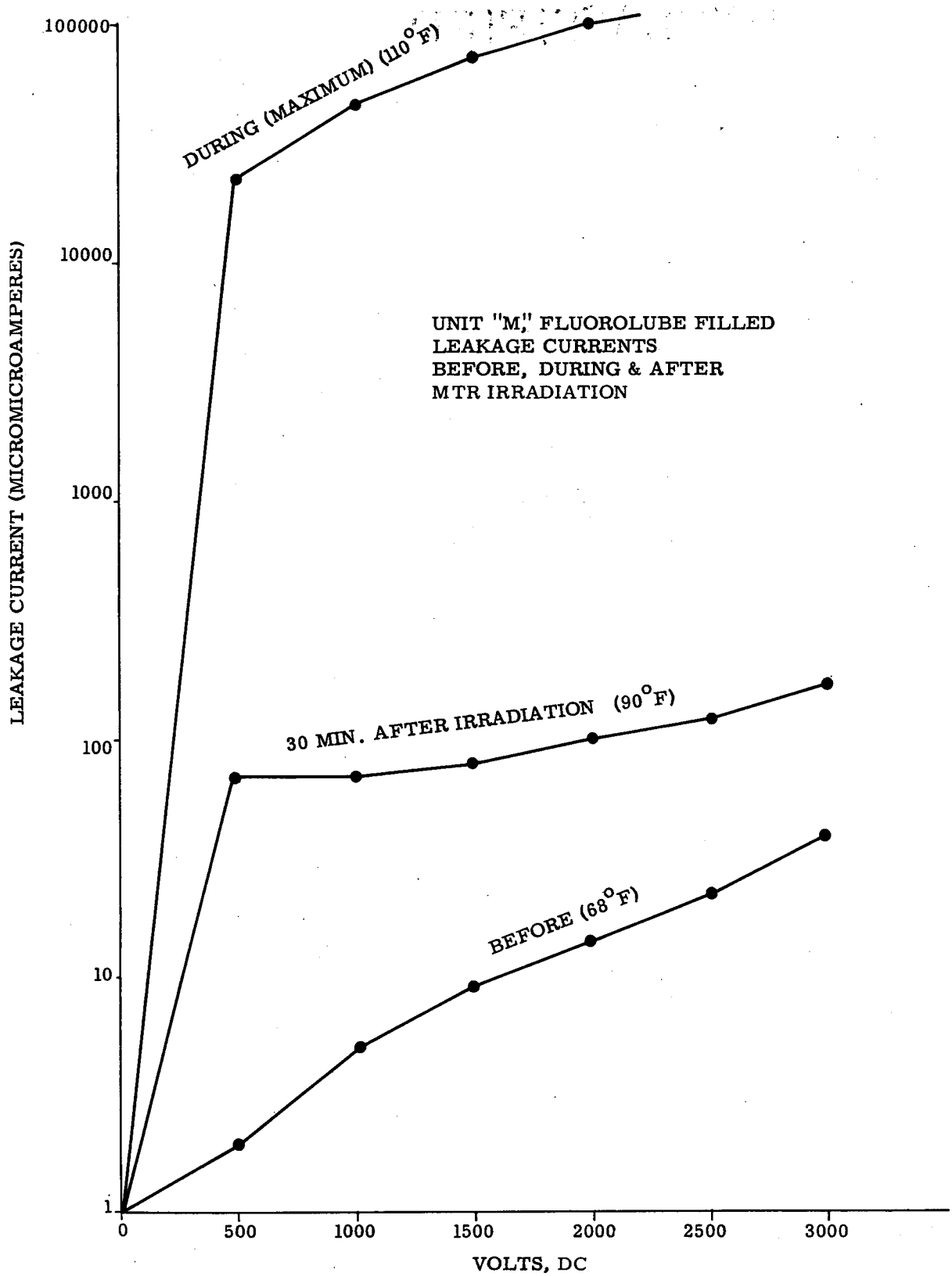

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Figure 18. Test Data Graph

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[redacted]

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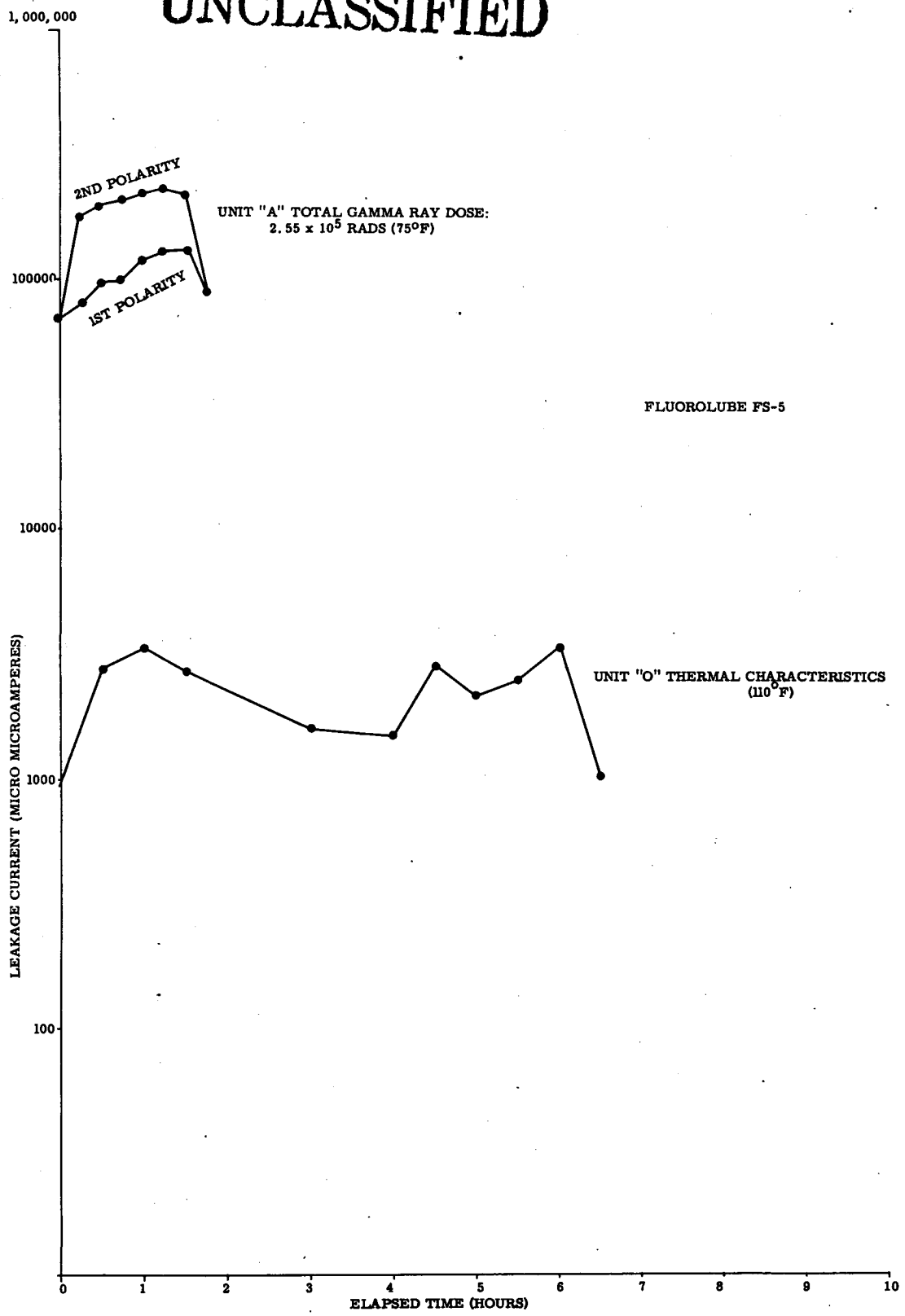

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Figure 19. Test Data Graph

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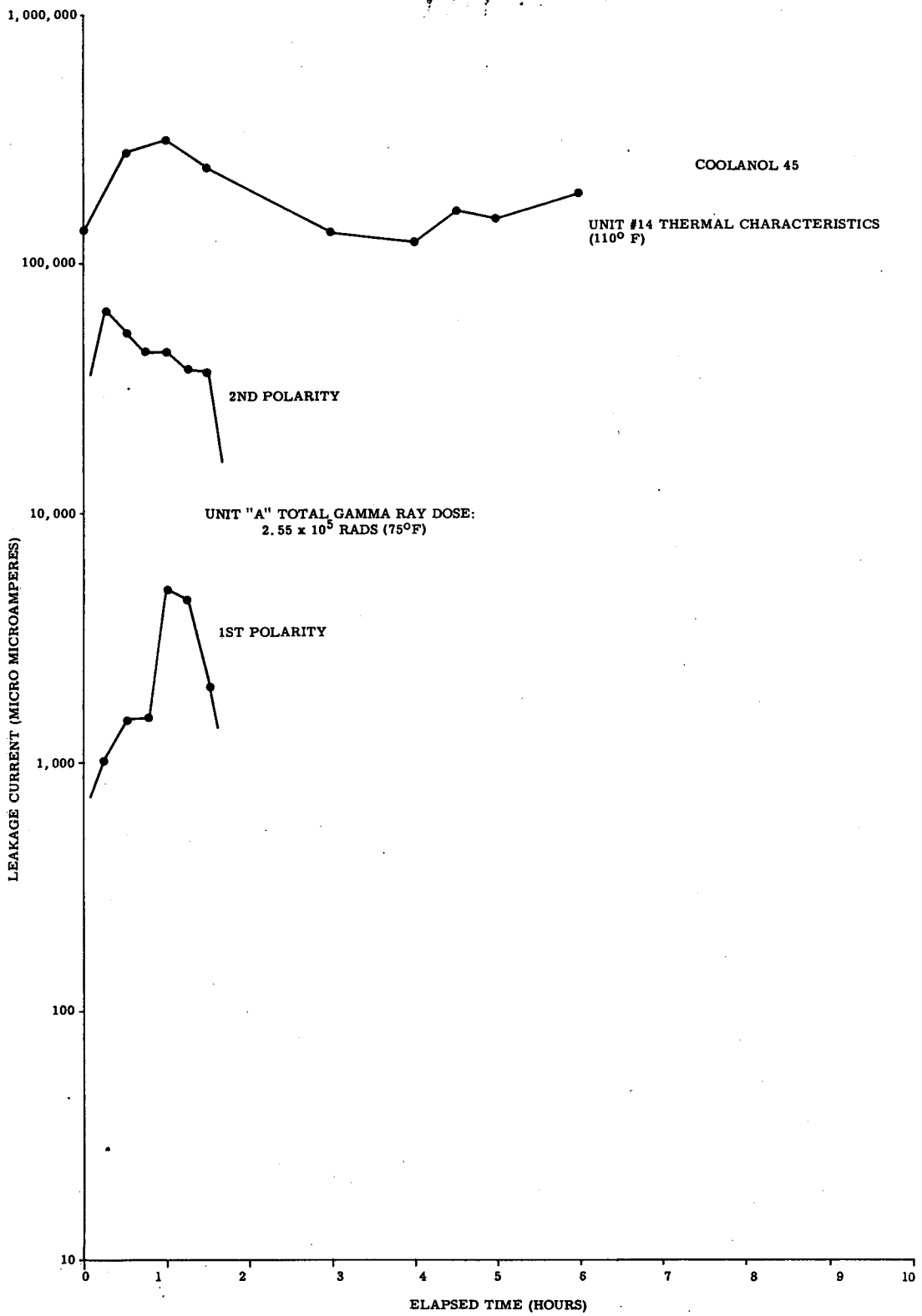

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Figure 20. Test Data Graph

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[redacted]

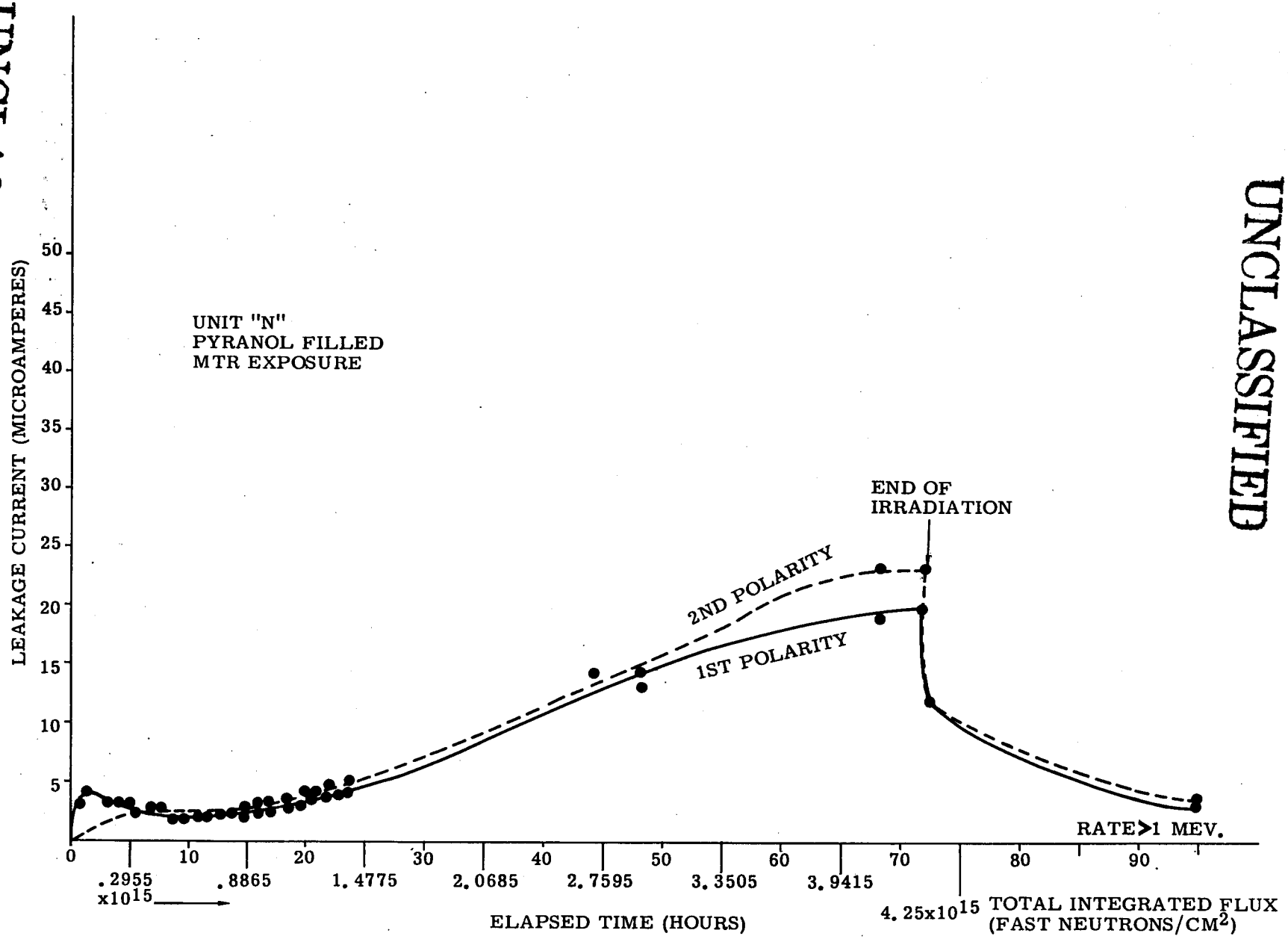

Figure 21. Test Data Graph

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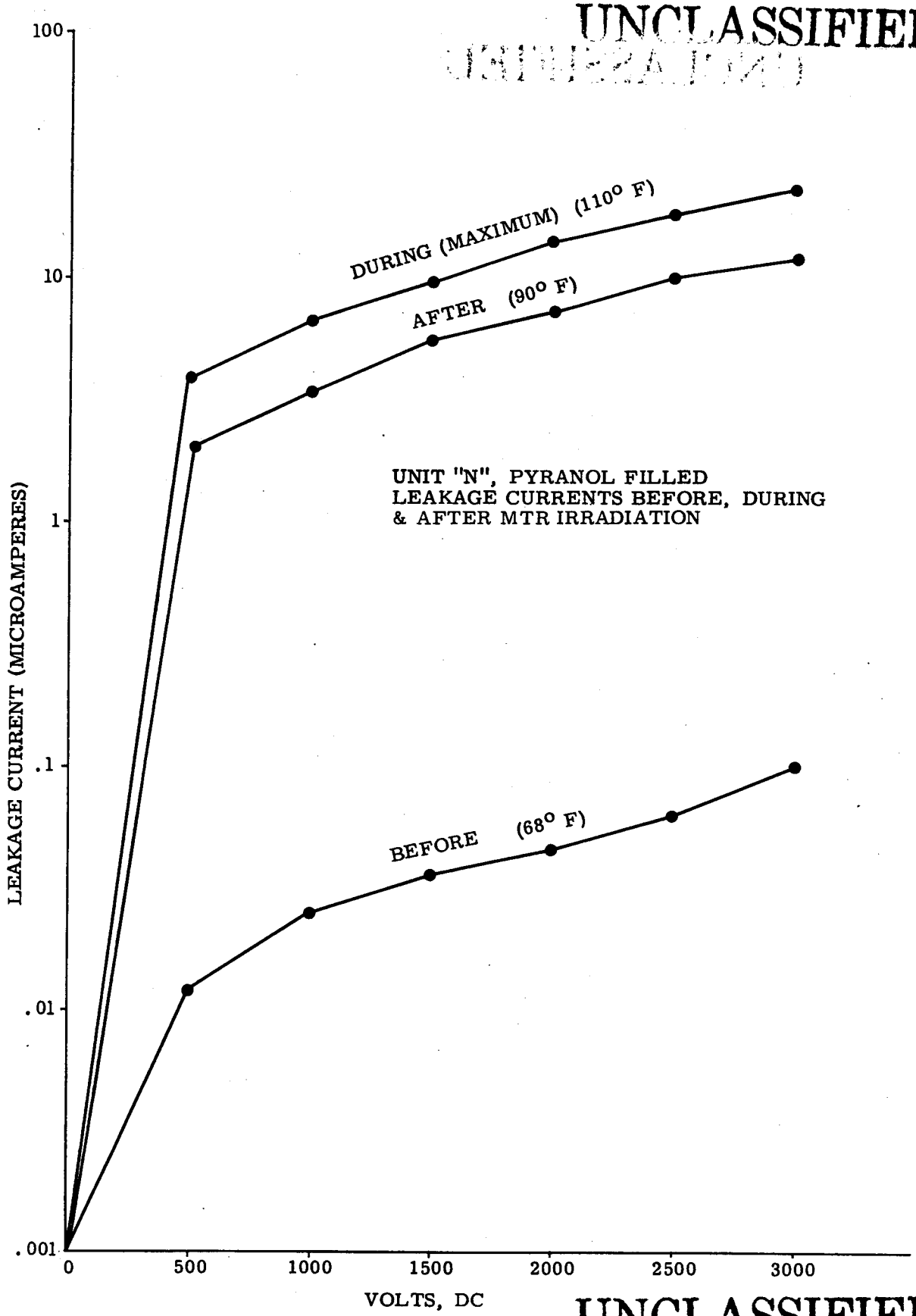

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Figure 22. Test Data Graph

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[redacted]

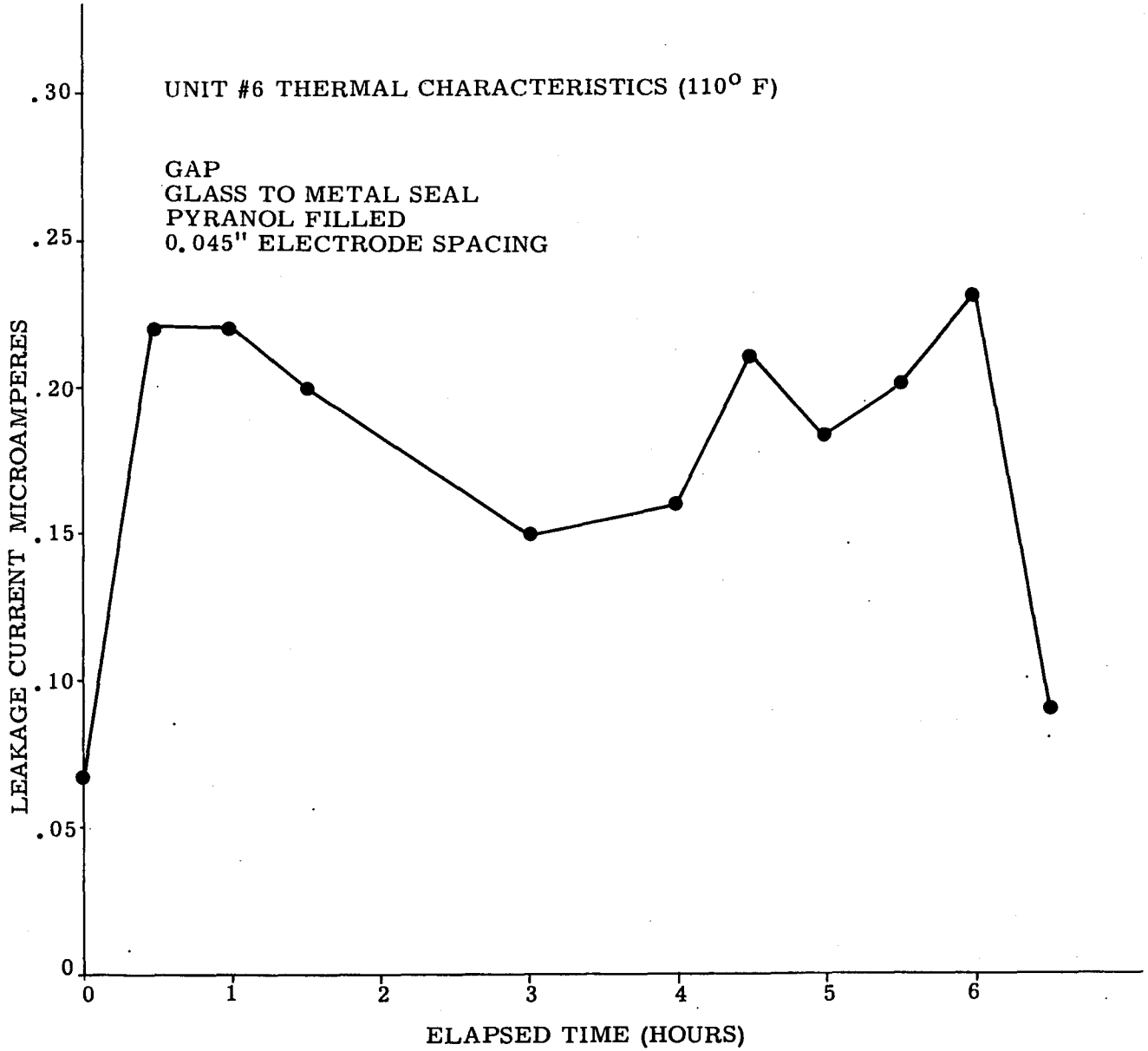

Figure 23. Test Data Graph

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TABLE I

Sample Exposure in MTR

Top Deck (Liquid Samples)

Radiation	Integrated Flux	Neutron Energies
Neutrons	4.9×10^{14} n/cm^2	>2.5 mev
Neutrons	1.2×10^{15} n/cm^2	>1.5 mev
Neutrons	1.5×10^{15} n/cm^2	>1 mev
Neutrons	6.5×10^{15} n/cm^2	>4 kev
Gamma Ray	7×10^{8} rads (H_2O)	

Middle Deck (Gap No. "M")

Neutrons	8.5×10^{14} n/cm^2	>2.5 mev
Neutrons	2.1×10^{15} n/cm^2	>1.5 mev
Neutrons	2.6×10^{15} n/cm^2	>1 mev
Neutrons	1.1×10^{16} n/cm^2	>4 kev
Gamma Ray	7×10^{8} rads (H_2O)	

Bottom Deck (Balance of Samples not on other Decks)

Neutrons	1.4×10^{15} n/cm^2	>2.5 mev
Neutrons	3.7×10^{15} n/cm^2	>1.5 mev
Neutrons	4.4×10^{15} n/cm^2	>1 mev
Neutrons	1.9×10^{16} n/cm^2	>4 kev
Gamma Ray	7×10^{8} rads (H_2O)	

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TABLE II

Maximum Leakage Currents of Samples in the MTR

Type Gap Insulation	Insulation	Maximum Leakage Current (μa)
Gas	Nitrogen	0.038
Gas	SF_6	0.046
Gas	Vacuum	0.13
Liquid	Fluorolube FS-5	0.42
Liquid	Pyranol 1481	23

TABLE III

Samples Irradiated in the MTR

Type Insulation	Sample (Note 1) No.	Sample (Note 1) Type and Terminal Insulation -(Note 2)	Insulation	Remarks
Gas	27	"A" Gap, Ceramic	Nitrogen	
Gas	9	"A" Gap, Ceramic	Sulphur Hexa-fluoride (SF_6)	
Gas	60	Switch, glass	Vacuum	Pulsed with 2000 amperes
Gas	50	Switch, glass	Vacuum	Epoxy encapsulated
Liquid	M	"A" Gap, glass	Fluorolube FS-5	
Liquid	Y	"A" Gap, glass	Coolanol 45	Terminal broken at start of test; not repairable
Liquid	N	"A" Gap, glass	Pyranol	

[1] Refer to Figure 1 for illustrations of samples used.

[2] This switch failed after encapsulation, but, because time was short, it was included in the tests anyway.

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TABLE IV

Samples Irradiated in the Cobalt 60 Facility

Type Insulation	Sample No.	Sample Type and Terminal Insulation	Insulation	Remarks
Gas	1	"B" Gap, glass	Nitrogen	Epoxy encapsulate
Gas	2	"B" Gap, glass	Nitrogen	
Gas	30	"A" Gap, glass	Nitrogen	
Gas	5	"B" Gap, glass	Nitrogen	
Gas	7	"A" Gap, ceramic	SF_6	
Gas	3	"B" Gap, glass	SF_6	Epoxy encapsulate
Gas	6	Switch, glass	Vacuum	
Liquid	A	"A" Gap, glass	Fluorolobe FS-5	
Liquid	B	"A" Gap, glass	Coolanol 45	

TABLE V

Samples Exposed to the Thermal Environment

Insulation	Sample No.	Sample Type and Terminal Insulation	Insulation	Remarks
Gas	1	"B" Gap, glass	Nitrogen	Epoxy encapsulate
Gas	2	"B" Gap, glass	Nitrogen	
Gas	5	"B" Gap, glass	Nitrogen	
Gas	100	"B" Gap, glass	SF_6	
Gas	3	"B" Gap, glass	SF_6	Epoxy encapsulate
Gas	6	Switch, glass	Vacuum	
Gas	4	"B" Gap, glass	Air	
Liquid	0	"B" Gap, glass	Florolube FS-5	
Liquid	14	"B" Gap, glass	Coolanol 45	
Liquid	6	"B" Gap, glass	Pyranol	

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TABLE VI

Summary of Test Results

Source: Reactor (Neutron and Gamma Ray)

Type of Insulation	Sample (Note 3) No.	Sample (Note 3) Type and Terminal Insulation	Internal Insulation	Max. I @ 3kv
Gas	27	"A" Gap, Ceramic	Dry Nitrogen	0.038μa
Gas	9	"A" Gap, Ceramic	SF_6	0.046μa
Gas	60	Switch, Glass	Vacuum	0.13μa (Note 1)
Gas	50	Switch, Glass	Vacuum	Shorted (Note 2)
Liquid	M	"A" Gap, Glass	Fluorolube FS-5	0.42μa
Liquid	Y	"A" Gap, Glass	Coolanol 45	(Note 5)
Liquid	N	"A" Gap, Glass	Pyranol	23μa

Source: Co^{60} (Gamma Ray)

Type of Insulation	Sample (Note 3) No.	Sample (Note 3) Type and Terminal Insulation	Internal Insulation	Max. I @ 3kv
Gas	1	"B" Gap, Glass	Nitrogen	540μμa (Note 4)
Gas	2	"B" Gap, Glass	Nitrogen	800μμa
Gas	30	"A" Gap, Glass	Nitrogen	0.025μa
Gas	5	"B" Gap, Glass	Nitrogen	875μμa
Gas	7	"A" Gap, Ceramic	SF_6	0.007μa
Gas	3	"B" Gap, Glass	SF_6	0.0013μa (Note 4)
Gas	6	Switch, Glass	Vacuum	0.0022μa
Liquid	A	"A" Gap, Glass	Fluorolube FS-5	0.23μa
Liquid	B	"A" Gap, Glass	Coolanol 45	0.065μa

Source: Oven (110°F)

Type of Insulation	Sample (Note 3) No.	Sample (Note 3) Type and Terminal Insulation	Internal Insulation	Max. I @ 3kv
Gas	1	"B" Gap, Glass	Nitrogen	0.050μa (Note 4)
Gas	2	"B" Gap, Glass	Nitrogen	17μμa
Gas	5	"B" Gap, Glass	Nitrogen	2μμa
Gas	100	"B" Gap, Glass	SF_6	4μμa
Gas	3	"B" Gap, Glass	SF_6	0.040 μa (Note 4)
Gas	6	Switch, Glass	Vacuum	18μμa
Gas	4	"B" Gap, Glass	Air	15μμa
Liquid	0	"B" Gap, Glass	Fluorolube FS-5	0.0034μa
Liquid	14	"B" Gap, Glass	Coolanol 45	0.31μa
Liquid	6	"B" Gap, Glass	Pyranol	0.23μa

Note 1. Pulsed with 2000 amperes through closed contacts.
Note 2. Switch failed after encapsulation, but because of time scales was included anyway.
Note 3. Refer to Figure 1 for illustrations of samples.
Note 4. Epoxy encapsulated.
Note 5. Terminal broken at start of test; not repairable.

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APPENDIX

PRELIMINARY MEASUREMENTS PRIOR TO MTR IRRADIATION

Unit Identification	Continuity Check	Temperature Before Insertion	Temperature After Insertion	No. 60 Loop Resistance	No. 60 Current Pulse	Transducer Resistance In	Transducer Resistance Out	Transducer Output
9	ok	68°F	110°F	0.5 Ω	5 times	6.5	54	0
27	ok							
60	ok							
Y	ok							
N	ok							
50	ok							

LEAKAGE CURRENTS

	500 V	1000 V	1500 V	2000 V	2500 V	3000 V
9	2μμa	8μμa	10μμa	11μμa	12μμa	12.5μμa
27	2μμa	6μμa	9μμa	10μμa	11μμa	12μμa
60	7μμa	13μμa	22.5μμa	65μμa	650μμa	.0018μa
N	.012μa	.025μa	.036μa	.046μa	.063μa	.100μa
M	2μμa	5μμa	9μμa	14μμa	22μμa	38μμa

	50 V	100 V	150 V	200 V	250 V	300 V	350 V
50	8μμa	11μμa	13μμa	15μμa	17μμa	18μμa	20μμa

Experiment immersion time: 1328, 2/7/59

Experiment withdrawal time: 1410, 2/10/59

Experiment conclusion time: 1310, 2/11/59

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CURRENT MEASUREMENTS DURING MTR IRRADIATION

Unit No. 27

Elapsed Time (hours)	Actual Time	1st Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)	2nd Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)
1/2	1402(2/7)						.028						
1	1433	.008	.011	.014	.018	.023	.030						
1-1/2	1501				Reactor Inoperative		.031						
2	1510-1540												
2-1/2													
3	1630						.031						
3-1/2	1700	.0072	.013	.018	.024	.029	.033						
4	1730						.032						
4-1/2	1800						.031						
5	1833						.031						.033
5-1/2	1901						.031						.033
6	1937	.008	.012	.016	.022	.027	.031	.008	.012	.016	.018	.026	.033
6-1/2	2007						.032						.034
7	2029						.031						.034
7-1/2	2104						.032						.033
8	2132	.009	.012	.016	.022	.027	.031	.010	.012	.016	.020	.026	.034
9	2234						.031						.033
10	2330						.032						.034
11	0033(2/8)						.033						.033
12	0138	.010	.013	.017	.022	.027	.032	.011	.013	.017	.021	.025	.033
13	0232						.033						.033
14	0341						.033						.034
15	0434						.032						.033
16	0528	.010	.013	.018	.024	.030	.033	.012	.013	.017	.021	.027	.033
17	0633						.033						.035
18	0732						.033						.035
19	0833						.033						.035
20	0930	.008	.014	.018	.023	.025	.033	.008	.013	.017	.023	.026	.033
21	1030						.033						.034
22	1136						.033						.034
23	1240						.033						.034
24	1335	.010	.013	.017	.022	.028	.033	.012	.014	.017	.022	.027	.034
28													
32													
36													
40													
44	0931 (2/9)						.034						.036
48	1326	.011	.013	.018	.023	.029	.034	.012	.014	.017	.022	.027	.035
56													
68	0952 (2/10)	.011	.013	.018	.023	.029	.034	.012	.015	.018	.023	.029	.037
72	1330	.009	.014	.019	.024	.030	.035	.013	.016	.019	.024	.032	.038
						Box Lifted 1410, 2/10/59							
25 mins	1432	2μμa	2μμa	3μμa	6μμa	7μμa	8μμa	80μμa	80μμa	80μμa	90μμa	100μμa	100μμa
23 hours	1300 (2/11)	2μμa	3μμa	8μμa	11μμa	12μμa	13μμa	130μμa	130μμa	130μμa	140μμa	160μμa	130μμa

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CURRENT MEASUREMENTS DURING MTR IRRADIATION

Unit No. 9

Elapsed Time (hours)	Actual Time	1st Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)	2nd Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)
1/2	1400(2/7)						.038						
1	1430	.004	.010	.014	.018	.028	.036						
1-1/2	1500						.035						
2	1510-1540		Reactor Inoperative										
2-1/2													
3	1630						.037						
3-1/2	1657	.0054	.0083	.016	.021	.028	.037						
4	1728						.037						
4-1/2	1800						.037						
5	1832						.037						.035
5-1/2	1858						.038						.036
6	1933	.006	.009	.014	.019	.029	.038	.008	.012	.018	.024	.029	.036
6-1/2	2005						.038						.036
7	2028						.039						.036
7-1/2	2103						.039						.037
8	2127	.0048	.0078	.016	.021	.030	.041	.0057	.0096	.019	.025	.031	.038
9	2232						.041						.037
10	2330						.040						.040
11	0030 (2/8)						.043						.040
12	0133	.007	.011	.016	.023	.032	.042	.008	.012	.019	.025	.032	.039
13	0230						.043						.038
14	0338						.043						.039
15	0430						.043						.041
16	0525	.007	.012	.016	.023	.036	.042	.008	.012	.018	.024	.032	.041
17	0630						.043						.040
18	0730						.043						.040
19	0830						.043						.040
20	0925	.005	.009	.017	.023	.033	.043	.008	.010	.016	.022	.032	.042
21	1030						.043						.040
22	1134						.043						.038
23	1237						.042						.039
24	1331	.005	.0086	.017	.022	.031	.042	.0057	.009	.018	.024	.031	.039
28													
32													
36													
40													
44	0930(2/9)						.043						.040
48	1323	.0054	.0088	.016	.021	.034	.046	.0061	.012	.018	.023	.031	.038
56													
68	0948(2/10)	.0056	.011	.017	.023	.031	.041	.0057	.012	.018	.023	.032	.038
72	1323	.0061	.012	.017	.023	.030	.040	.0067	.013	.018	.025	.033	.041
						Box Lifted, 1410, 2/10/59							
5 mins							.005						.0035
20 mins	1430	5μμa	5μμa	5μμa	7μμa	25μμa	900μμa	10μμa	11μμa	22μμa	63μμa	.0014	.0028
23 hrs	1245(2/11)	.018	.067	.14	.24	.40	.50	.0013	.0038	.058	.19	.48	.82

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CURRENT MEASUREMENTS DURING MTR IRRADIATION

Unit No. 60

Elapsed Time (hours)	Actual Time	1st Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)	2nd Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)	Current Pulse
1/2	1402(2/7)						.10							
1	1434	.009	.019	.038	.058	.080	.10							5 times
1-1/2	1502						.046							
2	1510-1540				Reactor Inoperative									
2-1/2														
3	1631						.11							
3-1/2	1704	.0051	.018	.037	.059	.081	.12							5 times
4	1731						.12							
4-1/2	1801						.11							20 times
5	1834						.11						.048	
5-1/2	1903						.11						.047	
6	1941	.007	.018	.038	.062	.086	.11	.005	.011	.018	.026	.036	.046	
6-1/2	2008						.11						.046	
7	2031						.10						.046	
7-1/2	2106						.11						.047	
8	2137	.0052	.018	.038	.060	.082	.11	.0045	.012	.018	.027	.036	.047	10 times
9	2236						.11						.047	
10	2332						.11						.048	
11	0035(2/8)						.11						.048	
12	0140	.008	.021	.038	.062	.083	.12	.007	.012	.019	.028	.037	.048	
13	0234						.12						.048	
14	0343						.12						.048	10 times
15	0435						.12						.048	
16	0531	.007	.021	.042	.064	.088	.12	.007	.012	.021	.029	.037	.048	
17	0635						.12						.048	
18	0735						.12						.048	
19	0836						.12						.048	
20	0932	.005	.020	.042	.061	.090	.12	.005	.012	.020	.028	.038	.048	
21	1030						.12						.048	
22	1140						.12						.048	
23	1242						.12						.048	
24	1338	.0051	.020	.038	.060	.085	.12	.0048	.013	.020	.028	.038	.048	10 times
28														
32														
36														
40														
44	0933(2/9)						.12						.047	10 times
48	1330	.010	.023	.043	.068	.10	.13	.0057	.013	.019	.028	.037	.047	
56														
68	0955(2/10)	.011	.025	.048	.073	.10	.13	.0067	.014	.022	.030	.040	.049	
72	1333	.012	.026	.050	.073	.097	.13	.010	.015	.022	.029	.039	.047	10 times
							Box Lifted 1410, 2/10/59							
25 mins	1435	90μμa	90μμa	110μμa	350μμa	.0016	.0026	100μμa	100μμa	100μμa	100μμa	100μμa	100μμa	
23 hours	1305	150μμa	210μμa	460μμa	.0013	.0023	.0041	160μμa	160μμa	160μμa	160μμa	170μμa	180μμa	10 times

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CURRENT MEASUREMENTS DURING MTR IRRADIATION

Unit N

Elapsed Time (hours)	Actual Time	1st Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)	2nd Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)
1/2	1430(2/7)						3						
1	1435	.2	.4	.65	1.0	1.5	3.5						
1-1/2	1583						3.8						
2	1510-1540				Reactor Inoperative								
2-1/2													
3	1633						3.6						
3-1/2	1706	.22	.42	.69	1.1	1.7	3.1						
4	1732						3.1						
4-1/2	1802						3.1						
5	1837						3.1						2.5
5-1/2	1905						2.6						2.5
6	1948	.23	.47	.72	1.0	1.4	2.3	.27	.51	.79	1.1	1.4	2.6
6-1/2	2009						2.3						2.3
7	2033						2.4						2.8
7-1/2	2107						2.5						2.7
8	2140	.28	.54	.82	1.2	1.6	2.5	.30	.57	.90	1.2	1.6	2.3
9	2238						1.8						2.1
10	2334						1.9						2.1
11	0038(2/8)						2.1						2.3
12	0143	.40	.61	1.1	1.4	1.7	2.2	.37	.71	1.2	1.4	1.9	2.6
13	0238						2.4						2.6
14	0350						2.5						2.7
15	0437						2.6						2.9
16	0535	.49	.87	1.3	1.7	2.2	2.7	.52	.89	1.5	1.9	2.5	3.1
17	0638						2.8						3.3
18	0737						3.2						3.4
19	0839						2.8						3.6
20	0938	.66	1.2	1.7	2.2	2.8	3.5	.70	1.2	1.7	2.4	3.2	4.0
21	1030						3.7						4.0
22	1142						4.0						4.6
23	1248						4.3						4.7
24	1342	.70	1.3	1.9	2.7	3.5	4.3	.80	1.6	2.2	3.0	3.8	4.9
28													
32													
36													
40													
44	0935(2/9)						14						13
48	1334	2.0	3.7	5.6	7.5	11.0	13	2.4	4.5	6.7	9.0	12.0	14.0
56													
68	0958(2/10)	3.0	5.1	8.0	12.0	14.0	19.0	3.6	6.3	9.2	13.0	17.0	23.0
72	1336	3.2	5.3	8.3	12.0	16.0	20.0	3.9	6.6	9.7	14.0	18.0	23.0
					Box Lifted 1410, 2/10/59								
15 mins	1425	1.3	3.2	5.0	6.8	8.9	12.0	2.0	3.4	5.5	7.1	10.0	12.0
23 hours	1300(2/11)	.58	1.1	1.6	2.0	2.7	3.3	.61	1.2	1.7	2.3	3.0	3.7

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CURRENT MEASUREMENTS DURING MTR IRRADIATION

Unit No. 50

Elapsed Time (hours)	Actual Time	1st Polarity 50 V (μa)	100 V (μa)	150 V (μa)	200 V (μa)	250 V (μa)	300 V (μa)	350 V (μa)	2nd Polarity 50 V (μa)	100 V (μa)	150 V (μa)	200 V (μa)	250 V (μa)	300 V (μa)	350 V (μa)
1/2	1405(2/7)							.048							
1	1440	.018	.029	.035	.040	.047	.053	.039							
1-1/2	1505							.024							
2	1510-1540					Reactor Inoperative									
2-1/2															
3	1635							.026							
3-1/2	1712	.0037	.008	.014	.017	.020	.024	.027							
4	1735							.027							
4-1/2	1805							.025							
5	1844							.023							.033
5-1/2	1910							.026							.032
6	1958	.0043	.0077	.013	.017	.020	.023	.027	.025	.042	.052	.060	.067	.072	.076
6-1/2	2012							.026							.077
7	2036							.026							.079
7-1/2	2116							.026							.079
8	2150	.004	.0077	.013	.017	.020	.024	.027	.027	.044	.055	.063	.070	.076	.079
9	2240							.026							.082
10	2336							.027							.047
11	0041(2/8)							.027							.038
12	0148	.008	.012	.014	.017	.022	.025	.027	.011	.017	.022	.025	.027	.033	.037
13	0243							.027							.037
14	0355							.027							.035
15	0440							.027							.035
16	0541	.0056	.0092	.017	.020	.022	.024	.028	.009	.016	.020	.024	.031	.034	.038
17	0643							.028							.035
18	0744							.028							.035
19	0843							.028							.035
20	0948	.005	.009	.017	.021	.023	.025	.028	.007	.012	.019	.024	.028	.032	.035
21	1045							.028							.033
22	1148							.028							.033
23	1255							.028							.027
24	1355	.0047	.012	.016	.019	.022	.026	short	D. C. Resistance - 220 ohms						
28															
32															
36															
40															
44	0939(2/9)		Shorted. D. C. Resistance - 12 ohms												
48	1340		Shorted. D. C. Resistance - 12 ohms												
56															
68	1003(2/10)		Shorted. D. C. Resistance - 12 ohms												
72	1342		Shorted. D. C. Resistance - 12 ohms												
						Box Lifted 1410 2/10/59									
10 mins	1442		Shorted. D. C. Resistance - 12 ohms												
23 hours	1305		Shorted. D. C. Resistance - 12 ohms												

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CURRENT MEASUREMENTS DURING MTR IRRADIATION

Unit M

Elapsed Time (hours)	Actual Time	1st Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)	2nd Polarity 500 V (μa)	1000 V (μa)	1500 V (μa)	2000 V (μa)	2500 V (μa)	3000 V (μa)
1/2	1403(2/7)						.013						
1	1438	190μμa	630μμa	.0018	.0034	.0066	.013						
1-1/2	1504						.088						
2	1510-1540				Reactor Inoperative								
2-1/2													
3	1634						.12						
3-1/2	1708	.0042	.011	.018	.030	.054	.082						
4	1733						.12						
4-1/2	1803						.12						
5	1839						.11						.42
5-1/2	1908						.16						.37
6	1954	.016	.032	.051	.073	.110	.17	.023	.047	.073	.100	.16	.25
6-1/2	2010						.21						.32
7	2034						.26						.30
7-1/2	2110						.28						.28
8	2145	.024	.051	.087	.12	.16	.23	.018	.048	.042	.069	.11	.20
9	2239						.33						.37
10	2335						.37						.35
11	0040(2/8)						.37						.31
12	0146	.042	.078	.13	.16	.19	.28	.026	.046	.078	.11	.14	.19
13	0240						.37						.28
14	0352						.37						.30
15	0438						.33						.25
16	0538	.034	.071	.12	.15	.17	.27	.013	.022	.035	.048	.058	.077
17	0641						.28						.17
18	0740						.21						.18
19	0841						.19						.12
20	0943	.017	.032	.048	.065	.090	.16	.005	.012	.017	.020	.032	.05
21	1040						.10						.033
22	1145						.083						.034
23	1251						.060						.032
24	1348	.0025	.0058	.014	.019	.027	.045	.0016	.0035	.0055	.0083	.017	.027
28													
32													
36													
40													
44	0938(2/9)						.013						.019
48	1337	450μμa	.001	.0025	.004	.0061	.012	.001	.0021	.0035	.006	.013	.018
56													
68	1000(2/10)	530μμa	.0016	.0029	.0043	.0063	.0092	.0012	.0021	.0039	.0066	.0095	.018
72	1340	600μμa	.0014	.0032	.0041	.0063	.0088	.0012	.0022	.0039	.0062	.013	.017
						Box Lifted 1410, 2/10/59							
30 mins	1440	1μμa	3μμa	7μμa	17μμa	25μμa	33μμa	70μμa	70μμa	80μμa	100μμa	120μμa	170μμa
23 hrs	1300(2/11)	1μμa	1μμa	7μμa	11μμa	16μμa	23μμa	160μμa	160μμa	160μμa	160μμa	200μμa	200μμa

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CURRENT MEASUREMENTS DURING GAMMA RAY IRRADIATION

Elapsed Time (Minutes)	Unit No. 2 (μμa) Polarity 1	Unit No. 2 (μμa) Polarity 2	Unit No. 5 (μμa) Polarity 1	Unit No. 5 (μμa) Polarity 2	Unit No. 6 (μμa) Polarity 1	Unit No. 6 (μμa) Polarity 2	Unit No. 30 (μμa) Polarity 1	Unit No. 30 (μμa) Polarity 2	Unit No. 3 (μμa) Polarity 1	Unit No. 3 (μμa) Polarity 2	Unit No. 1 (μμa) Polarity 1	Unit No. 1 (μμa) Polarity 2
0	5	–	3	–	2	2	0	0	46	50	37	37
15	750	700	630	825	2200	1400	650	25000	1300	1300	530	530
30	750	700	700	825	2100	1400	700	22000	1200	1200	540	540
45	750	700	750	850	2000	1500	670	17000	1200	1200	530	530
60	800	650	700	850	2100	1400	650	23000	1300	1200	530	540
75	700	625	700	875	2000	1400	700	22000	1200	1200	530	530
90	750	650	700	850	2000	1300	700	23000	1200	1200	530	530
After Dose	3	3	3	6	2	2	0	0	170	170	230 (Note 1)	230

Note 1: Unit No. 1 epoxy encapsulated

Total Dose: 2.55×10^5 Rads

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CURRENT MEASUREMENTS DURING GAMMA RAY IRRADIATION

Elapsed Time (Minutes)	Unit No. 7 ($\mu\mu$a) Polarity 1	Unit No. 7 ($\mu\mu$a) Polarity 2	Unit No. 4 (μa) Polarity 1	Unit No. 4 (μa) Polarity 2	Unit A (μa) Polarity 1	Unit A (μa) Polarity 2	Unit B ($\mu\mu$a) Polarity 1	Unit B ($\mu\mu$a) Polarity 2
0	12	16	.03	.02	.076	.071	150	160
15	7000	4500	.08	.03	.082	.18	1200	65000
30	7000	4800	.075	.065	.098	.20	1600	53000
45	5500	5000	.070	.068	.10	.21	1700	43000
60	5000	4700	.067	.060	.12	.22	5000	43000
75	4500	5000	.075	.062	.13	.23	4500	38000
90	7000	6000	.068	.062	.13	.22	2000	37000
After Dose	11	5200	.026	.022	.065	.088	270	25

Total Dose: 2.55×10^5 Rads

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CURRENT MEASUREMENTS DURING GAMMA RAY IRRADIATION

Elapsed Time (Minutes)	Unit No. 7 ($\mu\mu$a) Polarity 1	Unit No. 7 ($\mu\mu$a) Polarity 2	Unit No. 4 (μa) Polarity 1	Unit No. 4 (μa) Polarity 2	Unit A (μa) Polarity 1	Unit A (μa) Polarity 2	Unit B ($\mu\mu$a) Polarity 1	Unit B ($\mu\mu$a) Polarity 2
0	12	16	.03	.02	.076	.071	150	160
15	7000	4500	.08	.03	.082	.18	1200	65000
30	7000	4800	.075	.065	.098	.20	1600	53000
45	5500	5000	.070	.068	.10	.21	1700	43000
60	5000	4700	.067	.060	.12	.22	5000	43000
75	4500	5000	.075	.062	.13	.23	4500	38000
90	7000	6000	.068	.062	.13	.22	2000	37000
After Dose	11	5200	.026	.022	.065	.088	270	25

Total Dose: 2.55×10^5 Rads

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