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NUCLEAR RADIATION EFFECTS AND POST-RADIATION TEMPERATURE EFFECTS ON SA-750 SILICON DIODES

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ABSTRACT

This report deals with nuclear radiation and post-radiation temperature effects on the SA-750 silicon diode. The theory of displacement damage is examined with respect to how this phenomenon influences diode parameters. Experimental data and the subsequent effects of irradiated SA-750 diodes on Zipper timer operation are discussed. It was concluded that, up to the present radiation level requirements, these diodes will function in timer circuits with negligible degradation in timer operating characteristics.

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NUCLEAR RADIATION EFFECTS AND POST RADIATION TEMPERATURE EFFECTS ON SA-750 SILICON DIODES

Introduction

Radiation requirements have been imposed on several of the Zipper L-C Timers which employ SA-750 silicon diodes for grid clamping. Previously accumulated test data would imply that some diodes could be a prominent cause of weakness in timer-nuclear radiation susceptibility. It is the purpose of this report to show, by experimental evidence, that the present SA-750 diode will not appreciably affect timer operation after exposure to neutron flux levels greater than those specified in the present requirements. It will be necessary to extract conclusions from the referenced memo to make this point.

Summary of Results

1. The forward voltages at 100 ma, at 52°C, increase from a pre-radiation range of 0.77 to 0.95 volts to a post-radiation range of 2.2 to 5.2 volts after exposure to 4.8×10^{15} NVT (E>KEV). In terms of bulk resistance, the dynamic forward resistance underwent changes from a pre-radiation value of 1.6 ohms to a post-radiation range of 8.0 to 40 ohms after exposure to 4.8×10^{15} NVT (E>KEV).

2. Diode inverse leakage current increases linearly (1:1) as the total integrated neutron flux is increased. In these tests, there appears to be a threshold of roughly 10^{13} NVT (E>KEV) beyond which the increases were observed.

3. Avalanche breakdown voltage at 100 μa, at -55°C, increases as the neutron flux level is increased.

4. After a threshold of roughly 3×10^{14} NVT (E>KEV) is reached, the diode depletion region capacitance at -4 volts dc bias decreases linearly with integrated flux.

5. Recovery time at 250 μa, as measured in the JAN-256 recovery test circuit, decreased from an average pre-radiation value of 0.4 μsec to an average value of about 0.2 μsec after 10^{15} NVT (E>KEV). Above flux levels of 10^{15} NVT (E>KEV) recovery time increases rapidly from 0.2 to roughly 1.0 μsec at 4.8×10^{15} NVT (E>KEV).

6. No prominent degradation in the forward voltage at 100 ma as a function of temperature was observed after exposures up to 7.2×10^{14} NVT (E>KEV). However, the -50°C forward voltage drops at 10 ma ranged from 3.5 to 18.5 volts after exposure to 4.8×10^{15} (E>KEV). This is indicative of a bulk resistance range, measured as dynamic forward resistance in the 0.5 to 1.0 ma region, from 1000 to 4800 ohms as taken from post-radiation V-I characteristics.

7. The general shape of the inverse leakage as a function of temperature curves is not changed by irradiation. Diode bulk inverse leakage, discounting surface leakage, doubles for about every eight degrees centigrade rise in temperature. Leakage measurements at low (50V) and high (200V) inverse voltage revealed no radiation induced surface conditions and subsequent leakage paths.

8. Avalanche breakdown voltage, at 100 μa, decreased with temperature after exposures to neutron irradiation. Post-radiation measurements of breakdown are not too valid if made at 100 μa since the breakdown region becomes increasingly soft with higher flux exposure. To make measurements in the avalanche region necessitates either using higher inverse currents,

using pulse techniques, or, as in No. 3, using a low ambient temperature to accomodate the low current.

Procedure

The Transitron SA-750 qualification sample was used for this experiment. After the usual qualification sample tests were completed, the sample was separated into two groups of twenty each and subjected to the following integrated flux levels.

Unit Identification	NVT	E	Exposure
1a, 1b, 1c, 1d 5d	3.3×10^{13}	>KEV	1st
6a, 6b, 6c, 6d 10d	2.3×10^{14}	>KEV	1st
1a, 1b, 1c, 1d 5d	7.2×10^{14}	>KEV	2nd
6a, 6b, 6c, 6d 10d	4.8×10^{15}	>KEV	2nd

The irradiations were completed in the Idaho Falls, Materials Testing Reactor in the VG-9 hole, which has the following spectrum, with a corresponding Gamma (γ) rate of 1.2×10^{7} R/hr.

Energy		NV(Neutrons) cm^2 sec	Percent
$P\mu$	>KEV	2.0×10^{11}	100
U	>1.5 MEV	3.3×10^{10}	16
S	>2.5 MEV	1.2×10^{10}	6
Ni	>5.0 MEV	2.6×10^{9}	1.3

The diode samples were tested thoroughly both previous to and after irradiation. From these data, limit curves of the various parameters as a function of total integrated neutron flux were plotted (Figures 1 through 11).

Conclusions

The forward voltage as a function of NVT at both high and low current shows a negative coefficient before going positive (Figure 1). The negative coefficient can be attributed to radiation-induced, decreased minority-carrier lifetime. The positive slopes show the region where resistivity changes become predominant. These shifts in parameters imply no degradation in Zipper L-C timer performance. In the worst case, the bulk diode resistance increased to 40 ohms, or, for four diodes in series, a total of 200 ohms. It was shown in Reference 1 that the addition of bulk resistance resulted in a time interval shift of roughly 0.63 nanoseconds per ohm.

Figure 2 shows that diode inverse leakage increases linearly with increasing NVT, this change being attributed to minority-carrier-lifetime changes. Since in the application the diodes are paralleled with a one-megohm grid-shunting resistance, the timer interval should not be adversely affected by this increased leakage. The measurements at two voltages are attempts to differentiate between bulk and surface leakage, however, any surface conditions arising from irradiation are masked by the more prominent bulk leakage effects.

The curves of average leakage as a function of NVT (Figure 3) show the significance of having a low initial bulk leakage in diodes in order to attain radiation tolerance with this parameter. The ideal behavior of this parameter shows the feasibility of predicting radiation-induced leakage. A fair approximation is 1:1 beyond 10^{13} NVT (E>KEV).

In order to actually show avalanche breakdown at low breakdown currents, it was necessary to test at -55°C ambient temperature. The increase in breakdown is attributed to increased resistivity (see Figure 4).

The linear decrease in capacitance beyond 3×10^{14} NVT (E>KEV) (Figure 5) is attributed to the decrease in charge Carrier concentration resulting from radiation. Zipper timers are sensitive to changes in this capacitance and in Reference 1 it was shown that the time interval would lengthen 0.2μsec/$\mu\mu$fd. However, it should be kept in mind that diode capacitance behaves according to $C \propto V^{-n}$ and $1/3 < n < 1/2$ with $n \simeq 1/3$ for graded junctions.

These measurements were made at -4 volts bias. In applications using higher voltages, the change in diode capacitance will be less effective.

Figure 6 shows two phenomena. The negative slope shows the decrease in charge storage resulting from minority-carrier-lifetime changes. This effect could have been presented more effectively were an instrument available to measure charge storage directly rather than by the indirect recovery time measurement used. Beyond 10^{15} NVT (E > KEV), the positive slope indicates that the increasing RC time is prominent. R is the diode bulk resistance and C is the space charge capacitance. Reference 1 shows Zipper timer intervals to be relatively insensitive to recovery differences, providing diodes are faster than 0.5 μ seconds. Since the charge storage far overshadows the RC time constant the positive going portion of this aspect of diode parameters is negligible.

Figure 7 shows that there is essentially no change in diode-temperature characteristics at low forward bias current out to flux levels of 7.2×10^{14} NVT (E > KEV). Beyond 7.2×10^{14} NVT (E > KEV), the change in forward voltage-temperature characteristics is influenced by the increased diode bulk resistance and shows a much greater slope. This is perhaps better seen in the starred notation above the curves of Figure 8. Using, from Reference 1, the time interval versus bulk resistance coefficient of .63 nanoseconds/ohm it is obvious that a significant shift in time delay would be observed at the subzero temperature after these diodes are exposed to 4.8×10^{15} NVT (E > 1 KEV).

By using the curves of post radiation leakage versus temperature in Figures 9 and 10, one can establish the maximum neutron dosage and operating temperature for any given application with a fair degree of accuracy. A common leakage requirement at rated voltage for high temperature applications is about 100 μamp. From Figure 10, the maximum allowable neutron dosage for a 100°C requirement would be 7.2×10^{14} NVT(E>KEV). No firm leakage requirements are made on Zipper timer diodes at this time.

Figure 11 shows the degradation of diode breakdown at 100 μa, through the temperature range. This figure probably serves best to show the inadequacy of low current measurements. At the higher temperatures the increasing softness of the breakdown characteristic is measured rather than the actual breakdown.

Future and Present Efforts

Additional Work Now in Progress on the SA-750 Diode

Organization 1431-3 is presently investigating methods of controlling the diode radiation tolerance either through the specification of parameter values or by using pre-irradiation techniques.

A close study of the relationships of diode parameters to fabrication techniques is under way. Further, the relation of diode parameters and fabrication techniques (junction area, resistivity, diffusion program, and starting material) to radiation damage is being investigated.

Should pre-irradiation techniques be necessary, several programs are near completion which are intended to show neutron-electron bombardment damage equivalence. Electron bombardment would be a logical means of handling pre-irradiation because of the availability of accelerators and because it would overcome residual radiation hazards. Another program which supplements the n-B equivalence work is one which should show that the displacement damage is dependent on the average spectrum ($\bar{E}$) energy. This program will show the discrepancies involved by testing in a variety of pile-type reactors with different energy distribution curves.

LIST OF REFERENCES

Confidential memo, C. I. Westmark, 1431-3, to Distribution, Subject, "Radiation Effects on Zipper L-C Timer Diodes", Ref. Sym: 1431(1003), July 16, 1959.

APPENDIX A

SUMMARY OF PERMANENT DAMAGE MECHANISM

The electrical properties of semiconductor devices are such that they depend heavily on an ordered crystal lattice structure. It has been shown that the prominent permanent damage mechanism resulting from fast neutron bombardment in silicon is the introduction of Frenkle defects (elastic collisions or billiard ball impacts between the nuclei of the silicon atoms and fast neutrons creating recoil nuclei). Depending upon the angle of incidence of this initial knock-on process, the energy of the incident neutron involved, and, subsequently, the energy transfer, there may be additional knock-on processes occurring (secondary, tertiary etc). This knock-on process will continue until the knocked-on silicon has insufficient energy to cause another dislocation. The initial collision and knock-on processes result in a distorted silicon crystal lattice. Atoms are displaced from their normal lattice positions, leaving vacancies and taking on interstitial positions. Consequently, new energy levels are introduced into the forbidden band. The immediate implication as regards the radiation induced energy levels is that it requires less energy to raise electrons to the conduction band.

The significance of these lattice disorders, as applied specifically to silicon diodes, is that through this type of impurity injection, from fast neutron bombardment, the number of charge carriers per unit volume is altered. It has been shown that there is a ten percent reduction in charge carr carriers per unit volume per incident fast neutron. This is equivalent to sayin the material is going intrinsic and, as regards the P-N junction, is being destroyed. As the material goes intrinsic, significant increases in resistivity are encountered. Several diode parameters sensitive to resistivity changes are governed by the following relationships:

$$V_f = Vo + I_f r_b, \text{ assuming } \rho_P << \rho_n \quad (1)$$

$$V_b = 8\rho_P + 39\rho_n \quad (2a)$$

$$V_b = CN^{-n} \text{ if } \frac{10^{13}}{cc} < N < \frac{10^{16}}{cc} \quad (2b)$$

where V_f is the forward voltage drop at high current

Vo is the threshold voltage

I_f is the high forward current

r_b is the base (N region) bulk resistance

V_b is avalanche breakdown voltage

ρ_P is the resistivity of the P region

ρ_n is the resistivity of the N region

$C = 3x10^{13}$ (a constant)

$n = 3/4$ (a constant)

N = number of charge carriers per cm^3

Equation (1) shows that the forward voltage drop at high forward current will increase with the resistivity of the base, which increases with neutron dosage. As the N region increases in resistivity, it is obvious from Equation (2a) that breakdown will become greater. From Equation (2b) one can see that the breakdown voltage varies inversely as the number of charged carriers. The charge carriers decrease with increasing neutron

dosage. The region of NVT in which the aforementioned changes will become prominent is dependent largely on the initial charge carrier concentration (doping), the thickness of the base region, the junction area, the diffusion program (infers variations in junction gradation), and even, as has been shown, on the oxygen impurity content of the bulk material from which the junctions are fabricated. Another consequence of the radiation induced vacancy-interstitial pair production is that by acting as electron-hole trapping centers these lattice disorders appreciably affect minority carrier lifetime. Introduction of recombination centers will be reflected in changes in diode parameters according to the following relationships:

$$I = I_s \left(\exp \frac{V}{KT} - 1\right) \tag{3}$$

solving (3) for the junction voltage (V)

$$V = KT \ln \left(\frac{I}{Is} + 1\right) \tag{4}$$

where (5) $$I_s = (Npo) \frac{Ln}{\tau n} + (Pno) \frac{Lp}{\tau p} \tag{5}$$

where I is the junction current in (amps/cm^2)

Is is the saturation current

q is electron charge

V is the voltage across the junction at low current

K is Boltzman's constant

T is absolute temperature

Npo is the thermal electron density in the P region

Pno is the thermal hole density in the N region

Ln is the diffusion length of electron on the P region

Lp is the diffusion length of holes in the N region

τn is the electron lifetime in the P region

τp is the hole lifetime in the N region

Using these latter relationships, one can predict the behavior of threshold voltage (from 4) and saturation current (from 5) after exposure to fast neutron flux. The saturation current (Is) varies inversely as the minority carrier lifetime, which is known to decrease with dosage. From equation (5) saturation current (inverse leakage) will increase.

From equation (5) it can be seen that I_s, which was just shown to increase as a result of irradiation, will cause V, the forward voltage at low current, to decrease as $Ln \frac{I}{I_s}$.

Several other parameters of the diode are also affected by irradiation. The depletion region capacitance is a function of junction area, diffusion program (junction graduation), and the end region charge carrier concentration. It was shown that charge carrier concentration decreases 10 percent per incident neutron. The space charge capacitance is related to the charge carrier concentration directly, i.e. $C \alpha N$, and it would be expected that C would decrease as the integrated flux decreased.

Diode inverse recovery, as reviewed in most recovery test sets, consists of two components. There is the actual hole storage effect, during which time the diode is essentially a short. During this period, the minority carrier (holes) trapped in or near the depletion region are swept out with the application of inverse voltage. At the time the diode space charge region is essentially swept free of minority carriers the junction looks like a capacitor and will recover in an exponential manner with RC time dependent on the depletion region capacitance and base and/or the loop resistance of the charging circuit.

The hole storage effect will vary directly as the minority carrier life and will then decrease with increasing integrated flux. Beyond this effect, two competing variables are present, *i.e.* space charge capacitance and base bulk resistance. Past experiments have shown that this RC time increases with increasing flux because r_b changes overshadow the changes in capacitance.

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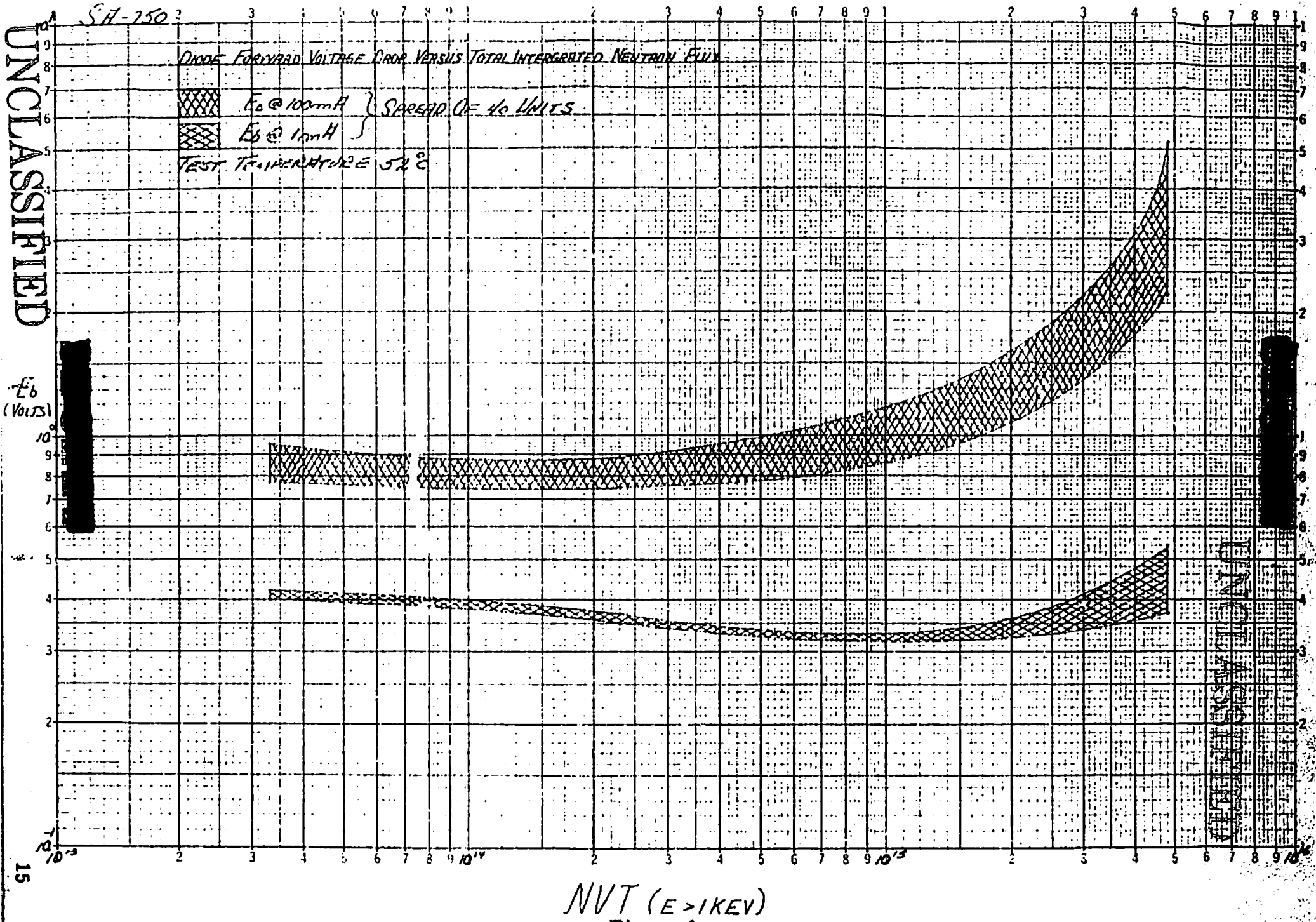

Figure 1.

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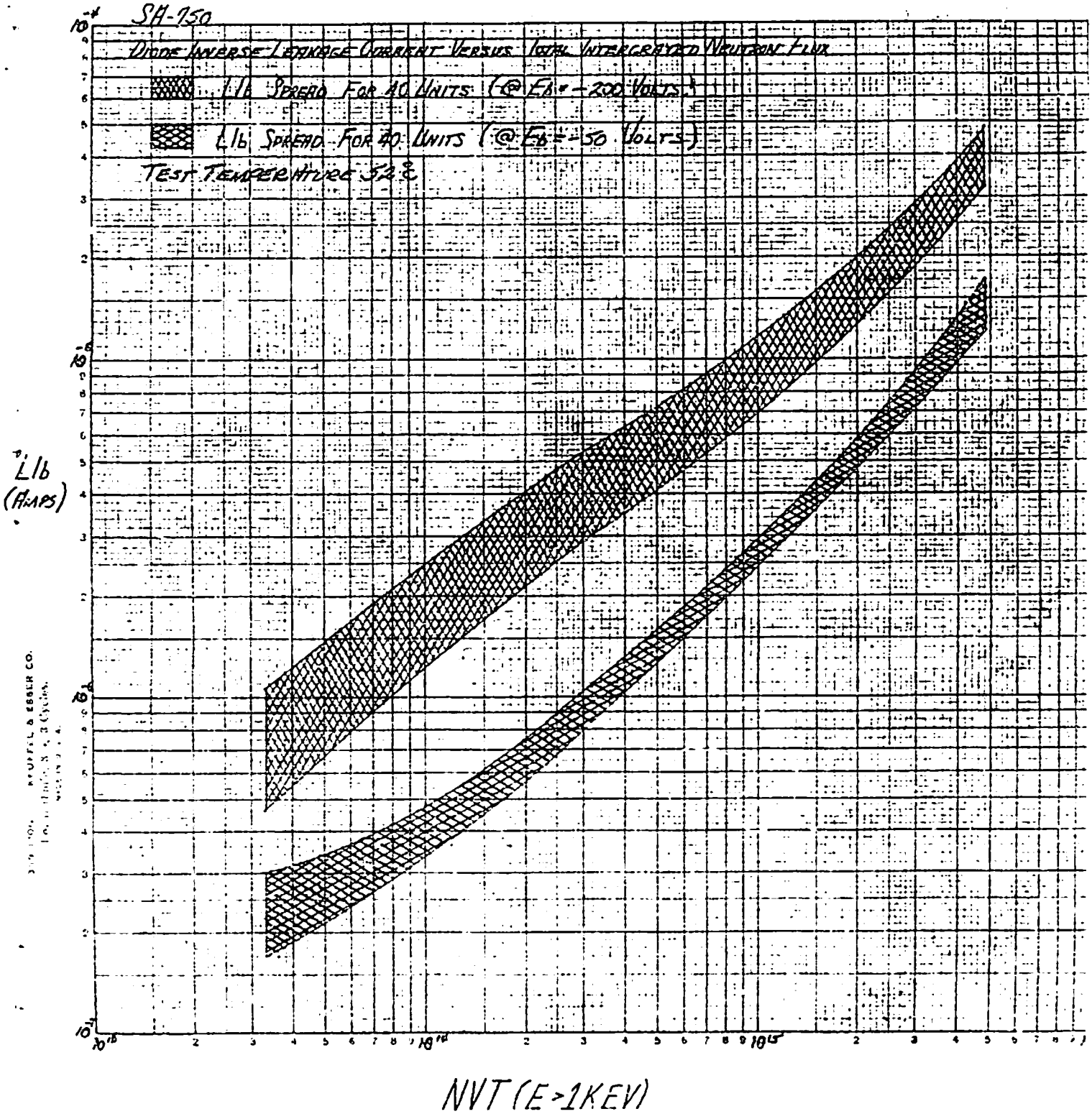
SH-750
DIODE INVERSE LEAKAGE CURRENT VERSUS TOTAL INTERGRATED NEUTRON FLUX
Ilb SPREAD FOR 40 UNITS (@ EB = -200 VOLTS)
Ilb SPREAD FOR 40 UNITS (@ EB = -50 VOLTS)
TEST TEMPERATURE 52°C
Ilb (AMPS)
NVT (E>1KEV)

Figure 2.

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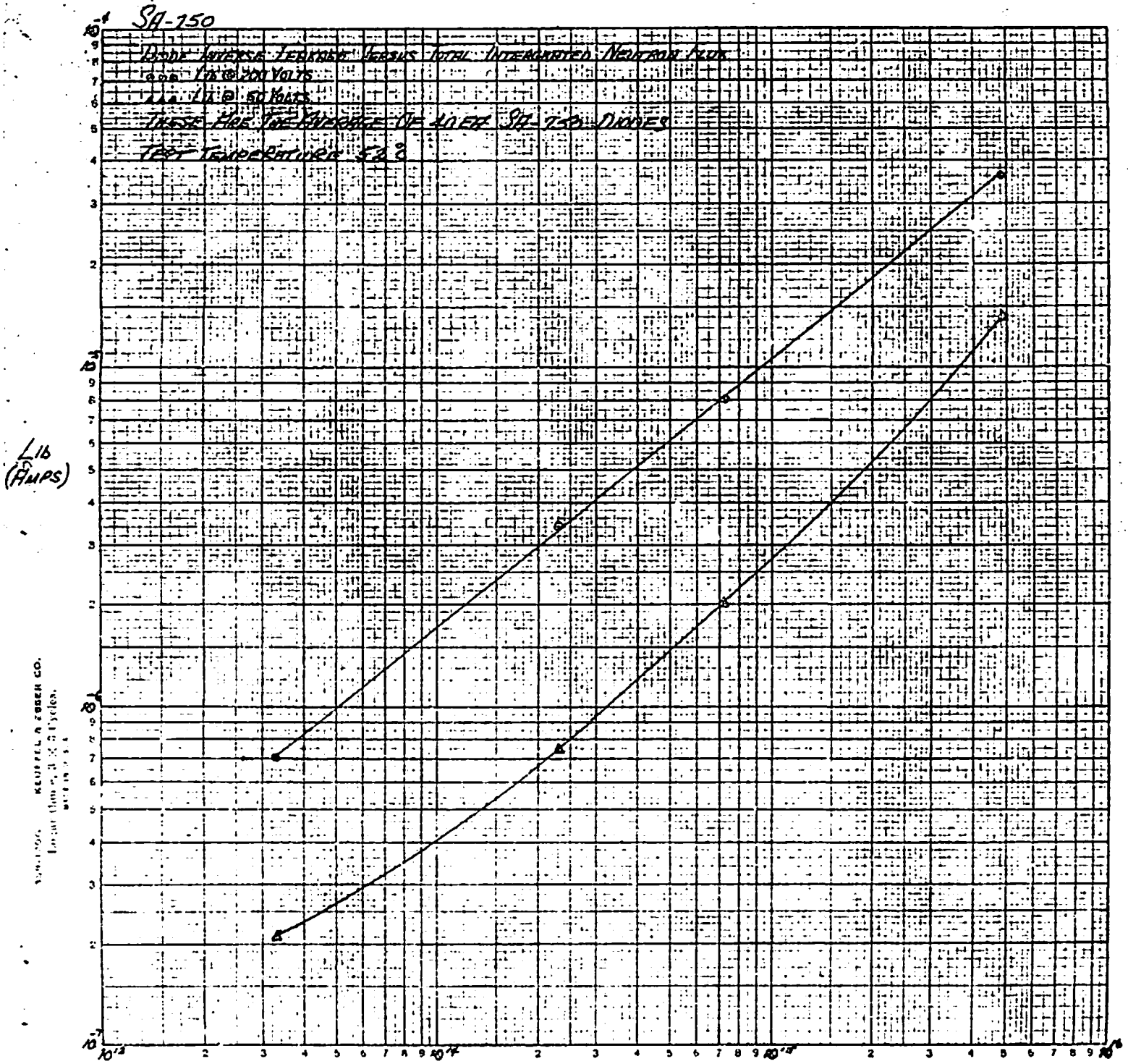

Figure 3.

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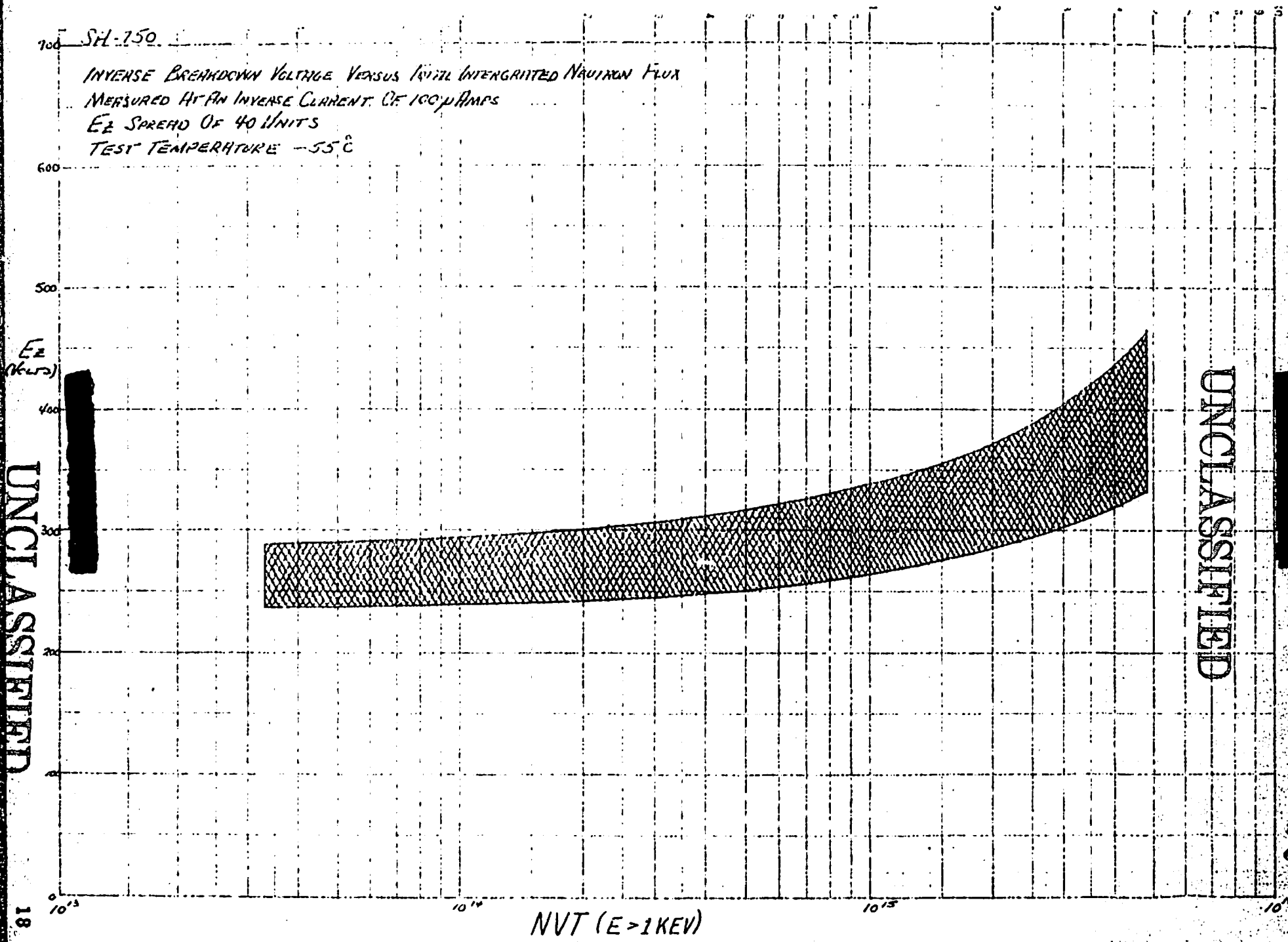

Figure 4.

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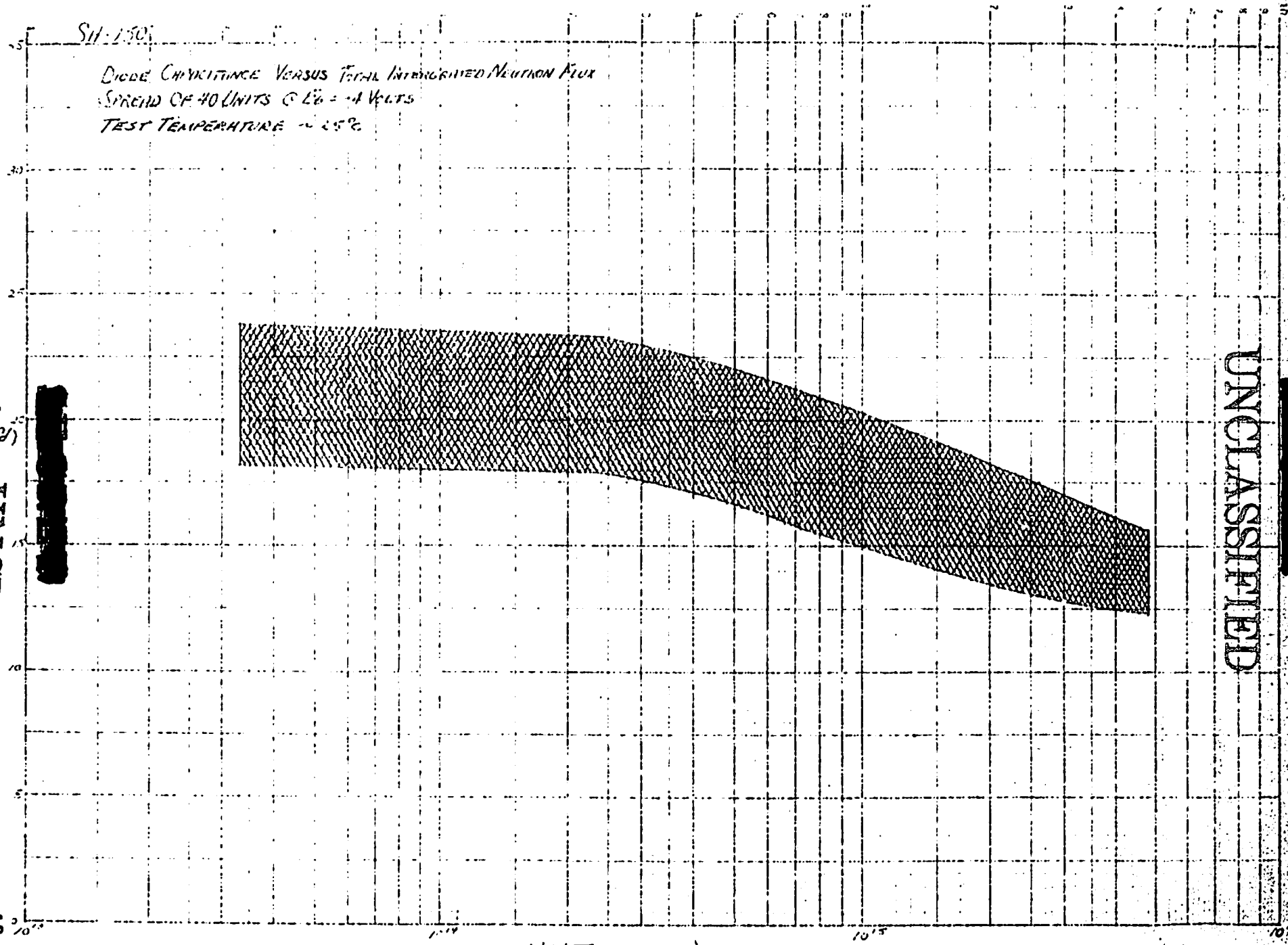

Figure 5. N.V.T (E>1KEV)

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K•E LOGARITHMIC 359-112
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 3 CYCLES

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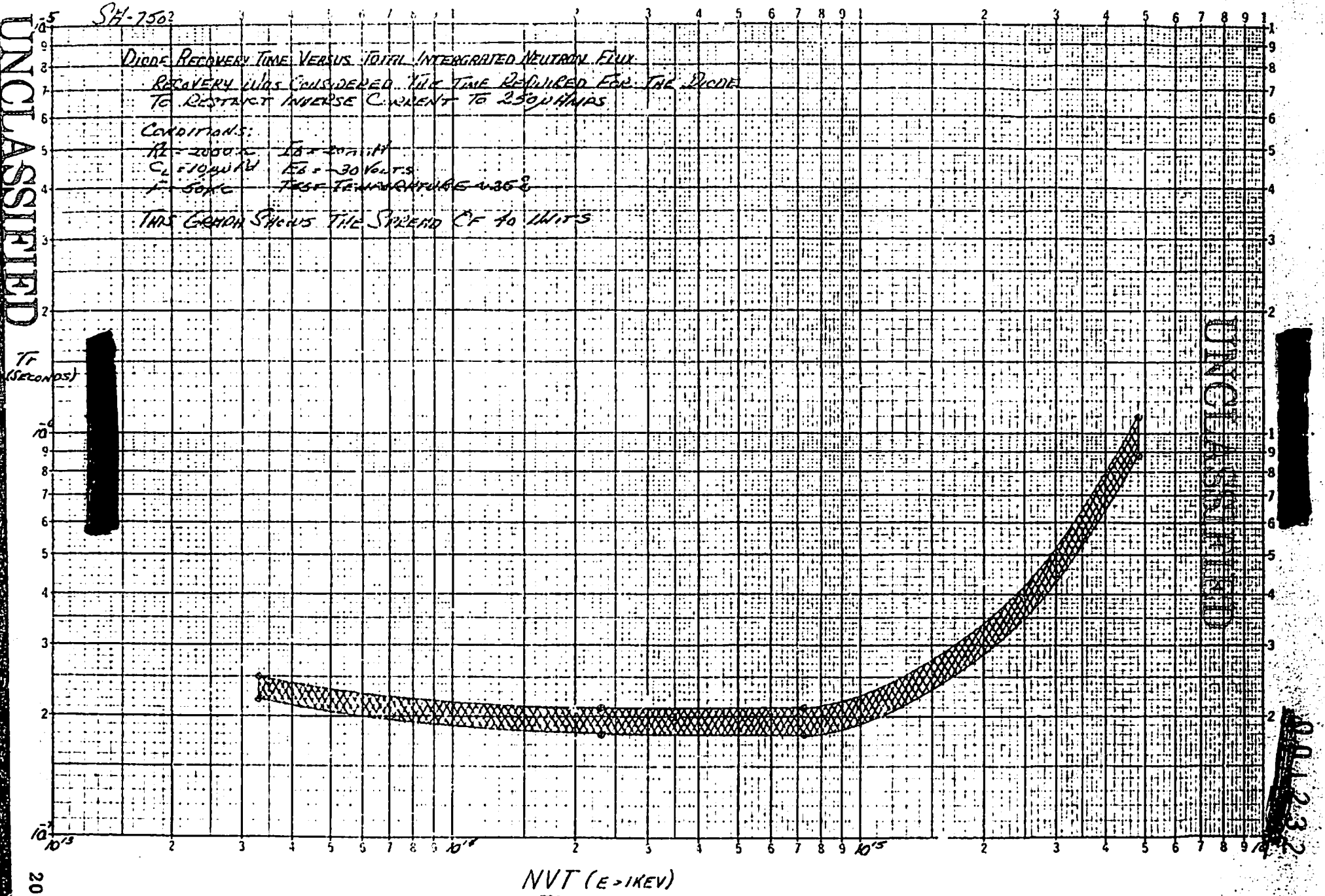

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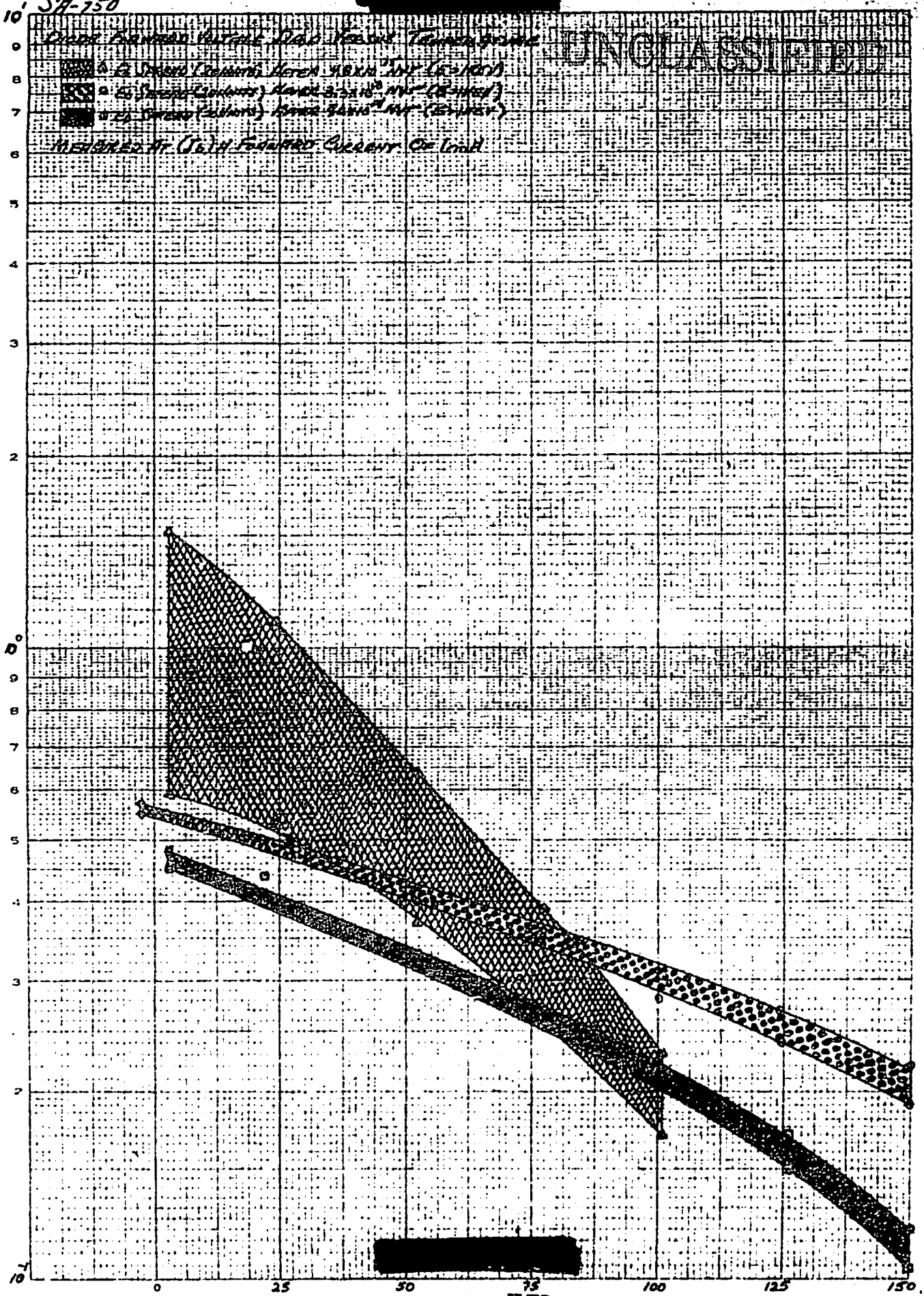

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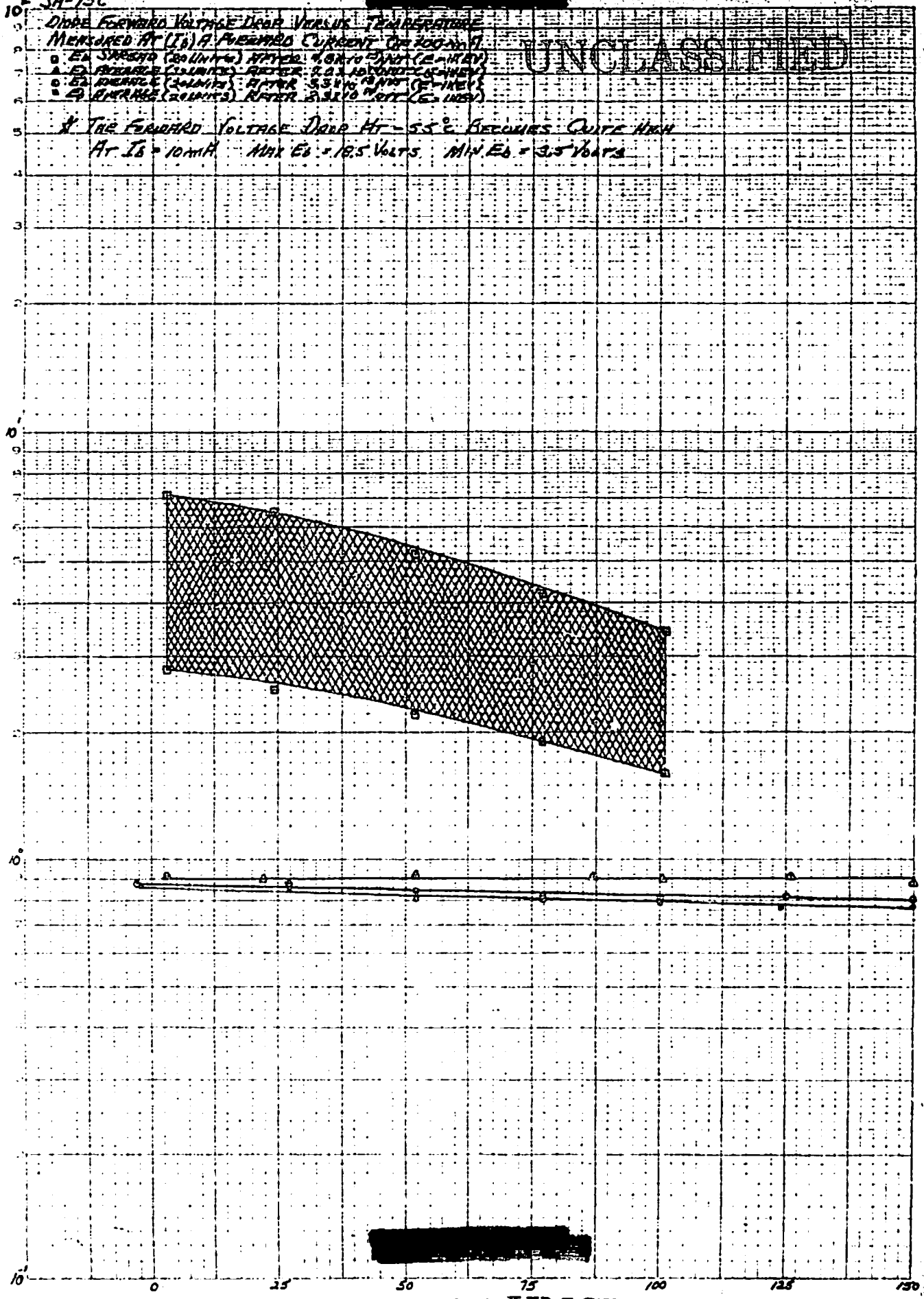

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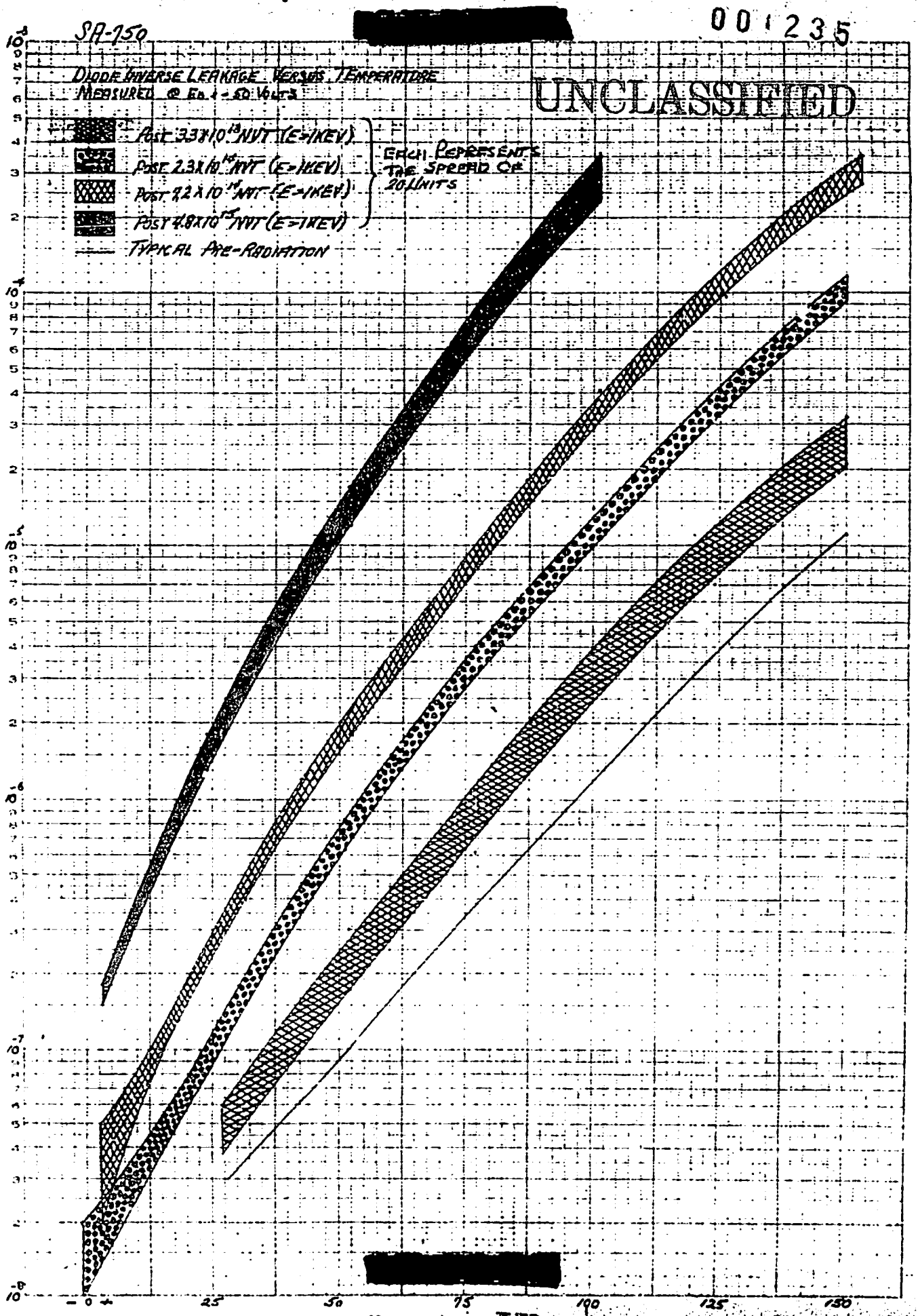

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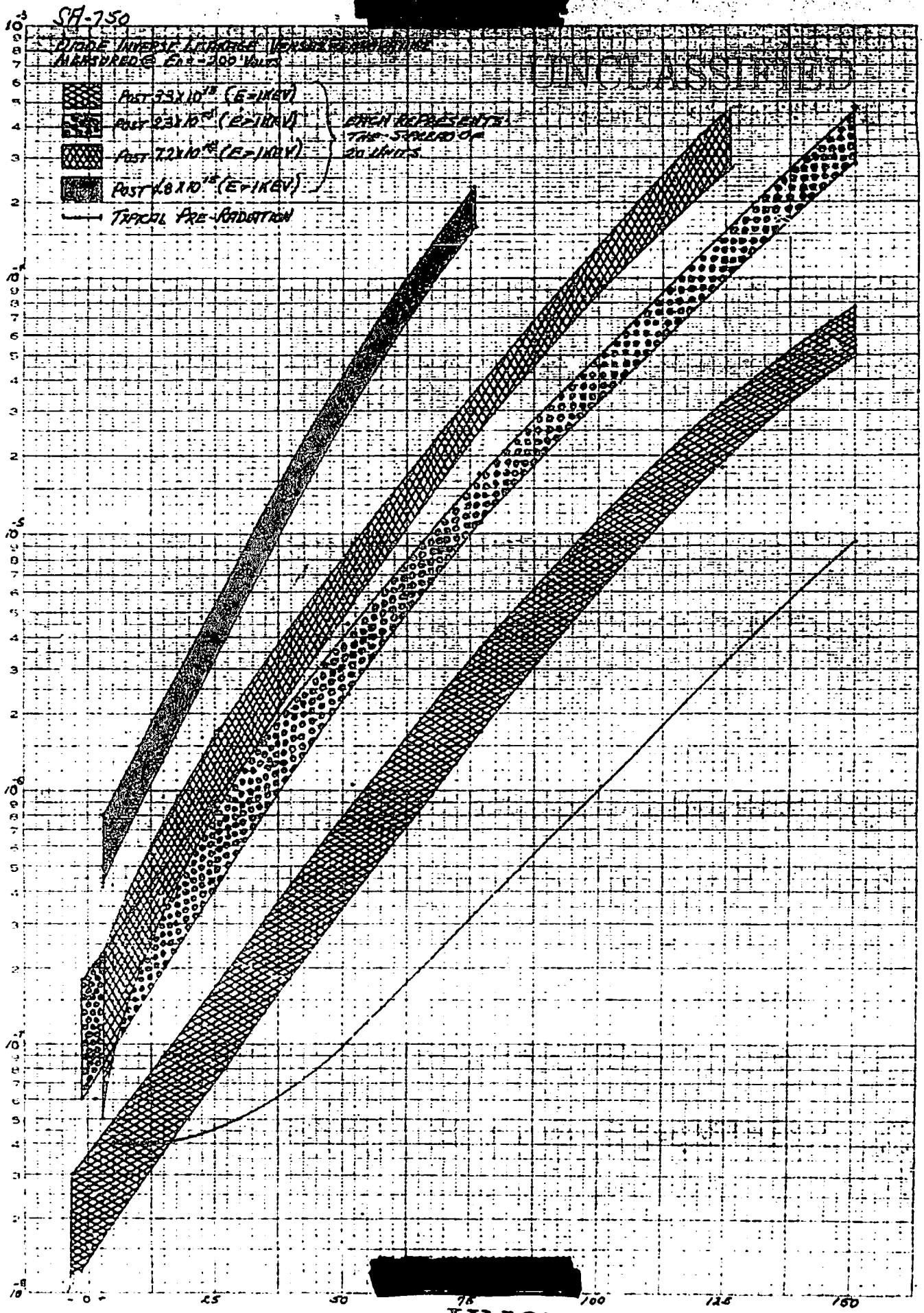

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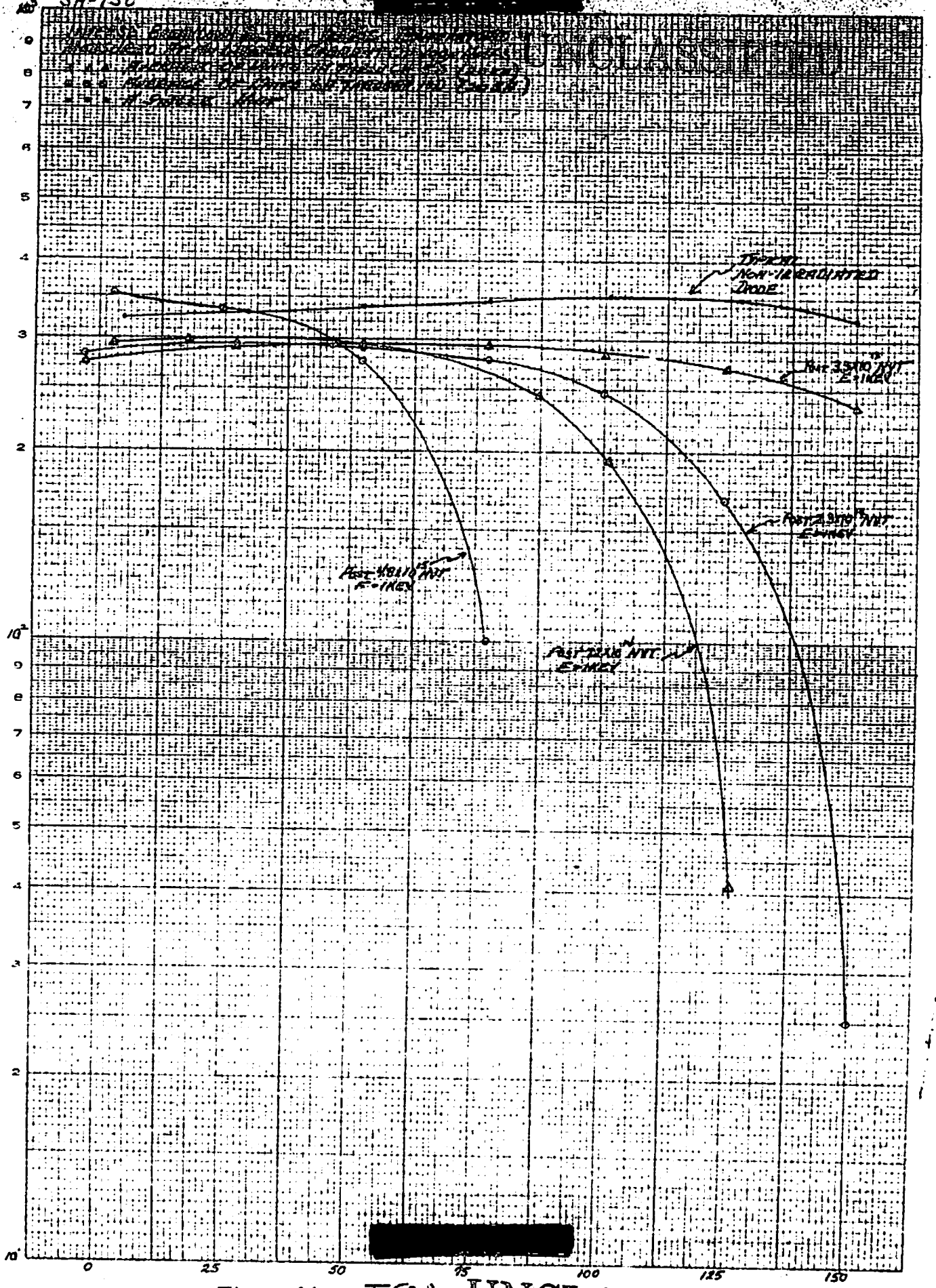

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Figure 11.

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