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August 18, 1966

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MARK XII, V-TO PHYSICS PARAMETERS

INTRODUCTION

Uranium-233 has previously been produced in a 4:2 mixed lattice of Mark VI-C two tube drivers and 82 lb. Mark V-TO ThO_2 targets (Ref. 1). A subsequent campaign is planned that will use a 3:3 lattice of Mark XII-A three tube drivers with similar ThO_2 target assemblies. This report documents a parametric study of this second campaign; the production rates and reactivities of various combinations of driver and target design are presented. The specifications for campaign II (Ref. 7) were based on values described herein.

DISCUSSION

The purpose of this study was to provide background material for design of a ^{233}U producing lattice. The organization of the study was as follows:

1. Design a series of ^{232}Th target assemblies. In this case assemblies weighing 62, 82, 103, 123, and 144 lbs were studied. Dimensions of the target designs are listed in table I.

2. Calculate the lattice reactivity of each target design in a 3:3 array with Mark XII-A driver assemblies for each case, determining the optimum concentration of ^{235}U in the driver assemblies. The initial Mark XII-A Uranium isotopic composition is shown in Table I.

3. Evaluate the productivity of each target design, considering both ^{233}U and ^{232}U.

In general this study was based on a) technology developed during the first ThO_2 campaign (Ref. 1), b) some SE measurements of control rod worth in a lattice of 1 kg Mark XII-A drivers and 82 lb targets, and c) new calculational methods developed during this study. Although the product quality, ppm ^{232}U, has not been specified for the ThO_2 campaign, the study assumed that it would be in the 5-10 ppm range.

Material Bucklings

Mark XII-A and Mark V-TO cold clean cell calculations were made with the HAMMER code; cell parameters and the lattice orientation shown in figure 1 were used as input to the SRL HERESY I code to calculate the lattice material bucklings shown in figure 2 and the relative control rod worths shown in table II. A comparison of calculated and experimentally determined rod worths for the Mark XII-A, V-TO lattice is shown in figure 3.

An estimate of the margin of control for initial critical is shown in figure 4. A similar estimate of the Mark VI-C, V-TO margin of control was 163 microbucks; the observed value was 146 microbucks.

Lattice Burnup - Reactivity

The decrease in lattice reactivity with fuel burnup was calculated for each target content using the HAMMER-HERESY codes. The Mark XII-A initial uranium content was chosen to give a flat zone material buckling of 170 microbucks after an exposure of three target cycles (the geometrical buckling of the reactor is about 150 microbucks; 20 microbucks were added for control). The reactivity transients are shown in figure 5.

^{233}U Production

The OFFYURN code is a one group point calculation which solves the ^{232}Th to ^{233}U equation chain; the data input consists of effective pile cross sections, (n, 2n) neutron fluxes and target to fuel thermal flux ratio (Ref. 2). The effective pile cross sections, defined for isotopes i by

$$(1) \quad \sigma^{i}_{effective} = \sigma^{i}_{thermal} + \sigma^{i}_{fast} \frac{\phi_{fast}}{\phi_{thermal}} ,$$

were calculated with the HAMMER-HERESY code sequence for a critical lattice and are listed in table III. The derivation of the n,2n neutron flux contributions from adjacent fuel and target fissions are discussed in the appendix. Target-to-Fuel thermal flux ratios were calculated as described below.

[redacted]

Let A = neutron absorptions, designated thermal = S, fast = F

i = any isotope in cell

j = reference isotope in cell

= Th^{232} in target cell, U^{235} in fuel cell

Then

(2) Total Neutron Absorptions = $\sum_{i=1}^{N} (A_S + A_F)_i$

$$= \sum_{i=1}^{N} \left(1 + \frac{A_F}{A_S}\right)_i A_S^i$$

$$= \sum_{i=1}^{N} K_i A_S^i \quad ,$$

and to calculate via separate absorptions for i + j isotopes one obtains

$$= \sum_{i \neq j=1}^{N-1} \left[\frac{K_i}{K_j}\beta_i + 1\right] A_S^j K_j$$

where

(3) $$\beta_i = \frac{A_S^i}{A_S^j} \, .$$

K_i, B_i and A_S^1 can be found from the HAMMER-HERESY calculation sequence for a critical lattice. Now let A_T, A_F represent target and fuel total absorptions, respectively; then:

(4)

$$\frac{A_T}{A_F} = \frac{\sum_{i \neq j=1}^{N-1} \left(\frac{K_i}{K_{02}}\beta_i + 1\right) A_S^{02} K_{02}}{\sum_{k \neq l=1}^{N-1} \left(\frac{K_k}{K_{25}}\beta_k + 1\right) A_S^{25} K_{25}}$$ = from HERESY

or

(5) $\frac{\phi_T}{\phi_F}$ = thermal flux ratio

$$= \frac{\sum_{k\neq j=1}^{N-1}\left(\frac{\Sigma_k}{\Sigma_{25}}\beta_k + 1\right)}{\sum_{j\neq j=1}^{N-1}\left(\frac{\Sigma_i}{\Sigma_{02}}\beta_i + 1\right)} \cdot \frac{\Sigma_{25}^{EFF}\,\nu_{25}}{\Sigma_{02}^{EFF}\,\nu_{02}} \cdot \frac{A_T}{A_F}$$

A plot of $\frac{\phi_T}{\phi_F}$ is shown in figure 6.

In all production calculations, Mark XXI-A assembly power was held constant at 11 MW. The dependence of ^{232}U on fuel exposures, plotted from the OFFYURN results, is shown in figure 7; the exposure dependence is the same for the three target cycles for 5 ppm ^{232}U contamination. Uranium-233 production is shown in figures 8, 9, 10 and 11.

As stated previously the OFFYURN code is a single point calculation. The data in figures 8 through 11 are shown in this way. Adjustment of the point calculation to the "charge average" ppm can be made in two ways: by integrating over each target subregion, or by multiplying the "point" ppm by a shape factor. For the lattice size considered here, and at five ppm, the shape factor is≈1.15(exposure dependent). The 5 ppm charge average point is shown on figures 8 through 11 for convenience; the shape factor is discussed in Appendix B.

Temperature Coefficients

Calculation of the temperature coefficients in the Mark XXI-A, V-TO lattice using the HAMMER-HERESY code sequence cannot be made because the HERESY thermal utilization parameters do not consider septifoil cells with shadowed control rods. An alternate procedure combines HERESY calculations for the Mark VI-C, V-TO lattice with measured temperature coefficients to define septifoil parameters for each control rod configuration.

The Mark VI-C, V-TO calculations are plotted in figure 12; measured temperature coefficients are listed in Reference 3. The septifoil cell parameters thus defined are listed in table IV.

The Mark XXI-A, V-TO HERESY calculations (for 82 lb targets) are plotted in figure 13. The septifoil prarmeters (table V) were used with figure 13 to predict the temperature coefficients listed in table VI.

LWP:gvb

[redacted]

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Table I

- Mark V-TO

	ThO_2 Target Weight, lbs				
	62	82	103	123	144
Outer Cladding, in.					
O.D.	3.076	3.076	3.076	3.076	3.076
I.D.	3.026	3.026	3.026	3.026	3.026
ThO_2 Core, in.					
O.D.	3.026	3.026	3.026	3.026	3.026
I.D.	2.605	2.450	2.283	2.104	1.905
Inner Cladding, in.					
O.D.	2.605	2.400	2.283	2.104	1.905
I.D.	2.555	2.450	2.233	2.054	1.855

- Ten slugs per target assembly, slug length = 15.2"
- ThO_2 compacted density = 6.406 gms/cc

- Mark XII-A: Initial Isotopic Composition

Isotope	% Abundance
^{234}U	1.5
^{235}U	80.0
^{236}U	11.0
^{238}U	7.5

[redacted]

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Table II

Control Rod Worths

ΔB^2 XXI, V-TO = K · ΔB^2 VI-C, V-TO

Gms ^{235}U in Mark XIX	K
750	0.9934
1000	0.9560
1250	0.9278

. Rod worth is only a slight function of target weight.

[redacted]

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Table XXI

Effective Cross Sections, barns

Isotope	Reaction	Target Weight, lbs. 62	82	103	123	144
^{232}Th	capture	6.15	6.06	5.97	5.94	5.90
	n,2n	.0123	.0123	.0123	.0123	.0123
^{233}Th	capture	1125	1125	1125	1125	1125
^{231}Pa	capture	218	218	218	218	218
^{232}Pa	capture	601	601	601	601	601
^{233}Pa	capture	67	67	67	67	67
^{232}U	capture	105	105	105	105	105
^{233}U	fission	421	418	414.7	406	400
	capture	75	75	75	75	75
^{235}U	fission	405	397	394	388	387
	capture	75	76	76	77	77

Table IV

SRL HERESY I
Septifoil Parameters

Rod Configuration	(1 - ?) control rods* Cold	Hot
empty septifoil	0.224	0.109
1 x 3.2S	.0195	.018
1 x 14.4S	.0116	.0099
2 x 3.2S	.0108	.0094
14.4S + 3.2S	.0069	.0060
3 x 3.2S	.0066	.0060
2 x 14.4S + 2.x 3.2S	.0038	.0034

* Cold = all components at 20°C

Hot = all components at 90°C

[redacted]

Table V

Mark XII, V-TO*
Temperature Coefficients

Lattice Configuration	Calculated Coefficient, μb/°C	Measured Coefficient, μb/°C
Prompt Coefficient		
FZ-0	-0.55	
FZ-5	-0.50	
Over-all Coefficient		
FZ-0	-1.10	-0.91
-1 (3.2S)	-0.57	
-1 (14.4S)	-0.64	
-2 (2 x 3.2S)	-0.64	
-2 (14.4S, 3.2S)	-0.71	
-3 (14.4S, 2 x 3.2S)	-0.43	-0.85
-4 (2 x 14.4S, 2 x 3.2S)	-0.29	

* Mark XII = 1000 Gms ^{235}U

Mark V-TO = 82 lbs ThO_2

[redacted]

Table VI

n,2n Flux Calculation, Adjacent Fuel Data

ℓ_o, cm	No. of Drivers VI-C	No. of Drivers XIIA	Ki_1 (0.0913/ℓ_o)
17.78	4	3	0.150
30.79	4	3	0.039
35.56	4	3	0.024
46.20	5	3	0.008
53.34	4	5	0.004

$$\sum_{j=1}^{N} \frac{Ki_1 (0.0913/\ell_{oj})}{\ell_{oj}}$$

VI-C	XII-A
0.347	0.260

[redacted]

Figure 1

MARK XII

MARK V-TO

SEPTIFOIL

LOADING PATTERN*
MARK XII, V-TO

* this pattern is repeated infinitely

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10 X 10 PER INCH
EUGENE DIETZGEN CO.
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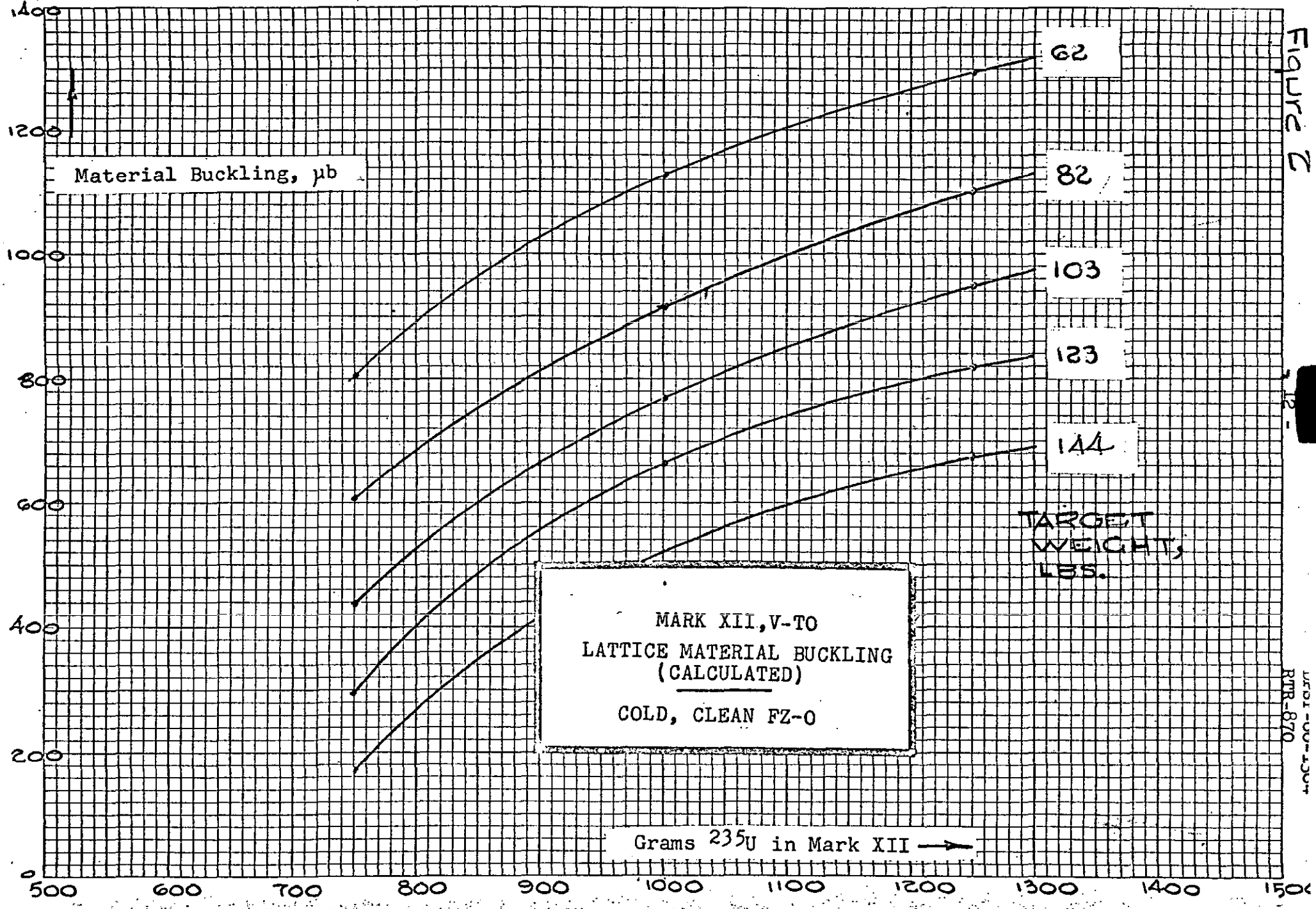
Figure 2



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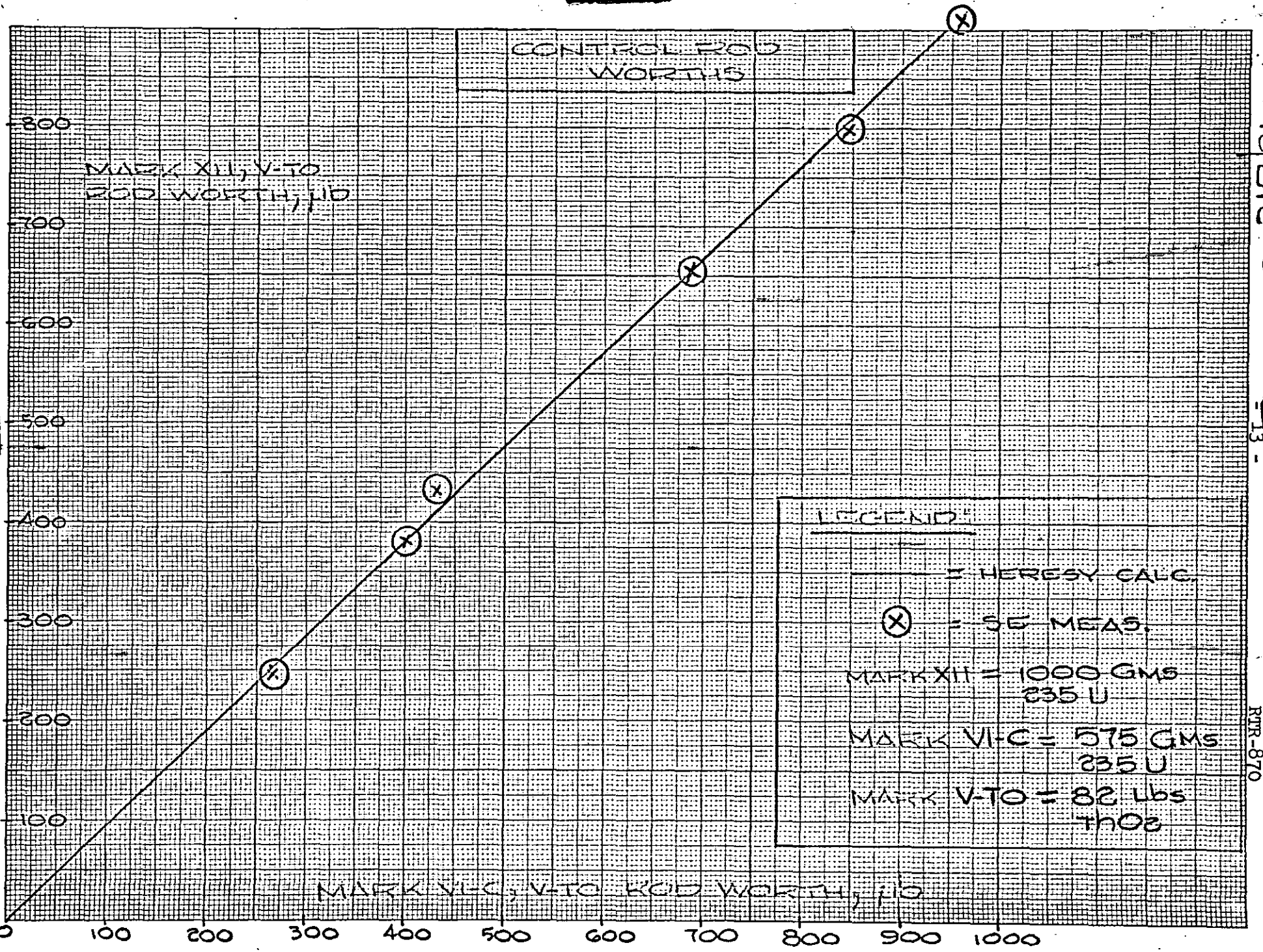

Figure 3

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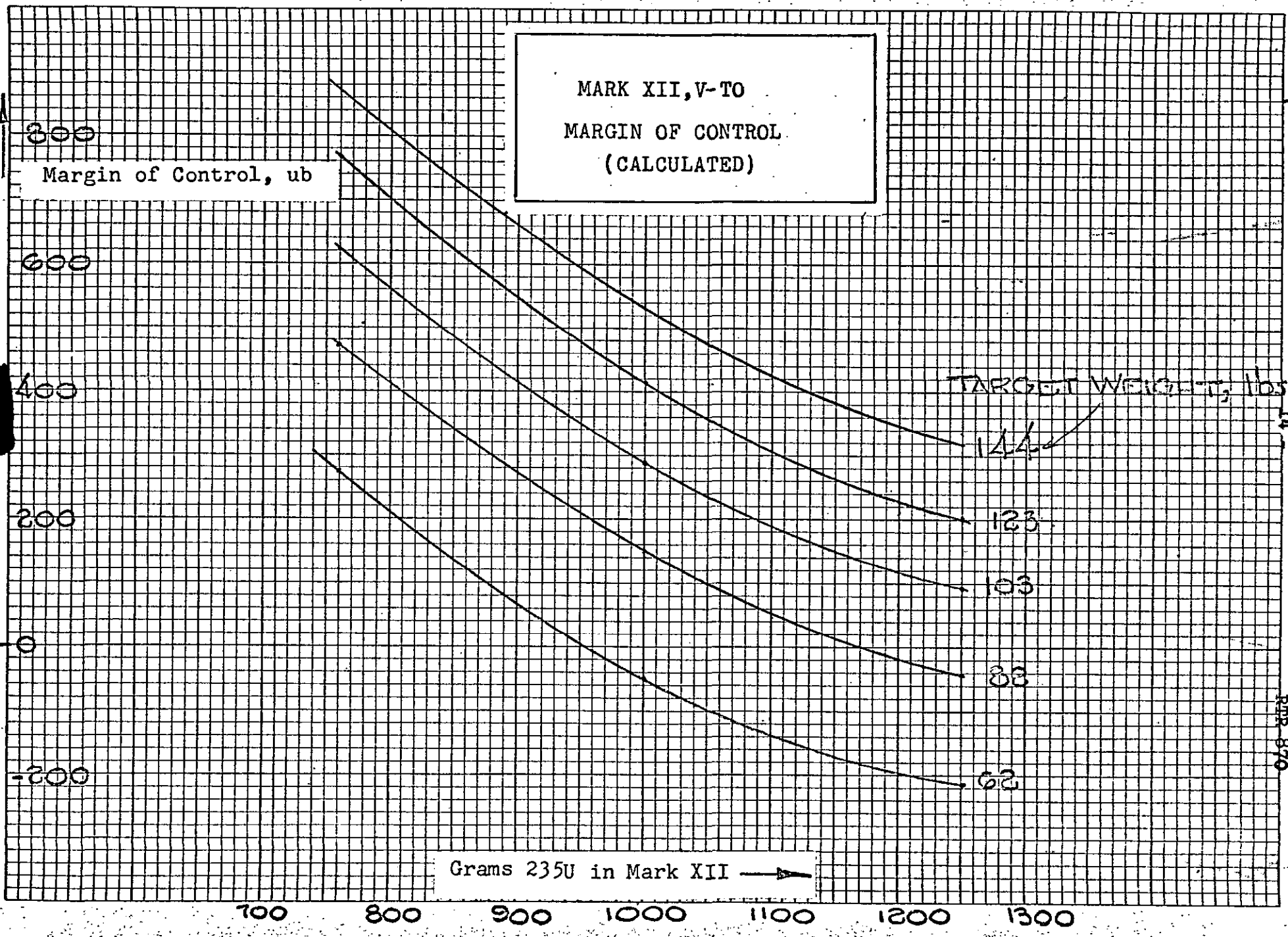

Figure 4.

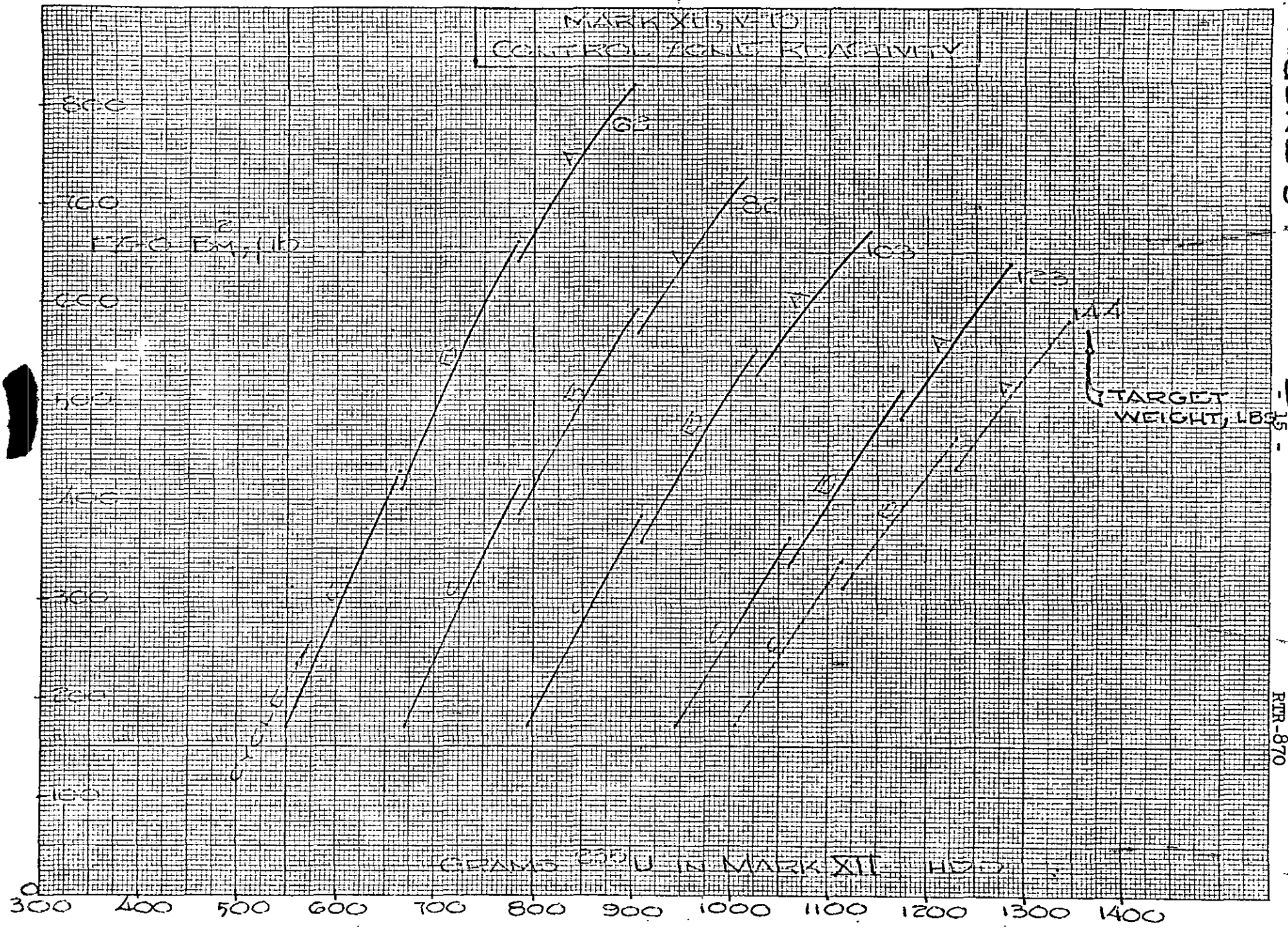

FIGURE 5

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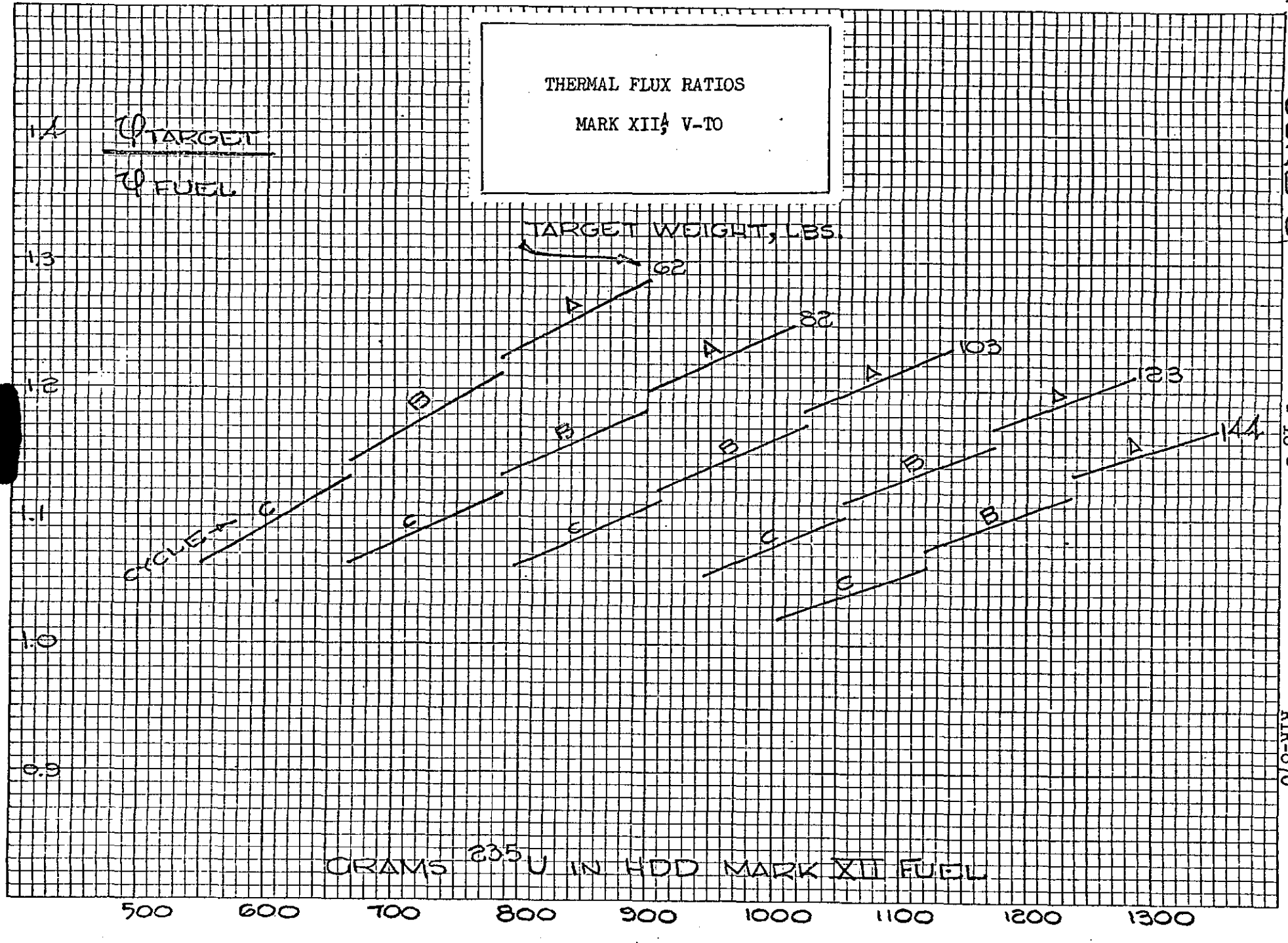

FIGURE 6

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FIGURE 7

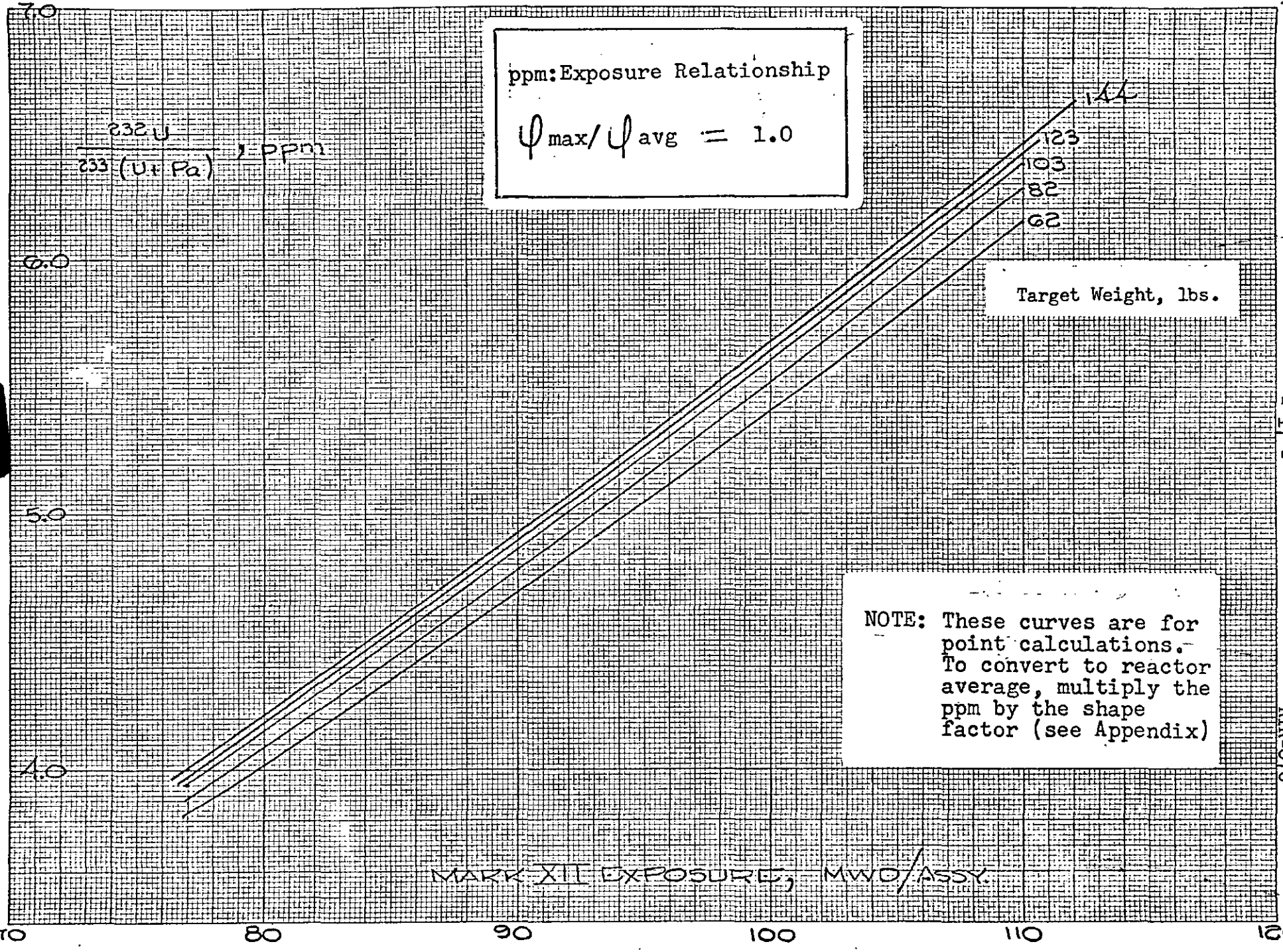

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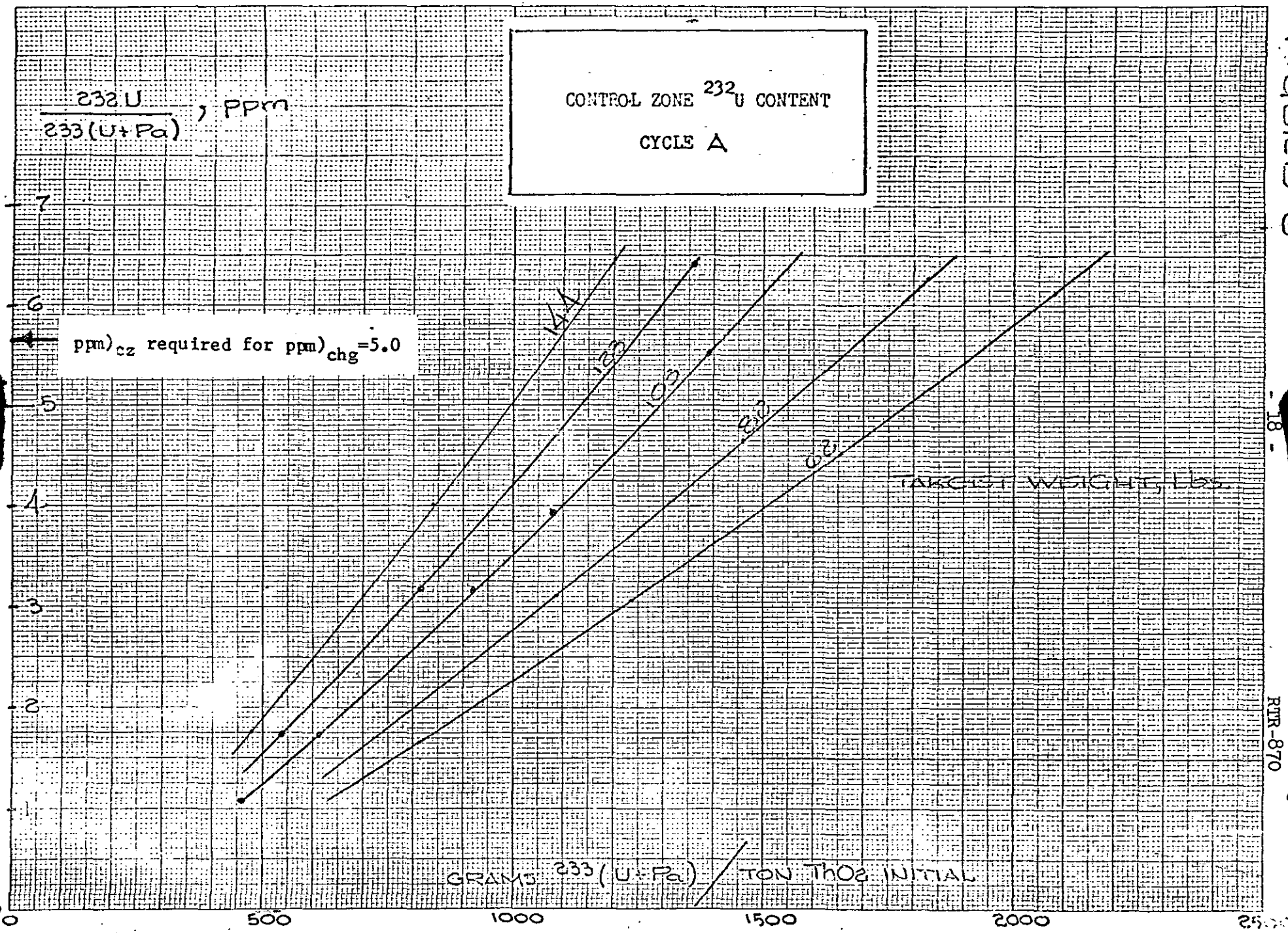
FIGURE 8



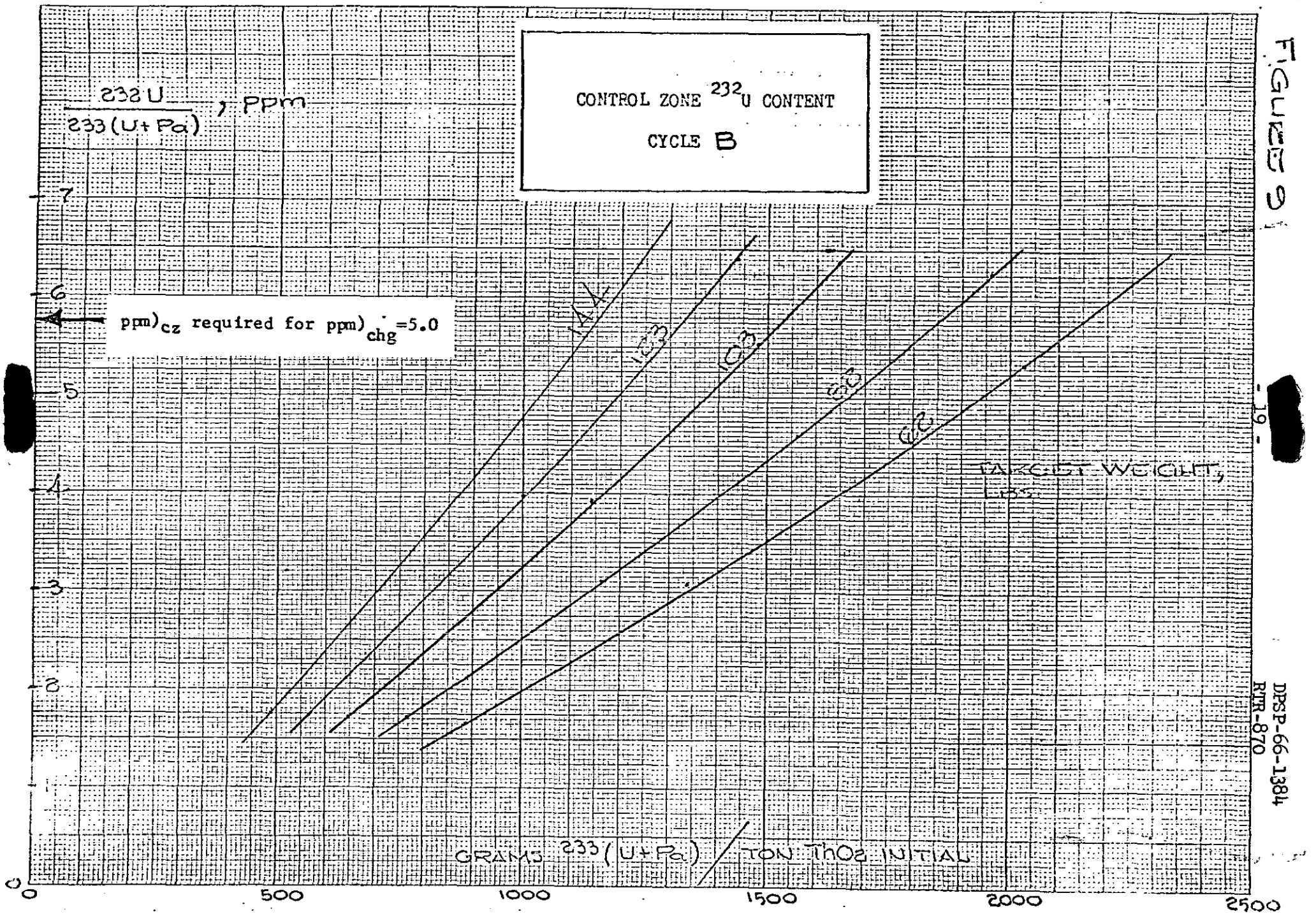


FIGURE 9

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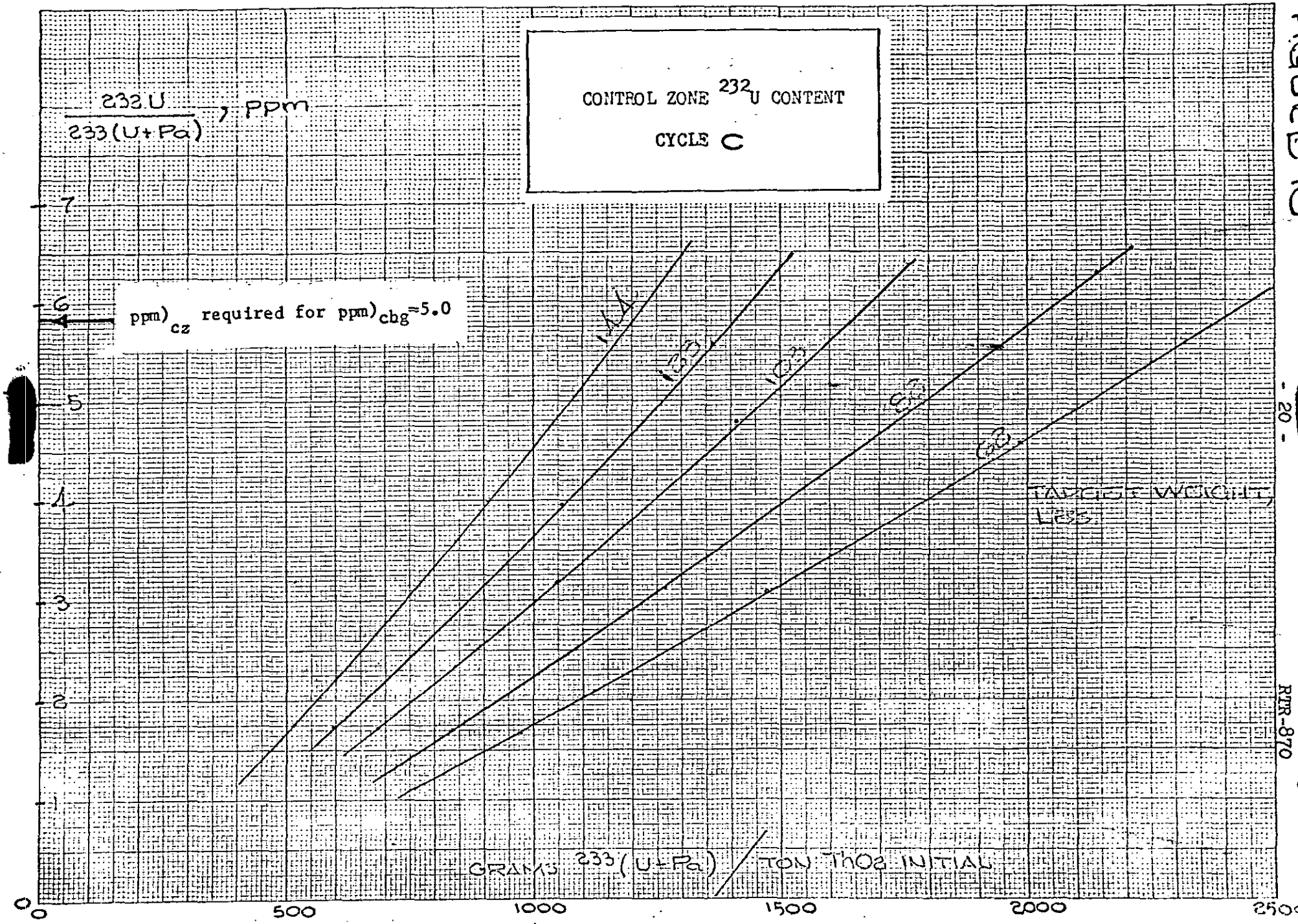

FIGURE 10

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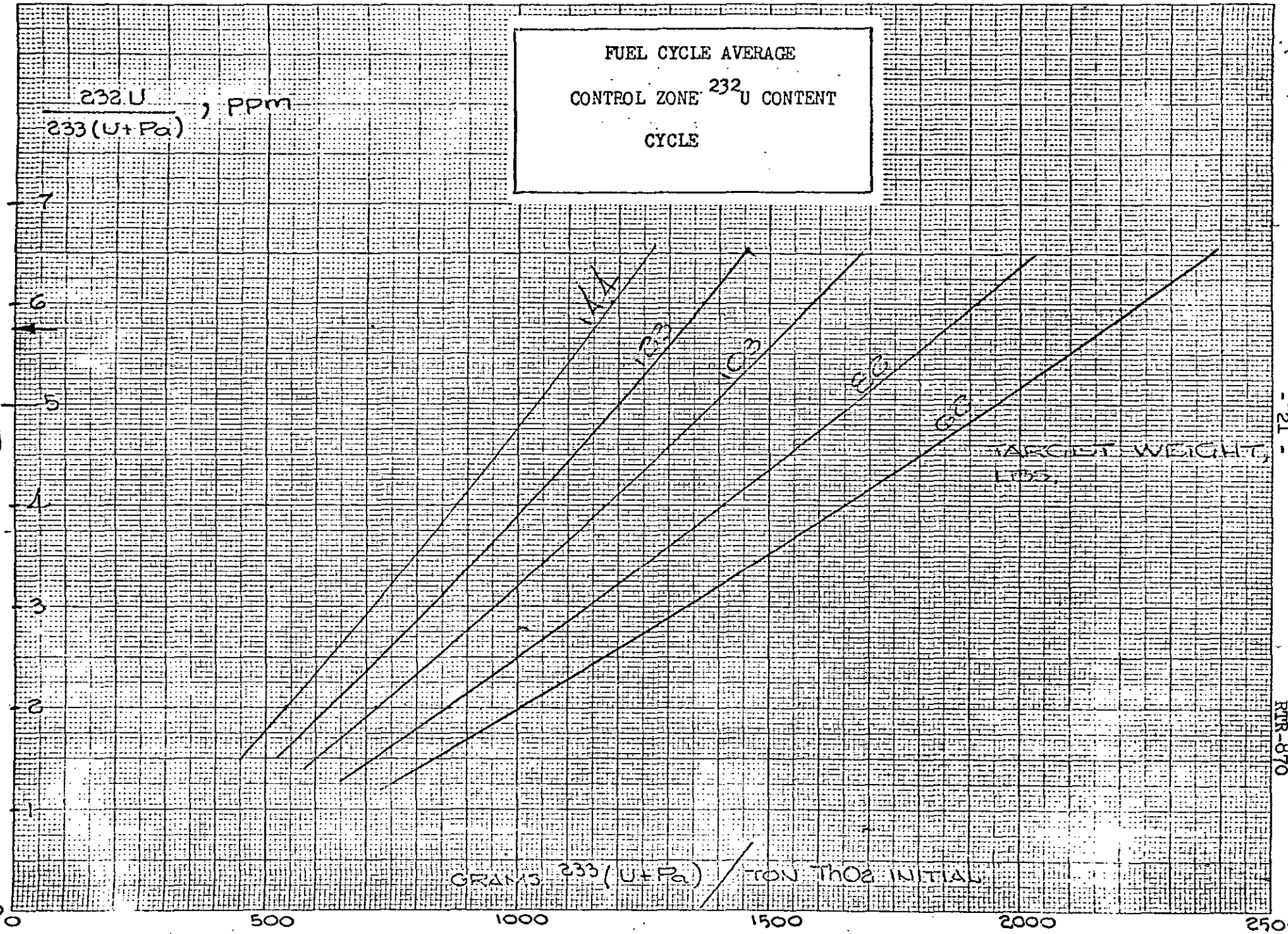

FIGURE 11

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FIGURE 12

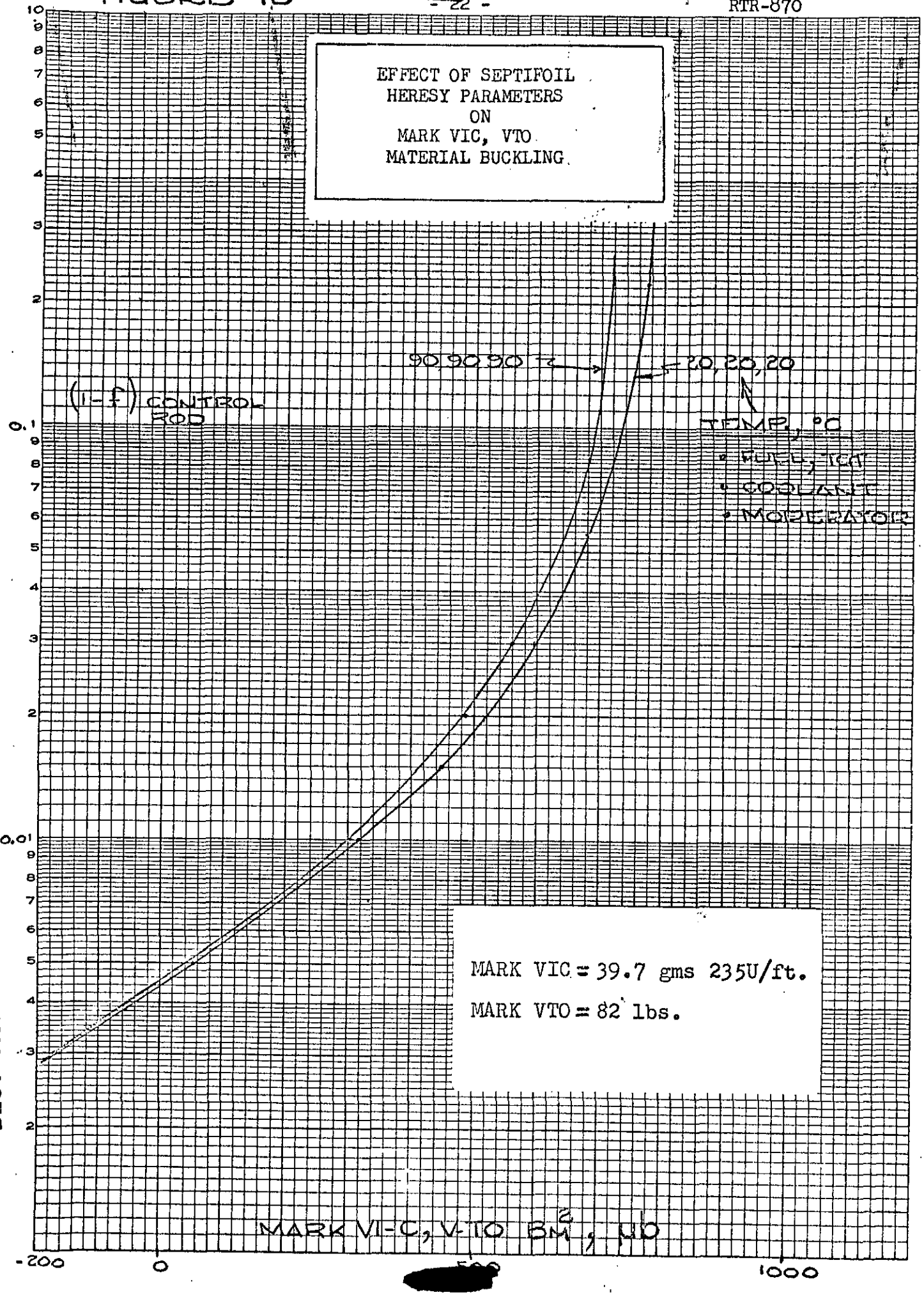

FIGURE 13

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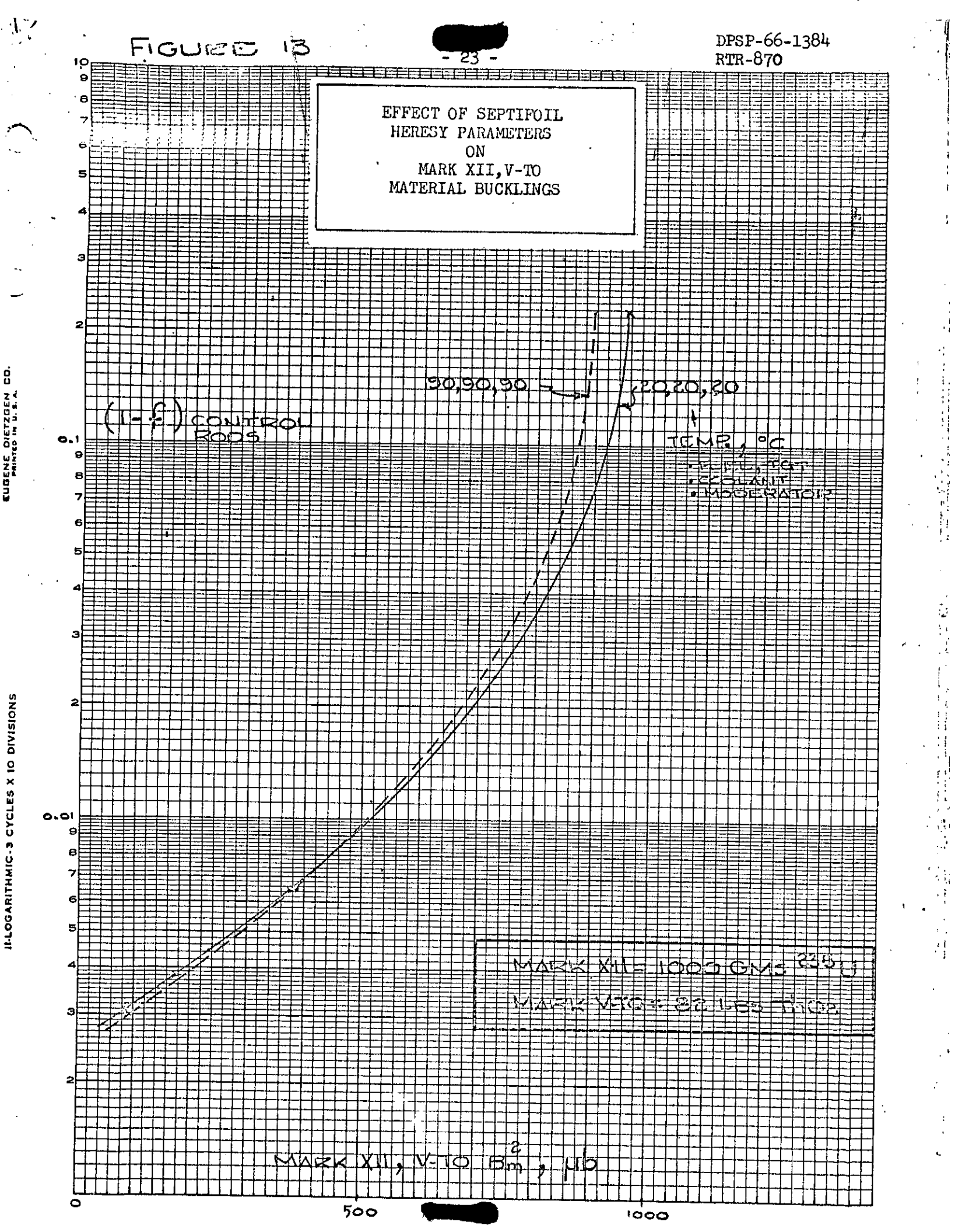


APPENDIX A

Irradiation of ^{232}Th produces ^{233}U contaminated with ^{232}U. The hard gamma activity of the daughters of ^{232}U creates a radiation handling problem; for example, a sphere of ^{233}U three inches in diameter contaminated with 10 ppm ^{232}U has a radiation level of 135 R at contact 10 years after separation (Ref. 4). About 97% of the ^{232}U (in the 5-10 ppm range) is formed by the following chain:

$$^{232}Th \xrightarrow{n,2n} {}^{231}Th \xrightarrow[25h]{\beta} {}^{231}Pa \xrightarrow{n,\gamma} {}^{232}Pa \xrightarrow[1.3d]{\beta} {}^{232}U$$

The n,2n reaction threshold in thorium is 6.37 Mev in the laboratory system; neutrons with energies above the threshold result from fissions in adjacent driver assemblies and ^{233}U fissions within the ThO_2 targets. The total ^{232}U formation is the sum of the contributions from each neighboring fuel elements and the contributions due to ^{233}U fissions; these contributions are derived below.

Fast (n,2n) Flux due to Adjacent Fuel Assemblies

The n,2n cross section in ^{232}Th is defined such that it does not vary from one reactor to another:

$$\bar{\sigma}_{2n} = \int_{6.37}^{\infty} \sigma_{2n}(E)\ f(E)\ dE \qquad (A\text{-}1)$$

where

$\sigma_{2n}(E)$ = listed in Reference 5

$f(E)$ = fraction of fission neutrons emitted with energies between E and E + dE

Numerical integration of equation (A-1) yields a cross section value

$\bar{\sigma}_{2n} = 0.0123$ barns

Toops and St. John (Ref. 6) have shown that the n,2n collision probability per thorium atom per second at a distance λ_0 in D_2O from a line fission source isotropically emitting ρ fission neutrons per centimeter per second is given by

$$\bar{\sigma}_{2n}\,\phi_{2n} = \frac{A\rho\ Ki_1(0.0913/\lambda_0)}{\lambda_0}$$

where

A = a constant of the D_2O moderator

and

$$Ki_1(0.0913/\lambda_0) = \int_0^{\pi/2} e^{-(0.0913)\lambda_0 \sec\theta}\, d\theta .$$

A numerical integration of $Ki_1(X)_{\mathcal{N}}$ is shown in figure A-1.

For the Mark XII-A and Mark VI-C drivers the line source strength is given by

$$\rho = \frac{\nu_o \text{ fissions/sec}}{\text{length}} = B \circ P \qquad \text{(A-3)}$$

where

B = constant = 7.58×10^{16}

P = linear power density, MW/cm

The fast (n,2n) flux is thus written

$$\varphi_{2n}^{1} = A \circ 6.16 \times 10^{18} \circ P \circ \frac{Ki_1(0.0913/r_o)}{r_o} \qquad \text{(A-4)}$$

Assuming all driver powers are equal, the fast flux due to N surrounding fuel assemblies is the sum of the individual contributions:

$$\varphi_{2n}^{N} = (A \circ 6.16 \times 10^{16} \circ P) \sum_{j=1}^{N} \frac{Ki_1(0.0913/r_{oj})}{r_{oj}} \qquad \text{(A-5)}$$

OFFFURN calculations of the ^{232}U contaminant in the Mark VI-C, V-TO lattice agreed well with observed values for a fast n,2n flux of

$$\varphi_{2n}^{N})_{\text{VI-C}} = 5.4 \times 10^{12} \text{ / (driver MW)}$$

The corresponding fast flux in the Mark XII-A, V-TO lattice is found from the $\varphi_{2n}^{N})_{\text{VI-C}}$ results:

$$\left(\varphi_{2n}^{N}\right)_{\text{XII}} = \frac{\left[\sum_{j=1}^{N} \frac{Ki_1(0.0913/r_{oj})}{r_{oj}}\right]_{\text{XII-A}}}{\left[\sum_{\ell=1}^{M} \frac{Ki_1(0.0913/r_{o\ell})}{r_{o\ell}}\right]_{\text{VI-C}}} \circ \left(\varphi_{2N}^{M}\right)_{\text{VI-C}} \qquad \text{(A-6)}$$

$$= 4.06 \times 10^{12} \text{ / (driver MW)} .$$

The data for calculating equation A-6 are shown in table VI.

[redacted]

Fast (n,2n) Flux from ^{233}U Fissions

The n,2n contribution from ^{233}U was calculated for each target weight by the following procedure:

Assume

- ^{233}U fissions uniformly and emits fast neutrons isotropically
- scatterings and fast neutron absorptions do not appreciably affect the mean free path of escape from the target

Let

$n(E)$ = fast neutrons emitted/cc/sec

$$= \frac{(3.12 \times 10^{16})(\nu 23) f(E) P_T}{V} \qquad \text{(A-7)}$$

where

$f(E)$ = ^{233}U fission spectrum (assumed same as ^{235}U)

P = target power, MW

V = target volume

Let

$\tau(E)$ = average time a fast neutron remains in the target after emission

$$= \frac{\overline{d}}{\overline{\nu}(E)}$$

where

$\overline{d}$ = mean free path of escape from target, cm

$\overline{\nu}(E)$ = neutron velocity, cm/sec

Then

$$\phi 2n = n(E)\,\tau(E)\,\overline{\nu}(E) = n(E)\,\overline{d}$$

$$= \frac{(3.32 \times 10^{16})(\sigma 23\, f(E)\, \overline{d})\, P}{V} \qquad \text{(A-8)}$$

To calculate $\overline{\overline{d}}$, the cylindrical Mark V-TO targets were approximated by an infinite slab of thickness t equal to the target thickness and width w, chosen to make the slab area equal to the transverse area generated by fast neutrons traveling from the center of the target thickness. Data for calculating φ_{2n} are listed in Table A-I.

[redacted] calculations for the Mark VI-C, V-TO lattice were in good agreement with observed ^{232}U values with

$$\varphi_{2n)\ \substack{82\ lb. \\ target}} = 4 \times 10^{13}/(\text{target MW})$$

For other target weights, the fast (n,2n) flux may be found by

$$\varphi_{2n}]_x = \frac{(\overline{\overline{d}}/V)_x}{(\overline{\overline{d}}/V)_{82}} \therefore 4 \times 10^{13}/(\text{target MW}) \qquad (A\text{-}9)$$

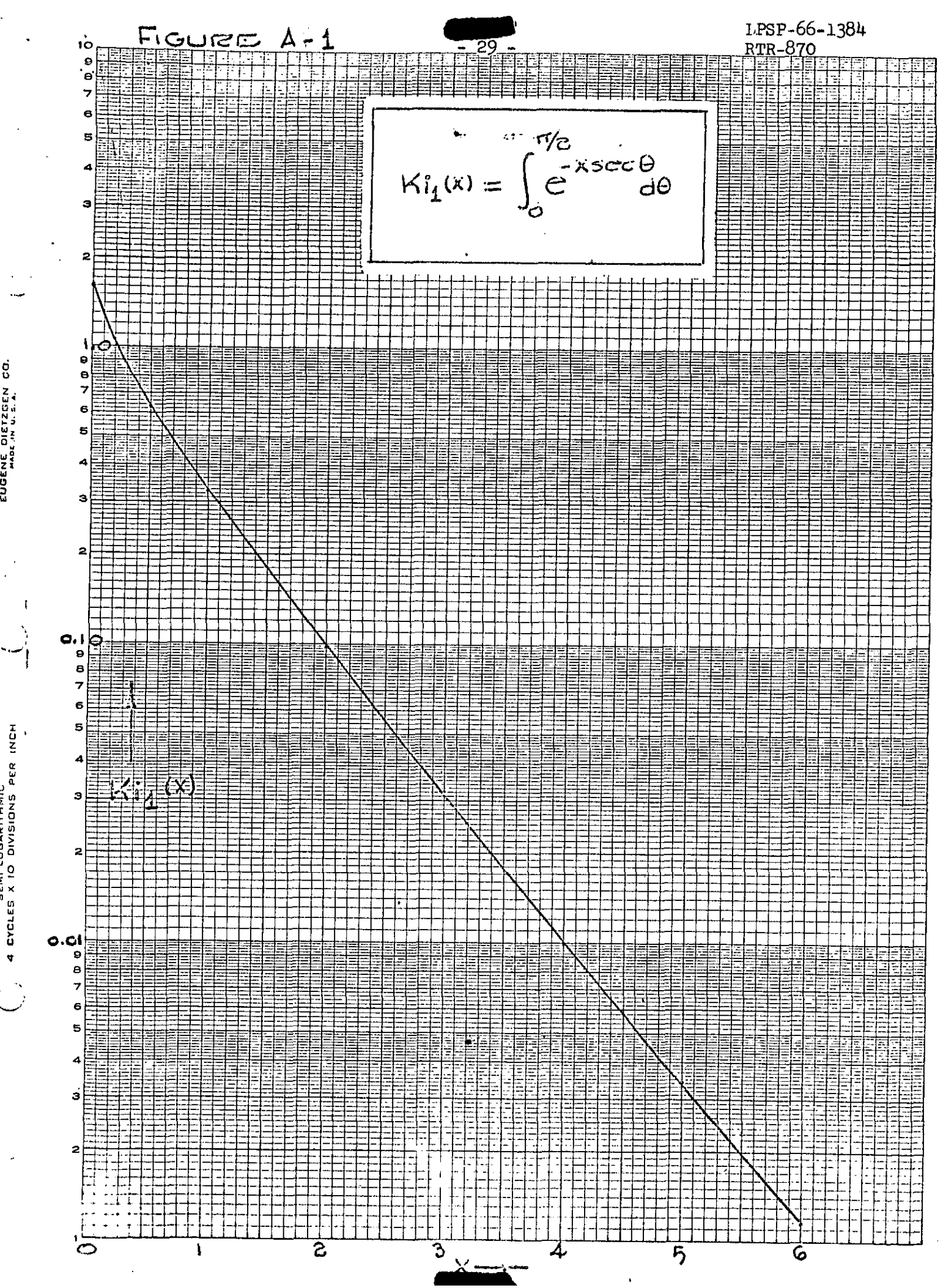
Table A-I

n,2n Flux due to ^{233}U Fissions

Tgt. Wt., lbs	Volume, cc	$\frac{1-1}{d}$, cm	$\ell 2n/(tgt.\ MW)$
62	4332	0.363	0.35
82	5764	0.556	0.40
103	7209	0.692	0.40
123	8644	0.831	0.39
144	10,087	0.955	0.39

FIGURE A-1

$$Ki_1(x) = \int_0^{\pi/2} e^{-x\sec\theta}\, d\theta$$



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4 CYCLES X 10 DIVISIONS PER INCH

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APPENDIX B

Production Shape Factors

Point production rates may be converted to reactor average production by using a shape factor to combine the production within an arbitrary number of radial zones. A general expression for the production shape factor is derived in this section and sample calculations for three Mark XII, V-TO target cycles with two radial zones are included.

The ^{232}U produced at a point in a target irradiated for time τ may be approximated by

$$^{232}U)_{point} \cong k_{22} * \phi_{2n} * \phi_T * \tau^2 \qquad \text{(B-1)}$$

where k_{22} = constant proportionality

The $^{233}(Pa+U)$ point production may be approximated by

$$^{233}(Pa+U) \cong k_{23} * \phi_T * \tau \qquad \text{(B-2)}$$

$$k_{23} = \text{constant}$$

The ^{232}U contaminant is usually expressed as the ratio to total product, expressed in ppm, and is averaged over an assembly by integrating axially:

$$\left.\frac{^{232}U}{^{233}(Pa+U)}\right]_{ASSY} = \left.PPM\right]_{ASSY} = \frac{k_{22}\tau^2 \int_0^H \phi_{2n}\phi_T dz}{k_{23}\tau \int_0^H \phi_T dz} \qquad \text{(B-3)}$$

where H = Target Length.

If the axial differential ^{235}U burnup of the Mark XXI drivers is neglected, the axial dependence of ψ_{2n} is the same as ψ_T,

$$\psi_T = (\psi_T)_{MAX} * f(z) \qquad (B\text{-}4)$$

$$\psi_{2n} = (\psi_{2n})_{MAX} * f(z)$$

and

$$ppm]_{ASSY} = C' * \frac{\int_0^H f^2(z)\,dz}{\int_0^H f(z)\,dz} \qquad (B\text{-}5)$$

where

$$C' = \frac{k_{22}\tau(\psi_{2n})_{MAX}}{k_{23}} \qquad (B\text{-}6)$$

Equation (B-5) may be rewritten

$$ppm]_{ASSY} = C * \gamma(z) * \overline{\psi_T}^{-1} \qquad (B\text{-}7)$$

where

$$C = \frac{C'}{(\psi_T)_{MAX}} = \frac{k_{22}\tau(\psi_{2n})_{MAX}}{k_{23}(\psi_T)_{MAX}} \qquad (B\text{-}8)$$

$$\gamma(z) = \frac{\frac{1}{H}\int_0^H f^2(z)\,dz}{\left\{\frac{1}{H}\int_0^H f(z)\,dz\right\}^2} \qquad (B\text{-}9)$$

(as plotted in figure B-1)

$$\overline{\psi_T}^{-1} = \frac{1}{H}\int_0^H (\psi_T)_{MAX} f^{-1}(z)\,dz \qquad (B\text{-}10)$$

[redacted]

The reactor may now be divided into a number of radial zones where a zone is defined as a group of assemblies having the same ppm)assy, equation (B-7). The ppm)assy of the radial zones may be properly combined to give the charge average ^{232}U, ppm)chg.

$$\left.\frac{^{232}U}{^{233}(Pa+U)}\right]_{\substack{CHG.\\AVG.}} = \left.ppm\right]_{CHG} = \frac{\sum_{i=1}^{N} {}^{232}U_i}{\sum_{j=1}^{N} {}^{233}(Pa+U)_j} \qquad \text{(B-11)}$$

where N = the number of radial zones.

Equation (B-11) may be rewritten:

$$\left.ppm\right]_{CHG} = \sum_{i=1}^{N} \frac{^{232}U)_i}{^{233}(Pa+U)_i} * \frac{^{233}(Pa+U)_i}{\sum_{j=1}^{N} {}^{233}(Pa+U)_j} \qquad \text{(B-12)}$$

$$= \sum_{i=1}^{N} [ppm]_{i,ASSY} * \Omega_i$$

where

$$[ppm]_{i,ASSY} = \frac{^{232}U)_i}{^{233}(Pa+U)_i}$$

$$= \text{Equation (B-7)},$$

and, defining

η_i = number of target assemblies in the zone i,

$$\Omega_i = \frac{233(Fa+U)_i}{\sum_{j=1}^{N} 233(Fa+U)_j} \qquad \text{(B-13)}$$

$$\cong \frac{n_i \psi_{Ti}}{\sum_{j=1}^{N} n_j \psi_{Tj}} \quad \text{[see equation (B-2)]}$$

Ideally, the ppm)chg is found by solving equation (B-12) from data obtained during or after the charge irradiation. In practice, however, it is desirable to irradiate the charge for that time which yields a specified ppm)chg and in this case equation (B-12) may be used to determine the irradiation time. First a reference zone is chosen which provides close control of the variables affecting ppm)assy (ϕ_{max}/ϕ_{avg}, ϕ_T); the ppm)chg ratio is then written as a function of the reference zone ppm)assy.

$$ppm\big]_{CHG} = \left\{ \Omega_{ref} + \sum_{i=1}^{N-1} \frac{ppm)_{i,ASSY}}{ppm)_{ref,ASSY}} * \Omega_i \right\} * ppm\big]_{ref,ASSY} \qquad \text{(B-14)}$$

$$= m * ppm\big]_{ref,ASSY} ,$$

where

$$m = \left\{ \Omega_{ref} + \sum_{i=1}^{N-1} \frac{ppm)_{i,ASSY}}{ppm)_{ref,ASSY}} * \Omega_i \right\} \qquad \text{(B-15)}$$

[redacted]

The relationship between ppm/assy and Mark XXX assembly exposure for $\phi_{max}/\phi_{avg} = 1.0$ is shown in figure 7; correction for other ϕ_{max}/ϕ_{avg} is made as follows:

$$\text{ppm}]_{1.0} = C * \gamma_{1.0}(Z) * \overline{\phi_T} \quad \text{for } \phi_{MAX}/\phi_{AVG} = 1.0 \tag{B-7}$$

$$\text{ppm}]_{x} = C * \gamma_{x}(Z) * \overline{\phi_T} \quad \text{for } \phi_{MAX}/\phi_{AVG} = x$$

$$= \frac{\gamma_x(Z)}{\gamma_{1.0}(Z)} * \text{ppm}]_{1.0}$$

$$= \gamma_x(Z) * \text{ppm}]_{1.0} \tag{B-16}$$

Equation (B-16) indicates figure 7 may be used for any Qmax/Qavg by entering the figure at the driver assembly exposure and multiplying the result by $\gamma(Z)$.

The general expression for the production shape factor, S, can now be derived.

$$S = \frac{\text{ppm}]_{ref,ASSY}}{\text{ppm}]_{CHG}} \tag{B-17}$$

$$= \frac{\gamma_{ref}(Z) * \text{ppm}]_{1.0}}{\text{ppm}]_{CHG.}}$$

$$= \frac{\gamma_{ref}(Z)}{m}$$

$$= \gamma_{ref}(Z) \Big/ \left\{ \frac{\eta_{ref}\overline{\phi_{T_{ref}}}}{\sum_{j=1}^{N}\eta_j\overline{\phi_{T_j}}} + \sum_{i=1}^{N-1} \frac{\gamma_i(Z)\,\eta_i\,\overline{\phi_{T_i}}^2}{\gamma_{ref}(Z)\,\eta_{ref}\,(\overline{\phi_{T_{ref}}})^2} \right\}$$

Equation (B-17) can be solved by determining $f(\epsilon)$ and ϕ_{Ti}/ϕ_{Tref} with the "UNCLE IV" buckling codes and the reactivity information shown in figure 5.

For a desired charge average ^{232}U contaminant ratio, the reference zone contamination is calculated from

$$ppm]_{ref} = S\,\%\; ppm]_{CHG} \qquad \text{(B-18)}$$

Since the shape factor includes Qmax/Qavg of the reference zone, figure 7 may be used to determine the adjacent driver assembly exposure from which reactor exposure may be calculated:

$$E_{RX} = \sum_{i=1}^{N} N_i \epsilon_i \qquad \text{(B-19)}$$

$$= \left\{ N_{ref} + \sum_{i=1}^{N-1} N_i \frac{P_i}{P_{ref}} \right\} \epsilon_{ref}$$

$$= \mu\, \epsilon_{ref}$$

where:

N_i = the number of Mark XII-A assemblies in zone "i"

P_i = Mark XII-A assembly power in zone "i"

$= \Sigma_{f_i} V \phi_{F_i}$

ϵ_{ref} = reference zone assembly exposures, determined from Figure 7.

Sample calculations for ppm/chg = 5.0 for assumed operating conditions, FLK reactors, with two radial zones (the control and buckled zones) are listed in Table B-I. For this case, equation (B-17) reduces to

$$S = \nu_c(\Sigma) \Big/ \left\{ \frac{\eta_c \psi_{Tc}}{\eta_c \psi_{Tc} + \eta_B \psi_{TB}} + \frac{\nu_B(\Sigma)\, \eta_B\, \psi^2_{TB}}{\nu_c(\Sigma)\, \eta_c\, \psi^2_{Tc}} \right\}$$

and equation (B-19) reduces to

$$E_{RX} = \left\{ N_c + N_B \frac{P_B}{P_c} \right\}$$

where the subscripts B and C denote the buckled and control zones, respectively.

[redacted]

Table B-I

Sample Production Calculations
FLK Reactors, Three Target Cycles

	Target Cycle A	Target Cycle B	Target Cycle C
$\psi_{MAX}/\psi_{AVG}]_C$	1.15	1.20	1.25
$f_C(Z)$	1.035	1.052	1.070
$\psi_{MAX}/\psi_{AVG}]_B$	1.25	1.30	1.35
$f_B(Z)$	1.070	1.092	1.114
ψ_{TB}/ψ_{TC}	0.595	0.470	0.345
$\eta_B/\eta_C = {}^{78}/_{177}$	0.441	0.441	0.441
P_B/P_C	0.610	0.514	0.415
$N_B/N_C = {}^{78}/_{183}$	0.426	0.426	0.426
m	0.920	0.912	0.915
s	1.13	1.15	1.17
$ppm]_{CB}$	5.65	5.75	5.85
e_{CB}, MWD	101.6	103.0	104.4
μ	230.6	223.1	215.4
E_{RX}, MWD	23,430	22,980	22,490

[redacted]

Figure B-1

The Relationship Between ppm)$_{assy}$ and Average Thermal Flux

$$\gamma(z) = \frac{\frac{1}{H}\int_0^H f^2(z)\,dz}{\left[\frac{1}{H}\int_0^H f(z)\,dz\right]^2}$$

1.3

1.2

1.0

1.0 1.25 1.50 1.75

$\varphi_{max}/\varphi_{avg}$

$f(z)$ = thermal flux axial dependence factor

(= $\sin\frac{\pi}{H}z$ for homogeneous reactor)