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70-TON SHIPPING CASK STUDY

INTRODUCTION AND SUMMARY

A study has been made to define safe loading configurations for the 70-ton casks when shipping bundles of tubular fuel assemblies. The study produced a universal set of shipping limits that are applicable to a wide range of fuel types, bundle designs, and cask loadings. These shipping limits are given in figure 1 for ^{235}U fuel and in figure 2 for ^{239}Pu fuel. Shipping limits for current fuel assemblies are as follows:

Assembly Type	Gms ^{235}U per ft	Fuel Assemblies per Bundle	Limit on Bundles per Cask	Cask Slot Numbers
Mark XII-A	85	4	5	1,2,3,4,5
Mark 14	136	4 (assumed)	4	1,2,4,5
Mark 16	240	3 (assumed)	3	1,3,5

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In the past, safe cask loading configurations have been determined on an individual basis for each new type of fuel that was used. The universal limits system that was developed as a result of this study ensures the same degree of safety for fuel assemblies over a wide range of process variables. When applied to current fuel assembly designs, the new system confirms the adequacy of the present shipping restrictions.

DISCUSSION

Analytical Technique

The analytical technique used in this study was to calculate k_{eff} for different cask loading configurations using established computer programs (Reference 1). Buckling and two-group diffusion theory parameters were obtained from cell calculations performed with the Multigroup Buckling code (MGB). These parameters were then employed in the Two-Group Analytical code (TGA) to compute the interaction between rows of assemblies. Standard methods were used to calculate k_{eff} from the output of the codes.

Basic Calculations

Basic calculations were performed assuming Mark XII-A dimensions. These dimensions are given in Table I. Fuel concentrations were varied from 50 to 600 g per foot for both ^{235}U and ^{239}Pu fuel. Corresponding alloy compositions are given in Table II. Bundles containing 3, 4, 5, 6, and 7 assemblies, with the assemblies in contact in the bundles, were considered. Each assembly included three concentric tubular fuel elements. Three cask loading configurations were considered:

(1) Single bundles loaded into cask slots 1, 2, 3, 4, and 5.

(2) Single bundles loaded into cask slots 1, 2, 4, 5.

(3) Single bundles loaded into cask slots 1, 3, 5.

A standard cadmium partition (0.040 in. of cadmium) clad in stainless steel (total 0.250 in. of stainless steel) was assumed to be in place between each slot. The center to center spacing between slots is 5 inches. Vacant slots were assumed to be filled with water with an infinite sea of water surrounding all configurations. Results of these calculations are shown in figures 3-8 as follows:

Figure	Type of Fuel	Cask Slots Used
3	^{235}U	1,2,3,4,5
4	^{235}U	1,2,4,5
5	^{235}U	1,3,5
6	^{239}Pu	1,2,3,4,5
7	^{239}Pu	1,2,4,5
8	^{239}Pu	1,3,5

Effect of Assembly Dimensions

Additional k_{eff} calculations were performed using both Mark 16 and Mark VI-E fuel dimensions to determine the effect of assembly dimensions on the calculations. These dimensions are given in Table III. Alloy compositions are given in Table IV. Both Mark XII-A and Mark 16 assemblies consist of three concentric, cylindrical fuel tubes; however, the cross-sectional area of the fuel core of the Mark 16 assembly is about 4 times as large as that of the Mark XII-A assembly and the OD of the outer fuel tube is 3.700 in. compared with 3.561 in. for the Mark XII-A. A comparison of Mark XII-A and 16 is shown in figure 9; it indicates a slightly higher calculated k_{eff} for Mark XII-A which is attributed to the difference in aluminum content between the assemblies.

A single k_{eff} calculation was made with Mark VI-E nested fuel dimensions. The cross-sectional area of the Mark VI-E fuel core (two nested tubes) is about twice as large as that of the Mark XII-A; the OD of the outer fuel tube is only 3.020 in. The calculation was for the normal situation of shipping 5 nested sets of Mark VI-E fuel tubes per bundle with single bundles in cask slots 1, 3, and 5. The standard fuel concentration of 220 g ^{235}U per foot for a nested set of fuel tubes was used. Calculated k_{eff} for this array is 0.81 (the point is plotted on figure 9) compared with k_{eff} = 0.88 assuming Mark 16 dimensions and k_{eff} = 0.93 assuming Mark XII-A dimensions. The lower k obtained with the Mark VI-E dimensions is attributed to higher neutron leakage resulting from the smaller fuel OD and the inherently less reactive arrangement of fuel and moderator with two concentric fuel tubes compared with three. (Three concentric fuel tubes in water more nearly approximate a homogeneous mixture of fuel and moderator than do two.)

The foregoing analysis indicates that the basic calculations that were made using Mark XII-A dimensions result in calculated k_{eff} values that will not be exceeded for current fuel designs or for tubular fuel designs being considered for the foreseeable future.

Effect of Spacing of Assemblies

Past studies (Reference 2) indicate that a slight separation of assemblies in a cask slot results in an increase in k_{eff}. This effect is shown in figures 10 through 13. It should be noted that a positive effect (increasing k_{eff}) exists; k_{eff} increases with fuel concentration and reaches a maximum at approximately 0.5 in. separation.

Comparison of Calculations with Experiments

During the past several years exponential experiments have been performed with U-Al alloy tubular fuel elements in water to provide a basis for the nuclear criticality safety specifications for these elements (Reference 3). Correlations of the results of these experiments with k_{eff} calculations performed with the combination of MGB and TGA codes have been made. The correlations have been expressed in terms of a k_{eff} calculated for the steady state experimental conditions and are shown in figure 14. If experimental and calculated results agreed exactly, k_{eff} would be unity. A value greater than unity indicates the calculated k_{eff} is greater than the experimental k_{eff} - a conservative condition. It should be noted that in all cases the calculations do overestimate the reactivity found experimentally; however, for most cases the difference is less than 0.1 k_{eff}.

Cask Limit System

In defining the cask limit system, it was first assumed that any configuration for which k_{eff} is calculated to be one or greater would be critical. Next an allowance of 0.013 Δk is made for ^{235}U fuel and an allowance of 0.015 Δk is made for ^{239}Pu fuel to account for manufacturing tolerances. Most fuel concentration specifications are ±3%; these allowances account for about ±5%. These Δk allowances were determined from figures 3 and 6 using the maximum slope at k_{eff} = 0.95. Allowance for assembly separation within bundles is shown in figure 15 for ^{235}U fuel and figure 16 for ^{239}Pu fuel. These figures were plotted using data obtained from figures 10, 11, 12, and 13. Finally, an allowance of Δk = 0.02 is made for contingencies. These allowances are depicted in figure 17 for ^{235}U fuel and in figure 18 for ^{239}Pu fuel. The lowest curve shown on these figures represents the maximum calculated k_{eff} that will be permitted.

The shipping limit curves given in figure 1 for ^{235}U fuel and in figure 2 for ^{239}Pu fuel were constructed by combining the k_{eff} limit curves (figure 17 for ^{235}U fuel and figure 18 for ^{239}Pu fuel) with the calculated k_{eff} curves (figures 3 through 8). Safe cask loading configurations are defined by the region to the left of the bundles per cask limit curves that are given in figures 1 and 2. For example, assume that fuel elements containing initially (unirradiated) 300 g ^{235}U per foot are to be bundled 3 assemblies per bundle (the bundle size is determined by other considerations) and shipped. Figure 1 indicates that shipment of three bundles per cask (in slots 1, 3, 5) is permissible (the 300 g per foot - 3 assemblies per bundle point falls in the

[redacted]

region to the left of the 3 bundles per cask limit curve); four or five bundles per cask would be prohibited (the points lie in the region to the right of both the 4 and 5 bundles per cask limit curves). Figure 1 also shows that for 300 g ^{235}U per foot fuel assemblies, the bundle size is limited to 4 assemblies per bundle if 3 bundles per cask are to be shipped. Five or more assemblies per bundle give points that fall in the region to the right of the 3 bundles per cask limit curve.

Comparison with Current Shipping Restrictions

The limits developed here are in agreement with the shipping limits currently specified in standard operating procedures; no changes in the shipping methods now followed are necessary. The advantage to the new limit system lies in its inherent continuity as new types of fuel are developed and its elimination of the necessity to exhaustively analyze each new case. The following examples illustrate the agreement of the new system with current shipping practices:

(1) Mark VI-E nested fuel elements (220 g ^{235}U per foot) are bundled 5 nested sets per bundle; 3 bundles per cask (slots 1, 3, 5) are permitted in agreement with figure 1. k_{eff} for this arrangement will not exceed 0.93 (figure 5).

(2) Mark XII-A assemblies (85 g ^{235}U per foot) are bundled 4 assemblies per bundle; 5 bundles per cask (slots 1, 2, 3, 4, 5) are permitted in agreement with figure 1. k_{eff} for this arrangement will not exceed 0.90 (figure 3).

(3) Mark VI-PS nested Pu-Al target elements (172 g total Pu per foot) are bundled 5 nested sets per bundle; 3 bundles per cask (slots 1, 3, 5) are permitted in agreement with figure 2. k_{eff} for this arrangement will not exceed 0.93 (figure 8).

Application to New Types of Fuel

The following examples illustrate the use of the new system for Mark 14 and Mark 16 assemblies (new types of fuel):

(1) Mark 14 assemblies (136 g ^{235}U per foot) will probably be bundled 4 assemblies per bundle (200-Area criticality considerations will govern the bundle size). Figure 1 shows that 4 bundles per cask (slots 1, 2, 4, 5) will be permitted for either 4 or 5 assembly bundles. For this arrangement k_{eff} will not exceed 0.93 for 4 assembly bundles and will not exceed 0.95 for 5 assembly bundles (figure 4). In the event 3 assembly bundles are required, figure 1 shows that 5 bundles per cask (slots 1, 2, 3, 4, 5) will be permitted. k_{eff} for this arrangement will not exceed 0.96 (figure 3).

(2) For Mark 16 assemblies (240 g ^{235}U per foot) figure 1 shows that shipping will be limited to 3 bundles per cask (slots 1, 3, 5) for 3, 4, 5, or 6 assembly bundles. The bundle size for Mark 16 fuel will probably be either 3 or 4 assemblies per bundle as dictated by process criticality restrictions. For this shipping arrangement, k_{eff} will not exceed 0.89 for 3 assembly bundles and will not exceed 0.92 for 4 assembly bundles (figure 5).

Evaluation and Application of Results

The following items that pertain to an evaluation of the calculations and the use of the curves developed from this study should be considered:

(1) The nominal fuel concentration (g of ^{235}U or g total Pu per foot) before irradiation in the reactors should be used for entering the curves. This offers conservatism for the normal situation of shipping irradiated material because fissionable material is consumed in the reactors, rendering the material less reactive after irradiation. Under unusual circumstances bundles of unirradiated or slightly irradiated material might be shipped.

(2) In the calculations, uranium assemblies were assumed to be an alloy of oralloy (93.5% ^{235}U, 1.0% ^{234}U, 5.5% ^{238}U) and aluminum. In practice, unirradiated assemblies contain varying amounts of ^{236}U because of the recycle program, but the ^{235}U content of a particular type of unirradiated assembly remains approximately constant. The ^{236}U affects the reactivity only slightly; for example, compared with oralloy, a 1:1 ratio of ^{236}U to ^{235}U would have a k_{eff} about one percent less for Mark 16 assemblies (Reference 2). The nominal g ^{235}U per foot before irradiation should be used for entering the curves.

(3) In the calculations, plutonium assemblies were assumed to be an alloy of ^{239}Pu and aluminum. In practice, plutonium assemblies contain varying proportions of individual Pu isotopes, more than one of which is fissionable. Assuming that all of the plutonium is ^{239}Pu presents the most reactive situation; hence, for conservatism, the g total Pu per foot for assemblies should be taken as g ^{239}Pu per foot for entering the curves in this document.

(4) In defining the cask limit system, no allowance was made for the observed general overestimation of calculated values for k_{eff} compared with k_{eff} determined experimentally (figure 14). This is because the agreement was very close for some cases.

(5) Normal assembly shapes and arrays were assumed for all calculations. Distortion of arrays resulting from physical damage to tubes or bundles (crushing, bending, twisting, etc.) could increase k_{eff} drastically.

(6) The limit system developed in this document is applicable to assemblies in current use and to tubular assemblies being considered for the foreseeable future. If it becomes necessary to ship assemblies having ODs greater than the Mark 16 or consisting of more than three concentric tubes, additional calculations will be required.

CWT:gvb

REFERENCES

1. Clark, H. K., "Computer Codes for Nuclear Criticality Safety Calculations", DP-1121, November 1967, Unclassified.

2. Clark, H. K., "Nuclear Criticality Safety of Heavy Three-Tube Drivers", DPST-67-207, January 17, 1967, Secret.

3. Clark, H. K., "Correlation of Calculations with U-Al Tube Experiments", DPST-67-478, August 2, 1967, Unclassified.

Table I

Mark XII-A Tube Dimensions

	Radius, cm
Inner Tube	2.7661
	2.8169
	2.8727
	2.9413
Middle Tube	3.5674
	3.6182
	3.6741
	3.7376
Outer Tube	4.3701
	4.4209
	4.4717
	4.5225

Table II

A. Uranium Alloy Composition - Mark XII-A Dimensions

(Uranium assumed to be 93.5% ^{235}U, 1.0% ^{234}U, 5.5% ^{238}U)

g ^{235}U/ft	Density, g/cm^3	% Uranium	% Aluminum
50	3.081	15.40	84.60
100	3.463	27.41	72.59
200	4.226	44.92	55.08
300	4.988	57.08	42.92
400	5.751	66.01	33.99
600	7.277	78.26	21.74

B. Plutonium Alloy Composition - Mark XII-A Dimensions

(Plutonium assumed to be 100% ^{239}Pu)

g ^{239}Pu/ft	Density, g/cm^3	% Plutonium	% Aluminum
50	3.050	14.55	85.45
100	3.400	26.10	73.90
200	4.101	43.28	56.72
300	4.801	55.45	44.55
400	5.502	64.52	35.48
600	6.903	77.14	22.86

Table III

A. Mark 16 Tube Dimensions

	Radius, cm
Inner Tube	2.1819
	2.2835
	2.5705
	2.6467
Middle Tube	3.2893
	3.3655
	3.6525
	3.7287
Outer Tube	4.3612
	4.4374
	4.6228
	4.6990

B. Mark VI-E Tube Dimensions

	Radius, cm
Inner Tube	2.6010
	2.6772
	2.9134
	3.0175
Outer Tube	3.4747
	3.5509
	3.7592
	3.8354

[redacted]

Table IV

Uranium Alloy Composition - Mark 16 and Mark VI-E Dimensions

(Uranium assumed to be 93.5% ^{235}U, 1.0% ^{234}U, 5.5% ^{238}U)

Dimensions	g ^{235}U/ft	Density, g/cm^3	% Uranium	% Aluminum
Mark 16	50	2.788	3.94	96.06
	100	2.877	7.63	92.37
	220	3.088	15.64	84.36
	400	3.406	25.79	74.21
	600	3.759	35.05	64.95
Mark VI-E	220	3.395	25.48	74.52

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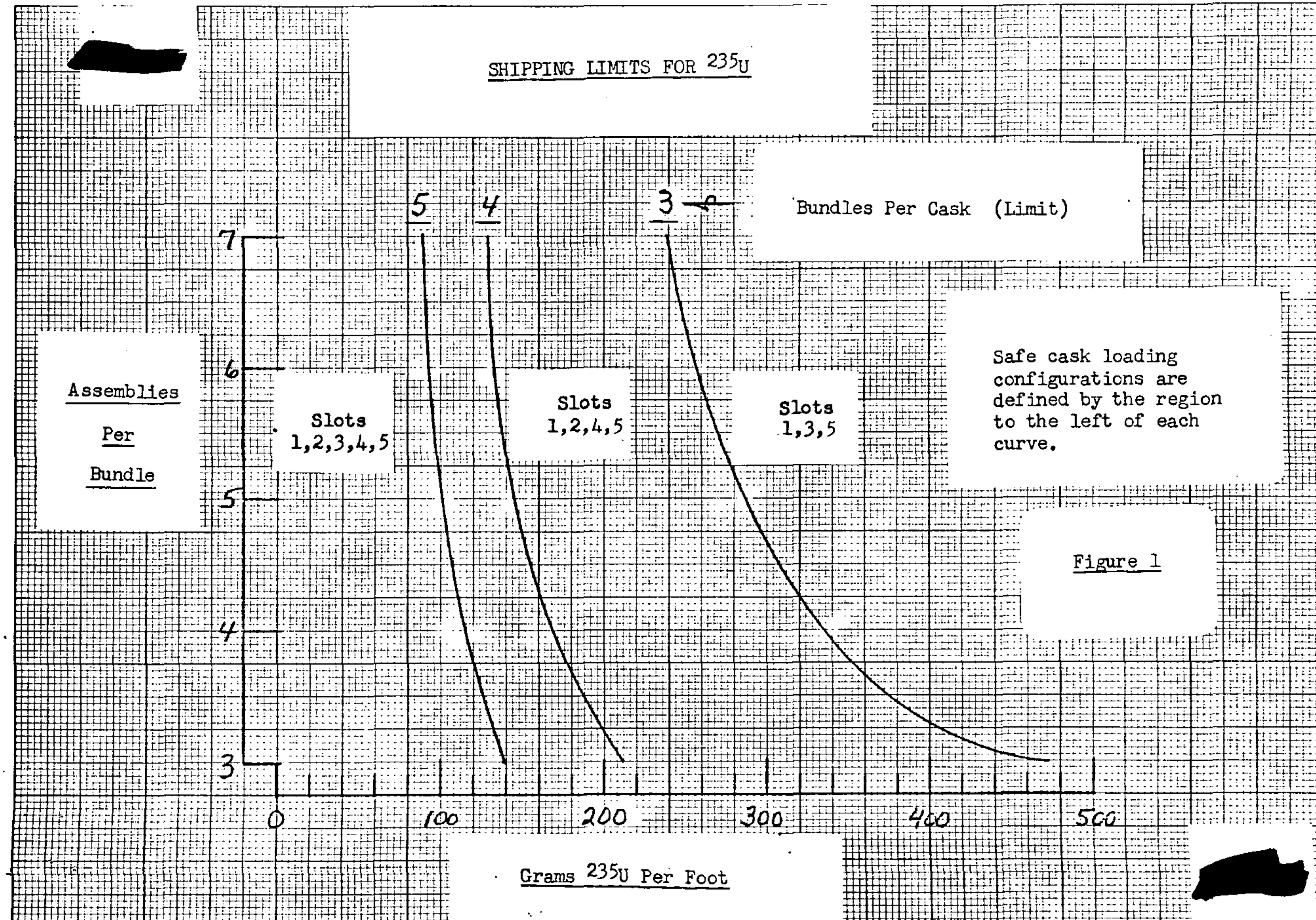

Figure 1

[redacted]

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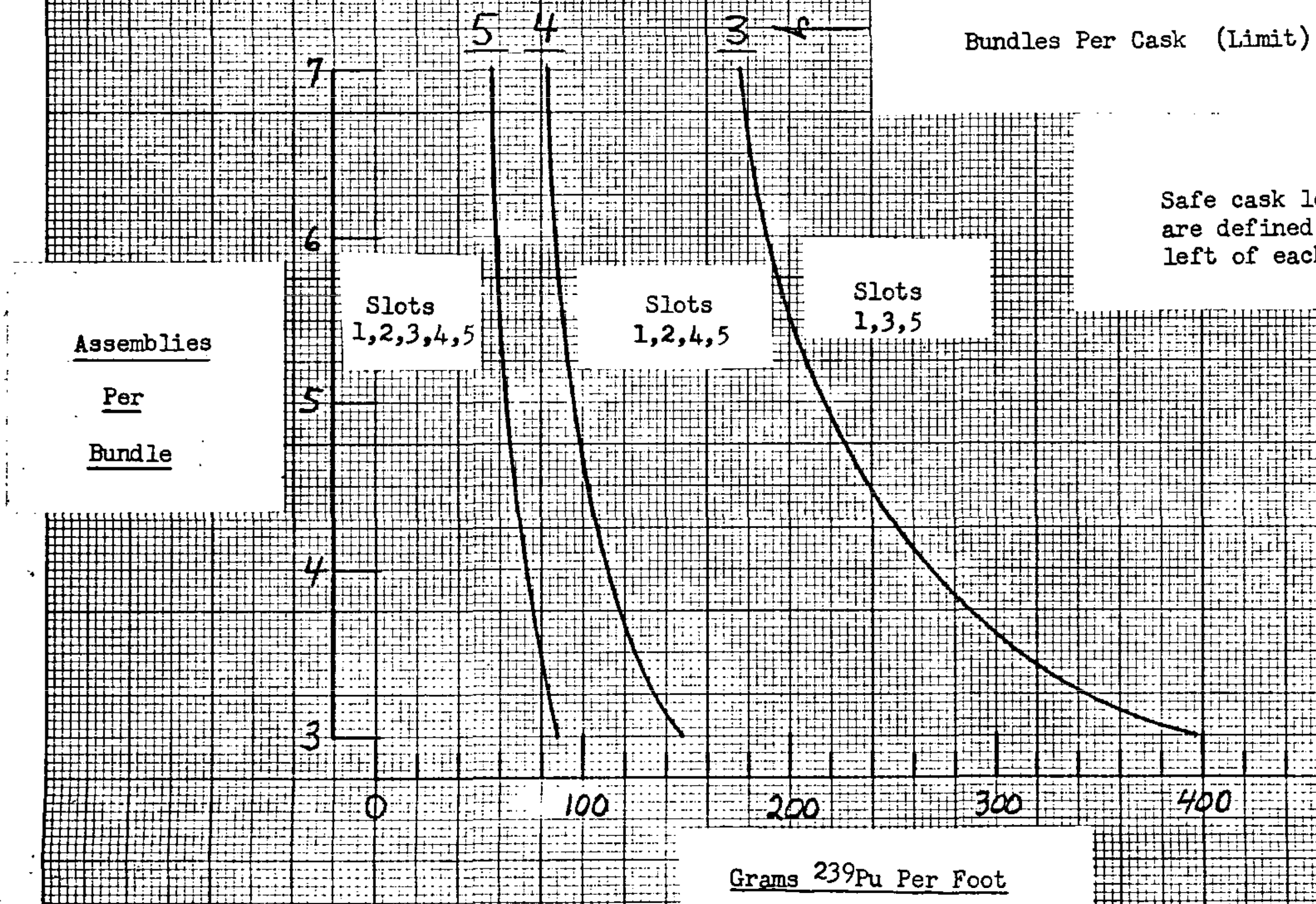
SHIPPING LIMITS FOR ^{239}Pu



Safe cask loading configurations are defined by the region to the left of each curve.

Figure 2

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[redacted]

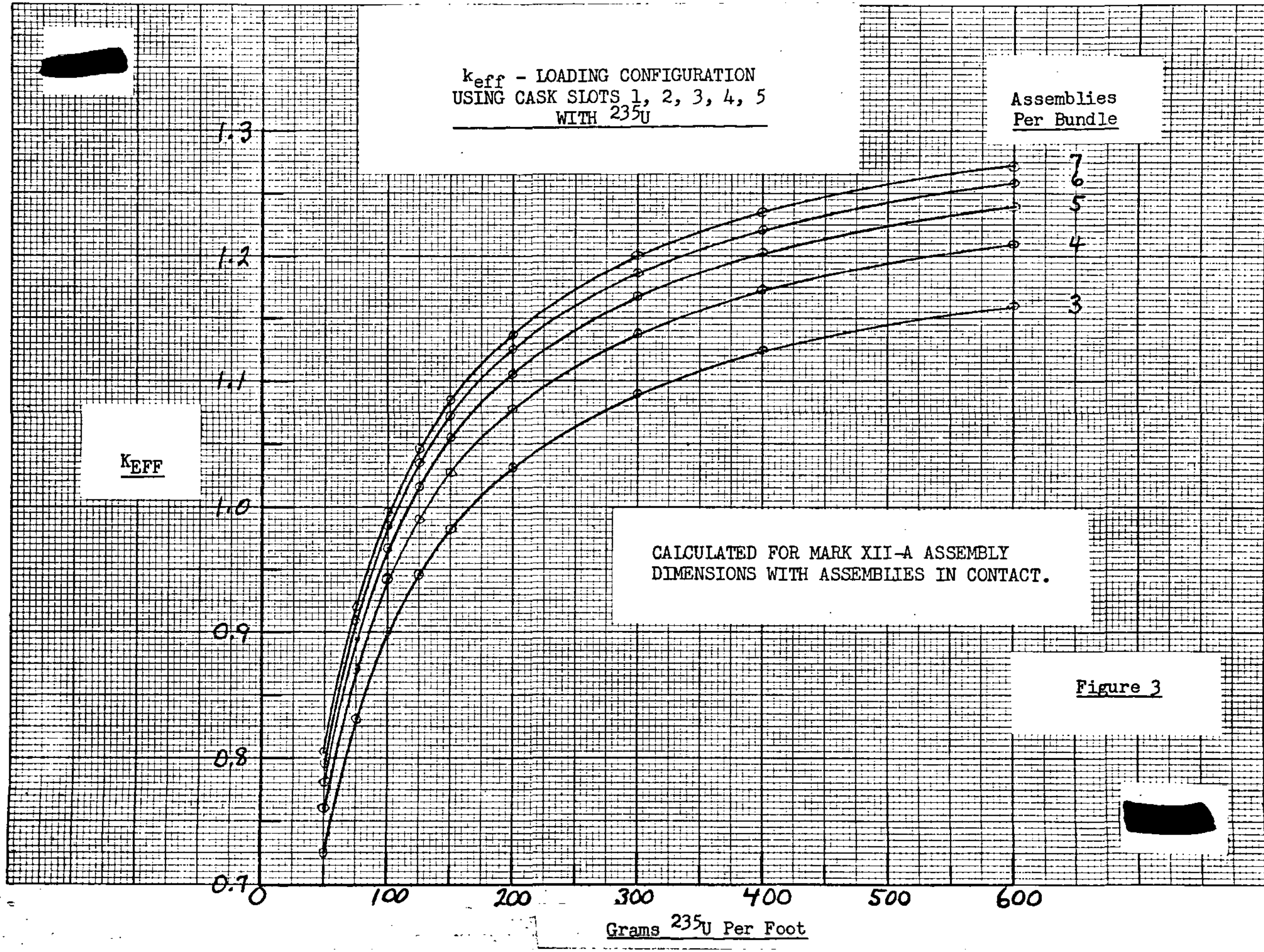

Figure 3

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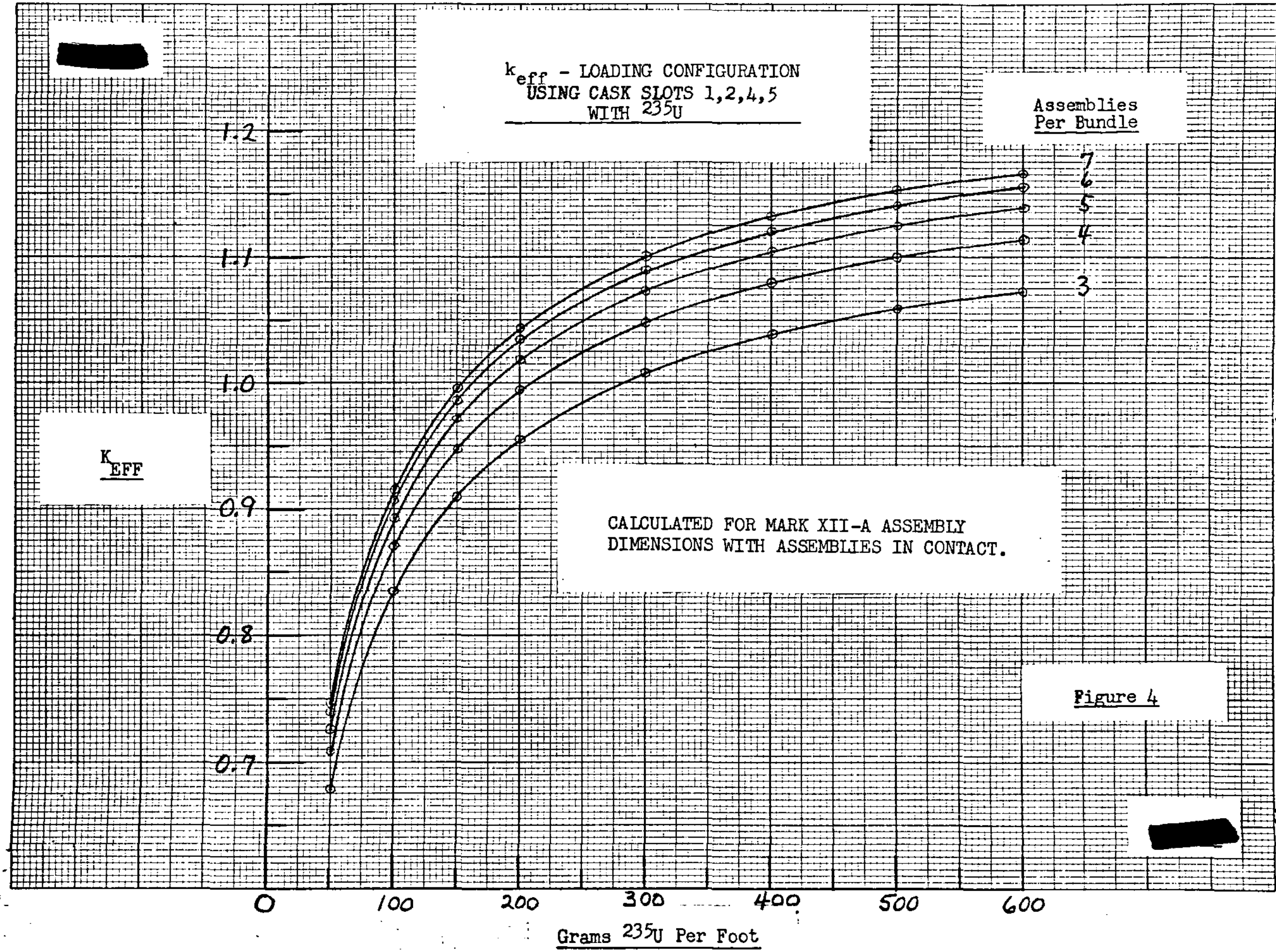

Figure 4

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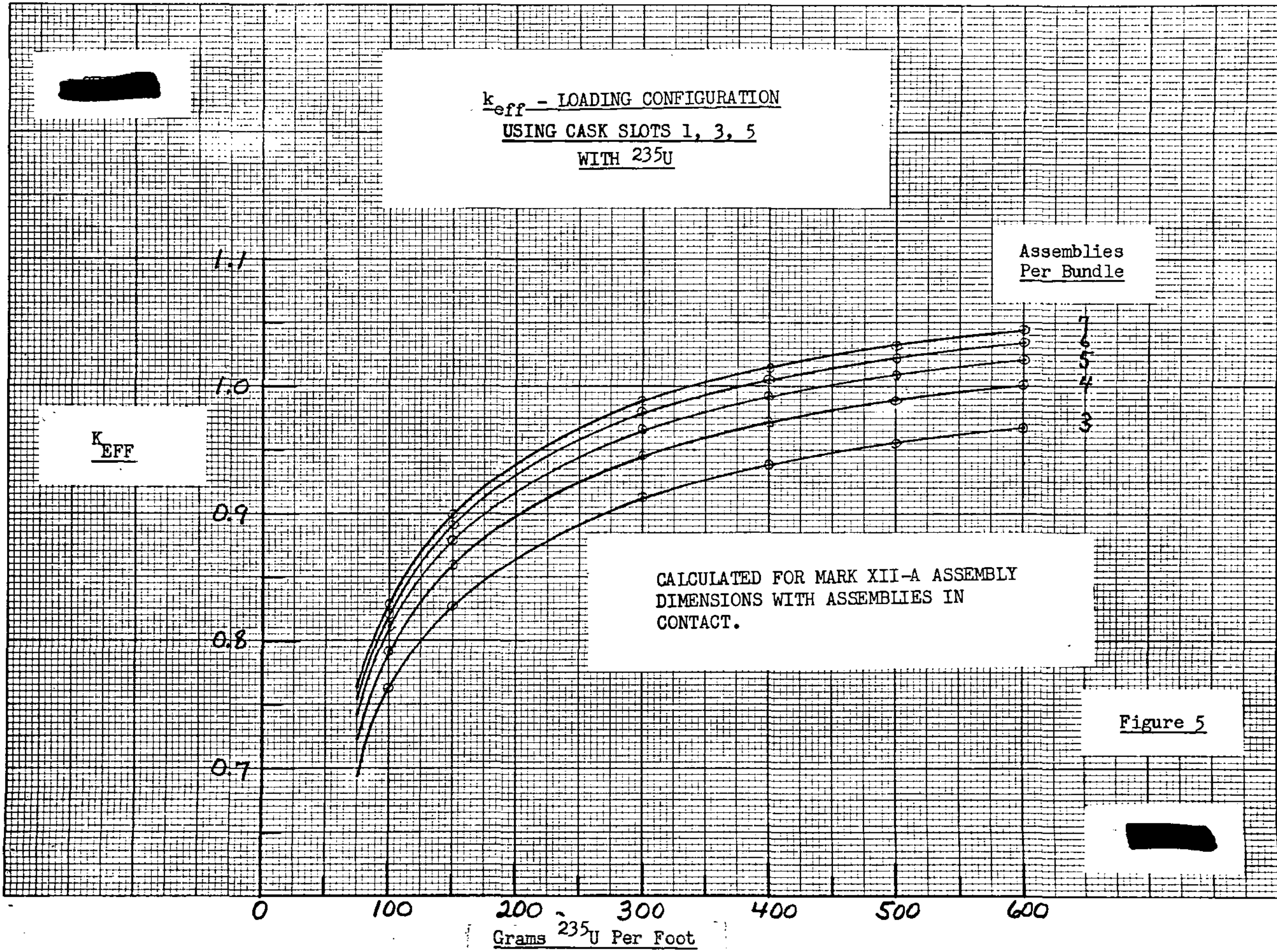

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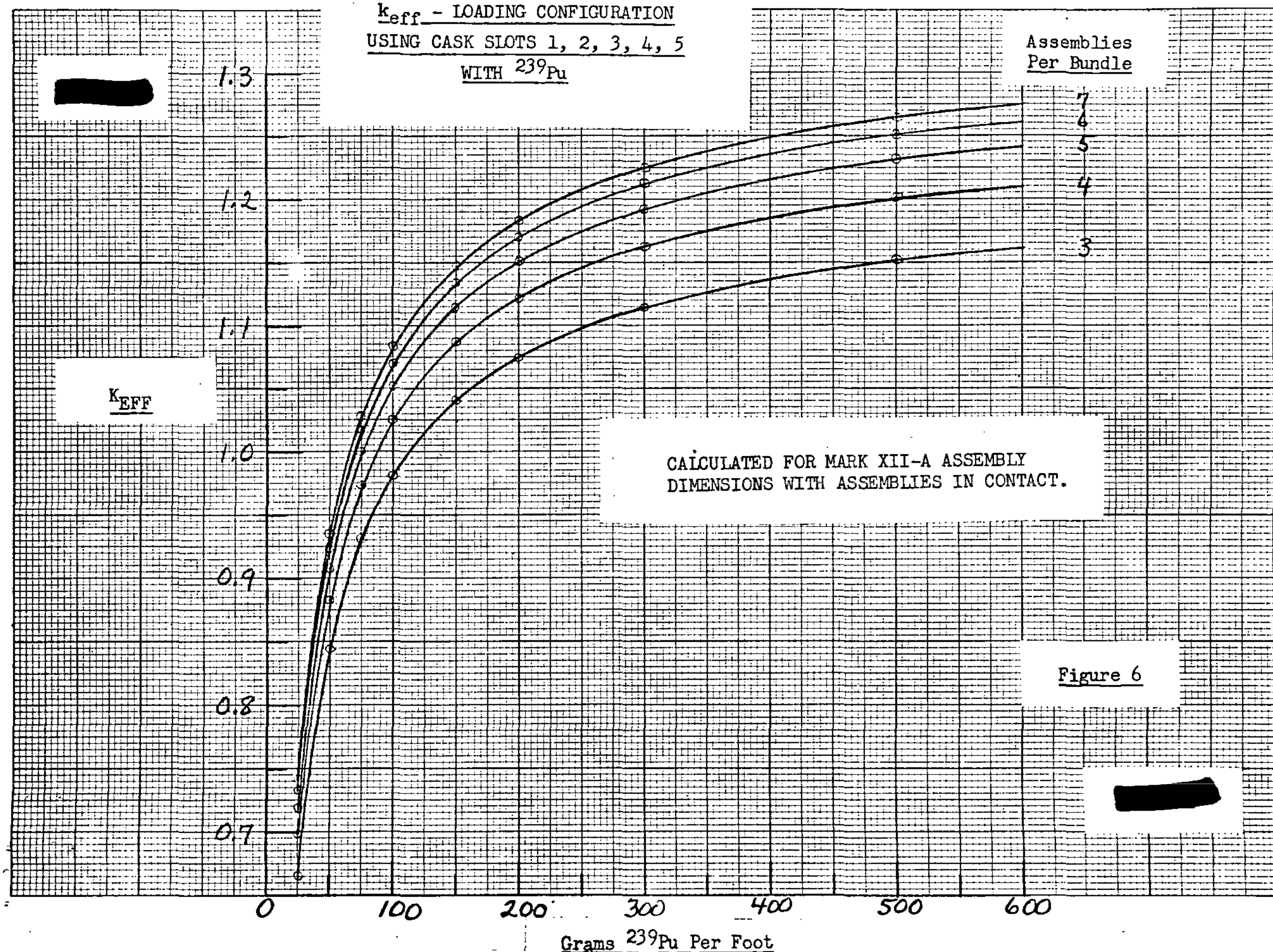
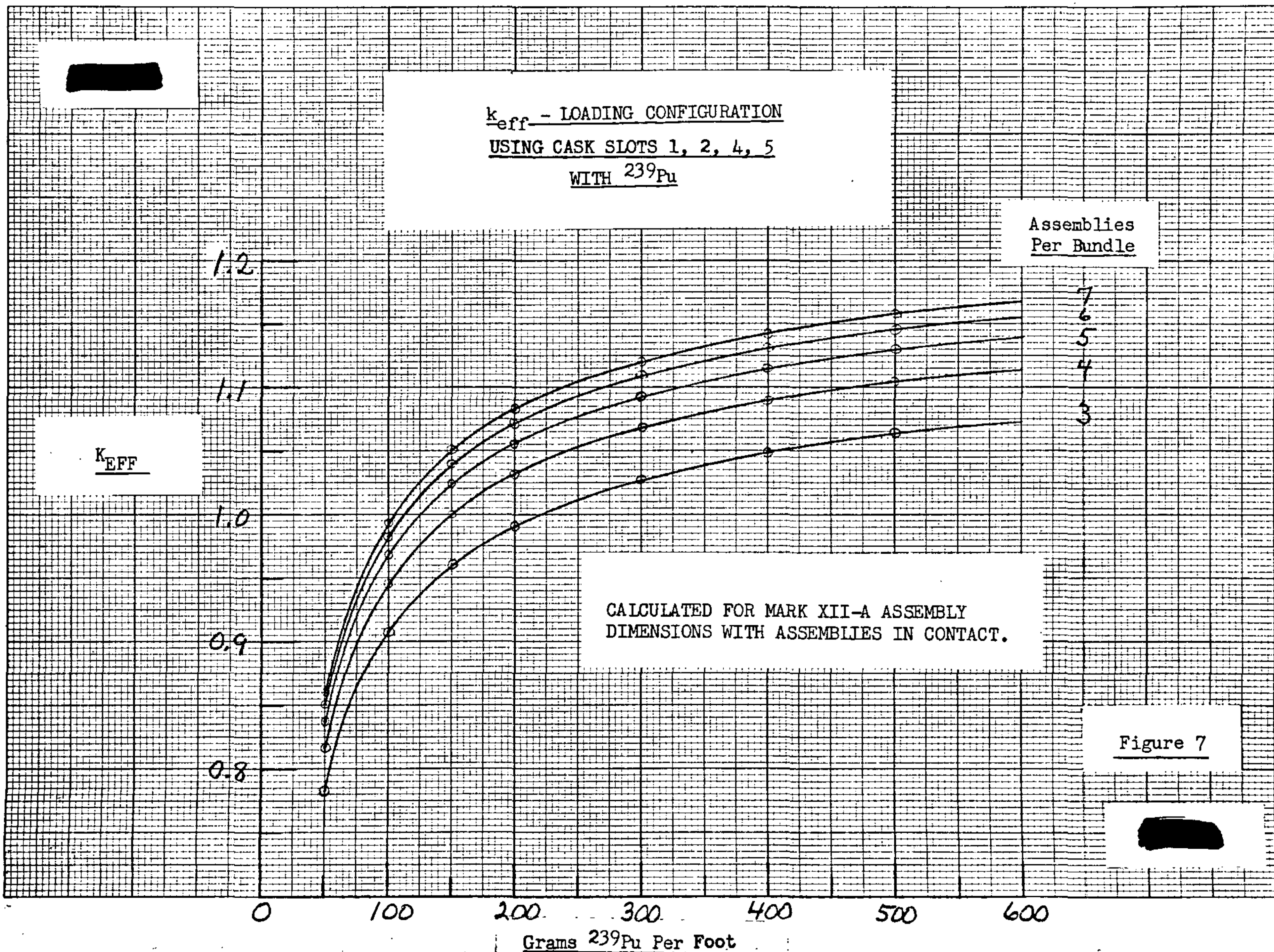
k_{eff} - LOADING CONFIGURATION
USING CASK SLOTS 1, 2, 3, 4, 5
WITH ^{239}Pu



CALCULATED FOR MARK XII-A ASSEMBLY
DIMENSIONS WITH ASSEMBLIES IN CONTACT.

Figure 6

[redacted]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k_{eff} - LOADING CONFIGURATION
USING CASK SLOTS 1, 2, 4, 5
WITH ^{239}Pu
Assemblies
Per Bundle
7
6
5
4
3
K_{EFF}
1.2
1.1
1.0
0.9
0.8
CALCULATED FOR MARK XII-A ASSEMBLY
DIMENSIONS WITH ASSEMBLIES IN CONTACT.
[redacted]
0
100
200
300
400
500
600
Grams ^{239}Pu Per Foot

Figure 7

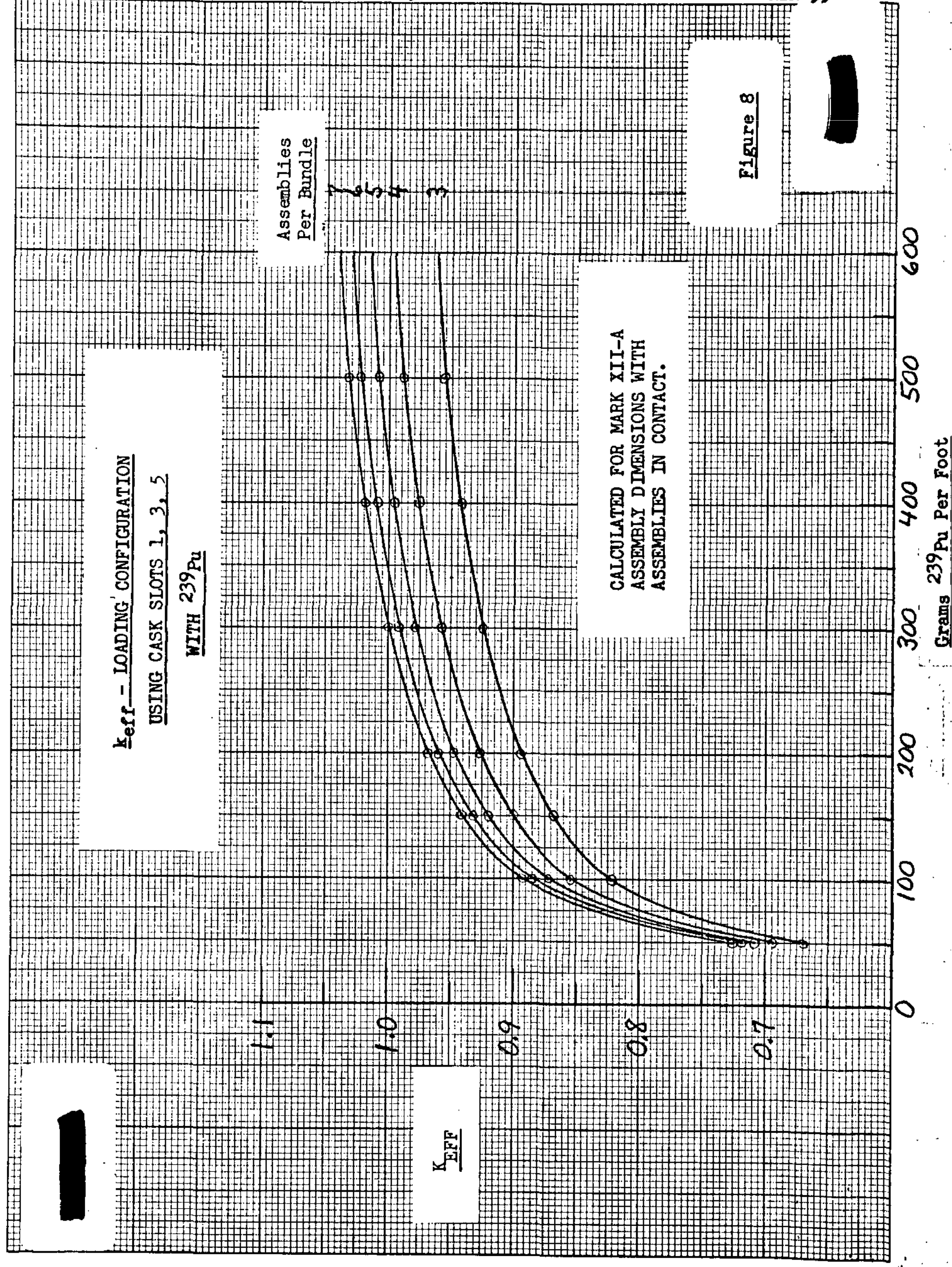

Figure 8

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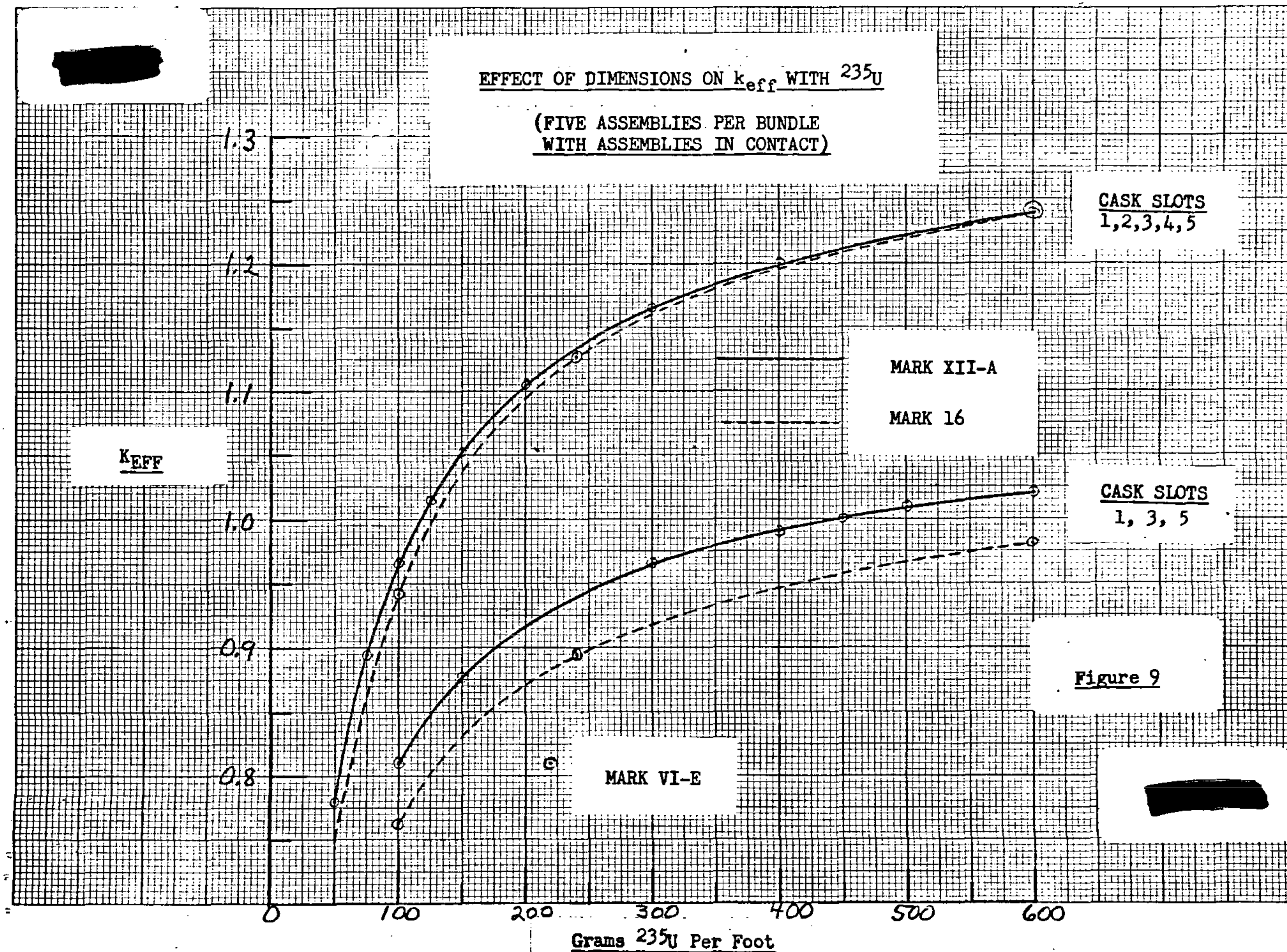

Figure 9

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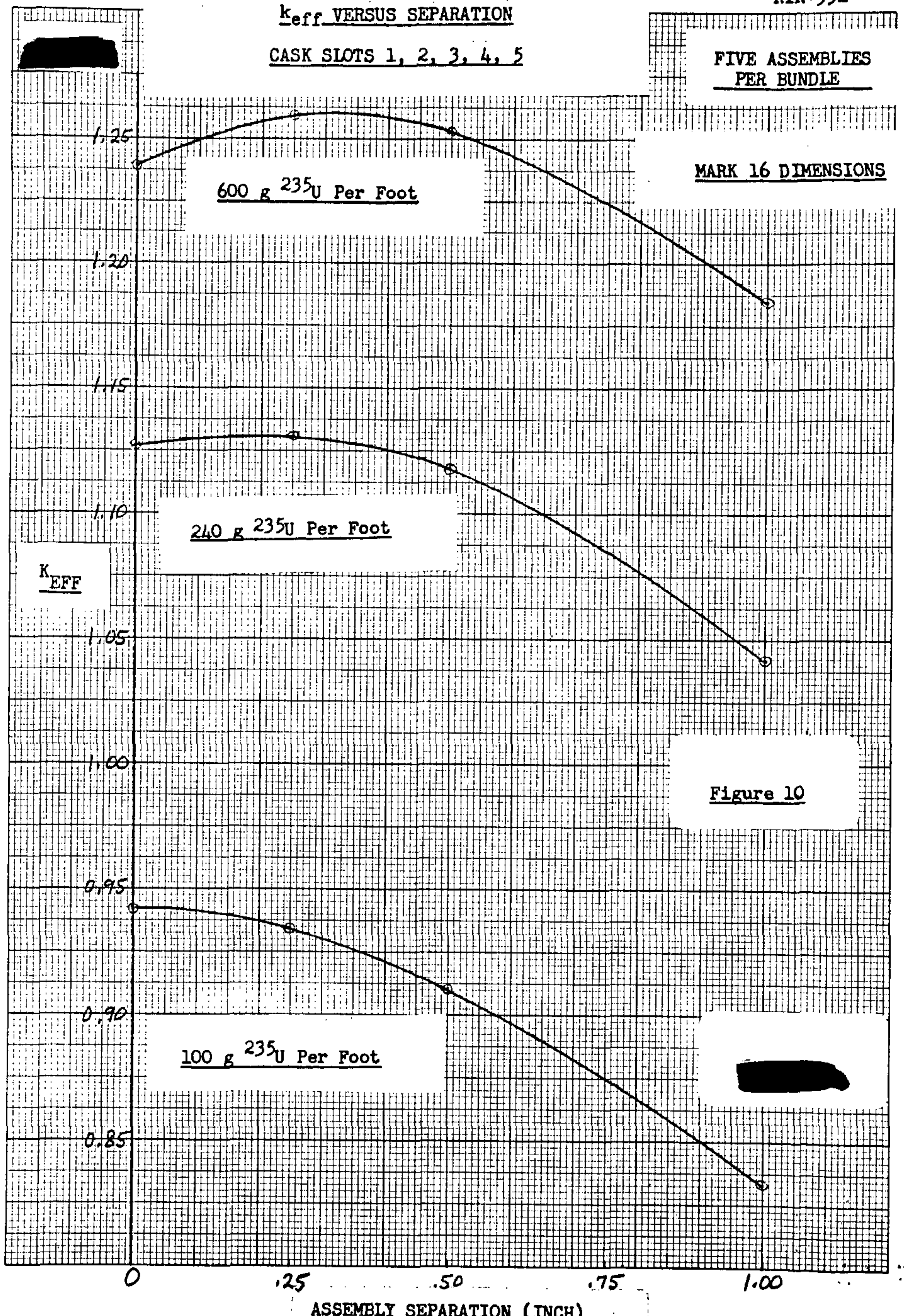
keff VERSUS SEPARATION
CASK SLOTS 1, 2, 3, 4, 5
[redacted]
FIVE ASSEMBLIES PER BUNDLE
MARK 16 DIMENSIONS
600 g 235U Per Foot
240 g 235U Per Foot
100 g 235U Per Foot
KEFF
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0
.25
.50
.75
1.00
ASSEMBLY SEPARATION (INCH)
[redacted]

Figure 10

[redacted]

k_{eff} VERSUS SEPARATION

CASK SLOTS 1, 3, 5

FIVE ASSEMBLIES PER BUNDLE

MARK 16 DIMENSIONS

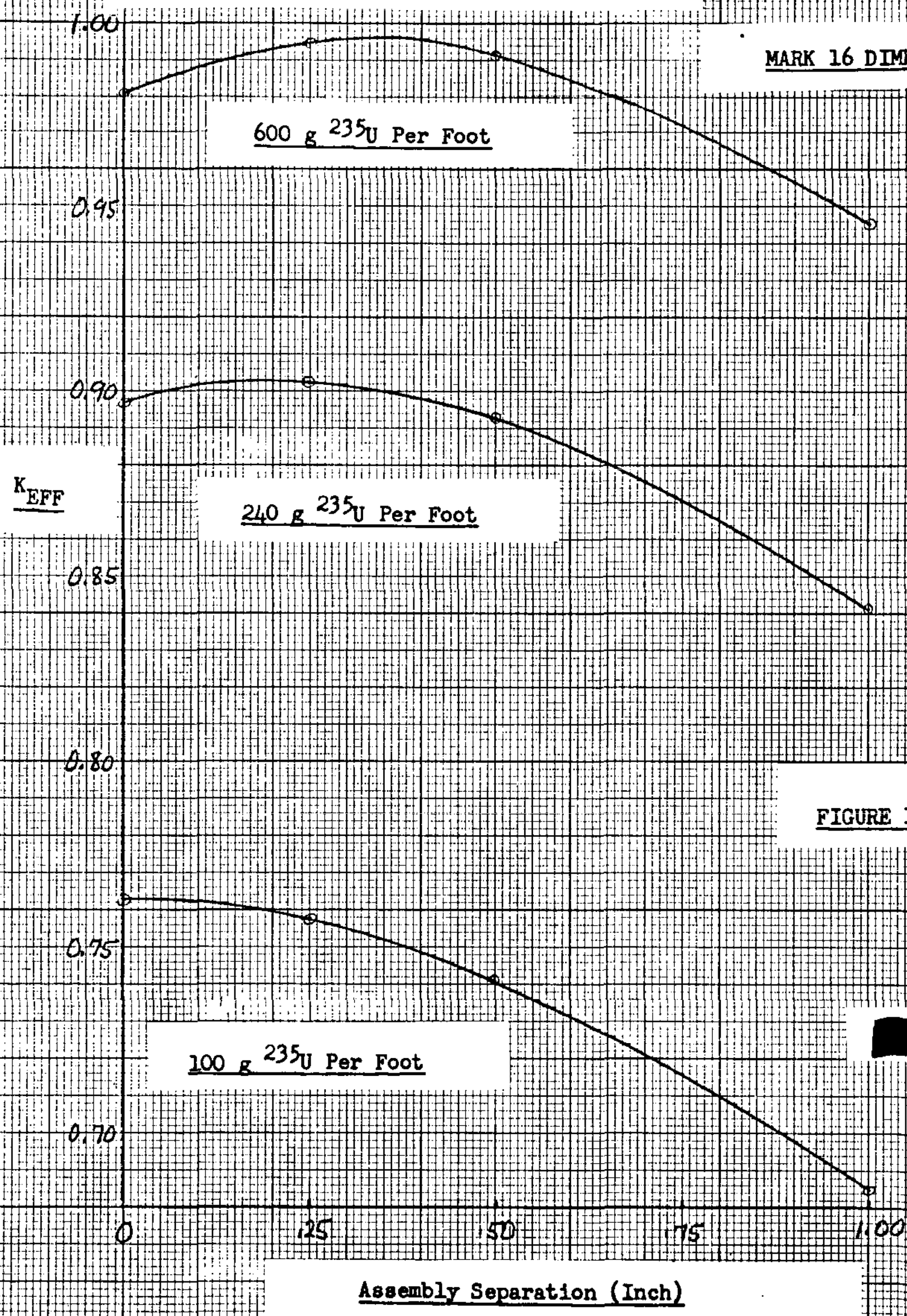

FIGURE 11

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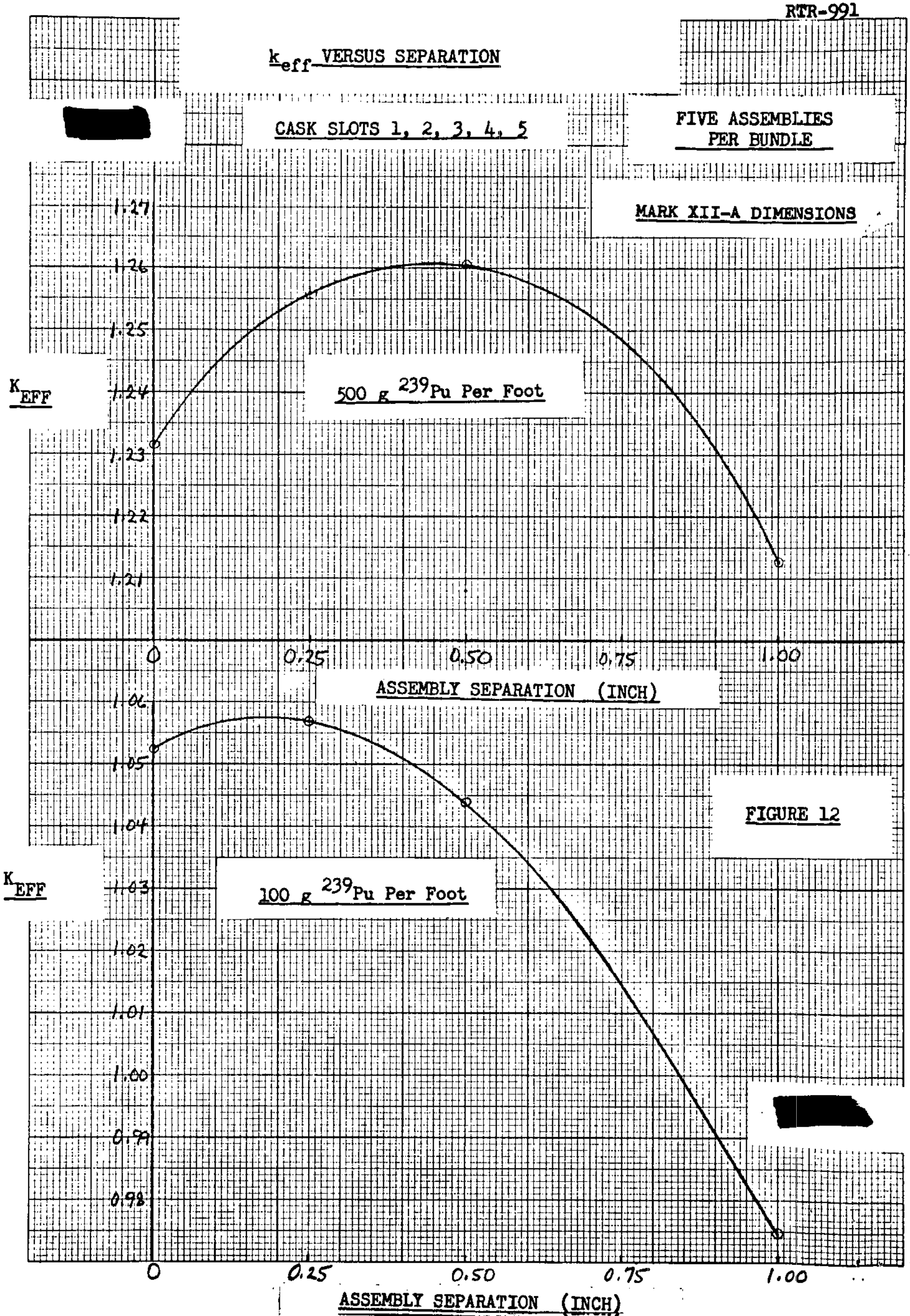
k_{eff} VERSUS SEPARATION
[redacted]
CASK SLOTS 1, 2, 3, 4, 5
FIVE ASSEMBLIES PER BUNDLE
MARK XII-A DIMENSIONS
K_{EFF}
1.27
1.26
1.25
1.24
1.23
1.22
1.21
500 g ^{239}Pu Per Foot
0
0.25
0.50
0.75
1.00
ASSEMBLY SEPARATION (INCH)
K_{EFF}
1.06
1.05
1.04
1.03
1.02
1.01
1.00
0.99
0.98
100 g ^{239}Pu Per Foot
[redacted]
0
0.25
0.50
0.75
1.00
ASSEMBLY SEPARATION (INCH)

FIGURE 12

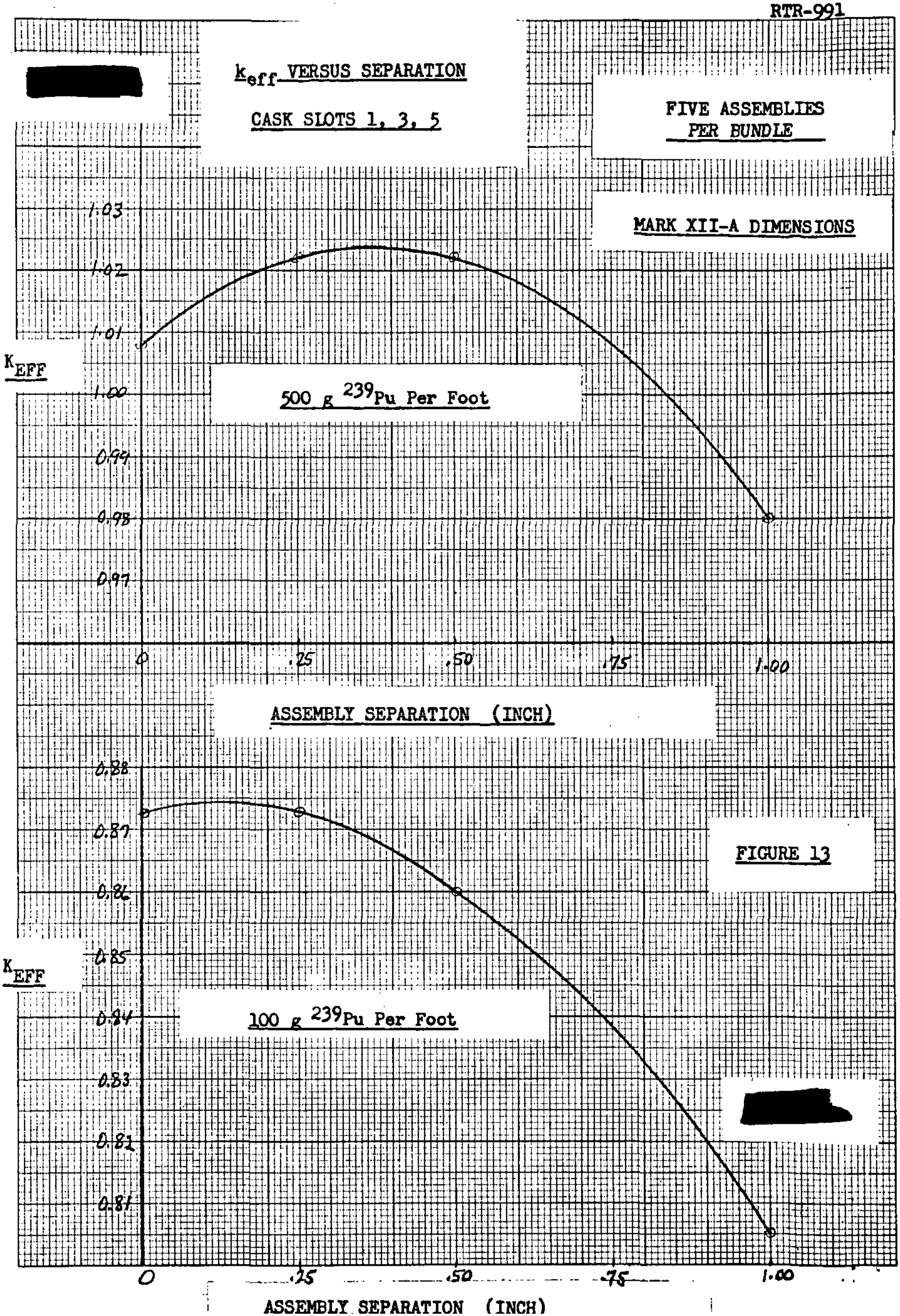
[redacted]
k_{eff} VERSUS SEPARATION
CASK SLOTS 1, 3, 5
FIVE ASSEMBLIES PER BUNDLE
MARK XII-A DIMENSIONS
K_{EFF}
1.03
1.02
1.01
1.00
0.99
0.98
0.97
500 g ^{239}Pu Per Foot
0
.25
.50
.75
1.00
ASSEMBLY SEPARATION (INCH)
K_{EFF}
0.88
0.87
0.86
0.85
0.84
0.83
0.82
0.81
100 g ^{239}Pu Per Foot
[redacted]
0
.25
.50
.75
1.00
ASSEMBLY SEPARATION (INCH)

FIGURE 13

[redacted]

CALCULATED K_{eff} COMPARED TO EXPERIMENTAL K_{eff}

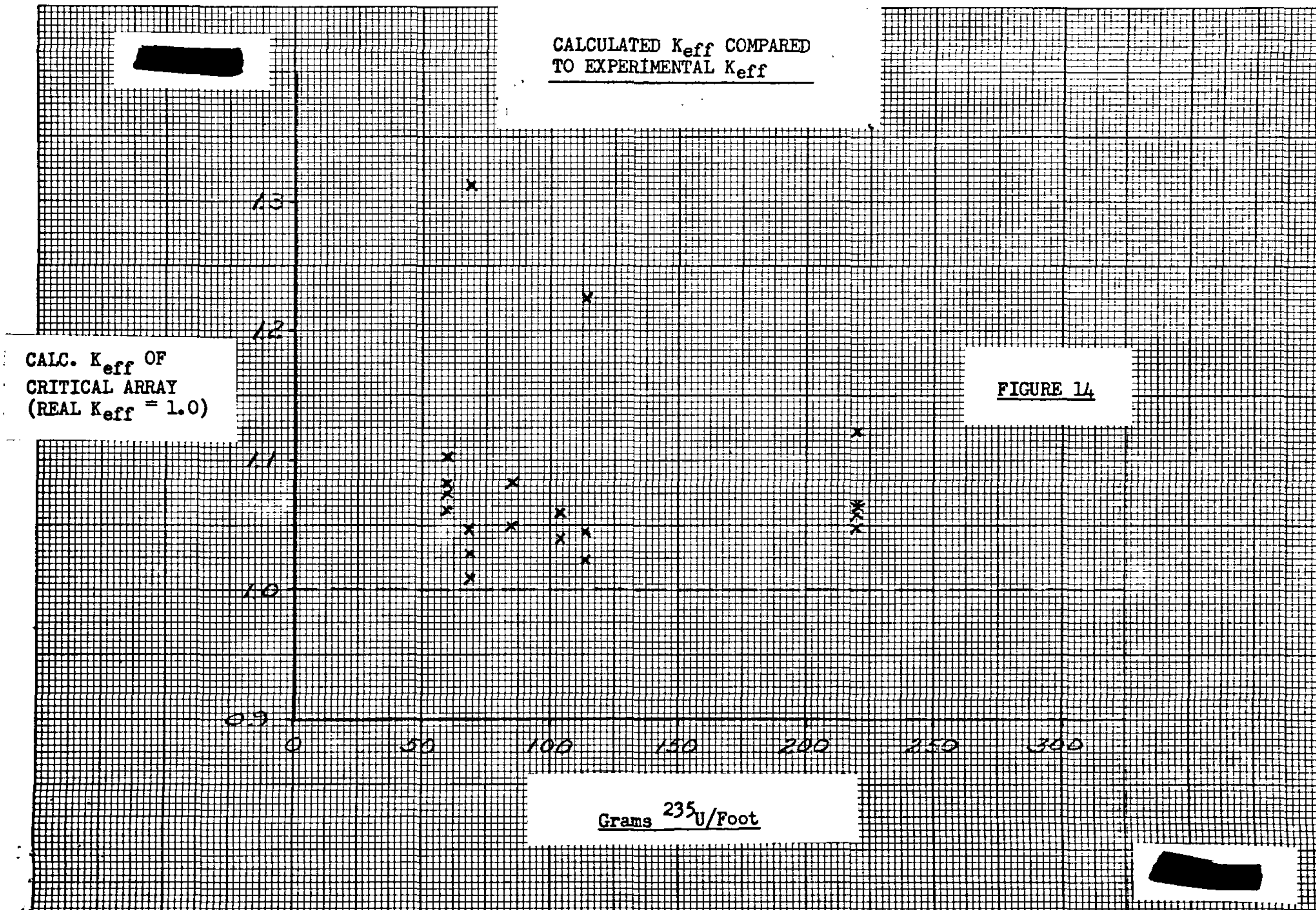

FIGURE 14

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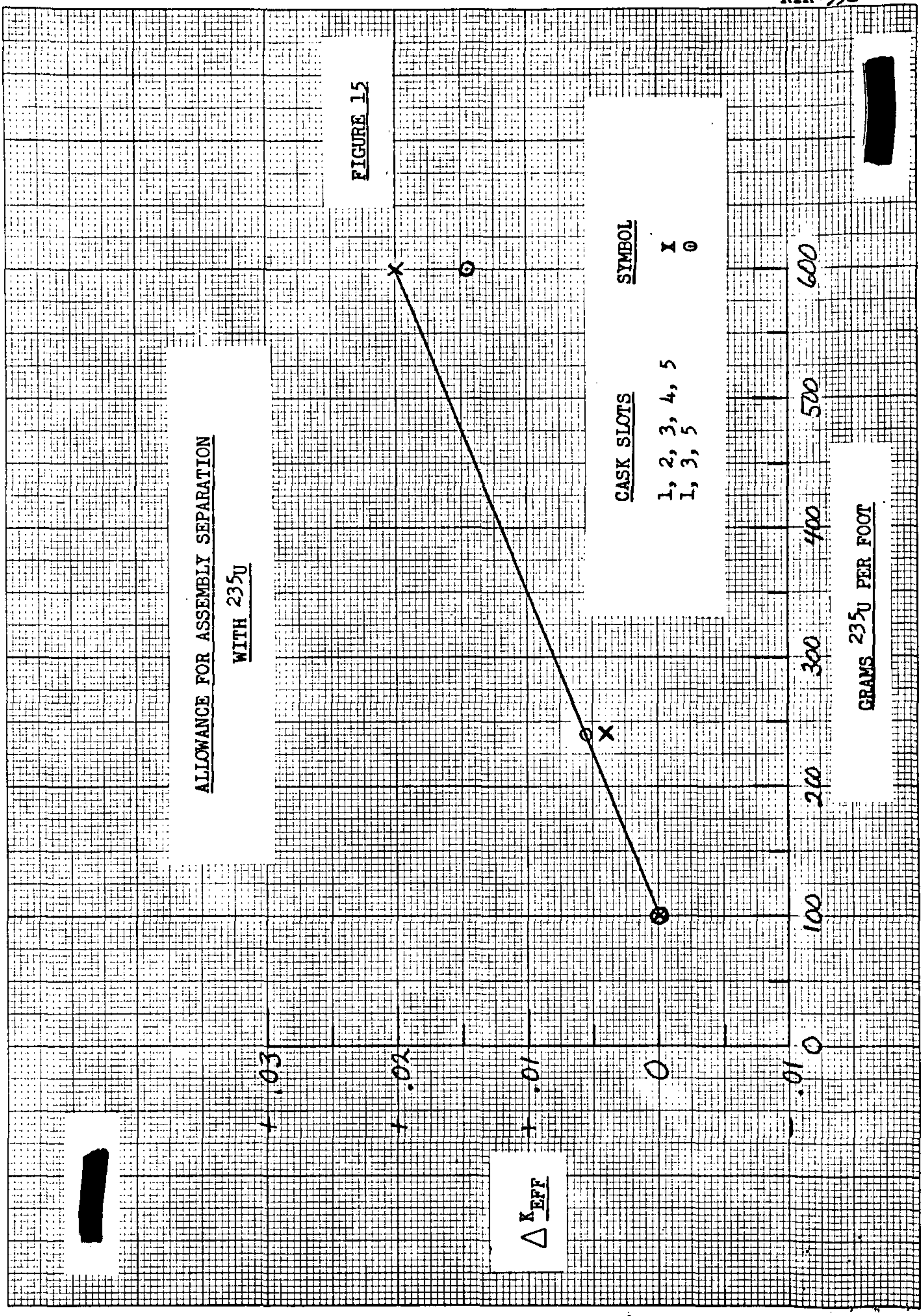

FIGURE 15

ALLOWANCE FOR ASSEMBLY SEPARATION WITH ^{235}U

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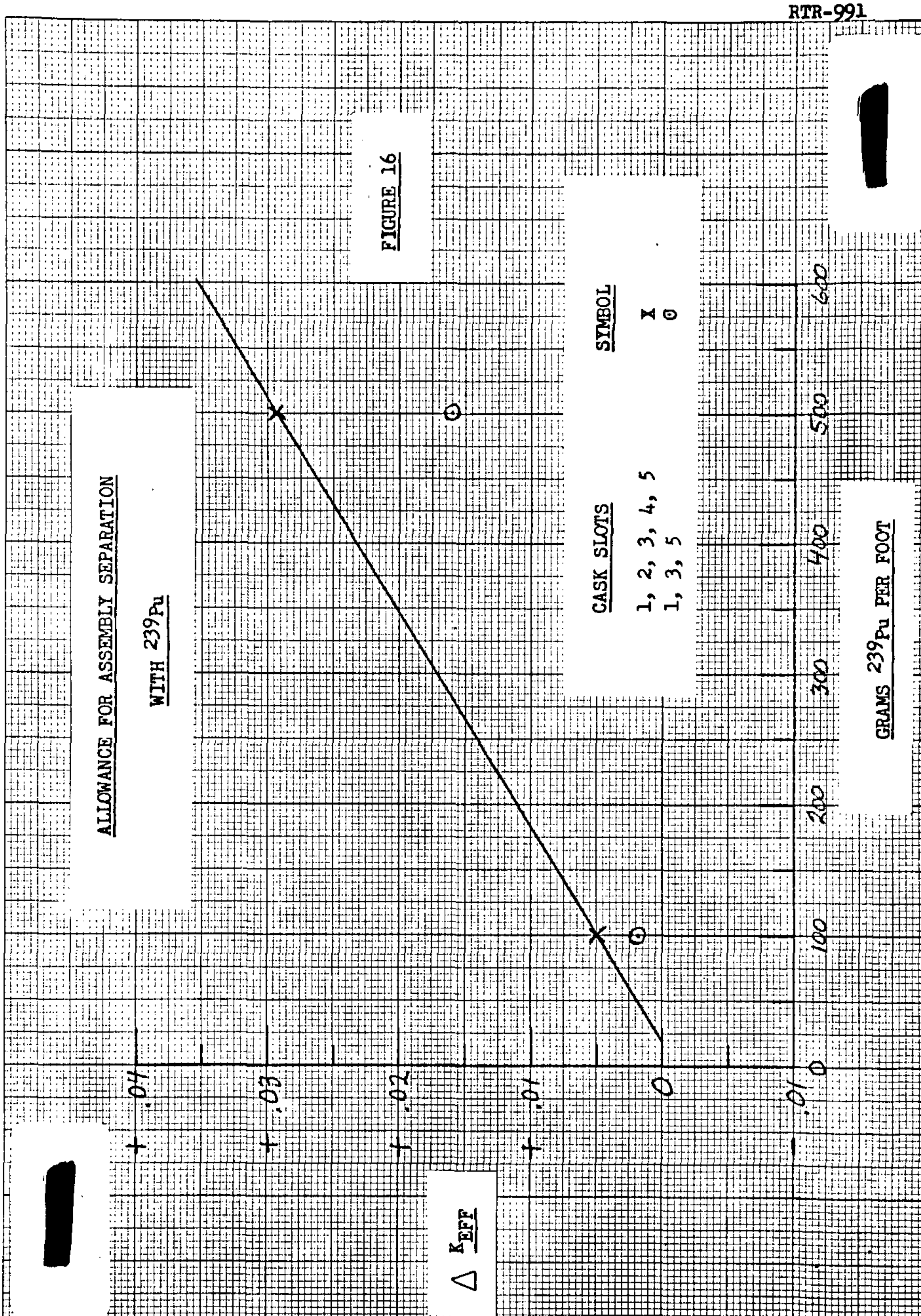

FIGURE 16

ALLOWANCE FOR ASSEMBLY SEPARATION WITH ^{239}Pu

[redacted]

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LIMIT ANALYSIS FOR ^{235}U

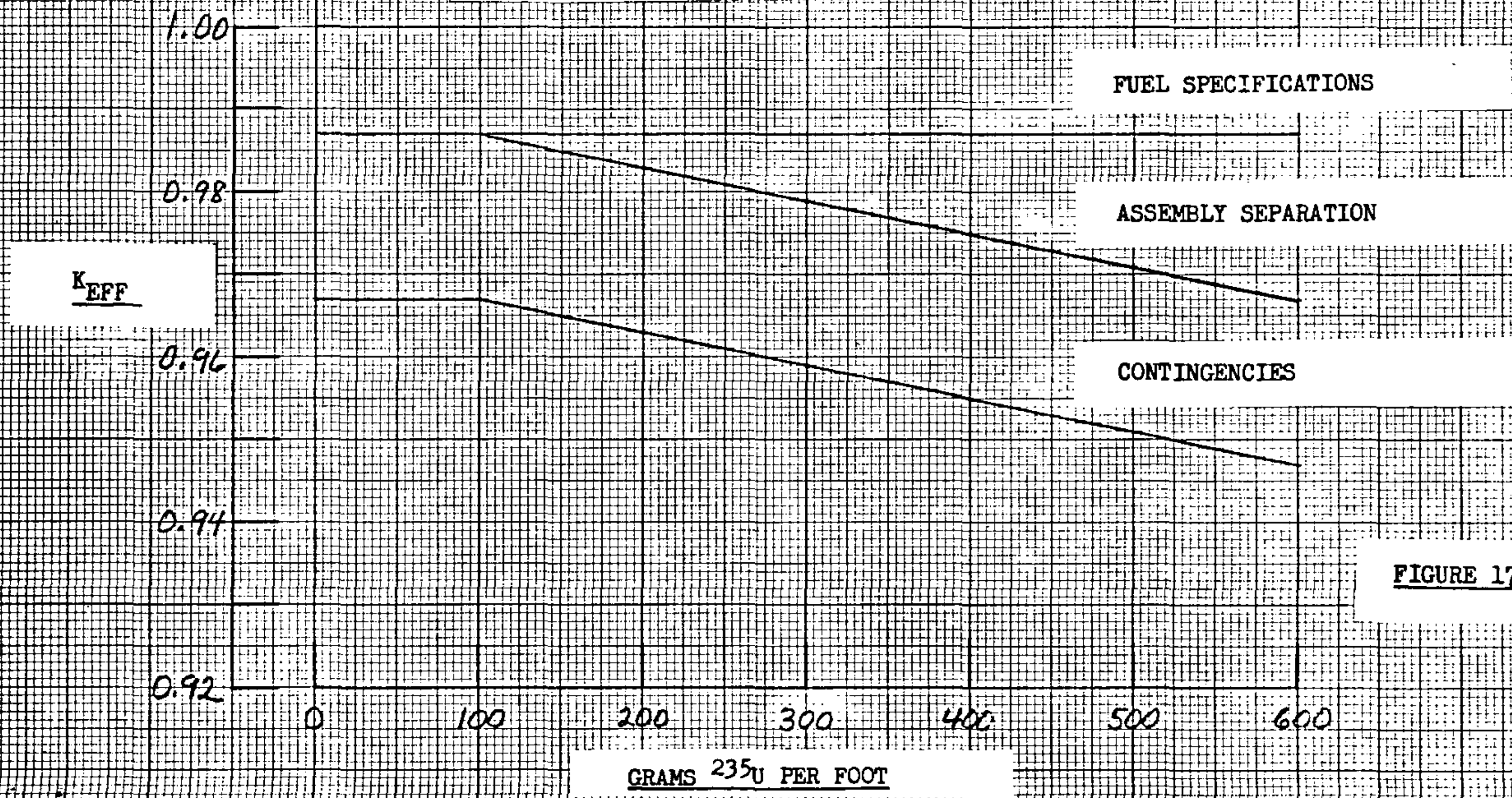

FIGURE 17

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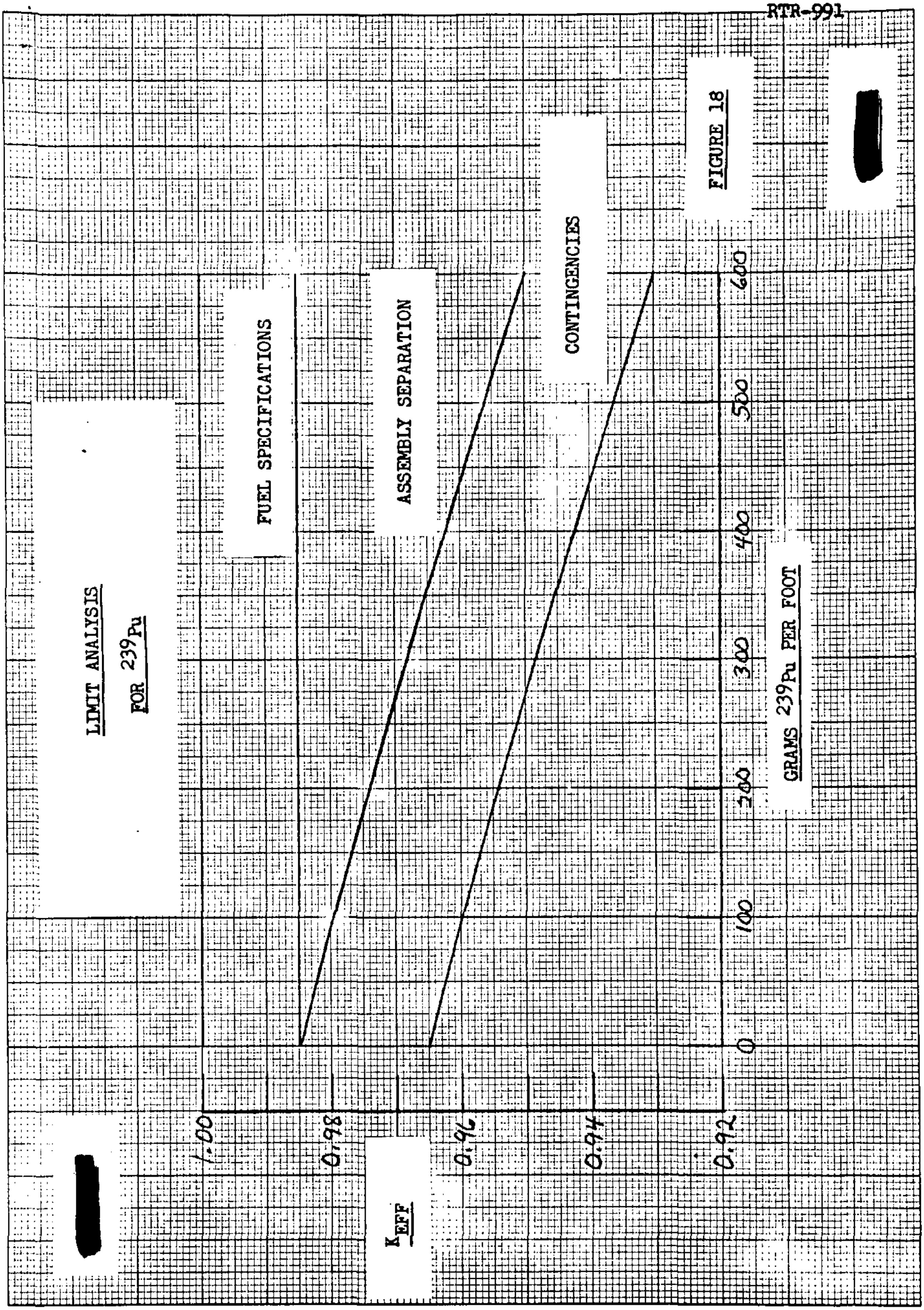
LIMIT ANALYSIS
FOR ^{239}Pu
FUEL SPECIFICATIONS
ASSEMBLY SEPARATION
CONTINGENCIES
K_{EFF}
1.00
0.98
0.96
0.94
0.92
0
100
200
300
400
500
600
GRAMS ^{239}Pu PER FOOT

FIGURE 18