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PLUTONIUM BURNING

INTRODUCTION

The possibility of burning reactor-grade Pu (~20% ^{240}Pu) in a mixed lattice patterned after the current Mark 14-30 charge was investigated as a means of supplying feed material for production of ^{244}Cm or ^{252}Cf . The major problem in designing a Pu burner charge is to balance the power fractions in driver Pu, driver ^{235}U and targets so as to keep temperature coefficients of reactivity sufficiently negative for stable operation of the charge without imposing a severe limitation on Pu throughput. The investigation described here was a survey calculation, providing only a gross definition of a feasible charge sequence.

SUMMARY

Reactor-grade Pu can be burned satisfactorily in a mixed lattice comprised initially of three Pu fuel assemblies plus three depleted uranium target assemblies per hex. As Pu exposure proceeds, the depleted-uranium target load would have to be lightened, and eventually replaced by enriched uranium fuel, to maintain operable reactivity. If Pu with an initial content of 20% ^{240}Pu , 7% ^{241}Pu , 1% ^{242}Pu were exposed until 75% of the fissionable Pu isotopes were burned, the degree of burnup achieved in the Cm-I charge, the average Pu power fraction would be 0.65, about 40% better than Cm-I. Assuming a reactor power level of 2100 MW and innage of 80%, the corresponding exposure of the Pu assemblies would be about 400 KMWD/reactor year for a throughput of 660 kg(Pu)/reactor year. The ultimate yield of

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such a Pu-burning campaign (requiring a second reactor to carry out the high flux Cm-II type irradiation) would be 100 kg/reactor year of ^{242}Pu (or a mixture of ^{242}Pu and higher isotopes).

Such a Pu-burning program would displace normal Mark 14-30 charges from the present reactor schedule. In the Pu-burning reactor, MWD generated in enriched uranium would be reduced to $\sim 1/4$ and ^{239}Pu production would be reduced to $\sim 1/2$ that of a Mark 14-30 charge.

A summary of the characteristics of such a campaign is given in Table I.

Table I
Summary of Pu Burning Stages

Stage	Previous Pu Exposure, n/kb	No./hex			EU ^{235}U Content, kg	Power Ratio Pu/EU	Temp. Coeff., $10^{-5}\text{k}/^{\circ}\text{C}$
		EU	DU	Vacant			
1	0	0	3	0	-	-	-10^a
2	0.20	0	2	1	-	-	$\sim -10^a$
3	0.43	0	2 ^b	1	-	-	$\sim -10^a$
4	0.70	1	2	0	1.0	1.2	-14
5	1.00	1	2	0	2.4	0.7	-13
6	1.30	1	1	1	0.2	2.9	- 7
7	1.67	1	1	1	0.5	1.3	- 9
8	2.07	1	1	1	1.0	0.7	- 9
9	2.50	1	1	1	1.6	0.5	- 9
10	2.95 ^c	1	0	2	0.4	1.2	- 2

^aCalculated only for the end of stage one

^bRequires Mark 30B rather than Mark 30A

^c3.42 n/kb at end of stage 10

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1. Charge Design

The starting lattice was a Mark 14-30 type mixed lattice using Mark 30-A depleted uranium (DU) targets but with all Mark 14 enriched uranium fuel replaced by Pu fuel in Mark 14 geometry. Each Pu assembly contained 2500 g (Pu), including 20% ^{240}Pu , 7% ^{241}Pu , 1% ^{242}Pu , initially. The 2500-gram content was chosen to provide an initial hot-poisoned buckling of ~ 200 uB. (To manufacture a Mark 14 with 2.5 kg of Pu per assembly requires the use of 20 mil cladding. To use 30 mil cladding would require the Mark 16 or another geometry.)

While lattice reactivity increases during a given target stage, due to buildup of Pu in the DU targets, reactivity drops from stage to stage as the Pu fuel burns up (just as in a normal Mark 14-30 charge). Thus, as Pu exposure proceeds, the DU target load must be reduced and, eventually, enriched uranium (EU) fuel must be added to maintain operable reactivity. These changes in loading take place in the three lattice positions per hex initially occupied by DU targets, i.e., the lattice contains three Pu assemblies per hex at all times.

2. Constraints

The only inflexible constraint on the system is that the temperature coefficient of reactivity be negative to permit stable operation of the charge. A more qualitative requirement is that the Pu power fraction be kept as high as possible to permit the maximum Pu burnup rate. A guideline derived from this requirement is that the power in the individual Pu assemblies should be higher than the power in any other single assembly. Although not a rigid requirement, having any other assembly power higher than the Pu assembly power would necessitate reducing flux in Pu assemblies in order to achieve full reactor power. This would introduce a complicated flow zoning schedule.

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Another guideline is that the Pu exposure should proceed as far as in the Cm-I charge, in terms of fraction of fissionable Pu isotopes burned, before the Pu is discharged. This fraction was .75. The plutonium would then be processed through the 200 Area and refabricated into new reactor assemblies for irradiation in a Cm-II type charge.

3. Approach

The present analysis is a survey, in the sense that a coarse definition of charge composition (number and content of DU targets and enriched uranium fuels) suffices to show whether the Pu could be burned up within the constraints listed in the preceding section. Thus, to simplify the analysis, the only DU targets considered were fresh Mark 30A targets. In fact, the results show that Mark 30A targets would not serve well at all times, and that some lighter (30B or C) DU targets probably should be used. It is also recognized that some charge characteristics such as temperature coefficients and power ratios would be slightly different at stage end from those given here which for the most part are for the beginning of a stage.

Charge characteristics were calculated for each of several patterns of DU targets and EU fuels as functions of Pu exposure. For each loading pattern and Pu exposure, the amount of ^{235}U in the EU fuel required for criticality was derived and then temperature coefficients and power ratios were calculated for this lattice.

A second simplifying approximation was made to estimate the neutron spectrum encountered by the Pu (and hence the Pu reaction rates). The spectrum encountered during the initial target stage was derived explicitly from THOR calculations. The ultimate spectrum was assumed to approach that derived for the Cm-II charge. The interim spectrum was estimated by interpolation between these extremes. The composite spectrum was used in an APE calculation to estimate Pu composition as a function of exposure after the initial stage.

The essential results of the APE calculation are summarized in Figure 1. The ultimate energy yield of the Pu is $\sim .82$ MWD/initial gram of Pu. To burn up 75% of this energy, the exposure goal of the preceding section, requires a Pu exposure of 3.5 n/kb.*

* $1 \text{ n/kb} = 10^{21} \text{ n/cm}^2$

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As stated earlier, one of the major problems is to design the lattice to overcome the tendency toward positive temperature coefficients of reactivity. This characteristic arises primarily from the fact that the effective cross section of ^{240}Pu decreases with neutron temperature while that of fissile ^{239}Pu increases. Presence of other assemblies in the lattice can introduce negative contributions to the coefficient by characteristics inherent in the other assemblies and by interaction of these assemblies with the Pu assemblies.

The inherent characteristic contributing to the negative temperature coefficient is increased resonance absorption in the DU targets both from Doppler broadening of ^{238}U resonances and from decreased moderator density as the moderator temperature rises. The magnitude of this negative effect increases with DU target weight. The inherent coefficient of EU fuel is also negative but small compared to that of the DU targets. The interaction cited above refers to the general tendency to equalize fluxes among assemblies as the lattice heats up. Thus, if $\beta_{\text{Pu}}/\beta_{\text{DU}} > 1$, raising temperature increases DU absorptions relative to Pu absorptions, which makes a negative contribution to the coefficient. But, if $\beta_{\text{Pu}}/\beta_{\text{EU}} > 1$, the contribution to the temperature coefficient is positive. The present survey assesses the combined effects of all these factors.

B. Detailed Calculations

1. Reactivity Levels

The initial lattice was arbitrarily assumed to contain three Pu and three Mark 30A targets per hex. The quantity of Pu per assembly was then derived from the condition that the hot-poisoned lattice buckling be about 200 μB , comparable with the normal Mark 14-30 charge. The calculated values of buckling vs. Pu content, plotted in Figure 2, for the hot clean condition, were used to estimate that a 2500 gram assembly of Pu containing 20% 240 would provide the required buckling when adjusted for the hot-poisoned condition.

As the Pu is burned the target loading must be lightened and, in most cases, enriched uranium fuel added to obtain a hot-poisoned buckling of about 200 μB at the start of a target stage. To find the amount of ^{235}U required in the EU fuel, HERESY calculations were made using a search on control rod thermal utilization (f_{CR}) for criticality. From these results (Figure 3) values of ^{235}U content that yielded $f_{\text{CR}} = .975$ were selected. The criterion of a fixed value of f_{CR} was prescribed to facilitate interpretation of temperature coefficient data, as described in the following section. The derived values of ^{235}U content required to provide a fixed control rod complement at the start of a target stage are plotted as functions of Pu exposure in Figure 4.

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For cases involving vacant lattice spaces the HAMMER's were run with increased pitches to simulate the correct fuel-to-moderator ratios (7.56" for one vacancy per hex, 8.28" for two vacancies per hex).

2. Temperature Coefficients

Temperature coefficients of reactivity were calculated with the combined HAMMER-HERESY code as functions of exposure for each of several complements of DU targets (using the appropriate amount of ^{235}U in EU fuel for each case). The coefficients derived were "total" coefficients, i.e.,

$$\alpha = (k_{\text{hot}} - k_{\text{cold}})/70^{\circ}\text{C},$$

where the hot condition implies 90°C moderator, 60°C coolant, 120°C Pu or EU metal temperature and 200°C Du metal temperature. All cold temperatures were taken to be 20°C.

In calculating temperature coefficients the effects of control rods were included by employing a recipe developed in the Mark XIIA-50 Technical Manual, viz., that

$$(1-f_{\text{CR}}^{\text{hot}}) = 0.9 (1-f_{\text{CR}}^{\text{cold}}).$$

The coefficient calculated at the end of the first target stage was -10×10^{-5} k/°C. As Pu exposure proceeds the coefficient varies widely, depending on DU target loading and Pu exposure. The calculated results, plotted in Figure 5, indicate that the temperature coefficient of reactivity can be kept negative at all times.

3. Power Ratios

Relative powers in different assemblies were calculated from HERESY absorptions plus the fission-to-absorption ratios from DIED. These ratios are plotted as functions of Pu exposure in Figure 6. Figure 7 shows the Pu power fraction, i.e., the ratio of power in three Pu assemblies to total power in the hex.

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4. Pu Exposure

Pu exposure was translated (roughly) from n/kb to other units in two ways. Figure 1 shows MWD/initial g(Pu) as a function of Pu exposure. Total elapsed time can be derived from this Figure. Assuming an initial loading of $258 \times 2.5 = 645$ kg (Pu), an operating reactor power level of 2100 MW, an average Pu power fraction of 0.65, and a reactor innage of 80% yields the result that the Pu would be exposed to the "3/4-point" (3/4 of fissionable isotopes burned up) in 361 days =

$$\frac{(611 \text{ MWD/kg}) \times (645 \text{ kg})}{(2100 \text{ MW}) \times 0.65 \times .80}$$

Still another measure of Pu exposure is provided by finding the corresponding number of DU target stages. The Pu/DU flux ratio was computed from HERESY calculations and is plotted in Figure 8. The calculations showed that flux ratio varied by only about 1% as the number of DU targets per hex was changed. From the flux ratio plus the observation that the average DU target exposure to obtain 6% ^{240}Pu assay plutonium in Mark 14 charges is about 0.38 n/kb, one can derive the number of Pu target stages as a function of Pu exposure. This result is shown in Figure 9.

C. Conclusions

1. Optimum Procedure

The Pu power fraction decreases with exposure for a given DU target loading and increases as the number of DU targets per hex is reduced. Thus, the optimum procedure would be to reduce the number of DU targets per hex at the earliest exposure permitted by the requirement for a negative temperature coefficient of reactivity. Thus, if one were restricted to Mark 30A targets, the irradiation would begin with three DU targets per hex, change to two DU targets per hex in stage 2, change to 1½ DU targets per hex in stage 3, then use two DU targets plus one EU fuel per hex in stage 4. At this point one could operate with one DU target plus 1 or 2 EU fuels per hex until Pu exposure reaches about 3 n/kb (9 target stages) where the last DU target could be removed.

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The path just described would provide a reasonably high average power fraction in the Pu, but the fraction could be increased appreciably if one were not required to follow the "1-DU curve" of Figure 7 for the greatest part of the irradiation. The apparent solution to this problem is to utilize lighter DU targets than Mark 30A. If curves of temperature coefficient and power ratios were sketched intuitively for one Mark 30B target per hex, they would lie between the corresponding curves for zero and one Mark 30A target per hex, which illustrate the possibility of changing to an equal number of lighter weight DU targets before reducing the number of DU targets per hex.

The optimum procedure is therefore to begin with three Mark 30A targets per hex, lighten the target load; go to two Mark 30A plus one EU fuel per hex, lighten the target load; go to one Mark 30A plus one or two EU fuel per hex, lighten the target load; and finally, operate with no DU targets but one to three EU fuels per hex.

2. Pu Throughput

The average Pu power fraction, from Figure 7, is about 0.65. If an average operating power level of 2100 MW and a reactor innage of 80% are assumed, it follows that the Pu could generate 403 KMWD/reactor-year. If the Pu is exposed to the "3/4-point", this corresponds to a Pu throughput of 660 kg (Pu/reactor-year). The product is 240 kg of Pu having an assay of 17% ^{239}Pu , 48% ^{240}Pu , 13% ^{241}Pu and 22% ^{242}Pu . Using fission/absorption ratios of 0.68 and 0.71 for the 239 and 241 isotopes of Pu, respectively, yields an ultimate production rate of about 100 kg of ^{242}Pu and higher mass nuclides per year, but the burnup of the 240 - 100 = 140 kg of Pu requires a second reactor.

If one assumes the remaining 35% of reactor power distributed equally between DU targets and EU fuel this represents a roughly 4-fold reduction in MWD/reactor-year generated in EU fuel compared to a normal Mark 14-30 charge. The reduction in DU target exposure (hence normal Pu production would be roughly twofold.

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3. Flow Zoning

Figure 6 shows that the ratio of Pu assembly power to other assembly powers varies rapidly with Pu exposure. This implies that relative flow to each type assembly will have to be adjusted before each target stage, and over a fairly wide range. Since these ratios vary above and below 1.0 the Pu assemblies themselves will require flow restricting orifices in some cases. Thus, careful study will be required to devise flow zoning schedules to provide reasonably high reactor power levels.

D. Program

The work discussed in this report is sufficient to "rough in" a program for burning plutonium. Further work is required to improve the definition of problem areas and to develop better estimates of production capability. A program aimed at these improvements is as follows:

1. Further define the target and ^{235}U fuel stages
 - o Calculate approximate reactor power distributions and flow zoning requirements
 - o Estimate reactor power capability
 - o Improve the estimates of production.
2. Examine safety problems
 - o Evaluate the loss-of-target incident at points throughout such a campaign
 - o Calculate reactivity coefficients
 - temperature (this report goes only far enough to assure that they can be made negative)
 - H_2O addition
 - Void
 - o Worth of components during C & D
 - o Evaluate stability and xenon effects.

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3. Examine cost optimization

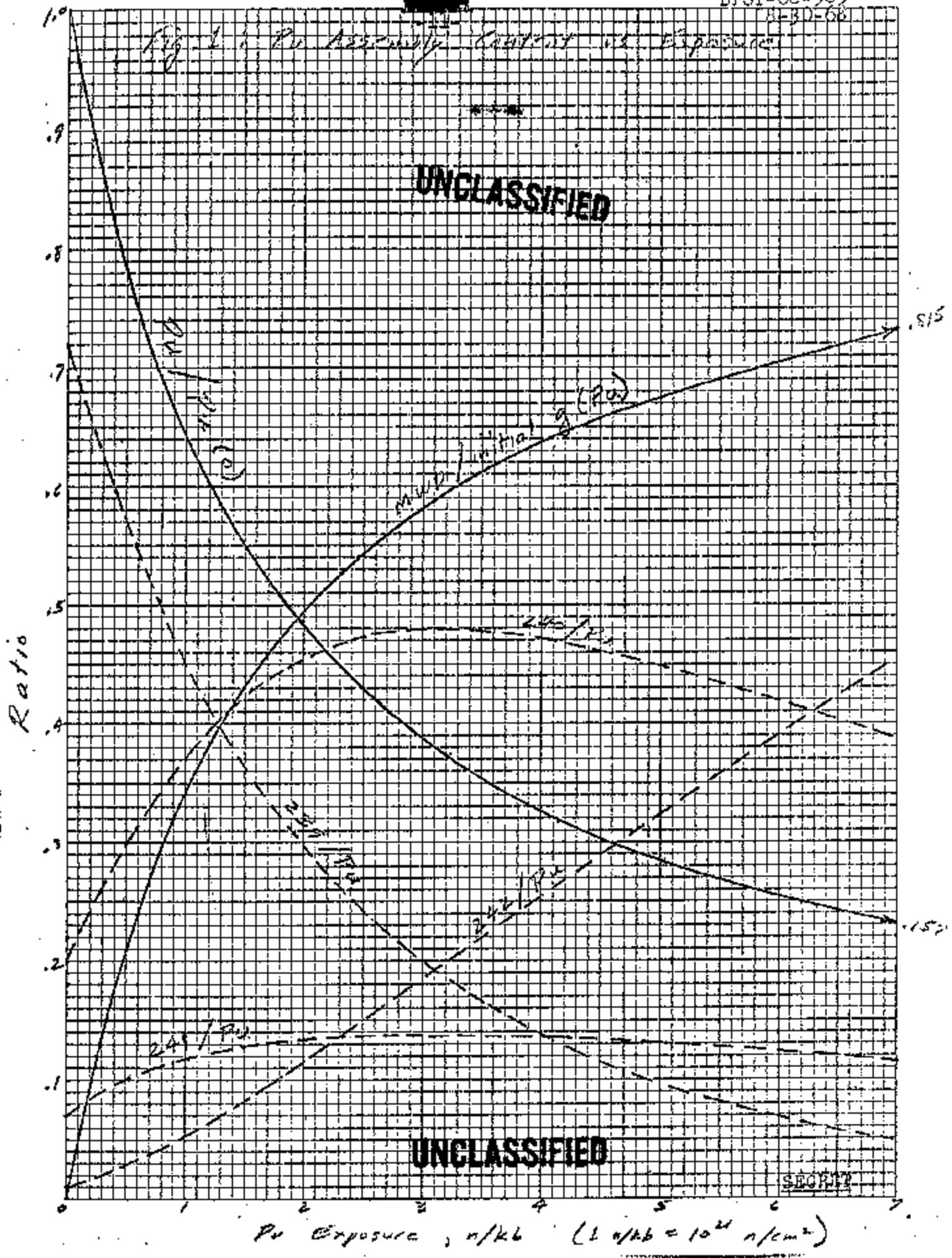
- o Select program objective (product - 244Cm or 252Cf -, and time scale)
- o Determine cost as a function of fractional Pu burnup in the first phase.

At this time it is assumed that this program will be given a low priority and that work on the design of Mark 16-30 charges will take precedence. Detailed design of a Pu burning campaign can not be started in any case until an actual production commitment is made because the details are sensitive to the starting assay of the plutonium to be burned.

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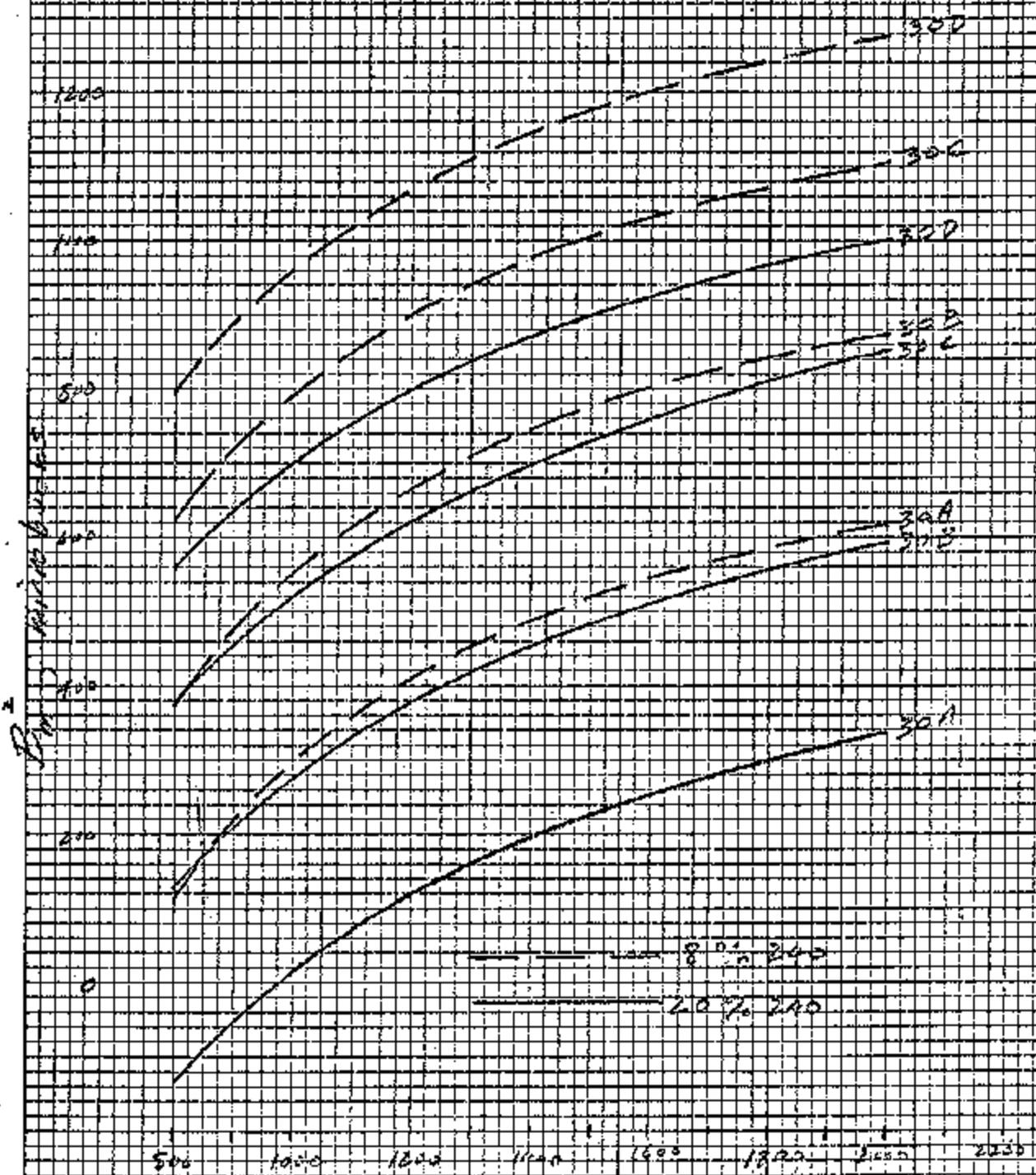
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Fig. 1. Pu Assembly Content vs. Exposure



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Target
Mark How



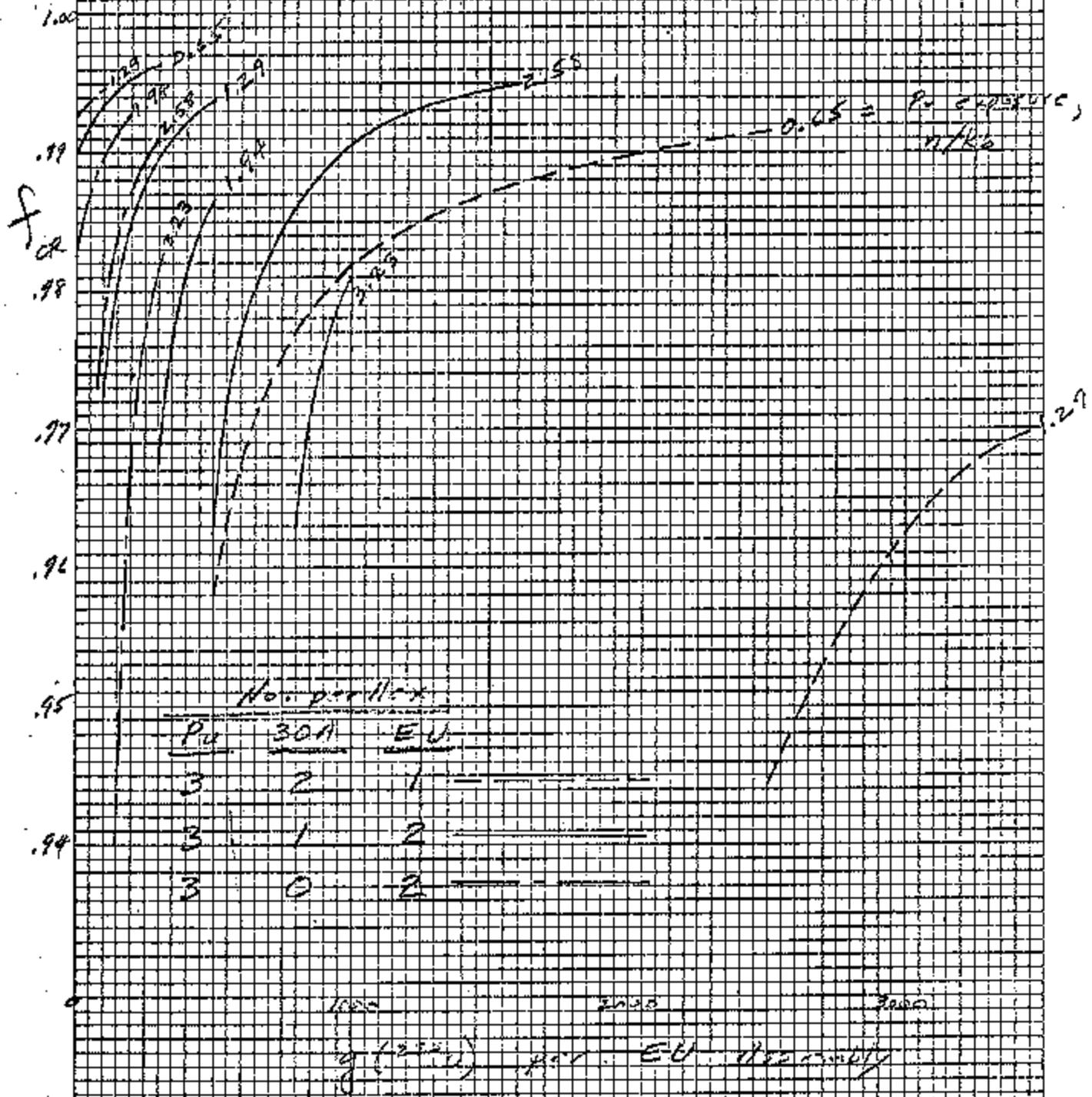
g (Pu) per Assembly

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Fig. 2: Hot-Clean Buckling of Pu:DU FZ Lattice

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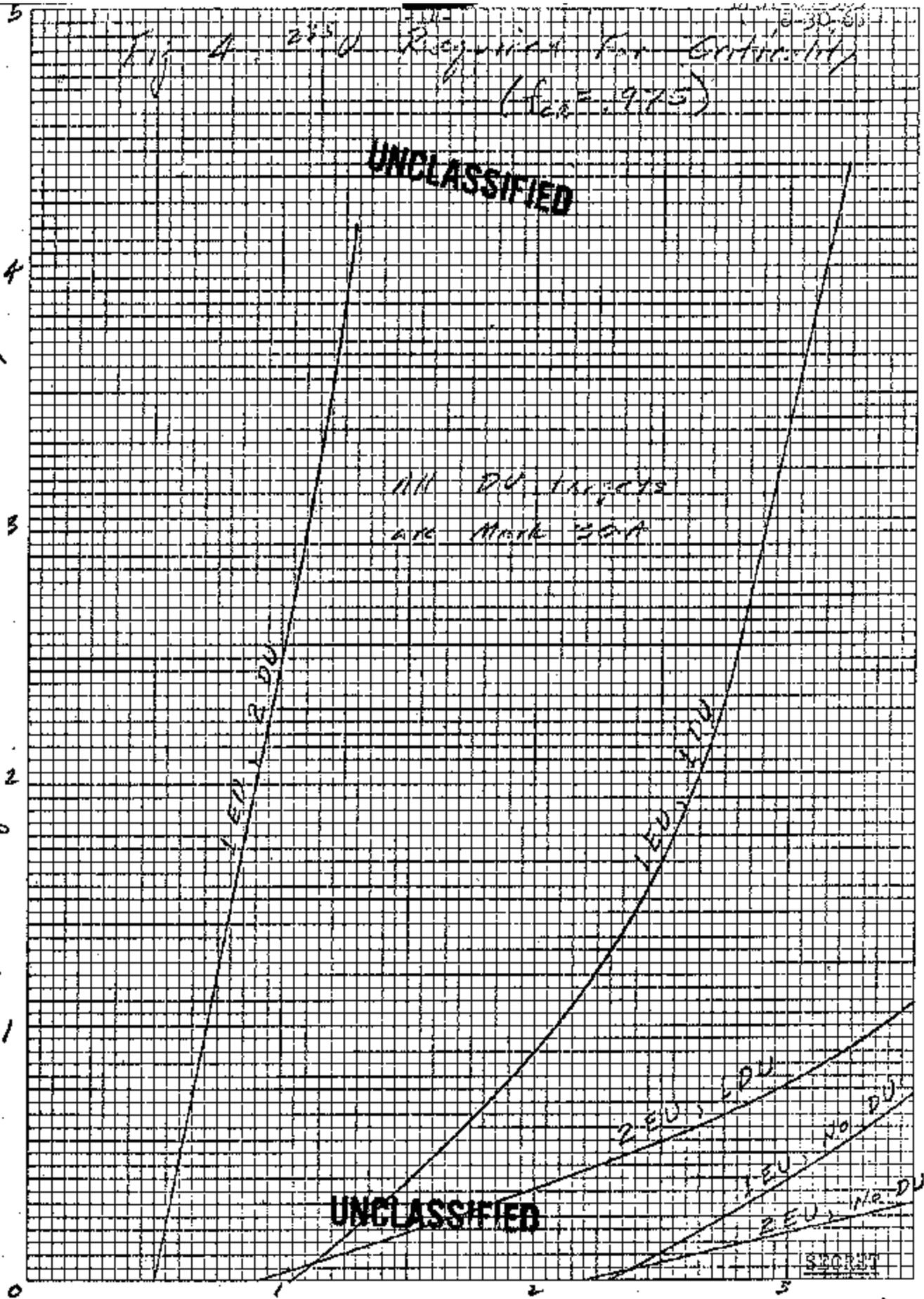
Fig. 3: Thermal Utilization (HEREST) of Control Rods Required For Criticality

EUROPE GIEZBEN CO.
MADE IN U.S.A.

NO. 341-10 DIETZBEN DRAWING BOARD
10 X 10 PER INCH

Kg (235U) per EW Assembly

Fig 4. 235U Requirement for Criticality
(Apr. 1975)



Pu Exposure, n/kb ($1 \text{ n/kb} = 10^{21} \text{ n/cm}^2$)

NO. 341-10 DIETZGEN GRAPH PAPER
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EUGENE DIETZGEN CO.
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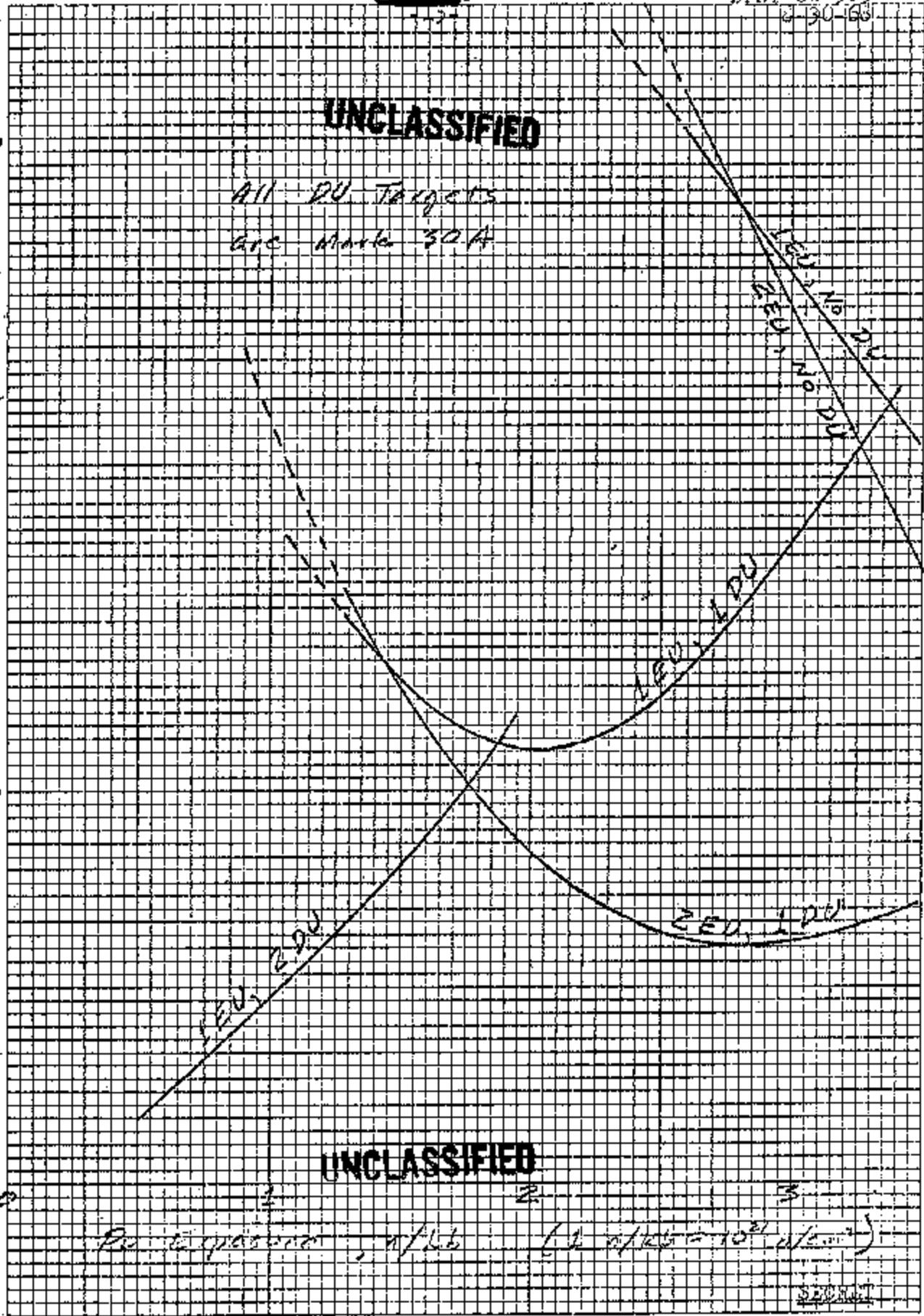
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All DU Targets
Arc Mark 30A

Temperature Coefficient, units of $10^{-5} \text{ K}/^{\circ}\text{C}$

0
-2
-4
-6
-8
-10
-12
-14



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Pressure, n/lb (1 n/lb = 10^{21} n/cm²)

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Fig. 5: Temperature Coefficients

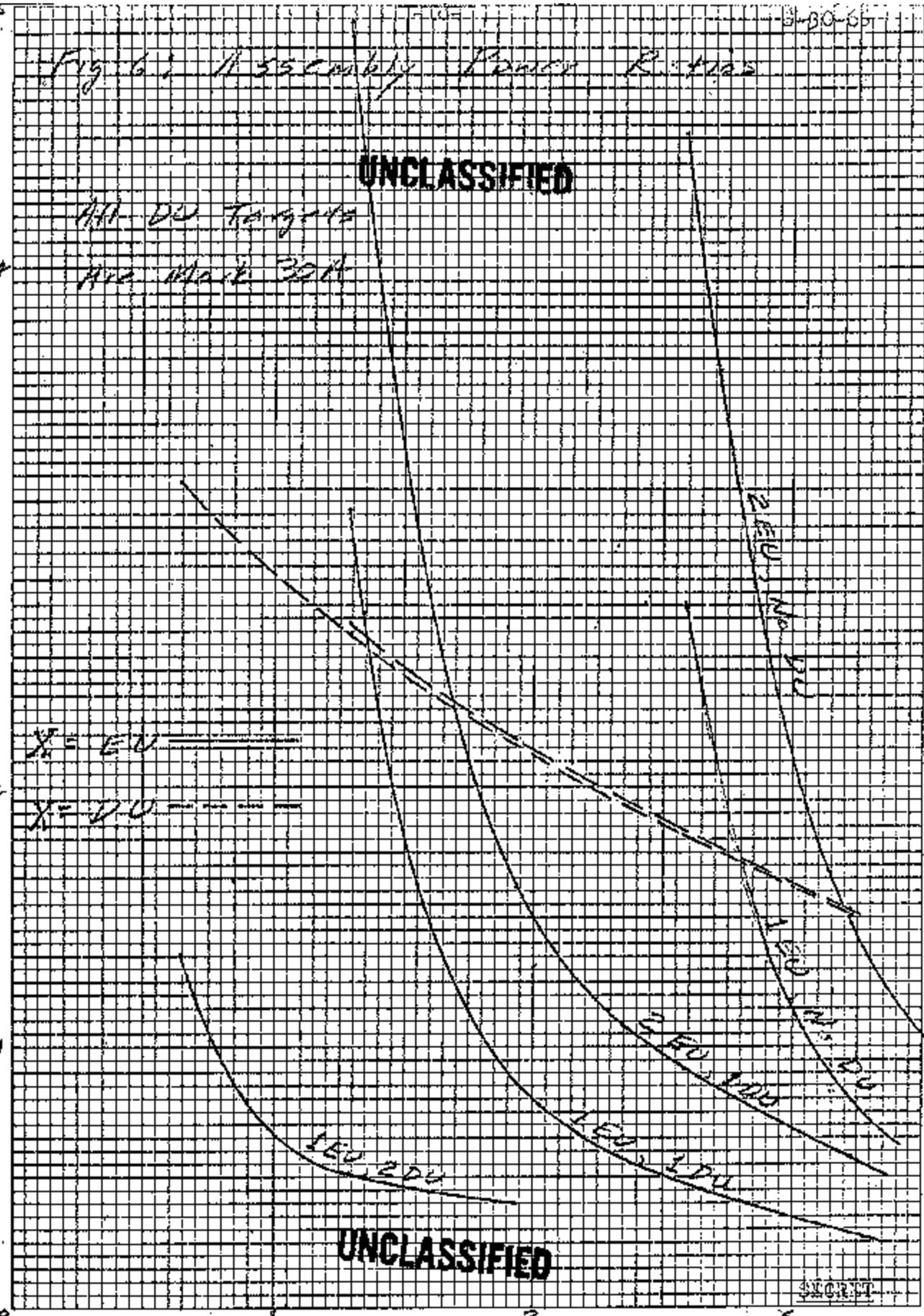
Assembly Power Ratio, P_u/X

Fig 6: Assembly Power Ratio

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HP DU Target
Ave Mark 30M

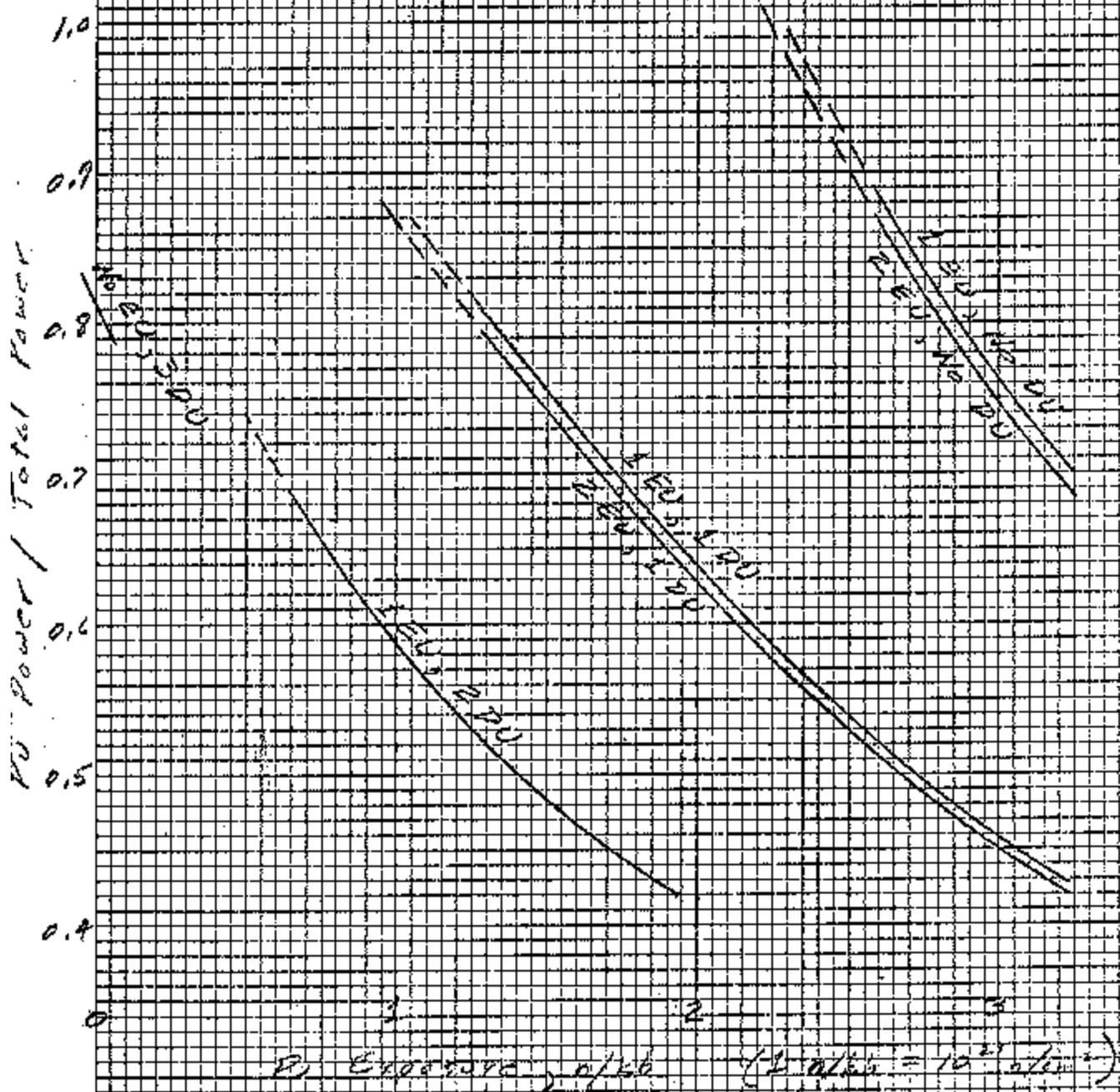
$X = EU$ ———
 $X = DU$ - - - -



P_u Exposure, n/kb ($1 n/kb = 10^{21} n/cm^2$)

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All Pu targets
are made 30.4



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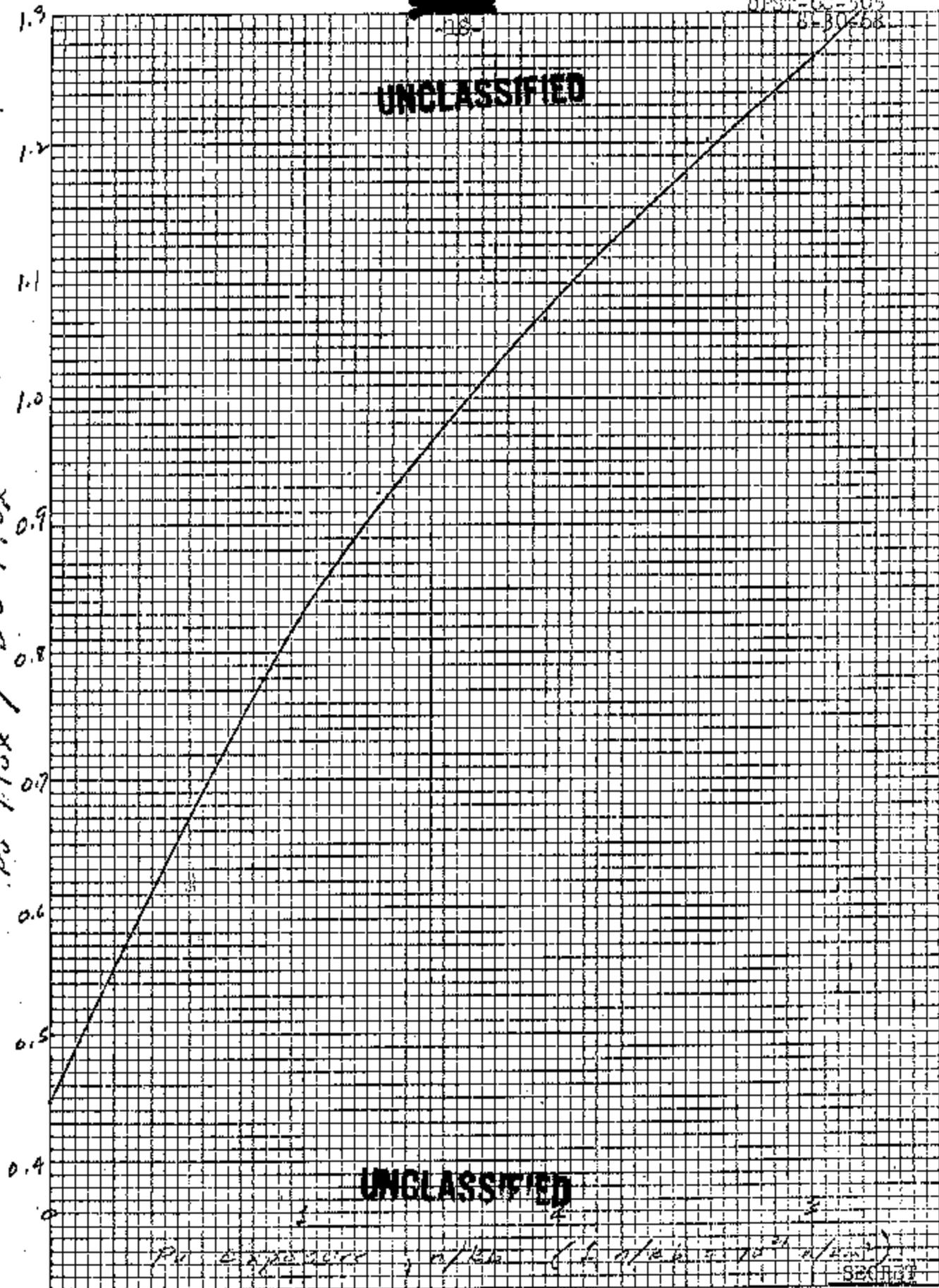
Fig. 7: Fraction of Reactor Power Generated in Pu

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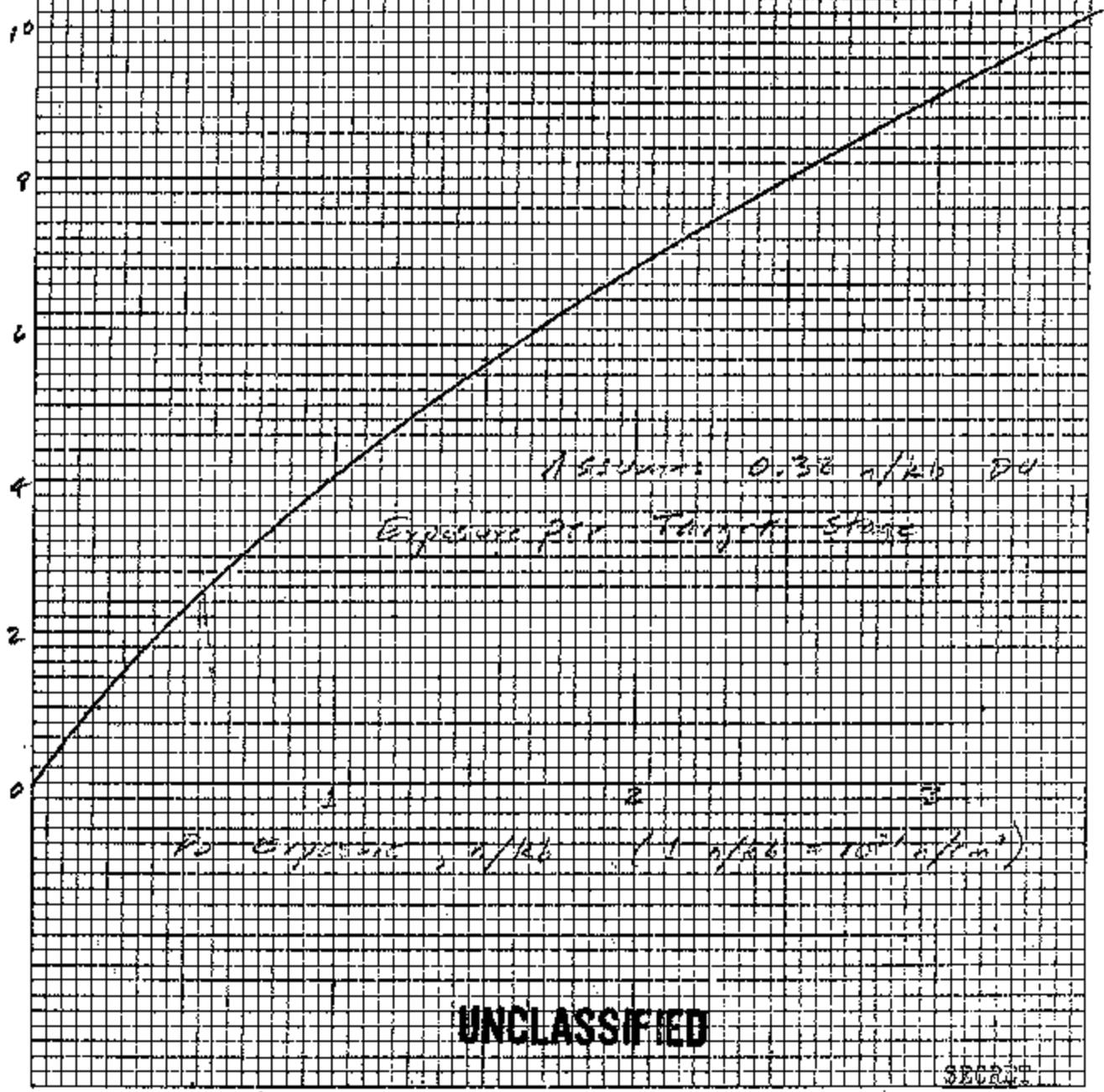
$Pu \text{ Flux} / Pu \text{ Flux}$



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Fig: 8 : Relative Thermal Flux in Pu and Mark 30A

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Fig. 9: Pu Exposure in Terms of No. of DU Target Stages

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