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FROM: J. A. SMITH *jas*

244 Cm IN RESONANCE REACTORS

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By: *P.T. O'Malley*

Date: *12/17/73*

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INTRODUCTION

An investigation of curium production in a resonance reactor indicated that such a program is feasible although no explicit reactor design or operating procedure was devised before the preliminary study was completed. Details of the study are collected here as a basis for future studies.

SUMMARY

A resonance reactor (one with a fuel-to-moderator volume ratio on the order of 1) could be operated with plutonium fuel to make ²⁴⁴Cm. A continuous production program could be maintained in a single resonance reactor, where two different reactors, operating simultaneously, would be required to maintain a comparable continuous program with thermal reactors (low flux to burn ²³⁹Pu and high flux to burn ²⁴²Pu). The ratio of capture-to-fission reactions in the Pu isotopes is greater in a resonance reactor, providing an advantage on the

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order of 10% in equilibrium conversion ratio ($\frac{C_{m, out}}{Pu_{in}}$) over a thermal reactor system. The present study did not establish whether the resonance reactor has any advantage over a thermal system in capacity for burning Pu (primarily ^{239}Pu). If both resonance and thermal systems were restricted to a single reactor, the resonance system would have an advantage in the rate of approach to equilibrium because the relative cross section of ^{242}Pu is large enough to avoid the bottleneck that occurs in the thermal system. This advantage can be overcome, however, by using two reactors in the thermal system.

Results of the study are summarized in Figure 6.

DETAILS

A. Scope of Calculations

When this study began, a uranium-fueled resonance reactor had been proposed for production of ^{238}Pu , and the problem was to assess the feasibility of substituting Pu for U fuel to make curium instead of neptunium. As the study proceeded, the mechanical design proposed for the U-fueled resonance reactor underwent a series of revisions and the design considered here was revised accordingly. Thus, initial calculations were done for a displaced-moderator design: nominally Mark VIB-type fuel assemblies on a 7" triangular pitch with 80% of the moderator displaced by aluminum. This was replaced by a flat plate design (1:1 fuel-to-moderator volume ratio) and this, in turn, by a close-packed tube design (6" OD assemblies on a 6.25" triangular pitch).

Physics characteristics and, in particular, relative cross sections were derived from HAMMER calculations. Changes in composition were calculated either by hand or with the GOSPEL code, using constant cross sections. For cases in which cross sections changed appreciably during irradiation, a series of exposure intervals was used with different constant cross sections for each interval.

A standard assay of input Pu was assumed for all problems, namely, 239:240:241:242::1:.11:.025:.00218, i.e., nominally 10% ^{240}Pu .

B. All-Pu Reactor

The first problem considered was operation of a reactor on Pu fuel alone. The displaced-moderator design was assumed with a fuel assembly with an initial content of 1.5 kg of ^{239}Pu over a 10-ft length. The calculated change in composition of such an assembly with exposure is illustrated in Figure 1. Corresponding data calculated for the Curium-I irradiation is superposed for comparison. The most conspicuous differences are lower ^{240}Pu and higher ^{242}Pu in the resonance case, both due primarily to a higher relative cross section for ^{240}Pu .

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Temperature coefficients of reactivity were calculated at a series of exposures (up to 80% burnup of the ²³⁹Pu) for the 1.5 kg per assembly design, as well as for the zero exposure level in a slightly heavier design (1.75 kg per assembly). Both coolant and moderator temperature coefficients were negative in all cases considered and small in magnitude. For example, at 40% burnup of the ²³⁹Pu, $\alpha_c = -2 \times 10^{-5}$ and $\alpha_m = -4 \times 10^{-5}$ k/°C. These numbers are based on

$$\rho = \frac{\Delta k_{\infty}}{k_{\infty}(H)} * \frac{1 + M_H^2 B_g^2}{1 + M_C^2 B_g^2} - \frac{B_g^2 \Delta M^2}{1 + M_C^2 B_g^2}$$

where C and H refer to cold and hot; $\Delta X = X_H - X_C$; $B_g^2 = 70 \mu B$ (flat zone only). In all cases, both the Δk term and the ΔM^2 term were negative.

It was assumed that the all-Pu resonance reactor would be operated in a series of short cycles defined by the reactivity lifetime of the core. The core would be comprised of several batches of Pu fuel in various stages of exposure. A batch of fresh Pu would be charged each cycle with the expectation that adding fresh Pu frequently would maintain reactivity at satisfactory levels as nonfissile heavier isotopes build in. As the cross section data reviewed in Section D show, this problem is more severe in a resonance reactor than in a thermal reactor.

Superposed on the series of reactivity cycles would be another longer term periodicity due to chemical reprocessing of the Pu. Thus, the first "generation" of cycles would include only fuel that had never been reprocessed. The second generation would include once-reprocessed Pu, the third generation twice-reprocessed Pu, etc.

The time schedule for a reactivity cycle is determined entirely from reactor operating characteristics. The time schedule for a generation of reactivity cycles is determined primarily by the reprocessing interval, the major part of which is an assumed six months cooling period between discharge from the reactor and processing through the 200 Area. These points are illustrated quantitatively below.

Consider the first generation (no reprocessed Pu). Assuming equal flux in all batches makes power proportional to

$$\sum_1 N_1 \sigma_1^F$$

and reactivity proportional to

$$\frac{\sum_1 N_1 \sigma_1^F \nu_1}{\sum_1 N_1 \sigma_1^A}$$

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A given number of batches and a given one-cycle exposure of the first batch determine the operating characteristics of the mixed core. Reactivity at cycle-end is plotted versus first-batch exposure in Figure 2 for up to six batches in the core. Absorptions in fission products and structural material, derived from HAMMER calculations, were included. In the curves of Figure 2, cycle-end is defined by the arbitrary choice of first-batch exposure. In practice, cycle-end would be determined by some minimum reactivity required for criticality. Using a typical M^2 value of 660 cm^2 from HAMMER and an assumed B_g^2 of $200 \mu\text{B}$ gives a minimum k value of 1.13. This requirement and the curves of Figure 2 then determine the exposure of the first and all succeeding batches. Exposure of the last batch, the one discharged each cycle, is illustrated in Figure 3. Characteristics of interim batches in the six-batch case are illustrated in Table I.

A full charge would contain $516 \times 1.53 = 790$ initial kg of ^{239}Pu . Using data from Table I, the reactor exposure of a single reactivity cycle is $\frac{790 \text{ kg} \times 238 \text{ MWD/kg}}{6} = 31.3 \text{ KMWD}$. Also, the average batch power is 88% of the initial batch power so the one-cycle operating time is $\frac{31.3 \text{ KMWD}}{.88 \times 2400} = 15$ days. With allowance for charge/discharge and unscheduled shutdowns, a single reactivity cycle should require about 19 days.

To keep batch power up in the second generation, four first-generation batches would be combined to make three second-generation batches. Allowing something on the order of three months reprocessing time plus six months cooling yields the generation time schedule shown in Table II.

In the second generation, the core would consist of three unprocessed batches plus three once-processed batches. Exposure of the fresh Pu batch could be increased from 45 to 52 MWD/kg (cycle time increased from 19 to 25 days) because of the slower reactivity transient in second generation Pu. In spite of this, however, the final exposure of unprocessed Pu would be less than in the first generation because it would be exposed for only three cycles instead of six. Similarly, in the third generation, with two batches each of unprocessed, once-processed, and twice-processed Pu, final exposures of both unprocessed and once-processed Pu will be less than in the preceding generation, and so on. Numerical values estimated for the first three generations are listed in Table III.

The total quantity of americium plus curium discharged from the reactor during the first three generations would be about 69 kg which is less than that produced in the thermal case described in Section E in the same time period.

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The type of operation described here is doomed to fail because the exposure per cycle is so short that Pu is being charged faster than it can be burned up. The reactor power level can accommodate about 700 KMWD per year which is equivalent to about 700 kg of ^{239}Pu input per year. But, in the case illustrated, fresh Pu was being charged at a rate of one batch per cycle = 15 batches per year = 2000 kg per year. This situation could be avoided by spiking, i.e., by devoting some fraction of reactor power ($\sim 50\%$) to a fuel (either ^{239}Pu or ^{235}U) that maintains reactivity but is not required to burn up completely. The remaining reactor power could then be devoted to complete burnup of 300-400 kg of ^{239}Pu per year.

C. Uranium Spiked Reactor

1. Approach

In switching to the plate design of the resonance reactor, uranium was added on the basis of experience with the displaced-moderator design. The approach used was to consider a case in which the Pu and Trans-Pu nuclides were in equilibrium because the need for uranium spiking should be greatest in this case. The procedure was therefore to define a consistent set of starting and ending Pu compositions, run HAMMERS to get the amount of lithium (at the start) or uranium (at the end) required, and finally to deduce the average fraction of power generated in the Pu. Only one such set of calculations was done for the plate design before switching to the close-packed tube design and the estimated equilibrium compositions proved incorrect for this run. Still, the same data were used to investigate the H_2O addition problem so the plate reactor data is included in this Report.

2. Plate Reactor

The plate design consisted of flat plates with 0.08" cores and 0.02" cladding separated by 0.08" coolant channels. Plutonium was included in two plates out of three - the third containing aluminum and lithium or uranium. Pu was assumed charged at the casting limit of 1.3 grams/cc which results in a fuel loading of about 10 kg of Pu per cubic foot of core volume. Uranium, if added at the same gram per cc, would be present at an average density of 5 kg per cubic foot of core volume.

For equilibrium the differences between starting and ending compositions of the Pu must be equal to the amount of fresh Pu charged each cycle. In the present case this is assumed to be one unit of ^{239}Pu plus proportionate units of the higher Pu isotopes as itemized in Section A. The actual values used for starting and ending composition were derived from an extension of the calculations for the displaced-moderator case and are summarized below:

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<u>Pu Isotope</u>	<u>Start</u>	<u>End</u>
239	1.107	0.107
240	0.183	0.073
241	0.176	0.151
242	0.314	

The assumed compositions proved inconsistent with the cross sections derived from HAMMER calculations but the data are included for such information as they may convey. HAMMER results for D₂O cases are summarized in Table IV, and those for H₂O cases in Table V.

The geometric buckling of a plate reactor of the size contemplated by designers of the ²³⁸Pu-producing plate resonance reactor was on the order of 700 μB. Thus, the estimated amounts of lithium required at the start and uranium required at the end are both too low. Addition of more uranium would reduce the final Pu power fraction below the value of 0.4 indicated in Table IV, which means that the cycle average Pu power fraction must be something less than 0.7. The H₂O buckling values indicate several things. First, the very large increase from D₂O to H₂O implies that some special precautions will be required to maintain control if emergency addition of H₂O to a D₂O reactor is required. This is also the case for a resonance reactor fueled with uranium. The second point is that lithium is required to maintain proper reactivity even at cycle end, which implies that operation with only Pu fuel (no uranium spikes) may be possible if the reactor is operated on H₂O coolant. The third observation is that lithium is a much more effective absorber in the H₂O lattice. The basic reason for this is the general shift of absorptions from epithermal toward thermal neutron energies in the H₂O reactor. This is illustrated in some detail in Table VI. Another consequence of this shift toward a more thermal reactor is the change in relative cross sections. Note in particular that the ratio of ²⁴²Pu cross section to ²³⁹Pu cross section drops to about 0.1, which means that ²⁴²Pu would again constitute a bottleneck in the curium production chain. Also, the ratio of capture-to-fission increases toward levels characteristic of normal thermal D₂O reactors. This point is treated in more detail in Section E.

3. Close-Packed Tube Reactor

The tubular reactor design considered here consisted of 6" OD assemblies on 6.25" pitch, with interstitial control. (Later work with the ²³⁸Pu resonance reactor revised this design to 4" assemblies with control displacing some fuel positions.) Actual dimensions of the assembly are listed in Table VII. In this design plutonium was included in two-thirds of the assemblies with lithium

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or uranium included in the remaining one-third. To account for this in HAMMER problems the pitch was increased to 7.65" ($6.25 \sqrt{3/2}$). The region outside the fuel assembly was a homogenized mixture of aluminum and D₂O (75 vol % Al) and the active materials intended for the other assembly (Li, U) were included in the Pu assembly.

The initial ²³⁹Pu inventory included was 620 kg distributed among 120 6-foot assemblies. With this design, equilibrium contents were found for the case in which the fresh Pu charge is burned to a level of 900 megawatt days per initial kg (²³⁹) or 90% burnup of the ²³⁹. This was done by trial and error, i.e., compositions were assumed, HAMMERS run, cross sections derived, compositions recomputed, etc. The changes in composition with exposure for this case are illustrated in Figure 4. In the process of these calculations, it appeared that cross sections were relatively insensitive to composition so a code was written to derive equilibrium contents for other values of the percent burnup of ²³⁹ in the fresh Pu using the same set of constant cross sections derived for the case illustrated in Figure 4. The resulting equilibrium concentrations are plotted in Figure 5. HAMMER data for a series of exposures in the case illustrated in Figure 4 are listed in Table VIII. In these cases, the material buckling is held reasonably close to the required value of 700 μB so the associated data may be considered realistic. In particular, the Pu power fraction is seen to vary approximately linearly during the cycle from 100% at the start to about 20% at the end, for an average of 60%.

One other situation was calculated with the close-packed tube design, i.e., a core with the starting inventory of ²³⁹Pu decreased from 620 to 400 kg. The HAMMER data (Table IX) show that uranium would be required to raise the buckling even at the start, which implies that the average Pu power fraction is somewhat sensitive to Pu inventory.

D. Neutron Economy

The ultimate conversion ratio of Pu to curium is governed by the fractional loss to fission at each step of the irradiation. These fractions are listed for several of the resonance reactor cases calculated here in Table X, along with some thermal reactor cases calculated expressly to provide this comparison. The thermal reactor cases include a series of different weight assemblies intended to show the effect of hardening spectrum within the range ordinarily subtended by thermal reactor cases. Two sets of values are included for the Cm-I thermal case. The one labeled "HAMMER results" represents the mean of HAMMER data calculated for compositions corresponding to start and end of the Cm-I irradiation. The data labeled "BURNUP" are derived from the burnup code calculation used to predict contents at the end of Cm-I. The burnup results agree well with experience (cross section data having been deduced

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from experience with transplutonium campaigns I and II). It follows that the cross sections now built into the HAMMER code, notably those for ^{241}Pu , are inconsistent with this experience. (Improved cross section data have become available recently and should be utilized in any future studies of this problem.) Still, the trend indicated within the framework of all HAMMER data (less fission in resonance reactors) is expected to hold true.

Neutron absorption and production have been calculated for a hypothetical equilibrium case in which the input Pu is burned completely to ^{244}Cm , assuming no absorptions in ^{244}Cm , no fission in ^{243}Am , and fission in Pu as indicated in Table X, with an average of 2.95 neutrons produced per fission. The coefficients used to calculate actinide absorptions are itemized in Table XI. Absorptions for a 10% ^{240}Pu input (Section A) are listed in Table XII. Also included are absorptions in structural material (for the resonance case) derived from typical absorption ratios observed in HAMMER calculations. The last item to be included in the neutron economy table is fission product absorption. The "saturating" fission product (^{135}Xe , ^{149}Sm , ^{151}Sm , ^{105}Rh) all have very large thermal absorption cross sections so they always absorb neutrons at a rate equal to their yield times the fission rate. The combined yield of the fission products itemized is about 0.14 for ^{239}Pu fission. Thus, the number of absorptions in saturating fission products is equal to 0.14 times the number of fissions in thermal reactors. In the absence of explicit knowledge otherwise, it is assumed that the same holds true for a resonance reactor. (In any future study this assumption should be re-examined.) The remaining fission products, the "nonsaturating" type, may be considered to form but not burn up, i.e., when one product absorbs a neutron it forms a new product with the same cross section. Thus, the number of fission products present at any time is equal to the cumulative number of fissions. Then absorptions in fission products are equal to

$$\int (\text{No. Fiss.}) * \sigma_{FP} \phi * dt.$$

This expression can be evaluated explicitly by assuming a constant fission rate in the resonance reactor and in the ^{239}Pu burning phase of a thermal reactor case. For the high flux phase of a thermal reactor case, it may be assumed that power stays constant for some fraction, f, of the time (25-30%) and then drops abruptly to zero. With these assumptions, absorptions in fission products may be expressed as a function of total number of fissions as follows:

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$$\text{In Res. Rx: Abs(FP) = } \frac{1}{2} \sigma_{\text{FP}} \phi t * (\text{No. Fiss.})$$

$$\text{In Th. Rx: Abs(FP) = } \frac{1}{2} \sigma_{\text{FP}} \phi_{\text{I}} t * (\text{No. Fiss.})_{\text{I}}$$

$$+ (1 - f) \sigma_{\text{FP}} \phi_{\text{II}} t * (\text{No. Fiss.})_{\text{II}}$$

The expression $\sigma_{\text{FP}} \phi t$ may be evaluated conveniently as the product of $\frac{\sigma_{\text{FP}}}{\sigma(^{239}\text{Pu})}$, which is read directly from the HAMMER printout (the fission product included being nuclide No. 3 on the HAMMER tape) and $\sigma(^{239}\text{Pu}) \phi t$ which may be deduced from ^{239}Pu burnup during the irradiation cycle. Thus, in the resonance reactor case, $\sigma_{\text{FP}}/\sigma_{49} = 0.24$ and, with relative start and end concentrations of ^{239}Pu equal to 1.107 and 0.107, $\sigma_{239} \phi t = 2.33$. In the thermal reactor case, $\sigma_{\text{FP}}/\sigma_{49} = 0.05$. Assuming the ^{239}Pu burning phase would be cut off at 750 MWD/1 kg as in the Cm-I charge, the $\sigma_{239} \phi t$ value during this phase would be about 2.6. In the high-flux phase, $\sigma_{239} = 1000$ barns and $\phi t = 20$ n/kb so $\sigma_{239} \phi t = 20$. Thus, the total number of fission product absorptions is approximately the same in both resonance and thermal cases. These data are entered in Table XII.

From the sum of neutrons absorbed and neutrons produced, itemized in Table XII, one can deduce the net number of neutrons available for production of other nuclides, such as tritium production in control rods. Observe that the net number available in the resonance reactor cases is negative, implying that this mode of operation is not possible without uranium spikes.

E. Explicit Comparison of Resonance and Thermal Reactor Cases

Most of the preceding calculations and results have been indicative of production rates during an equilibrium situation. For any program of practical importance, the approach to this equilibrium must take only a few years. In any of these programs, the principal obstacle to approaching equilibrium is ^{242}Pu , the nuclide with the smallest cross section. In most resonance reactor cases, this cross section is less than that of ^{239}Pu by a factor of about 3, while in thermal reactor cases the ratio is about 20. The factor of 3 provides a satisfactory approach to equilibrium but the factor of 20 requires separate high and low flux phases in the thermal reactor case, i.e., to allow ^{242}Pu burnup to keep pace with ^{239}Pu burnup.

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The other major factor governing production rates is the rate of input of fresh Pu. It was demonstrated in the resonance reactor calculations that this would be limited by reactivity considerations which require some minimum fraction of reactor power to be generated in uranium spikes. Although not considered explicitly, some similar limit may exist for thermal reactors. In the present comparison, rather than beg the question in favor of one type reactor or another, the input Pu was assumed to be the same for both reactors, i.e., 400 initial kg of ^{239}Pu per year. Thus, Pu would generate about 400 KMWD per year in the resonance reactor case, about 300 KMWD per year in the ^{239}Pu -burning phase of the thermal case, and about 100 KMWD per year in the high-flux phase.

All batches of Pu were assumed to be in the reactor one year and then out one year for reprocessing. All Pu and americium was recycled. Conversion ratios for the resonance reactor case were those used earlier in the displaced-moderator design. Data for the thermal reactor case were taken directly from BURNUP code calculations for the 3 kg curium program and then scaled up in the ratio of the equilibrium yield according to HAMMER data given in Table X. In the resonance reactor case, the one-year exposure corresponds to 90% burnup of the initial ^{239}Pu (750 MWD per initial kg). In the thermal reactor case, the ^{239}Pu -burning phase proceeds to 91% burnup of the ^{239}Pu (750 MWD per initial kg), while the high-flux phase is assumed to accumulate 20 n/kb exposure per year.

Results were calculated in terms of total quantity of transplutonium nuclides produced per unit input of ^{239}Pu (still assuming input Pu to be of the assay described in Section A). Results are plotted in Figure 6, once assuming resonance and thermal cases to start up at the same time and again for a thermal case that begins three years earlier than the resonance case. The results indicate that a resonance reactor would have an advantage measured in tens of percents for equal startup dates but this advantage could be overcome by starting the thermal reactor earlier. In view of developments required for the resonance reactor case, a three-year earlier startup for an already demonstrated thermal operation seems quite reasonable.

JAS:shb

TABLE ICHARACTERISTICS OF 6-BATCH, FIRST-GENERATION REACTOR CHARGE

<u>Batch</u>	<u>Point in Cycle</u>	<u>MWD/1 kg (239)</u>	<u>Relative Values</u>	
			<u>$\Sigma \sigma^F$</u>	<u>$\Sigma \sigma^A$</u>
1	Start	0	1.00	0.81
1	End	45.0	0.95	0.79
2	End	87.8	0.90	0.77
3	End	128.4	0.85	0.75
4	End	166.9	0.81	0.725
5	End	203.3	0.77	0.705
6	End	238.0	0.73	0.68

TABLE IISCHEDULE FOR OPERATION OF CHARGE FUELED ONLY WITH Pu

<u>Elapsed Time</u>		<u>Operation</u>
<u>Mo.</u>	<u>Cycles</u>	
0		Start reactor with fresh Pu (first generation)
3.8	6	First reactor-batch discharged
6.3	10	First separations-batch (4 reactor batches) discharged
12.7	20	Start separations
16.5	26	Start second generation in reactor
33	46	Start third generation in reactor

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TABLE IIICHARACTERISTICS OF CHARGE FUELED ONLY WITH Pu

	<u>1st Generation</u>	<u>2nd Generation</u>	<u>3rd Generation</u>
Days/cycle	19	25	25
Cycles/generation	26	20	20
Mo/generation	17	17	17
<u>No. of Batches</u>			
Un-reprocessed	6	3	2
Once-reprocessed	0	3	2
Twice-reprocessed	0	0	2
<u>MWD/1 kg at Discharge</u>			
Un-reprocessed	238	147	103
Once-reprocessed	-	238 + 141	147 + 83
Twice-reprocessed	-	-	379 + 81

TABLE IVHAMMER DATA FOR PLATE REACTOR CASES WITH 60°C D₂O

	<u>"Equilibrium" Cases</u>				<u>Fresh Pu Conc.</u>	
	<u>Start of Cycle</u>		<u>End of Cycle</u>			
<u>Loading</u>						
kg (Pu)/ft ³ *	9.8	9.8	3.5	3.5	6.3	6.3
kg (²³⁵ U)/ft ³	0	0	0	2.9	0	0
g (⁶ Li)/ft ³	0	160	0	0	0	160
<u>Reactivity</u>						
B ² , μB	2390	1164	-1181	83	2035	586
k	1.502	1.211	0.737	1.017	1.486	1.115
L ² , cm ²	3	2	12	8	4	2
τ, cm ²	194	179	246	210	220	197
<u>Pu Power</u>						
Total Power				0.40		
<u>Relative σ's</u>						
239A	1	1	1	1	1	1
239F	.61	.61	.59	.59	.62	.61
240A	.87	.68	1.07	.86	1.58	.91
240F	.030	.032	.008	.016	.023	.025
241A	1.51	1.41	1.18	1.17	1.71	1.54
241F	.93	.84	.74	.70	1.09	.94
242A	.335	.31	.25	.26	1.20	.72
242F	.031	.032	.008	.016	.023	.025
235A				.67		
235F				.46		
⁶ Li		.40				
<u>Abs./1000 n</u>						
Mod.	3.3	3.2	3.9	3.6	3.3	3.5
A1	11.4	11.8	26	16	14.0	14.1
FP			515	246		

*Distribution of Pu isotopes is given in Section C.2 for the "Equilibrium" cases and in Section A for fresh Pu.

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TABLE VHAMMER DATA FOR PLATE REACTOR CASES WITH 60°C H₂O

<u>Loading</u>	<u>Start of Cycle</u>		<u>End of Cycle</u>	
kg (Pu)/ft ³ *	9.8	9.8	3.5	3.5
kg (²³⁵ U)/ft ³	0	0	0	2.9
g (⁶ Li)/ft ³	0	160	0	0
<u>Reactivity</u>				
B ² , μB	6660	1330	1690	3390
k	1.464	1.083	1.123	1.237
L ² , cm ²	0.8	0.6	2.7	1.7
τ, cm ²	63.4	61.6	68.3	65.4
<u>Pu Power</u>				
Total power				0.53
<u>Relative σ's</u>				
239A	1	1	1	1
239F	0.64	0.64	0.65	0.64
240A	1.50	1.47	0.81	0.97
240F	0.024	0.029	0.006	0.009
241A	1.37	1.42	1.05	1.01
241F	0.91	0.93	0.72	0.69
242A	0.30	0.33	0.10	0.13
242F	0.024	0.029	0.006	0.009
235A				0.37
235F				0.29
⁶ Li		0.57		
<u>Abs/1000 n</u>				
Mod.	6.9	7.1	23.1	12.2
Al	8.8	9.5	24.2	13.9
FP			188	141

* Distribution of Pu isotopes is given in Section C-2.

TABLE VI

DISPOSITION OF NEUTRONS IN PLATE REACTOR CASES

<u>Loading</u>	<u>Start of Cycle</u>				<u>End of Cycle</u>			
	<u>D₂O</u>	<u>H₂O</u>	<u>D₂O</u>	<u>H₂O</u>	<u>D₂O</u>	<u>H₂O</u>	<u>D₂O</u>	<u>H₂O</u>
kg (Pu)/ft ³ (1)	9.8		9.8		6.3		6.3	
kg (²³⁵ U)/ft ³	0		0		0		2.9	
g (⁶ Li)/ft ³	0		160		0		0	
Coolant	<u>D₂O</u>	<u>H₂O</u>	<u>D₂O</u>	<u>H₂O</u>	<u>D₂O</u>	<u>H₂O</u>	<u>D₂O</u>	<u>H₂O</u>
<u>n/1000 n</u>								
Absorption	658	681	820	923	1366	891	983	809
Leakage	342	319	180	77	-366	109	17	191
<u>Distribution⁽²⁾</u>								
<u>Absorption</u>								
Grp. 1	.052	.037	.045	.035	.015	.019	.026	.025
Grp. 2	.128	.032	.148	.039	.037	.011	.083	.022
Grp. 3	.806	.503	.799	.576	.889	.398	.865	.479
Grp. 4	.015	.426	.009	.351	.060	.571	.024	.475
<u>Leakage</u>								
Grp. 1	.208	.496	.200	.480	.120	.459	.162	.481
Grp. 2	.439	.304	.444	.312	.339	.294	.404	.304
Grp. 3	.354	.194	.350	.195	.538	.220	.428	.204
Grp. 4	.002	.006	.00008	.004	.003	.018	.001	.010

Notes:

(1) Distribution of Pu isotopes is given in Section C.2.

(2) HAMMER groups correspond to the following energy ranges:

- 1 = 10 Mev - 0.821 Mev, 2 = 821 kev - 5.53 kev,
- 3 = 5530 ev - 0.625 ev, 4 = 0.625 ev - 0.

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TABLE VIICLOSE-PACKED TUBE DESIGN

<u>Component</u>	<u>OD, in.</u>	<u>ID, in.</u>
Housing	6.00	5.84
Tube 1	5.70	5.42
Tube 2	5.20	4.92
Tube 3	4.70	4.42
Tube 4	4.20	3.92
Tube 5	3.68	3.40
Tube 6	3.16	2.88
Plug	2.72	0

Pitch = 6.25"

 $V_{(D_2O)}/V_{(fuel)} = 1.2$

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TABLE VIIIHAMMER DATA ON COMPACT TUBE CASES (620 i kg (239))

MWD/1 kg (239)	<u>0</u>	<u>300</u>	<u>600</u>	<u>900</u>
kg (Pu) in core*	1060			340
kg (²³⁵ U) in core	0	310	620	940
kg (⁶ Li) in core	6.4	0	0	0
<u>Reactivity</u>				
B ² , μB	468	677	650	700
k	1.155	1.227	1.209	1.221
L ² , cm ²	9	18	19	22
τ, cm ²	326	324	312	305
<u>Pu Power</u>				
Total Power	1.00	0.65	0.39	0.18
<u>Relative σ's</u>				
239A	1.00	1.00	1.00	1.00
239F	0.60	0.60	0.60	0.58
240A	1.21	1.00	0.88	0.92
240F	0.017	0.017	0.017	0.016
241A	1.67	1.50	1.34	1.20
241F	1.07	0.95	0.83	0.74
242A	0.39	0.37	0.33	0.29
242F	0.016	0.017	0.017	0.016
243A	0.49	0.38	0.30	0.30
244A		0.51	0.34	0.21
235A		0.79	0.72	0.62
235F		0.55	0.49	0.43
⁶ Li	0.26			
<u>Abs/1000 n</u>				
Mod.	2.9	2.9	2.9	2.9
Al	24.8	23.5	22.6	22.5
FP	0	33.4	75.2	98.1
L kg	137	-	-	184

* See Figure 4 for isotopic composition of Pu.

TABLE IX

HAMMER DATA ON COMPACT TUBE CASES (400 i kg (239))

MWD/1 kg (239)	0	900
kg (Pu) in core*	680	220
kg (²³⁵ U) in core	0	810
kg (⁶ Li) in core	0	0
<u>Reactivity</u>		
B ² , μB	499	652
k	1.190	1.220
L ² , cm ²	19	25
τ, cm ²	367	324
<u>Pu Power</u>		
Total Power	1.00	.16
<u>Relative σ's</u>		
239A	1.00	1.00
239F	.60	.59
240A	1.67	1.10
240F	.012	.012
241A	1.68	1.18
241F	1.09	.74
242A	.45	.30
242F	.012	.012
243A	.75	.39
244A		.24
235A		.57
235F		.39
<u>Abs/1000 n</u>		
Mod.	2.9	2.9
A1	32.0	25.6
FP	0	88.0
L kg	162	183

* See Figure 4 for isotopic composition of Pu.

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TABLE X
FISSION/ABSORPTION RATIOS

<u>Resonance Reactors</u>	<u>^{239}Pu</u>	<u>^{240}Pu</u>	<u>^{241}Pu</u>	<u>^{242}Pu</u>
Compact tube (D_2O)	.585	.017	.626	.052
Plate (D_2O)	.60	.03	.60	.08
Plate (H_2O)	.64	.02	.69	.07
<u>Thermal Reactors</u>				
150 g (239)/ft	.665	.004	.684	.010
100 g (239)/ft	.669	.003	.688	.009
50 g (239)/ft	.678	.002	.691	.008
Cm-I (HAMMER)	.68	.001	.69	.005
Cm-I (BURNUP)	.66	0	.77	0

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TABLE XI

ABSORPTION COEFFICIENTS*

	a_i			
	<u>1 = 239</u>	<u>1 = 240</u>	<u>1 = 241</u>	<u>1 = 242</u>
<u>Resonance</u>				
Compact tube	2.120	2.699	1.729	1.948
<u>Thermal</u>				
50 g (239)/ft	1.841	2.612	1.616	1.993
Cm-I (BURNUP)	1.836	2.460	1.460	2.000

* Absorptions in actinides per initial atom of ^{239}Pu =

$$\sum_1 a_i N_i(o), \text{ assuming no absorptions in } ^{244}\text{Cm},$$

no fissions in ^{243}Am .

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TABLE XII

NEUTRON ECONOMY

	Events per initial atom of $^{239}\text{Pu}^*$		
	<u>Resonance</u>	<u>Thermal</u>	
	<u>(Comp. Tube)</u>	<u>50 g (239)/ft</u>	<u>Cm-I (BURNUP)</u>
Production	2.783	2.936	3.026
Absorption			
Actinides	2.465	2.173	2.148
Structure	0.07		
Fiss. Prod.	0.4	0.4	0.4
Total	2.935		

* Assumes no absorptions in ^{244}Cm , no fissions in ^{243}Am .

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MILLIMETER

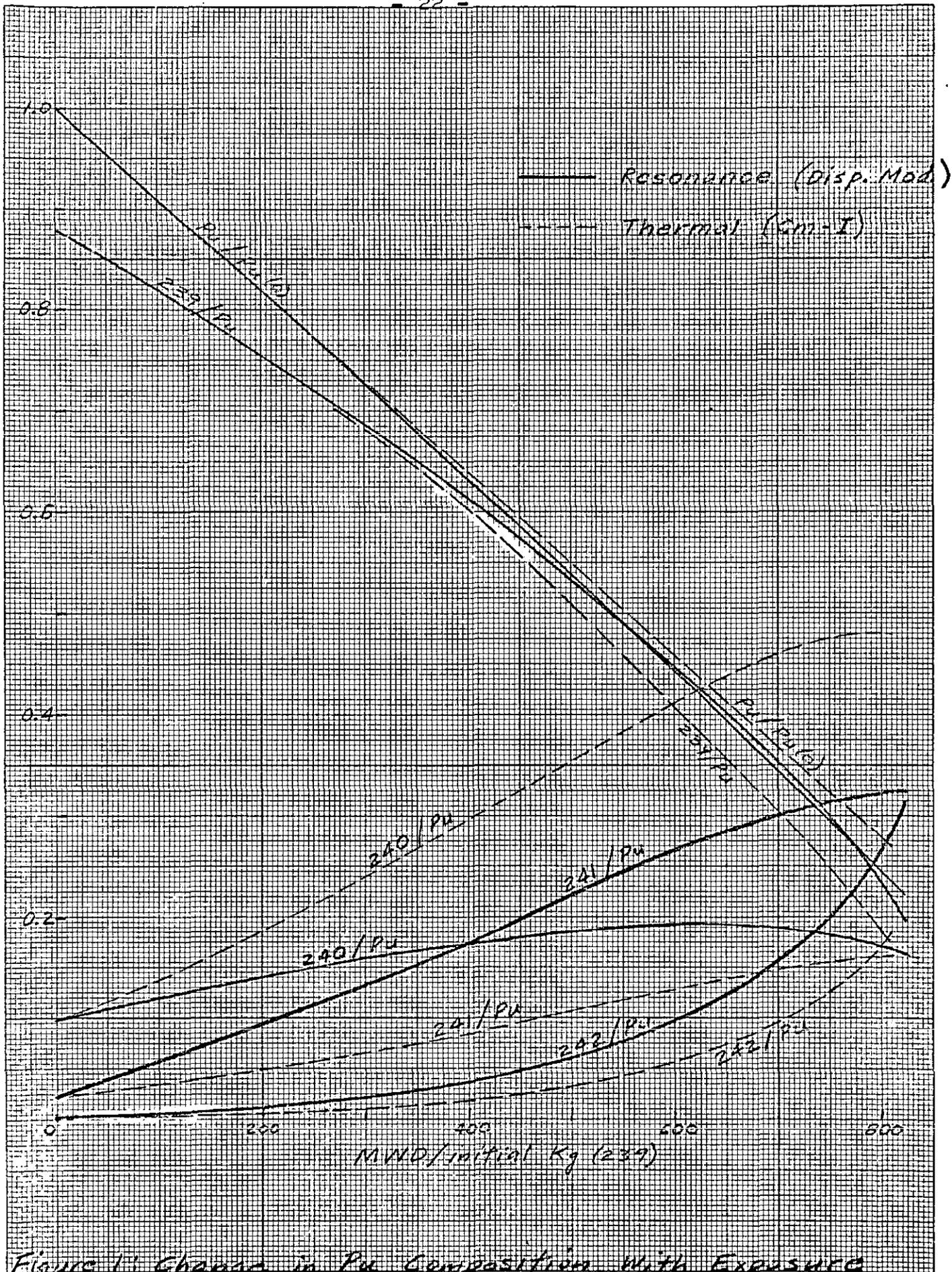


Figure 1: Change in Pu Composition With Exposure

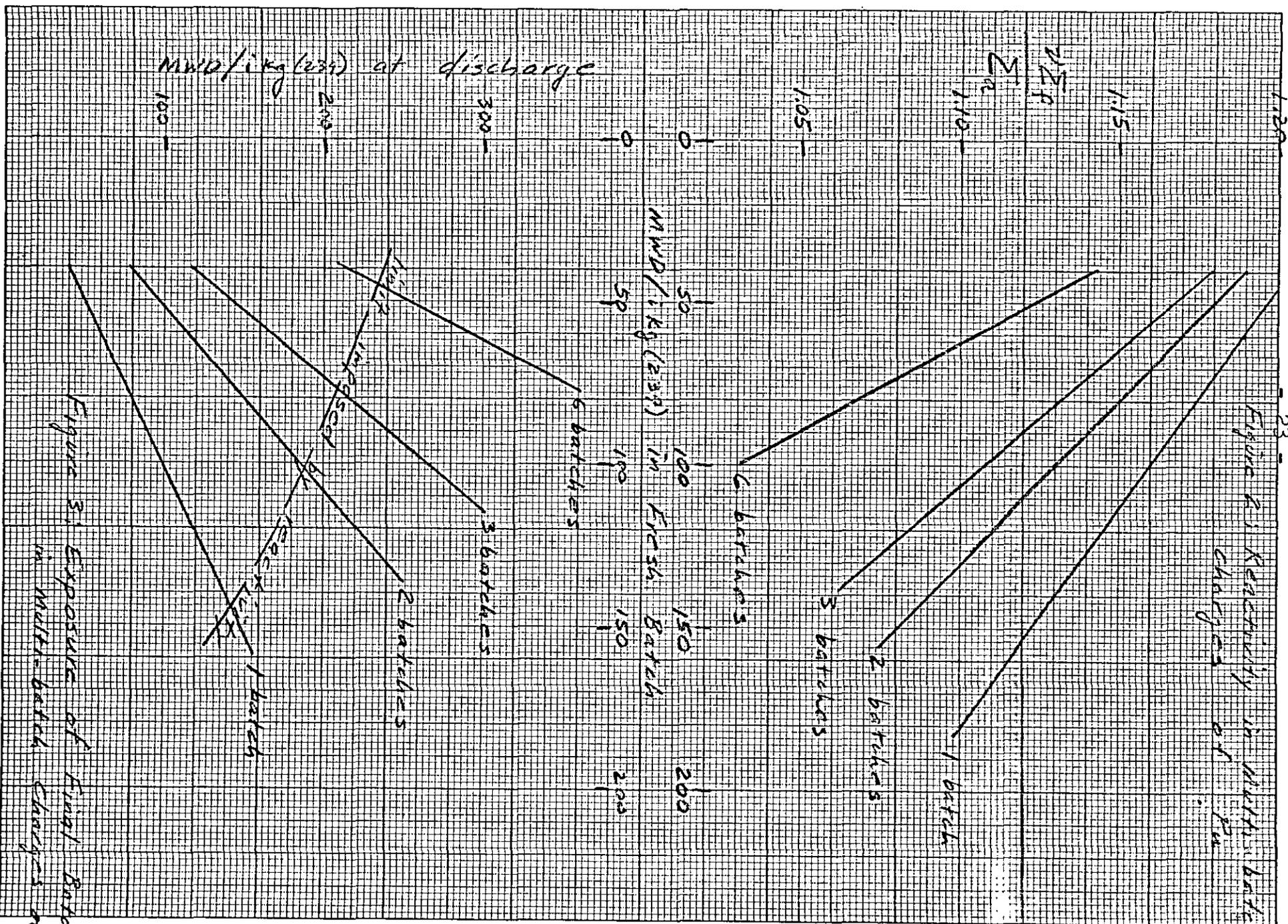


Figure 2. Reactivity in multi-batch charges of R_2

Figure 3. Exposure of single batch charges of R_2 in multi-batch charges of R_2

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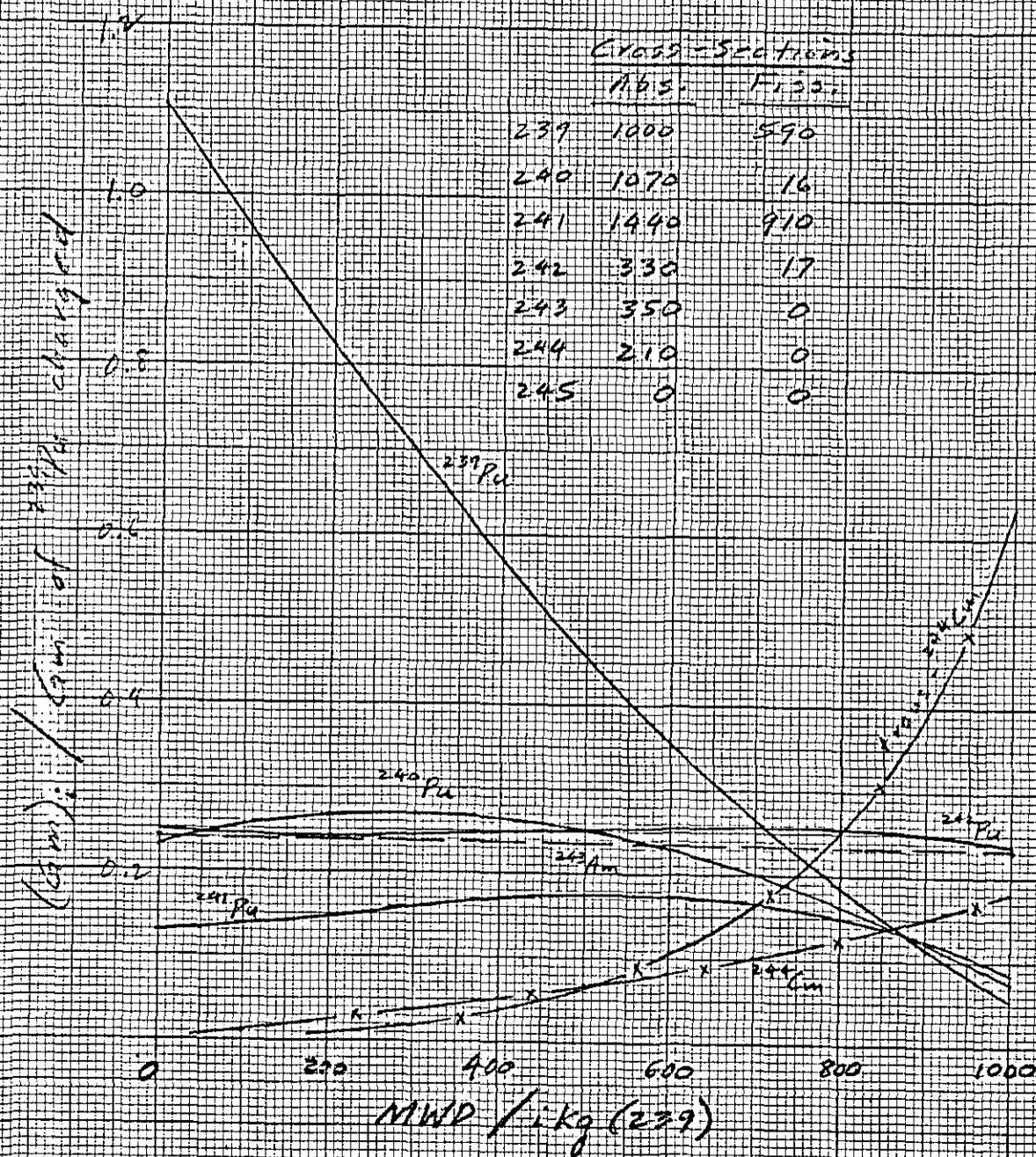


Figure 4: Composition vs Exposure in Compact Tube Case

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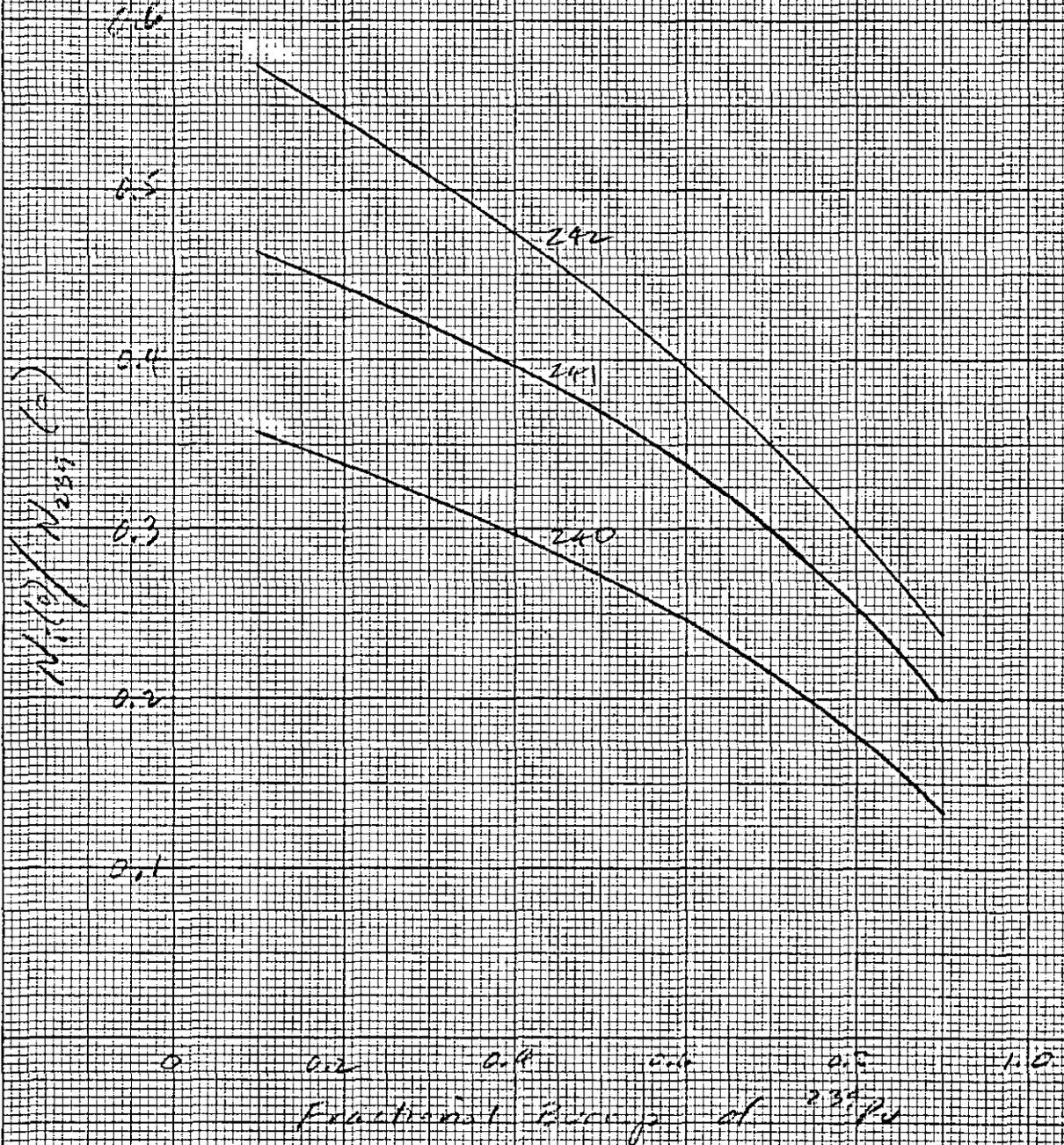


Figure 5: Equilibrium contents of Eu Isotopes (Compact Tube)

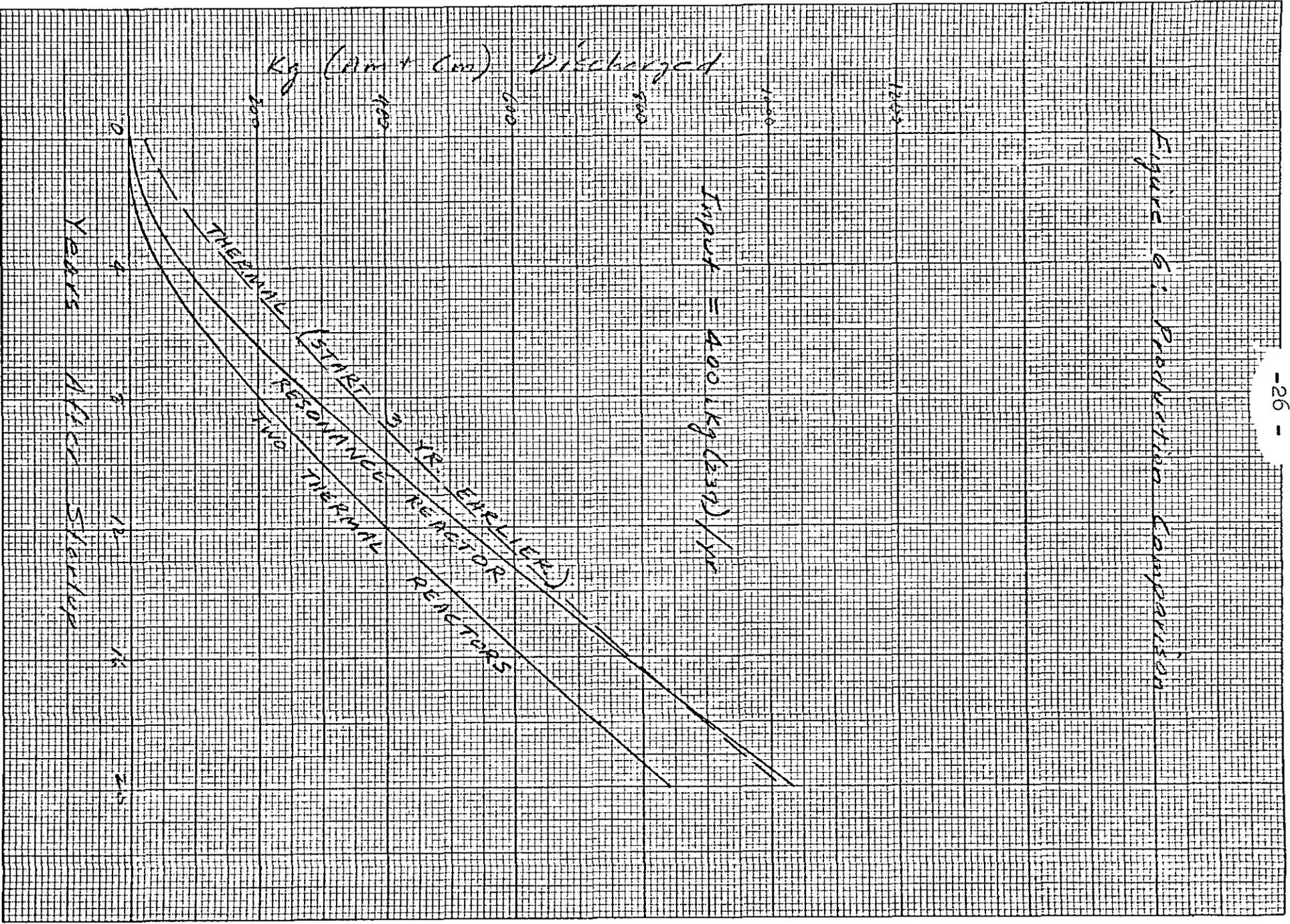


Figure 6: Production Comparison

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