AN ECONOMIC STUDY OF
1000 MEGAWATT
HOMOGENEOUS REACTOR

by

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AEC RESEARCH AND DEVELOPMENT REPORT

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ACKNOWLEDGMENT

We would like to thank R. B. Briggs and the other members of the Reactor Experimental Engineering Division for the help given us in preparing and writing this memo. We would also like to thank D. E. Ferguson of Chemical Technology for his assistance in the section on estimates of chemical processing costs.

We would further like to acknowledge the use of the Commonwealth Edison - Public Service Company report, CEPS-1101, for those cost figures for which time did not permit an independent study by the authors.

Introduction

One field in which the homogeneous reactor shows promise for future use is that of simultaneous power and plutonium production. This memo has been written as the result of an investigation of a Large Scale Homogeneous Reactor (LSHR) for this purpose. The authors have attempted, within the limitations of time and information available to them, to determine the unit cost of plutonium resulting from the operation of a fifteen foot homogeneous reactor, employing uranyl sulfate solution, at a heat production rate of 1028 megawatts. The cost so determined is $104.45 per gram of plutonium.] delete

The general layout of the reactor system includes the reactor core surrounded by five unit cells, each one handling 20,000 gallons per minute of uranyl sulfate solution from the core. In each cell, this soup is divided into two streams, each one passing through a heat exchanger of 100 megawatt heat capacity. A quantity of the water passing through the heat exchangers is converted to 215 psi steam which then collects briefly in a steam drum, external to the heat exchanger cell, before passing through the steam turbines. Each unit cell of 200 megawatt heat capacity is connected, through the steam drum, to a turbogenerator unit of 50,000 kilowatt capacity.

Engineering and production data, as well as a brief summary of the operating conditions and specifications for the reactor are compiled in figures 1 and 2, on pages 10 and 11 . It may be noted thereon, that the reactor annually produces for sale 1.438 x 10^9 kilowatt hours of electricity. In determining the unit cost for plutonium, a credit was taken for this electricity at the rate of seven mils per kilowatt hour.

The capital investments considered in arriving at the final plutonium cost figure are tabulated in summary in figure 3, on page 12 , and are outlined in detail in appendices B, C and D. Briefly, investment costs were determined for the reactor and all its related equipment, instrumentation, and shielding, for the power plant including the steam turbo-generator units and their related equipment, the transmission terminal and electric plant, for the land required and the improvements thereon, for the structures necessary, and for the engineering required. In addition, approximate allowances of fifteen percent were made for both contingencies and overhead.

Annual costs for plutonium production are shown in figure 4 on page 13 . The capital charges indicated thereon include the amortization of the pile area and chemical processing plant over a ten year period, as well as a two percent charge for the use of government money and a four percent charge for taxes and insurance. The total yearly capital charge, therefore, amounts to sixteen percent of the capital investment. The direct operating costs include the fuel burnup, the payrolls of the operating personnel, the heavy water and oxygen makeup, maintenance materials, supervision and administration, and uranium and plutonium separations. These are detailed in appendices C and E. The annual inventory charges indicated are made in accordance with the recommendations of the Operational Analysis Staff. These include a sixteen percent annual inventory charge against all source and fissionable material, and a two

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percent cost of money charge against other inventories. The calculation of these charges are outlined in appendix D.

For continuous chemical processing 12,870 liters of uranyl sulfate solution must be removed each day from the circulating fuel system. The uranium therein could be returned to the diffusion plant for reenrichment following a 100 day cooling period. The resulting enrichment necessary from the diffusion plant would be 1.11% uranium 235 if a critical enrichment of 1.075% is to be maintained inside the reactor. An alternate method would be to allow the soup removed for chemical processing to cool for 35 days. The uranium could then be put back into the reactor along with the proper amount of 52.5% enriched fuel which would exactly make up for the 25 and 28 atoms consumed during the previous day. The latter method was decided upon since the decrease in inventory charges which results outweighs the higher enrichment costs.

Of the several annual charges attributed to the plutonium production, that one most likely to offer a considerable reduction is the cost of chemical processing. The separations cost included in this report involves the daily processing of approximately ten percent of the circulating fuel solution for the removal of plutonium and the decontamination of the uranium by mean of a slightly modified Purex process. It presently appears feasible that the plutonium be removed directly from the reactor circulating system as a precipitate, and that only enough uranium be regularly processed to prevent excessive fission product buildup. The possible savings of this type of chemical processing method over the Purex system presently included in this memo's cost data would amount

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to $ 29 per gram of plutonium. In addition, the plutonium produced would have an estimated plutonium 240 content of .2% instead of the 2% plutonium 240 content in the present proposal, and would, therefore, be worth considerably more as a military weapons material. A more detailed analysis of this suggestion may be found in appendix C, Chemical Processing.

In accordance with ORNL 1096 there is also the possibility of operating a fifteen foot core at 2000 megawatts. Since some saving would thus be induced in the total system holdup per gram of plutonium produced, it might be thought that unit cost could be reduced through use of the larger plant. This is not true to any significant extent, however, as all other costs of major importance increase in direct proportion to the increased power. It should also be kept in mind that there is a desirable limit to the amount of electricity for which any one unit can supply the generating heat. One thousand megawatts of heat or approximately 220,000 kilowatts of electricity at the busbar appears to be close to this upper limit.

There are several facts which may be observed from the summary cost sheet. The total cost of the fuel burned in this reactor during one year is $17,860,000 or 12.4 mils per kilowatt hour of electricity sold. The total power credit is only $10,066,000 per annum or seven mils per kilowatt hour. This would seem to indicate that fuel burnup alone makes the production of competitive power prohibitive. Perhaps, a more realistic view of the cost of fuel burnup per kilowatt hour of electricity produced may be gained if only the net loss of fissionable material for the year is considered as the burnup. In that

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case only 1.2 mils per kilowatt hour may be charged as fuel burnup.

It should also be noted that alteration of the capital investment in the reactor plant does not largely effect the unit cost of the product plutonium. For our particular circumstances the capital total charge against annual expense is only thirty percent of the total unit plutonium cost. In addition, a change in capitalization of $11,500,000 is required to alter the final cost of a gram of plutonium by $5.00.

Nuclear calculations for the operating and engineering specifications used in the economic analysis may be found in detail in appendix A. The method employed is that of Feynmann and Welton as described in LA-524. Appendix A also includes curves showing the change of nuclear characteristics, for the reactor under consideration, with varying conditions of operation.

Nuclear calculations to determine the rate of soup removal for chemical processing are based upon a limiting plutonium 240 content, and may also be found in appendix A.

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Figure 1

ENGINEERING AND PRODUCTION DATA

1. Fuel in Reactor - Kilograms of Uranium (1.075% U-235) 32,700

2. Unspent Fuel in Storage
   a) Highly enriched (52.5% U-235) Kilograms of Uranium.......... 16.5
   b) Depleted (1.071% U-235) Kilograms of Uranium.......... 22,500

3. Spent Fuel in Storage (1.071% U-235) Kilograms of Uranium.......... 112,600

4. Plutonium in pile, kilograms.................... 10.8

5. Plutonium in storage, kilograms,................ 39.2

6. Heat Power, megawatts.......................... 1026

7. Fuel Consumed - Kilograms of Uranium per Year (52.5% U-235)........ 772

8. Uranium - Plutonium Conversion Ratio............ .91

9. Plutonium Production, kilograms per year........ 368

10. Reactor Innage Factor.......................... .90

11. Electrical Power Sales, kw-hr/yr................ 1.438×10^9

12. Electrical Power Factor........................ .80

13. Reactor Core Diameter, feet..................... 15

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Figure 2

OPERATING CONDITIONS

OF REACTOR

1.	Soup Solution.................	Uranyl sulfate
2.	Uranium concentration, grams per liter..	250
3.	Enrichment of U-235, percent...........	1.075
4.	Temperature of soup in core, °C.........	250
5.	Operating core pressure, psia..........	1000
6.	Steam conditions, inlet to turbine, psia...............	210 sat.

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Figure 3

SUMMARY OF CAPITAL INVESTMENT
(thousands of dollars)

	Investment	Percent of Total Investment
I - Plant Investment		
A. Pile Area..............$	67,000	39.7
B. Chemical Processing.....	23,240	13.8
II - Inventories		
A. Heavy Water.............	36,421	21.6
B. Unspent Fuel in Storage.	4,964	2.9
C. Spent Fuel in Storage...	22,910	13.6
D. Fuel in Pile............	6,707	4.0
E. Plutonium in Pile.......	1,623	1.0
F. Plutonium in Storage....	5,880	3.5
G. Process Materials.......	100	.6
Total	$ 168,845	

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Figure 4

ESTIMATED ANNUAL COST OF PRODUCING PLUTONIUM
(thousands of dollars)

	Charge		Percent of Gross Annual Charge	
I - Capital Costs				
A. Pile Area	$ 10,720		22.1	
B. Chemical Processing	3,718		7.7	
Total Annual Capital Costs		$ 14,438		29.8
II - Operating Costs				
A. Fuel	$ 17,860		36.8	
B. Pile Cooling and Power Systems	2,509		5.2	
C. Uranium Separations	5,300		10.9	
D. Plutonium Separations	920		1.9	
Total Annual Operating Costs		$ 26,589		54.8
III - Inventories				
A. Heavy Water	$ 728		1.5	
B. Unspent Fuel in Storage	794		1.6	
C. Spent Fuel in Storage	3,666		7.6	
D. Fuel in Pile	1,073		2.2	
E. Plutonium in Pile	260		.5	
F. Plutonium in Storage	941		1.9	
G. Process Materials	2		0.0	
Total Annual Inventory Charges		$ 7,465		15.4
Gross Annual Charges to Plutonium		$ 48,492		100.0%
Credit - Electrical Power Sales		10,066		
Net Annual Charge to Plutonium		$ 38,426		
Plutonium Unit Cost		$ 104.45 per gram		

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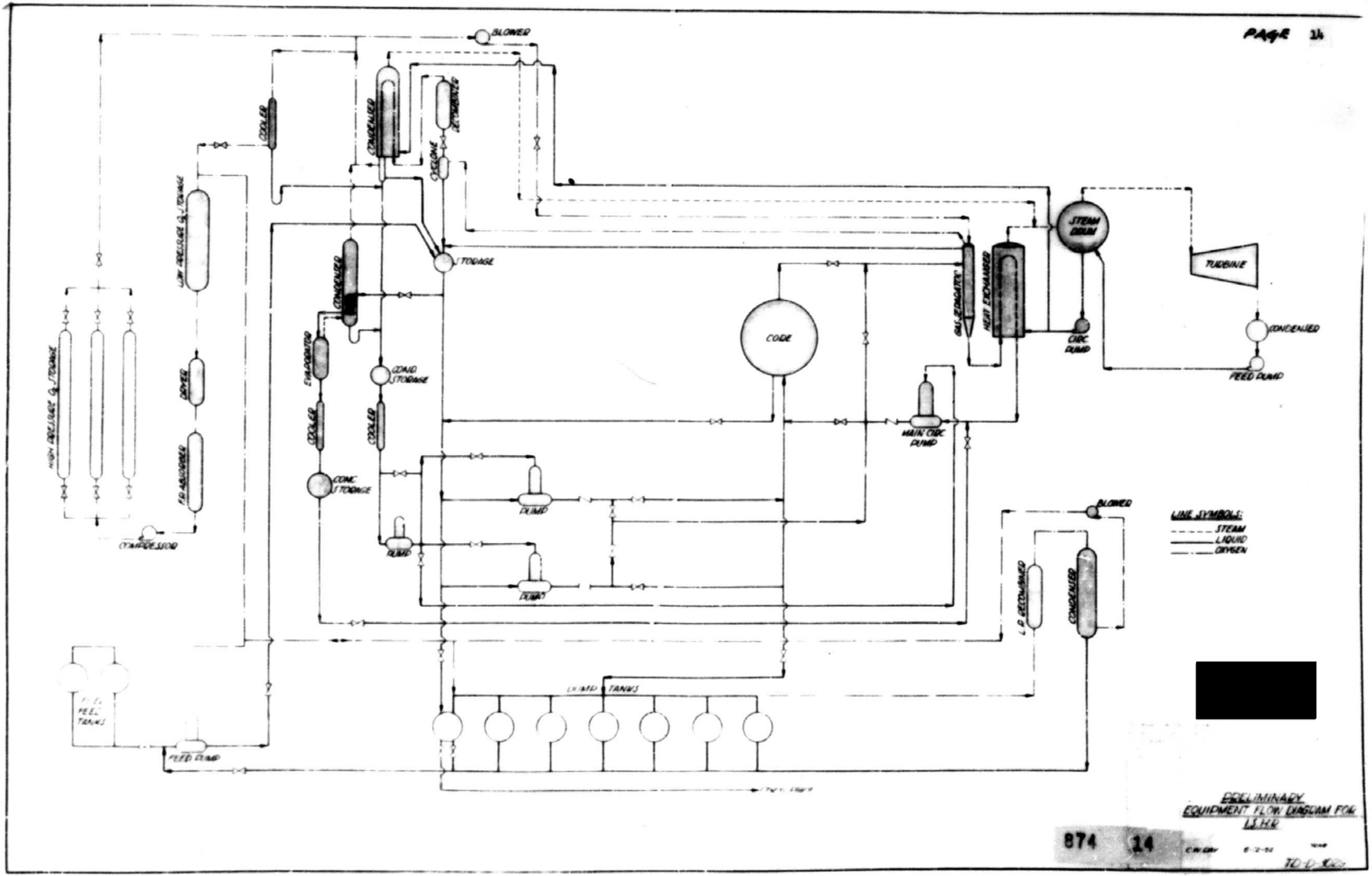
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BLOWER
COOLER
CONDENSER
DECOMBINER
CYCLONE
LOW PRESSURE O2 STORAGE
HIGH PRESSURE O2 STORAGE
STORAGE
CONDENSER
EVAPORATOR
COND STORAGE
DRYER
COOLER
COOLER
CONC STORAGE
F.P. ABSORBER
COMPRESSOR
CORE
GAS SEPARATOR
HEAT EXCHANGER
STEAM DRUM
CIRC PUMP
TURBINE
CONDENSER
FEED PUMP
MAIN CIRC PUMP
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BLOWER
LINE SYMBOLS:
STEAM
LIQUID
OXYGEN
L.P. RECOMBINER
CONDENSER
DUMP TANKS
FEED PUMP
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PRELIMINARY
EQUIPMENT FLOW DIAGRAM FOR
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APPENDIX A

NUCLEAR CALCULATIONS .....

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Nuclear Calculations

The reactor under investigation has a core diameter of fifteen feet and employs slightly enriched U-235 in a UO_2SO_4-D_2O solution as fuel. The core tank is of laminated construction having a total metal thickness of approximately seven inches. In practice only the inner container would be made of 347 stainless steel, but for the purposes of the following calculations the entire seven inches is assumed to be 347 stainless. The nominal power level of the reactor is taken as 1000 MW.

The method employed in these calculations is that of Feynmann and Welton as described in LA-524.

The first step in the solution of the problem is the determination of some constants describing the nuclear properties of the core, c; shell, s; and reflector, r. Subscripts 1 and 2 refer to fast and slow groups of neutrons, respectively.

The constants which must be found are D_1, κ_1, D_2 and κ_2 for each region (core and reflector). The definitions of these constants are as follows:

$$D_1 = \frac{1}{3\Sigma_{T_1}} = \frac{1}{3(\Sigma_{s_1} + \Sigma_{a_1} + \Sigma_1)} \qquad (1)$$

$$\text{where,} \quad \Sigma_1 \equiv \frac{\Sigma_{s_1}}{\frac{1}{\xi}\ln\left(E_0/E_{th}\right)} \qquad (2)$$

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$$\varkappa_1 = \sqrt{\frac{1}{\tau}} = \sqrt{\frac{\Sigma_1 + \overline{\Sigma}_{a_1}}{D_1}} \qquad (3)$$

$$D_2 = \frac{1}{3\Sigma_{T_2}} = \frac{1}{3(\Sigma_{s_2} + \Sigma_{a_2})} \qquad (4)$$

$$\varkappa_2 = \sqrt{\frac{1}{L^2}} = \sqrt{\frac{\Sigma_{a_2}}{D_2}} \; ; \qquad (5)$$

$$\varkappa_{2c} = \sqrt{\frac{\gamma\sigma_a(25) + (1-\gamma)\sigma_a(28) + \sigma_a(S) + \beta\sigma_a(D_2O)}{L^2(D_2O)\,\sigma_a(D_2O)\,\beta/F2}}$$

Using the values of D and $\varkappa$ substitution is made in the following equation,

$$\frac{Z_1}{\tan Z_1} = 1 - \frac{D_{1r}}{D_{1c}}\left[\frac{\varkappa_{1r} R}{\tanh \varkappa_{1r} T_1} + 1\right] \qquad (6)$$

where R is the core radius and T_1 the extrapolated thickness of the reflector for the fast neutron group. The value of Z_1 is determined from (6) and used in the following equation to determine η_1, [where, $\eta_1 = (1 + B_1^2\tau)$.

$$\eta_1 = 1 + \left(\frac{Z_1}{\varkappa_{1c} R}\right)^2 \qquad (7)$$

Similiarly, one determines η_2 and η_x from equations 8 through 11 as follows:

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$$\frac{z_2}{\tan z_2} = 1 - \frac{D_{2r}}{D_{2c}}\left[\frac{\varkappa_{2r} R}{\tanh \varkappa_{2r} T_2} + 1\right] \qquad (8)$$

$$\eta_2 = 1 + \left(\frac{z_2}{\varkappa_{2c} R}\right)^2 \qquad (9)$$

$$z_x = 1 - \frac{D_{2r}}{D_{2c}}\left[\frac{\varkappa_{1r} R}{\tanh \varkappa_{1r} T_1} + 1\right] \qquad (10)$$

$$\eta_x = 1 + \left(\frac{z_x}{\varkappa_{2c} R}\right)^2 \qquad (11)$$

One next determines Σ_x from the relation.

$$\Sigma_x = \varkappa_{1r}^2 D_{2r} - \Sigma_{a2r} \qquad (12)$$

The product ηf is found to be:

$$\eta f = \frac{\nu \gamma \sigma_f(25)}{\gamma \sigma_a(25) + (1-\gamma)\sigma_a(28) + \sigma_a(S) + \beta \sigma_a(D_2O)} \qquad (13)$$

where $\gamma \equiv N_{25}/N_U$

$\beta \equiv \frac{D_2O}{U}$

The values of the resonance escape probability, p, have been taken from report CF-50-11-41 by Lansing and Noderer.

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One may now calculate k_{eff} as,

$$K_{eff} = \frac{\eta p f}{\eta_1 \eta_2}\left\{ 1 + (\eta_1 - 1)\left[\frac{\eta_x - \eta_2}{\eta_x - 1}\right]\left[\frac{\Sigma_x + \Sigma_{2r}}{\Sigma_x}\right]\right\} \qquad (14)$$

In the case of a stainless steel shell the expression within the curly brackets is equation (14) is but minutely different from unity so that one may write equation (14) as,

$$K_{eff} = \frac{\eta p f}{\eta_1 \eta_2} \qquad (15)$$

where,

$$\eta_1 = 1 + B_1^2 \tau \qquad (15a)$$

$$\eta_2 = 1 + B_2^2 L^2 = 1 + \left(\frac{\Sigma_2}{R}\right)^2 \frac{1}{K_{2c}^2} \qquad (15b)$$

Recall that

$$\eta f = \frac{\gamma \nu \sigma_f(25)}{\gamma\left[\sigma_a(25) - \sigma_a(28)\right] + \sigma_a(28) + \sigma_a(S) + \beta \sigma_a(D_2O)} \qquad (16)$$

and,

$$B^2 L^2 = \frac{L^2(D_2O) B_2^2 \sigma_a(D_2O) \beta / F^2}{\gamma\left[\sigma_a(25) - \sigma_a(28)\right] + \sigma_a(28) + \sigma_a(S) + \beta \sigma_a(D_2O)} \qquad (17)$$

Taking the desired k_{eff} = 1.02, using (16) for ηf and 1 + (17) for η_2, equation (15) bdcomes,

$$\frac{(\eta f) p}{1.02\, \eta_1} = \eta_2$$

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Figure I.
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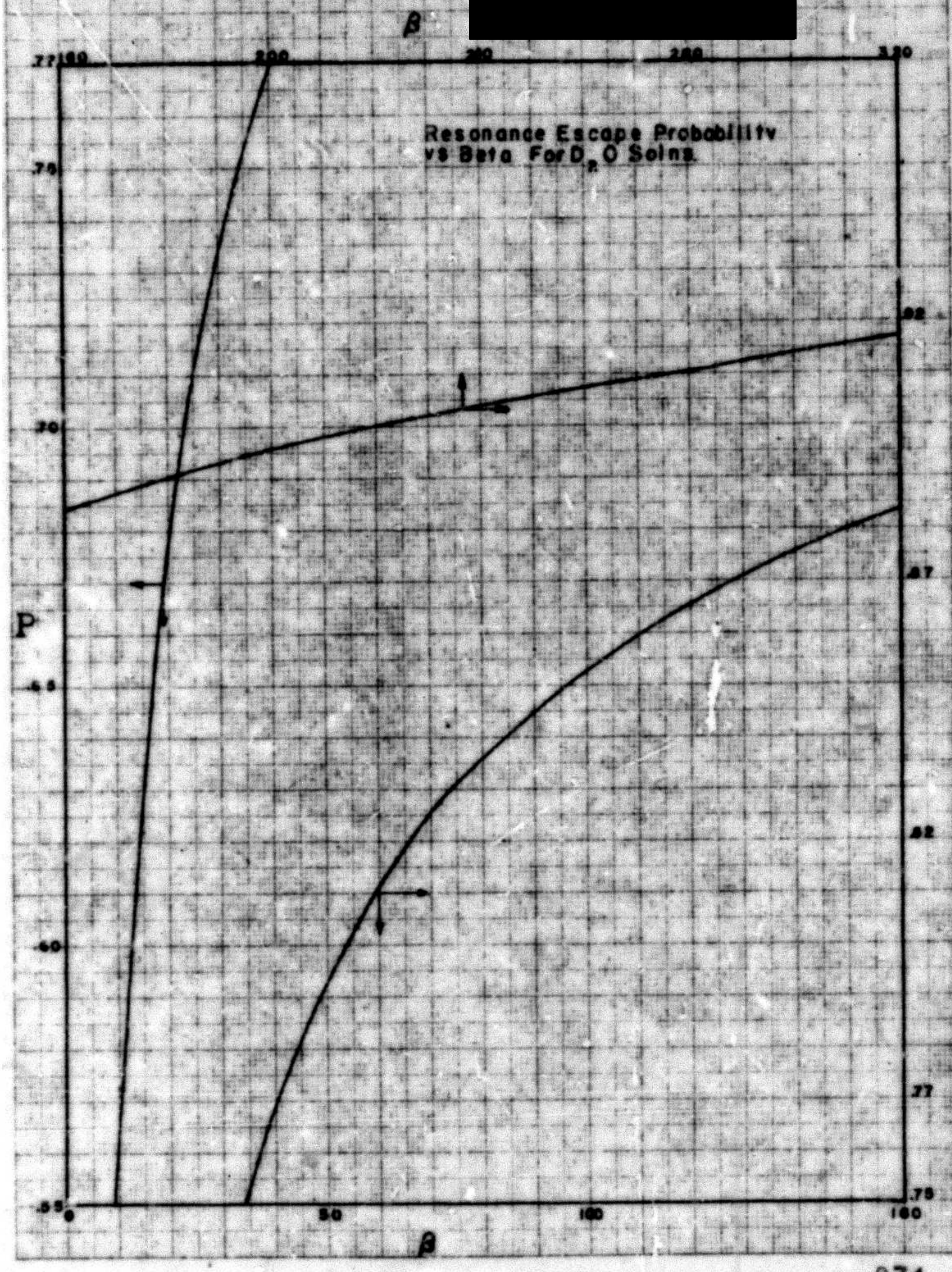

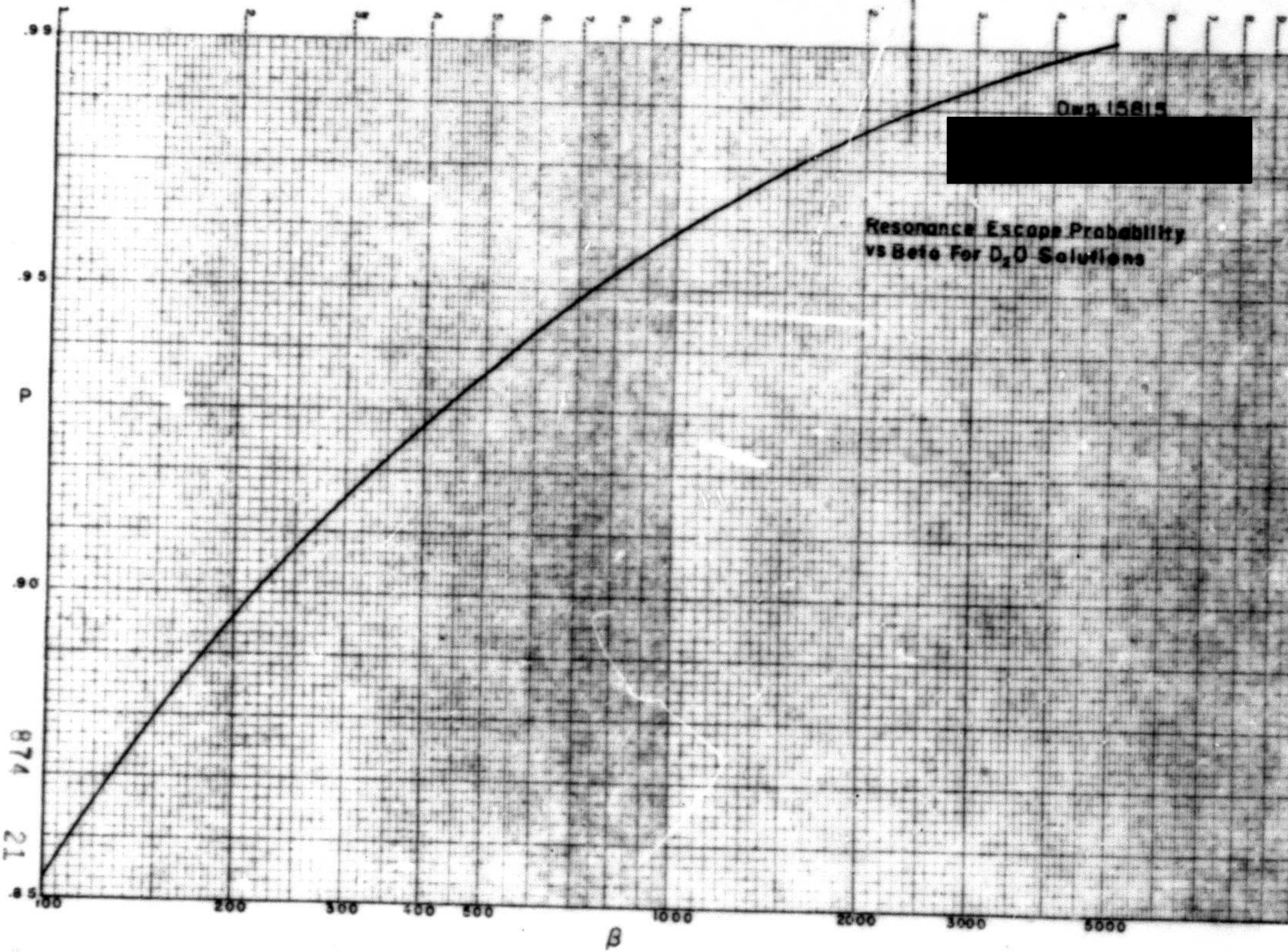

Figure 2

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or $$\frac{p}{1.02\eta_1} \times \frac{\nu\sigma_f(25)\gamma}{[\gamma(\sigma_a(25)-\sigma_a(28)] + \sigma_a(28)+\sigma_a(S)+\beta\sigma_a(D_2O)} = 1 + \frac{L^2(D_2O)B_z^2\sigma_a(D_2O)\beta/F^2}{\gamma[\sigma_a(25)-\sigma_a(28)]+\sigma_a(28)+\sigma_a(S)+\beta\sigma_a(D_2O)}$$

Solving for γ gives an expression for the required critical enrichment,

$$\gamma = \frac{\sigma_a(28)+\sigma_a(S)+\beta\sigma_a(D_2O)+L^2(D_2O)\sigma_a(D_2O)\beta/F^2\left(\frac{z_1}{R}\right)^2}{\frac{\nu\sigma_f(25)p}{1.02\eta_1} - [\sigma_a(25)-\sigma_a(28)]} \qquad (18)$$

Using the cross sections tabulated below equation (18) becomes,

Table 1

$\sigma_a(28)$	$\sigma_a(S)$	$\sigma_a(D_2O)$	$\sigma_f(25)$	$\sigma_a(25)$	ν
2.706	0.49	.001824	546	644	2.50

$$\gamma = \frac{3.196 + 0.001824\left[\beta + L^2\left(\frac{z_1}{R}\right)^2\beta/F^2\right]}{1338\frac{p}{\eta_1} - 641.3} \qquad (19)$$

The Function β/F^2 vs. β

Using the relation given on page five of CF-52-5-230,

$$F = 1 - \frac{\rho(D_2O)}{1 + .2707\beta}$$

one obtains the values for β/F^2 given in table II

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Table II

β	β/F^2					
	20°C	100°C	150°C	200°C	250°C	300°C
20	29.18	28.72	28.21	27.55	26.79	25.97
50	58.56	58.19	57.78	57.23	56.59	55.87
100	108.35	108.01	102.63	107.12	106.51	105.84
150	158.29	157.96	157.58	157.68	156.49	155.82
200	208.26	207.93	207.56	207.07	206.47	205.82
250	258.24	257.91	257.54	257.06	256.47	255.81

An examination of the body of table II shows β/F^2 to very nearly linearly with β . The only departure from this relation being a small one for values of β of less than 100. In table III are given suitably accurate expressions of β/F^2 for various temperatures.

Table III

	β/F^2		
	$\beta \approx 20$	$\beta \approx 50$	$\beta > 100$
20°C	$\beta + 9.2$	$\beta + 8.6$	$\beta + 8.3$
100°C	$\beta + 8.7$	$\beta + 8.2$	$\beta + 8.0$
150°C	$\beta + 8.2$	$\beta + 7.8$	$\beta + 7.6$
200°C	$\beta + 7.6$	$\beta + 7.2$	$\beta + 7.1$
250°C	$\beta + 6.8$	$\beta + 6.6$	$\beta + 6.5$
300°C	$\beta + 6.0$	$\beta + 5.9$	$\beta + 5.8$

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The expressions listed under the heading $\beta \gtrsim 20$ may be used over the entire range of β with no more than a 1% error from the values given in table III.

The expression $L^2(D_2O)(Z_2/R)^2$ which occurs in equation (19) has been calculated for various temperatures from 20°C to 300°C, the values being found in table IV.

table IV

	20°C	100°C	150°C	200°C	250°C	300°C
η_1	1.0188	1.0202	1.0220	1.0246	1.0287	1.0345
Z_2	3.0961	3.0904	3.0855	3.0801	3.0725	3.0625
$L^2(D_2O)$	15130	19041	22582	27499	34716	45352
$(Z_2/R)^2L^2$	2.7750	3.4800	4.1139	4.9922	6.2711	8.1384

Using the expressions for β/ϵ^2 given in the first column of table III and the values of $(Z_2/R)^2L^2$ given in table IV, equation (19) yields expressions for the required critical enrichment at each of the temperatures of interest. These equations are given below.

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Figure 3

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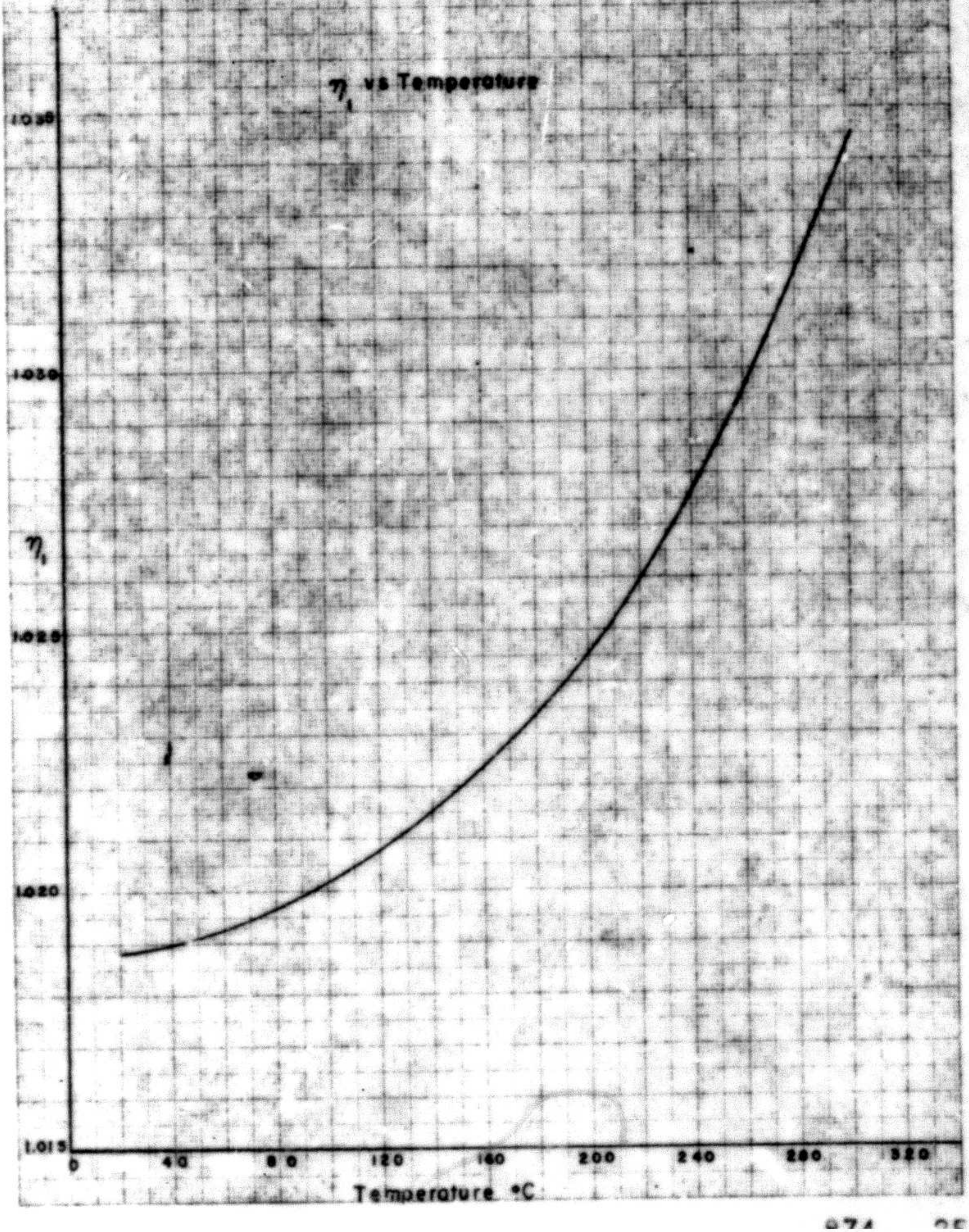

Figure 4

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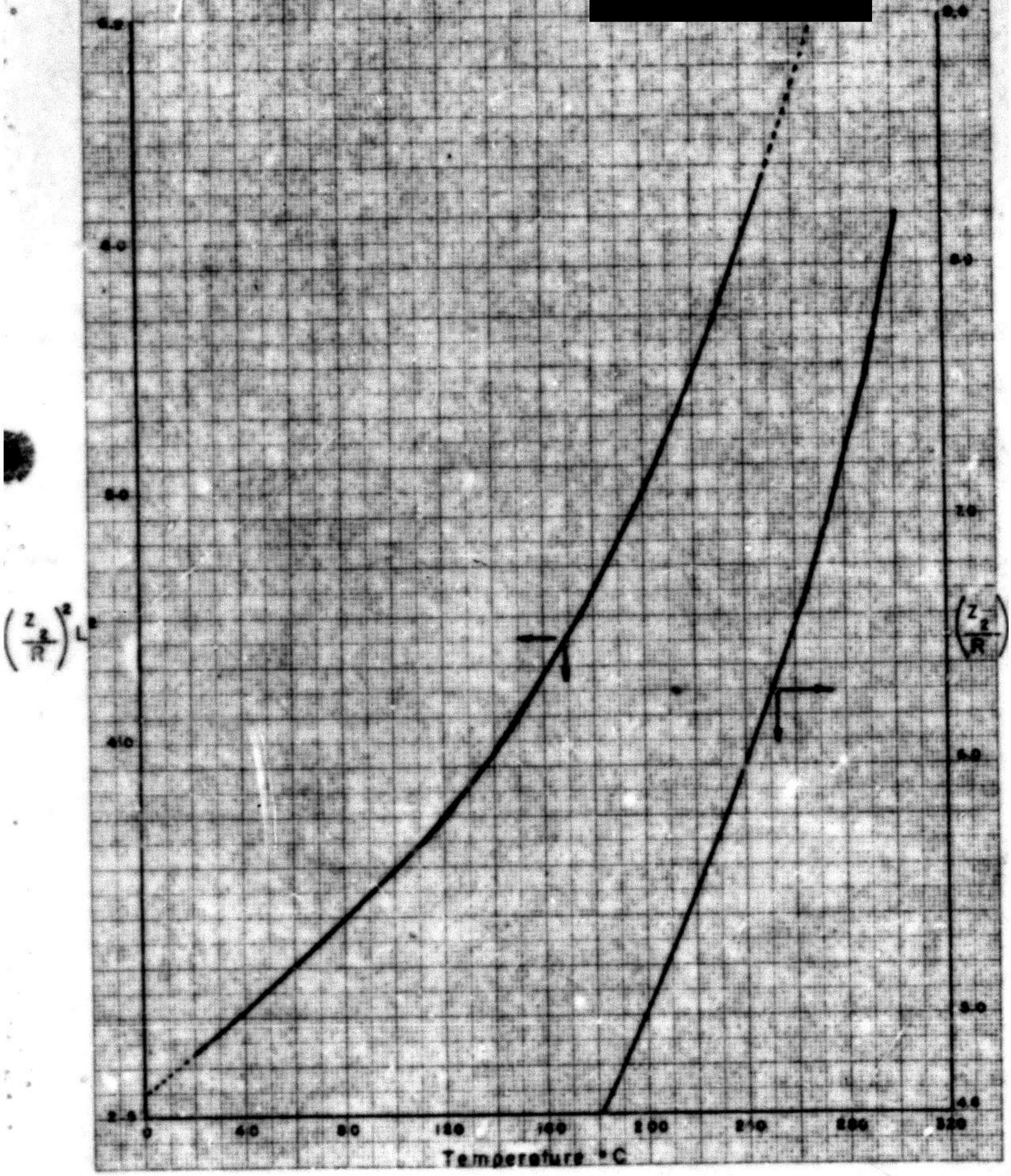

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Table 7

Temperature	Equation for critical enrichment
20°C	$\gamma = \dfrac{3.243 + 0.006886\,\beta}{1313p - 641.3}$
100°C	$\gamma = \dfrac{3.251 + 0.008172\,\beta}{1312p - 641.3}$
150°C	$\gamma = \dfrac{3.258 + 0.009328\,\beta}{1309p - 641.3}$
200°C	$\gamma = \dfrac{3.265 + 0.01093\,\beta}{1306p - 641.3}$
250°C	$\gamma = \dfrac{3.274 + 0.01326\,\beta}{1300p - 641.3}$
300°C	$\gamma = \dfrac{3.285 + 0.01667\,\beta}{1293p - 641.3}$

Temperature Corrections for the Two Group Constants:

The corrections applied to the two group constants for variations in temperature are obtained from the following equations which were obtained from page 84 of ORNL-1121.

(T_0 refers to 20°C.)

$$L^2(T) = L^2(T_0)\,\frac{\rho^2(T_0)}{\rho^2(T)}\sqrt{\frac{T}{T_0}}\,\frac{\sigma_s(T_0)}{\sigma_s(T)}$$

$$\tau(T) = \tau(T_0)\,\frac{\rho^2(T_0)}{\rho^2(T)}$$

$$D_1(T) = D_1(T_0)\,\frac{\rho(T_0)}{\rho(T)}$$

$$D_2(T) = D_2(T_0)\,\frac{\rho(T_0)}{\rho(T)}\,\frac{\sigma_s(T_0)}{\sigma_s(T)}$$

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Figure 5

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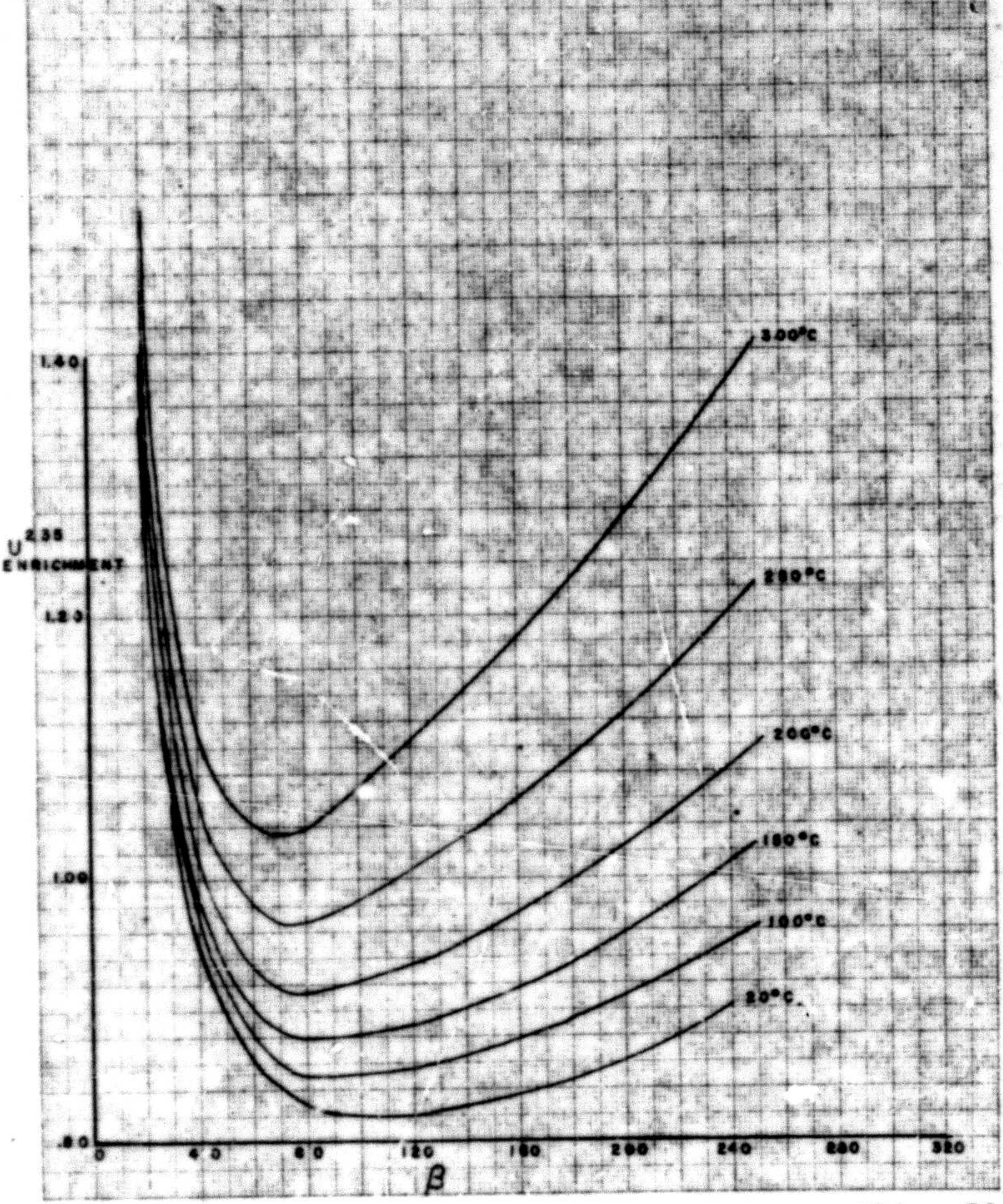

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where, L = thermal diffusion length

τ = age from fission to thermal

D_1 fast group diffusion constant

D_2 thermal group diffusion constant

ρ = density of D_2O

$\sigma_s(T)$ = microscopic scattering cross section of D_2O at energy kT

The following several pages are curve sheets showing the variations of the two group constants with temperature.

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Figure 6
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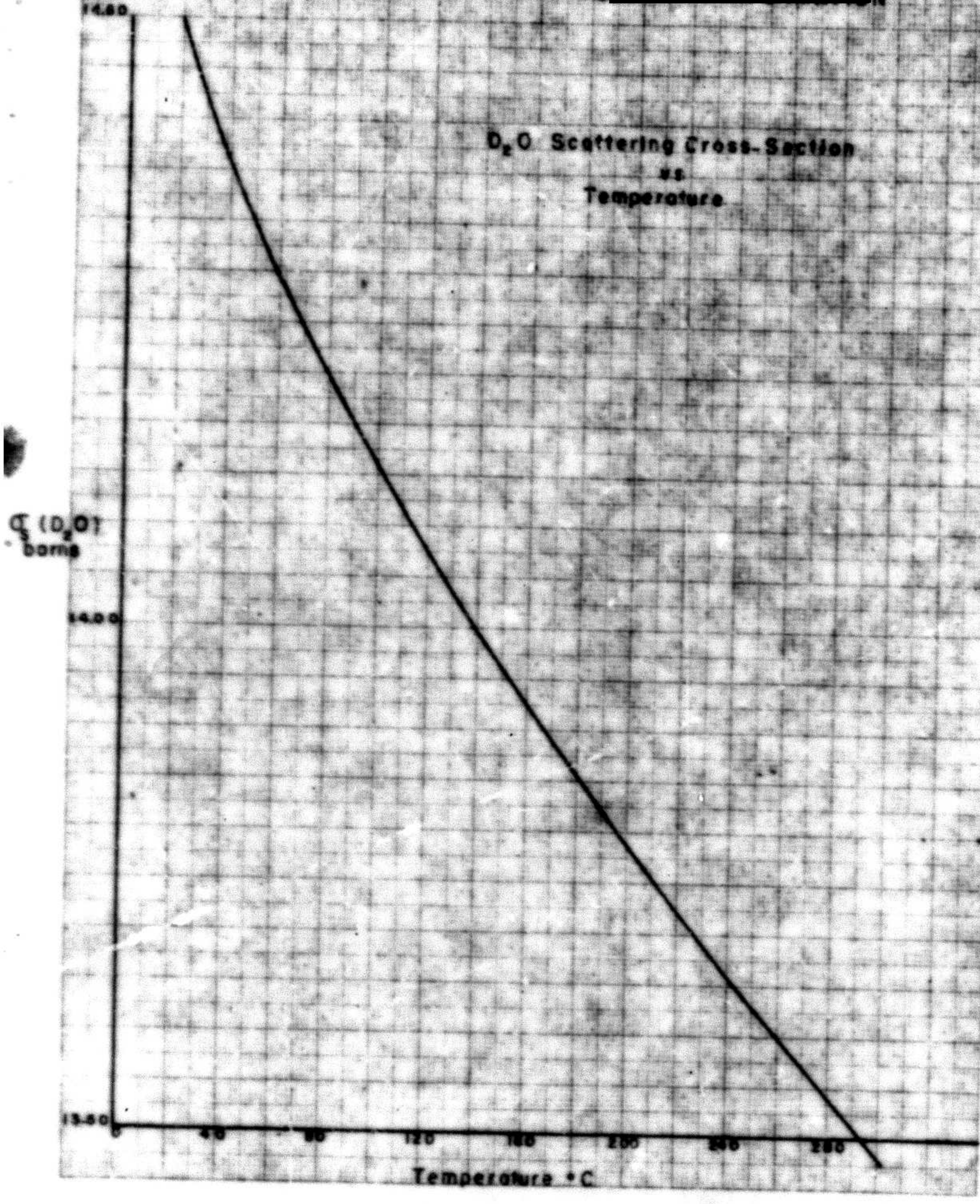

Figure 7
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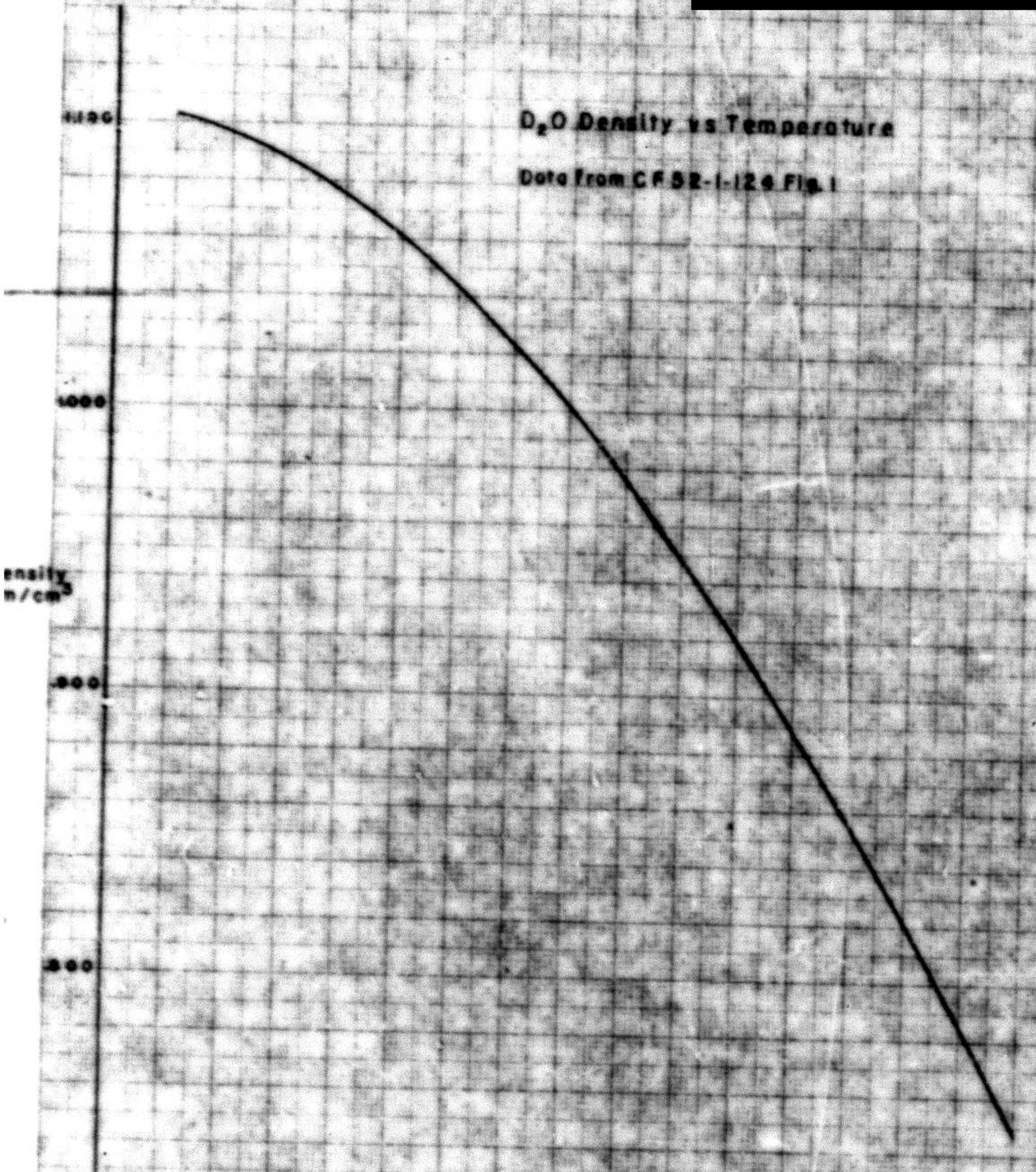

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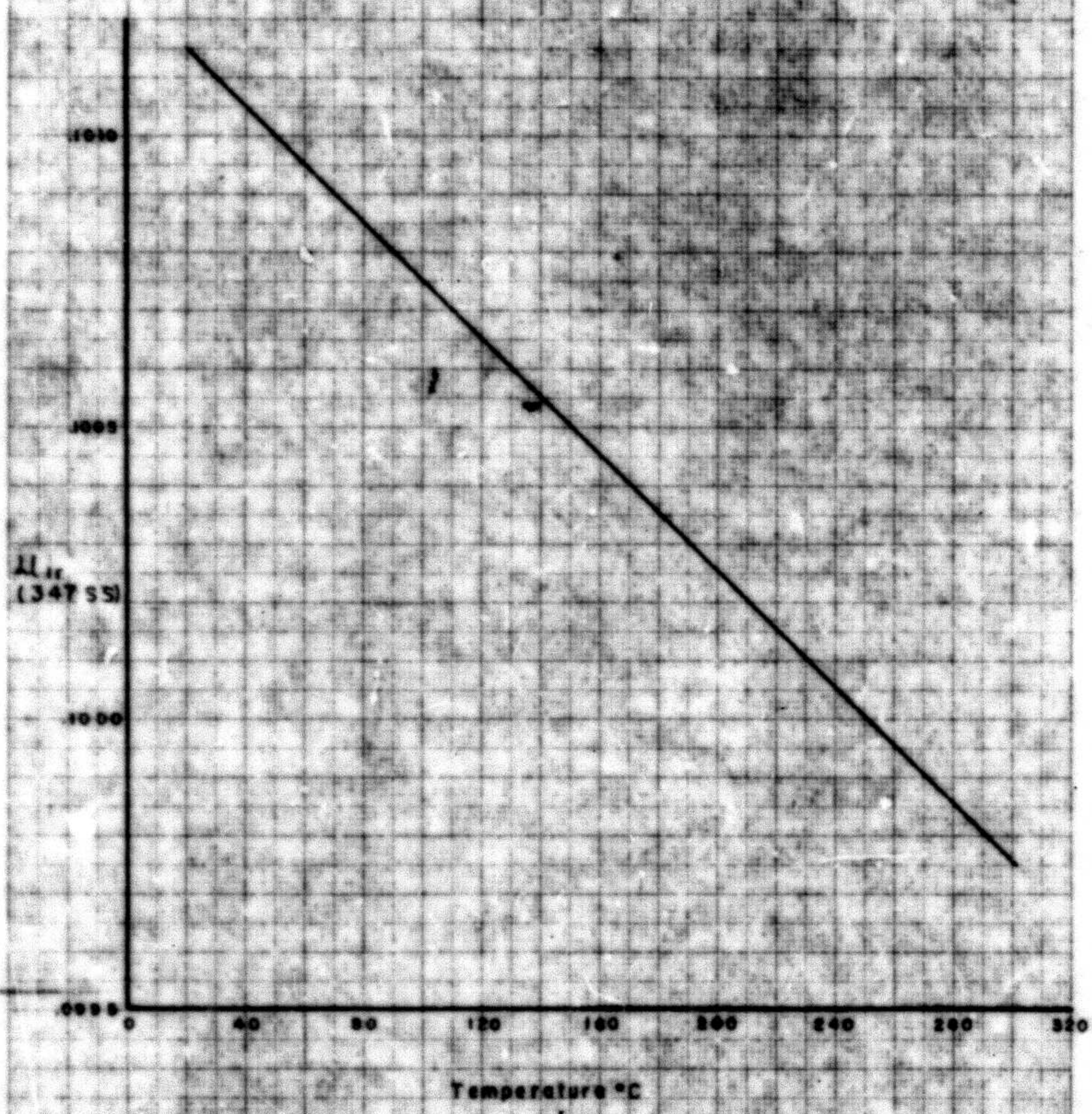
Figure 8

μ_{ir} vs Temperature For Stainless Steel 347



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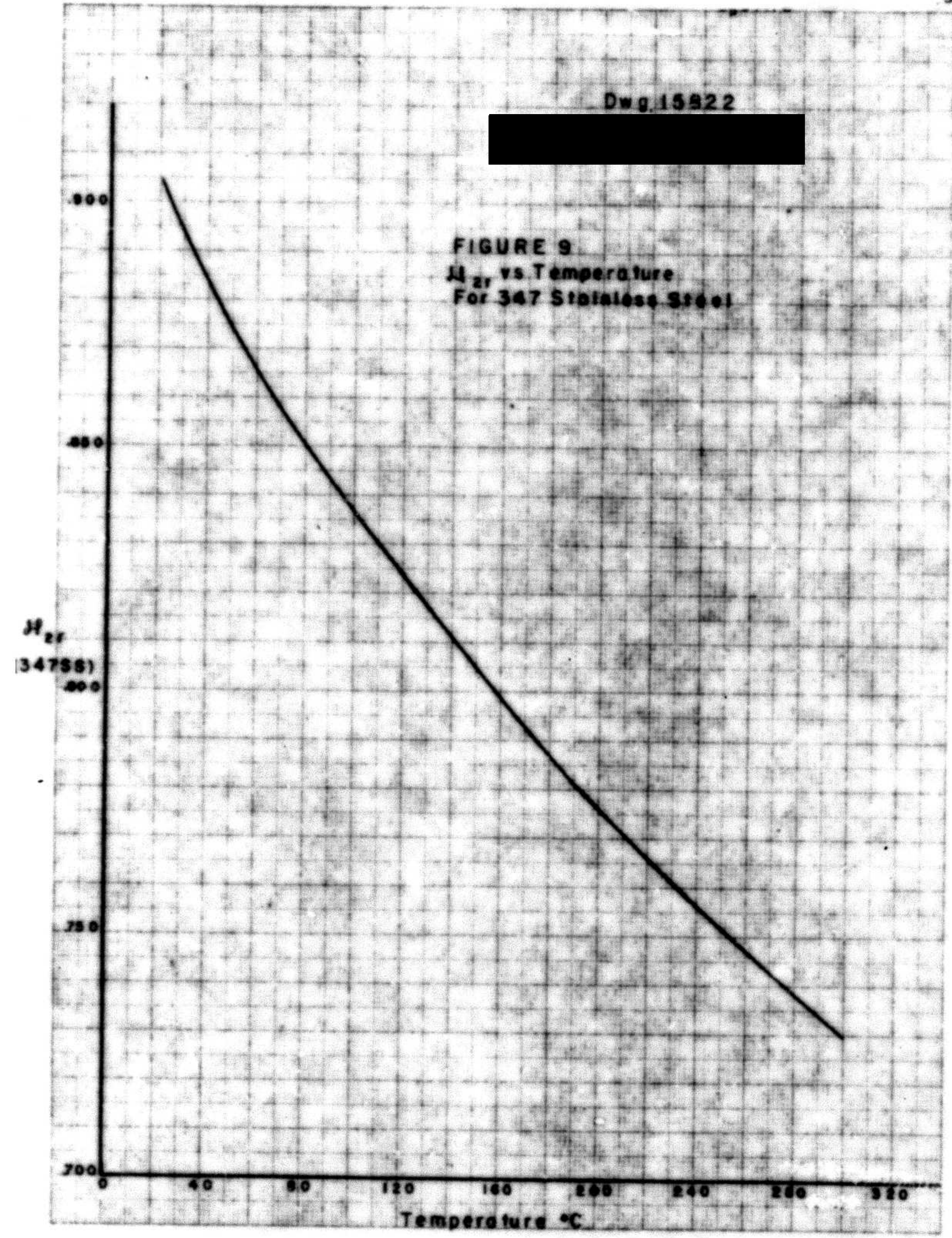

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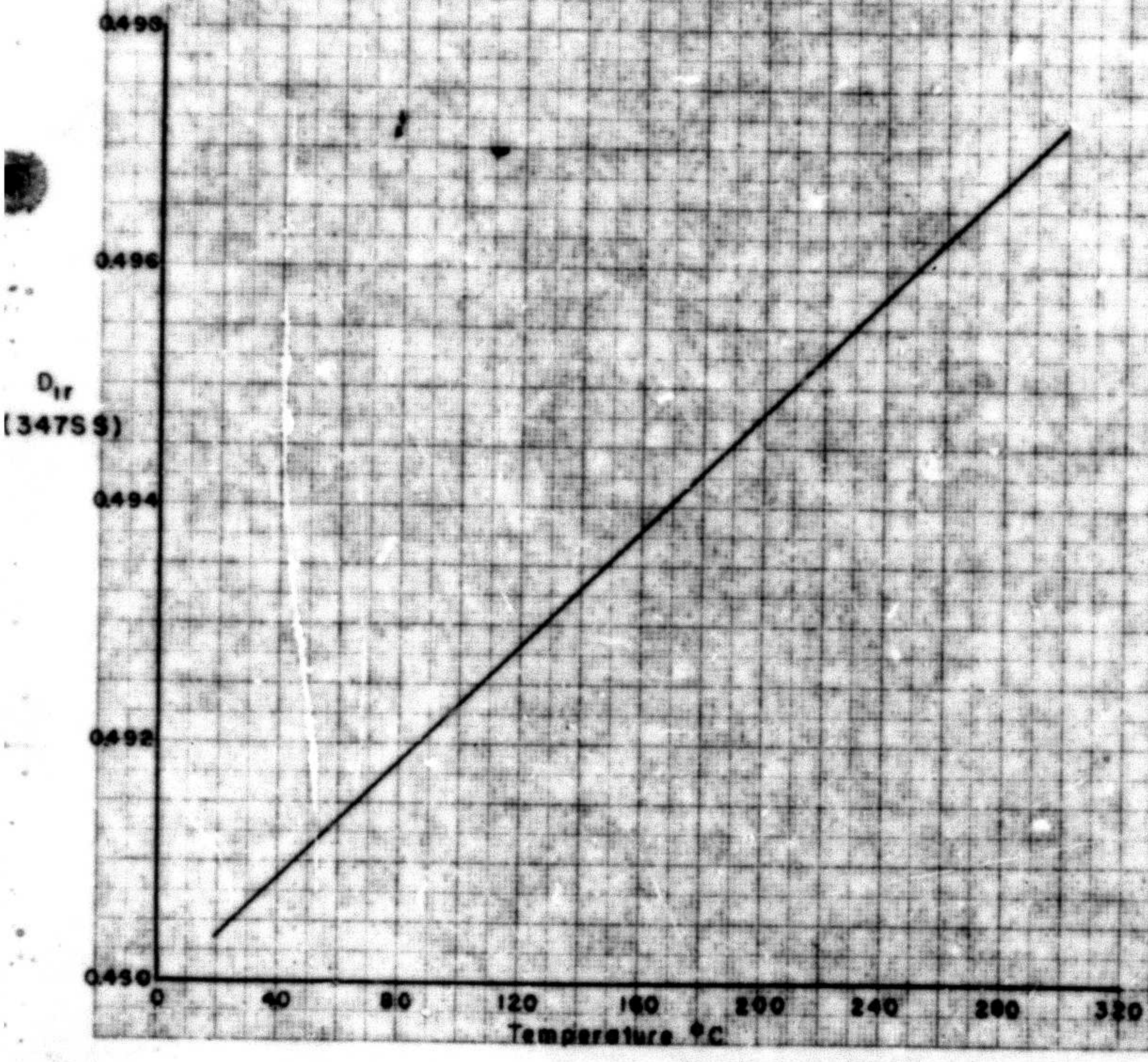
Figure 10

D_{ir} vs Temperature
For 347 Stainless Steel



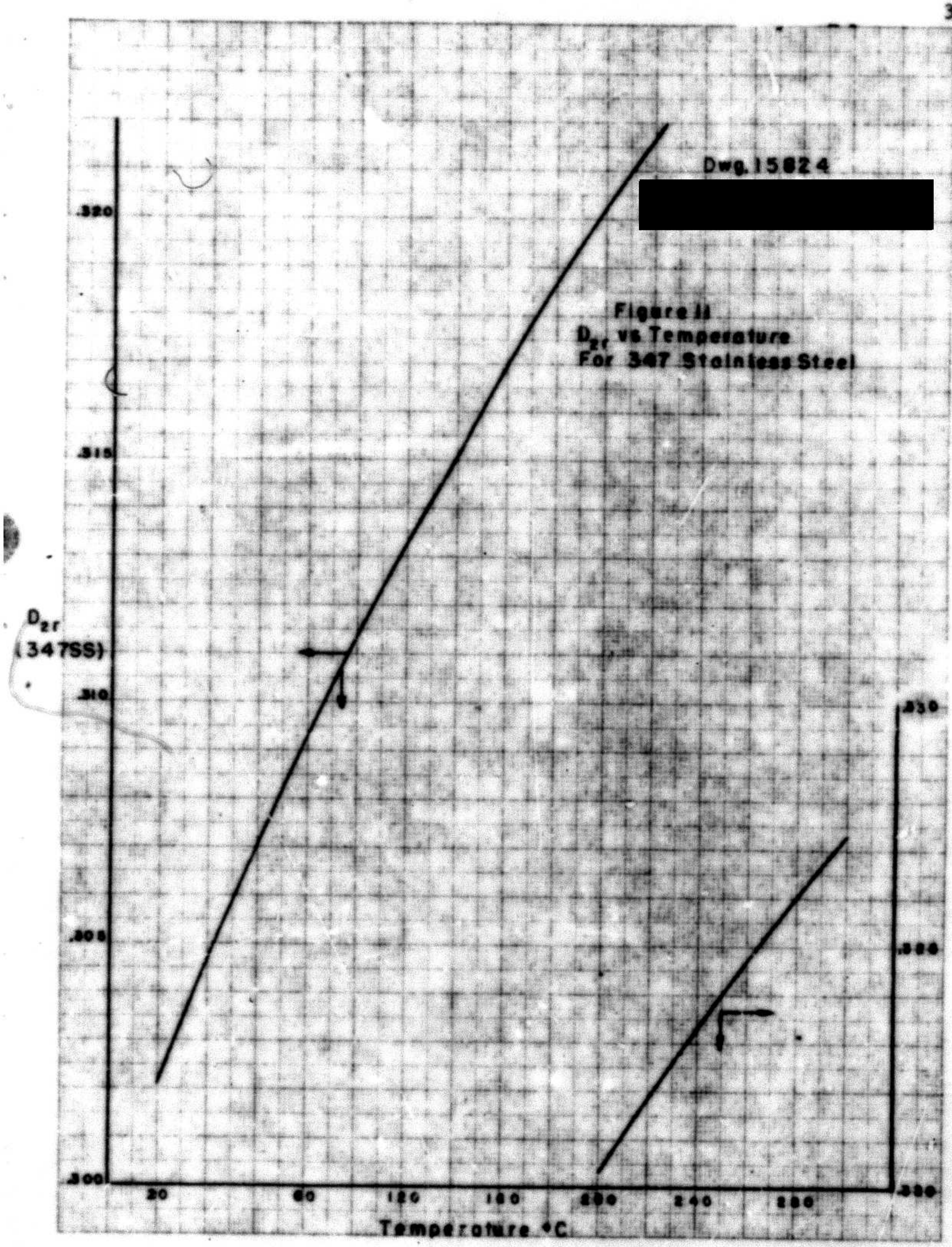

Dwg. 15824
[redacted]
Figure 11
D_{2r} vs Temperature
For 347 Stainless Steel
D_{2r} (347SS)
.300
.305
.310
.315
.320
20
120
160
200
240
Temperature °C

Figure 12

Dwg. 15825

[redacted]

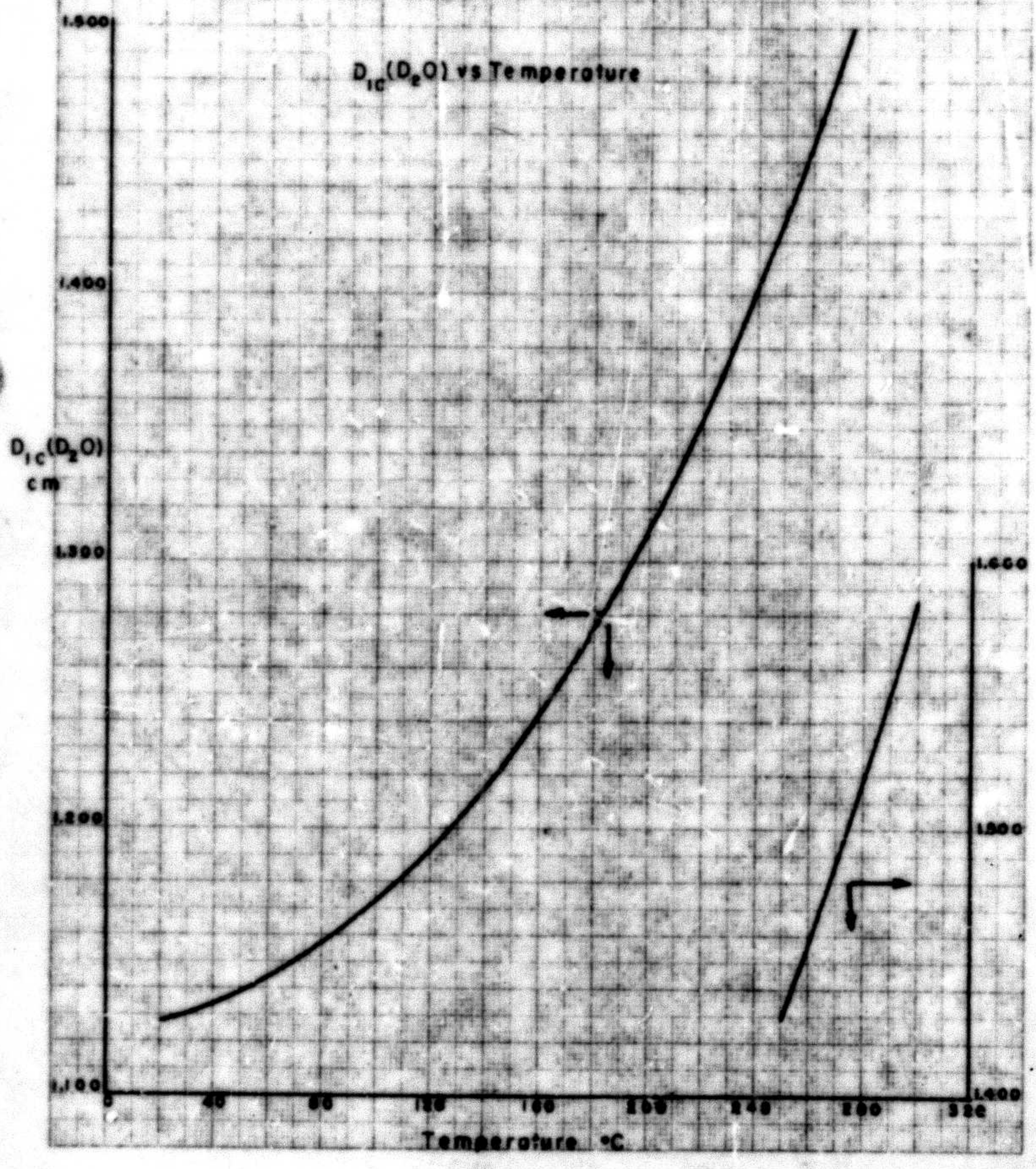


Figure 13 Dwg. 15826

[redacted]

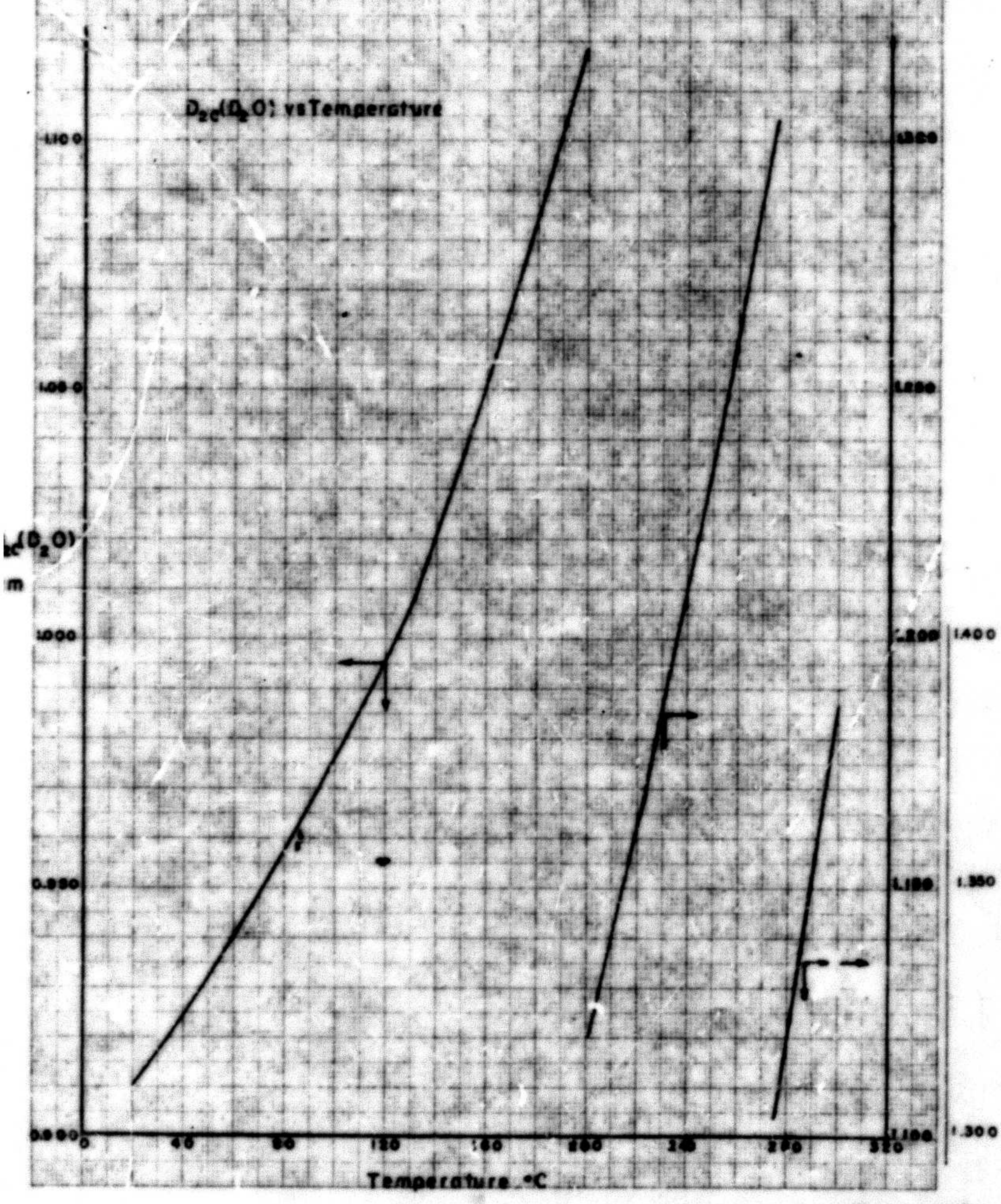


Figure 14 Dwg. 15827

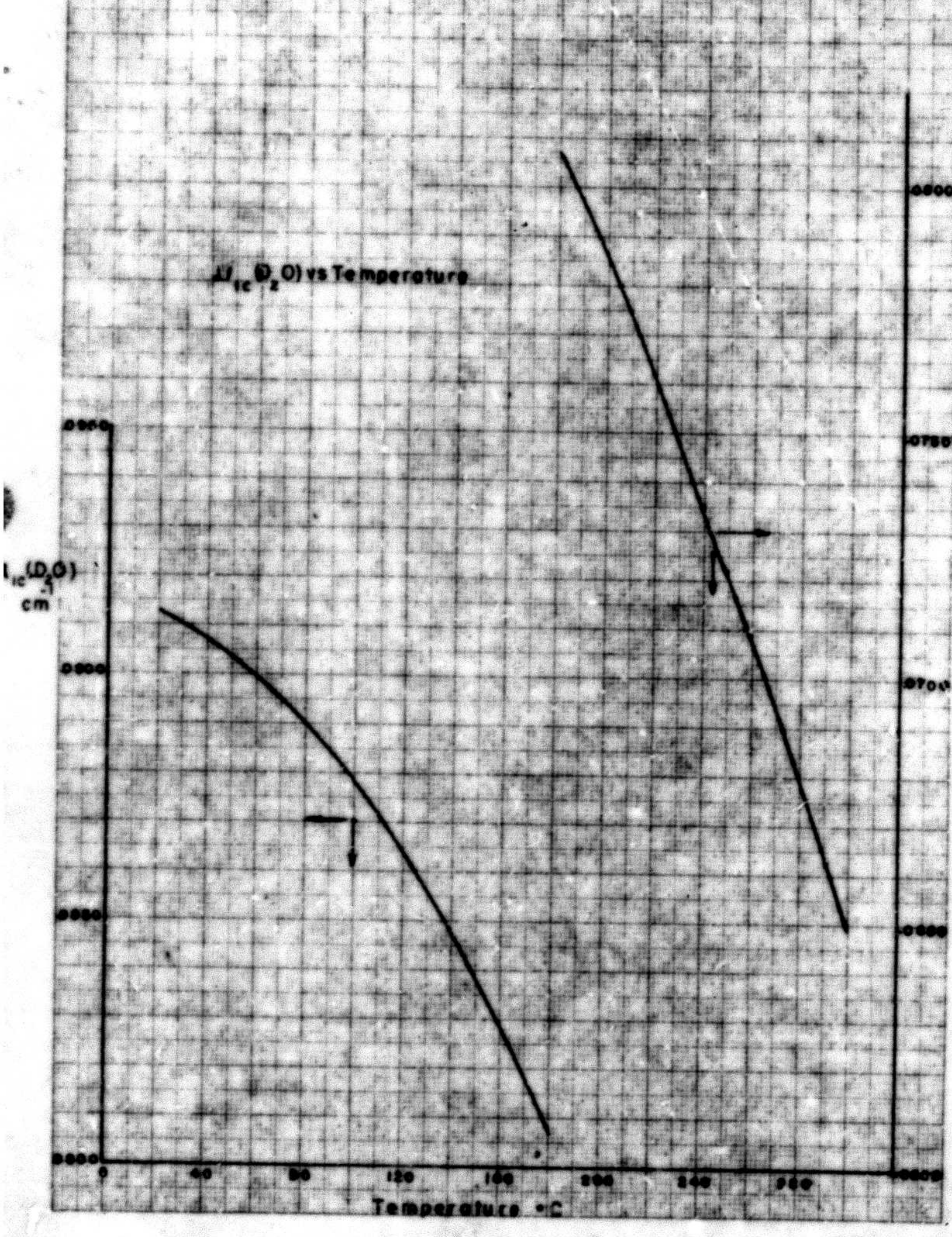
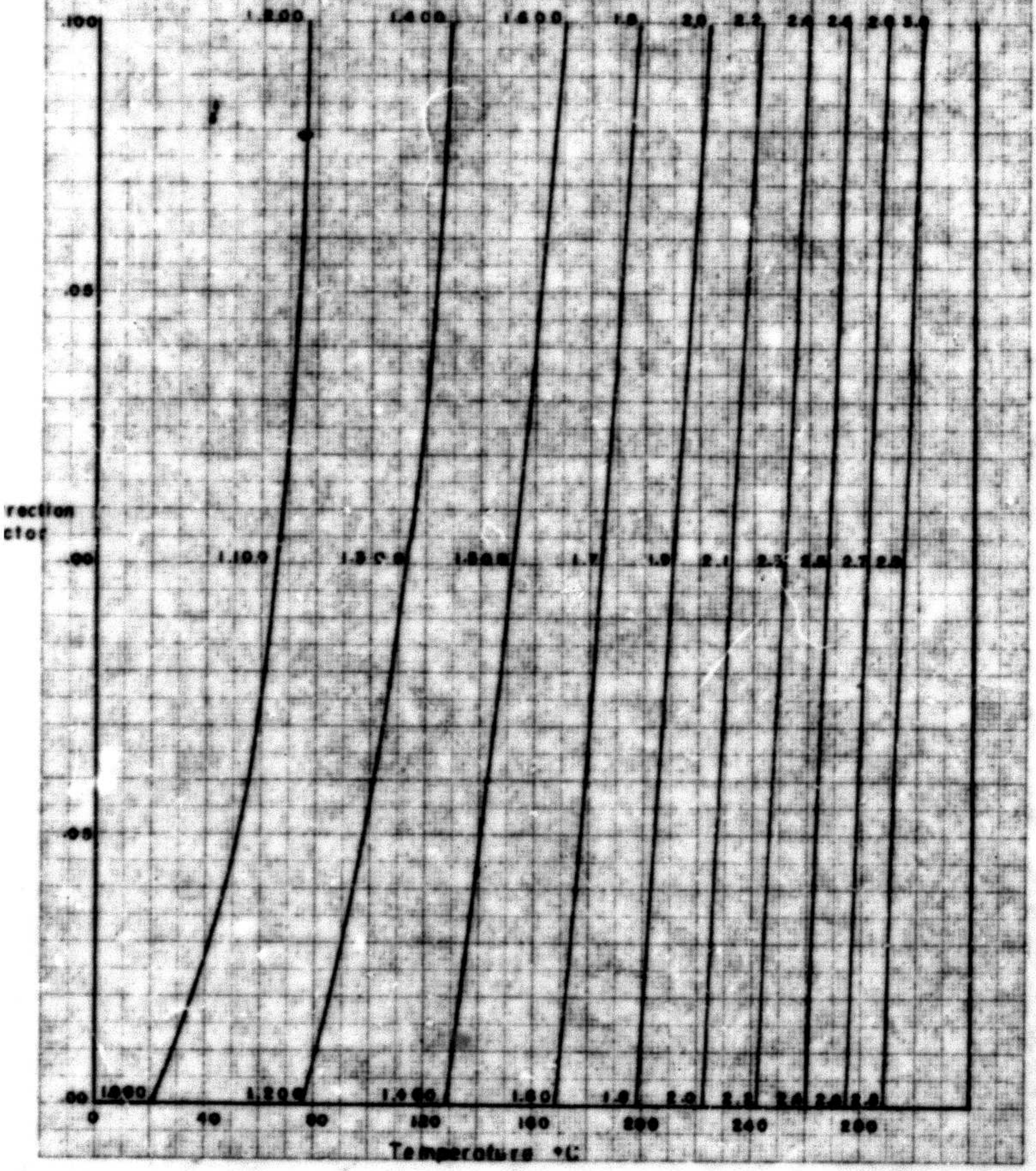


Figure 15
Dwg. 15828

[redacted]

L² Correction Factor vs Temperature
[L²(20°) = 15130 cm²]



[redacted]

Effectiveness of the Stainless Steel Shell as a Reflector:

With a core diameter of fifteen feet the neutron leakage is quite small so one would not expect the inclusion of the reflecting properties of the container to be of significance.

A verification of this conclusion was obtained by calculating the critical enrichment required vs. β at 250°C for the case of a seven inch stainless steel reflector and also for the case of a bare sphere. The findings, which follow, are of considerable interest in regard to control of a reactor of this size since they show that control by the movement of external reflectors or absorbers will not be satisfactory.

β	with s.s. reflector	bare
38.5	1.008	1.017
40	1.000	1.008
50	.960	.967
60	.937	.945
70	.918	.926
80	.928	.937
90	.931	.942
100	.939	.950
110	.949	.960
120	.960	.973
130	.973	.986
140	.988	1.002
150	1.002	1.017
160	1.018	1.033
170	1.035	1.050
180	1.060	1.067
190	1.075	1.084
200	1.092	1.102
210	1.108	1.120
220	1.126	1.136
230	1.145	1.159
240	1.158	1.179
250	1.180	1.200

[redacted]

[redacted]

Conversion of Beta to Concentration in grams Uranium per liter.

Van Winkle presents in report CF-52-1-124 the following expression for Uranium concentration in terms of Beta and the density of D_2O.

$$\frac{\text{gms U}}{\text{liter}} = \left(\frac{4.95 + 0.2707\beta}{1 + \frac{0.2707}{\rho(D_2O)}\beta}\right)\left(\frac{650.237}{1 + 0.054704\beta}\right)$$

The following figure shows the evaluation of concentration vs. β for selected temperatures from 20°C to 300°C. It may be noted that these functions are nearly linear on log-log paper, and may be closely approximated by an equation of the form,

$$\text{Log}_{10}\,(\text{conc}) = A - B\,\text{Log}_{10}\beta - \frac{C}{\beta}$$

At 250°C this empirical relationship becomes,

$$\text{Log}_{10}(\text{conc}) = 3.994 - 0.990\,\text{Log}_{10}\beta - \frac{1.112}{\beta}$$

Critical Enrichment under Operating Conditions.

The prescribed operating condition is 250°C with a Uranium concentration of 250 grams per liter. The value of beta required to satisfy these conditions is obtained by solving the equation,

$$\frac{4.95 + 0.2707\beta}{1 + \left(\frac{0.2707}{0.873}\right)\beta} \quad \frac{650.237}{1 + 0.054704} = 250 \text{ gm U/liter}$$

hence,

$$\beta = 38.29$$

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[redacted]

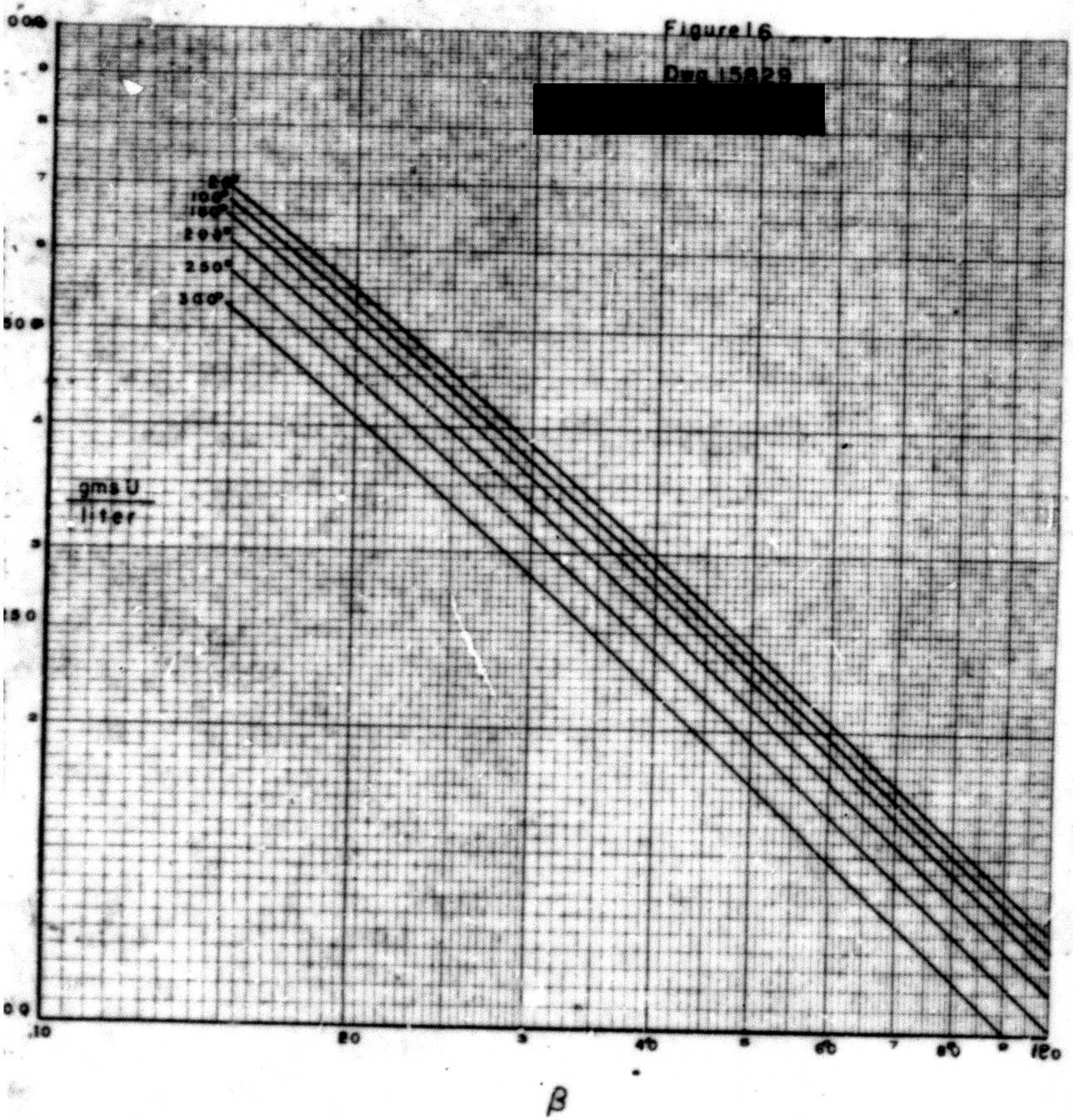


Figure 16

Dwg 15829

[redacted]

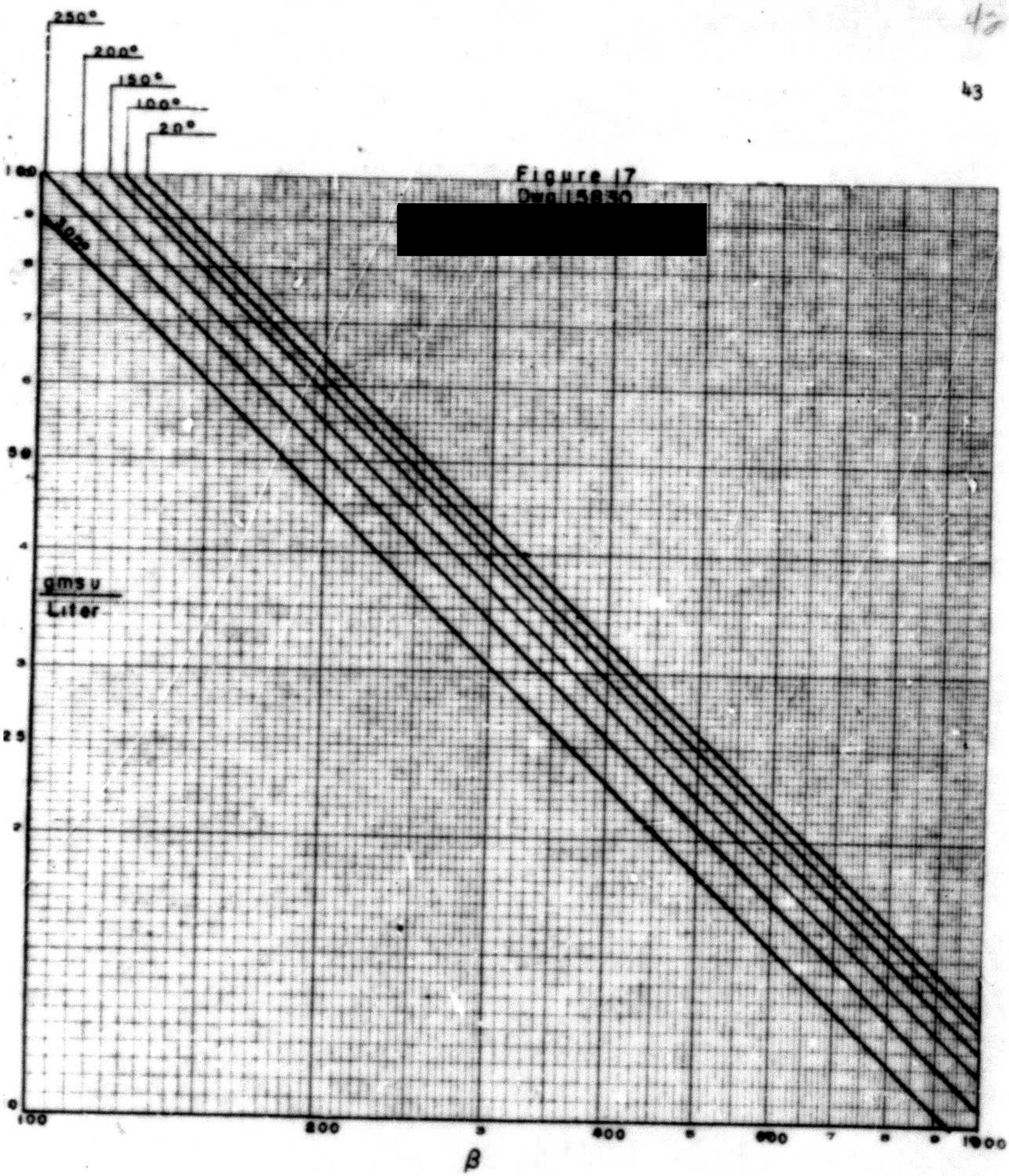


Figure 17
Dwg 15830
[redacted]
250°
200°
150°
100°
20°
gms U
Liter
β
100
200
400
600
1000

[redacted]

The resonance escape probability for this value of beta is obtained from figure 1 to be .7640.

From Table V we find, for 250°C,

$$\gamma = \frac{3.274 + 0.01326\beta}{1300p - 641.3}$$

hence,

$$\gamma = 0.01075$$

Critical Values of Beta and Concentration at Various Temperatures.

In order to predict the critical temperatures corresponding to various concentrations of the 1.075% U-235 fuel use is first made of equations 19a through 19f found in Table V. From these equations it is possible to determine, at each temperature, the value of beta required for $\gamma = .01075$.

The results of these calculations are as follows:

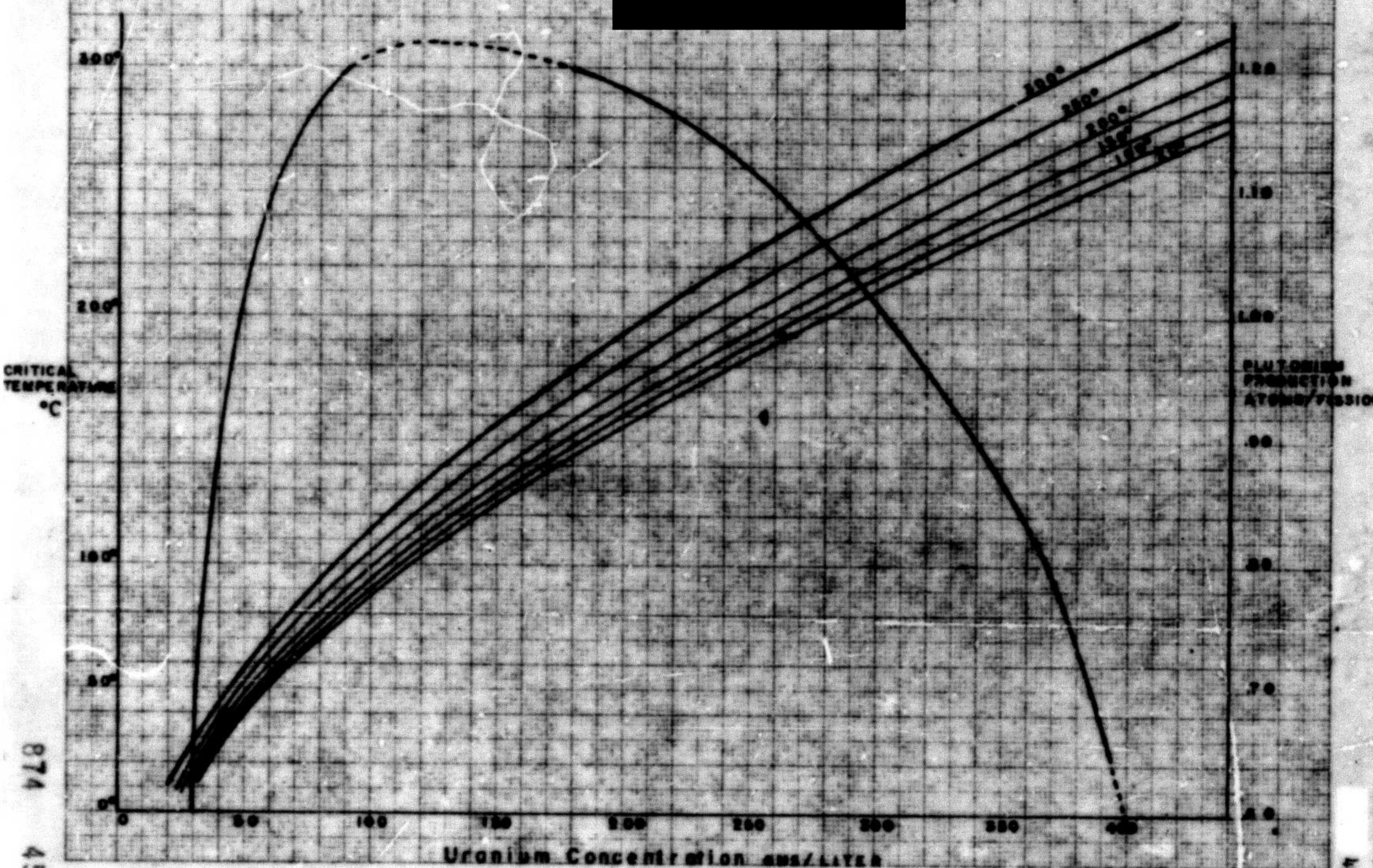
Table VI

Temp, °C	Critical	Critical Conc, gms U/liter
20	29.2 435.7	395 29.8
100	30.3 349.6	369 35.7
150	31.7 287.2	340 41.4
200	33.8 229.3	302 48.5
250	38.3 157.9	250 60.6
300	49.3 102.0	179 89.0

A plot of critical temperature vs. Concentration of the 1.075% U-235 [redacted] fuel solution is given in Figure 18. [redacted]

Figure 18 Dwg. 15831

[redacted]



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[redacted]

Plutonium Production vs. Uranium Concentration

Each fission produces ν neutrons. Of these, $\nu\left(1-\frac{1}{\eta_1}\right)$ are lost by leakage, leaving ν/η_1 available for slowing down. Of this latter number $\frac{\nu}{\eta_1}(1-p)$ are captured in U-238 resonances and ultimately become available as Pu-239. In addition to this Pu production by resonance neutrons there is thermal capture by the U-238, the ratio of thermal capture by 28 to fission by 25 being $\Sigma_a(28)/\Sigma_f(25)$, which is equal to $(1-\gamma)\sigma_{28}/\gamma\sigma_f(25)$. The number of Pu atoms formed per fission is therefore,

$$\text{Pu atoms/fission} = \frac{(1-\gamma)\sigma_{28}}{\gamma\sigma_f\,(25)} + \frac{\nu}{\eta_1}(1-p)$$

For the situation of interest, $\gamma = .010747$, $\nu = 2.50$, $\frac{\sigma_a(28)}{\sigma_f(25)} = \frac{2.706}{546}$

$$\text{Pu atoms/fission} \quad .4562 + 2.50\,\frac{(1-p)}{\eta_1}$$

To evaluate the Pu production rate at various temperatures, η_1 must be known as a function of temperature, as given below:

Temp, °C	20	100	150	200	250	300
η_1	1.0188	1.0202	1.0220	1.0246	1.0287	1.0345
2.50/	2.45387	2.45049	2.44618	2.43997	2.43025	2.41662

A plot of Pu 239 production (atoms/fission) bs. concentration of the fuel is given in Figure 18.

[redacted]

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[redacted]

[redacted]

Burnup of U-235

$$\frac{dN_{25}}{dt} = -N_{25}\,\sigma_a(25)\,\phi$$

$$N_{25} = N_{25_0}\,e^{-\sigma_a(25)\phi t}$$

Buildup of U-236

$$\frac{dN_{26}}{dt} = N_{25}\sigma_c(25)\phi - N_{26}\sigma_a(26)\phi$$

$$dN_{26} + N_{26}\sigma_a(26)\phi\,dt = N_{25_0}\sigma_c(25)\phi\,e^{-\sigma_a(25)\phi t}\,dt$$

$$N_{26} = \frac{N_{25_0}\sigma_c(25)}{\sigma_a(25) - \sigma_a(26)}\left[e^{-\sigma_a(26)\phi t} - e^{-\sigma_a(25)\phi t}\right]$$

Buildup of Np-239

Assume: (1) N_{28} is constant

(2) Np-239 destroyed by decay only

$$\frac{dN_{39}}{dt} = N_{28}\sigma_a'(28)\phi - N_{39}\lambda_{39}$$

define, $\sigma_a'(39) \equiv \dfrac{\lambda_{39}}{\phi}$

$$\sigma_a'(28) \equiv \frac{dN_{28}}{dt}\Big/ N_{28}\phi_{th} = \sigma_a(28) + \frac{\gamma\sigma_f(28)}{(1-\gamma)}\left(\frac{\nu}{1+B^2\tau}\right)(1-p)$$

$$\frac{N_{39}}{N_{28}} = \frac{\sigma_a'(28)}{\sigma_a'(39)}\left[1 - e^{-\sigma_a'(39)\phi t}\right]$$

[redacted] 874

[redacted]

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Buildup of Pu-239

$$\frac{dN_{49}}{dt} = N_{39}\sigma_a'(39)\,\phi - N_{49}\sigma_a(49)\,\phi$$

$$= N_{28}\sigma_a'(28)\,\phi\left[1 - e^{-\sigma_a'(39)\phi t}\right] - N_{49}\sigma_a(49)\,\phi$$

$$\frac{N_{49}}{N_{28}} = \frac{\sigma_a'(28)}{\sigma_a(49)} + \frac{\sigma_a'(28)\, e^{-\sigma_a'(39)\phi t}}{\sigma_a'(39) - \sigma_a(49)} - \frac{\sigma_a'(28)\sigma_a'(39)\, e^{-\sigma_a(49)\phi t}}{\sigma_a(49)\left[\sigma_a'(39) - \sigma_a(49)\right]}$$

Buildup of Pu-240

$$A \equiv \frac{\sigma_a'(28)\sigma_c(49)}{\sigma_a(49)\sigma_a(40)}$$

$$B \equiv \frac{\sigma_a'(28)\sigma_c(49)}{\left[\sigma_a'(39) - \sigma_a(49)\right]\left[\sigma_a'(39) - \sigma_a(40)\right]}$$

$$C \equiv \frac{\sigma_a'(28)\sigma_a'(39)\sigma_c(49)}{\sigma_a(49)\left[\sigma_a(49) - \sigma_a(40)\right]\left[\sigma_a'(39) - \sigma_a(49)\right]}.$$

$$D \equiv (A+B+C) = \frac{\sigma_a'(28)\sigma_c(49)\sigma_a'(39)}{\sigma_a(40)\left[\sigma_a'(39) - \sigma_a(40)\right]\left[\sigma_a(49) - \sigma_a(40)\right]}$$

$$\frac{N_{40}}{N_{28}} = A - B e^{-\sigma_a'(39)\phi t} + C e^{-\sigma_a(49)\phi t} - D e^{-\sigma_a(40)\phi t}$$

[redacted]

Fictitious Total Absorption Cross-sections for U-238 and Np-239 ;

$$\frac{dN_{28}}{dt} = \phi_{th} N_{28} \sigma_a'(28), \qquad \text{define } \sigma'(28) = \left[\frac{dN_{28}}{dt}\right] \Big/ N_{28}\phi_{th}$$

$$\frac{\text{absorptions in U-238}}{\text{fission}} = \frac{N_{28}\sigma_a'(28)}{N_{25}\sigma_f(25)}$$

$$\text{also,} = \frac{N_{28}\sigma_a(28)}{N_{25}\sigma_f(25)} + \frac{\nu}{1+B_1^2\tau}(1-p)$$

$$\sigma_a'(28) = \frac{N_{25}}{N_{28}}\sigma_f(25)\left[\frac{N_{28}\sigma_a(28)}{N_{25}\sigma_f(25)} + \frac{\nu}{1+B_1^2\tau}(1-p)\right]$$

$$\text{But,} \quad \frac{N_{25}}{N_{28}} = \frac{\gamma}{1-\gamma}; \qquad 1+B_1^2\tau = \eta_1$$

$$\therefore \sigma_a'(28) = \sigma_a(28) + \frac{\gamma\sigma_f(25)}{(1-\gamma)}\left(\frac{\nu}{\eta_1}\right)(1-p)$$

$$\sigma_a(39) \equiv \frac{\lambda_{39}}{\phi_{th}} = \frac{3.488 \times 10^{-6}\ \text{sec}^{-1}}{\phi_{th}}$$

Average Flux

Power = constant × $\phi_{av}\Sigma_f V$

$$\phi_{av} = \frac{P}{a\,\Sigma_f V}, \qquad a = \frac{\text{kw-sec}}{\text{fission}}$$

If V is the volume of the entire circulating system, then ϕ_{av} is the average flux over the entire system.

Assume that 180 Mev/fission is available as heat.

$$a = 180\ \frac{\text{Mev}}{\text{fission}} \times 4.45 \times 10^{-20}\ \frac{\text{kw-hr}}{\text{Mev}} \times 3600\ \frac{\text{sec}}{\text{hr}} = 2.88 \times 10^{-14}\ \frac{\text{kw-sec}}{\text{fission}}$$

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[redacted]

$Vol_{core} = 5.00 \times 10^4$ liters $= 1765$ cubic feet

$Vol_{total} = 4620$ cubic feet $= 1.308 \times 10^5$ liters

$P = 10^6$ kw

At 250°C

$$\sigma_f(25) = 544 \sqrt{293/523} = 407 \text{ b}$$

For 250 gm U/1, 1.075% enrichment,

$$N_U = 250/238 \times 6.02 \times 10^{23} = 6.32 \times 10^{20} \text{ cm}^{-3}$$

$$N_{25} = .01075 \times 6.32 \times 10^{20} = 6.796 \times 10^{18} \text{ cm}^{-3}$$

Thus,

$$\Sigma_f = 6.796 \times 10^{18} \times 407 \times 10^{-24} = .002766 \text{ cm}^{-1}$$

$$\phi_{Av}(\text{system}) = \frac{10^6 \text{ kw}}{2.88 \times 10^{-14} \frac{\text{kw-sec}}{\text{fission}} \times .02766 \text{ cm}^{-1} \times V_{system} \text{ cm}^3}$$

$$= \frac{1.255 \times 10^{22}}{V_{system} \text{ cm}^3} = 9.365 \times 10^{13} \text{ n/cm}^2\text{-sec}$$

$$\phi_{Av}(\text{core}) = \phi_{Av}(\text{system}) \frac{V_{system}}{V_{core}} = 9.365 \times 10^{13} \times \frac{13.08}{5.00}$$

$$= 2.45 \times 10^{14} \text{ n/cm}^2\text{-sec}$$

[redacted]

[redacted]

Constants Used

		σ_a		σ_c		σ_f	
		20°C	250°C	20°C	250°C	20°C	250°C
U-235	(25)	644	482	98	73	546	409
U-236	(26)	23	17	23	17	-	-
U-238	(28)	2.71	2.03	2.71	2.03	-	-
Np-239	(39)	0	0	0	0	-	-
Pu-239	(49)	1080	808	330	247	750	561
Pu-240	(40)	250	187	210	157	40	30
Pu-241	(41)	1500	1123	500	374	1000	748
Pu-242	(42)	100	74.8	100	74.8	-	-

[redacted]

[redacted]

[redacted]

Buildup of Pu-239 After Clean Startup

$$\frac{N_{49}}{N_{28}} = \frac{\sigma_a'(28)}{\sigma_a(49)} + \frac{\sigma_a'(28)\,e^{-\sigma_a'(39)\phi t}}{[\sigma_a'(39) - \sigma_a(49)]} - \frac{\sigma_a'(28)\,\sigma_a'(39)\,e^{-\sigma_a(49)\phi t}}{\sigma_a(49)[\sigma_a'(39) - \sigma_a(49)]}.$$

Data: $\sigma_a'(28) = 4.58$ barns

$\sigma_a'(39) = 37,250$ barns

$\sigma_a(49) = 808$ barns

$$\frac{N_{49}}{N_{28}} = \left\{5.6683 + .1257\,e^{-\sigma_a'(39)\phi t} - 5.7940\,e^{-\sigma_a(49)\phi t}\right\} \times 10^{-3}$$

Buildup of Pu-240 after Clean Startup

$$\sigma_a'(28) = \sigma_a(28) + \frac{\gamma\,\sigma_f(25)}{(1-\gamma)}\left(\frac{\nu}{\eta_1}\right)(1-p)$$

At 250°C and 250 gm U/liter of enrichment of 1.074%:

$\gamma = .010747$

$\frac{\gamma}{1-\gamma} = .010863$

$\sigma_f(25)$ 409 b.

$\sigma_a(28)$ 2.03 b.

$\eta_1 = 1.0287$

$\beta = 38.3$

$p = .764$

$$\sigma_a'(28) = 2.03 + 0.010863 \times \frac{2.50}{1.0287} \times .236 \times 409 = 2.03 + 2.55$$

$$= 4.58 \text{ barns}$$

[redacted]

$$\sigma_a'(39) = \frac{3.488 \times 10^{-6}}{\phi_{av}} = \frac{3.488 \times 10^{-6}\ cm^2}{9.365 \times 10^{13}} = 3.725 \times 10^{-20}\ cm^2$$

$$= 3.725 \times 10^{9} \text{ barns}$$

$$A \equiv \frac{\sigma_a'(28)\ \sigma_c(49)}{\sigma_a(49)\ \sigma_a(40)} = \frac{4.58 \times 247}{808 \times 187} = 7.486 \times 10^{-3}$$

$$B \equiv \frac{\sigma_a'(28)\ \sigma_c(49)}{[\sigma_a'(39) - \sigma_a(49)][\sigma_a'(39) - \sigma_a(40)]} = \frac{4.58 \times 247}{(37250 - 808)(37250 - 187)}$$

$$= 8.375 \times 10^{-7}$$

$$C \equiv \frac{\sigma_a'(28)\ \sigma_a'(39)\ \sigma_c(49)}{\sigma_a(49)[\sigma_a(49) - \sigma_a(40)][\sigma_a'(39) - \sigma_a(49)]}$$

$$= \frac{4.58 \times 37250 \times 247}{808(808 - 187)(37250 - 808)} = 2.303 \times 10^{-3}$$

$$D \equiv \frac{\sigma_a'(28)\ \sigma_c(49)\ \sigma_a'(39)}{\sigma_a(40)[\sigma_a'(39) - \sigma_a(40)][\sigma_a(49) - \sigma_a(40)]}$$

$$= \frac{2.036 \times 247 \times 37250}{187(37250 - 187)(808 - 187)} = \frac{1.87327 \times 10^{7}}{.4304015 \times 10^{20}} = 9.\text{[illegible]} \times 10^{-3}$$

The Ratio of Pu-239/Pu-240 as a Function of Time After Clean Startup

Using, for the convenience of notation:

$a = \sigma_a'(28)$	$b = \sigma_a'(39)$	$c = \sigma_a(40)$	$d = \sigma_a(49)$	$f = \sigma_c(49$
$= 4.58$ b.	$= 37250$ b.	$= 187$ b.	$= 808$ b.	$= 247$ b.

The foregoing expressions for the Pu-239 and Pu-250 concentrations, relative to U-238, become,

$$\frac{N_{49}}{N_{28}} = \frac{a}{d} + \frac{ae^{-b\phi t}}{b - d} - \frac{abe^{-d\phi t}}{d(b - d)}$$

$$\frac{ac\left\{(b-c)(b-d)(d-c) + d(b-c)(d-c)e^{-b\phi t} - b(b-c)(d-c)e^{-d\phi t}\right\}}{cd(b-c)(b-d)(d-c)}$$

$$\frac{N_{40}}{N_{28}} = \frac{af}{cd} - \frac{afe^{-b\phi t}}{(b-d)(b-c)} + \frac{abfe^{-d\phi t}}{d(d-c)(b-d)} - \frac{abfe^{-c\phi t}}{c(b-c)(d-c)}$$

[redacted]

Figure 19
Dwg 15832
[redacted]

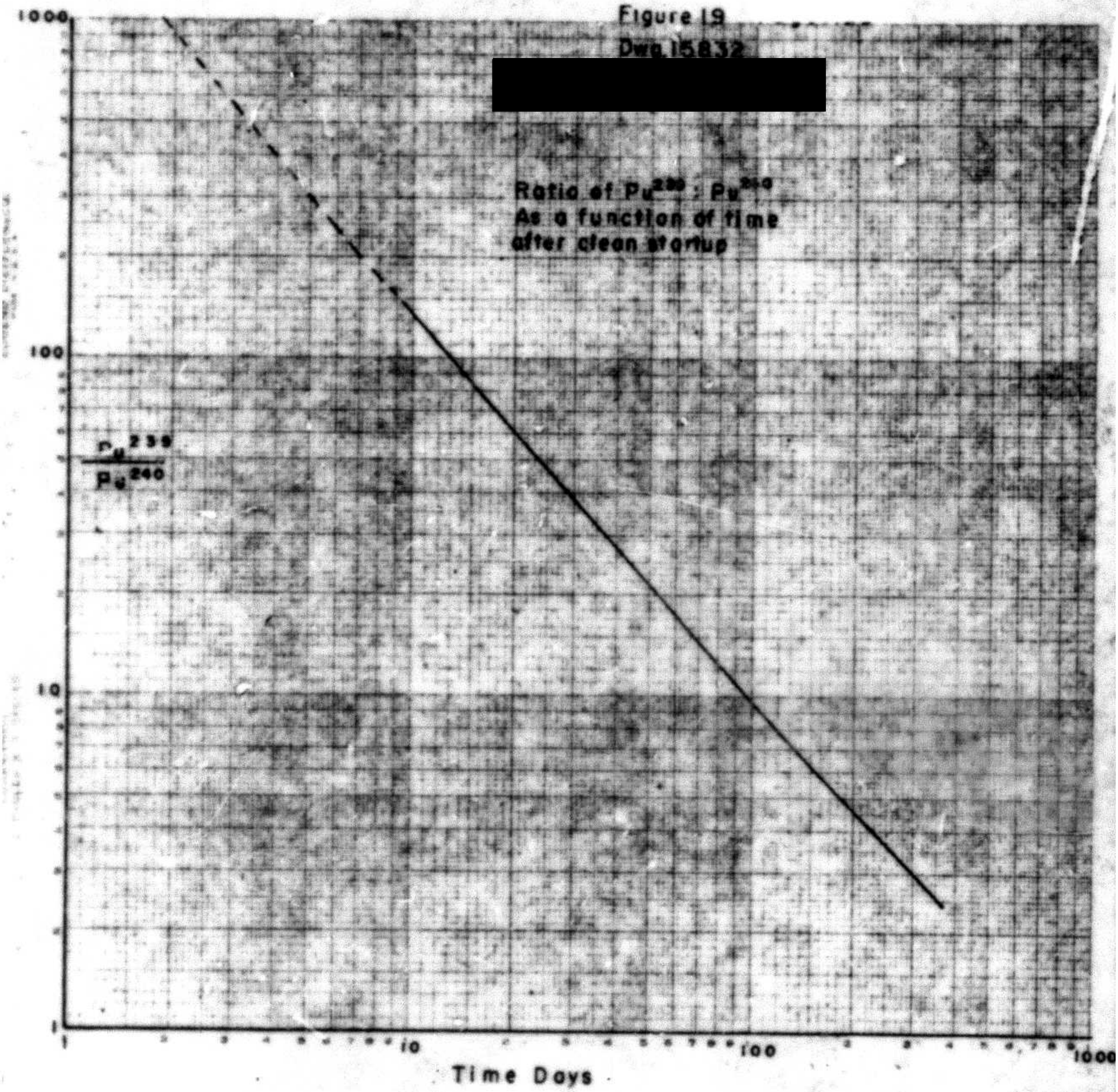
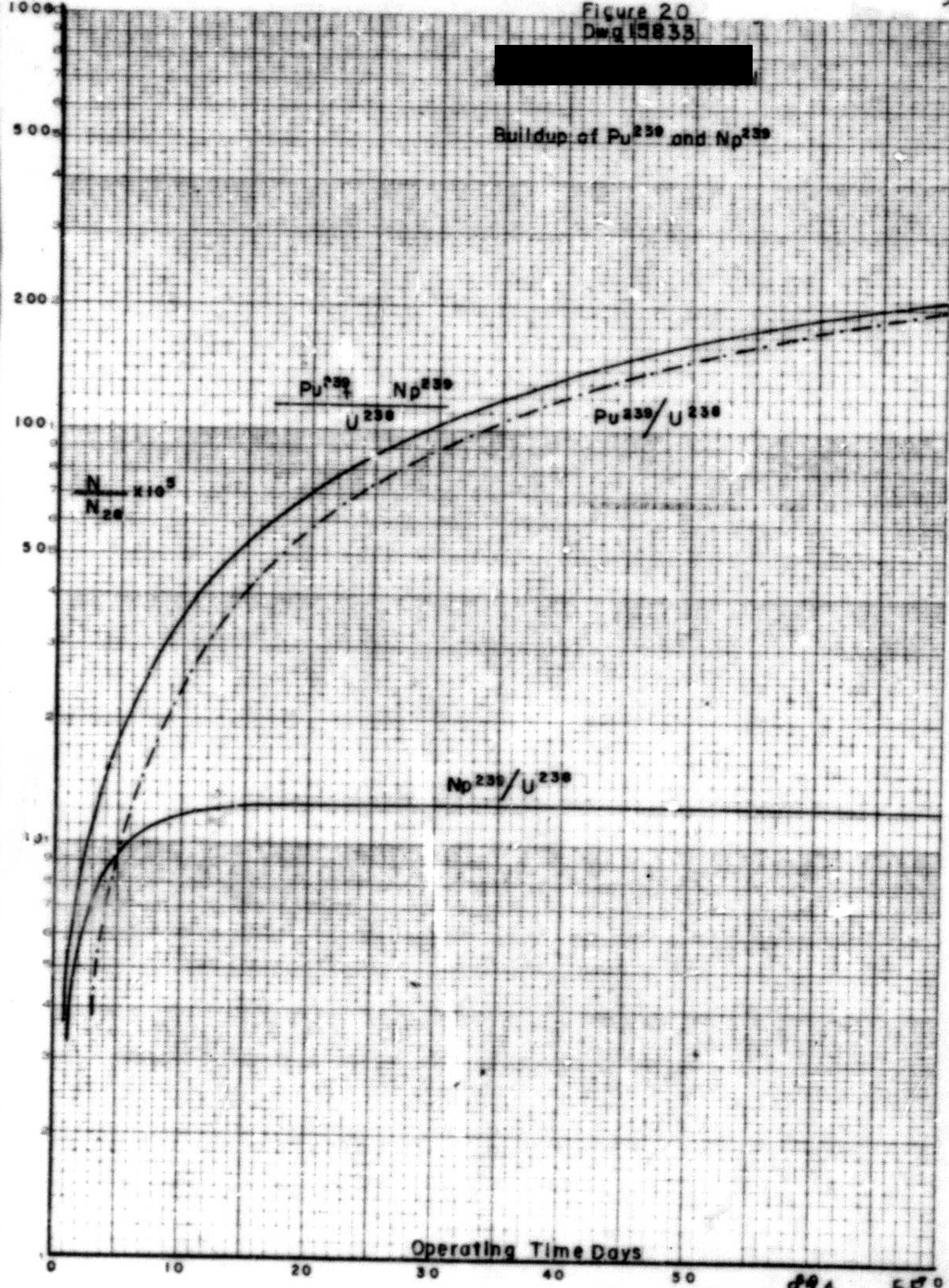


Figure 20
Dwg 15833
[redacted]

Buildup of Pu^{239} and Np^{239}



$$\frac{N_{40}}{N_{28}} = af \left\{ \frac{(b-c)(b-d)(d-c) - cd(d-c)e^{-b\phi t} + bc(b-c)e^{-d\phi t} - bd(b-d)e^{-c\phi t}}{cd(b-c)(b-d)(d-c)} \right\}$$

By taking the ratio of these two expressions one obtains the ratio of Pu-239/Pu-240.

$$\frac{N_{49}}{N_{40}} = \frac{c}{f} \times \frac{(b-c)(b-d)(d-c) + d(b-c)(d-c)e^{-b\phi t} - b(b-c)(d-c)e^{-d\phi t}}{(b-c)(b-d)(d-c) - cd(d-c)e^{-b\phi t} + bc(b-c)e^{-d\phi t} - bd(b-d)e^{-c\phi t}}$$

Insertion of the above numerical values gives,

$$\frac{N_{49}}{N_{40}} = \frac{6.35008 + 0.140795e^{-b\phi t} - 6.490873e^{-d\phi t}}{8.387536 - 0.0009383e^{-b\phi t} + 2.581716e^{-d\phi t} - 10.96831e^{-c\phi t}}$$

A plot of the ratio of N_{49}/N_{40} as a function of time is given on the attached sheet.

Continuous Processing Rate

In the foregoing calculations it has been shown that twenty three days of continuous full power operation (clean startup) will be possible before the limiting Pu-240 concentration is reached.

It is now desired to determine the proper rate of continuous processing necessary to maintain the equilibrium ratio of Pu-240/Pu-239 = 0.02.

If we represent by C the fraction of the total volume withdrawn per second we may express the time rate of change of the Pu-239 and Pu-240 content at equilibrium as:

[redacted]

$$\frac{dN_{49}}{dt} = \phi_{av}\sigma_c(28)N_{28} + \phi_{av}\sigma_f(25)N_{25}\frac{\nu}{\eta_1}(1 - p) - \phi_{av}\sigma_a(49)N_{49} - CN_{49} = 0$$

$$\frac{dN_{40}}{dt} = \phi_{av}\sigma_c(49)N_{49} - \phi\sigma_a(40)N_{40} - CN_{40} = 0$$

At equilibrium these rates of change will be zero, thus enabling us to solve the second equation for the ratio of N_{40}/N_{49}.

$$\frac{N_{40}}{N_{49}} = \frac{\phi_{av}\sigma_c(49)}{\phi_{av}\sigma_a(40) + C}$$

It will be noted that the limiting value of the ratio of N_{40}/N_{49} for a zero processing rate is simply $\sigma_c(49)/\sigma_a(40)$ which agrees with the limiting value of the expression for this ratio derived for the case of infinite exposure under batch processing.

Substituting the following:

$$\phi_{av} = 9.365 \times 10^{13}\ cm^{-2}\ sec^{-1}$$
$$\sigma_c(49) = 2.47 \times 10^{-22}\ cm^2$$
$$\sigma_a(40) = 1.87 \times 10^{-22}\ cm^2$$
$$N_{40}/N_{49} = 0.02$$

gives,

$$C = 1.1391 \times 10^{-6}\ sec^{-1} = 0.09841\ day^{-1}$$

Since the total system volume is 1.308×10^5 liters one must withdraw and process daily 1.308×10^5 liters $\times\ 0.09841\ day^{-1} = 12,870$ liters/day.

[redacted] 874

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[redacted]

Equilibrium Concentrations of Pu-239 and Pu-240 - Continuous Processing:

As developed in the preceding section, the equations which determine the Pu-239 and Pu-240 concentrations at equilibrium are;

$$\phi_{AV}\sigma_c(28)N_{28} + \phi_{AV}\sigma_f(25)N_{25}\frac{\nu}{\eta_1}(1-p) - N_{49}\left[\phi_{AV}\sigma_a(49)+C\right] = 0$$

$$\phi_{AV}\sigma_c(49)N_{49} - N_{40}\left[\phi_{AV}\sigma_a(40)+C\right] = 0$$

Inserting numerical values for the known constants these equations become;

$$1.1886 \times 10^{11} + 1.479 \times 10^{11} - N_{49}(7.567 \times 10^{-8} + 113.91 \times 10^{-8}) = 0$$

$$2.313155 \times 10^{-8} N_{49} - 115.65775 \times 10^{-8} N_{40} = 0$$

At 250 gm U/liter, $N_U = 6.32 \times 10^{20}$ cm^{-3}, the U-238 content is $(1 - \gamma) =$ 0.989253, hence,

$$N_{28} = 0.989253 \times 6.23 \times 10^{20} = 6.252 \times 10^{20} \text{ cm}^{-3}$$

$$N_{25} = 0.010747 \times 6.32 \times 10^{20} = 6.792 \times 10^{18} \text{ cm}^{-3}$$

$$N_{49} = 2.196 \times 10^{17} \text{ cm}^{-3}$$

and, $$N_{40} = 4.392 \times 10^{15} \text{ cm}^{-3}$$

It follows that the equilibrium Pu-239 concentration is,

$$\frac{2.196 \times 10^{17} \text{ cm}^{-3}}{6.023 \times 10^{23} \text{ mol}^{-1}} \times 239 \text{ gm/mol} \times 10^3 \frac{\text{cm}^3}{\text{liter}} \times 10^3 \text{ mg/g} =$$

$= 87.1$ mg Pu-239/liter

and, the equilibrium Pu-240 concentration is 1/50 the above or,

$$\frac{87.1}{50} = 1.74 \text{ mg Pu-240/liter}$$

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Concentrations of Pu-239 and Pu-240 at Discharge, Batch Processing:

After 23 days of full power operation the allowable Pu-240 content is reached. Examination of a plot of N_{49}/N_{28} vs. time (Fig. 20) shows that at this time,

$$\frac{N_{49}}{N_{28}} = 7.98 \times 10^{-4}$$

hence,

$$N_{49} = 7.98 \times 10^{-4} \times N_{28} = 7.98 \times 10^{-4} \times 6.252 \times 10^{20} \text{ cm}^{-3}$$
$$= 4.99 \times 10^{17} \text{ cm}^{-3}$$

and,

$$N_{40} = \frac{N_{49}}{50} = 9.98 \times 10^{15} \text{ cm}^{-3}$$

At discharge, the Pu-239 concentration will be,

$$\frac{4.99 \times 10^{17} \text{ Pu-239/cm}^{-3}}{6.023 \times 10^{23} \text{ Pu-239/mol}} \times 239 \frac{\text{gm}}{\text{mol}} \times 10^{3} \frac{\text{cm}^3}{\text{liter}} \times 10^{3} \frac{\text{mg}}{\text{gm}} =$$
$$= 198 \text{ mg Pu-239/liter}$$

and the discharge concentration of Pu-240 will be,

$$\frac{198}{50} = 3.96 \text{ mg Pu-240/liter}$$

Plutonium Production Rates: Batch and Continuous Processing:

For batch processing, the average daily Pu-239 production is,

$$1.308 \times 10^{5} \text{ liters} \times \frac{1}{23} \text{ days}^{-1} \times 198 \times 10^{-3} \frac{\text{gm Pu}}{\text{liter}} = 1125 \frac{\text{gm Pu-239}}{\text{day}}$$

For continuous processing, the daily Pu-239 production is,

$$0.09841 \text{ day}^{-1} \times 1.308 \times 10^{5} \text{ liters} \times 87.1 \times 10^{-3} \frac{\text{gm Pu}}{\text{liter}} =$$
$$= 1120 \text{ gm Pu-239/day}$$

APPENDIX B

PILE AREA

Introduction:

This appendix contains a detailed analysis of the reactor pile area, as originally referred to in the introductory summary capital cost analysis, presented on page 12 . Those components described in this section appear in the breakdown designated as figure 1.

1 - Reactor:

a) Reactor Core

The reactor shell incorporated in this design consists of four independent spheres or "laminations". The inner three spheres, with a total thickness of three inches, act as a shield, attenuating the core radiations to such an extent that the external sphere, which acts as the pressure shell, absorbs little of the "leakage" radiations. This type of construction is necessary to prevent abnormally high thermal stress in the pressure shell. A thickness of four inches is employed in the outer shell. Approximately three inches of this is necessary to withstand the 1000 psi system pressure. The additional inch is required for that thermal stress which does exist.

Cooling of the shell is accomplished by passing water through one inch annuli existing between the shells. About 1.6% of the total energy of fission is emitted as heat in the steel spheres and is removed by these water streams.

Data relative to the shells follow:

Shell A -

Inside diameter	-	15' 0"
Outside diameter	-	15' 1½"

[redacted]

Figure 1

Estimated Capital Costs of the Pile Area

in thousands of dollars

1 - Reactor			
a) Reactor Core		$ 1,226	
b) Major Cell Equipment		4,894	
c) Auxilliary Equipment		2,450	
d) Instrumentation		1,000	
e) Concrete Shield		909	
f) Crane		100	
	Sub total	$ 10,579	$ 10,579
2- Power Plant			
a) Turbo-generators with foundations		$ 10,000	
b) Steam drums		150	
c) Condenser and Condensate Pumps		1,800	
d) Piping, Valves and Insulation		1,800	
e) Crane		100	
f) Controls		1,000	
g) Circulating water pumps, circulating water system, screens, piping and chlorination equipment		2,850	
h) Dimineralization Plant		175	
i) Miscellaneous Power Plant Equipment		342	
j) Transmission Terminal		1,000	
k) Electric Plant		3,413	
l) Miscellaneous		675	
	Sub total	$ 23,305	$ 23,305
3 - Land			
a) Site (500 acres)		250	
b) Improvements		830	
	Sub total	$ 1,080	$ 1,080

[redacted]

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[redacted]

Figure 1 (continued)

Estimated Capital Costs of the Pile Area

in thousands of dollars

4 - Structures			
a) Reactor, Steam Generation and Turbine Building with Control Room, including Heating, Ventilation, Lighting, Excavation and Foundation Costs		$ 4,000	
b) Offices and Shops, including Tools and Equipment		860	
c) Crib House		2,150	
d) Water System		565	
e) Decontamination and Waste Storage		114	
f) Sewerage Disposal Plant, Storm and Sanitary Sewers		750	
g) Miscellaneous Buildings (gate house, portal, canteen, etc.)		200	
h) Stack		300	
	Sub total	$ 8,939	$ 8,939
5 - Miscellaneous			
a) Operating Tools and Materials		$ 300	
b) Spare Parts		500	
c) Temporary Construction		960	
d) Health Physics Instruments		150	
	Sub total	$ 1,910	$ 1,910
6 - Engineering		$ 5,000	$ 5,000
7 - Contingencies (14.7%)		$ 7,470	$ 7,470
	Total Direct Cost		$ 58,283
8 - Overhead (15%)		$ 8,717	$ 8,717
	Grand Total Cost		$ 67,000

[redacted]

Thickness	-	3/4"
Material	-	347 Stainless Steel
Weight	-	21,680 lbs

Shell B -

Inside diameter	-	15' 3½"
Outside diameter	-	15' 5½"
Thickness	-	1"
Material	-	Carbon Steel
Weight	-	30,110 lbs

Shell C -

Inside diameter	-	15' 7½"
Outside diameter	-	15' 10"
Thickness	-	1¼"
Material	-	Carbon Steel
Weight	-	40,150 lbs

Shell D -

Inside diameter	-	16' 0"
Outside diameter	-	16' 8"
Thickness	-	4"
Material	-	Carbon Steel
Weight	-	135,950 lbs

The estimated cost of the shell may be computed by assuming a cost for the stainless steel (347) of $9.00 per pound, and for the carbon steel of $5.00

[redacted]

per pound. These figures include fabrication and installation charges. The cost so determined is $1,226,000.

b) Major Cell Equipment

A rather complete cost analysis of the major pieces of equipment in the heat exchanger cells is presented in the summary following (figure 2). It should be pointed out that many items listed are minor in cost and appear, therefore, somewhat naive in a report of this nature. However, for the sake of completeness these details are included.

Since this reactor is a "scale-up" of the ISHR (Intermediate Scale Homogeneous Reactor), preliminary design data from that project has been incorporated wherever possible. Many pieces of equipment such as the heat exchangers, gas separators, and recombiners fall into this category and are subject to change should further design work show this to be desirable.

All the equipment shown within the unit cell in figure 3 is included in the following compilation (figure 2). Auxilliary equipment such as oxygen storage tanks, piping from these tanks, small pumps, and similar equipment not directly associated with the main circulating system are included in the succeeding section.

Also indicated are the soup holdup figures for the appropriate equipment.

[redacted]

Figure 2

Cost Analysis of Unit Cell

Mechanical Equipment

[redacted]

Equipment Description	Material of Construction	Cost per Basic Unit	Basic Units per Component	Cost per Component	Components per Cell	Cost per Cell	Soup Holdup per Cell, ft^3
1. Main Circulating Pump	347 ss	-	-	$150,000	1	$150,000	31
2. Heat Exchangers	347 ss	$ 5/lb	33,000 lb	$165,000	2	$330,000	187
3. Gas Separators	347 ss	$ 5/lb	6,700 lb	$ 33,500	2	$ 67,000	64
4. Cyclone Separators	304 ss	$4.75/lb	750 lb	$ 3,563	2	$ 7,126	-
5. Catalytic Recombiner	304 ss	$4.75/lb	2,700 lb	$ 12,825	2	$ 25,650	-
6. Condenser	304 ss	$4.75/lb	5,800 lb	$ 27,550	1	$ 27,550	-
7. Oxygen Blower and Motor	304 ss	-	-	$ 30,000	1	$ 30,000	-
8. Isolation Valve, 24"	347 ss	-	-	$ 40,000	2	$ 80,000	19
9. Check Valve, 24"	347 ss	-	-	$ 35,000	1	$ 35,000	10
10. Soup Piping, 24" Schedule 60	347 ss	$ 714/ft	21.9 ft	$ 15,637	1	$ 15,637	59
11. Soup Piping, 18" Schedule 40	347 ss	$ 398/ft	49.4 ft	$ 19,661	1	$ 19,661	73
12. High Pressure O_2 Piping, 4", Sch. 40S	304 ss	$ 30/ft	58.0 ft	$ 1,740	1	$ 1,740	-

[redacted]

Figure 2 (con'd)

[redacted]

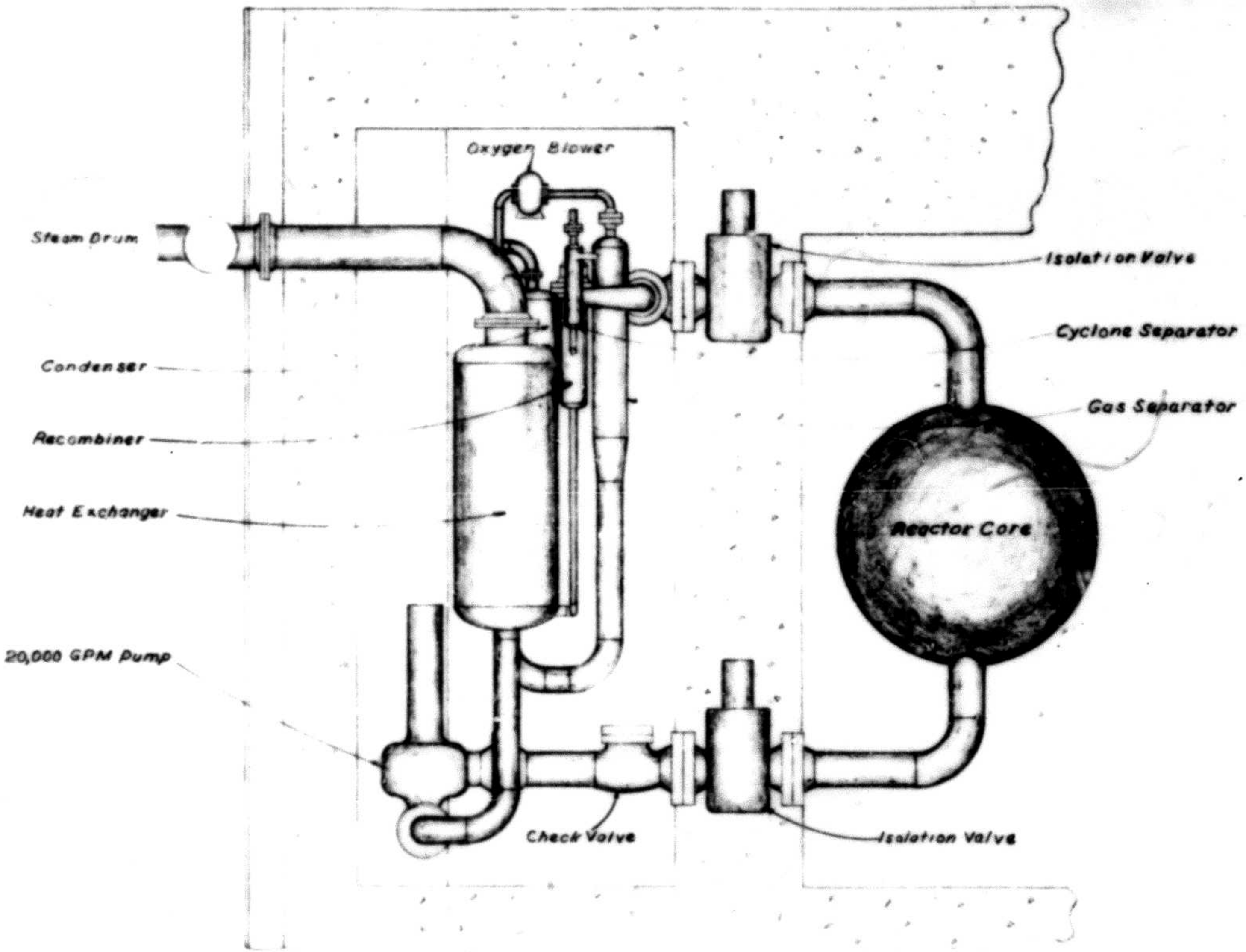
Equipment Description	Material of Construction	Cost per Basic Unit	Basic Units per Component	Cost per Component	Components per Cell	Cost per Cell	Soup Holdup per Cell, ft^3
13. High Pressure O_2 Piping, 6", Sch. 40S	304 ss	$52.25/ft	29.5 ft	$ 1,541	1	$ 1,541	-
14. Flanges, soup line, 24", 1500 psia	347 ss	-	-	$ 8,642	10	$ 86,420	36
15. Flanges, soup line, 18", 1500 psia	347 ss	-	-	$ 4,443	8	$ 35,544	14
16. Flanges, O_2 system, 4", 1500 psia	304 ss	-	-	$ 202	8	$ 1,616	-
17. Flanges, O_2 system, 6", 1500 psia	304 ss	-	-	$ 481	4	$ 1,924	-
18. Tee, soup line, 24"x18"x18", Sch. 60	347 ss	-	-	$ 4,930	2	$ 9,860	10
19. Tee, O_2 system, 4"x4"x6", Sch. 40S	304 ss	-	-	$ 215	2	$ 430	-
20. Elbows, soup system, 24", Sch. 60	347 ss	-	-	$ 4,940	2	$ 9,880	26
21. Elbows, soup system, 18", Sch. 40	347 ss	-	-	$ 2,590	8	$ 20,720	42
22. Elbows, O_2 system, 6", Sch. 40S	304 ss	-	-	$ 226	3	$ 678	-
23. Elbows, O_2 system, 4", Sch. 40S	304 ss	-	-	$ 94	8	$ 752	-
					Totals per Unit Cell =	$958,729	571 ft^3

Estimate for Foam Glass Insulation for Above Equipment and Core Itself = $100,000

Total Cost for Major Cell Equipment = $4,894,000

[redacted]

Figure 3A
Unit Cell
1000 MW-LSHR
Scale 1" = 10' 0"



Dwg. TD-C-3030

[redacted]

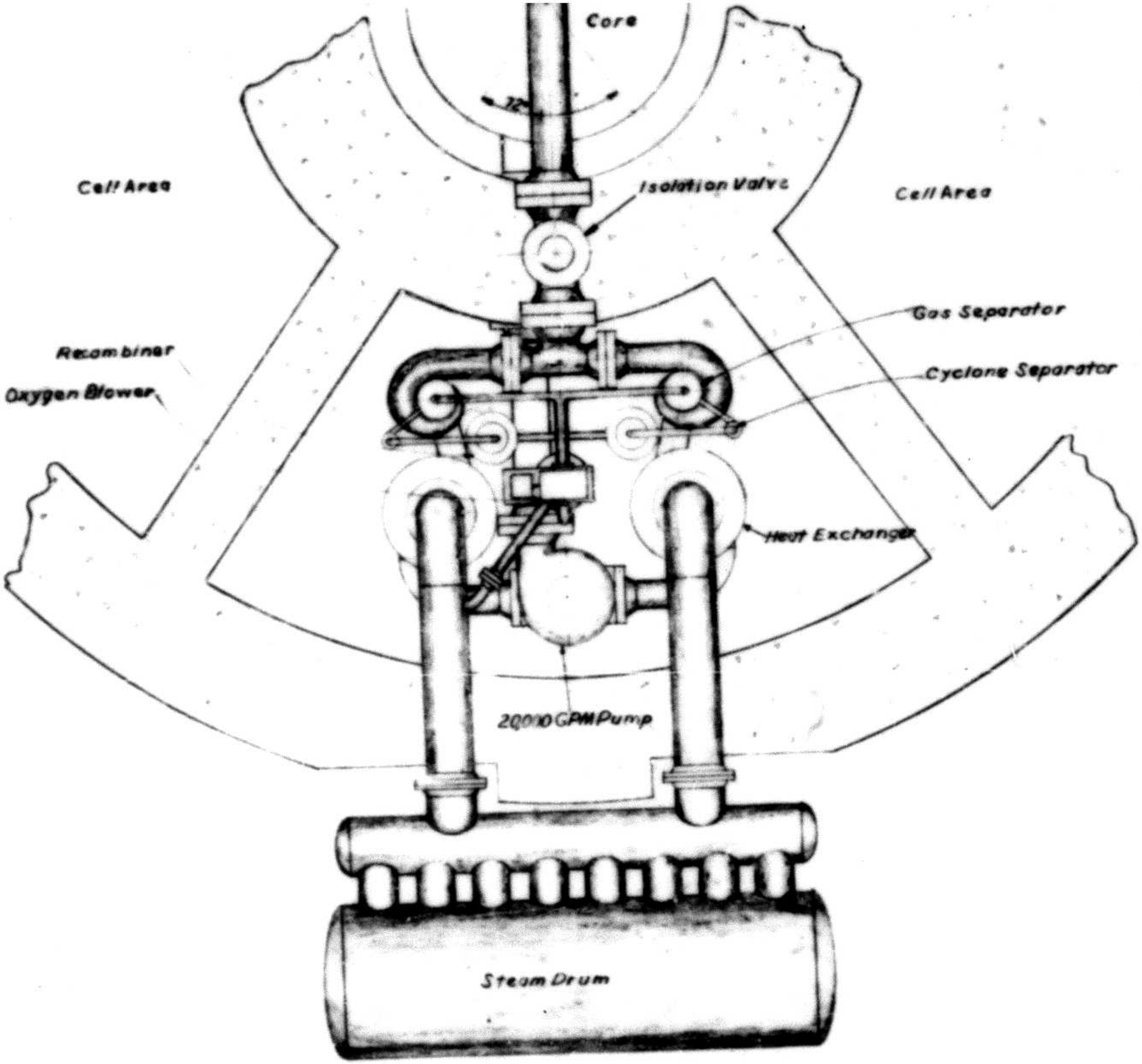


Figure 3B
Unit Cell
1000 MW-LSHB

Scale 1" = 10'

Dwg. TD-C-3031

c) Auxilliary Equipment

A compilation of the major items of auxilliary equipment is shown below. For the most part, preliminary design and layout has not yet been done. Hence, an accurate cost figure for this equipment is not presently available.

Cost Estimate of Auxiliary Equipment

1 - Oxygen System - Total cost $400,000

a) Low pressure oxygen storage
b) Oxygen cooler
c) Dryer
d) Fission Product Absorber
e) Compressor
f) High pressure oxygen storage

2 - Auxilliary Pumps - Total cost $350,000

a) 100 gpm Canned Rotor Circulating Pumps
b) 30 gpm Canned Rotor Circulating Pumps
c) 100 gpm Canned Rotor Feed Pumps

3- Evaporator and Feed System - Total cost $400,000

a) Fuel Feed Tanks
b) Heavy Water Condensate Storage Tanks
c) Heavy Water Condensate Coolers
d) Soup Condensers
e) Evaporators
f) Soup Coolers
g) Concentration Storage Drums

4 - Low Pressure Recombiner System - $60,000

a) Recombiner
b) Blower
c) Condenser

5 - Dump Tank System - Total cost $750,000

6 - Piping and Valving - Total cost $490,000

a) for Oxygen System
b) Evaporator and Feed System
c) Low Pressure Recombiner System
d) Dump System

[redacted]

[redacted]

d) Instrumentation

The instrumentation and control cost figures were taken as those estimated for a liquid cooled reactor of similar power in CEPS-1101 .

e) Concrete Shield

The biological concrete shield includes the following components:

1) Ordinary concrete surrounding the core
2) Ordinary concrete surrounding the unit cells
3) Ordinary concrete dividing the unit cells
4) Barytes blocks for use as temporary shielding. These blocks may be stacked inside a unit cell, thus allowing a workman to enter a non-operating cell after decontamination without complete shut-down of the reactor itself. The shielding would otherwise be insufficient.

Ordinary concrete required for shielding = 5100 cubic yards @ $120/cu yd

= $ 793,000

Barytes blocks (temporary shielding for two cells)

= 53,440 blocks @ $ 2.17/block

= $ 116,000

Total Shield Cost = $ 793,000 $ 116,000 = $ 909,000

It should be noted that the shielding also serves a structural purpose, and helps to reduce the reactor building costs.

[redacted]

[redacted]

f) Crane - 50 ton

The reactor unit cell building is circular in shape and is served by a gantry crane which operates with a circular motion. It is supported, in part, by the outer wall of the unit cells. In order to decrease the overall suspended length of the crane, additional supports are dropped to the circular wall surrounding the core. It is estimated that this crane will cost $ 100,000.

A separate crane is planned for servicing the turbo-generators and condensers in the generation system.

2 - Power Plant:

Steam Cycle

The steam cycle chosen was that involving the use of moisture separators between the high and low pressure stages of the turbines. The resultant thermal efficiency was calculated to be 24%, and the moisture content at the turbine exhaust was found to be 10%.

Following are the assumptions made in the steam cycle calculations:

a) The moisture separator is located in the crossover between the high and low pressure stages of the turbine, operating at a pressure of 10 psia. The efficiency of moisture separation is 75%.

b) The engine (turbine) efficiency is 76%.

c) The steam entering the high pressure end of the turbine is saturated at 210 psia.

d) A pressure drop of ½ psi occurs through the moisture separator.

e) The turbine exhaust pressure is 1.5" Hg.

[redacted]

A steam flow of approximately 620,000 lb/hr was found to be generated in each of the five heat exchanger cells for a total plant steam flow of 3,100,000 lb/hr.

It is estimated that 18,720 kilowatts of electrical power are necessary for the operation of auxilliary equipment in the reactor-generator system itself. Hence, a total of 228,000 kilowatts are available at the busbar. A reactor innage factor of 0.9 was assumed and an electrical power factor of 0.8 was considered adequate.

Therefore, the annual credit received for power at a rate of seven mils per kilowatt-hour is,

228,000 kw x 24 hr/day x 365 day/yr x 0.8 (power factor) x

x 0.9(reactor innage factor) x \$ 0.007/kw-hr =

= \$ 10,066,000 per year

a) <u>Turbine Design and Cost Analysis</u>

There are a total of five 50,000 kilowatt turbo-generator units in this power system. These units are 1800 rpm, tandem compound, double flow, utilizing moisture separators as outlined above. Figure 4, following, indicates the turbo-generator layout.

[redacted]

[redacted]

SCALE: 1" = 40'

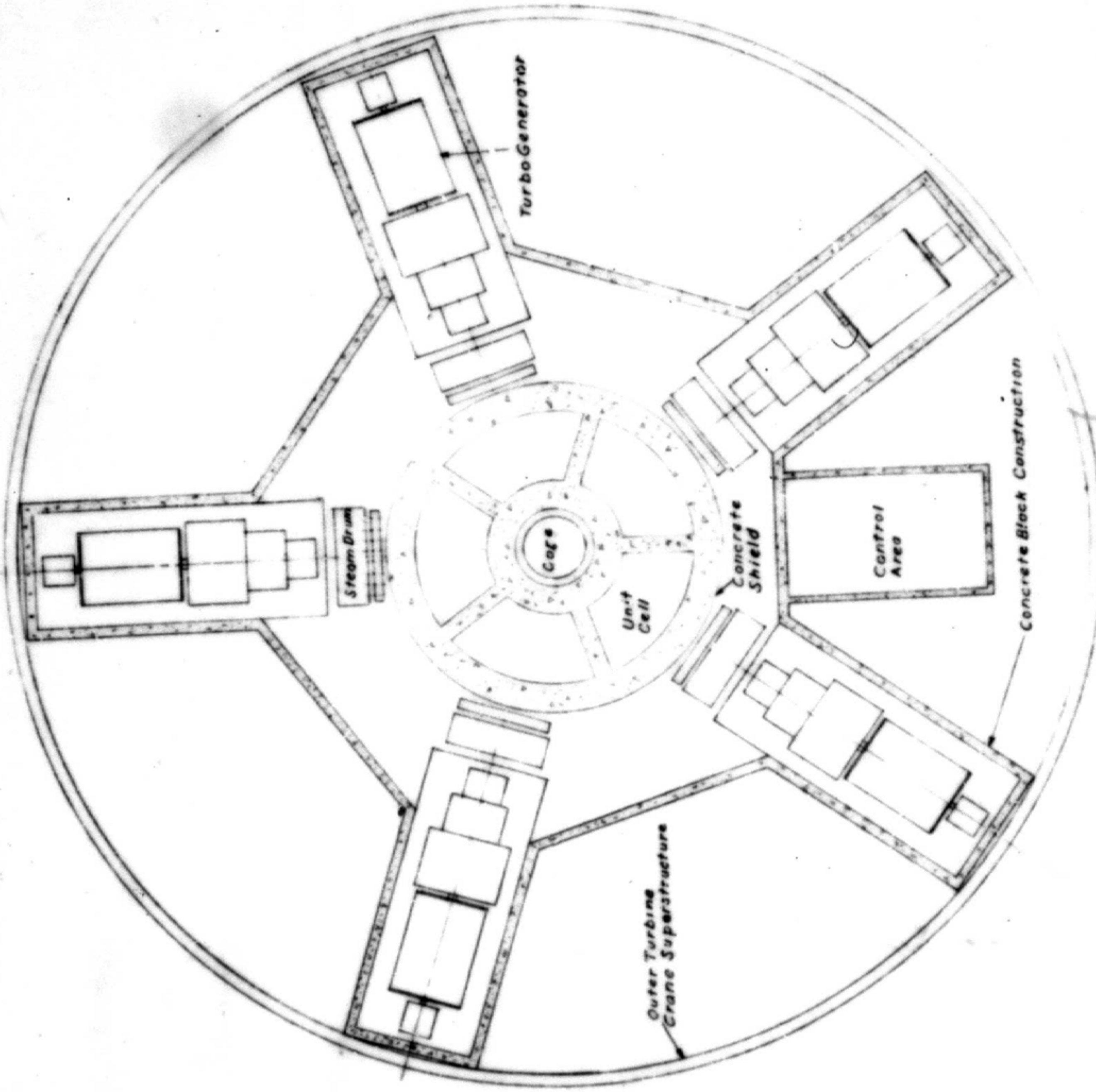


FIGURE 4
TURBO-GENERATOR
LAYOUT
1000 MW - LSHR

Dwg. TD-C-3032

[redacted]

Cost Estimate of a 50,000 kilowatt Turbo-Generator:

One high pressure cylinder with valves	$ 300,000
Two low pressure exhaust ends with 30" blades	1,000,000
One 50,000 Kilowatt Generator	500,000
Sub total	$ 1,800,000
Foundation and Installation	200,000
	$ 2,000,000

The total turbo-generator cost for the plant is, then, $10,000,000.

b) Steam Drums

The steam drums were estimated to weigh 60,000 lb each. An average figure for the cost of miscellaneous tanks and drums at the TVA Johnsonville Steam Plant was about fifty cents a pound, including insulation and installation. This figure was used as the basis for the cost of the steam drums which amounted to a total of $ 150,000 for the five drums in the system.

c) Condensers

The use of one condenser with a surface area of 60,000 square feet was proposed for each turbo-generator unit. Condensate pumps and air ejectors were included in the cost of $ 1,800,000 for the five condensers. This was also estimated from Johnsonville cost data.

[redacted]

[redacted]

d) Piping, Valves and Insulation

Since the plant layout for this reactor compares quite closely with that of the CP-7 as reported in CEPS-1101, several costs of comparable items were taken from this report.

Piping, valves and insulation for the steam plant alone, one of the items referred to above, was estimated at $ 1,800,000.

e) Crane

A crane servicing the turbo-generators is suspended by circular tracks on the outer periphery of the unit cells and on an elevated steel framework at the outer perimeter of the turbo-generators. The crane was estimated to cost $ 100,000.

f) Controls

Control equipment for the steam and turbo-generator plant was estimated at $ 1,000,000 as per CEPS-1101.

g) Circulating Water System

Johnsonville data show that the cost of a circulating water system is $5.70/gpm. It is estimated that the water requirements will be 100,000 gpm per condenser. The total cost of the circulating water system, including pumps, screens, piping and chlorination was found to be $ 2,850,000 for the five condensers.

[redacted]

[redacted]

h) Dimineralization Plant

The remaining five items in this section, including this one, make use of similar equipment described in CEPS-1101.

Total cost - $ 175,000

i) Miscellaneous Power Plant Equipment

1)	Air Compressers and System	$ 117,000
2)	Fire Fighting Equipment	85,000
3)	Miscellaneous hoists, laboratory equipment, heat exchangers pumps, etc.	140,000
	Total	$ 342,000

j) Transmission Terminal

Total cost - $ 1,000,000

k) Electric Plant

Total cost - $ 3,413,000

This includes the following equipment:

a) Main Power Equipment

b) Electric Services for Steam Generator, Tubro-Generators and Buildings.

c) Communications, Alarms, etc.

It may also be pointed out that the total costs at the Johnsonville Plant for the above two items (transmission terminal and electric plant) came

[redacted]

[redacted]

to $ 21.00 per kilowatt of electricity capacity. Using this figure, the cost determined is within 10% of that stated in this report.

1) Miscellaneous

This item refers to foundations, painting, supports, office furniture, and other small equipment not covered elsewhere.

Total cost - $675,000

3 - Land:

According to the rules established by the Reactor Safeguard Committee, a reactor with a power level of 1000 megawatts would need a protective area of over 200,000 acres of land. Since the site envisioned for the LSHR is in a reasonably well populated area where an adequate electrical network tie-in is available, such a land requirement would be prohibitive financially. It is, therefore, assumed that by the time a machine such as this is built, this requirement will be relaxed.

The amount of land provided for the plant site is 500 acres, at an assumed unit cost of $500/acre.

Yard improvements were taken from the CEPS-1101 estimate. They include the following items:

[redacted]

[redacted]

a)	Site clearance, grading and roadways	$ 335,000
b)	Guard towers, fences, roadways and protective lighting	235,000
c)	Railroad Tracks	210,000
d)	Miscellaneous	50,000
	Total	$ 830,000

4 - **Structures:**

The estimates on building costs followed CEPS-1101 quite closely with the exception of the reactor building. Since the concrete shielding previously discussed also serves a structural purpose, the building cost was reduced.

5 - **Miscellaneous:**

Total allowance, $ 1,910,000, based upon CEPS - 1101.

6 - **Engineering:**

Approximately 10% of the base capital cost was assumed for engineering.

7 - **Contingencies:**

Approximately 15% was taken for contingencies.

8 - **Overhead:**

Approximately 15% was assumed for office and administrative overhead.

[redacted]

[redacted]

APPENDIX C

CHEMICAL PROCESSING

[redacted]

[redacted]

Process Description and Cost Estimate

It is proposed that a slightly modified Purex process be evaluated and analyzed economically for use in the plutonium and uranium separations essential to the operation of the reactor system. Modifications necessary for adapting the Hanford type process include the elimination of the metal dissolution step, and the incorporation of heavy water removal and addition steps at the beginning and end of the process, respectively. In addition, since the uranium leaving the chemical process is returned to the reactor and not to a diffusion plant, the second uranium decontamination cycle becomes unnecessary and may be eliminated.

The amount of solution removed from the reactor each day depends upon the plutonium 240 buildup. The nuclear calculation section (appendix A) indicates the desired soup volume for removal to chemical processing is 12,870 liters per day, containing 1120 grams of plutonium and 3218 kilograms of uranium.

The processing plant removes and decontaminates the plutonium and has it ready for transfer to the government at the end of thirty-five days. The uranium is separated, passed thru one decontamination cycle and is returned to unspent fuel storage, to await its return to the reactor circulating system. Thirty-five days also elapse during the uranium processing period.

If a ten year amortization period is used for the chemical processing plant and a total capital charge of sixteen percent against capital investment

[redacted]

is adopted, then the following annual capital charges may be assumed:

For plutonium - \$ 2.50 per gram

For uranium - \$ 1.20 per lb

The quantities of materials processed annually are:

Plutonium - 368 kilograms

Uranium - 1166 tons

The annual charges then become,

For plutonium:

368,000 gm/yr x \$ 2.50/gm = \$ 920,000/yr

For uranium:

1166 tons/yr x 2000 lb/ton x \$ 1.20/lb

= \$ 2,798,400/yr

Total annual charges:

\$ 920,000 + \$ 2,798,400 = \$ 3,718,400/yr

And the capital investment for the plant is calculated as,

$$\frac{\$\ 3,718,400}{.16} = \$\ 23,240,000$$

Plant operating costs for plutonium and uranium are assumed as,

For plutonium - \$ 2.50/gm

For uranium - \$ 5.00/kg

The plutonium operating cost covers the standard purex decontamination

[redacted]

cycles and subsequent conditioning (i.e. as proposed for Hanford) for transfer to the AEC. The uranium operating cost includes the charge for removal and return of heavy water to the uranyl sulfate, a single decontamination cycle, and the reconversion of the uranyl nitrate, resulting from the decontamination cycle, to the sulfate.

The annual operating costs then are:

For plutonium:

368,000 gm/yr x \$2.50/gm = \$ 920,000/yr

For uranium:

1166 tons/yr x 2000 lb/ton x 1/2.2 lb/kg x \$ 5.00/kg

= \$ 5,300,000/yr

The total annual chemical separations cost is computed then as,

\$ 3,718,400 + \$ 920,000 + \$ 5,300,000

= \$ 9,938,000

And the unit cost of separations is:

$$\frac{\$\ 9{,}938{,}400/\text{yr}}{368{,}000\ \text{gm/yr}} = \$27/\text{gm Pu}$$

Alternate Processing Proposal

It is possible that the plutonium may be removed from the reactor circulating system as a precipitate by means of a settling basin or some similar device. This proposal appears feasible, particularly as it is felt that a large portion of the plutonium in the reactor may be held in the IV oxidation state. In this state, the plutonium does not dissolve in the sulfate solution.

[redacted]

The removal of the plutonium in this fashion results in a substantial saving in inventory charges and chemical processing costs of uranium. These are tabulated below and show that the cost per gram of plutonium may be reduced by roughly $29.

The following assumptions were made for the calculations necessary to determine the unit savings:

1) No change in fuel burnup cost when compared to original processing scheme.

2) Only 600 kilograms per day of uranium necessary for chemical processing. (based upon amount of decontamination necessary to keep fission product buildup at a reasonable level)

3) Holdup time for spent and unspent fuel does not change.

4) Plutonium removed continuously from the reactor circulating system. Twenty percent remains in the "soup".

5) The settling tank holds up approximately five percent of the total system volume.

6) Plutonium production does not change.

7) Unit investment charges do not change.

8) Unit operating costs do not change.

9) Replacement of U-235 and U-238 atoms based upon the use of highly enriched material, as previously.

[redacted]

[redacted]

Effective Savings per gram of Plutonium

1) Chemical Processing	$ 17.92
2) Heavy Water Holdup	.75
3) Unspent Uranium Inventory	1.62
4) Spent Uranium Inventory	8.10
5) Plutonium in Reactor	.56
Gross Savings	$ 28.95
6) Uranium in Circulating System	- .15
Net Savings	$ 28.80

[redacted]

[redacted]

APPENDIX D

INVENTORIES

[redacted]

[redacted]

A. **Heavy Water**

1) Holdup in Reactor System -

As shown in the analysis of the major cell equipment in figure 2 of appendix B, the estimated holdup per cell is 571 cubic feet. The holdup in the spherical core is 1765 cubic feet. Hence, the total estimated holdup in the reactor system is 5(571) + 1765 = 4620 cubic feet. At 250°C it has been found that there are 49.7 lb of heavy water per cubic foot of soup, if the fuel concentration is 250 grams of uranium per liter. The number of pounds of heavy water in the reactor system is, then, 49.7(4620) = 229,614 lb.

The cost of heavy water is taken as $ 80/lb. Hence, the inventory investment of heavy water in the reactor system = $ 18,369,000.

2) Holdup After Removal for Chemical Processing -

Every day 12,870 liters of soup are removed for chemical processing. This is approximately 12,870 liters x 796 gm D_2O/liter x x 1/454 gm/lb = 22,560 lb of heavy water removed each day. It is assumed that a lapse of five days is necessary for the removal of the heavy water from the other constituents in the soup. The chemical processing inventory is then equal to 5 days x 22,560 lb/day x $ 80/lb = $ 9,026,000.

3) Holdup in Heavy Water Purification and in Return of Heavy Water to System -

[redacted]

[redacted]

It is estimated that a five day holdup will be required for the necessary heavy water purification and return to the system. As seen above, the total cost for five days of heavy water holdup equals $9,026,000.

The total heavy water inventory is:

1)	Heavy Water in Reactor System	$ 18,369,000
2)	Heavy Water in Chemical Processing	9,026,000
3)	Heavy Water in Purification Plant	9,026,000
	Total	$ 36,421,000

B. Unspent Fuel in Storage

A seven day supply of fuel is to be kept on hand. This relatively small inventory of unspent fuel is considered to be adequate since this production reactor requires the shipment of only 2½ kilograms of 52.5% enriched uranium from a diffusion plant each day. Such a quantity could quite feasibly be shipped by air.

As will be explained in detail in the study on loading methods in appendix F, the reactor is fed daily with depleted material which comes directly from chemical processing (1.071% - U-235) plus approximately 2½ kilograms of 52.5% enriched uranium (1234 grams of U-235) from a diffusion plant.

[redacted]

[redacted]

The inventory costs on fuel in storage previous to loading are as follows:

1) 52.5% enriched material -

7 days x 1234 gm burned/day x $ 44.06/gm 25 =

= $ 381,000

2) Depleted material (1.071%) from chemical processing -

7 days x 12,870 liters/day x 250 gm U/liter x

x .01071 gm 25/gm U x $ 19/gm 25 =

= $ 4,583,000

The total unspent fuel inventory = $ 4,964,000

As can be seen above, the inventory of 52.5% enriched material is relatively small compared to the other inventory costs. If one insisted upon a greater standby quantity of 52.5% enriched material, the unit cost of plutonium would not be effected appreciably. For example, if a 70 day supply of this highly enriched material were kept on hand instead of the 7 day supply now considered, the unit cost of plutonium would be increased by only $ 1.50/gm.

C. Spent Fuel in Storage

As stated in the section on chemical processing, fuel must be held up for 35 days before leaving the processing plant. Therefore, the inventory attributed to spent fuel is

[redacted]

[redacted]

as follows:

35 days x 12,870 liters/day x 250 gm U/liter x

x .01071 gm 25/gm U x $ 19/gm 25 =

= $ 22,910,000

D. Fuel in Pile

The critical enrichment of the reactor is 1.075% U-235, and the value of this material, as ascertained in appendix F, is $ 19.08/gm of 25. The inventory of fuel in the pile then becomes:

1.308×10^5 liters (volume of soup in system) x 250 gm U/liter x

x .01075 gm 25/gm U x $ 19.08 /gm 25 =

= $ 6,707,000

E. Plutonium in Pile

Withdrawl each day = 1120 gms Pu per 12,870 liters of solution

= 0.08702 gm Pu/liter

Plutonium in reactor immediately before withdrawl =

= .08702 gm Pu/liter x 1.308×10^5 liters

= 11,382 gm

Plutonium in reactor immediately following withdrawl =

= 11,382 - 1120 = 10,262 gm

[redacted]

[redacted]

$$\text{Average inventory in system} = \frac{11,382 + 10,262}{2}$$

$$= 10,820 \text{ gm}$$

Assume, for investment purposes, that the value of plutonium is $ 150/gm.

Investment in plutonium inventory in pile = $ 1,623,000

It should be noted that these calculations assume, for the sake of simplicity, that none of the material is in the form of neptunium.

F. Plutonium in Storage

There is a thirty-five day holdup of plutonium in the chemical processing plant, resulting in an investment of $ 5,880,000.

35 days x 1120 gm/day x $ 150/gm = $ 5,880,000

G. Process Materials

Process materials inventory, including a three day supply of TBP for the Purex process and a thirty day supply of Nitric Acid, also for Purex, as well as the other necessary miscellaneous chemicals and supplies, has been estimated at $ 100,000.

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[redacted]

APPENDIX E

OPERATING COSTS....

[redacted]

[redacted]

Operating Costs:

A. Fuel Costs -

The annual fuel costs are based on the cost of 52.5% enriched material which is the only "fresh" fuel from the diffusion plant added to the reactor each day.

1234 gm 25 burned/day x 365 days/yr x 0.9 (innage factor) x
x $ 44.06/gm of 25 = $ 17,860,000

B. Pile Cooling and Power Systems -

Taken from CEPS-1101, as follows:

Operating Payroll	$ 650,000
Maintenance Payroll	135,000
Maintenance Materials	135,000
Reactor Maintenance	85,000
Heavy Water Makeup *	919,000
Oxygen Makeup	5,000
Supplies and Miscellaneous	150,000
Total	$ 2,079,000
General Supervision and Administration	$ 190,000
Contract and Other Maintenance	240,000
Grand Total	$ 2,509,000

* This assumes that 5% of the Heavy Water is lost each year at the total cost of 0.05 x $ 18,370,000 (heavy water in reactor) = $ 918,500.

[redacted]

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[redacted]

C. Uranium Separations -

As indicated previously under chemical processing, this total cost amounts to $ 5,300,000. (see Appendix C, pages 81 and 82)

D. Plutonium Separations -

As indicated previously under chemical processing, this total cost amounts to $ 920,000. (see Appendix C, pages 81 and 82)

[redacted]

[redacted]

APPENDIX F

ENRICHMENT COSTS

[redacted]

[redacted]

I - Cost of Fissionable Material

In order to calculate the original investment cost of fissionable material in a reactor, the cost of natural uranium and the cost of enriching must be known or calculated.

The basis for these calculations is the same as that used in ORNL 1096, namely,

1) The ideal separative work equation is employed.

2) A figure of $110 per kilogram of separative work is used in this equation.

In addition, however, two items have been altered from the study in ORNL 1096, namely,

1) Natural uranium cost - $ 40 per pound (instead of $ 10 per pound)

2) Optimum depletion in the diffusion plant is .200% of U-235 (instead of .423% of U-235).

A. Development of Ideal Separative Work Equation

$$F = P + W \qquad (1)$$

where, F = quantity of uranium feed

P = quantity of product

W = quantity of waste

$$FN_F = PN_P + WN_W \qquad (2)$$

where N_F, N_P and N_W are decimal amounts of U-235 present in feed, product, and waste streams, respectively.

[redacted]

[redacted]

Hence, equation (2) is a material balance of the U-235.

Multiplying equation (1) by N_W, we obtain:

$$FN_W = PN_W + WN_W \qquad (3)$$

Subtracting equation (3) from equation (2),

$$F(N_F - N_W) = P(N_P - N_W)$$

$$\text{or, } F = \frac{P(N_P - N_W)}{N_F - N_W} \qquad (4)$$

Similiarly, $W(N_F - N_W) = P(N_P - N_F)$

$$W = \frac{P(N_P - N_F)}{N_F - N_W} \qquad (5)$$

Enrichment Cost = C_E = \$ 110/kg x V

where, V = number of kilograms of separative work required

$$= WV_W + PV_P - FV_F \qquad (6)$$

where, V_W, V_P and V_F are the value functions of the waste, product and feed, respectively

The value functions are obtained as follows:

1) For enrichments between 0 and 50%,

$$V_X = (2N_X - 1) \ln (N_X/(1 - N_X))$$

2) For enrichments between 50% and 100%,

$$V_X = V(1 - N_X)$$

Hence,

$$V = F \left\{ \left(\frac{N_P - N_F}{N_F - N_W} \right) (V_W - V_F) + (V_P - V_F) \right\}$$

[redacted]

[redacted]

$$C_E = 110\ P \left\{ \left(\frac{N_P - N_F}{N_F - N_W}\right) (V_W - V_P) - (V_F - V_P) \right\}$$

B. **Total Cost of Fissionable Material**

Total cost = C_E + cost of feed material

= C_E + 88F

where, the feed material costs $ 88/kg

Enrichment cost/gm U-235 in product = P = $\frac{1.0 \times 10^{-3}}{N_P}$

Therefore, the total cost, $/gm of 25 =

$$= \frac{0.110}{N_P} \left\{ \left(\frac{N_P - N_F}{N_F - N_W}\right) (V_W - V_P) - (V_F - V_P) \right\} +$$

$$+ \frac{.088}{N_P} \frac{(N_P - N_W)}{(N_F - N_W)} \qquad (7)$$

C. **Enrichment of Material Present in Reactor Immediately Prior to Recharging**

Since it was shown previously that 12,870 liters per day must be removed for chemical processing, one must add a sufficient amount of both U-235 and U-238 to bring the required enrichment back up to 1.075% and the concentration back to 250 grams per liter.

The total volume of the system is 1.308×10^5 liters. Since the concentration and enrichment are 250 gm/liter and 1.075%, the total mass of U-235 present in the system at the beginning of the day is:

[redacted]

$$1.308 \times 10^5 \text{ liters} \times 250 \text{ gm/liter} \times .01075 \text{ gm } 25/\text{gm U} =$$

$$= 351,500 \text{ gm of U-235}$$

Power level = 1028 megawatts

Also, 1.2 grams of U-235 are destroyed per megawatt day of heat produced.

Hence, U-235 destroyed/day = 1028 megawatts x 1.2 gm of 25/MWD

= 1234 gm 25/day

Therefore, U-235 present in reactor prior to recharging =

= 351,000 - 1234 = 350,300 gm

Assuming the concentration to remain effectively constant at 250 gm/liter, the enrichment prior to recharging =

$$= \frac{350,300 \text{ gm of } 25}{130,800 \text{ liters} \times 250 \text{ gm U/liter}} \doteq 1.071\%$$

D. <u>Calculation of the Cost of 1.075% Enriched Material</u>

$$\text{Total cost} = \frac{0.110}{0.01075}\left\{\left(\frac{.01075 - .007115}{.007115 - .002}\right)(6.18778 - 4.8704) + - (4.8704 - 4.4304)\right\} + \frac{.088}{.01075} \times \frac{(.01075 - .002)}{(.007115 - .002)}$$

$$= 5.077 + 14.004 = \$\ 19.08 \text{ per gram of } 25$$

[redacted]

[redacted]

E. Calculation of Cost of 1.071% Enriched Material

$$\text{Total cost} = \frac{0.110}{.01071}\left\{\left(\frac{.01071 - .007115}{.007115 - .002}\right)(6.18778 - 4.8704) + - (4.8704 - 4.4308)\right\} + \frac{.088}{.01071}\left(\frac{.01071 - .002}{.007115 - .002}\right)$$

$$= 4.9947 + 13.9915 = \$\ 18.99/\text{gm of } 25 \text{ (or } \$19/\text{gm } 25)$$

F Calculation of Cost of 52.5% Enriched Material

$$\text{Total cost} = \frac{.0110}{.525}\left\{\left(\frac{.525 - .007115}{.007115 - .002}\right)(6.18778 - 4.8704) + - (4.8704 - 0.0050)\right\} + \frac{.088}{.525}\left(\frac{.525 - .002}{.007115 - .002}\right)$$

$$= 26.93 + 17.13 = \$\ 44.06 \text{ per gram of } 25$$

G. Calculation of Cost of 1.11% Enriched Material

$$\text{Total cost} = \frac{0.110}{.0111}\left\{\left(\frac{.0111 - .007115}{.007115 - .002}\right)(6.18778 - 4.8704) + - (4.8704 - 4.3872)\right\} + \frac{.088}{.0111}\left(\frac{.0111 - .002}{.007115 - .002}\right)$$

$$= 5.59 + 14.13 = \$\ 19.72 \text{ per gram of } 25$$

II Study on Loading Methods

Since approximately thirty-five days are required for the complete transformation of Np-239 to Pu-239, the soup must be allowed to cool for this length of time. Moreover, if it seems desirable to reload the reactor with this

[redacted]

[redacted]

material, after being slightly enriched in a diffusion plant, then an additional cooling time must be allowed for the decay of the U-237. In total, approximately one hundred days cooling time is necessary if the material is to go back to a diffusion plant.

Following is a calculation showing that the enrichment necessary for this method of loading is 1.11% U-235.

Amount of U-238 destroyed each day = 1120 gm Pu produced/day x 238/239

= 1115 gm U-238

(neglecting U-238 destroyed from fast fission effect)

Amount of U-235 burned each day = 1028 megawatts x 1.2 gm/MWD

= 1234 gm U-235

Amount of U-235 removed each day in the 12,870 liters of soup going to chemical processing. = 12,870 liters x 250 gm U/liter x .01071 gm 25/gm U

= 34,459 gm of U-235

(The concentration will not remain precisely at 250 gm/liter, but for the purposes of these calculations, it is assumed to do so)

Amount of U-238 removed each day = (12,870 liters x 250 gm/l) - 34,459 gm 25

= 3,183,041 gm U-238

Amount of U-235 added each day = 34,459 + 1234 = 35,693 gm

Amount of U-238 added each day = 3,183,041 + 1,115 = 3,184,156 gm

Therefore, enrichment necessary = $\frac{35,693}{3,219,849}$ = 1.11% U-235

[redacted]

[redacted]

It can also be shown that the reactor might be fueled each day in another manner. Instead of sending each batch of material from chemical processing back to the diffusion plant for enrichment, one can charge the reactor with the depleted material from chemical processing along with the proper quantity of 52.5% enriched uranium. This highly enriched material exactly makes up for the amounts of U-235 and U-238 burned up the previous day.

The 52.5% value for the enrichment of the added uranium may be calculated as follows:

1115 grams of U-238 destroyed per day

1234 grams of U-235 destroyed per day

Therefore, enrichment of fuel added = 1234/(1115 + 1234)

= 52.5%

The major advantage to this method lies in the fact that a cooling period of only thirty-five days is necessary in chemical processing, and none thereafter since none of the uranium returns to the diffusion plant. However, the enrichment and fuel inventory charges will be somewhat greater. A study of the two methods follows to determine the more economical course of fueling.

A. Loading by Adding 1.11% Material

1. Annual fuel costs -

U-235 added each day = 35,693 grams

Cost of 1.11% enriched material = $ 19.72 per gram of U-235

Total cost of the fuel = 35,693 x 19.72 = $ 703,866 per day

[redacted]

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Credit is received for 34,459 grams per day of U-235 at an enrichment of 1.071% as received by the diffusion plant.

Cost of 1.071% U-235 = $19/gram U-235

Total credit received = 34,459 x 19 = $ 654,721 per day

Net deficit chargeable to fuel costs = $ 49,145/day

= $ 16, 144,000/yr

(assuming a .9 innage factor to compute the annual figure)

2. Annual Unspent Fuel Storage Costs -

With a one week's supply on hand,

7 days x $ 703,866/day x .16 (capital charge rate) =

= $ 788,000 per year

3. Annual Spent Fuel Storage Costs -

With the material in storage for 100 days,

100 days x $ 654,721/day x .16 (capital charge) =

= $ 10,476,000 per year

B. <u>Loading with Highly Enriched (52.5%) Material plus Material from Chemical Processing.</u>

1. Annual Fuel Costs -

Each day 1234 grams of 25 are burned. The annual fuel cost is: 1234 gm/day x 365 days/yr x $ 44.06/gm x .9 (innage) =

= $17,860,000 per year

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2. Annual Unspent Fuel Storage Costs -

With a one week's supply of 52.5% enriched material and depleted material from chemical processing, as shown in appendix D, page 3, the inventory for unspent fuel = $ 4,964,000

Hence, the annual charge = $ 794,000

3. Annual Spent Fuel Storage Costs -

With the material in storage for thirty-five days, as shown in appendix D, page 3, the inventory for spent fuel = = $ 22,910,000

Hence, the annual charge = $ 3,666,000

The estimated total cost by method A is, therefore, $ 27,408,000, and, by method B, is $22,320,000. The latter method is the more economical one and has been adopted for the reactor under consideration.

It may also be noted that, in addition to the items listed above, a greater cost would be encountered if method A were to be used, since much larger quantities of materials must be transported to and from the diffusion plant, and and the shipping costs would then increase the above noted differential in charges.