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THE COOLING OF IRRADIATED 25 MTR FUEL ASSEMBLIES AND ITS EFFECT ON 25 INVENTORY IN THE MTR PROJECT

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THE COOLING OF IRRADIATED 25 MTR FUEL ASSEMBLIES AND ITS EFFECT ON 25 INVENTORY IN THE MTR PROJECT

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THE COOLING OF IRRADIATED 25 MTR FUEL ASSEMBLIES AND ITS EFFECT ON 25 INVENTORY IN THE MTR PROJECT

0.0 Abstract

The U^{235} consumption, U^{236} and U^{237} production, total and gaseous fission product production, and shielding, based on La^{140} gamma emission, have been calculated for a 12-day MTR irradiation period at a power level of 30,000 KW for a loading of 3.2 kg of U^{235}. The resulting data is applied to cooling and inventory requirements in the MTR Project.

1.0 Purpose

This report is a compilation of the present state of knowledge regarding the handling, properties, and inventory of irradiated 25 MTR fuel assemblies in the period between their discharge from the MTR and their entry into the 1200 and 1400 area process facilities. This report presents the results of new calculations made on the present operating specifications of the MTR, and supersedes previous data.

The information contained in the report is divided into three main sections. First, the 25 consumption, 26 production, and number of allowable MTR passes is discussed. Second, the cooling period for various enrichments, based on 27 activity alone, which is the cooling criteria for cold metallurgical operations is reviewed. Additional information on the cooling problems associated with total fission product activity, gaseous fission product liberation, and the effect of La^{140} gamma radiation on shielding are discussed in their bearing on a minimum cooling time. Finally, the effect of shorter cooling cycles on chemical processing is discussed.

The final section contains a detailed discussion of inventory, and includes information on the minimum inventories anticipated for startup operations, a theoretical steady state mode of operation, and the actually anticipated realistic proposal for operation of the MTR and MTR recycle.

This report should be of particular value in determining the exact fuel cooling period desired and the 25 inventories to be encountered during the operation of the MTR.

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2.0 Summary

Calculations showing that MTR fuel assemblies, which initially contain 140 grams of 25 of 93.4% enrichment, can be passed through the reactor ten times before reaching the minimum permissible enrichment of 60% have been made. During each irradiation, 17.4 grams of 25 are consumed, of which 14.9 grams become fission products, and 2.5 grams U^{236}. Loss of U^{234} and U^{238} during irradiation is negligible.

It was found that the cooling time required to reduce the U^{237} activity to 1 millicurie per 200 grams 25, the former cooling standard, was 126 days for first pass and 160 days for tenth pass fuel. Other calculations indicated that fission product activity is independent of 25 enrichment. Total fission product activity is reduced by 10^3 in about 4 days cooling, and by 10^4 in 135 days. The total energy is roughly equally divided between beta and gamma emission from fission products during this period. Gaseous fission product activity is reduced from about 10^5 curies for 2 days cooling to about 5 curies after about 120 days cooling.

Shielding calculations were made on the basis of the concrete shielding thickness required to reduce the La^{140} gamma activity to 0.1 r/8 hrs. It was found that five feet of concrete are required for assemblies cooled two days, four feet for fifty days, and three feet for a 100-day cooling period. It is recommended that 60 days be set as the minimum cooling time.

The total 25 inventory required for operating the MTR Project was studied, and it was found that 13.7 kg 25 are required if no cooling period is considered. For each day's cooling an additional 0.2 kg 25 is added to the inventory. The average 25 makeup required is 0.20 kg 25 per week before 60% enriched 25 is produced, and 0.26 kg 25 afterwards. The 60% 25 reject class assemblies are first produced in three to five years, depending on the cooling period chosen; after that time about 13.0 kg of new 25 is required per year, of which 10.4 kg is "burned" and an average 2.6 kg is discarded as 60% 25. The total operating inventories for 72, 100, and 128 day mean cooling, from Figure 3, are 27.3, 33.4, and 29.2 kg 25 respectively.

3.0 Basic Data for Calculations

The MTR design and operating specifications set forth in "Materials Testing Reactor Design Data Sheets", Central Files No. 49-10-232, by D. J. Mallon, have been used in this report for all calculations. A short summary of pertinent data from the above reference is given below.

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3.0 Basic Data for Calculations (Con't.)

MTR Power Level	30,000 KW
Total 25 in MTR as Fuel Assemblies	3.2 kg.
Total Number of Fuel Assemblies (slab loading)	23
Total 25 per Fuel Assembly	0.140 kg.
Composition of Initial Fuel Material	
U^{234} (24)	1.1%
U^{235} (25)	93.4%
U^{238} (28)	5.5%
Total MTR Cycle Time	336 hrs. (14 days)
Irradiation Time per Cycle	288 hrs. (12 days)
Down Time Between Cycles	48 hrs. (2 days)

The nuclear data used in this report are primarily from a previous transuranic isotope MTR production report by Ott and English entitled "Expected Formations of Heavy Isotopes in the Proposed Clinton Heterogeneous Pile". Central File No. 47-3-8.

4.0 Depletion and Recycling of 25

The MTR operating specifications[1] provide for a cyclic operation in which partially consumed fuel is periodically decontaminated from fission products and transuranic elements by a countercurrent solvent extraction process for re-use in the reactor. Starting with uranium containing 93.4% 25, the fuel will be recycled until a 25 concentration of 60% is reached, at which time it will be no longer suitable for further use in the MTR because of the build-up of transuranic neutron "poisons". The data in this section is concerned chiefly with the mechanism of depletion and recycling, and with the changing composition of the various transuranic isotopes.

4.1 Recycle Mechanism

MTR operating specifications call for the initial use of uranium containing 93.4% 25. The 3.2 kg of 25 required in the reactor will be distributed through 23 fuel assemblies, each containing 140 grams of 25.

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4.1 Recycle Mechanism (con't)

The reactor will be operated for twelve days at a power level of 30,000 KW and at the end of this time will be shut down and all the fuel assemblies discharged to the MTR canal. Then 23 new assemblies will be charged to the reactor and the next 12-day operating cycle started. The down time between cycles will be two days, giving a total MTR time cycle of two weeks.

During irradiation in the MTR, 17.4 grams of 25 or 12.4% of the total 25 per fuel assembly is consumed. Of this amount, 14% or 2.45 grams of 25 is used in producing 2.46 grams of U^{236}, and 86% or 14.95 grams undergo nuclear fission. The nuclear reactions in which U^{235} is produced by neutron capture in U^{234}, U^{237} from U^{236}, and Pu^{239} from U^{238} occur in milligram quantities, and therefore affect the uranium composition but slightly.

The fuel assemblies, initially discharged to the MTR canal, will be stored temporarily and then moved in shielded carriers to the 1200 Area canal for further cooling. When the assemblies have been sufficiently cooled, they will be chemically processed in the 1200 Area. This operation will consist of the quantitative separation of the fission products and transuranic elements from the uranium by solvent extraction with hexone (methyl isobutyl ketone). The recovered uranium, in the form of $UO_2(NO_3)_2$ solution, will be evaporated to dryness, decomposed to U_3O_8 and sent to the metallurgical area (1400 Area) where the oxide will be reduced to uranium metal, melted in with an appropriate amount of aluminum, and the resulting alloy fabricated into new fuel assemblies.

Sufficient make-up uranium will be used in these new fuel assemblies to provide 140 grams of 25 per assembly. Thus new assemblies will contain more total uranium, but the same amount of 25 as assemblies made from unirradiated enriched uranium.

4.2 Class Nomenclature

In order to set up an S.F. accountability system for the variously enriched materials to be handled in the MTR and its associated chemical and metallurgical plants, the following nomenclature is suggested and is used in this report.

Class A material will be designated as newly received enriched uranium containing 93.4% 25.

Class B material represents once irradiated fuel, and such material is so classified from the time it is discharged from the reactor until it is decontaminated, refabricated into new fuel assemblies, and recharged to the reactor.

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4.2 Class Nomenclature (con't.)

Class C, D, E, etc., material is fuel which has been irradiated twice, three times, etc., in the reactor.

Class L material is totally spent fuel which contains approximately 60% 25 and is no longer considered practical for further use in the MTR.

In reality, it will probably be necessary to assign ranges of 25 concentrations to the various class materials actually handled, and close analytical and assay control will be required to prevent mixing of various class materials.

4.3 Changes in U Composition

The fuel assemblies of any class charged to the MTR will all contain 140 grams 25, while those leaving the reactor will contain only 122.6 grams 25. As already pointed out, the 24 and 28 content will remain nearly constant, and the 26 content will increase. However, in bringing the 25 content of recycled material back to 140 grams 25 in new assemblies, the 24, 26, and 28 content will be increased in the reactor fuel assembly chemical decontamination and refabrication processes.

Table I presents the various uranium isotope concentrations for the various classes of fuel handled. U^{237} (27) is omitted because it has little material balance significance. However, it is controlling in activity considerations, so that this isotope is discussed in Section 5.1. Table I also presents the masses of the various uranium isotopes in the metallurgical batch which contains 200 grams of 25 and in fresh and irradiated fuel assemblies which contain 140 and 122.6 grams of 25 respectively. Finally, the notes of Table I contain pertienent information relative to the changing uranium composition of the assemblies.

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TABLE I

DISTRIBUTION OF U ISOTOPES
IN MTR FUEL ASSEMBLIES

Class Mat'l.	PERCENTAGE DISTRIBUTION				MASS DISTRIBUTION (GRAMS)											
					Metallurgical Batch		Fuel Assemblies to MTR					Fuel Assemblies from MTR				
	24	25	26	28	25	Total	24	25	26	28	Total	24	25	26	28	Total
A	1.10	93.40	0.00	5.50	200	214	1.65	140.0	0.00	8.25	149.9	-	-	-	-	-
B	1.22	90.86	1.82	6.10	200	220	1.88	140.0	2.81	9.42	154.1	1.65	122.6	2.46	8.25	135.0
C	1.36	88.07	3.79	6.78	200	228	2.16	140.0	6.03	10.78	159.0	1.88	122.6	5.27	9.42	139.2
D	1.50	85.11	5.90	7.49	200	235	2.46	140.0	9.70	12.30	164.5	2.16	122.6	8.49	10.78	144.0
E	1.65	81.95	8.15	8.25	200	244	2.82	140.0	13.9	14.08	170.8	2.46	122.6	12.16	12.30	149.5
F	1.81	78.65	10.50	9.04	200	254	3.22	140.0	18.7	16.08	178.0	2.82	122.6	16.36	14.08	155.9
G	1.97	75.17	13.00	9.86	200	266	3.68	140.0	24.2	18.38	186.3	3.22	122.6	21.16	16.08	163.1
H	2.14	71.54	15.60	10.72	200	280	4.20	140.0	30.5	21.00	195.7	3.68	122.6	26.66	18.38	171.3
J	2.32	67.87	18.20	11.61	200	295	4.80	140.0	37.6	24.00	206.4	4.20	122.6	32.96	21.00	180.8
K	2.51	64.08	20.90	12.51	200	312	5.49	140.0	45.7	27.40	218.6	4.80	122.6	40.06	24.00	191.5
L	2.69	60.24	23.65	13.42	-	-	-	-	-	-	-	5.49	122.6	48.20	27.40	203.7

NOTES:

(1) Any class material has constant uranium composition from reactor discharge to reactor recharge.
(2) Class A material is unirradiated enriched uranium.
(3) Class L material is final pass material after irradiation.
(4) 24 and 28 depletion is negligible.
(5) 25 depletion is 17.4 grams/assembly - pass.

a. 14.95 grams fission products formed/assembly - pass.
b. 2.45 grams 25 used in 26 production/assembly - pass.
c. 2.46 grams 26 produced from 25/assembly - pass.

(6) Concentration factor between passes - 1.142.
(7) 25 ratio of metallurgical batch to used assembly - 1.632.
(8) 25 ratio of metallurgical batch to new assembly - 1.429.

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5.0 MTR Fuel Assembly Cooling Considerations

Until recently, the basic standard in the cooling of the MTR fuel assemblies was the reduction of the U^{237} activity to one millicurie per 200 grams 25, a standard which would reduce the ionization potential of the residual U^{237} per 200 gram batch to 0.7 mr per hour at contact during direct metallurgical refabrication. Previous estimates indicated the need for 158 days average cooling time to achieve these requirements.

In order to reduce the 25 inventory of the MTR, it has been suggested recently that the fuel assembly cooling time be reduced. This would mean that much more 27 would pass through the 1200 Area into the 1400 Area operations since 27 is not separable from other uranium isotopes by ordinary chemical means. Therefore, the 1400 Area metallurgical operations would have to be accomplished using remote techniques.

With this in mind, a closer study of the cooling period problem has been made. The U^{237} activity was re-evaluated, and the total fission product activity reviewed for various cooling periods. In addition, the effect of La^{140} and various gaseous fission products which would be liberated from the 1200 Area have been studied. Each of the above cooling considerations will be discussed in turn in the following sections.

5.1 U^{237} Activity

U^{237} is formed by neutron capture in U^{236} and is therefore proportional to the amount of U^{236} present. Since the amount of U^{236} in a fuel assembly is inversely proportional to the 25 enrichment, the later class materials (i.e. J, K, L) will contain the most U^{237} activity. U^{237} decays to long-lived Np^{237} (2.25×10^6 yrs.) with a half life of 6.7 days emitting a 0.5 Mev beta and an 0.27 Mev gamma.(4)

The calculated data on U^{237} mass and activity versus cooling time for the various class fuels is given in Table II and Figure 1. Table II indicates the amount and activity of U^{237} associated with 200 grams 25 (1 metallurgical batch) for various class fuels at the moment of reactor shutdown, while Figure 1 shows graphically the U^{237} activity versus cooling time for the various class fuels. Since 27 is chemically inseparable from other uranium isotopes, the activities shown are the minimum to be expected in the 1400 Area for the cooling periods chosen.

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TABLE II

27 ACTIVITY FOR VARIOUS CLASS MATERIALS AT MTR SHUTDOWN

Class Mat'l.	mg. 27/assembly (122.6 gms. 25)	Curies 27 Activity/assembly	mg. 27/metallurgical batch (200 gms. 25)	Curies 27 Activity/metallurgical batch
B	2.64	214	4.31	350
C	7.69	622	12.52	1020
D	13.49	1190	22.0	1780
E	20.1	1630	32.8	2660
F	27.6	2230	45.0	3640
G	36.4	2950	59.4	4800
H	46.2	3740	75.4	6100
J	57.5	4650	93.8	7600
K	70.3	5690	114.5	9280
L	85.0	6890	138.7	11200

Notes:

1 mg. 27 = 81 curies

Average energy of 27 gamma activity is 0.27 Mev

1 gamma ray emitted per 35 beta ray emissions

Radiation dosage at metal surface of assembly = 0.7 mr/hr/millicurie.

5.2 Total Fission Product Activity

Estimates have been made of beta, gamma, and total fission product activity formed in the MTR fuel assemblies, using the decay curves in the Clinton Project Handbook(6) and the Borst Wheeler Curves(8). The former were experimentally determined, while the latter are the results of theoretical considerations. In general, the Borst Wheeler values are about twice the Clinton values. In this report the Clinton data have been used for cooling period of 16 days and longer. Since they are not available for cooling times less than

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16 days, Borst Wheeler values were corrected to conform to the Clinton values for 1, 2, 5, and 10 day cooling.

The fission product activity data are given in Table III, for cooling times of from 1 to 200 days and are plotted in Figure 2. Table III, includes beta, gamma, and total fission product activity reduction factors and activities in both watts and curies. Figure 2, presents a plot of activity reduction in both watts and curies versus cooling time. It should be noted that the activity reduction in the first 24 hours after MTR shutdown is greater than that occurring in the next 200 days. Fission product activity, unlike 27 activity, is independent of 25 enrichment and is therefore the same for all classes of assemblies.

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TABLE III

COOLING TIME DATA FOR FISSION PRODUCTS PRODUCED IN MTR

14.95 g. Fission Products/Assembly
Power Level - 1300 KW/Assembly
10.6 KW/g. 25 at Discharge
Irradiation Time - 12 Days

Cooling Time (days)	Power Reduction		Power Distribution		Energy per Assembly			Total Curies (Clinton Proj. Handbook)
	From Borst Wheeler Data	From Clinton Proj. Handbook	% Beta	% Gamma	Beta Watts	Gamma Watts	Total Watts	
0	1	1	40	60	5.2×10^{5}	7.8×10^{5}	1.30×10^{6}	(2.1×10^{8})
1	2.0×10^{-3}	(1.14×10^{-3})	(40)	(60)	5.9×10^{2}	8.9×10^{2}	1.48×10^{3}	(2.5×10^{5})
2	1.45×10^{-3}	(8.3×10^{-4})	(41)	(59)	4.4×10^{2}	6.4×10^{2}	1.08×10^{3}	(1.84×10^{5})
5	1.0×10^{-3}	(5.7×10^{-4})	(42)	(58)	3.2×10^{2}	4.3×10^{2}	7.4×10^{2}	(1.26×10^{5})
10	7.7×10^{-4}	(4.4×10^{-4})	(43)	(57)	2.45×10^{2}	3.2×10^{2}	5.7×10^{2}	(9.7×10^{4})
16	6.2×10^{-4}	3.5×10^{-4}	44	56	2.02×10^{2}	2.58×10^{2}	4.6×10^{2}	7.8×10^{4}
20	5.3×10^{-4}	3.1×10^{-4}	46	54	1.84×10^{2}	2.16×10^{2}	4.0×10^{2}	6.9×10^{4}
30	3.8×10^{-4}	2.15×10^{-4}	48	52	1.34×10^{2}	1.46×10^{2}	2.8×10^{2}	5.1×10^{4}
50	2.2×10^{-4}	1.2×10^{-4}	50	50	7.8×10^{1}	7.8×10^{1}	1.56×10^{2}	3.1×10^{4}
70	1.4×10^{-4}	7.8×10^{-5}	50	50	5.0×10^{1}	5.1×10^{1}	1.01×10^{2}	2.2×10^{4}
100	7.8×10^{-5}	5.0×10^{-5}	50	50	3.25×10^{1}	3.25×10^{1}	6.5×10^{1}	1.4×10^{4}
120	6.4×10^{-5}	4.2×10^{-5}	51	49	2.75×10^{1}	2.75×10^{1}	5.5×10^{1}	1.2×10^{4}
140	4.8×10^{-5}	3.4×10^{-5}	52	48	2.8×10^{1}	2.12×10^{1}	4.4×10^{1}	9.7×10^{3}
160	4.0×10^{-5}	2.8×10^{-5}	54	46	1.94×10^{1}	1.66×10^{1}	3.6×10^{1}	8.0×10^{3}
180	3.3×10^{-5}	2.4×10^{-5}	56	44	1.74×10^{1}	1.36×10^{1}	3.1×10^{1}	6.8×10^{3}
200	2.8×10^{-5}	2.1×10^{-5}	57	43	1.54×10^{1}	1.16×10^{1}	2.7×10^{1}	6.0×10^{3}

Values in parentheses are Borst Wheeler values corrected to conform to Clinton Project Handbook values.

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5.3 La^{140} Activity and Shielding

One of the important considerations for the 1200 Area chemical plant is biological shielding. For material cooled from 1 to about 60 days the main source of high energy gamma activity is the 2.1 Mev gammas emitted from La^{140}, and in this period a close approximation to the actual shielding thickness required can be obtained by considering only this one gamma source.

Table IV is a summary of activity and shielding calculations made to determine concrete shield thickness versus cooling time, and is based on a chemical batch obtained by dissolving three fuel assemblies in such a manner as to obtain about 80 gallons of solution (2 grams U per liter). It is evident that appreciable savings in building cost can be achieved in permitting the fuel assemblies to cool at least 60 - 100 days. It should be noted that the amount of La^{140} is independent of the 25 enrichment since the same amount of 25 is present at the start of each MTR irradiation.

Shielding calculations were based on formula (7) of Chapter V in the Clinton Project Handbook[7,9].

TABLE IV

CONCRETE SHIELDING REQUIRED
BASED ON 2.1 Mev GAMMAS FROM La^{140}

Assumptions: One chemical batch contains 3 assemblies
Batch volume is 80 gallons.

Cooling Time Days	g. La^{140} per Assembly	Activity/Assembly		% of Total γ Energy	Source Strength r/8hr/cc	Thickness of Concrete Req'd. Reduce Activity to 0.1 r/8 hr.
		Curies	γ Watts			
1	0.0461	2.61×10^4	326	37	2.98×10^5	5.0 ft.
10	0.0343	1.94×10^4	243	43	2.20×10^5	4.8
20	0.0202	1.14×10^4	143	66	1.30×10^5	4.7
30	0.0118	6.67×10^3	83.5	57	7.6×10^4	4.6
50	0.0039	2.20×10^3	27.5	35	2.4×10^4	4.0
60	0.0023	1.30×10^3	16.3	16	1.47×10^4	3.8
80	0.0008	4.5×10^2	5.6	8	5.1×10^3	3.5
100	0.0002	1.1×10^2	1.4	4	1.27×10^3	3.0

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5.4 Gaseous Fission Product Activity

A second consideration of importance in the design of the 1200 Area is the liberation of gaseous fission products from the fuel assembly dissolving operation. Here, the concern is air polution by the gaseous fission products which at best can be removed only partially from the tank vessel vent system.

Since all the gaseous fission products (Br, I, Kr, and Xe) are relatively short-lived (except Kr^{85}), their effect is greatly reduced by moderate fuel cooling. Of the twenty-odd gaseous fission products formed[9], the majority have half lives less than one day. Therefore, in calculating these activities only 9.4 year Kr^{85}, 8 day I^{131}, 2.4 hour I^{132} (arising from 77 hour Te^{132}), 22 hour I^{133}, and 5.3 day Xe^{133} have been considered as of much importance after about one week's cooling.

The results of these gaseous fission product calculations are given in Table V. for cooling periods of from 1 to 120 days and in Figure 7. for 1 to 140 days. The total activity values are purposely not given for the first day's cooling since the neglected shorter lived gaseous fission products are still of importance at this time. As will be noted, a great saving can be made in air pollution and/or gas absorption and adsorption equipment costs by allowing at least 50 to 60 days for cooling.

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TABLE V

GASEOUS FISSION PRODUCT ACTIVITY

All activities in curies

Cooling Time (Days)	Kr^{85}	I^{131}	I^{132}	I^{133}	Xe^{133}	Total
0	5.5	1.81×10^4	3.40×10^4	4.30×10^4	3.78×10^4	-
1	5.5	1.66×10^4	2.74×10^4	2.02×10^4	3.64×10^4	-
2	5.5	1.52×10^4	2.19×10^4	9.50×10^3	3.25×10^4	7.91×10^4
3	5.5	1.39×10^4	1.78×10^4	4.47×10^3	3.01×10^4	6.63×10^4
4	5.5	1.28×10^4	1.43×10^4	2.06×10^3	2.67×10^4	5.59×10^4
5	5.5	1.17×10^4	1.15×10^4	9.80×10^2	2.36×10^4	4.78×10^4
7	5.5	9.81×10^3	7.50×10^3	2.24×10^2	1.83×10^4	3.58×10^4
10	5.5	7.53×10^3	3.90×10^3	2.2×10^1	1.26×10^4	2.41×10^4
15	5.5	4.82×10^3	1.32×10^3	-	6.53×10^3	1.27×10^4
20	5.5	3.12×10^3	4.60×10^2	-	3.43×10^3	7.01×10^3
30	5.5	1.29×10^3	5.50×10^1	-	9.10×10^2	2.26×10^3
40	5.5	5.35×10^2	-	-	2.59×10^2	7.94×10^2
50	5.5	2.22×10^2	-	-	6.90×10^1	2.91×10^2
60	5.5	1.05×10^2	-	-	-	1.10×10^2
70	5.5	3.78×10^1	-	-	-	4.33×10^1
80	5.5	1.56×10^1	-	-	-	2.11×10^1
100	5.5	2.7	-	-	-	8.2
120	5.5	0.5	-	-	-	6.0

5.5 1200 Area Experimental Data

The final consideration in regard to shorter cooling of MTR fuel assemblies is the lack of experimental data on short cooled ($<$ 100 days) material in the 1200 Area chemical process studies. All chemical research and development work on the 25 process has been done on material cooled at least 120 days and in some cases more than 200 days. Consequently, the applicability of the process for short cooled fuel is somewhat uncertain because of the more complicated fission spectrum present. In other words, the decontamination from certain elements not present in the longer cooled material has not been demonstrated; additional experimental and pilot plant work would be required to obtain this information.

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5.6 Cooling Period Recommendations

In the light of these calculations and from present ORNL operating experience, it is recommended that all irradiated assemblies be cooled no less than 60 days and no more than that required to reduce 27 activity per metallurgical batch to one millicurie, this period varying from 112 to 146 days for the highest and lowest enrichments handled respectively and exclusive of the additional 14 days of cooling achieved by 25 processing in the 1200 Area.

The lower limit is based primarily on the gaseous fission product liberation. The 60 day cooling period reduces gaseous fission product activity by a factor of over 200 compared to the amount liberated after one week's cooling, and thereby greatly simplifies the air cleaning problem. The 60 day cooling also permits a reduction of one foot in the concrete shielding requirements compared to a week's cooling and thereby reduces the construction cost of the chemical processing facility.

The upper limit on cooling has been discussed and is based on the maximum 27 activity which can be safely tolerated in direct handling operations in the 1200 finishing area and in the 1400 Area. Longer cooling is undesirable only in that it adds to the operating inventory. As will be pointed out later, the inventory differences between 60 and 140 day cooling is small compared to the total 25 acquired and consumed in several years of operation.

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6.0 U^{235} Inventory Consideration

The MTR Project will require the acquisition and handling of sizeable amounts of highly enriched (93.4%) 25; the handling and storage of even larger amounts of 25 in the enrichment range of 60 to 90%; and the handling and storage or disposal of 60% enriched 25 which is no longer useable in the MTR. This section is devoted to a discussion of the amounts and disposition of the variously enriched 25 material handled in the MTR Project.

As previously explained, 25 enters the MTR recycle as 93.4% 25, is irradiated in the MTR for 12 days, and is cooled a predetermined length of time. Then, it is chemically decontaminated from fission products and transuranic elements in the 1200 Area, and finally refabricated into new assemblies of lower enrichment in the 1400 Area for re-admission to the reactor. Recycling is continued until the 25 enrichment falls to 60%; this requires ten passes through the MTR. In this report, it has been assumed that the 1200 and 1400 Area operations are each of 14 days duration.

6.1 Average U^{235} Consumption, Discard, and Makeup

In Section 3.0 it was shown that the 25 consumed in a single MTR operation was 17.4 grams per assembly, or 0.400 kg. 25 per a normal MTR loading of 23 assemblies. Later, it will be shown that under steady state condition an average of 16.92% of the 25 in any MTR loading will be Class A material. Thus, of the 3.22 kg. 25 loaded, only 0.545 kg. 25 are present as Class A fuel. It will be further shown that for any amount of Class A material entering the reactor, $(0.876)^{10}$ or 26.4% will eventually be rejected as Class L material. Thus, on the average, 0.545 x .264 or .144 kg. 25 are discarded as Class L material per MTR cycle, assuming steady state conditions.

It is apparent that the average 25 makeup is equal to the 25 consumed in the fuel assemblies plus the 25 discarded as Class L material. For any MTR cycle after Class L material is first produced the average 25 makeup required by the project is 0.544 kg. 25. In that period before Class L material is produced, the 25 makeup is equal to 25 consumption alone since no Class L material has been produced and is only 0.400 kg. 25 per MTR cycle.

6.2 Minimum Inventory

To obtain the minimum inventory for the MTR Project, the total cycle time must be evaluated and is defined as the length of time between the admission of an assembly to the MTR and its subsequent re-admission as the next lower class. Thus, the total cycle time is the summation of the MTR irradiation time, the cooling period, and the 1200 and 1400 Area process times. Since the MTR

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operation is a batch type operation, the total cycle time is, of necessity, some integral value of the MTR cycle of two weeks. The MTR cycle time which is two weeks, includes 12 days of operation and two days down time.

The normal MTR 25 inventory, which is the 25 content of 23 assemblies, is 3.22 kg. The 1200 Area inventory is 3.22 kg 25 prior to the production of Class L 25. This includes 2.82 kg of irradiated 25 and 0.40 kg of newly acquired 25 for makeup. After Class L 25 is produced, the 1200 Area inventory becomes 3.36 kg 25, the sum of the 2.82 kg of irradiated 25 and the 0.54 kg of makeup 25. The 1400 Area 25 inventory is the same as that in the MTR, or 3.22 kg. Thus, if the project were operated with only two days cooling (to take advantage of the MTR shutdown period), the minimum inventory would be 9.66 kg 26 prior to the production of Class L material and 9.80 kg afterwards. When unavoidable tailings and recycle scrap 25 is added to this, the inventory varies from 9.97 kg 25 when only Class A 25 is being processed to 13.57 kg when Classes A through K are in process. After Class L is being produced, the minimum inventory becomes 13.71 kg 25 because of the added makeup.

Such an idealized schedule is hardly possible, since a considerably longer cooling period is required. However, the minimum 25 inventory for any cooling period can be easily obtained as follows. Each 14 day 23 irradiated assemblies are discharged from the MTR to the cooling canal. Thus, 23/14's of an assembly are equivalent to one day's cooling. Since a batch of 23 irradiated assemblies contain 2.82 kg 25 the total inventory is increased by 2.82/14 or 0.201 kg 25 for each day's cooling. Therefore, that part of the total inventory in the canal is 0.201 D kg 25 in which D is the cooling period in days. If the 2 days "free" cooling is deducted from the minimum cooling inventory, the total minimum inventory under steady state conditions for any mean cooling time becomes (13.31 + 0.201 D) kg 25. This equation is plotted in Figure 3.

Since it may not be clear just how the tailings and metal scrap originate, the remainder of this section is devoted to a discussion of these necessary additions to the inventory. First, there will always be some tailings in the 1200 Area because the 1200 Area output of any class will seldom be of just the correct amount to produce an integral number of assemblies. At best, this factor will be 0 kg and at worst 1.8 kg 25, the amount equivalent to just less than one metallurgical batch each of Classes B through K.

A second factor which will increase the minimum inventory is the 1200-1400 recycle. About 2% of the 25 from any metallurgical aluminum alloying batch is taken up in the slag from the melt and must be recovered in the 1200 Area. Since each melt contains 280 grams 25, about 5.6 grams 25 is returned as slag from each melt. If it is assumed that this 25 is recovered weekly, the 25 in slag from the 18.8 melts equivalent to 23 assemblies amounts to an inventory addition of 105 grams 25. Experience in 1200 Area practices indicate that little

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if any 25 need be returned to the 1200 Area as metal scrap for 25 recovery. Damage to any plate or assembly in fabrication or handling would necessitate its return to the 1200 Area, and some facilities must be provided for such circumstances. However, no metal scrap should normally appear in the inventory exchange between the 1200 and 1400 Areas.

A third item which increases the minimum inventory is the 1400 Area metal scrap recycle. About 100 g 25 as U-Al alloy is lost from each melt as metal scrap from the rolling, trimming and punching of fuel plates. This is fed back into subsequent melts, and thus is kept in the 1400 Area. If it is assumed that two melts are produced each day and the scrap from any days fabrication operations are fed back in the next day's melt, then a minimum of 200 g of 25 are held up as scrap. The maximum hold up of this type would occur if the scrap from two melts of all classes from A to L were on hand simultaneously. This amounts to 2.00 kg 25.

A summary of the minimum inventories for three startup conditions and the final steady state condition exclusive of cooling holdup is given in Table VI below.

TABLE VI

Minimum 25 Inventory for Startup and Steady State Operations

25 Disposition	Minimum Class A Inventory	Minimum Class A & B Inventory	Minimum Class A-K Inventory	Minimum Class A-L Inventory
MTR holdup	3.22 kg 25	3.22 kg 25	3.22 kg 25	3.22 kg 25
1200 Area process holdup	2.82	2.82	2.82	2.82
1200 Area makeup holdup	0.40	0.40	0.40	0.54
1200 Area tailings holdup	0.00	0.20	1.80	1.80
1400 Area process holdup	3.22	3.22	3.22	3.22
1400 Area metal scrap holdup	0.20	0.40	2.00	2.00
1400 Area slag holdup	0.11	0.11	0.11	0.11
Total Inventory Including two days cooling	9.97	10.37	13.57	13.71
25 Equivelant to two day cooling	0.40	0.40	0.40	0.40
Total Inventory Exclusive of all cooling	9.57 kg 25	9.97 kg 25	13.17 kg 25	13.31 kg 25

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6.3 Steady State Operations

The continued operation of the MTR will eventually lead to steady state conditions in which the 25 makeup, consumption, Class L discard and amounts of 25 in various classes will all tend to become constants. A pseudo-steady state will be reached after Class L material is first produced, but the true steady state is not reached until much later. For a 168 day mean total cycle time (12 MTR cycles) Class L material and the pseudo-steady state is reached in about five years; however, true steady state is not attained for about 20-25 years. Pseudo-steady state will be discussed further in Section 6.4.

The calculation of true steady state conditions is comparitively simple and is independent of cooling time. For any pass through the MTR a quantity, Q, of 25 is decreased by 12.4%, or 87.6% of the initial amount of 25 remains unused. Thus, of any amount Q charged to the MTR 0.876 Q is discharged. Similiarly, of the 0.876 Q recharged to the MTR, $(0.876)^2$ Q is discharged, and after the nth pass $(0.876)^n$ Q remains. In the more general case, where K is that fraction remaining after one pass through the reactor, the amount initially charged is QK^0, and that discharged the first, second, and nth time is QK^1, QK^2, and QK^n respectively. Now, if a total amount of material T distributed over n classes is considered, the distribution by classes is:

$$T = QK^0 + QK^1 + QK^2 + --- + QK^n,$$

which in the present MTR example becomes:

$$T = Q\left[1 + (0.876)^1 + (0.876)^2 + --- + (0.876)^{10}\right],$$

where Q is the steady state amount of Class A 25 charged to the MTR.

Since the 1400 Area and the reactor will process only assemblies in Classes A through L, and since the 1200 Area decontamination activities apply only to classes B through K, the above equation must be modified as follows:

For 1400 Area and MTR distribution

$$T = Q\left[1 + (0.876)^1 + (0.876)^2 + --- + (0.876)^9\right].$$

For the 1200 Area distribution

$$T = Q\left[(0.876)^1 + (0.876)^2 + --- + (0.876)^{10}\right].$$

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However, it can be easily shown that on a percentage basis the solution of the two equations are the same. These equations were solved for both cases, and the results given in Figure 4.

At steady state, the mean 25 enrichment is obtained by multiplying each class enrichment by the percentage of that class involved and summing over all classes. This calculation indicates that the mean 25 enrichment of fuel assemblies charged is 84.7% whereas that of discharged assemblies is 80.0%.

Another steady state concept useful in calculations is the mean cooling time. This can be obtained as the summation of all the products of the cooling times for the various classes, times their steady state fraction of total material considered. If 27 activity is used as the basis for assigning cooling times and Class B assembly cooling period is D days then the cooling period for each of the other classes is:

Class	Cooling time-days	Class	Cooling time-days
B	D	G	D + 26
C	D + 10	H	D + 28
D	D + 16	J	D + 30
E	D + 20	K	D + 32
F	D + 23	L	D + 34

Now if each time above is multiplied by its fraction of the class present from Table 1, the mean cooling time is D + 18 days. If however, the cooling time is the same for all class assemblies, the mean will also equal this time. The mean total cycle time will be the mean cooling time plus 40 days (MTR time, 12 days; 1200 Area time, 14 days; 1400 Area time, 14 days).

The steady state is an average and somewhat hypothetical condition. Actual operations will vary considerably from the steady state when individual MTR loadings, and 1200 and 1400 operations are considered. However, when many such operations are considered, the averages will closely approximate steady state conditions. For this reason the steady state concept is valuable in predicting long term effect.

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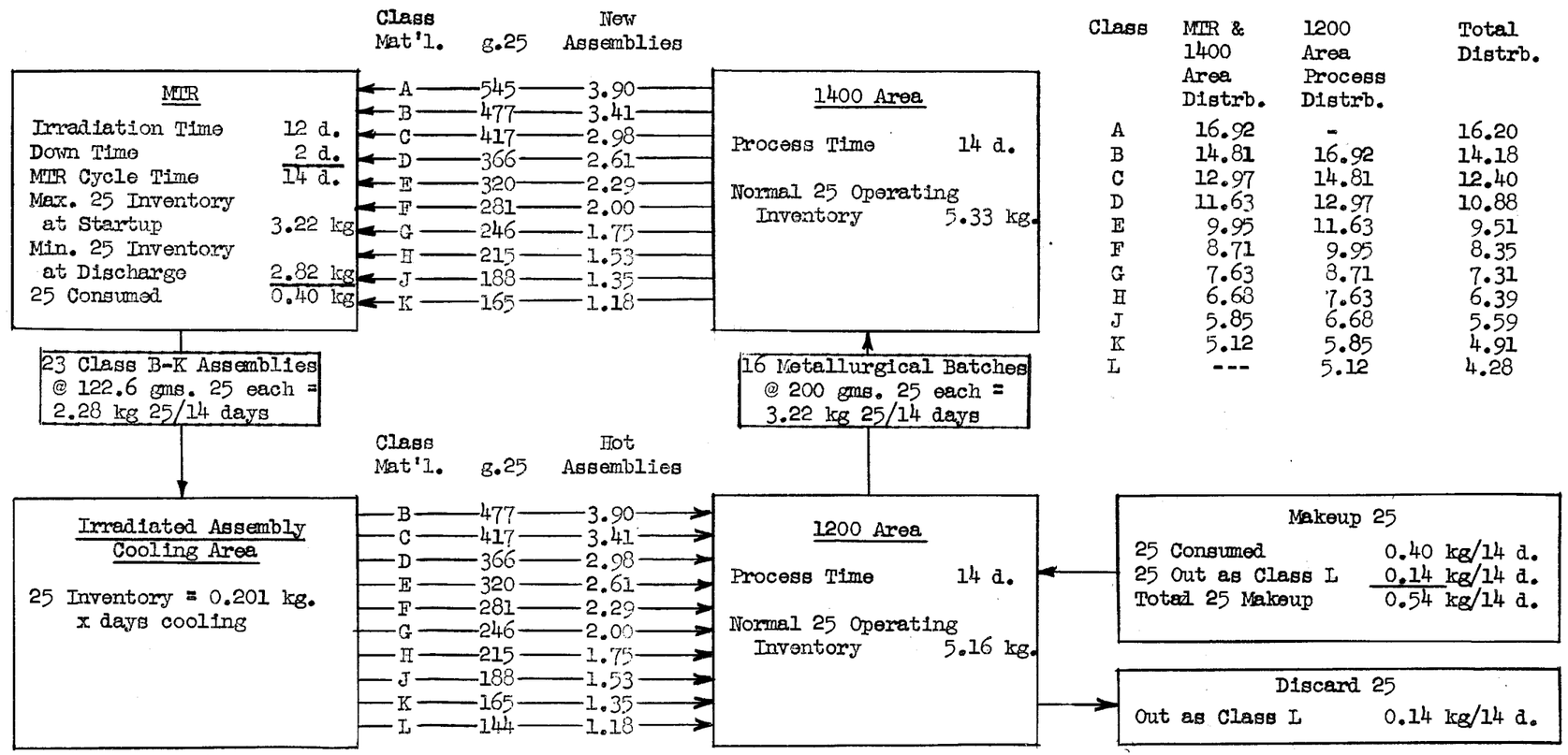
FIGURE 4

25 DISTRIBUTION BY CLASSES
IN VARIOUS AREAS
UNDER STEADY STATE CONDITIONS



Class	MTR & 1400 Area Distrb.	1200 Area Process Distrb.	Total Distrb.
A	16.92	-	16.20
B	14.81	16.92	14.18
C	12.97	14.81	12.40
D	11.63	12.97	10.88
E	9.95	11.63	9.51
F	8.71	9.95	8.35
G	7.63	8.71	7.31
H	6.68	7.63	6.39
J	5.85	6.68	5.59
K	5.12	5.85	4.91
L	---	5.12	4.28

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6.4 Startup and Pseudo-Steady State Conditions

When the MTR is first put into operation, Class A assemblies will be charged until such time as Class B material has been decontaminated and refabricated for use in the MTR. The exact number of MTR cycles in which only Class A fuel is used is dependent on the irradiated assembly cooling period, but will be somewhere between 8 and 12 MTR cycles. The former is based on a 60-day cooling period; whereas the latter allows 130 days for cooling. The term stage will be used here to define that period of time between which any class material is loaded to the reactor and the time at which the next lower class is first loaded, and is 8 to 12 MTR cycles. Thus Stage 1 is that period in which only Class A assemblies are loaded; Stage 2, that period in which only Class A and B are used for fuel, etc.

Stage 1 requires the acquisition of a large amount of highly enriched 25 in a relatively short time, the quantity being from 26 to 40 kg of 25, depending on cooling conditions. In Stage 2, all of the Class B material formed in Stage 1 will be refabricated and recharged to the MTR. Thus, a rather small amount of Class A assemblies will be required as makeup. Similarly in Stage 3, the Class C material formed in Stage 2 will be recovered and reloaded to the MTR. In Stage 3, the Class B material formed in Stage 2 will also be refabricated and reloaded to the reactor, and again a relatively small amount of Class A makeup will be required.

This scheme will be reproduced through Stage 10, at which time the initial surge of 25 will be discharged as Class L assemblies no longer suitable for re-use in the MTR. Therefore, because of the loss of the initial 25 surge from the Stage 1 loading of all Class A assemblies, a fairly large Class A 25 makeup will be required in Stage 11. This second surge will not be as large as the initial surge because of the "cushioning" effect of the other classes now in the process, but will be considerably more than the steady state makeup of .544 kg per MTR cycle. In the 12th cycle, the Class A 25 makeup will be larger than in Stage 2 for two reasons. First, an additional amount of Class A 25 makeup is now required to replace the 25 now being lost in Class L assemblies, and second, the Stage 11 Class A 25 surge is considerably less than the Stage 1 surge. Similar Class A 25 makeup surges will occur in Stages 21, 31, 41, and 51 and Class L surges will occur in Stages 20, 30, 40, and 50. However, each such surge will be less pronounced until true steady state is attained by the 50th stage. In the interim stages (22 to 30 for Class A; 21 to 29 for Class L, etc.), the makeup requirements and discard also tend toward steady state, reaching steady state conditions about the 30th stage. The term stage after stage 10 is merely a period of 8 to 12 MTR cycles.

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One other notable effect of "surging" is that the amount of Class A 25 makeup is the same in all stages from 2 to 10, the same in stages 12 through 20, etc. Similarly, the Class L 25 discard is the same for stages 11 through 19, stages 21 through 29, etc. Since this effect does occur, it is possible to give a 25 makeup and discard schedule for an "average" MTR cycle of any stage. This is shown in Table VII, and indicates more clearly the conditions of the pseudo-steady state. Unfortunately, no such simple pattern occurs for fuel in Classes B through K. However, it is easy to envision how the initial surge carries through in Class B in Stage 2, Class C in stage 3, etc. and finally leaves the operating inventory in stage 10 as Class L discard.

The startup period is stages 1 through 10 and lasts 4 to 5 years. The pseudo-steady state lasts through stage 50 and lasts 16 to 20 years. Thus, true steady state is not achieved for 20 to 25 years.

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TABLE VII

THE EFFECT OF "SURGING" ON 25 ACQUISITION
AND
CLASS L DISCARD IN AN AVERAGE MTR CYCLE

CLASS A MAKEUP			CLASS L DISCARD		
Stage No.[1]	No. Class A Assemblies Charged/MTR Cycle	Kg Class A 25 Charged/ MTR Cycle	Stage No.	No. Class L Assemblies Discharged/ MTR Cycle	Kg Class L 25 Dis-charged/MTR Cycle
1	23[2]	3.220			
2-10	2.86[3]	0.400	10	6.95	0.853
11	8.96	1.253	11-19	0.86	0.106
12-20	3.62	0.506	20	2.38	0.291
21	5.23	0.731	21-29	1.09	0.134
22-30	3.82	0.535	30	1.59	0.195
31	4.26	0.596	31-39	1.15	0.141
32-40	3.87	0.542	40	1.28	0.157
41	3.99	0.559	41-49	1.17	0.143
42-50	3.88	0.544	50	1.20	0.147
51	3.90	0.546	51	1.17	0.144
Steady State	3.88	0.544	Steady State	1.173	0.144

NOTES:

1. Each stage represents 8 to 12 MTR cycles as follows:

   8 MTR cycles = 1 stage for 72 day mean cooling.
   10 MTR cycles = 1 stage for 100 day mean cooling.
   12 MTR cycles = 1 stage for 128 day mean cooling.

2. Thus, for 72 day mean cooling, requiring 8 MTR cycles per stage, 23 x 8 = 184 Class A assemblies required in stage 1 or as new 25 = 184 assemblies x.14 kg 25/assembly = 25.8 kg 25 required in stage 1.

3. For 72 day mean cooling, requiring 8 MTR cycles per stage, 2.86 x 8 = 22.9 Class A assemblies required in stage 2 or as new 25 = 22.9 assemblies x.14 = 3.2 kg. Similarly, 22.9 Class A assemblies, requiring 3.2 kg 25 are required in stages 3, 4. etc. respectively.

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6.5 U^{235} Inventory and Consumption

The minimum inventory for mean cooling periods of 72,* 100, and 128 days is compared graphically with the total 25 acquisition, consumption, and Class L discard in Figures 5 and 6. The former illustrates those conditions which would prevail if operations were such that steady state began with the production of Class L 25, whereas the latter indicates the actual startup and pseudo-steady state conditions for 72 and 128 day mean cooling periods.

In Figure 5, the 25 consumption curve is a straight line through the origin indicating constant rate of fuel consumption. The lowest horizontal line is the minimum inventory of the MTR, 1200, and 1400 Areas. The breaks in the left end of this line are the effects of the tailings and metal scrap in the inventory. The three horizontal lines in ascending order, above this line, are the operating inventories for 72, 100, and 128 days mean cooling respectively, and are exclusive of Class L 25. The lines slanting upward from the horizontal axis represent Class L 25 produced and do not start until state 10 is reached. The parallel lines starting on the total inventory lines represent total inventory, including Class L 25. Finally, the lines originating on the vertical axis signify the total cumulative 25 acquired for use in the MTR Project. Before Class K material is produced, they are the sum of 25 consumed and of additional 25 tailings and metal scrap produced when new classes of 25 come into being. After Class L material is first produced, they are the sume of 25 consumed and Class L 25 discarded. In the interim period between the first appearance of Class K and Class L 25, the 25 acquired is equal only to the 25 consumed.

Figure 6 is similar to Figure 5 in all respects except that it includes the surging effect of the pseudo-steady state operations as discussed in Section 6.4.

These curves indicate that the total running inventory is small compared to total 25 acquired and consumed after a few years, and that the difference in inventories for various cooling times is of even slighter importance on a long term basis. Thus, compared to the total 25 to be used in the MTR lifetime, the minimum inventory, determined primarily by length of assembly cooling, is of minor importance.

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* The values of 72, 100, and 128 day mean cooling were chosen to make the total cycle times integral values of MTR cycles. Since total cycle time is equal to cooling time plus 40 days, the total cycle times are 112, 140, and 168 days, corresponding to 8, 10, and 12 MTR cycles respectively.

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Drawing No. 8340

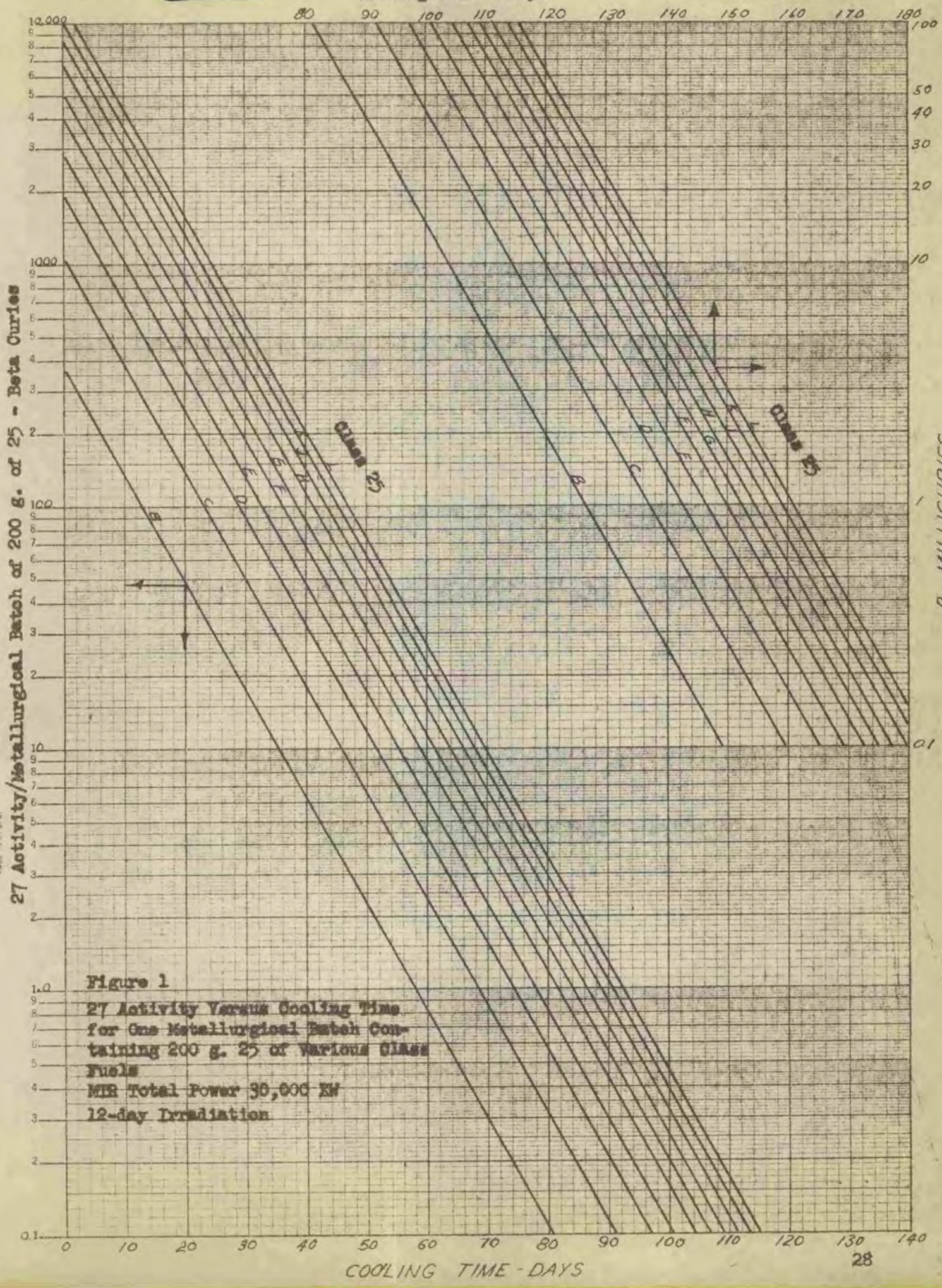

Figure 1

27 Activity Versus Cooling Time for One Metallurgical Batch Containing 200 g. 25 of Various Class Fuels

MIR Total Power 30,000 KW

12-day Irradiation

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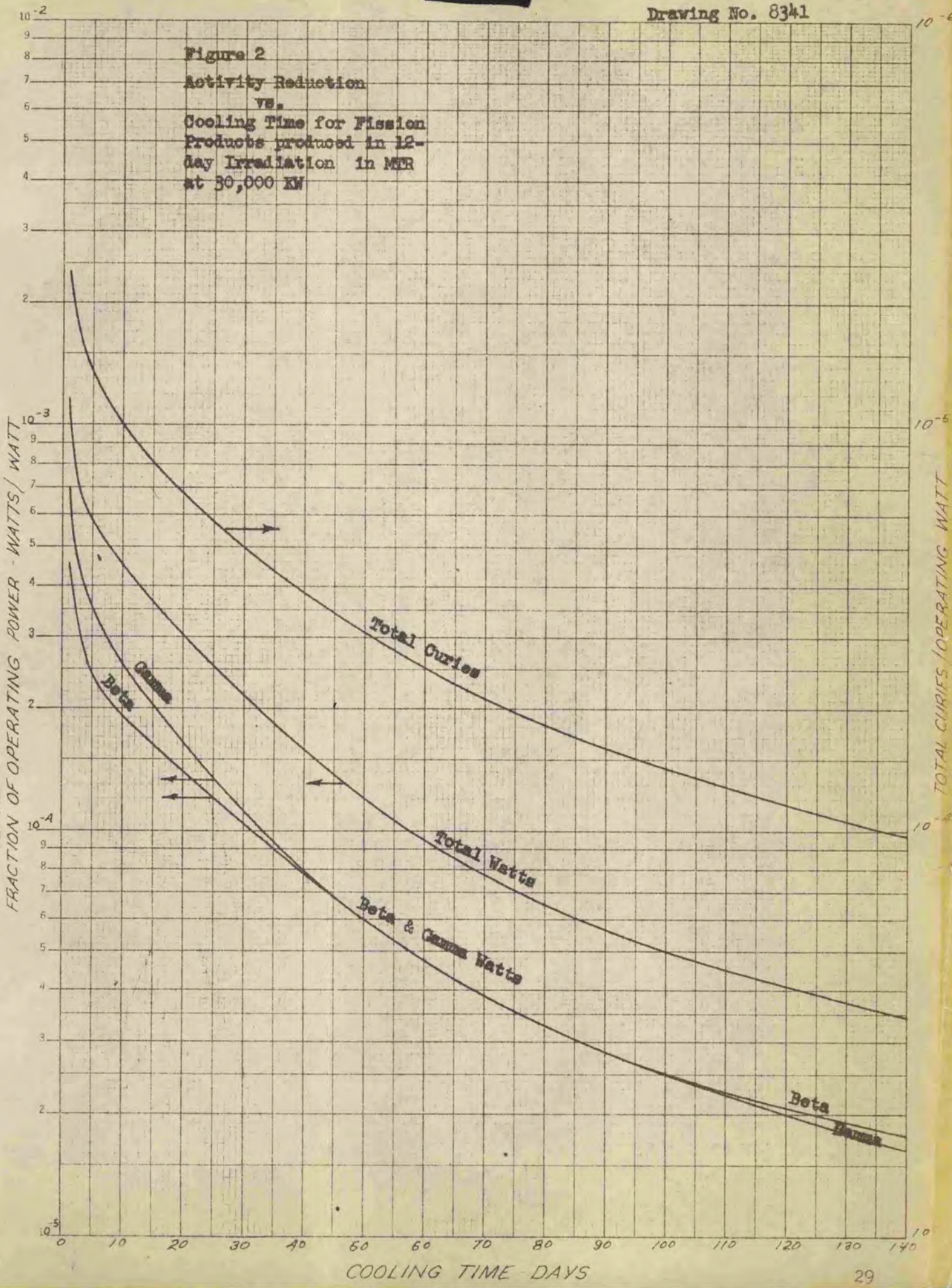
Drawing No. 8341



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Drawing No. 8342

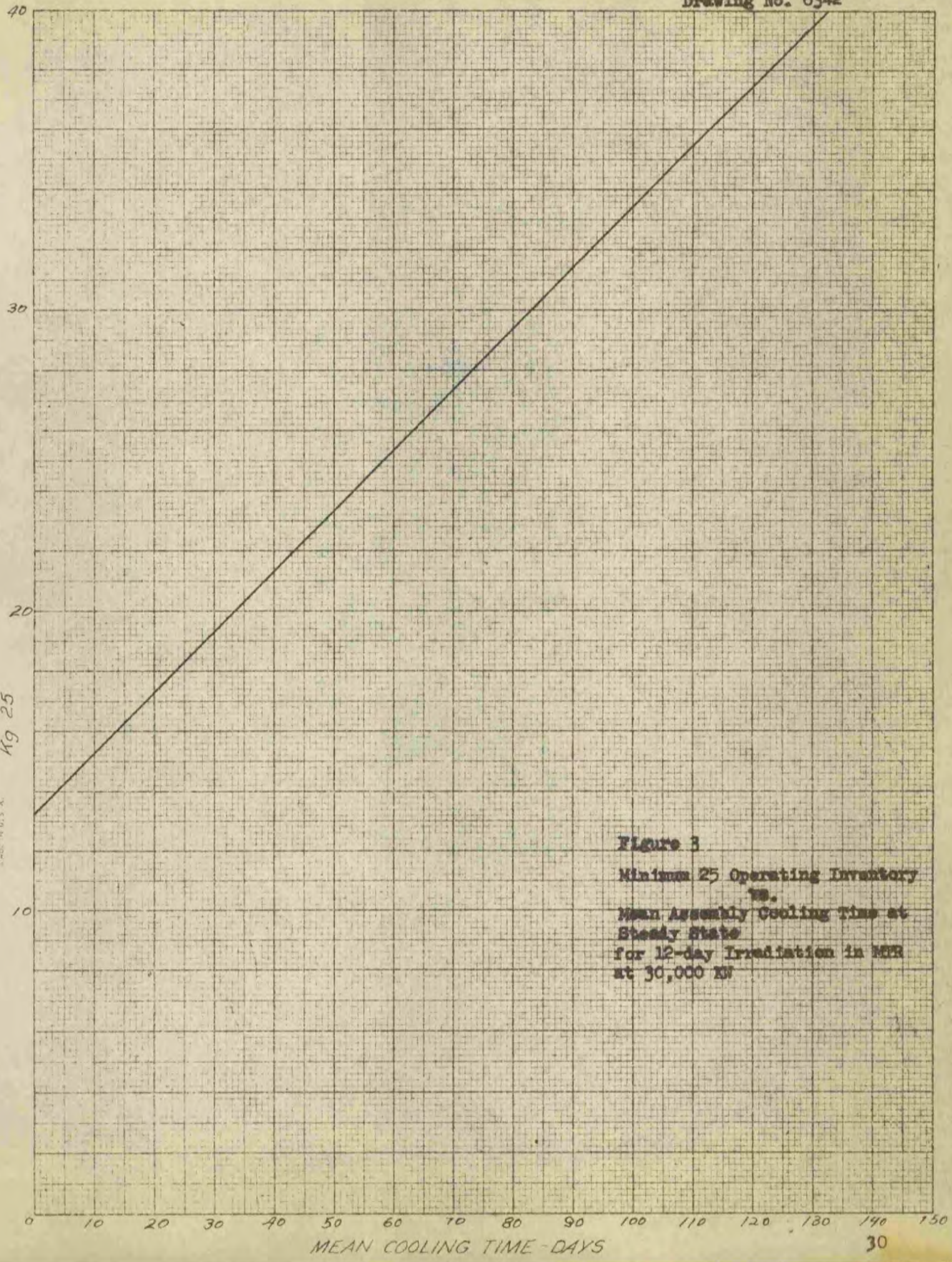

Figure 3

Minimum 25 Operating Inventory
vs.
Mean Assembly Cooling Time at
Steady State
for 12-day Irradiation in MTR
at 30,000 KW

Drawing No. 8343 [redacted]

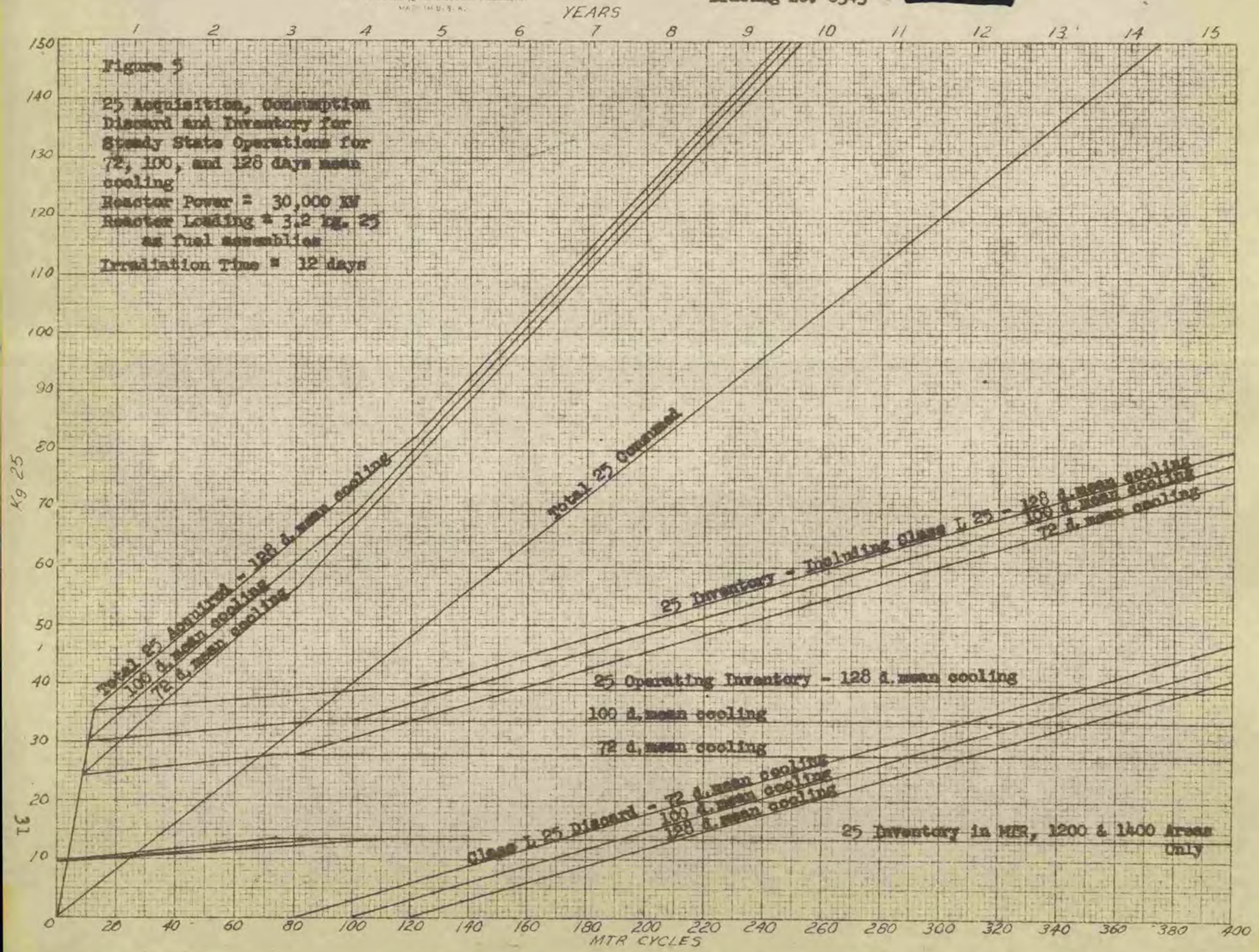

Figure 5

25 Acquisition, Consumption Discard and Inventory for Steady State Operations for 72, 100, and 128 days mean cooling

Reactor Power = 30,000 KW

Reactor Loading = 3.2 kg. 25 as fuel assemblies

Irradiation Time = 12 days

Drawing No. 8344 [redacted]

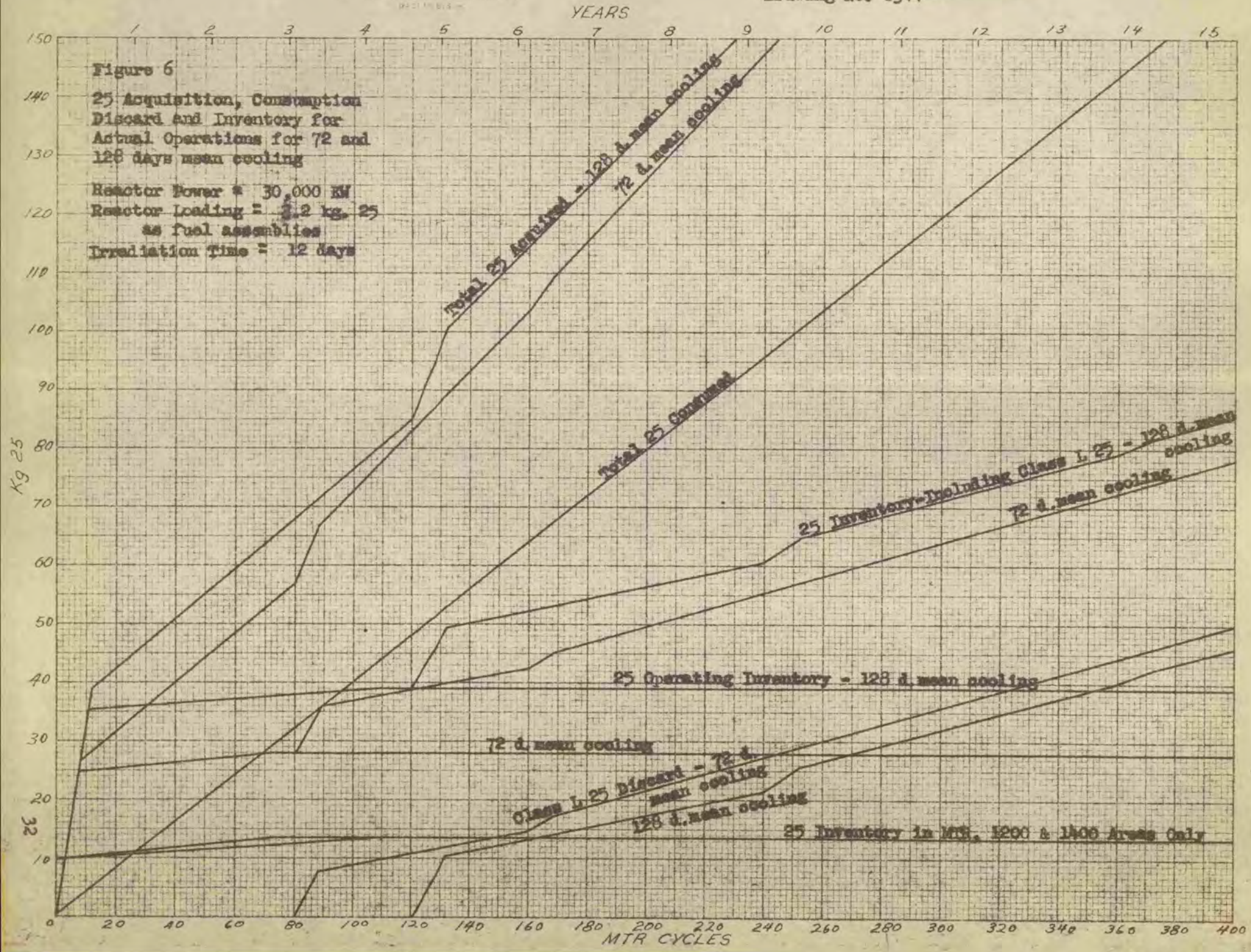

Figure 6

25 Acquisition, Consumption Discard and Inventory for Actual Operations for 72 and 128 days mean cooling

Reactor Power = 30,000 KW
Reactor Loading = 3.2 kg. 25 as fuel assemblies
Irradiation Time = 12 days

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Drawing No. 8362

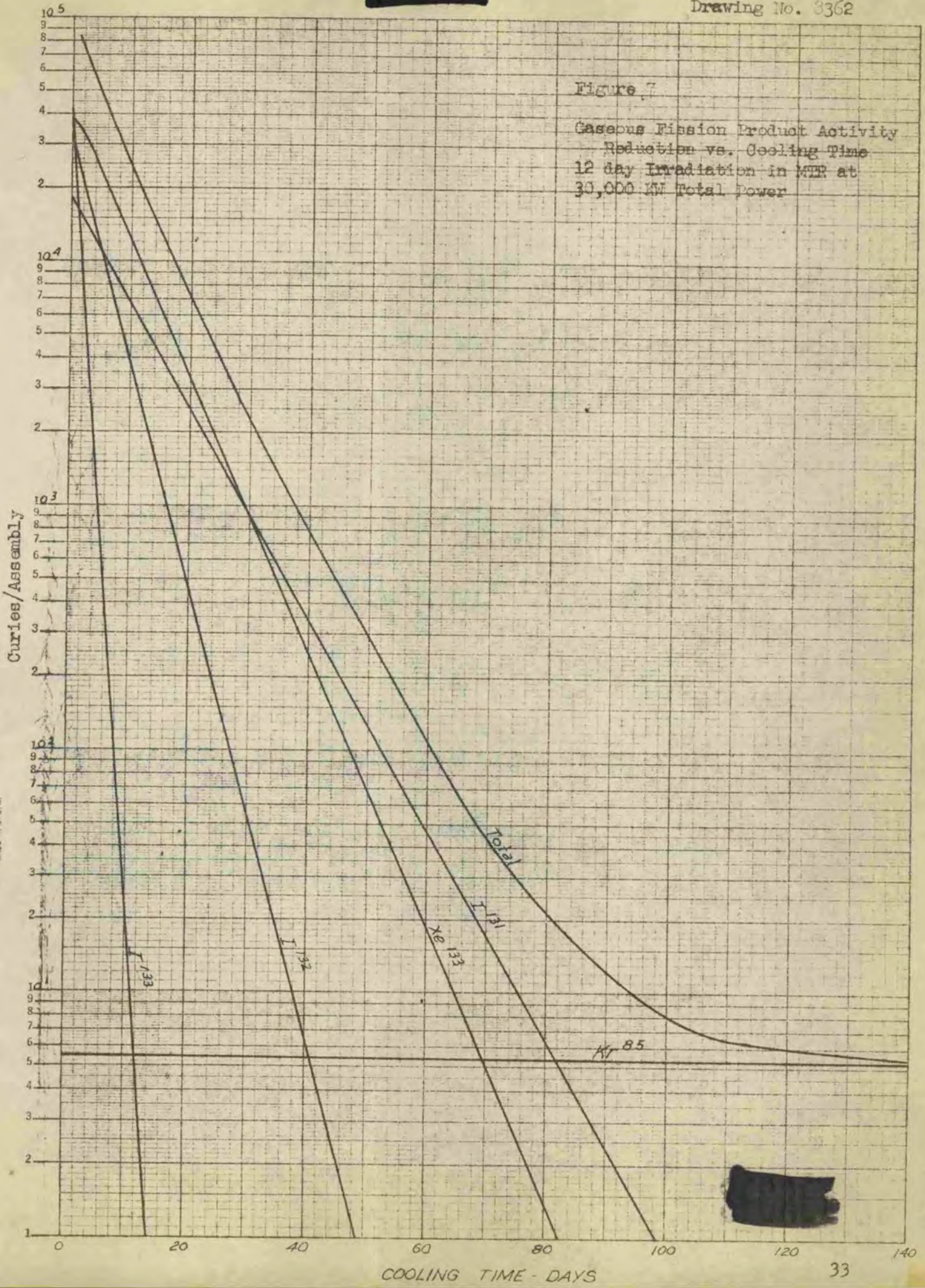

Figure 7

Gaseous Fission Product Activity Reduction vs. Cooling Time
12 day Irradiation in MTR at 30,000 KW Total Power

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