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~~October 31, 1958~~
Date

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REACTOR, SHIELD AND PERFORMANCE DATA FOR A NUCLEAR TURBOJET POWERPLANT

SPECIAL REREVIEW FINAL DETERMINATION	Reviewers	Class.	Date
Class. U	JR	U	10/28/81
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NO. 4 [redacted]			

A. POWERPLANT CHARACTERISTICS

1. Turbojet Engine Performance

The powerplant requirements for a nuclear conversion of the B-70 airplane have been investigated. The criteria for powerplant selection which were discussed during the meeting at North American Aviation in Los Angeles on September 11 and 12 are briefly outlined below:

(1) Nuclear engines are to provide sufficient thrust for a cruise at 0.9 Mach. number and 25,000 feet altitude with no chemical augmentation.

(2) Chemical augmentation is to be used during the supersonic portion of the mission at 3.0 Mach number and 65,000 feet altitude.

(3) Either the 1A or 2A modification of the J-58 engine is to be given first consideration for nuclear conversion.

(4) The envelope of the nuclear J-58 is not to exceed 57 in. in diameter and the overall length of the engine should not increase more than 2 to 3 feet.

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The current J-58 model as well as modifications 1A and 2A were studied in order to determine the engine best suited for the cruise portion of the mission. The engines fitted with a liquid metal to air radiator were compared on the basis of maximum thrust on nuclear power alone at 0.9 Mach number and 25,000 feet altitude. The current J-58 model was capable of producing the highest thrust at the above flight condition. The J-58 Mod 1A was about 3 per cent lower in thrust output, and the J-58 Mod 2A, about 15 per cent lower. On this basis the J-58 Mod 2A was not given any further consideration. The thrust to engine weight ratio of the other two engines was approximately the same and, since the engine airflow requirements of the J-58 Mod 1A were already matched to the B-70 airplane inlet characteristics, this engine was selected for further study.

Early in this study it became apparent that the engine size criteria in item (4) above imposed a severe requirement on the radiator which resulted in a large air-side pressure drop and low thrust output. The engine size limitations restricted the choice of radiator to an axial flow type which, with the limiting face area allowable by the restriction on engine diameter, resulted in high flow velocities through the radiator.

In an attempt to improve the performance, the criteria were relaxed by considering a radiator with a larger face area which would have corresponding lower gas velocities through the radiator. This radiator can be installed in the engine in two different ways. An axial flow type radiator

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[redacted]TRIBUTION OF THIS DOCUMENT IS UNLIMITED can still be used which would result in an increase in engine diameter but no increase in engine length. The second alternative is to use an inclined face type of radiator core in which the air is turned before entering and after leaving the radiator. In this arrangement, the engine length is increased but the engine diameter can be held the same. Both of these "large" radiators have been sized to yield the same thrust performance. In order to permit an evaluation by NAA, performance, weight and installation information for both the large and small radiator configurations have been prepared and are included in this report.

The nuclear system for this powerplant is the same as described in PWAC-257. The heat source is a 350 Mw lithium-cooled solid fuel element reactor with a columbium alloy as the structural material. The lithium enters and leaves the reactor at 1350F and 1750F respectively. NaK picks up the heat from the lithium in an intermediate heat exchanger and delivers the heat to the engine radiators at 1650F. The structural material in the NaK circuit is 316 stainless steel.

The two sets of engine performance are presented in Figs. 1 to 6. The engine performance on nuclear power alone at 0.9 Mach number is plotted against altitude in Fig. 1 for the J-58 Mod 1A engine with both the small and the large radiator. From this graph the difference in cruise performance between the two radiator sizes can be noted. The thrust at 25,000 feet altitude is not sufficient to fly the fully loaded B-70, therefore, a reduction in chemical fuel load must occur. However, a decrease in cruise altitude will restore the fuel carrying capacity. A difference between the performance of the engines at the supersonic 3.0 Mach number and 65,000 feet altitude portion of the mission in terms of fuel consumption versus thrust can be noted in Fig 2. The net thrust, fuel consumption, airflow and reactor power for the J-58 Mod 1A engine with the large radiator during nuclear-chemical power is plotted in Fig 3 to 6 over the spectrum of operating flight conditions.

2. Weight Estimation

The engine radiators have been studied in sufficient detail to arrive at a reasonable weight estimate. These estimates have been made for the "small" radiator which matches the NAA requirements outlined previously, and for each of the two "large" radiators also previously described. The basic turbojet engine weight, without the radiator, of the chemical engine counterpart has been retained without change. A weight estimate of the liquid metal and miscellaneous systems has also been made. These weights are all tabulated in Fig 7. The reactor and shield date is given later in this report. Piping data for this powerplant has also been computed and is tabulated in Fig 8. The piping schematic used as a basis for the liquid metal weight estimate is illustrated in Fig 9.

[redacted]

B. REACTOR AND SHIELD DATA

1. Scaling Factors

a. Basic Reactor Package

Two specific reactor sizes have been studied in order to provide scaling data. The dimensions and weights of these reactors are as follows:

Power, Mw	350	575
Diameter, inches	33.2	37.2
Height, inches	55.5	59.5
Weight, lbs.	5000	8000

The reactor envelope, which includes the active core, reflector, controls and pressure shell, is approximately cylindrical. The envelope dimensions and weight may be scaled using the relations below for the power range of 300 Mw to 600 Mw. These dimensions and weights are independent of reactor coolant temperature in the 1750F to 2000F range.

$$\text{Diameter, inches} = 1.72\ (\text{Reactor Power, Mw})^{0.4} + 15.3$$
$$\text{Height, inches} = 1.72\ (\text{Reactor Power, Mw})^{0.4} + 37.6$$
$$\text{Weight, lbs.} = 133\ (\text{Reactor Power, Mw}) + 350$$

b. Reactor and Shield Package

Three sets of shield optimization calculations have been made and the results are tabulated in Fig 10. The first two cases were requested by NAA in a letter dated September 12. The third case was requested later by telephone. The shielding for case 3 differs from the other two cases in that advantage is taken of a 50 foot long chemical fuel tank for shielding estimates.

The scaling formulae for gamma and neutron shield weights are given below. The doses and G. Lambda and N. Lambda have to be taken from previous shield calculations for the 350 and 575 Mw reactors which are reported in Fig 10. The use of the weight scaling formulae assumes a constant reactor envelope size. Adjustment may be made by assuming that the necessary change in reactor envelope is added to the outside of the shield as an identical thickness of lithium hydride.

$$\Delta W_G = \lambda_G \quad D_{oG} \quad \text{Ln} \left\{ \frac{D1 + K\ (D2 + D3)}{D4} \cdot \frac{P}{P_o} \right\}$$

$$\Delta W_N = \lambda_n \quad D_{on} \quad \text{Ln} \left\{ \frac{D5 + KD6}{D7} \cdot \frac{P}{Po} \right\} - \frac{\rho_n}{\rho_G} \Delta W_G$$

[redacted]

where Do_G = design gamma rate in crew compartment

Do_N = design neutron rate in crew compartment

D_1 = direct gamma rate in crew compartment

D_2 = air scattered gamma rate in crew compartment

D_3 = air capture gamma rate in crew compartment

D_4 = new gamma rate in crew compartment

D_5 = direct neutron rate in crew compartmnet

D_6 = air scattered neutron rate in crew compartment

D_7 = new neutron design rate in crew compartment

K = ρ/ρ_o = altitude density ratio

P/Po = ratio of "power scaled to" to "power scaled from"

ρ_n = density of neutron shield

ρ_G = density of gamma shield

λ_G = G. Lambda

λ_n = N. Lambda

ΔW_G = change in total reactor and crew comp. gamma shield

ΔW_n = change in total reactor and crew comp. neutron shield

c. Trade Between Reactor Life and Reactor Size and Weight

Increasing reactor life from, say, 100 hours to 1000 hours requires an increase of only 5 per cent in reactor weight. This is due to the fact that with the high strength of the optimum columbium alloy the pressure vessel and core support structure, which change in weight with reactor life, comprise only a small fraction of the overall reactor weight. Many major weight items, e.g. reflector, core, control drums, control drum drives, pumps and coolant are unaffected by changes in life within the range of operating lifetimes considered.

d. Installation of Reactor Package for Minimum Frontal Area

The mechanical design problem associated with designing the reactor for operation horizontally appears to be too difficult to recommend this at the present time. The change in reactor installation from a vertical position to a horizontal position would result in a decrease in shield envelope height from 116 in. to 93 in.

2. Reactor Radiation Characteristics

The neutron and gamma radiation flux at the reactor surface is given in Fig. 11 for the 350 Mw reactor. The neutron flux values are increased by 15 per cent for the 575 Mw reactor and the gamma flux values by 36 per cent. The direct dose patterns at 50 feet ~~the surface~~ of the reactor shields are tabulated in Figs. 12 to 14 for cases 1 to 3 of Fig. 10, respectively.

3. Basic Shield Data

The layout of a typical reactor shield is illustrated in Fig. 15. The reactor shield thicknesses for a 350 Mw reactor, case 1 of Fig. 10 is tabulated in Fig. 16. Similar data for cases 2 and 3 of Fig. 10 are given in Fig. 17 and 18, respectively. A 60 cm thick inner neutron shield should be added to the basic reactor before adding these thicknesses for case 1 and 30 cm for cases 2 and 3.

The shielding properties of various materials are presented in Fig. 19 to 27. These materials include uranium isotope 238, lead, boron, boron carbide, air, alkylbenzene, lithium hydride and uranium isotope 235.

The nitrogen (n, γ) reaction is reported in NARF-56-41T, Vol. 3, Nov. 14-15, 1956. The results given in this memo come from ORNL-2157, pt. 6, pg. 24. The references for scattering and absorption information on air follow:

a. Direct gamma dose - PWAC-198, pg. 16.
b. Air scattering gamma dose - PWAC-198, pg. 17 and ORNL-1575, pg. 188-200 and ORNL CF-56-5-73.
c. Air capture gamma dose - PWAC-198, pg. 18.
d. Direct neutron dose - PWAC-198, pg. 21 and ORNL-1843.
e. Air scattered neutron dose - PWAC-198, pg. 21 and ORNL-1947 and ORNL-2012.

4. General Startup Procedure

The system on which this procedure is based comprises a reactor and six turbojet engines incorporating liquid metal radiators and chemical fuel combustors. The reactor is cooled with lithium which flows through two intermediate heat exchangers in parallel. Each secondary loop uses NaK as coolant and circulates it through three engine radiators in parallel. Each radiator has isolation valves at inlet and outlet. Each secondary loop has a bypass valve across the radiators.

(1) Reactor is cold. Coolant systems are filled with helium. Radiator isolation valves are open on all engines. Air inlets and exhausts of five engines are covered to minimize losses. An air blower and air heater are coupled to air inlet of the sixth engine. Radiator bypass valve of the secondary coolant loop containing that engine is slightly open.

[redacted]

(2) If temperature is above the freezing point of NaK, the secondary coolant loops are filled and the NaK pumps are started using an auxiliary air compressor to supply air to the pump turbines. Helium is purged from the loops and isolation valves are closed on the engines not being used for heating. The other is positioned to maintain a normal flow through the radiator being used for heating. If the temperature is below the freezing point of NaK, the system is heated by circulating helium with the NaK and lithium pumps while heat is added by the air blower and heater until NaK can be put in without freezing. In this case isolation valves are left cracked in all radiators so that NaK will not freeze. Estimated time, one-half hour.

(3) Helium is circulated through lithium loop with lithium pumps driven by auxiliary air compressor. Combination of heat from pump work and heat transfer via the Li-NaK heat exchangers from hot air forced through the one radiator raises system temperature of 400F in about one-half hour. System is maintained at 400F by pump work and heat addition.

(4) Lithium pumps are stopped and lithium, preheated to 425F, is introduced into the system through the fill and drain valves. When the system is filled with lithium, the pump speeds are gradually increased to maximum allowed by the auxiliary compressor while the system is purged of entrained helium. Pump heat and the air heating system sustains system temperature. Estimated time, one-half hour.

(5) Control drums are unlocked and the reactor is made critical by drum rotation at rate of about two cents per second. The reactor will become critical on a period of about twenty seconds. During this operation, a period meter will be in operation which will inhibit reactivity increase if the period decreases to ten seconds and scram the reactor if the period reaches five seconds. Flux level and period will be recorded continuously. The coolant temperature will be maintained at about 425F by liquid metal pump work, and the air heating system. Time required, between 5 and 10 minutes.

If the engines are to be started and run chemically, steps (6) through (9) are taken:

(6) The reactor, on flux control, is brought to a power level which, with idle liquid metal pump power, will counteract heat losses by radiator and convection from the system. The air blower and heater are shut off but kept in position. All pumps are reduced to idle, both bypass valves are open, all isolation valves are shut or cracked depending on temperature. Estimated time, ten minutes.

(7) Engine covers are removed and engines are started normally on chemical fuel. When at least two engines are running, the liquid metal pumps are valved to use engine bleed air for power and the auxiliary air compressor and the engine inlet air blower and heater are removed.

[redacted]

This requires about ten minutes for sequential starting.

(8) During chemical operation of the powerplant, the reactor and liquid metal systems are heated to the normal reactor inlet temperature by manually increasing flux to some low value, say 5 per cent of design power. If cooling is required it can be controlled by the isolation valves. Estimated time, ten minutes which may coincide with step 7 if required.

(9) When nuclear operation is required the reactor is brought gradually up to 30 per cent power while isolation valves are slowly opened and bypass valves are closed. When the reactor is at this power and liquid metal pumps are at idle speed, the temperatures in the system should be at design values. The reactor is then transferred to temperature control, and the bypass valve is put on automatic control. Chemical power to the engines will have been reduced by the nuclear heat compensator so that total power will be unchanged. The reactor can now be brought to full power in thirty seconds. Chemical power may be cut off if desired. Estimated time, five to ten minutes.

If the engines are to be started and run on nuclear power, omit paragraphs 6 through 9 above and follow (10) through (14) below.

(10) The critical reactor is brought to about five per cent of full power on flux control as hot air heater is shut off but blower continues to operate. The covers are removed from the other engines. System temperature is raised by controlling bypass valves and blower airflow until reactor inlet temperature is at design conditions. Estimated time, 10 to 15 minutes.

(11) An engine other than the one with the blower, is started as its isolation valves are opened. System temperatures are maintained by reducing blower airflow until the blower is shut off and the isolation valves of the engine with blower are nearly closed. The liquid metal pumps are transferred from auxiliary compressor to engine bleed air. The engine inlet air blower and auxiliary air compressor for liquid metal pumps should remain in the ready condition. The reactor is now at stand-by. Time required about five minutes.

(12) The other engines are started one at a time by operation of bypass and isolation valves. The reactor, on flux control, is manually brought up to the required power as each engine is brought in. The blower is removed and that engine started last. The auxiliary air compressor for the liquid metal pumps is disconnected. The reactor is now at idle power, approximately 30 per cent of full power. Time required, about ten minutes.

(13) System is placed on temperature control. Time, about one minute.

(14) Nuclear design power may now be reached within 30 seconds and chemical augmentation may be added as required.

If no intermediate heat exchanger is used, step (2) referring to filling the NaK system is omitted. The other steps are modified to insure that lithium in the radiators is always above 400F to prevent freezing.

5. General Shutdown Procedure

(1) The reactor is brought from full nuclear power to idle (30 per cent of full power) in a minimum of thirty seconds by normal means which is reduction of NaK pump speed. If continued engine power is required, the nuclear heat compensator in the engine controls substitutes chemical heat for nuclear heat. The reactor is shifted to flux control.

If the engines are to continue to operate chemically follow paragraphs (2) through (5) of this procedure.

(2) The bypass valves are slowly opened, isolation valves are slowly closed and the reactor is manually reduced in power all in a coordinated process which keeps reactor inlet temperature at a constant value. When the power is down to afterheat level which is estimated at 2.5 per cent of design power, the control drums are rotated to their least reactive position and the reactor is shut down. By control of the valves, cooling is varied so that temperatures slowly fall to about 425F where they are maintained until the chemical power is to be shut down.

(3) A chemical engine is shut down and the air blower is positioned in front of that engine. The auxiliary air compressor is connected to the liquid metal pump air manifold. When the pumps are running on auxiliary air and the cooling load has been taken over by the blower, the other engines are shut down normally. At this time all engines except the one used for cooling have closed or cracked isolation valves depending on temperature. Estimated time, ten minutes.

(4) After a sufficient time for the afterheat to decay to a point where system losses by radiation and convection will dissipate the afterheat, the blower will be shut down. This time is estimated at one to twenty days depending on mission length, it is about 15 days for a thirty day mission.

(5) The liquid metals may now be drained and replaced by helium which is circulated by the pumps. If at any time when the system is not drained and the afterheat generation is not enough to keep the system above the freezing point of lithium, the heater in the air blower must be activated and heat put into the system. Estimated time, one half hour.

If the engines are to be shut down at the same time as the reactor, omit steps (2) and (3) of this procedure and follow (6) through (9) below, returning to steps (4) and (5) after (9) has been accomplished.

[redacted]

(6) The appropriate bypass valve is opened slowly as isolation valves are nearly closed on one engine. Reactor power is manually reduced as the engine shuts down. The isolation valves must be left open enough to prevent freezing of NaK in radiator if the ambient temperature is low. Time required, about one minute.

(7) An air blower is positioned at the inlet of the engine that was shut down and its isolation valves are opened. An auxiliary air supply is coupled to the liquid metal pump air manifold. These operations may overlap 6 and 8 and require about ten minutes.

(8) Step 6 is repeated on other engines leaving one at idle. Time for this operation is approximately 5 minutes. Reactor is now at standby which is about 5% of full power.

(9) The last engine is shut down as pump speeds are reduced and the drums are rotated to their least reactive position. Pump speed, drum rotation and blower airflow are programmed during the entire shut down procedure so that the system temperatures fall in stages to about 1000F. The reactor is now shut down and at afterheat level which is about 2.5 per cent of full power. Blower airflow and pump speeds are adjusted as required to maintain temperatures. Time required varies from 5 to 10 minutes depending on whether reactor is nearly new or has been at power for some time.

6. Afterheat Removal

Based on previous studies a generous time must be allowed to connect the ground cooling circuit. This time must be less than that for afterheat to raise the core temperature excessively. Fig. 28 shows the afterheat production of a reactor as a function of reactor continuous operation time and of time after shutdown. A criterion of 800F temperature rise results in the table below of allowable time available for heat transfer as a function of time after shutdown. The time for connecting the ground cooling circuit is tentatively considered to be one-half hour. Thus lithium cannot be drained or disconnected for 1200 hours in the 350 Mw reactor and 50 hours in the 575 Mw reactor. The 350 Mw reactor is based on 1000 hours operating time; and the 575 Mw reactor, 10 hours of continuous operation.

[redacted]

[redacted]

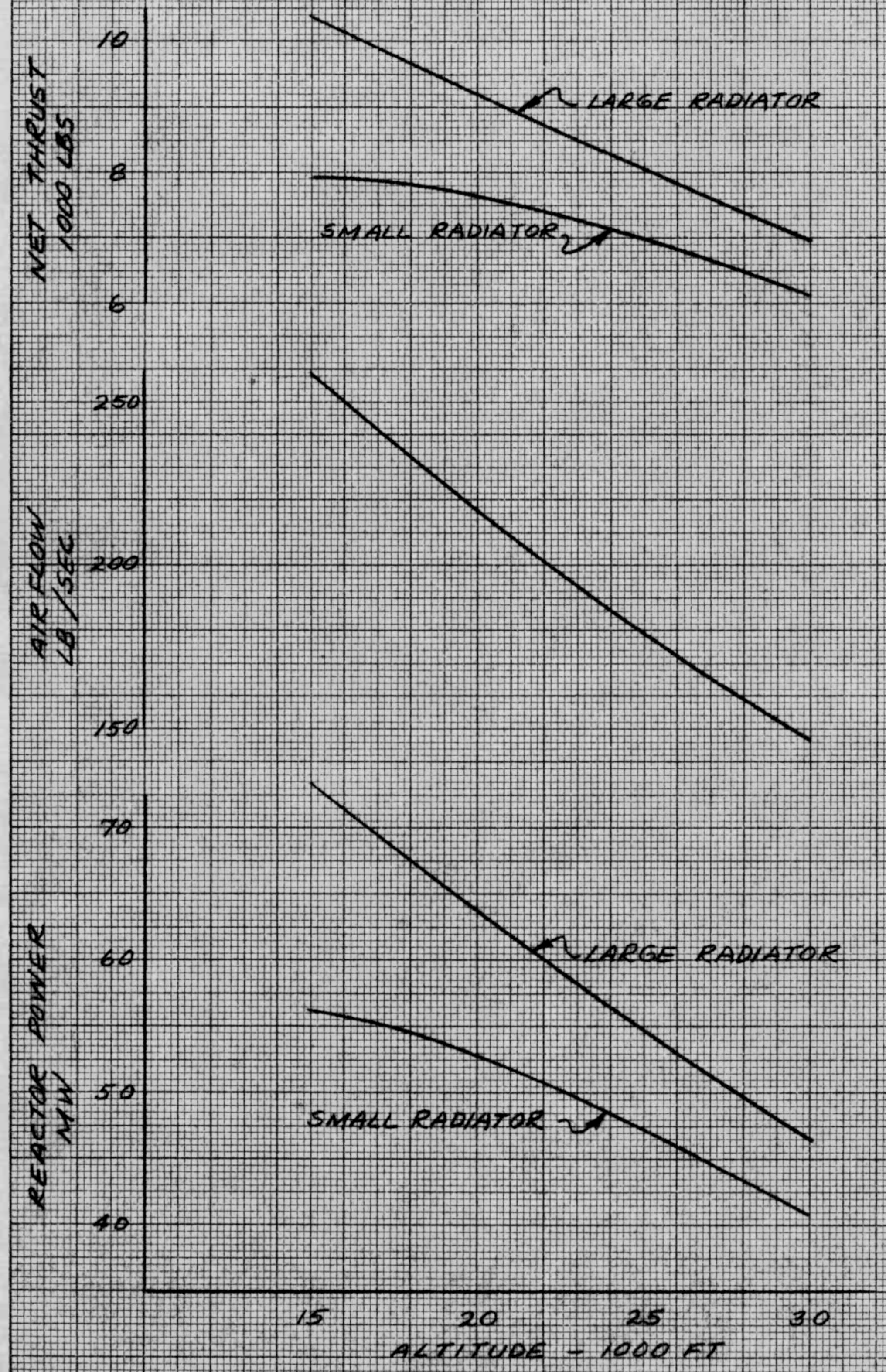
Time After Shutdown Hours	Heat Generated BTU/hr	Time for 800F Temperature Rise Min.
	350 Mw Reactor *	
1	2.27×10^7	.5
100	2.87×10^6	3.9
500	9.56×10^5	11.8
1000	5.00×10^5	22.4
2500	1.91×10^5	59
	575 Mw Reactor **	
1	2.16×10^7	.9
5	6.87×10^6	2.8
10	6.48×10^5	29.4
50	2.55×10^5	75

NOTE: * 1000 hours of continuous operation
** 10 hours of continuous operation

[redacted]

ENGINE PERFORMANCE ON NUCLEAR POWER

FLIGHT MACH NUMBER = 0.9

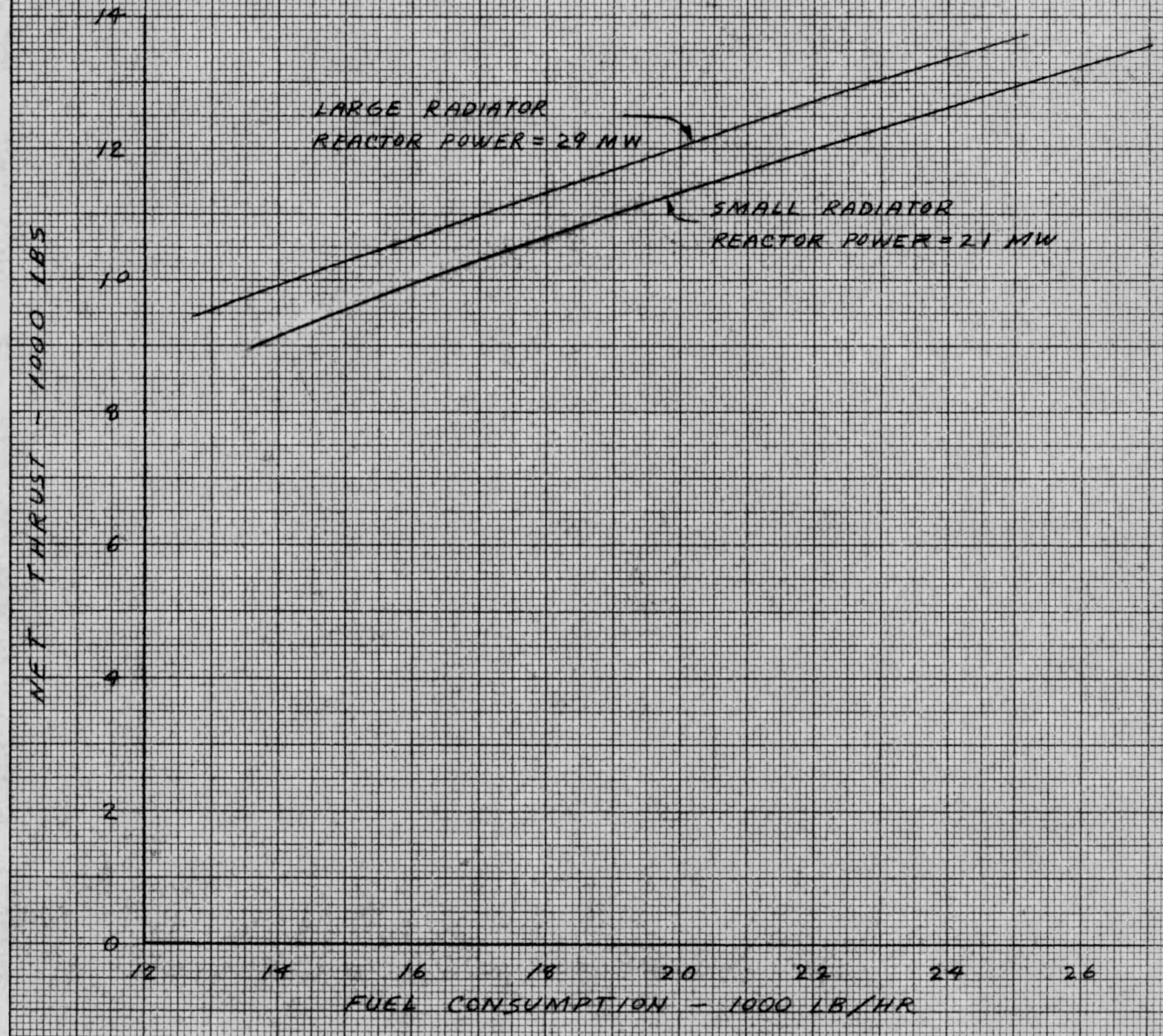


[redacted]

FIG. 2

ENGINE PERFORMANCE ON NUCLEAR-CHEMICAL POWER

FLIGHT MACH NUMBER = 3.0
ALTITUDE = 65,000 FT
AIRFLOW = 182 LB/SEC

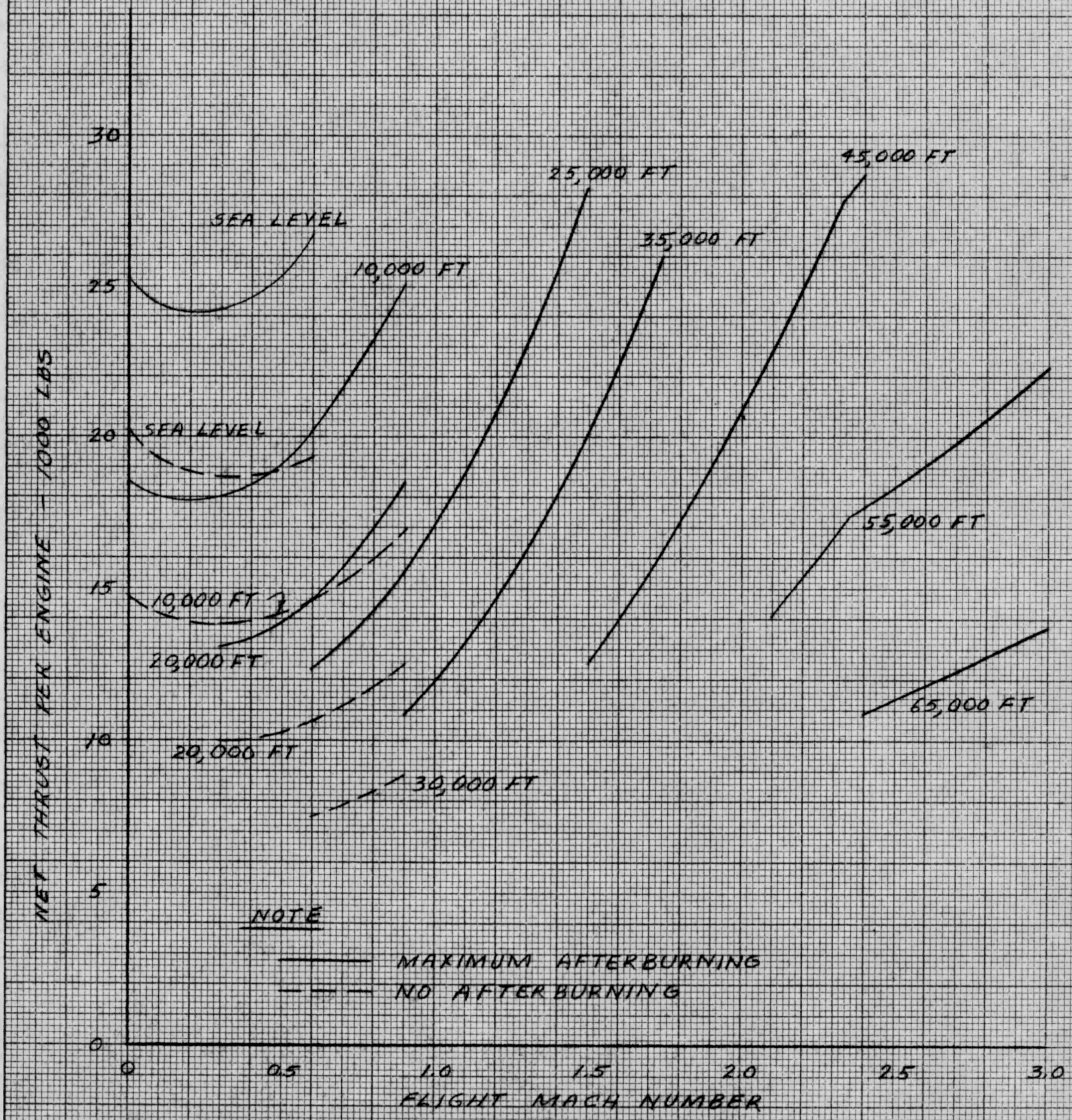


[redacted]

NET THRUST PER ENGINE

NUCLEAR-CHEMICAL POWER

LARGE RADIATOR



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[redacted]

FIG. 4

FUEL CONSUMPTION PER ENGINE

NUCLEAR-CHEMICAL POWER

LARGE RADIATOR

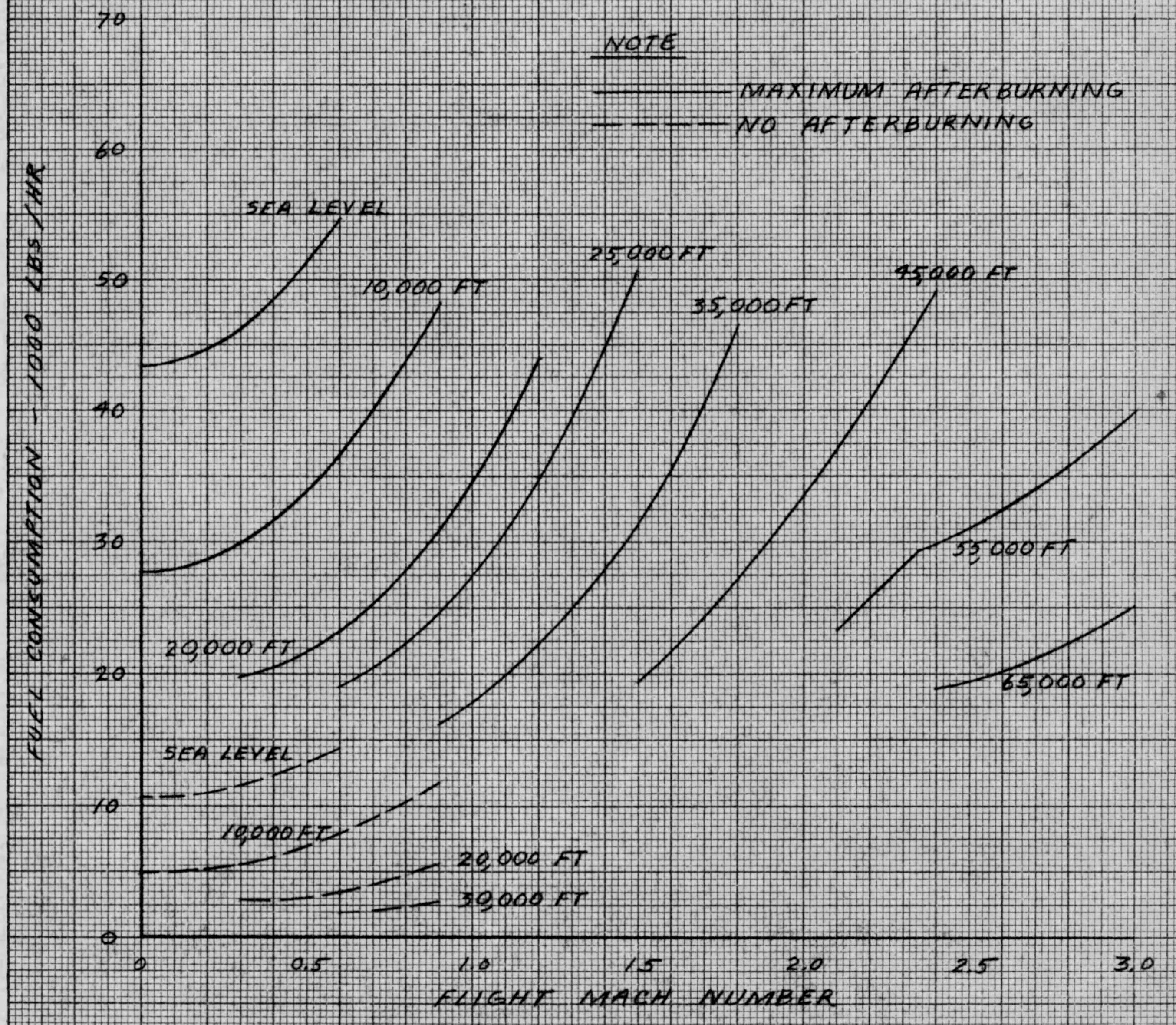

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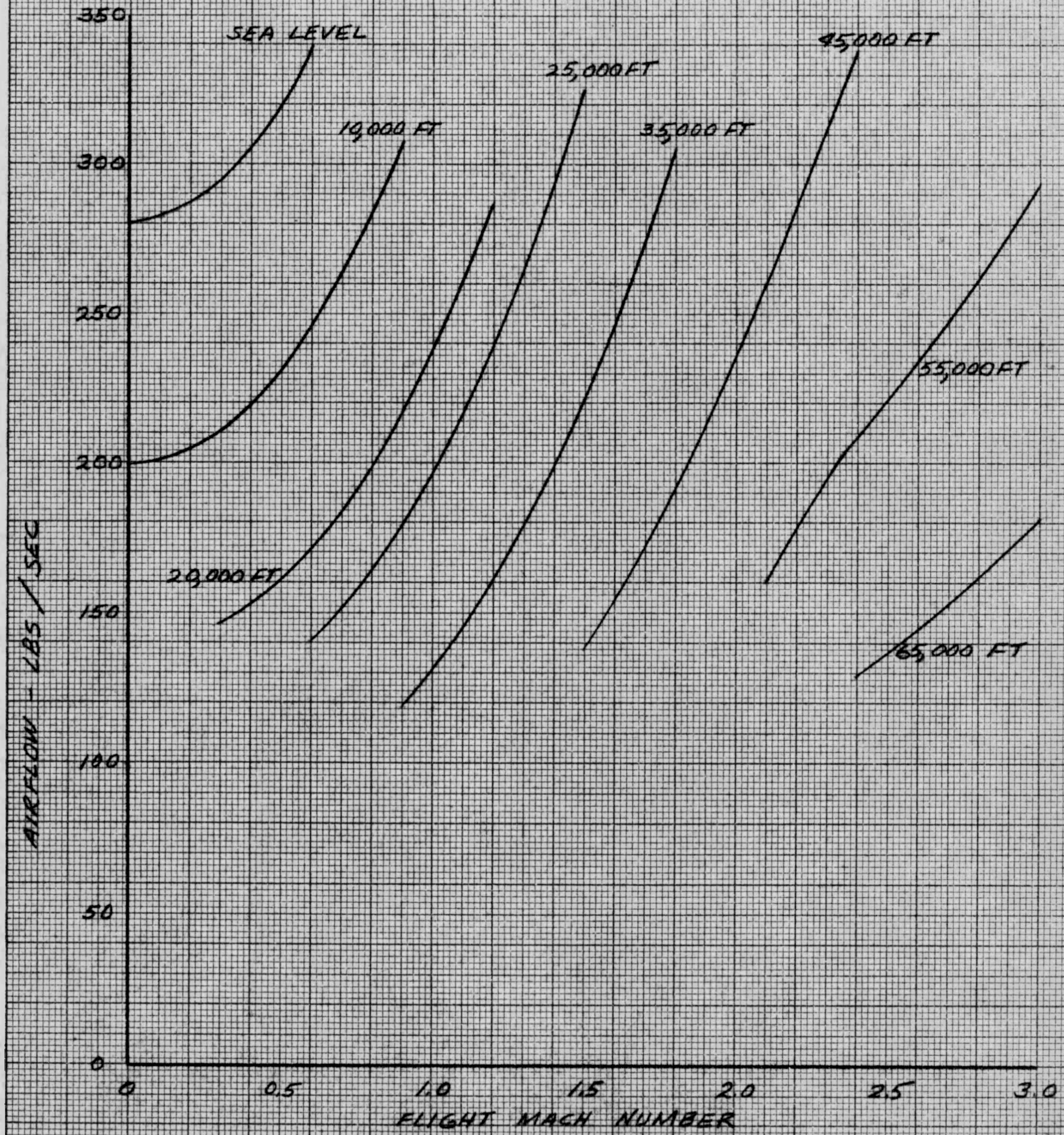
FIG. 5

AIRFLOW PER ENGINE

NUCLEAR-CHEMICAL POWER

LARGE RADIATOR



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REACTOR POWER PER ENGINE
NUCLEAR-CHEMICAL POWER

LARGE RADIATOR

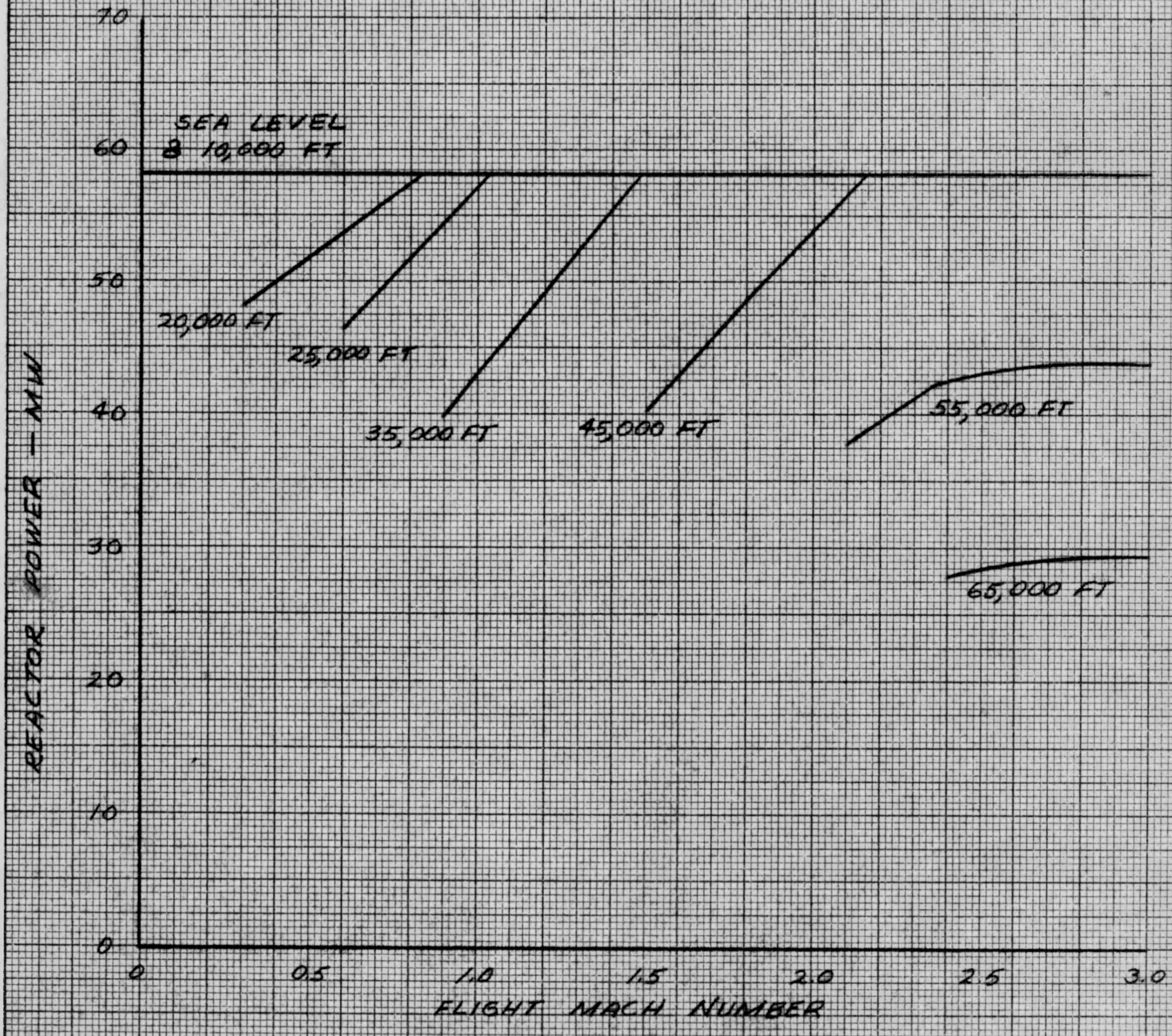


Fig. 7

WEIGHT ESTIMATE

Number of Engines	6	6	6
Radiator diameter, in.	57.0	72.4	57.0
Radiator length, in.	30	30	48.5
Turbojet Engine Weight, lb.			
Turbojet (exclusive of radiator)	5,200	5,200	5,200
Radiator	3,100	5,300	4,000
Total, lb/engine	8,300	10,500	9,200
Total, lb.	49,800	63,000	55,200
Liquid Metal System, lb.			
Piping (wet, insulated)	18,500	18,500	18,500
Valves	4,800	4,800	4,800
Expansion joints and couplings	800	800	800
Pumps and Drives (wet)	3,200	3,200	3,200
Accumulator (wet insulated)	2,700	2,700	2,700
Bleed air ducts	1,500	1,500	1,500
Total, lb.	31,500	31,500	31,500
Helium System, lb.	700	700	700
Shield Coolant System, lb.	500	500	500
Control System, lb.	2,200	2,200	2,200
Intermediate Heat Exchanger	8,700	8,700	8,700
Total Powerplant Weight, lb*	93,400	106,600	98,800
Layout Drawing Number	LH-100470	LH-100471	LH-100472

NOTE: * Does not include reactor and shielding. These items are reported in Fig. 10 of this report.

[redacted]

[redacted]

FIG. 8

PIPING DATA

Reactor-to-Intermediate Heat Exchanger Piping; Lithium

Outside diameter, in*	7.5
Wall thickness, in.	0.14
Weight (wet), lb/ft**	25.2
Insulation weight, lb/ft	4.4
Insulation thickness, in.	3.1
Length assumed (total), ft.	50
Number of lines	2

Intermediate Heat Exchanger-to-Reactor Piping; Lithium

Outside diameter, in*	7.5
Wall thickness, in.	0.14
Weight (wet), lb/ft**	23.5
Insulation weight, lb/ft	2.7
Insulation thickness, in.	2.1
Length assumed (total), ft.	50
Number of lines	2

Intermediate Heat Exchanger-to-Radiator Piping; NaK

Outside diameter, in*	6.8
Wall thickness, in.	0.14
Weight (wet), lb/ft**	25.4
Insulation weight, lb/ft	3.9
Insulation thickness, in.	3.0
Length assumed (total), ft.	150
Number of lines	6

Radiator-to-Intermediate Heat Exchanger Piping; NaK

Outside diameter, in*	6.8
Wall thickness, in.	0.14
Weight (wet), lb/ft**	28.8
Insulation weight, lb/ft	2.3
Insulation thickness, in.	2.0
Length assumed (total), ft.	150
Number of lines	6

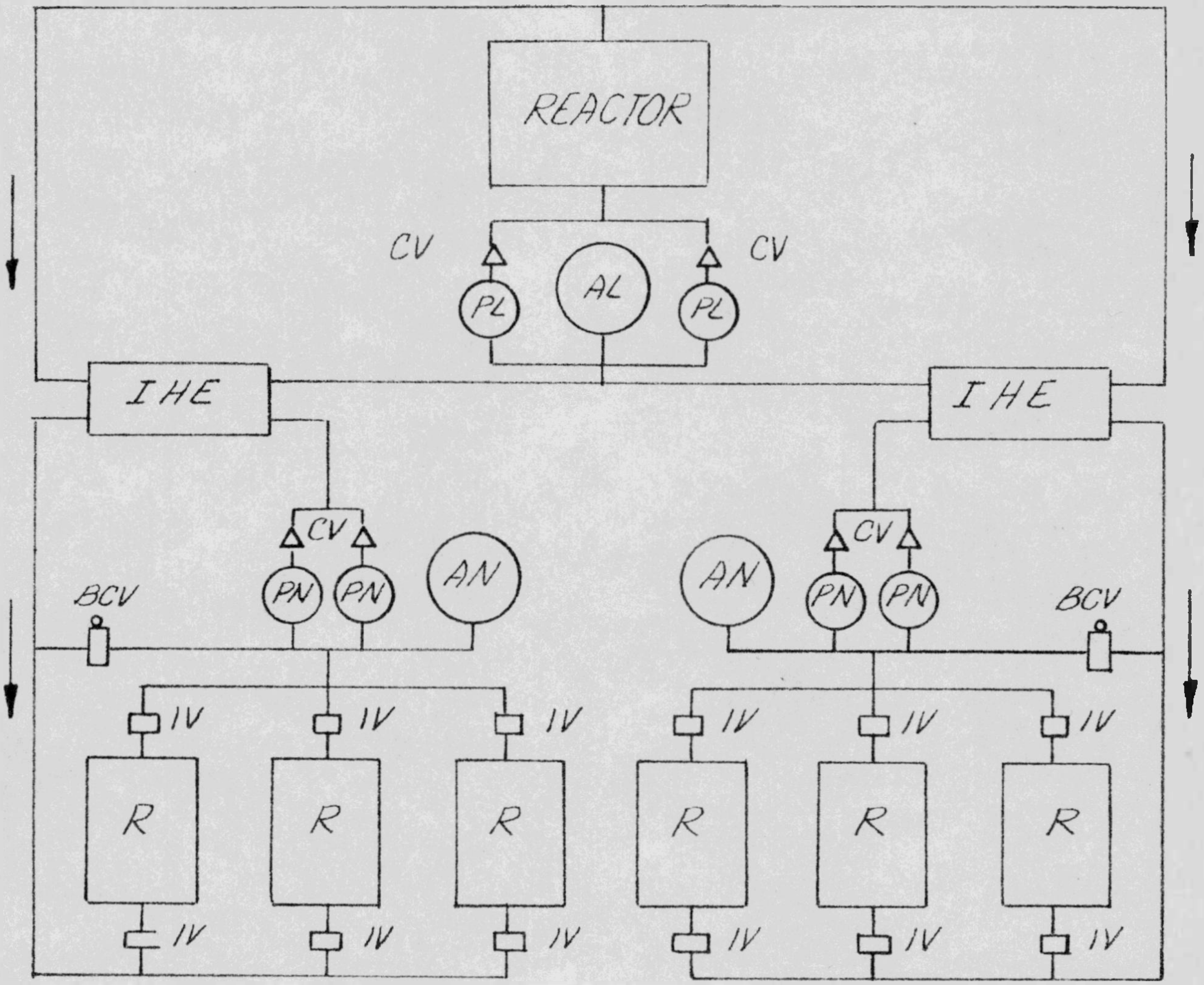
Radiator Bypass Piping; NaK

Outside diameter, in*	8.5
Wall thickness, in.	0.21
Weight (wet), lb/ft**	39.6
Insulation weight, lb/ft	4.2
Insulation thickness, in.	2.9
Length assumed (total), ft.	20
Number of lines	2

NOTE: * Does not include insulation thickness
** Includes insulation weight

[redacted]

LIQUID METAL PIPING SCHEMATIC



SYMBOLS

AL — LITHIUM ACCUMULATOR
AN — NaK ACCUMULATOR
BCV — BYPASS CONTROL VALVE
CV — CHECK VALVE
IHE — INTERMEDIATE HEAT EXCHANGER
IV — ISOLATION VALVE
PL — LITHIUM PUMP
PN — NaK PUMP
R — ENGINE RADIATOR

[redacted]

REACTOR AND SHIELD PACKAGE SUMMARY

	Case 1	Case 2	Case 3
Reactor Power, Mw	350	575	350
Altitude, ft.	25,000	65,000	25,000
Crew dose rate, gamma, rem/hr	.0037	.02	.111
Crew dose rate, neutron, rem/hr	.0013	.01	.139
Crew dose rate, total, rem/hr	.005	.03	.25
Crew compartment length, ft.	16	9	26
Crew compartment diameter, ft.	7	7	10
Reactor-to-crew comp. separation, ft.	100	100	100
Gamma shield material	U	U	U
Neutron shield material - reactor	LiH	LiH	LiH
Neutron shield material - crew compartment	Plastic	Plastic	Plastic
Weight Summary			
Reactor	5,000	8,000	5,000
Reactor inner neutron shield	10,200	3,900	3,100
Reactor outer neutron shield	11,200	8,700	27,300
Reactor gamma shield	18,700	9,500	18,100
Structure	1,900	1,300	1,100
Crew comp. side neutron shield	17,500	9,900	14,200
Crew comp. rear neutron shield	3,500	4,000	0
Crew comp. side gamma shield	9,800	4,000	9,600
Crew comp. rear gamma shield	5,700	3,900	0
Reactor shield assembly	47,000	31,400	54,600
Total crew compartment	36,500	21,800	23,800
Total reactor and shield weight	83,500	53,200	78,400*
G. Lambda	1.656×10^6	1.771×10^5	3.21×10^4
N. Lambda	1.656×10^6	1.771×10^5	3.21×10^4
Shield cooling load			
Lithium temp. used for calculation, F	1750	2000	1750
Shield heat, Mw	2.71	3.66	2.71

* Advantage is taken of 50 feet of chemical fuel located between reactor and crew compartment for shielding estimates.

NEUTRON AND GAMMA RADIATION FLUX AT REACTOR SURFACE

Spectrum Neutron Dose - 350 Mw

Energy Group	n/cm^2/sec
1	0.2 E13 *
2	4.2 E13
3	1.9 E13
4	2.3 E13
5	2.7 E13
6	2.9 E13
7	3.2 E13
8	3.7 E13
9	3.8 E13
10	3.7 E13
11	3.0 E13
12	2.4 E13
13	2.0 E13
14	1.5 E13
15	1.1 E13
16	0.7 E13
17	0.4 E13
18	0.2 E13
19	0.1 E13
20	0.05 E13
21	0.05 E13

Total = 4.0 E14 - scale for
575 Mw case, multiply by 1.15

* E13 is equal to 10^{13}

Spectrum Gamma Dose

The fraction of dose in rem at each energy value for both reactors is listed below:

.53 at 2 Mev
.29 at 4 Mev
.12 at 6 Mev
.06 at 7 Mev
0 at 9 Mev

Total Gamma Dose:
350 Mw - 3.6 E8 rem/hr
575 Mw - 4.9 E8 rem/hr

[redacted]

FIG. 12

Direct DOSE PATTERN AT 50 feet ~~SURFACE~~ OF 350 MW REACTOR SHIELD
(Case 1 of Fig 10)

Degrees From Foreward	Primary Gamma Dose	Secondary Gamma Dose	Neutron Dose
5	.059 rem/hr	.0093 rem/hr	.18 rem/hr
15	.114	.0097	.22
25	.411	.011	.34 .2
35	3.01	.012	.61
45	38.8	.014	1.05
55	450	.016	1.53
65	2407	.019	3.10
75	1.1 E4	.021	4.90
85	4.2 E4	.024	7.01
95	6.4 E4	.029	13.7
105	6.8 E4	.031	18.4
115	7.0 E4	.034	23.9
125	7.3 E4	.037	30.6
135	7.9 E4	.043	51.2
145	8.6 E4	.051	85.7
155	9.9 E4	.068	201
165	E5	.07	216
175	E5	.07	216

The dose outside the crew compartment is about 20 rem/hr
The dose inside the crew compartment = .0037 rem/hr for gammas
= .0013 rem/hr for neutrons
= .005 rem/hr total

[redacted]

Direct DOSE PATTERN AT 50 feet ~~SURFACE~~ OF 575 REACTOR SHIELD
(Case 2 of Fig 10)

Degrees From Foreward	Primary Gamma Dose	Secondary Gamma Dose	Neutron Dose
5	.037 rem/hr	.385 rem/hr	2.96 rem/hr
15	.114	.401	3.62
25	.522	.442	5.67
35	4.29	.515	11.4
45	73.6	.613	24.3
55	2525	.720	47.2
65	2.53 E4	.851	91.7
75	9.05 E4	.933	130.1
85	1.25 E5	1.05	207.2
95	1.37 E5	1.22	350
105	1.42 E5	1.30	442
115	1.48 E5	1.38	552
125	1.53 E5	1.46	679
135	1.63 E5	1.63	988
145	1.72 E5	1.79	1360
155	1.96 E5	2.24	2874
165	2.5 E5	3.48	11,500
175	2.5 E5	3.48	11,500

The dose outside crew compartment is about 10 rem/hr
The dose inside crew compartment = .02 rem/hr for gammas
= .01 rem/hr for neutrons
= .03 rem/hr total

[redacted]

Direct DOSE PATTERN AT 50 feet ~~SURFACE~~ OF 350 MW REACTOR SHIELD
(Case 3 of Fig 10)

Degrees From Foreward	Primary Gamma Dose	Secondary Gamma Dose	Neutron Dose
5	4.44 rem/hr	.224 rem/hr	4.16 rem/hr
15	7.48	.231	4.81
25	26.9	.237	5.48
35	59.9	.250	6.97
45	492	.261	8.50
55	1310	.276	10.9
65	2950	.301	15.9
75	7590	.322	21.1
85	1.45 E4	.342	26.8
95	3.11 E4	.382	42.0
105	6.08 E4	.396	48.5
115	7.98 E4	.421	61.4
125	8.16 E4	.436	69.8
135	8.59 E4	.471	94.1
145	8.70 E4	.481	102
155	8.91 E4	.500	117
165	9.18 E4	.523	138
175	9.41 E4	.544	159

The dose outside crew compartment is about 15 rem/hr
The dose inside crew compartment = .111 rem/hr for gammas
= .139 rem/hr for neutrons
= .250 rem/hr total

[redacted]

FIG. 15

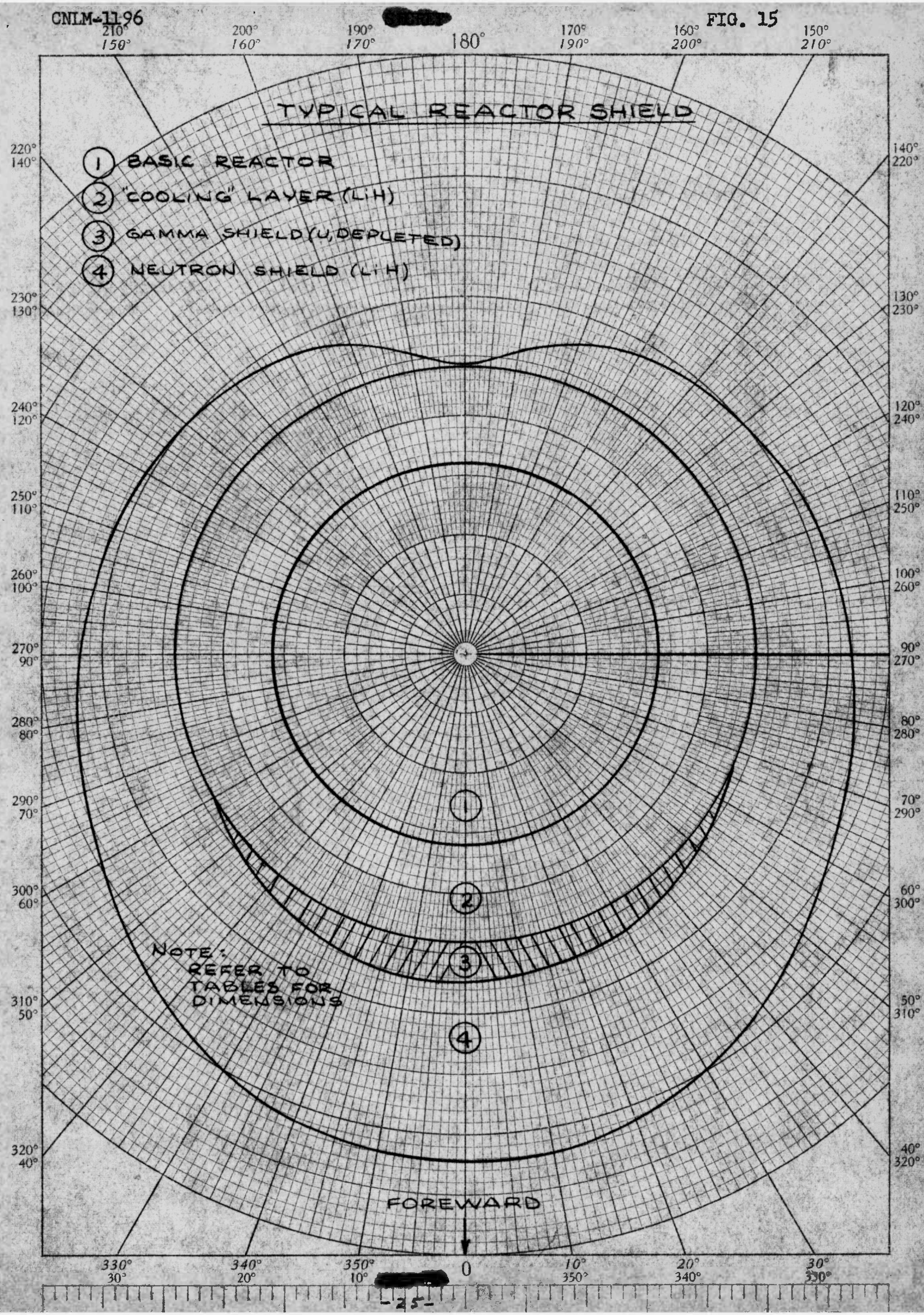


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FIG. 16

REACTOR SHIELD THICKNESSES FOR 350 MW REACTOR
(Case 1 of Fig 10)

Degrees From Foreward	Gamma Shield Thickness	* Neutron Shield Thickness	Total
5	15.71 cm	49.93 cm	65.63 cm
15	14.94	48.96	63.90
25	13.48	46.48	59.96
35	11.20	43.26	54.46
45	8.25	41.13	49.38
55	5.42	40.46	45.88
65	3.57	35.79	39.36
75	1.87	33.24	35.12
85	0.37	31.41	31.78
95	0	25.58	25.58
105	0	22.82	22.82
115	0	20.41	20.41
125	0	18.13	18.13
135	0	13.35	13.35
145	0	8.57	8.57
155	0	0.66	0.66
165	0	0	0
175	0	0	0

Add a 60 cm inner neutron shield layer (LiH) to basic reactor before adding these thicknesses.

	Gamma	Neutron	Total
Crew compartment shield - side	1.16 cm	22.11 cm	23.27 cm
rear	3.92	49.70	53.62

---

* Does not include 60 cm (24 in) of inner neutron shield (LiH)

REACTOR SHIELD THICKNESSES FOR 575 MW REACTOR
(Case 2 of Fig 10)

Degrees From Foreward	Gamma Shield Thickness	Neutron Shield Thickness*	Total
5	16.98 cm	56.40 cm	73.38 cm
15	15.67	55.92	71.59
25	13.91	53.68	67.59
35	11.51	49.89	64.40
45	8.28	46.41	54.69
55	4.25	44.53	48.78
65	1.69	41.19	42.88
75	0.29	39.44	39.73
85	0	35.64	35.64
95	0	30.99	30.99
105	0	28.91	28.91
115	0	26.94	26.94
125	0	25.11	25.11
135	0	21.77	21.77
145	0	18.95	18.95
155	0	12.29	12.29
165	0	0	0
175	0	0	0

Add a 30 cm inner neutron shield layer (LiH) to basic reactor before adding these thicknesses

	Gamma	Neutron	Total
Crew compartment shield - side	.80 cm	20.85 cm	21.65 cm
rear	2.67	57.12	59.79

---

* Does not include 30 cm (12 in) of inner neutron shield (LiH)

[redacted]

REACTOR SHIELD THICKNESS FOR 350 MW REACTOR
(Case 3 of Fig 10)

Degrees From Foreward	Gamma Shield Thickness	Neutron Shield Thickness*	Total
5	11.04 cm	56.08 cm	67.12 cm
15	10.44	55.34	65.78
25	8.95	55.66	64.60
35	8.04	54.36	62.40
45	5.59	54.99	60.58
55	4.48	53.81	58.28
65	3.59	51.27	54.86
75	2.54	49.71	52.25
85	1.83	48.24	50.06
95	1.02	44.95	45.97
105	0.27	44.38	44.65
115	0	42.48	42.48
125	0	41.31	41.31
135	0	38.58	38.58
145	0	37.89	37.89
155	0	36.62	36.62
167	0	35.09	35.09
175	0	33.78	33.78

Add a 30 cm inner neutron shield layer (LiH) to basic reactor before adding these thicknesses.

	Gamma	Neutron	Total
Crew compartment shield - side	.50 cm	8.44 cm	8.94 cm
rear	0	0	0

* Does not include 30 cm (12 in) of inner neutron shield (LiH)

[redacted]

SHIELDING PROPERTIES OF VARIOUS MATERIALS

Material	Σ_R	μ_2	μ_4	μ_6	μ_7	μ_9	P_2	P_4	P_6	P_7	P_9
U^{238}	.168	.91	.82	.88	.92	.97	.407	.481	.074	.037	0
Lead	.113	.51	.47	.50	.52	.56	0	0	.07	.93	0
Boron	.14	.101	.070	.058	.053	.046	0	0	0	0	0
$B_4{}^{10}C$, B_4C	.136	.091	.061	.055	.056	.071	0	0	0	0	0
O, Air, Void	5×10^{-5}	6×10^{-5}	3.7×10^{-5}	3×10^{-5}	2.9×10^{-5}	2.6×10^{-5}	0	0	0	0	0
Alkylbenzene	.086	.037	.027	.022	.021	.018	1.0	0	0	0	0
LiH	.113	.033	.022	.017	.016	.013	.005	0	0	0	0
U^{235}	.168	.91	.82	.88	.92	.97	3.84	.41	.06	0	0

Σ_R = Neutron Removal Cross Section, CM^{-1}

μ = Gamma Attenuation Cross Section, CM^{-1} - Subscript = Energy, Mev.

P = Gamma Probabilities - Fraction of Photons Emitted per Capture

For J. P. Fuel $\mu_3 = .0265$ CM^{-1} $\Sigma_R = .089$ CM^{-1}

Nitrogen Cross Sections - Absorption (n, γ) Reaction

$\sigma_a = .1 \pm .05$ Barns, $\Sigma_a = 4.19 \times 10^{-6}$ CM^{-1}

Gamma Attenuation Cross Sections for Crew Compartment

Uranium $\mu = .811$ CM^{-1}

Polyethelene $\mu = .025$ CM^{-1}

$Z_n B_r = \Sigma_R = .048$ CM^{-1}

Gamma Attenuation = 3 Mev.

Ft. of $Z_n B_r$	Fraction of Photons Remaining
0	1.0
.5	.51
1.0	.19
1.5	.054
2.0	.014
3.0	.0008

Density = 2.9 GM/cc

FIG. 19

FIG. 20

21 GROUP ENERGY AND LETHARGY LIMITS

$$\Sigma_{TR} = (1-\bar{\mu}_0)(\Sigma_s + .2\,\Sigma_a) \qquad \xi = \frac{2}{A + \frac{2}{3}} = \ln \overline{\frac{E_1}{E_2}}$$

Group	ΔU	U Interval	E Interval
1	.5	.5 - 1	6.06 - 3.68 Mev
2	1	1 - 2	3.68 - 1.35
3	1	2 - 3	1.35 - .498
4	.75	3 - 3.75	.498 - .235
5	.75	3.75 - 4.5	.235 - .111
6	1	4.5 - 5.5	.111 - .0409
7	1	5.5 - 6.5	.0409 - .015
8	1	6.5 - 7.5	.015 - .00553
9	1	7.5 - 8.5	5530 - 2030 Ev
10	1	8.5 - 9.5	2030 - 748
11	1	9.5 - 10.5	748 - 275
12	1	10.5 - 11.5	275 - 101
13	1	11.5 - 12.5	101 - 37.3
14	1	12.5 - 13.5	37.3 - 13.7
15	1	13.5 - 14.5	13.7 - 5.04
16	1	14.5 - 15.5	5.04 - 1.86
17	1	15.5 - 16.5	1.86 - .683
18	1	16.5 - 17.5	.683 - .251
19	.7	17.5 - 18.2	.251 - .125
20	.5	18.2 - 18.7	.125 - .0756
21	1.1 or 0	18.7 - 19.8	.0756 - .0252 1120°F 66[illegible]

lethargy, U = $\ln \frac{E_0}{E}$ $\qquad E_0$ = 10 Mev

[redacted]

MICROSCOPIC OXYGEN CROSS SECTIONS USED IN MULTIGROUP CODE BUT NOT IN SHIELD OPTIMIZATION CODE

Energy Gp.	σ_a	σ_{tr}	$\xi\sigma_r$	σ_κ
1	E-16	1.54	.195	E-11
2	↓	1.45	.183	↓
3	↓	4.09	.516	↓
4	↓	3.86	.487	↓
5	↓	3.67	.463	↓
6	↓	3.57	.451	
7		3.57	.451	
8		↓	↓	
9		↓	↓	
10		↓	↓	
11		↓	↓	
12				
13				
14				
15				
16				
17				
18		3.58	.452	
19		3.66	.462	
20		3.73	.471	
21		3.76	E-11	

[redacted]

BORON CARBIDE - $B_4{}^{10}C$

Energy Group Number	Σ_a (cm^{-1})	Σ_{Tr} (cm^{-1})	$\xi\Sigma_T$ (cm^{-1})	Σ_K (cm^{-1})
1	.07087	.1755	.03359	.1E - 10
2	.07810	.2292	.04356	↓
3	.0868	.2992	.05631	↓
4	.1749	.4504	.08606	↓
5	.2514	.4740	.0921	↓
6	.3542	.5155	.1020	↓
7	.5399	.5700	.1098	
8	.8125	.5000	.1085	
9	1.253	.4800	.1178	
10	1.919	.4400	.1275	
11	3.145	.4000	.1522	
12	5.294	.4200	.2051	
13	8.701	.5700	.3195	
14	13.29	.8800	.4844	
15	22.59	1.41	.8525	
16	33.04	2.125	1.340	
17	64.24	3.572	2.224	
18	106.3	5.90	3.673	
19	161.4	8.704	5.533	
20	216.9	11.28	7.36	
21	217.5	12.8	.1 E - 10	

2.5 Mev is "Q" for B^{10} (n,γ) reaction

ALKYLBENZENE

Energy Group Number	Σ_a (cm^{-1})	Σ_{Tr} (cm^{-1})	$\xi\Sigma_T$ (cm^{-1})	Σ_K (cm^{-1})
1	.28 E-5	.0769	.1072	.1 E - 10
2	.41 E-5	.7114	.1801	↓
3	.53 E-5	.1830	.3118	
4	.72 E-5	.2639	.4812	
5	.97 E-5	.3406	.6743	
6	.1411 E-4	.4314	.9131	
7	.2542 E-4	.5319	1.186	
8	.5305 E-4	.5476	1.233	
9	.8068 E-4	.5632	1.233	
10	.8068 E-4	.5532	1.233	
11	.1548 E-3	.5632	1.233	
12	.1289 E-3	.5633	1.233	
13	.5857 E-3	.5631	1.233	
14	.6930 E-3	.5630	1.233	
15	.001084	.5629	1.233	
16	.001884	.5681	1.297	
17	.003122	.5829	1.343	
18	.005147	.6225	1.462	
19	.008299	.7571	1.869	
20	.009754	.8137	2.040	
21	.01188	.8857	.1 E-10	

[redacted]

[redacted]

URANIUM (U-235)
(Used with U^{238} to Get Natural U)

Energy Group Number	Σ_a (cm^{-1})	Σ_{Tr} (cm^{-1})	$\xi\Sigma_T$ (cm^{-1})	Σ_x (cm^{-1})	Σ_f (cm^{-1})	ν
1	.06683	.0510	.00298	.19128	.0597	3.07
2	.06846	.2150	.00298	.16204	.0606	2.78
3	.06136	.2030	.00289	.04185	.0581	2.58
4	.08754	.2710	.00337	.01980	.0646	2.46
5	.10547	.3770	.00445	.00710	.0759	↓
6	.12124	.4690	.00510	.00162	.0947	
7	.19512	.4740	.00554	.1 E-10	.1456	
8	.28524	.5820	.00698	↓	.2038	
9	.32599	.66732	.00789		.2264	
10	.52734	.70280	.00956		.3575	
11	.91565	.73684	.01249		.6104	
12	1.6961	.80252	.01835		1.040	
13	2.3788	.96100	.02368		2.099	
14	2.7326	1.0183	.02722		1.822	
15	2.8860	1.1635	.02950		1.458	
16	1.5044	.67691	.01597		.9896	
17	3.5380	1.1932	.03418		2.876	
18	6.4719	1.7685	.05517		5.993	
19	11.231	2.7273	.09301		9.438	
20	15.059	3.3275	.12210		12.76	
21	16.187	3.4915	.1 E-10		13.72	

[redacted]

[redacted]

FIG. 25

URANIUM (U - 238)

$\xi = \frac{2}{238.67}$

Energy Group Number	Σ_a (cm^{-1})	Σ_{Tr} (cm^{-1})	$\xi \Sigma_T$ (cm^{-1})	Σ_K (cm^{-1})	Σ_f (cm^{-1})	ν
1	.0313	.0833	.00280	.18885	.03076	3.07
2	.0268	.1727	.00311	.17323	.02461	2.78
3	.0067	.2501	.00292	.04132	.00126	2.58
4	.0076	.3460	.00370	.01995	.1E-10	2.46
5	.0087	.4601	.00445	.00677	↓	↓
6	.0140	.5710	.00516	.1E-10		
7	.0225	.6650	.00582	↓		
8	.0294	.8160	.00695			
9	.0516	.9977	.00839			
10	.1287	1.347	.01131			
11	.3242	1.877	.01576			
12	.3261	3.146	.02641			
13	.2181	1.715	.01440			
14	1.000	10.20	.00931			
15	1.160	5.662	.04700			
16	.0115	.5400	.00454			
17	.0187	.5471	.00460			
18	.0312	.5599	.00470			
19	.0478	.5765	.00484			
20	.0653	.5940	.00499			
21	.0999	.6285	.1E-10			

[redacted]

MACROSCOPIC CROSS SECTIONS FOR LEAD

$\xi = \frac{2}{207.88}$

Energy Group Number	Σ_a (cm^{-1})	Σ_{tr} (cm^{-1})	$\xi \Sigma_T$ (cm^{-1})	Σ_κ (cm^{-1})
1	7 E-5	.241	.00233	.0632
2	↓	.196	.00190	.0366
3		.186	.00178	.00233
4		.208	.00201	0
5		.293	.00283	↓
6		.344	.00332	
7		.339	.00327	
8		.362	.00350	
9		.362	↓	
10		.362		
11		.362		
12		.362		
13	1.3 E-4	.362		
14	1.9 E-4	.360		
15	2.9 E-4	.360		
16	5.1 E-4	.361		
17	8.4 E-4	.361		
18	.00139	.361		
19	.00225	.360	.00342	
20	.00265	.358	.00346	
21	.00285	.355	E-11	

[redacted]

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FIG. 27

MACROSCOPIC LITHIUM HYDRIDE (LiH) CROSS SECTIONS

$\xi = \frac{2}{7.61}$

Energy Group Number	Σ_a (cm^{-1})	Σ_{Tr} (cm^{-1})	$\xi \Sigma_T$ (cm^{-1})	Σ_K (cm^{-1})
1	3.14 E-4	.157	.135	0
2	4.39 E-4	.163	.170	↓
3	.70	.177	.317	
4	1.11 E-3	.321	.510	
5	1.66 E-3	.288	.670	
6	2.52 E-3	.350	.895	
7	4.08 E-3	.445	1.17	
8	7.1 E-3	.449	1.21	
9	.0112	.459	1.26	
10	.0182	.459	1.26	
11	.0307	.453	1.26	
12	.050	.442	1.27	
13	.0790	.442	1.27	
14	.129	.414	1.28	
15	.224	.413	1.30	
16	.335	.419	1.35	
17	.595	.433	1.46	
18	1.0	.466	1.66	
19	1.57	.510	1.94	
20	2.13	.570	2.28	
21	2.28	.500	E-17	

[redacted]

[redacted]

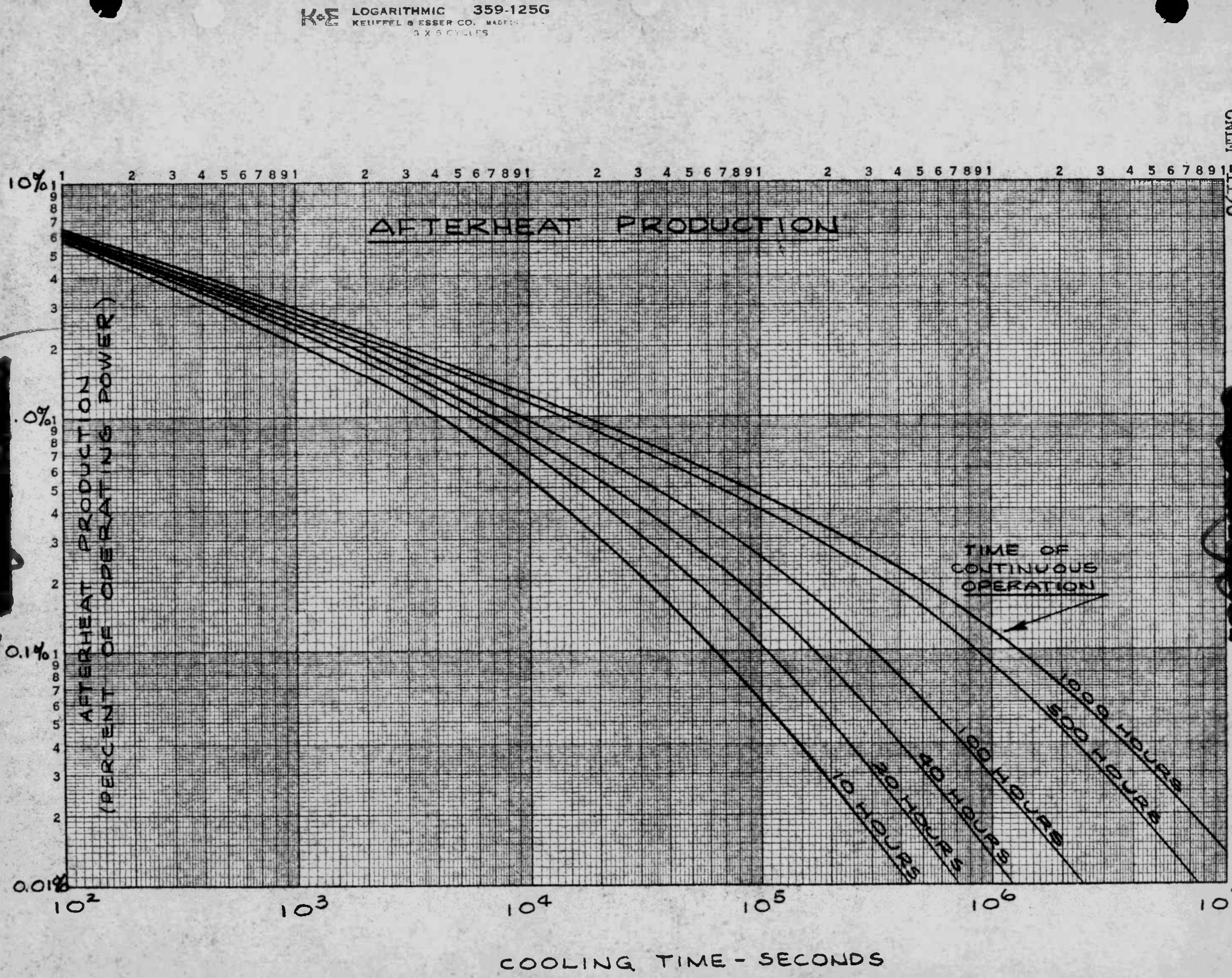

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FIG. 28