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RESEARCH MEMORANDUM

ANALYSIS OF A NUCLEAR-POWERED RAM-JET MISSILE

By Frank E. Rom

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
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RESEARCH MEMORANDUM

ANALYSIS OF A NUCLEAR-POWERED RAM-JET MISSILE

By Frank E. Rom

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SUMMARY

Calculations are made to determine the minimum uranium investment and corresponding gross weight and reactor operating conditions for a direct-air, shieldless, nuclear-powered, ram-jet missile. The reactor studied in this analysis is moderated by beryllium oxide and cooled by air flowing through smooth reactor passages. Studies are made for reactor average effective wall temperatures of 2200°, 2000°, and 1800° R. The pay load, plus controls and guidance mechanisms, is assumed to be 10,000 pounds. The design flight Mach number is 2.5 and the altitude is 50,000 feet.

The minimum uranium investment for uniform fuel loading with no allowance for xenon poisoning, burnup, or control is about 19 pounds for an average effective reactor wall temperature of 2200° R. The investment increases to about 23.5 pounds for an average effective wall temperature of 1800° R. The corresponding missile gross weight is about 48,000 pounds for an average effective reactor wall temperature of 2200° R and about 54,000 pounds for an average effective reactor wall temperature of 1800° R. If the uranium investment is permitted to be increased to 25 pounds, the missile gross weight can be reduced to 28,000 and 39,500 pounds for average wall temperatures of 2200° and 1800° R, respectively.

If the uranium and the free-flow ratio are distributed uniformly in the reactor, the maximum reactor wall temperature which occurs in the center tube of the reactor is about 4100° R for an average effective wall temperature of 2200° R. The maximum wall temperature can be reduced to 2600° R in the center tube by use of a sinusoidal variation of free-flow factor with a maximum value of 0.65 at the center of the reactor.

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If it should be necessary to use stainless steel liners with a thickness of 0.005 inch in the holes through the beryllium oxide to contain uranium or to prevent erosion by air, the uranium investment is increased by a factor of 3 to 4.4 depending on the reactor effective wall temperature. This factor is increased to 5 to 8 if 0.01-inch liners must be used. In addition, the use of stainless steel will limit the maximum reactor temperature to about 2400° R, which is the upper useful limit, in this application, of the best stainless steel materials. With a sinusoidal distribution of free-flow ratio, the effective reactor wall temperature is about 2000° R for the maximum wall temperature of 2400° R. 3077

INTRODUCTION

One of the greatest difficulties facing nuclear-powered flight arises from the extremely heavy shields required to protect the crew from lethal reactor radiations. These large shield weights require high-gross-weight airplanes and high-power reactors. The shield weight can be reduced by reducing the reactor diameter. The reactor diameter has a limiting lower value, however, determined by the criticality requirements of the particular reactor composition. The reactor must also have means built within it to remove the heat generated. If the heat cannot be removed within the volume determined by criticality requirements, then the reactor size is determined by heat-transfer considerations. It is desirable, therefore, to keep power requirements down. It is difficult to keep power requirements low with shielded reactors because of the very large airplanes required to carry the reactor shield. Small power requirements also help the nuclear aspects of the reactor inasmuch as less heat-transfer surface and fewer coolant fluid passages are needed. Smaller uranium investments are then required to achieve criticality.

It is therefore obvious that a shieldless nuclear-powered aircraft greatly reduces the problems of nuclear-powered flight associated with very large airplane gross weights and high power requirements. The disadvantages of such an aircraft are that remote guidance equipment must be used to fly the airplane and that the shieldless airplane would probably be used only once as a guided missile, with the attendant loss of the fissionable material. The loss of the fissionable materials would have to be balanced against the high unit cost of very large airplanes and the difficulty and cost of ground maintenance and handling of aircraft nuclear power plants.

The ram-jet missile studied in the present report is one type of shieldless missile which has the advantage of employing the simplest type of propulsion system. No details concerning the launching of this missile are considered; however, various schemes might be used. Rocket boost techniques which are considered for chemically fueled ram-jet missiles could be used to bring the missile up to flight speed and altitude. The reactor could be made critical on the ground before launching from a remote location or automatically after the booster drops off. Another system might be to carry the ram-jet missile aloft in a large manned airplane with the reactor inoperative. The ram-jet missile would then be released and accelerated to flight speed and altitude by rocket boost, while the reactor would be brought into operation after the missile left the airplane. If the crew in the carrier were shielded sufficiently, the reactor could be brought into operation before launching.

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Reactor control problems, although difficult because completely automatic handling is required, are not so severe as those for ordinary power reactors because the missile reactor would operate at constant power and with relatively low burnup.

A previous investigation of the nuclear ram-jet missile was made in reference 1. In this study, a particular reactor design with ceramic fuel elements operating at a temperature of 2960° R replaced the combustor section of an existing chemically fueled ram-jet missile. The study was of a preliminary nature, and therefore no attempt was made to calculate uranium investment or to find the best engine operating conditions or airframe configuration. The purpose of the present analysis is to determine the best combination of engine operating conditions and basic airplane configuration which gives a relatively low-gross-weight missile consistent with minimum fissionable material requirements. The calculations are carried out for a flight Mach number of 2.5 and altitude of 50,000 feet for a range of effective reactor wall temperatures of 1800° to 2200° R. (The effective wall temperature is defined as that uniform reactor wall temperature which gives the same air-temperature rise as the particular wall-temperature distribution under consideration.)

DESCRIPTION OF CYCLE

The nuclear-powered ram-jet cycle under investigation is conventional in all respects, except that a nuclear reactor is used to heat the air in place of a chemical fuel. (See fig. 1.) The diffuser slows down the free-stream air before the air enters the passages of the air-cooled reactor. The air is heated by contact with the hot walls of the reactor passages and is discharged from the power plant through a fully expanding exhaust nozzle to provide thrust. The single engine which includes the diffuser, reactor, and nozzle sections constitutes the fuselage to which wings and the necessary tail surfaces are attached. Inasmuch as no crew is carried, no shield is necessary. The reactor is moderated by beryllium oxide. Subsequent calculations show that side reflection is unnecessary; therefore, only end reflection amounting to 3 inches of beryllium oxide at each end is provided. The air passages in the reactor are assumed to be 0.50 inch in diameter. The uranium is assumed to be held by some suitable method near the surface of the air passages. In the case where stainless steel is thought to be necessary to contain the fuel or prevent erosion by air, stainless steel tubes of 0.50-inch internal diameter with 0.005- and 0.01-inch walls are assumed to line the air passages. The length and the number of air passages are determined by heat-transfer and air-flow requirements.

METHODS

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The object of the analysis is to determine the combination of engine operating conditions and basic airplane configuration which gives the minimum uranium investment for a direct-air nuclear-powered ram-jet missile designed to operate at an altitude of 50,000 feet and flight Mach number of 2.5. The effective reactor wall temperature is varied from 1300° to 2200° R. The reactor-inlet air Mach number and outlet air temperatures are varied systematically for a range of reactor free-flow ratios for each of the assigned values of reactor effective wall temperatures. The gross weight and the uranium investment are found for each combination of these variables to determine which combination gives the minimum uranium investment. The reduction in gross weight afforded by permitting an increase in uranium investment is also presented. Approximate maximum wall temperatures resulting from sinusoidal and uniform heat-generation distributions are estimated.

The calculations can conveniently be divided into seven parts: (1) internal flow, which gives the thrust per pound of air flow per second, (2) power-plant external flow, which gives the drag of the power plant (exclusive of wing drag) per pound of air flow per second, (3) power-plant weight calculation, which gives the weight of the power plant per pound of air flow per second, (4) wing and tail aerodynamic and weight calculations, (5) the over-all missile lift-drag and gross weight calculation, (6) uranium investment calculations, and (7) calculations for maximum reactor wall temperature for various heat generation distributions. The assumptions and details of these calculations are presented in appendix B. Appendix A contains the list of symbols used in the calculations.

RESULTS AND DISCUSSION

The uranium investment and reactor gross weight are found by use of the methods outlined in appendix B for the following range of variables:

Flight Mach number	2.5
Altitude, ft	50,000
Pay load and fixed equipment weight, lb	10,000
Reactor effective wall temperature, $^{\circ}R$	1800, 2000, 2200

The reactor-inlet air Mach number, reactor free-flow ratio, and reactor-outlet air temperature are varied over ranges to include the values which give the minimum uranium investment for each assigned reactor effective wall temperature.

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In general, the uranium investments are calculated considering no stainless steel liners for the air passages through the reactor. Inasmuch as the application is for an expendable missile, the containing of fission fragments which the stainless steel affords is considered unnecessary. The uranium in some suitable vehicle would be coated directly on the surface of the reactor air passages. Calculations are made, however, of the uranium investment in the event that it is necessary to use stainless steel tubes to contain the fissionable materials, or to protect the beryllium oxide moderator or uranium-bearing lining from erosion or corrosion by air.

Reactor-outlet air temperature for minimum uranium investment. - The uranium investment and gross weight are plotted in figure 2 as functions of all the variables investigated. The uranium investment W_U and missile gross weight W_g are plotted against the reactor-outlet air temperature T_3 for ranges of reactor-inlet air Mach number M_2, reactor free-flow ratio α, and reactor average wall temperature T_W. The maximum value of T_3 on each curve represents the value which results in choking at the reactor outlet. The curves show a T_3 which gives a minimum uranium investment for each combination of T_W, M_2, and α. In general, the value of T_3 which gives the minimum uranium investment appears to be within 50° F of the temperature which will result in choking at the reactor outlet.

Reactor-inlet air Mach number and free-flow ratio for minimum uranium investment. - The uranium investment and corresponding missile gross weight are plotted as functions of M_2 for the values of T_3 which give minimum uranium investment in figure 3. For the range of effective wall temperatures investigated, the best M_2 is about 0.28. The reactor free-flow ratios which give the minimum uranium investments are 0.36, 0.40, and 0.45 for reactor effective wall temperatures of 2200°, 2000°, and 1800° R, respectively.

Effect of temperature on minimum uranium investment and gross weight. - The minimum uranium investment and corresponding missile gross weight are plotted as a function of effective reactor wall temperature in figure 4(a). This figure plots the lowest value of uranium investment calculated for each of the three assigned effective wall temperatures. The investment calculations assume uniform uranium distribution, and no allowance is made for burnup or poisoning because of the short reactor life. The figure shows that the minimum uranium investment varies from 19 to 23.5 pounds for reactor effective wall temperatures of 2200° and 1800° R, respectively. The corresponding missile gross weights are 47,600 and 54,400 pounds, respectively.

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Effect of temperature on engine and airplane variables. - The reactor-inlet air Mach number, reactor-outlet air temperature, free-flow ratio, core length, core diameter, air flow, heat release, thrust minus drag per pound of air flow, thrust per pound of air flow, thrust minus drag per total engine weight, and over-all airplane lift-drag ratio are plotted as functions of reactor effective wall temperature for the condition of minimum uranium investments in figures 4(b) to 4(f). These quantities are tabulated for convenience:

Reactor effective wall temperature, °R	1800	2000	2200
Uranium investment (no stainless), lb	23.6	20.6	19.0
Uranium investment (with 0.005-inch thick stainless steel), lb	[illegible]	66	57
Uranium investment (with 0.01-inch-thick stainless steel), lb	181	112	[illegible]
Missile gross weight, lb	54,400	44,300	[illegible]
Reactor-inlet Mach number	0.28	0.28	0.28
Reactor-outlet air temperature, °R	1590	1680	1770
Reactor core diameter, ft	7.79	6.39	7.18
Reactor core length, ft	5.87	5.18	4.94
Reactor free-flow ratio	0.45	0.40	[illegible]
Reactor heat release, Btu/sec	109,500	[illegible]	94,800
Reactor air flow, lb/sec	[illegible]	421	411
Thrust per pound of air per second, lb/(lb/sec)	[illegible]	19.9	22.7
Thrust minus drag per pound of air, lb/(lb/sec)	10.0	[illegible]	13.0
Thrust minus drag per engine weight, lb/lb	0.144	0.153	[illegible]
Over-all airplane lift-drag ratio	5.44	5.28	5.10

Minimum missile gross weight. - Figure 4(a) gives the missile gross weight for the condition of minimum uranium investment. If the uranium investment is allowed to be larger than this minimum value, smaller reactors are permissible. Reducing the reactor size [illegible] the required missile gross weight. The effect on gross weight of [illegible] the uranium investment above the minimum value is shown in [illegible] for effective reactor wall temperatures of 1800°, 2000°, and [illegible] R. The following table presents the missile gross weights for various values of uranium investment for the three values of effective wall temperatures.

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Uranium investment, lb	Missile gross weight, lb, for T_W of		
	1800° R	2000° R	2200° R
19.0	------	------	47,600
20.6	------	44,300	34,300
23.6	54,400	32,100	29,100
25.0	39,500	30,400	28,000
30.0	31,500	27,500	26,000
35.0	30,000	26,500	25,100

Thus, if the uranium investment for an effective reactor wall temperature of 2200° R is allowed to increase from 19 to 25 pounds, the gross weight is reduced from 47,600 pounds to 28,000 pounds. Increasing the uranium investment to 35 pounds will reduce the gross weight only slightly more to 25,000 pounds. In order to reduce the gross weight for the effective wall temperature of 1800° R to 30,000 from 54,400 pounds, the uranium investment must be increased from 23.6 pounds to 35 pounds.

<u>Effect of stainless steel tubes on uranium investment</u>. - In the event that it is necessary to use stainless steel as a containing material for the fissionable material, the uranium investment must be increased to account for the absorption cross section of stainless steel. Tubes (fabricated of 310 stainless steel; I.D., 0.5 in.; and walls, 0.01 or 0.005 in.) containing the fissionable material are inserted in the holes of the beryllium oxide moderator. The uranium investment for these cases is compared with the case with no stainless steel in figure 4(a). The figure indicates that the addition of 0.005-inch stainless steel liners increases the uranium investment by factors of 4.4 and 3.0 for effective wall temperatures of 1800° and 2200° R, respectively. Likewise, 0.01-inch liners increase the investment by factors of 7.7 and 5.0 for the same effective wall temperatures.

<u>Effect of side reflection</u>. - In the previous discussion, no side reflection is assumed for the reactor. The effect of side reflection on uranium investment for a fixed-size ram-jet missile is found for the case where the reactor plus reflector diameter, air flow, and reactor-inlet Mach number (and hence over-all free-flow ratio) are held constant. Under these conditions, adding side reflecting material cuts down the reactor core diameter, but increases the core free-flow ratio. For the same reactor-outlet air temperature, the core length is unaffected by the addition of side reflectors under the stated conditions. Calculations for uranium investment are made for a range of reflector thicknesses

and the resultant investments plotted in figure 6. The reactor plus reflector diameter is 7.4 feet, the reactor length is 4.0 feet, and the free-flow ratio based on the total reactor plus reflector frontal area is constant at 0.35. The end reflector thickness is 3 inches and the average moderator and reflector temperature is assigned a value of 2200° R. The figure shows that uranium investment increases with increasing side reflector thickness, indicating that the increasing free-flow ratio which tends to increase uranium investment overrides the reduction in uranium investment expected by the reflector savings. Reactors without side reflection, therefore, give the minimum investment for the ram-jet missile application. 3077

Effect of nonuniform power distribution. - For a bare reactor without reflection and uniform uranium loading, the power generated per unit volume of reactor follows closely a sinusoidal variation with peak power production in the center of the reactor. Adding end reflectors gives an axial power distribution which can be approximated by a cut-off sine wave. For the purposes of the present study, the axial power distribution in the reactor core is assumed to be approximated by three-fourths of a full sine wave. The wall temperature of the central tube is calculated as a function of the reactor core length for this case according to the methods outlined in appendix B. The resultant wall temperature and air temperature variation are shown by the solid lines of figure 7 for one configuration with an average wall temperature of 2200° R. The maximum wall temperature is 4100° R for this case.

If the reactor free-flow ratio is varied sinusoidally, by adjusting the passage distribution, from a maximum value of 0.65 at the center of the reactor so that the average free-flow ratio is 0.35, the maximum reactor wall temperature can be reduced. (The air passage diameters are held constant at 0.5 in. and the distribution of power generated per unit reactor volume is assumed to be unaffected by the nonuniform distribution of air passages.) The high free-flow ratio in the center of the reactor introduces more heat-transfer surface at the center so that the power generated in this region can be removed with a lower wall temperature. The wall temperatures at the outer radii of the reactor are increased inasmuch as the free-flow factor is less than 0.35. The net result is that the reactor wall temperature is made more uniform by this distribution of free-flow ratio. The maximum wall temperature is reduced to 2600° R by this method, which is 400° above the average wall temperature of 2200° R. For an average wall temperature of 2000° R, the maximum wall temperature will then be of the order of 2400° R, assuming conservatively that the difference between the average and maximum wall temperatures is 400° R for this lower temperature. A temperature of 2400° R is within the maximum limits of stainless steel for low stress levels, so that if it is necessary to use stainless steel as a material to contain the fissionable material, it is possible to operate the reactor with an average wall temperature of 2000° R.

The effect of varying the free-flow ratio on uranium investment has not been calculated, inasmuch as it is beyond the scope of the simplified reactor analysis used in the present report.

SUMMARY OF RESULTS

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Minimum uranium investment and gross weight were calculated for a direct-air, nuclear-powered shieldless ram-jet missile operating at an altitude of 50,000 feet and flight Mach number of 2.5. The reactor was moderated by beryllium oxide. It was assumed that the missile carries a 10,000-pound load made up of pay load and guidance and control equipment. The following information can be drawn from the analysis:

1. The minimum uranium investments and corresponding missile gross weight, reactor free-flow ratio, inlet Mach number, and outlet air temperature are given in the following table as a function of average reactor wall temperature.

Average reactor wall temperature, °R	Minimum uranium investment, lb	Gross weight, lb	Reactor free-flow ratio	Reactor-inlet air Mach number	Reactor-outlet air temperature, °R
2200	19	47,600	0.36	0.28	1770
2000	20.6	44,300	.40	.28	1680
1800	23.6	54,400	.45	.28	1590

2. For uniform distribution of uranium and uniform free-flow ratio of 0.35, the maximum wall temperature for a reactor with an average wall temperature of 2200° R was about 4100° R.

3. For a uniform uranium distribution, but a sinusoidal radial variation of free-flow ratio with a maximum value of 0.65 at the center of the ractor and an average value of 0.35, the maximum wall temperature was approximately 2600° R for an average reactor wall temperature of 2200° R. On the basis of the conservative assumption that the difference between the maximum and the average wall temperature was 400° R for the lower wall temperatures, the maximum wall temperatures were approximately 2400° and 2200° R respectively, for average reactor wall temperatures of 2000° and 1800° R, for this case.

4. If stainless steel must be used to contain the fissionable material or protect the beryllium oxide from erosion by air, an average reactor wall temperature of 2000° R or less must be used for the previously given distributions of uranium and free-flow ratio.

[redacted]

5. If stainless steel liners with 0.005-inch walls were used to line the air passages in the reactor, the uranium investment was increased by a factor of 4.4 and 3.0 for effective reactor wall temperatures of 1800° R and 2200° R, respectively. If the stainless steel liners were increased to 0.01-inch thickness, the uranium investment was increased by a factor of 7.7 and 5.0 above the case with no liners.

6. The missile gross weight could be reduced appreciably by allowing an increase in uranium above the minimum value. The following table illustrates the reduction in gross weight which can be obtained: 3077

Uranium investment, lb	Missile gross weight, lb, for reactor effective wall temperatures of		
	1800° R	2000° R	2200° R
19.0	------	------	47,600
20.6	------	44,300	34,800
23.6	54,400	32,100	29,100
25.0	39,500	30,400	28,000
30.0	31,500	27,500	26,000

7. Reactors with no side reflection gave less uranium investment than reactors with side reflection for the application to the ram-jet direct-air nuclear-powered missile studied herein.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 24, 1954.

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APPENDIX A

SYMBOLS

The following symbols are found in this report:

A	frontal or flow area, ft^2
b	wing span, ft
C_D	drag coefficient
C_L	lift coefficient
C_V	nozzle velocity coefficient
c_p	specific heat at constant pressure, Btu/(lb)(^oR)
D	drag, lb
d	diameter, ft
d_e	hydraulic diameter, ft
F	thrust, lb
f	friction factor
g	acceleration due to gravity, ft/sec^2
H	enthalpy, Btu/lb
L	lift, lb
l	tube or reactor core length, ft
M	Mach number
P	total pressure, lb/ft^2
P_N	pressure number, $\frac{PA}{w\sqrt{T_W}}$
p	static pressure, lb/ft^2
Q	heat generation, Btu/sec
q	dynamic pressure, $\rho V^2/2g$, lb/ft^2

q'	total reactor power divided by reactor volume, Btu/sec/ft^3
R	gas constant, ft-lb/(lb)(°R)
Re	Reynolds number, $wd_e/A\mu_W$
S	surface area, ft^2
T	total temperature, °R
V	velocity, ft/sec
W	weight, lb
w	air flow, lb/sec
x	arbitrary length in direction of flow, ft
y	arbitrary length in radial direction, ft
α	free-flow ratio
γ	ratio of specific heats
μ	viscosity, lb/(ft)(sec)
ρ	density, lb/ft^3

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Subscripts:

0	free stream
1	diffuser exit
2	reactor tube inlet
3	reactor tube outlet
4	nozzle inlet
5	nozzle exit or jet
a	air
b	boattail or nozzle section
c	center section

d	diffuser or inlet section
f	friction
g	gross
j	jet
K	fixed
m	moderator
R	reactor
r	reflector
s	shell
T	total
t	tubes
U	uranium
W	wall
w	exposed wing alone
wb	wing plus body
wt	wing plus tail

APPENDIX B

ASSUMPTIONS AND METHODS OF CALCULATION

All the assumptions and details of calculating the performance of the ram-jet missile are presented in this appendix. The calculations are broken up into the seven parts described in the Methods section.

Internal Flow 3077

The internal flow path consists of an inlet diffuser, reactor passage, and exhaust nozzle.

Inlet diffuser. - The inlet diffuser is assumed to swallow all the air in the free-stream tube entering the engine and decelerate it to the assumed reactor-inlet Mach number. The diffuser total-pressure ratio P_1/P_0 used to calculate the total pressure entering the reactor passages is shown in figure 8 as a function of flight Mach number. The curve of figure 8 coincides closely with the experimental values given for the two-step cone diffuser in reference 2.

Reactor passage. - Air enters the reactor with total pressure P_2 and total temperature T_2 which are assumed to be equal to P_1 and T_1, respectively (the pressure and temperature of the air at the diffuser exit). The reactor-inlet Mach number M_2 within the tube is assigned a range of values of 0.22 to 0.38. The exit air temperature T_3 is varied over a range of values up to that corresponding to choking for each value of inlet Mach number. The tube length-diameter ratio required to attain the outlet air temperature with the assumed inlet Mach number is found by use of figure 9. Figure 9 plots the parameter $Re^{-0.2}\, l/d_e$ against T_2/T_W for various values of T_3/T_W and represents the solution of the equations of heat transfer to air at constant wall temperature. The ratio of specific heats is 1.4 and the Prandtl number is 0.66 for this plot. The derivation of the relation used for this curve is given in reference 3. The value of $Re^{-0.2}\, l/d_e$ is found from figure 9 at the values of T_3/T_W and T_2/T_W in question. The value of $Re^{-0.2}$ is defined as follows:

$$Re^{-0.2} = \left(\frac{wd_e}{A\mu_W}\right)^{-0.2}$$

where d_e is the assumed hydraulic diameter (0.04167 ft), μ_W is the viscosity of the air evaluated at the effective wall temperature T_W, and w/A is the air flow in pounds per square foot per second in the reactor air passages. The air flow per unit air flow area is given by the following one-dimensional flow relation:

$$\frac{w}{A_2} = \sqrt{\frac{\gamma g}{R}}\,\frac{M_2 P}{T_2}\left(1 + \frac{\gamma - 1}{2} M_2^2\right)^{-\frac{(\gamma+1)}{2(\gamma-1)}}$$

3077 where γ is assumed to be 1.4. The l/d_e of the tube is then

$$l/d_e = \frac{Re^{-0.2}\; l/d_e}{Re^{-0.2}}$$

and the reactor core length which is equal to the tube length is

$$l = l/d_e \times d_e$$

The total-pressure ratio of the air flowing through the reactor is found by means of curves presented in figure 10. The pressure number P_N, or $\frac{PA}{w\sqrt{T_W}}$ is plotted against T/T_W for a range of flow Mach numbers. The lines which curve downward to the right are lines of constant air flow per unit area and show the decrease in P_N, which is proportional to the total pressure, as the temperature and Mach number of the air flowing in a tube increase. The pressure ratio, P_3/P_2 across the tube is then the ratio of $P_{N,3}$ to $P_{N,2}$, where the value of $P_{N,2}$ is found at the assigned values of T_2/T_W and M_2, and $P_{N,3}$ is found by following down the solid lines to T_3/T_W. Assuming that the entrance, exit, and end reflector pressure losses amount to 0.10 of the pressure drop, the over-all pressure ratio P_3/P_2 is then given by

$$\frac{P_3}{P_2} = 1 - 1.1\left(1 - \frac{P_{N,3}}{P_{N,2}}\right)$$

Nozzle. - The air leaving the reactor is at temperature T_3 and pressure P_3 which are assumed equal, respectively, to T_4 and P_4. The value of T_3 is assigned previously and the value of P_3 is given by the following:

$$P_3 = \frac{P_3}{P_2} \times \frac{P_1}{P_0} \times \frac{P_0}{p_0} \times p_0$$

or in terms of nozzle pressure ratio

$$\frac{P_4}{p_0} = \frac{P_3}{p_0} = \frac{P_3}{P_2} \times \frac{P_1}{P_0} \times \frac{P_0}{p_0}$$

where P_0/p_0 is found for the flight Mach number from reference 4.

Thrust. - The jet thrust per pound of air flow per second for a fully expanding nozzle is given by: 3077

$$\frac{F_j}{w} = C_V \sqrt{\frac{2\gamma R}{g(\gamma - 1)}} \sqrt{T_3} \left[1 - \left(\frac{p_0}{P_3}\right)^{\frac{\gamma-1}{\gamma}}\right]^{1/2}$$

where C_V, the nozzle velocity coefficient, is assumed to be 0.97 and γ is 1.34. The net thrust per pound of air flow per second is then

$$\frac{F}{w} = \frac{F_j}{w} - \frac{V_0}{g}$$

Power-Plant External Flow

The air flowing external to the power plant creates a drag force which must be subtracted from the net thrust force to obtain the resultant thrust force which is available to overcome the drag of the wing and tail. For the purpose of the drag force calculations, the power plant is divided into three sections. They are the inlet cowl, the center section which contains the reactor, and the nozzle or boattail section. The inlet and boattail sections are assumed to be conical sections, while the center section is assumed to be cylindrical. The total external power-plant drag is composed of pressure drag on the inlet and nozzle sections and friction drag on all three portions of the power plant.

The pressure drag for conical surfaces is obtained from reference 5 where the generalized pressure drag coefficient $C_D\sqrt{M}$ is plotted as a function of cone area ratio (inlet area to maximum area) and cone length-to-diameter ratio.

The friction drag is computed assuming that the friction factor f based on surface area is 0.0025. The following relation relates the friction drag coefficient to the frontal area A, friction factor f, and surface area S.

$$C_{D,f} = f \frac{S}{A}$$

Both pressure and friction drag coefficients were computed for conical surfaces over a range of flight Mach numbers, area ratios, and
3077 length-to-diameter ratios. The friction and pressure drag coefficients, both based on the maximum frontal area of the cone, were added and plotted as a function of l/d. These curves indicated a minimum total drag (sum of friction and pressure drag) at some particular l/d. The minimum total drag coefficient found from these curves is plotted in figure 11 as a function of area ratio for a flight Mach number of 2.5. Also shown are the corresponding values of length-diameter ratio. (As an incidental observation, it was found that the cone included angle which gave minimum total drag was very close to 6° independent of area ratio and flight Mach number.) The total inlet external drag coefficient is found directly from figure 11 at the cone area ratio (assuming zero spillage), which is found by means of one-dimensional flow relations from the flight Mach number, the assumed reactor-inlet air Mach number M_2, and the reactor free-flow ratio α.

The drag coefficient $C_{D,b}$ of the boattail is also computed assuming that the data of figure 11 apply to an expanding as well as a compressing flow field. The basis for this assumption can be found in reference 6 where it is shown theoretically that the pressure drag of inlet cowls and boattails is the same. The area ratio used in this case is the ratio of nozzle-exit area to maximum area.

The drag of the cylindrical center section, which is assumed to have an l/d of 2 is due only to friction and is computed by the following:

$$C_{D,c} = f \frac{S_c}{A_1} = 4 f \left(\frac{l}{d}\right)_c$$

The total external drag coefficient of the entire power plant or fuselage based on the center section frontal area A_1 is then

$$C_{D,T} = C_{D,d} + C_{D,c} + C_{D,b}$$

The total fuselage drag per unit air flow is then

$$\frac{D_T}{w} \quad \frac{qC_{D,T}}{W/A_1}$$

where

$$\frac{w}{A_1} = \alpha\left(\frac{w}{A_2}\right)$$

neglecting the thickness of the center-section shell around the reactor.

Information on the interference drag on a body due to the addition of a wing on the body is meager, especially data at high Reynolds number with varying boattail lengths and area ratios. Reference 7 presents an experimental investigation which measured the effects of wing-body interference for a small-scale rectangular wing-body combination with various aspect ratios and flight Mach numbers. Only one boattail configuration was used, however. The addition of the wing on the body increased the body drag by about 30 to 40 percent because of a change from a laminar to a turbulent boundary layer on the boattail caused by the addition of the wing. Inasmuch as the ram-jet configuration of the present analysis would have a turbulent boundary layer on the boattail for the body alone configuration, the large increase in drag would not be expected with the addition of the wing. The drag interference of the wing on the body is therefore neglected because of the lack of applicable data; the data which do exist indicate a probable small effect.

Power-Plant Weight

The power-plant weight is composed of the reactor weight and the shell weight, which includes the diffuser, center section, and boattail.

Reactor weight. - The reactor core for weight calculation consists of a beryllium oxide matrix with 0.52-inch holes containing 0.50-inch-inside-diameter uranium-bearing stainless-steel tubes with 0.01-inch walls. No side reflection is provided for reasons indicated previously. End reflection is supplied by beryllium oxide 3 inches thick at both ends of the reactor with 1/2-inch-diameter flow passages as continuations of the reactor flow passages. The weight of the various reactor components per pound of air flow per second is then given by the following relations assuming that the density of beryllium oxide is 181 pounds per cubic foot and that of stainless steel 490 pounds per cubic foot.

$$\frac{W_m}{w} = 7.54\left(\frac{1 - \alpha}{\alpha} - 0.08160\right)\left(\frac{l}{d_e}\right)\left(\frac{A}{w}\right)_2 \qquad \text{(moderator)}$$

$$\frac{W_t}{w} = 1.67\left(\frac{l}{d_e}\right)\left(\frac{A}{w}\right)_2 \qquad \text{(tubes)}$$

$$\frac{W_r}{w} = 90 \left(\frac{1 - \alpha}{\alpha}\right)\left(\frac{A}{w}\right)_2 \qquad \text{(end reflectors)}$$

These relations hold only for a tube internal diameter of 0.5 inch and wall thickness of 0.01 inch. In calculating the weight of reactors without stainless steel, or with tubes of 0.005-inch wall thickness, the weight of tubes of 0.01-inch thickness is assumed for the sake of simplicity in calculations. An allowance of 15 percent of the total reactor weight is made for supporting structure.

<u>Shell weight</u>. - The shell weight is calculated assuming that:

(1) The shell diameter is equal to the power-plant center section diameter.

(2) The shell length is equal to the sum of the lengths of the diffuser, center section, and boattail.

(3) The shell thickness is 0.1 inch.

(4) The shell material is stainless steel with a density of 490 pounds per cubic foot.

The shell weight per pound of air flow per second, from these assumptions, is then given by

$$\frac{W_s}{w} = 16.33 \left(\frac{A}{w}\right)_2 \frac{l}{\alpha} \left[\left(\frac{l}{d}\right)_d + \left(\frac{l}{d}\right)_c + \left(\frac{l}{d}\right)_b\right]$$

Wing and Tail Lift and Drag

The lift and drag of the wing and tail are calculated by the methods outlined in reference 8. The wing is assumed to be a 60° delta wing with a 3-percent thickness. The tail surfaces are considered as 3-percent-thick 60° delta nonlifting surfaces having 15 percent of the wing area. Figure 12 gives the maximum lift-drag ratio and the corresponding optimum lift coefficient and wing loading as a function of flight Mach number. The lift-drag ratio is plotted including and not including the effect of the nonlifting tail surfaces.

Wing and Tail Weight

The wing weight was computed by the method presented in reference 9 for a typical configuration with a gross weight of about 45,000 pounds.

[redacted]

It was found that the wing would weigh about 4 percent of the gross weight, including a 15-percent increase to allow for tail surfaces. The stress in the wing, assuming the optimum wing loading of 123 pounds per square foot for the flight condition of the present report, gave a maximum value of about [illegible] pounds per square inch. The maximum allowable stress with a load factor of 3 is therefore slightly less than 80,000 pounds per square inch, which is less than the hot-rolled tensile strength of 1041 to 1095 carbon steels.

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Over-all Performance

The gross weight of the complete ram-jet missile configuration is given by the following:

$$W_g = \frac{W_K}{1 - \frac{W_{wt}}{W_g} - \frac{1}{\left(\frac{F - D_T}{W_T}\right)\left(\frac{L_w}{D_{wt}}\right)\left(\frac{L_{wb}}{L_w}\right)}}$$

where

W_K fixed equipment plus payload, lb

$\frac{W_{wt}}{W_g}$ $\frac{\text{wing plus tail weight}}{\text{gross weight}}$

$\frac{F - D_T}{W_T}$ $\frac{\text{thrust minus power-plant drag}}{\text{power-plant weight}} = \frac{(F - D_T)/w}{W_T/w}$

$\frac{L_w}{D_{wt}}$ $\frac{\text{lift of wing alone (zero body diameter)}}{\text{drag of wing plus tail}}$

$\frac{L_{wb}}{L_w}$ $\frac{\text{lift of wing-body combination}}{\text{lift of wing alone}}$

The fixed equipment plus payload is assumed to be 10,000 pounds; the ratio of wing plus tail weight to gross weight W_{wt}/W_g is 0.04; the value of $\frac{F - D_T}{W_T}$ is found from internal and external power-plant performance; the L_w/D_{wt} is the maximum value obtainable at the desired flight condition (fig. 12); and the L_{wb}/L_w is found from figure 13. Figure 13 is obtained from reference 10 where L_{wb}/L_w is shown to be a function of d/b, the ratio of body diameter to wing span.

The value of d/b in terms of quantities already evaluated is found for a 60° delta wing from the following relation:

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$$\frac{d}{b} = \frac{1}{1 + \left[\frac{\pi\left(\frac{L_w}{D_{wt}}\right)\left(\frac{F - D_T}{w}\right)}{\sqrt{3}\left(\frac{L_w}{S_w}\right)\left(\frac{A}{w}\right)_1}\right]^{\frac{1}{2}}}$$

All the quantities in this relation have previously been determined in calculating power-plant thrust and drag, and maximum wing lift-drag ratio. With the value of d/b found from equation (2) the value L_{wb}/L_w can be found from figure 13.

The gross weight is then found by use of equation (1) inasmuch as all the unknown quantities are now determined.

The power-plant air flow is given by:

$$w = \frac{W_g}{\left(\frac{F - D_T}{w}\right)\left(\frac{L_w}{D_{wt}}\right)\left(\frac{L_{wb}}{L_w}\right)}$$

The reactor heat release is then:

$$Q = w(H_3 - H_2)$$

where H_3 and H_2 are the air enthalpies at T_3 and T_2, respectively.

The power-plant or reactor frontal area neglecting the thickness of the shell skin is:

$$A_1 = \frac{w}{w/A_1} = \frac{w}{\alpha(W/A_2)}$$

The power-plant or reactor diameter is

$$d_1 = \sqrt{\frac{4A_1}{\pi}}$$

[redacted]

The over-all lift-drag ratio of the complete ram-jet missile in terms of quantities which are known is given by:

$$\frac{L}{D} = \left(1 - \frac{D_T/w}{F/w}\right)\left(\frac{L_w}{D_{wt}}\right)\left(\frac{L_{wb}}{L_w}\right)$$

Uranium Investment

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The calculations of the critical uranium mass are made by methods presented in reference 11 for cylindrical bare reactors. The effect of BeO reflection is evaluated by a two-group procedure from unpublished NACA data. These data are presented in figure 14 by a plot of reflector savings as a function of reflector thickness and ratio of void space of reflector to void space of core. This figure is used to calculate the equivalent bare core length and diameter when reflectors are used. Neutron cross-section data for the structural and moderating materials are obtained from reference 12. The slowing-down length of BeO is obtained from reference 13, and the uranium cross sections from reference 14. The thermal energy of the neutrons is assumed to be that corresponding to the assigned effective constant wall temperature. All absorption cross sections are assumed to vary inversely as the neutron velocity. The effect of xenon poisoning, burnup, and control is neglected.

The criticality equation for bare reactors considering thermal production only is given by

$$\frac{k_{th}e^{-\tau_0 B^2}}{1 + L_{th}^2 B^2} = 1 \tag{1}$$

where

k_{th} thermal multiplication constant

τ_0 age of fission neutrons, cm^2

B^2 buckling constant, cm^{-2}

L_{th}^2 mean square thermal diffusion distance, cm^2

The symbols used in this section of the text are conventional for reactor analyses and conflict with the symbols used in the cycle and aerodynamic analysis. In addition, it is conventional to use c.g.s. units for reactor analyses. The symbols and units used in this section are therefore omitted from the list of symbols in appendix A and defined at the point at which they appear. The thermal multiplication constant is given by:

$$k_{th} = \frac{2.5\, N^U \sigma_F{}^U}{N^U \sigma_A{}^U + \Sigma_A{}^{SS} + \Sigma_A{}^{BeO}}$$

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where

N^U atoms of U_{235} per unit volume of reactor, atoms/cm^3

$\sigma_F{}^U$ microscopic fission cross section of U_{235}, cm^2

$\sigma_A{}^U$ microscopic absorption cross section of U_{235}, cm^2

$\Sigma_A{}^{SS}$ macroscopic absorption cross section of stainless steel, (atoms/cm^3 of reactor)(cm^2)

$\Sigma_A{}^{BeO}$ macroscopic absorption cross section of beryllium oxide (atoms/cm^3 of reactor)(cm^2)

The mean square thermal diffusion distance is given by:

$$L_{th}^2 = \frac{\lambda_{tr}}{3\left(N^U \sigma_A{}^U + \Sigma_A{}^{SS} + \Sigma_A{}^{BeO}\right)}$$

where

λ_{tr} reactor macroscopic transport mean free path, cm

Substituting relations (2) and (3) into (1) and solving for N^U result in the following expression:

$$N^U = \frac{\Sigma_A{}^{BeO} + \Sigma_A{}^{SS} + \frac{B^2 \lambda_{tr}}{3}}{2.5\, \sigma_F{}^U e^{-B^2 \tau_0} - \sigma_A{}^U}$$

For criticality, the buckling constant B^2 is given by the following relation:

$$B^2 = \left(\frac{2.405}{15.24 d_l'}\right)^2 + \left(\frac{\pi}{30.48 H_c}\right)^2$$

where

d_l' equivalent bare core diameter, ft

H_c equivalent bare core length, ft 3077

The equivalent bare reactor diameter d_l' is equal to the actual core diameter d_l plus the side reflector savings h' found from figure 14 at the desired reflector thickness.

$$d_l' = d_l + h'$$

The equivalent bare core length H_c is equal to the actual core length l plus the end reflector savings h'' which is found from figure 14 for an end reflector thickness of 3 inches and ratio of reflector void space to reactor core void space of 1.0. The equivalent bare reactor length is given by

$$H_c = l + h''$$

The buckling constant is then

$$B^2 = \left[\frac{2.405}{15.24(d_l + h')}\right]^2 + \left[\frac{\pi}{30.48(l + h'')}\right]^2$$

The values of Σ_A^{BeO}, Σ_A^{SS}, λ_{tr}, and τ_0, as determined for a reactor free-flow factor (void percent) of 0.40, are tabulated in the following table for three assumed reactor mean temperatures. The values of σ_F^U, and σ_A^U obtained from reference 14 are also included in the table. The value of τ_0 is calculated from the results of reference 13.

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	Temperature, ^{o}R		
	1800	2000	2200
Σ_A^{BeO}	0.0001735	0.0001647	0.0001568
Σ_A^{SS}	.00450	.00384	.00366
λ_{tr}	2.427	2.427	2.427
τ_0	344	344	344
σ_F^U	316.6	290.5	277.0
σ_A^U	361.5	343.0	326.8

The values for Σ_A^{BeO}, Σ_A^{SS}, λ_{tr}, and τ_0 for any other values of free-flow ratio are obtained by use of the following relations

$$\Sigma_A^{BeO} = \left(\Sigma_A^{BeO}\right)_{\alpha=0.4} \left(\frac{1-\alpha}{0.6}\right)$$

$$\Sigma_A^{SS} = \left(\Sigma_A^{SS}\right)_{\alpha=0.4} \left(\frac{\alpha}{0.4}\right)$$

$$\lambda_{tr} = \left(\lambda_{tr}\right)_{\alpha=0.4} \left(\frac{0.6}{1-\alpha}\right)$$

$$\tau_0 = (\tau)_{\alpha=0.4} \left(\frac{0.6}{1-\alpha}\right)^2$$

With these constants and the dimensions of the reactor, it is possible to calculate the number of uranium atoms per cubic centimeter of reactor N^U. The uranium weight in pounds is then given by

$$W_U = \frac{235\ vN^U}{453.6\times6.023\times10^{23}}$$

where v is the reactor volume in cubic centimeters.

The value of Σ_A^{SS} given in the table is for a wall thickness of 0.01 inch. For a wall thickness of 0.005 inch Σ_A^{SS} is one half the value shown in the table, and for no stainless steel Σ_A^{SS} is zero.

[redacted]

Maximum Reactor Wall Temperature

In the foregoing analysis the reactor wall temperature is assumed to be constant for all reactor heat-transfer surfaces. The assumptions used in calculating the effect of nonuniform wall temperature distributions caused by various power and local free-flow ratio distributions is considered in this section. For a reactor with a uniform uranium loading, the power generated per unit reactor volume follows closely a sinusoidal variation with peak power production in the center of the reactor. Adding reflectors at the ends of the reactor results in a cut-off axial sinusoidal power generation. For the purposes of the present study, the 3077
axial power distribution in the reactor core is assumed to be approximated by three-fourths of a full sine wave. Varying the free-flow factor radially while maintaining a uniform uranium loading is assumed to have no effect on the power-generation distribution for the purposes of the present calculations. Actually, varying the free-flow factor will give a nonuniform moderator distribution which will affect the uranium investment. The various combinations of axial and radial power distributions (based on unit reactor volume) and free-flow ratio distribution considered are listed in the following table:

	Case	
	I	II
Uranium distribution	Uniform	Uniform
Radial power distribution	Full sine	Full sine
Axial power distribution	Cut-off sine (3/4 of a full sine curve)	Cut-off sine (3/4 of a full sine curve)
Radial free-flow ratio distribution	Uniform (equal to 0.35)	Cut-off sine (maximum equal to 0.65 in center; average equal to 0.35)

Calculations are made to determine the approximate maximum reactor wall temperature for each of these cases. The reactor diameter, length, average free-flow factor, end reflector thickness, inlet air temperature and pressure, inlet Mach number, and average outlet air temperature are fixed for both cases in order that the reactors be interchangeable in a fixed airframe. The value of these quantities used in the actual calculations are listed together with other quantities of interest:

Reactor diameter, ft	7.39
Reactor length, ft	4.03
Average free-flow ratio	0.35
3077 End reflector thickness, in.	8.0
Side reflector thickness, in.	0
Inlet air Mach number	0.32
Inlet air temperature, $^{\circ}R$	882
Outlet air temperature, $^{\circ}R$	1654
Air flow, lb/sec	477
Effective constant wall temperature, $^{\circ}R$	2200
Reactor hydraulic diameter, in.	0.5

The air flow distribution across the face of the reactor is assumed to be such that the air flow is divided evenly among all the tubes regardless of the particular heat input distribution. The air heat-transfer coefficient for all three cases is assumed to be constant and equal to the average heat-transfer coefficient assuming that all the reactor surfaces are at a temperature of 2200° R.

Case I

Uniform uranium distribution and uniform free-flow distribution are assumed for case I. The axial power distribution of an unreflected reactor can be approximated by a full sine curve. Inasmuch as the reactors in the present study have end reflection, it is assumed that the axial power distribution is represented by three-fourths of a full sine wave. The radial distribution is represented as a full sine curve since no side reflection is assumed. The wall temperature for the center tube as a function of the fraction of the total reactor core length is given by the following equation:

$$T_W = T_2 + q' \frac{d_e}{4\alpha}\left[\frac{0.924 - \cos \frac{x}{l}\pi}{1.849(w/S)c_p} + \frac{1.275}{h} \sin \frac{x}{l}\pi\right]$$

The heat-transfer coefficient is assumed to be constant and equal to 0.02 Btu/(sec)(sq ft)(°F) which is calculated assuming that the wall temperature is uniform. The mass flow of air per unit flow area is also assumed to be constant for the purposes of these calculations.

Case II

The second case considers uniform uranium distribution per unit reactor volume; however, the reactor free-flow ratio is varied radially. In order to keep the uranium distribution uniform in this case, the concentration of uranium on the surface of the tubes must vary inversely with the free-flow factor. Thus an increase in free-flow factor results in a decrease in uranium concentration on the surface of the tubes at a particular reactor core radius. The power produced per tube at the particular radius is therefore reduced inversely with the free-flow factor. 3077 The difference between the wall temperature and the air temperature is also reduced inversely with the free-flow factor if the heat-transfer coefficient remains constant. The result is a reduction in wall temperature at the particular radius of the reactor where the free-flow ratio is increased above the average. In the converse manner the wall temperature of the tubes at a particular reactor radius with low power production is increased by a reduction in free-flow factor. The net effect is to even out the radial wall temperature variation if free-flow factor is high in the center and low at the outer edge of the reactor. Inasmuch as the power distribution is sinusoidal, a sinusoidal variation of free-flow factor is desirable to flatten out the power generated in each tube. Without going to excessively close spacing of reactor flow passages, a maximum free-flow ratio of 0.65 is assumed for the center of the reactor. From this maximum value of 0.65, the free-flow ratio is varied sinusoidally to the outer edge of the reactor in such a manner as to give an average free-flow factor of 0.35. The free-flow ratio as a function of the local to maximum reactor core radius is given by the following relation for this case:

$$\alpha = 0.65 \cos\left(0.914 \frac{y}{R} \frac{\pi}{2}\right)$$

for the center tube of case II the wall temperature variation as a function of the fraction of reactor length is given by the equation of T_W for case I with α of 0.35 replaced by 0.65

$$T_W = T_2 + q' \frac{De}{4(0.65)} \left[\frac{0.924 - \cos \frac{x}{l} \pi}{1.849(w/S)c_p} + \frac{1.275}{h} \sin \frac{x}{l} \pi\right]$$

The heat-transfer coefficient is assumed to be constant and equal to the value of case I. The mass flow per unit flow area is also assumed constant for this case.

[redacted]

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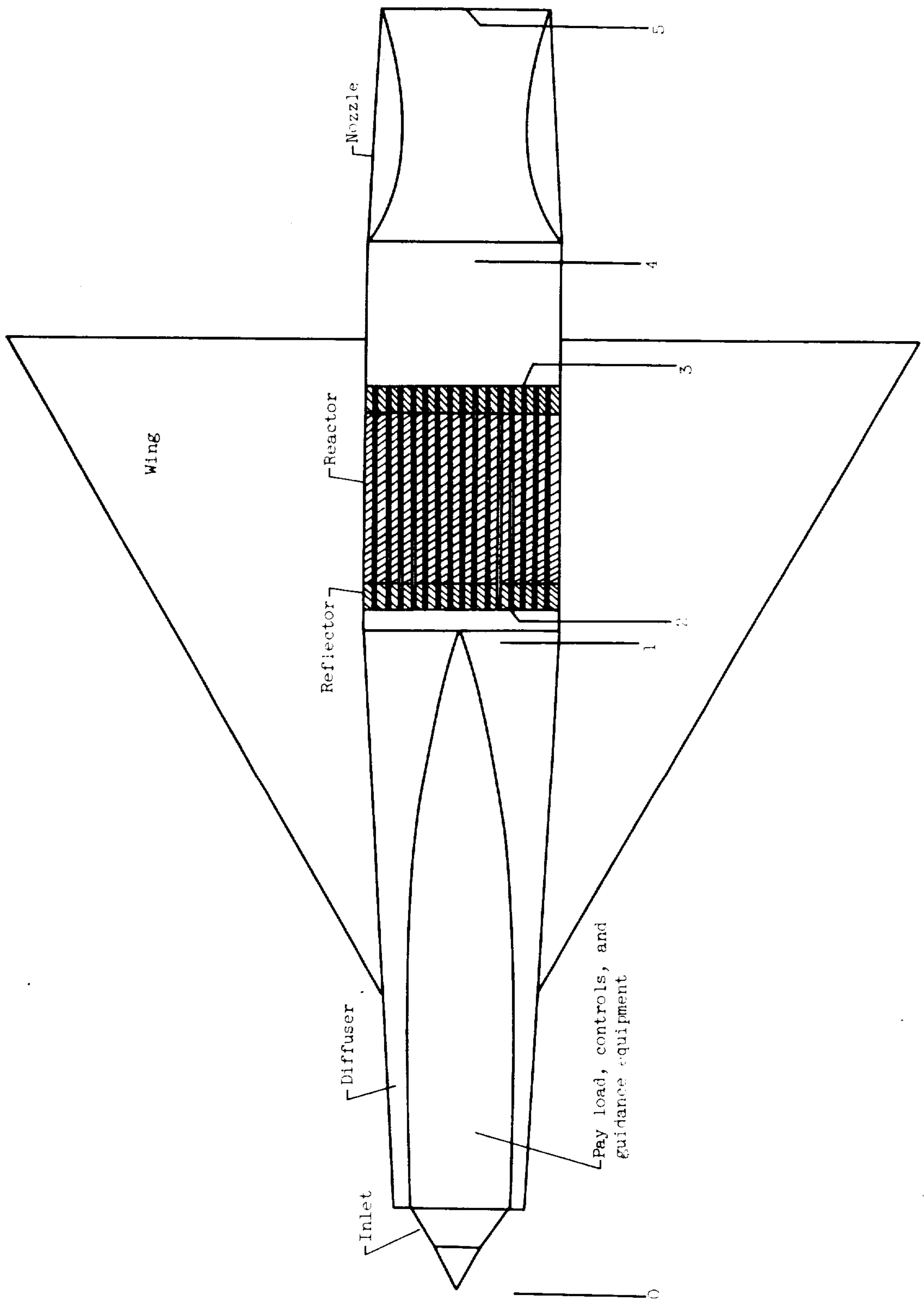

Figure 1. - Schematic sketch of shieldless nuclear-powered ram-jet missile.

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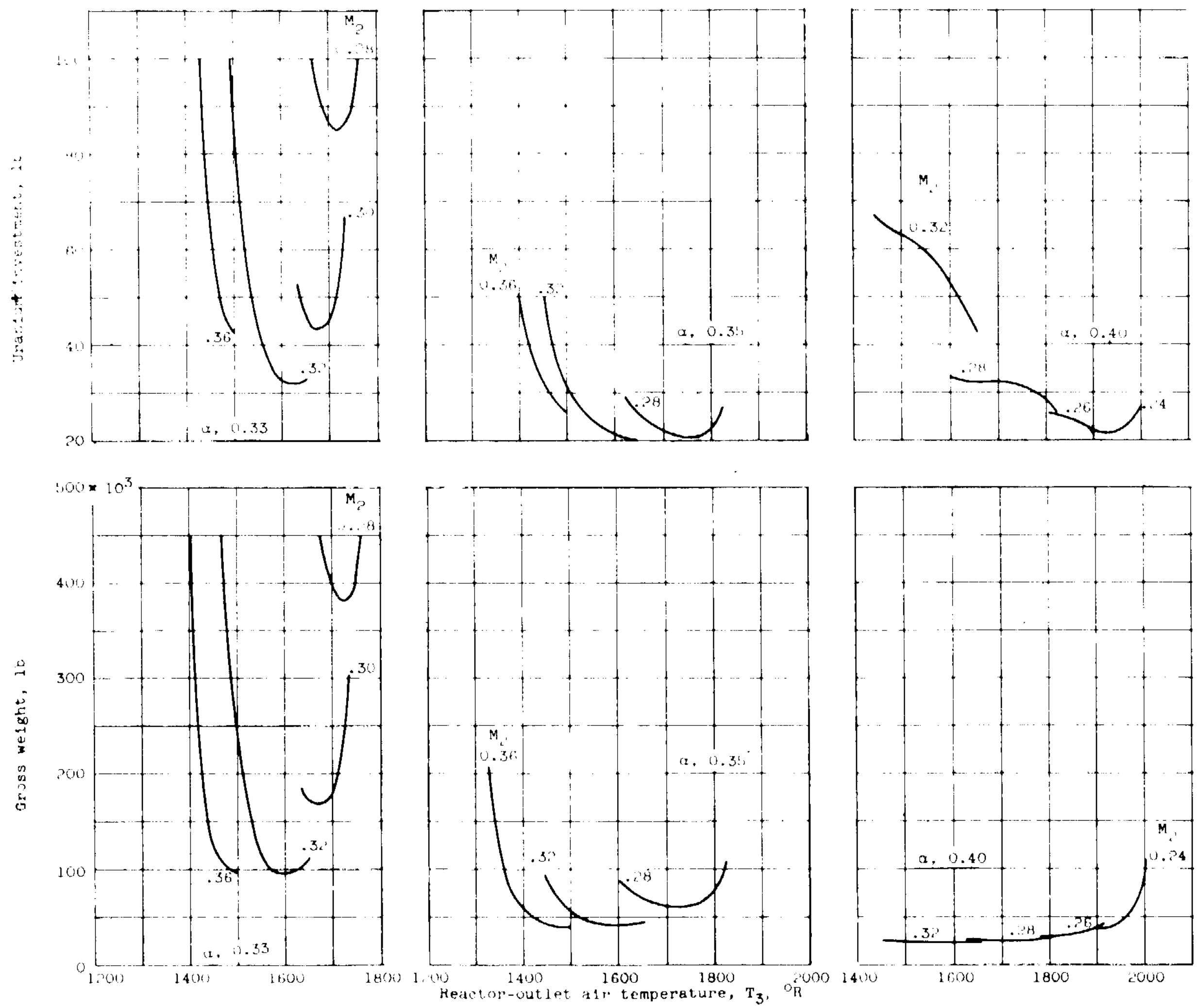

(a) Effective reactor wall temperature, T_w, 2200 °R.

Figure 2. - Uranium investment and missile gross weight as a function of reactor-outlet air temperature reactor-inlet air Mach number, and reactor free-flow ratio α. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

[redacted]

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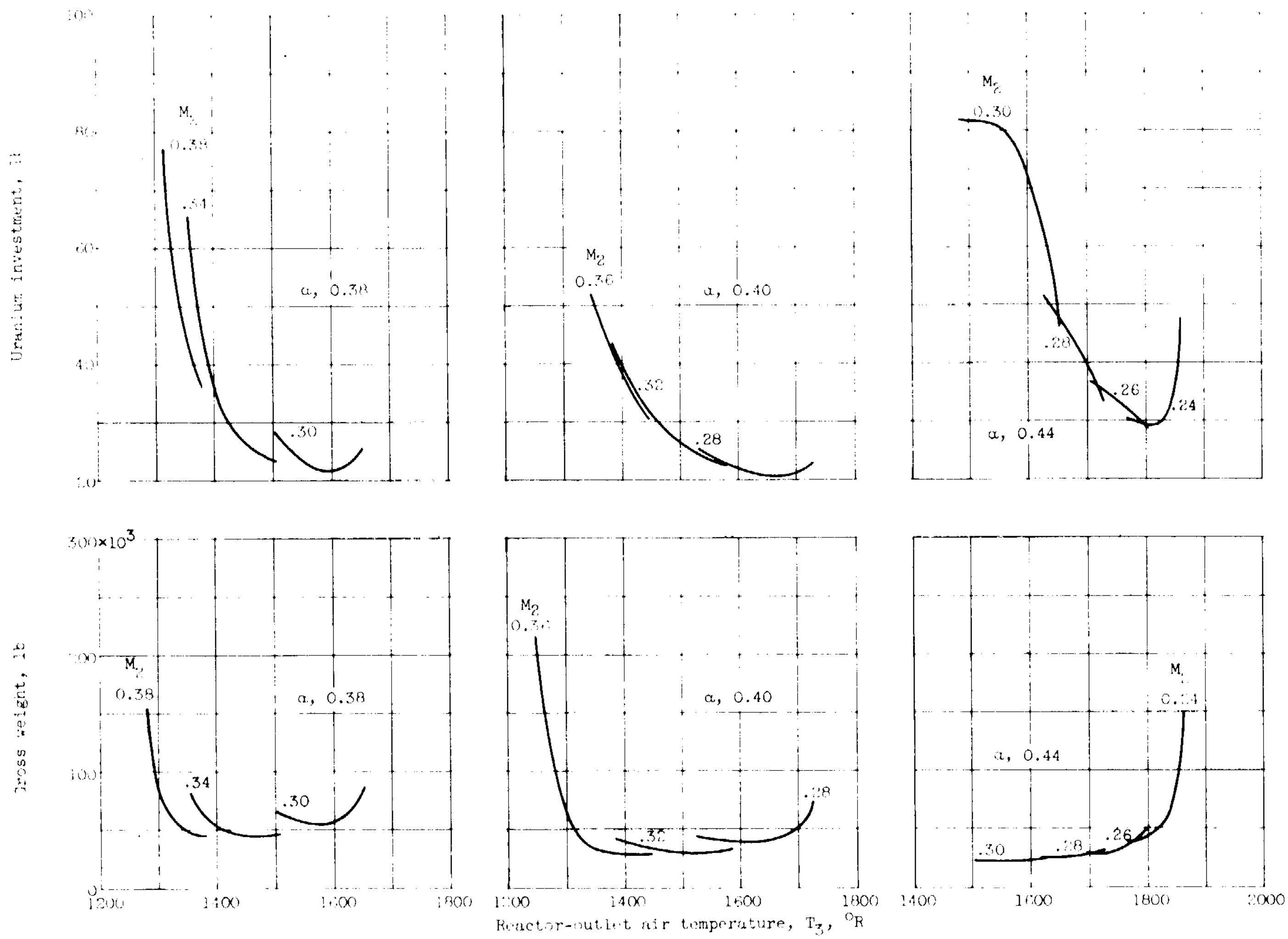

(b) Effective reactor wall temperature, T_W, 2000° R.

Figure 2. - Uranium investment and missile gross weight as a function of reactor-outlet air temperature, reactor-inlet air Mach number, and reactor free-flow ratio α. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

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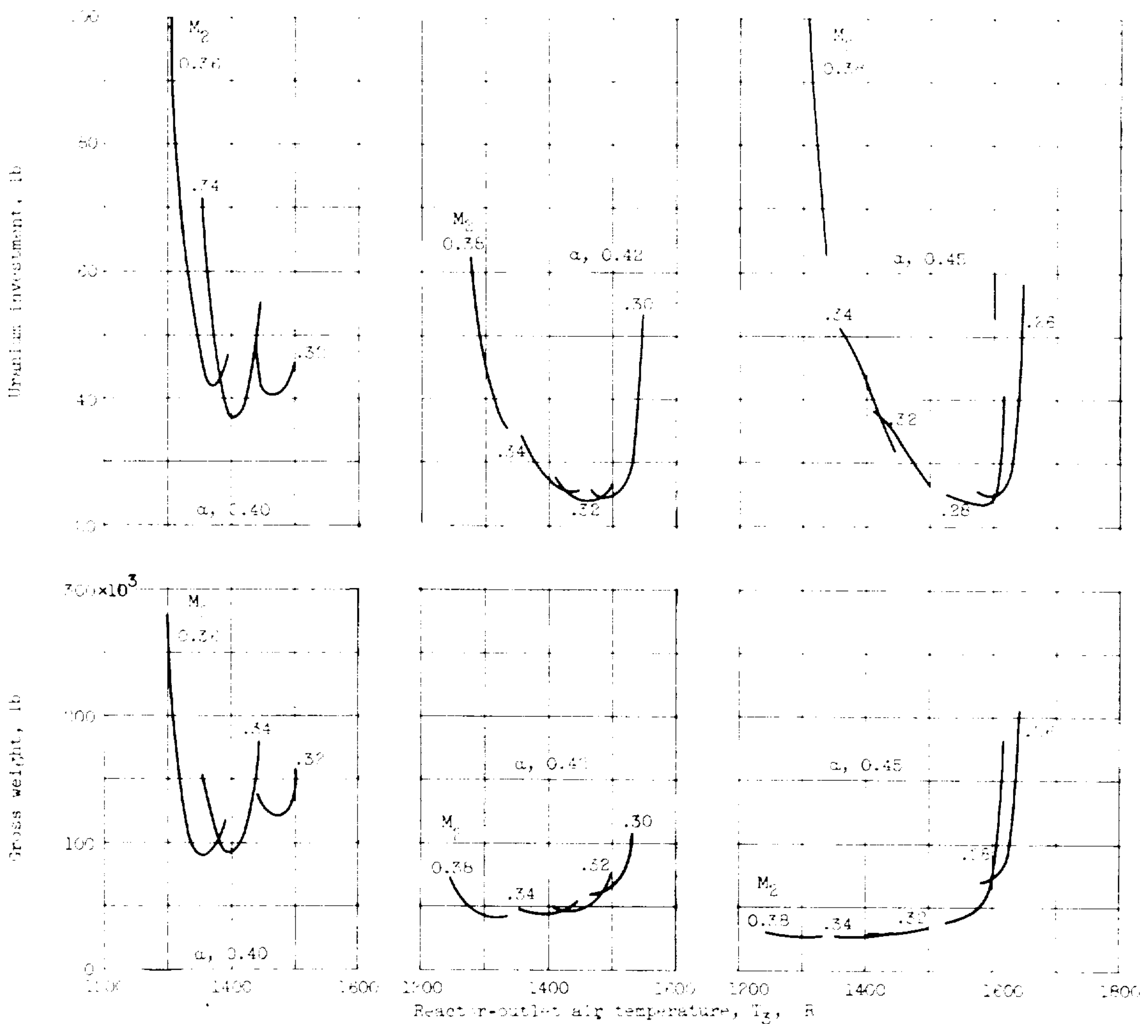

(c) Effective reactor wall temperature, T_W, 1800° R.

Figure [illegible]. - Concluded. Uranium investment and missile gross weight as a function of reactor-outlet air temperature, reactor-inlet air Mach number, and reactor free-flow ratio α. No stainless steel in reactor; flight Mach number, 1.5; altitude, 50,000 feet.

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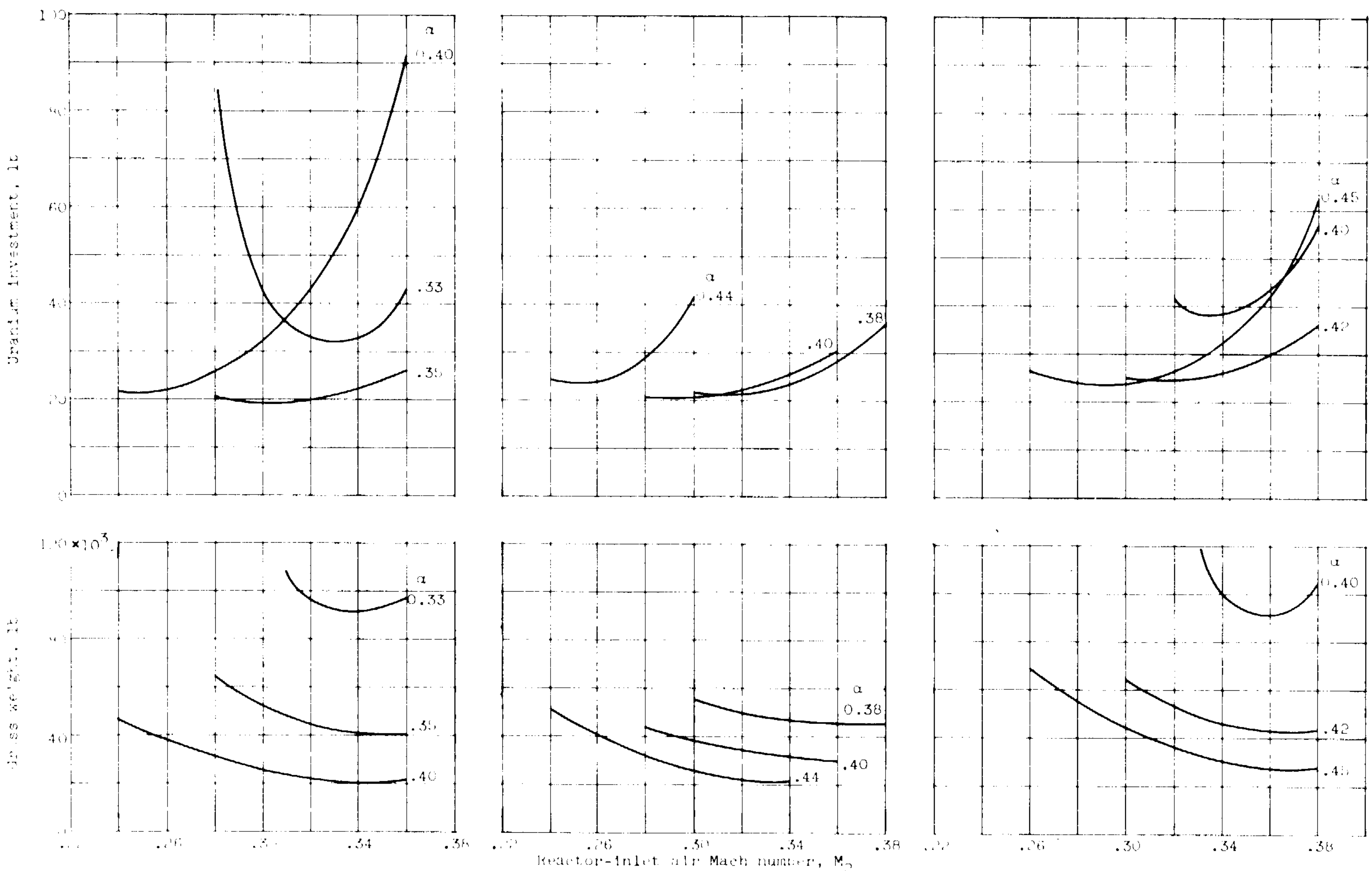

(a) Effective reactor wall temperature, T_W, 2200 °R.

(b) Effective reactor wall temperature, T_W, 2000 °R.

(c) Effective reactor wall temperature, T_W, 1800 °R.

Figure [illegible]. - Uranium investment and missile gross weight as function of reactor-inlet air Mach number and reactor free-flow ratio for reactor-outlet air temperature which gives minimum uranium investment. No stainless steel in reactor; flight Mach number, [illegible]; altitude, [illegible] feet.

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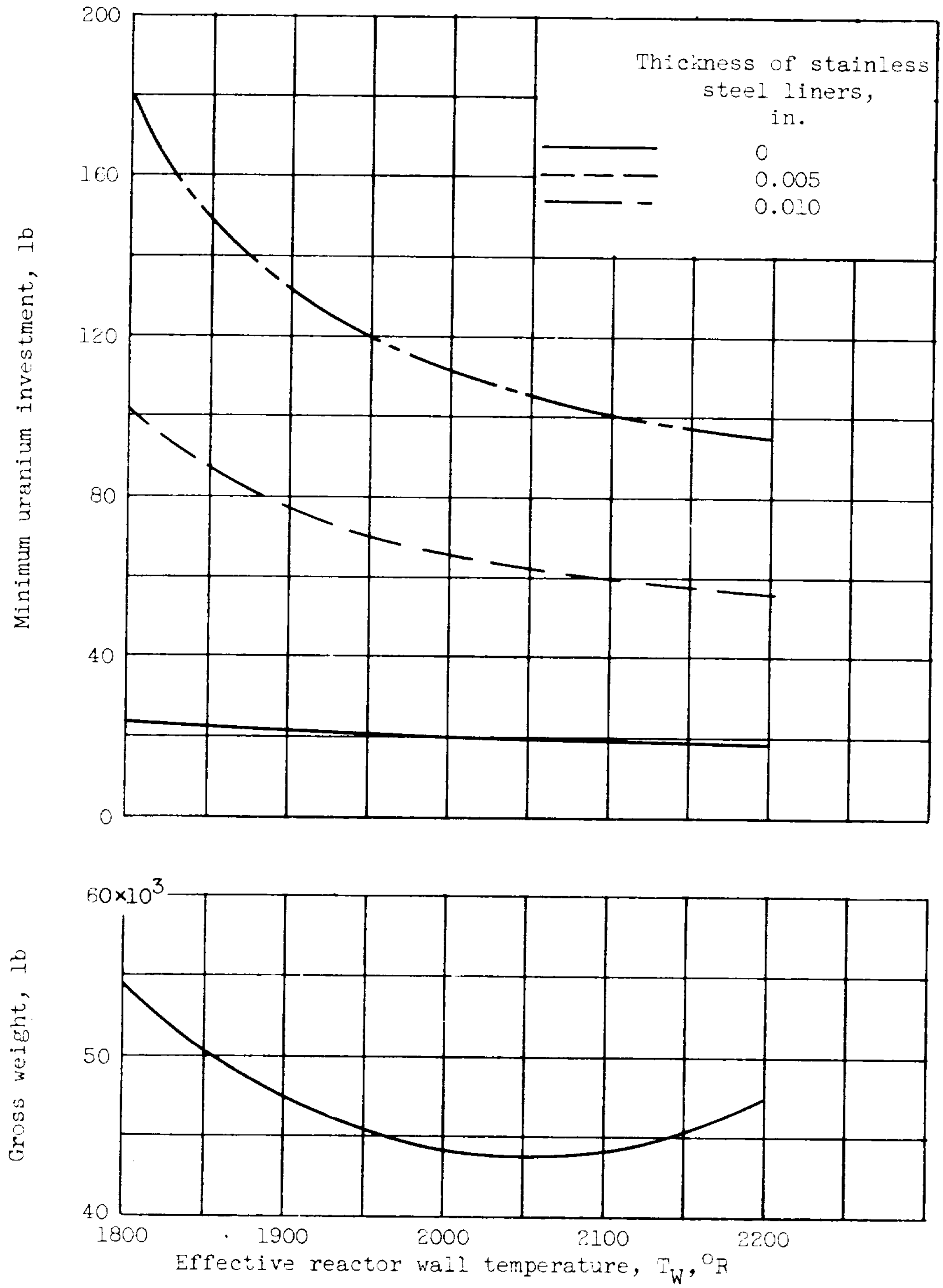

(a) Uranium investment and gross weight.

Figure 4. - Ram-jet missile operating conditions for minimum uranium investment as a function of effective reactor wall temperature. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

[redacted]

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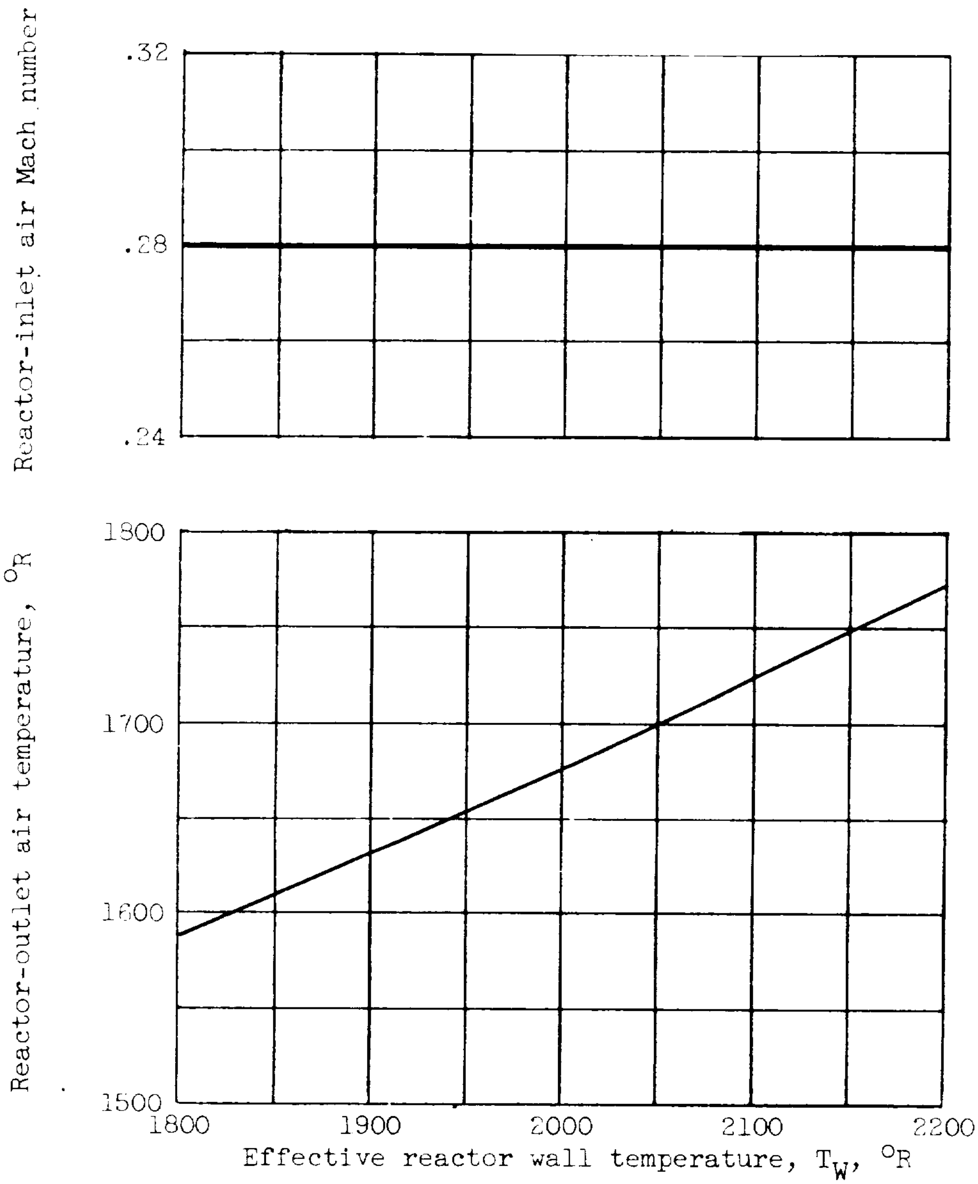

(b) Reactor-inlet air Mach number and reactor-outlet air temperature.

Figure 4. - Continued. Ram-jet missile operating conditions for minimum uranium investment as a function of effective reactor wall temperature. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

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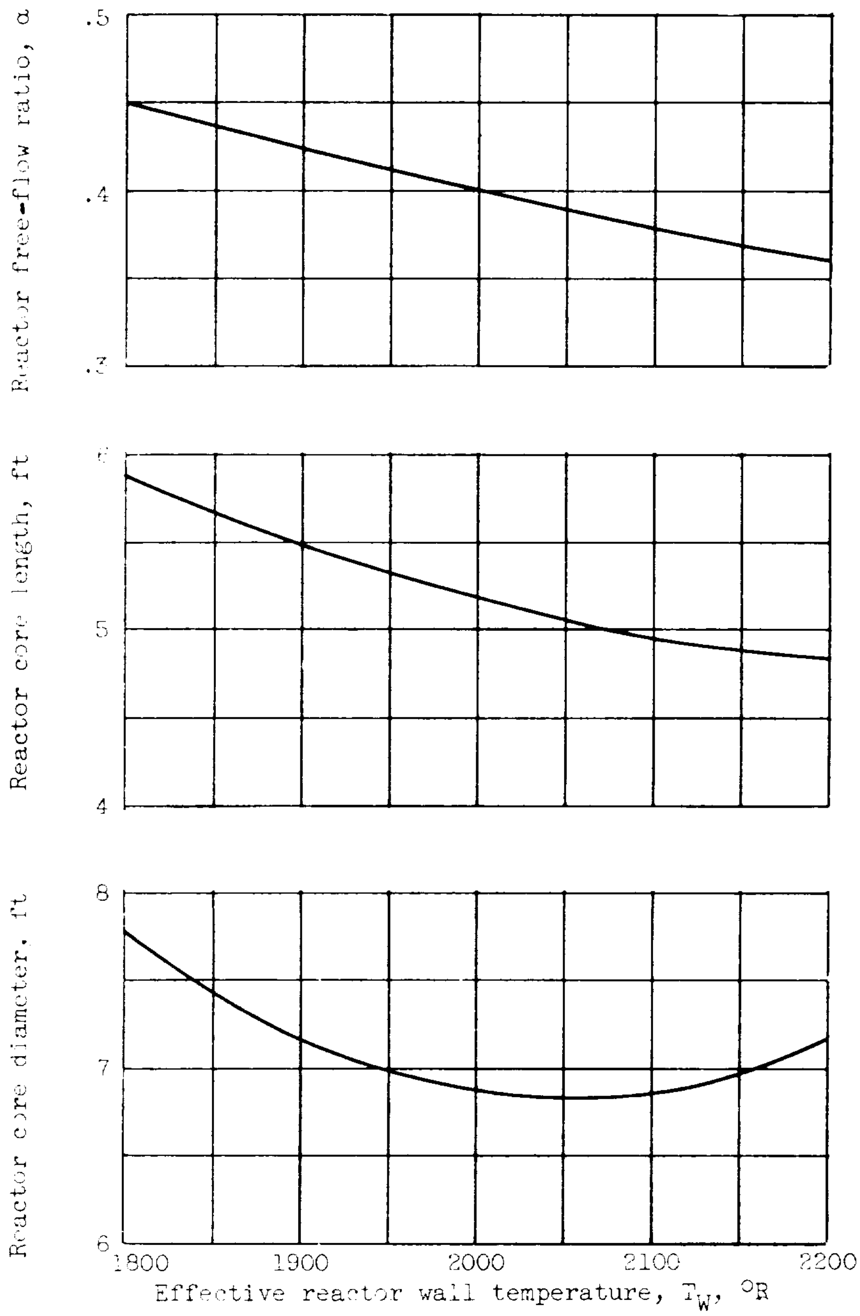

(c) Reactor core diameter, core length, and free-flow ratio.

Figure 4. - Continued. Ram-jet missile operating conditions for minimum uranium investment as a function of effective reactor wall temperature. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

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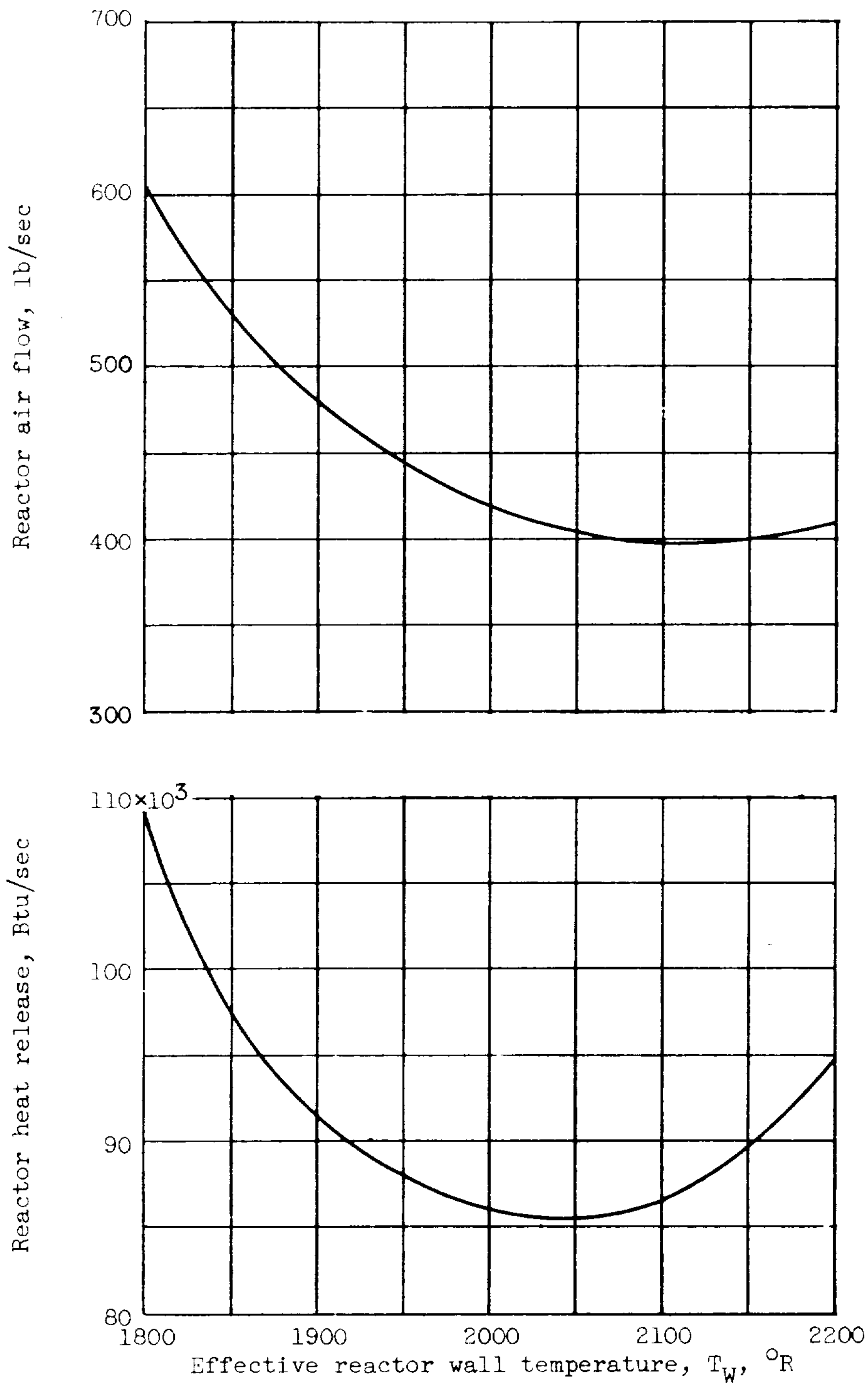

(d) Reactor heat release and air flow.

Figure 4. - Continued. Ram-jet missile operating conditions for minimum uranium investment as a function of effective reactor wall temperature. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

[redacted]

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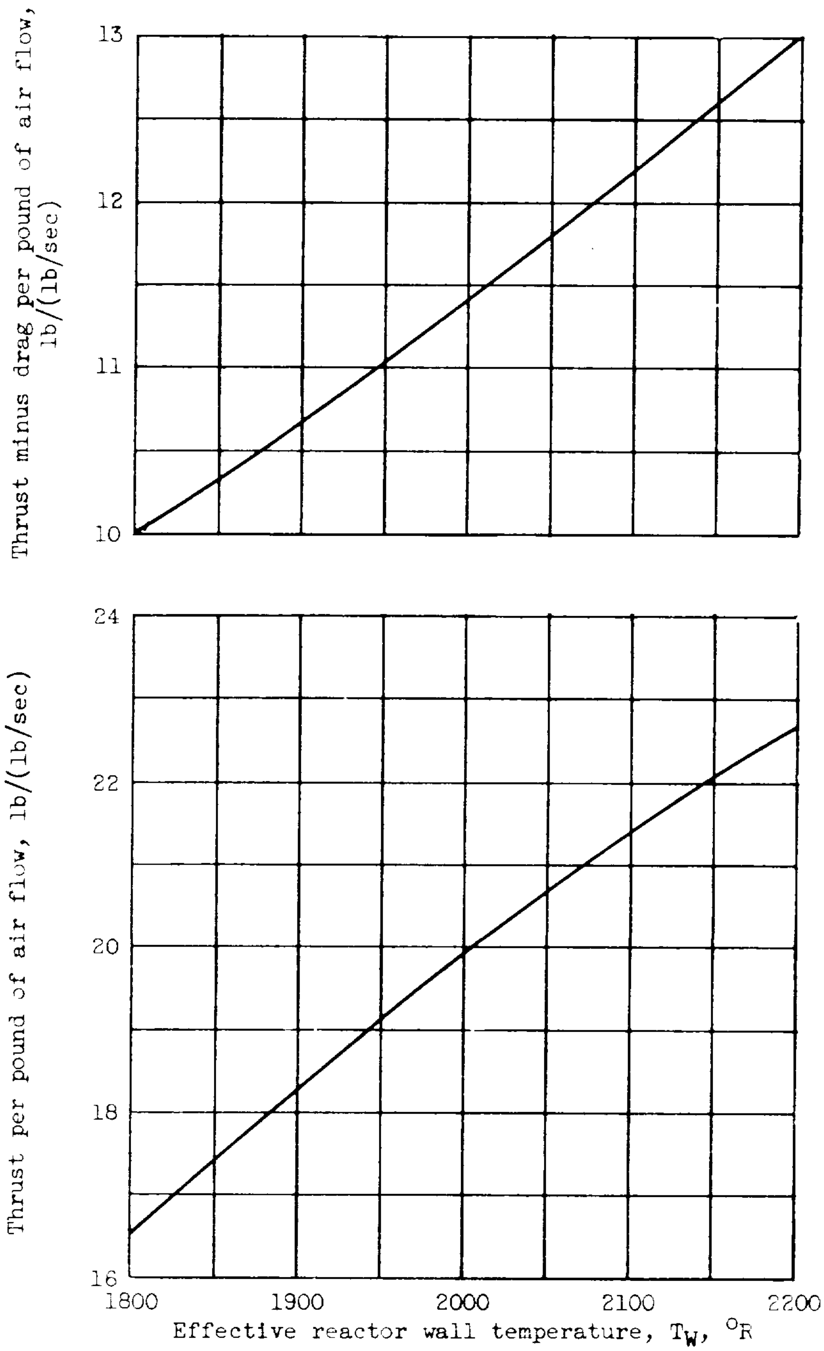

(e) Thrust per pound of air flow and thrust minus drag per pound of air flow.

Figure 4. - Continued. Ram-jet missile operating conditions for minimum uranium investment as a function of effective reactor wall temperature. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

[redacted]

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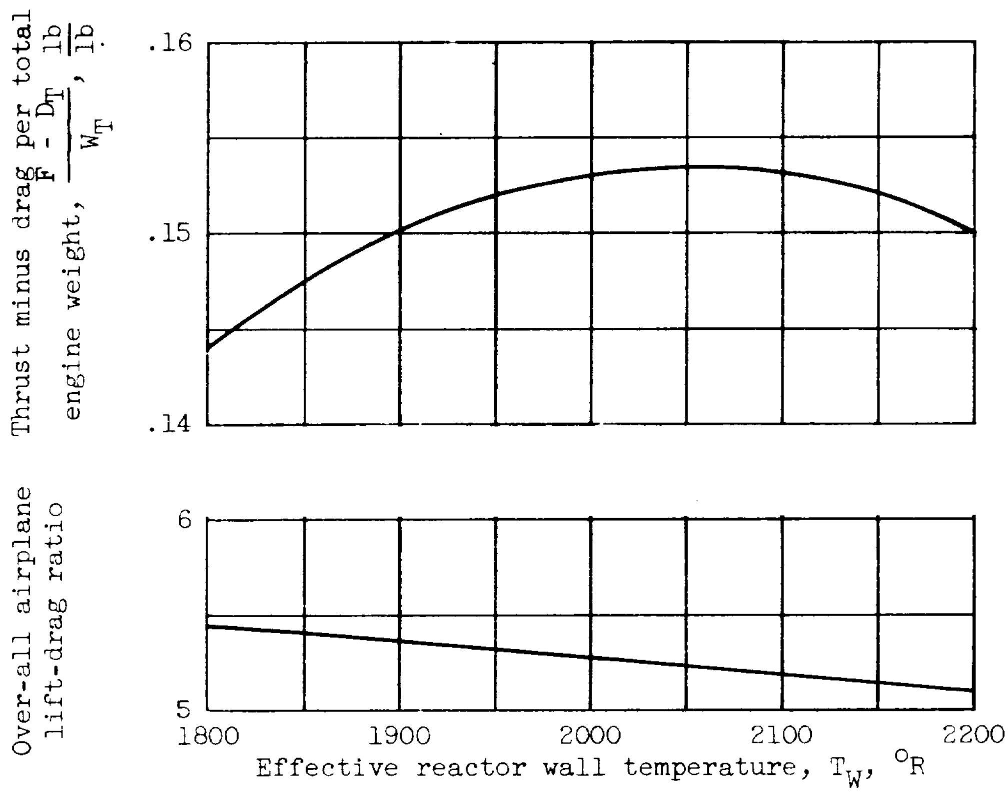

(f) Thrust minus drag per total engine weight and over-all lift-drag ratio.

Figure 4. - Concluded. Ram-jet missile operating conditions for minimum uranium investment as a function of effective reactor wall temperature. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

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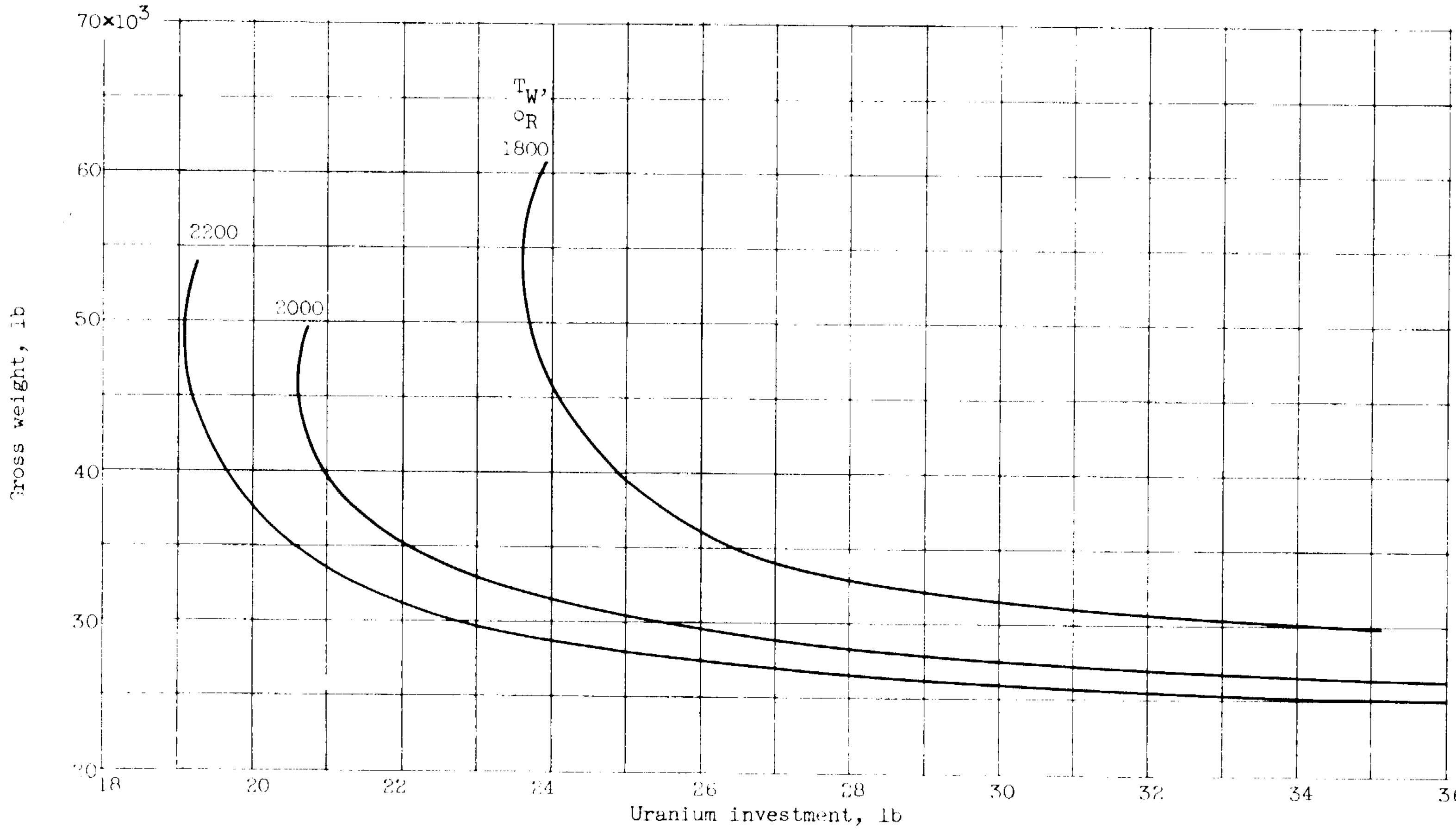

Figure 5. - Minimum missile gross weight as a function of uranium investment and reactor effective wall temperature. No stainless steel in reactor; flight Mach number, 2.5; altitude, 50,000 feet.

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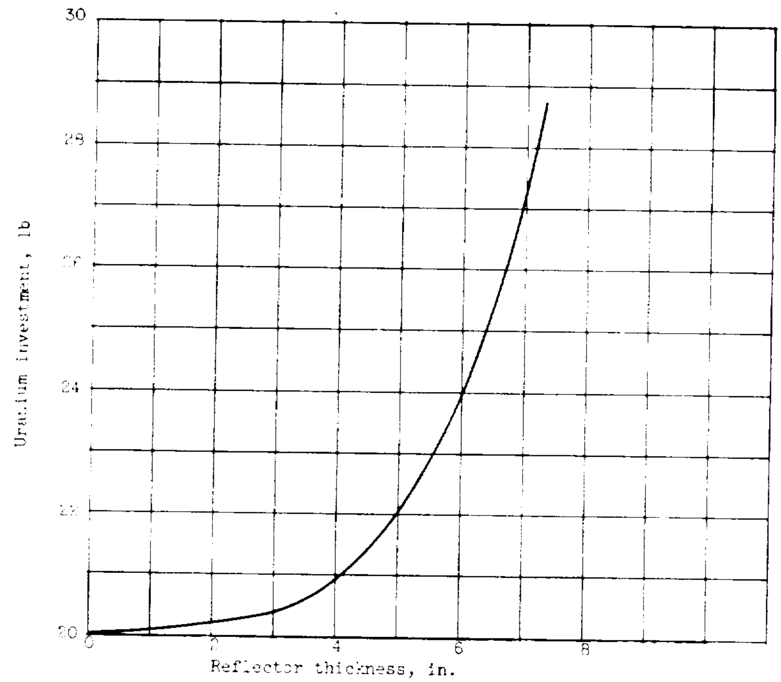

Figure 6. - Effect of side reflectors on uranium investment of beryllium oxide moderated and reflected reactor. Reactor core plus reflector diameter, 7.4 feet; reactor core length, 4.0 feet; end reflector thickness, 3 inches; average reactor temperature, 2200° R; free-flow ratio based on core plus reflector frontal area, 0.35; no stainless steel in core.

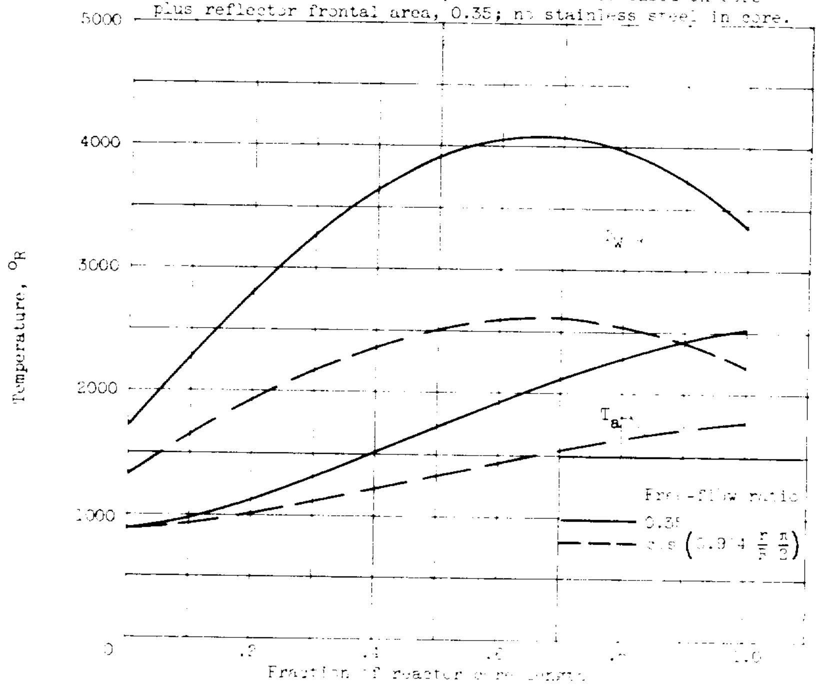

Figure 7. - Reactor center tube wall temperature as a function of reactor core length. Effective reactor wall temperature, 2200° R; free-flow ratio, 0.35; reactor-inlet air Mach number, 0.32; reactor heat release, 100,000 Btu per second; reactor diameter, 7.4 feet; average reactor-outlet temperature, 1650° R.

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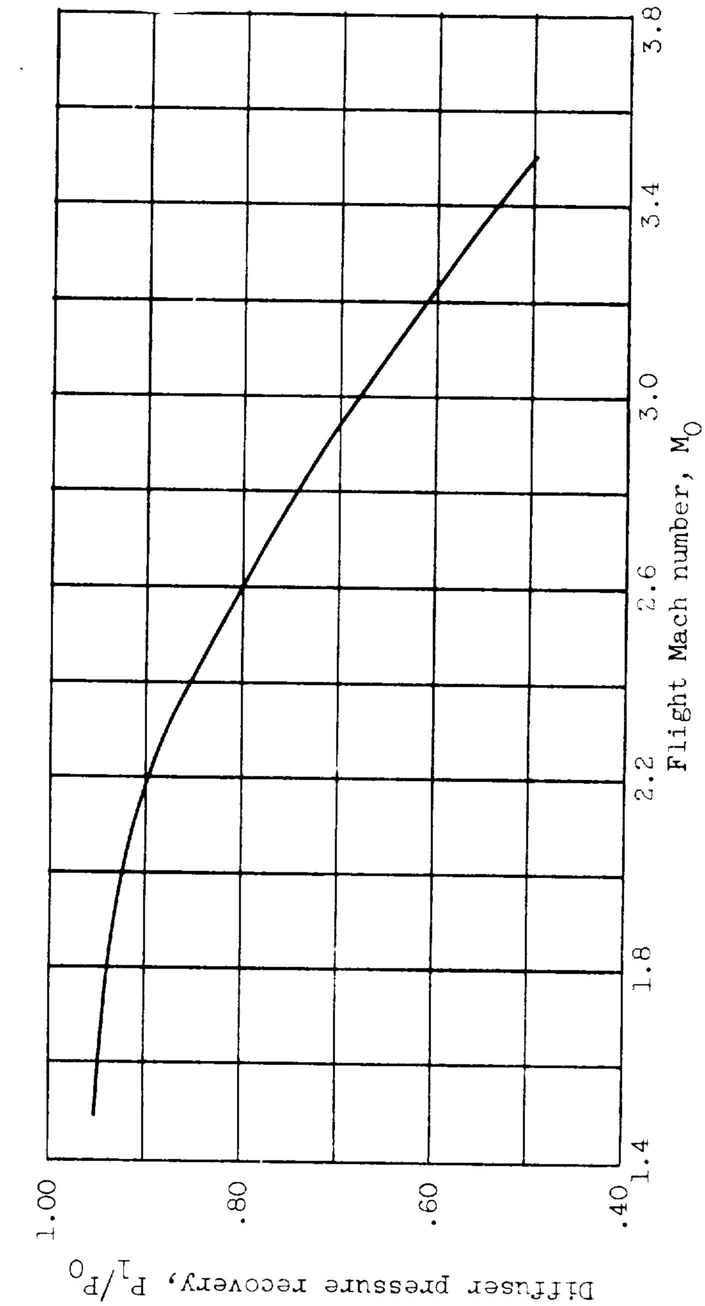

Figure 8. - Diffuser pressure recovery as a function of flight Mach number.

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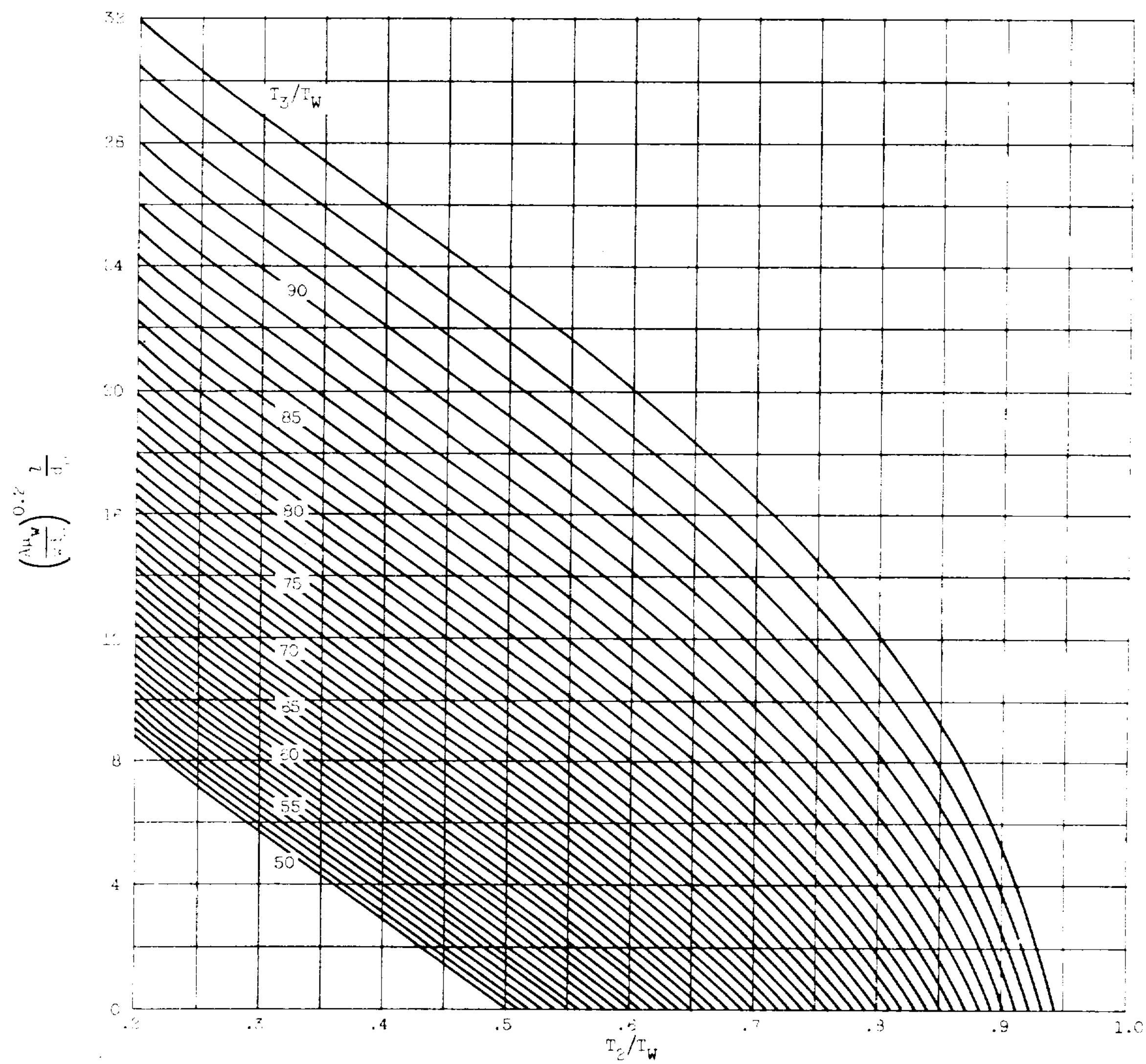

Figure 9. - Curve for computing tube length-to-diameter ratio for all values of reactor-inlet air Mach number. Ratio of specific heats, 1.4.

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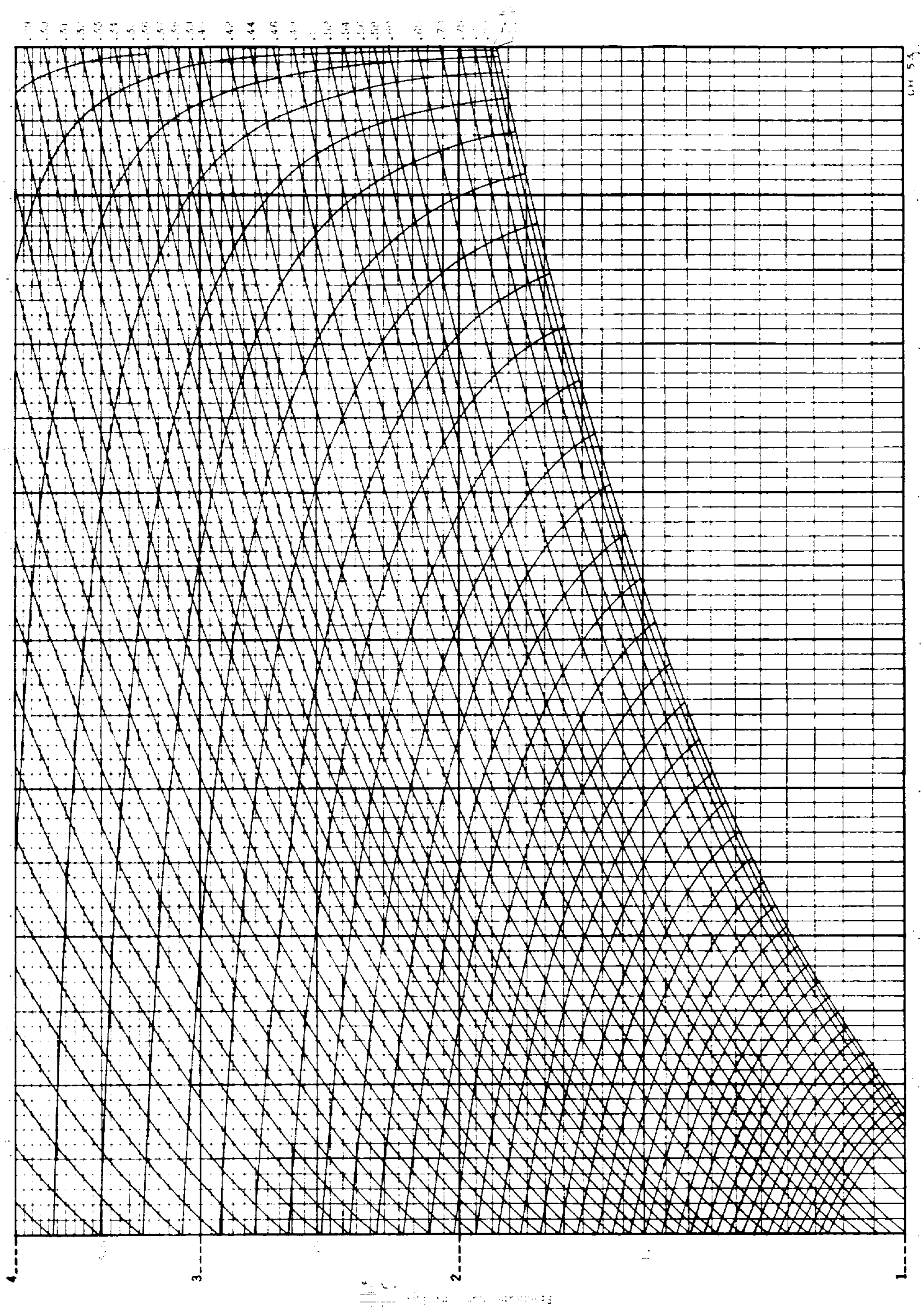

Figure 10. - Curve for computing tube pressure drop. Ratio of specific heats, 1.4.

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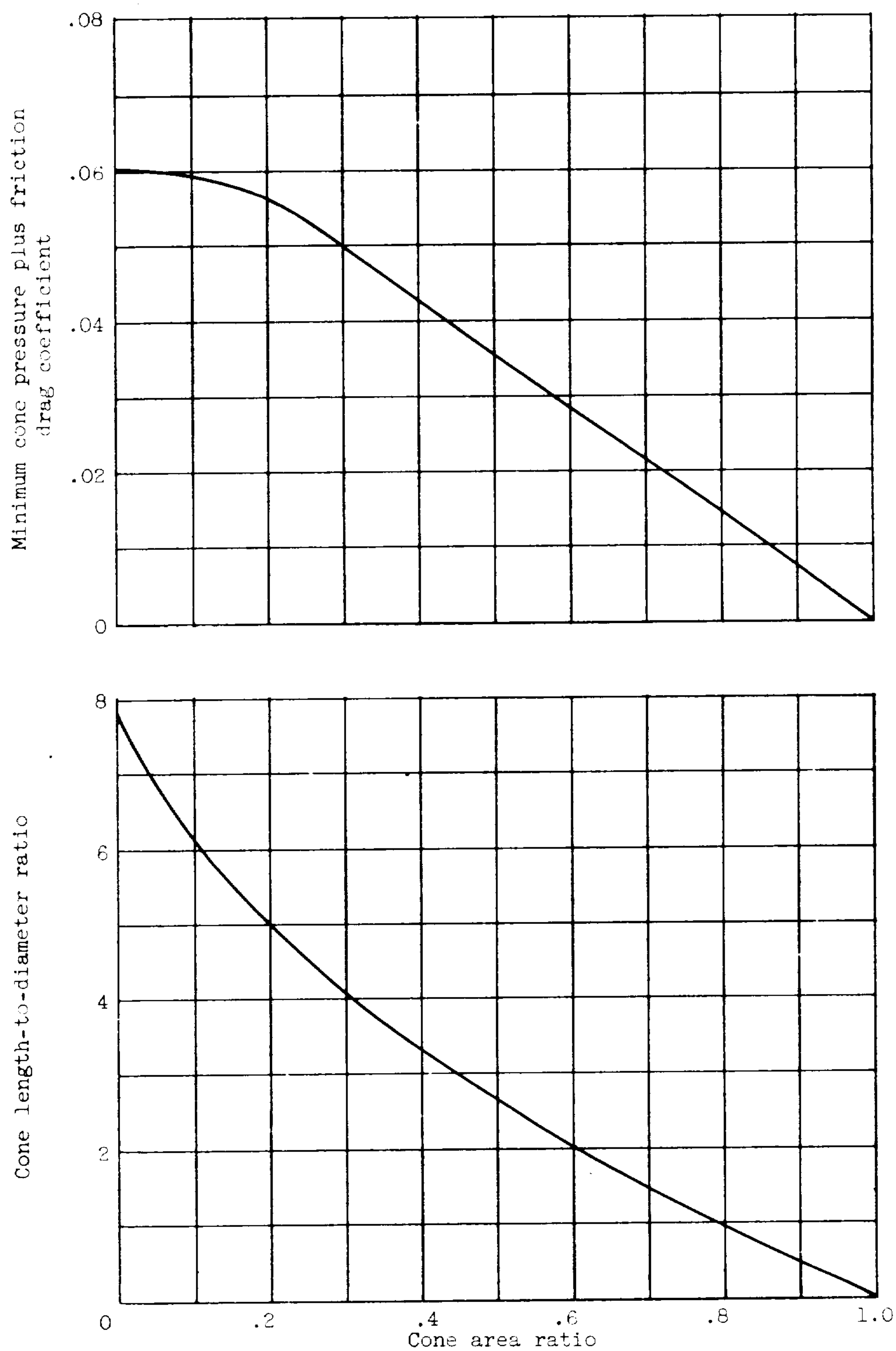

Figure 11. - Minimum cone pressure plus friction drag coefficient and corresponding cone length-to-diameter ratio. Flight Mach number, 2.5.

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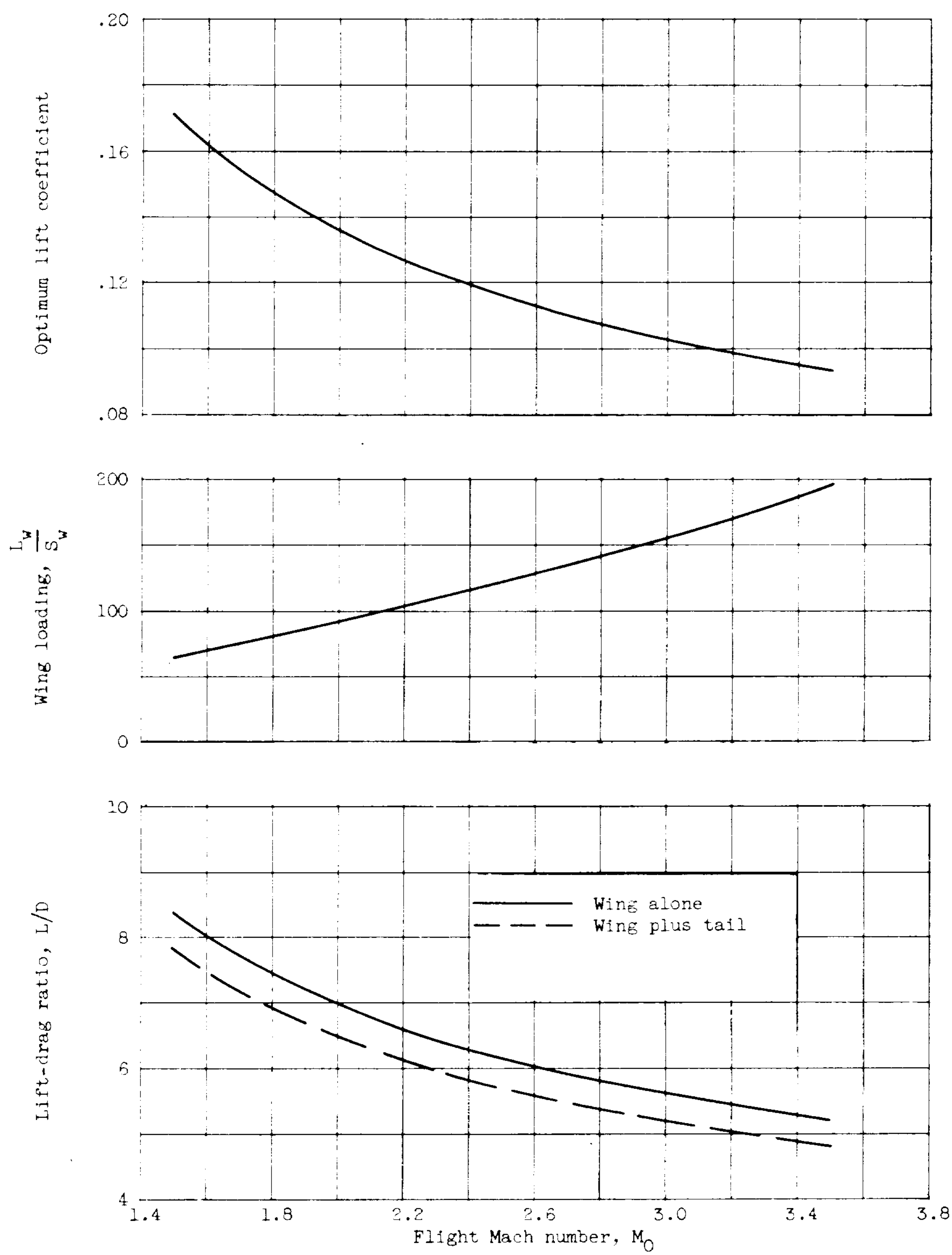

Figure 12. - Optimum lift coefficient, optimum wing loading, and maximum lift-to-drag ratio as a function of flight Mach number for a 60° delta wing with a thickness ratio of 0.03 and mean chord of 12 feet.

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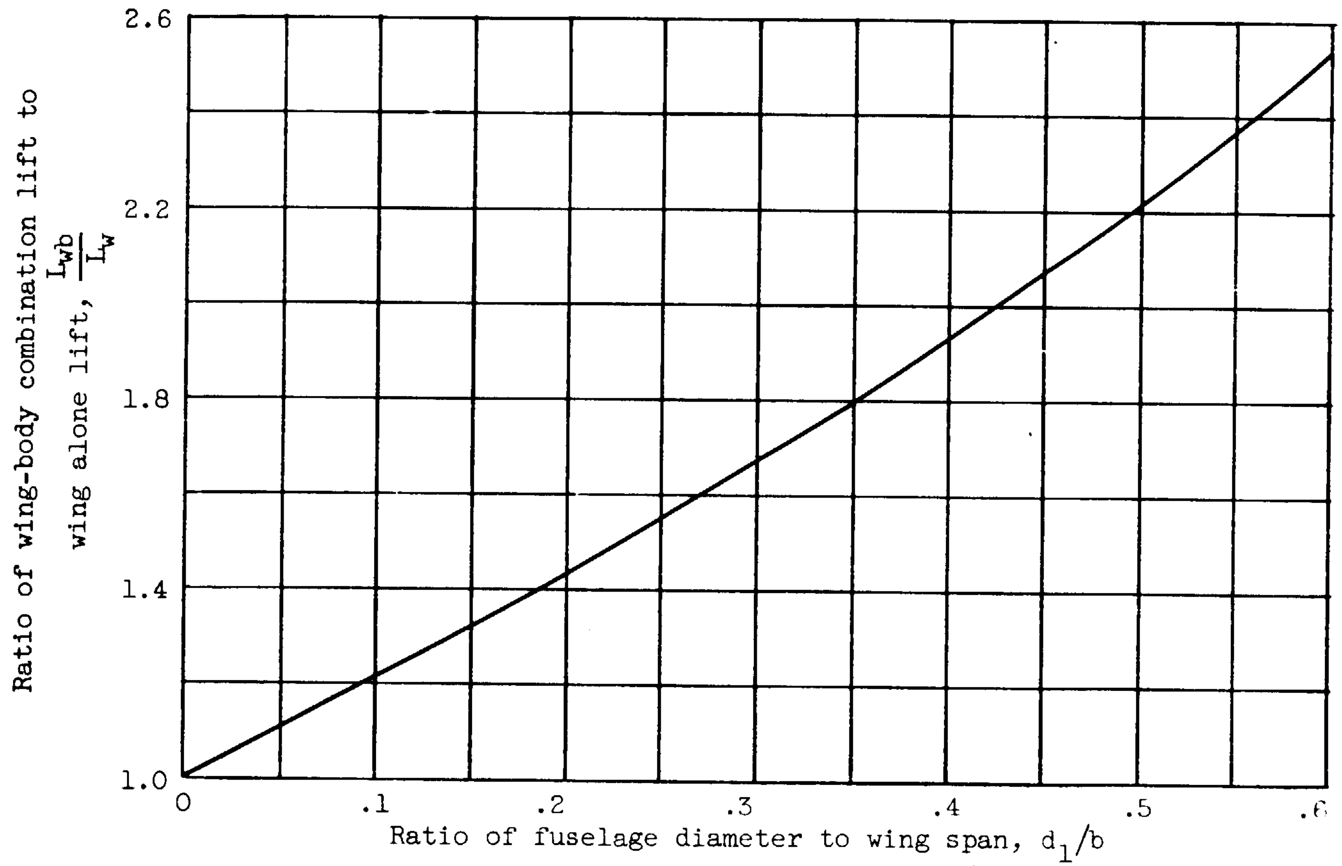

Figure 13. - Ratio of lift of wing-body combination to lift of wing alone as a function of the ratio of fuselage diameter to wing span.

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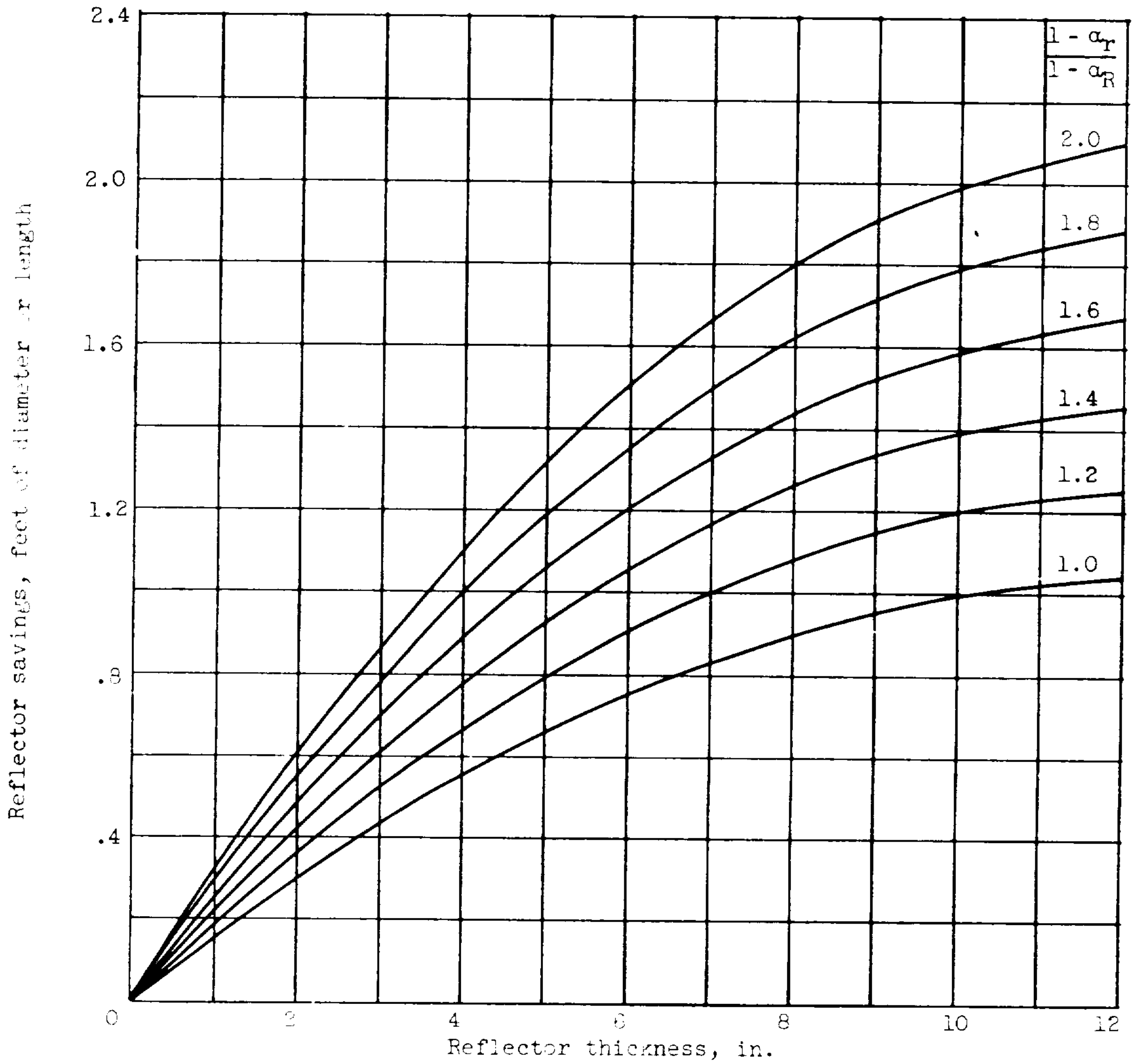

Figure 14. - Reflector savings for a beryllium oxide reflector as a function of reflector thickness, reflector free-flow ratio, and reactor free-flow ratio. Reactor moderator, beryllium oxide.

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Unclassified when detached from rest of report

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