RESEARCH MEMORANDUM

PERFORMANCE ANALYSIS OF APPLICATION OF ROCKET ENGINES TO INTERCEPTOR AIRPLANES

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

Local- and area-defense interceptor missions are considered in this report, ~~which discusses the missions for which the rocket interceptor is suitable and~~ The effect of rocket-engine performance on interceptor performance. Flight missions ~~suitable~~ for interceptors having rocket or turbojet engines are compared, ~~and circumstances under which~~ areas wh a combination of the rocket and the turbojet may be advantageous are presented. ~~The~~ A rocket-powered interceptor with a 3000-pound fixed load and 20,000-pound take-off gross weight was capable of combat at a Mach number of 2.0 at a combat radius of 80 nautical miles. This interceptor takes off vertically, reaches combat speed and altitude in about 1 minute, and has a high-altitude maneuverability, ~~much greater than that anticipated for a threat bomber.~~ The use of the rocket engine as an interceptor power plant, however, appears limited to flight Mach numbers under 2.4 because of the large quantity of fuel consumed in accelerating to speed and in combating at higher flight Mach numbers. Rocket-engine chamber pressures between 300 and 600 pounds per square inch were found to be near optimum with engine thrust-to-weight ratios near 40. why? clarify

Increasing the rocket specific impulse by using ~~the~~ a high-energy propellant combination ammonia-fluorine instead of gasoline-oxygen increased the interceptor combat radius 60 percent at a flight Mach number of 2.0.

Comparison of the rocket interceptor and a ~~typical~~ turbojet interceptor with the same gross weight and fixed load revealed ~~superior~~ greater radius capabilities for the turbojet interceptor, but at a sacrifice in maneuverability. Turbojet combat radius was 360 nautical miles at a Mach number of 2.0 for an interceptor capable of performing a 4-g maneuver at 38,000 feet without loss of speed or altitude. The rocket interceptors investigated were capable of performing a 4-g maneuver at altitudes up to 80,000 feet. ~~considerably above the altitude of 50,000 feet anticipated for the threat bomber.~~ The turbojet interceptor could not be designed for high maneuverability at high altitude without great sacrifices in combat radius.

When high-altitude maneuverability is ~~imperative~~ important for short time periods, supplementing the power of a turbojet interceptor with rocket power was found to be advantageous, compared with increasing the size of the turbojet power plant to achieve the same maneuverability.

INTRODUCTION

Rapid advances in the concepts of air defense and in the performance of aircraft power plants emphasize the need for continual analysis of the applications of various types of propulsion systems to airplanes in order to determine their functions and methods of improving performance. The purpose of this report is to study the application of ~~the~~ a rocket engine to interceptor airplanes. The missions for which the rocket interceptor is suitable when the rocket engine is the only power plant and the effect of rocket-engine performance parameters on interceptor performance are discussed. Flight missions suitable for interceptors having rocket engines are compared with missions suitable for interceptors having turbojet engines, and circumstances are presented in which a combination of rocket and turbojet power plants may be advantageous.

The variation of combat radius is shown for changes of aircraft gross weight from 10,000 to 30,000 pounds, for Mach numbers from 1.5 to 3.0, and for a range of required combat maneuverabilities. The effect on interceptor radius is also shown for changes in the following rocket-engine parameters: chamber pressure, 300 to 1200 pounds per square inch; engine thrust-to-weight ratio, 20 to 80; and engine specific impulse, 260 to 350 seconds.

BASIS FOR ANALYSIS

~~A number of~~ Several interceptor designs ~~was~~ were considered in order to study (1) the type of flight mission appropriate to various types of power plant and (2) the effect of engine type and characteristics on interceptor design and performance. Each airplane was assumed to carry 1000 pounds of armament, which is expended in combat, and 2000 pounds of other fixed equipment including the pilot and radar guidance equipment. A discussion of the methods and assumptions used in the airplane performance analysis is presented in appendix A.

The flight plan used to study the rocket interceptor is shown in figure 1. The rocket interceptor takes off vertically with a total acceleration of 2 g's (1 g of acceleration is available for changing velocity at take-off). At a flight Mach number of 0.3, the interceptor "pushes over" to a 45° climb angle and continues to accelerate and climb to cruise conditions. The use of 2 g's total acceleration results in 1 minute to reach combat speed and altitude. The interceptor cruises out to combat at Mach number 2.0, does a 220° combat maneuver, glides back to base and lands on skids with no fuel reserve. Some powered supersonic cruise flight back to the base is used when the glide distance is insufficient for the return to base after combat. In all cases, the interceptor fuel supply is exhausted before the glide begins. The wing loading at landing is about 25 pounds per square foot. A wide range in values of thrust is required for this mission, from 40,000 pounds at take-off to about 2000 pounds for cruise. This wide thrust requirement may be met by using multiple engines, variable-thrust engines, or a combination of these.

The over-all flight plan of the turbojet interceptor is illustrated in figure 2(a). As an example, the turbojet interceptor, which is used as a reference point, takes off in less than 5000 feet of runway, accelerates and climbs to a Mach number of 2.0 and an altitude of 55,000 feet, cruises out to combat at a Mach number of 2.0, does a 220° combat turn, cruises back to base at a Mach number of 2.0, holds for 15 minutes at subsonic speed at 5000 feet altitude and lands with a 5-percent fuel reserve. Afterburning to the assumed limiting temperature of 3500° R is used during acceleration and climb and during combat.

The type of combat assumed is illustrated in greater detail in figure 2(b). For example, as the reference turbojet interceptor approaches the bomber, it decreases its altitude from that for good cruise conditions (about 55,000 ft) to an altitude near 35,000 feet, where it has an appreciable maneuverability margin over the bomber. The interceptor maneuvers at low altitude until it is in a position to press home the attack by climbing to the bomber altitude.

In appendix B, several interceptor missions are discussed without reference to a particular engine design, in order to determine the combat radii and maneuverability requirements associated with these missions. The study of the local- or point-defense problem with a 260-nautical-mile radar warning range for a Mach 2.0 interceptor combating a Mach 1.5 threat bomber approaching the target at an altitude of 50,000 feet revealed that a combat radius of 90 nautical miles was desirable and that 30 nautical miles was the minimum useful radius of action. Consideration of several possible combat maneuvers showed that a maneuverability of 3 or 4 g's is desirable. For the problem of area defense, a greater combat radius is required, and a radius of 375 nautical miles is generally considered acceptable. These values should aid the reader in evaluating the results obtained herein.

In most of the discussion, the point-of-departure technique is used; that is, one airplane design is chosen as a point of reference and variations from this point are studied. This reference point appears as a circle in the pertinent figures. Where a specific figure of merit is required to study the effect of engine parameters, the radius of operation for a fixed mission and for a fixed gross weight is used.

RESULTS AND DISCUSSION

Rocket-Interceptor Performance

The combat radius that can be expected from a Mach 2.0 rocket interceptor is plotted in figure 3 against the take-off gross weight for both one- and two-stage interceptors using gasoline-oxygen as a propellant. For a one-stage rocket interceptor at a gross weight of 20,000 pounds (ref. rocket interceptor), a combat radius of 80 nautical miles can be attained, which is near the value of 90 nautical miles shown in appendix B to be desirable for a local-defense mission. The combat radius of the one-stage rocket interceptor does not increase rapidly with increasing gross weight; increasing the take-off gross weight from 20,000 to 30,000 pounds increases the radius from 80 to 115 nautical miles. The upper curve of figure 3 is for an interceptor with two stages of rocket propulsion, the propellant tanks and motors required to boost the interceptor to speed (but not to cruise altitude) being dropped at the end of their usefulness. This staging increased the radius from 80 to 110 nautical miles for a gross weight of 20,000 pounds. In neither case does the radius of the rocket interceptor approach the 375 nautical miles considered desirable for the area-defense mission.

Also of interest is the Mach number range in which the rocket interceptor may be expected to fly. Figure 4 presents combat radius as a function of flight Mach number for a single-stage, 20,000-pound-gross-weight interceptor. Mach 2.0 appears to be a good Mach number at which to cruise out and combat. At Mach numbers higher than 2.0, the fuel required to accelerate to speed and turn through the assumed 220° combat maneuver becomes excessive, and the radius of operation is decreased. At Mach number 2.4, the entire fuel capacity of the interceptor is used in reaching combat speed and altitude and in performing the combat maneuver; as a result, the combat radius is reduced to the distance traversed during acceleration and climb, which is about 10 miles. At Mach numbers less than 2.0, the cruise efficiency is reduced and the gliding distance is less. Although less fuel is consumed in combat, the net result is a slight decrease in radius. The one-stage rocket interceptor, therefore, appears practical only at Mach numbers less than about 2.4 for the type of mission considered.

An alternate flight plan was considered in which only one head-on pass is required and the interceptor does not return to base. Figure 5 illustrates the standard and alternate flight plans. Also shown in the figure is a so-called ferry distance for the rocket interceptor, defined as the combat distance plus the glide distance. The combat distance attainable with the alternate flight plan and the ferry distance are presented in figure 6, along with the combat radius that was shown in figure 4 for comparison. The combat distance attainable with the alternate flight plan, up to 180 nautical miles at a Mach number of 2.0, is considerably greater than that attainable with the standard flight plan, but still less than the 375-nautical-mile radius desirable for an area-defense mission. Therefore, no further consideration was given to the alternate flight plan.

The maneuverabilities of the rocket interceptor and a turbojet bomber are summarized in figure 7, which presents the maximum altitude at which a specified maneuverability can be attained. Based on calculations not presented in this report, the maximum level-flight altitude of the Mach 1.5 bomber as it approaches its target is expected to be about 50,000 feet. The maneuverability limits shown for the bomber result because the engine size and the airplane structure are designed for long range rather than for high maneuverability.

In contrast to the turbojet engine, the thrust of the rocket is not appreciably affected by altitude. Also, the ratio of engine thrust to airplane weight is necessarily large for the rocket interceptor to maintain minimum fuel consumption during the acceleration and climb phase of the flight, which consumes about 75 percent of the total fuel weight. Therefore, the altitude maneuver limit of the rocket interceptor is determined, not by the engine thrust, but by the maximum desirable lift coefficient on the wing. This limit is illustrated in figure 7 for a maximum lift coefficient of 0.8 at Mach numbers of 2.0 and 1.5. The maximum allowable maneuverability will be limited by the pilot tolerance to normal acceleration, which is shown in figure 7 as 4 g's. (The interceptor design structural limit was 5.3 g's). Thus, the rocket interceptor has large maneuver margins over the threat bomber at all altitudes.

Effect of Rocket-Engine Parameters

Several variables in the rocket engine that affect interceptor performance are considered in figure 8. Combat radius as a function of rocket chamber pressure for several values of the engine thrust-to-weight ratio T_e/W_e is given in figure 8(a). Increasing the rocket chamber pressure increases the specific impulse, which, at constant engine weight, increases the combat radius. Although the thrust-to-weight ratio is very favorable for the rocket engine compared with other types of power plants, engine weight is still important because of the large engines needed to produce the thrust equal to twice the interceptor weight that is required for vertical take-off and efficient acceleration.

For the rocket application under discussion, large gains in combat radius accrue by increasing the engine thrust-to-weight ratio from 20 to 40, and smaller gains result by further increasing the thrust-to-weight ratio to 80. In view of the fact that an engine thrust-to-weight ratio on the order of 80 may be very difficult to achieve, a value of 40 is used throughout most of this report. The variation of combat radius with chamber pressure for the schedule of weights given by equation (1) in appendix A is represented by the dashed line in figure 8(a). The variation of combat radius with chamber pressure for either a constant engine thrust-to-weight ratio or for the schedule of engine weights indicates that the rocket chamber pressure is not a critical variable when relatively high engine thrust-to-weight ratios exist. Chamber pressures on the order of 300 to 600 pounds per square inch appear desirable for engine thrust-to-weight ratios near 40.

The effect on the combat radius of improved specific impulse through better fuel-oxidant combinations is illustrated in figure 8(b). As an example, the radius of operation is increased from 80 nautical miles for gasoline-oxygen propellants to 130 nautical miles for ammonia-fluorine propellants, or over 60 percent, for an engine thrust-to-weight ratio of 40.

Comparison of Rocket and Turbojet Interceptors

Current interceptor development is largely devoted to turbojet-powered aircraft; it is, therefore, of interest to compare the capabilities of the rocket interceptor with those of a turbojet interceptor. Figure 9 shows turbojet-interceptor combat radius as a function of maneuverability at 50,000 feet altitude (estimated bomber altitude) for a series of turbojet-interceptor designs. The rocket interceptor is shown, for comparison, by a point at 4 g's, the assumed pilot limit.

For the turbojet interceptor, maneuverability is essentially a measure of the engine size designed into the interceptor. For instance, a maneuverability of 4 g's at 50,000 feet requires approximately twice as large an engine in the interceptor as a maneuverability of 2 g's at 50,000 feet. With increasing g's (increasing engine size), the engine size and weight displace increasing quantities of fuel in the airplane; at the same time, however, the acceleration, climb, and cruise portions of the flight become more efficient. The cruise portion of the flight is more efficient for the larger engine sizes because of the better specific impulses associated with the lower cruise afterburner temperatures. As a result of these factors, range maximizes as a function of maneuverability, as shown in the figure.

The design point selected for the reference turbojet is circled. In an effort to meet the area-defense combat-radius requirement with a minimum-gross-weight airplane, only a slight sacrifice in range was accepted to improve maneuverability. Furthermore, the engine size in the reference turbojet interceptor gives a time for acceleration to speed and for climb to cruise altitude of about 5 minutes, which is considered reasonable. The take-off distance was also less than 5000 feet.

Take-off distance and time to climb become shorter to the right of the design point and longer to the left. A scale of time to accelerate and climb to combat speed and altitude is also shown in the figure. As previously mentioned, the rocket interceptor reached Mach number 2.0 and 50,000 feet altitude in 1 minute. The reference rocket interceptor was also capable of 4 g's maneuverability at the bomber altitude of 50,000 feet. Based on the present assumptions, this capability of the rocket interceptor could not be equalled by the turbojet-powered interceptor. The rocket interceptor was capable of vertical take-off. Placing this requirement on the turbojet interceptor results in a radius of operation of about 120 miles. Figure 10 shows how the maneuverability of the reference turbojet interceptor varies with altitude and compares the maneuverability of the reference rocket and turbojet interceptors. The upper curve, for the rocket interceptor, is repeated from figure 7, as is the curve for the turbojet bomber. The two center curves are for the reference turbojet interceptor. Because the thrust output of the turbojet increases as the altitude decreases, the maneuverability also increases. The reference turbojet interceptor, which has a 2.2-g maneuverability at 50,000 feet, has a 4-g maneuverability at 38,000 feet altitude at a Mach number of 2.0. The type of flight plan, and in particular the combat maneuver, illustrated in figure 2 for the turbojet was therefore chosen as being most compatible with both the combat radius and maneuverability desired in an interceptor.

Figure 11(a) compares the effect of design take-off gross weight on combat radius for turbojet and rocket interceptors. In contrast with the rocket interceptor, as previously discussed, the range of the turbojet increases rapidly with increasing gross weight. Also, the magnitude of the combat radius of the turbojet interceptor is greater than that of the rocket interceptor. At 20,000 pounds gross weight, for example, the combat radius for the turbojet is about 360 miles, compared with 80 miles for the rocket interceptor. Thus, it may be concluded that the turbojet-powered interceptor is capable of long-range missions in contrast to the short-range capabilities of the rocket interceptor; on the other hand, however, the turbojet interceptor does not achieve as large a maneuverability at high altitude as does the rocket interceptor.

The Mach number potentialities of the rocket and turbojet interceptors are compared in figure 11(b). The greater efficiency of the turbojet engine gives the turbojet interceptor a greater Mach number potentiality than the rocket. For the rocket interceptor, it was previously pointed out that at a flight Mach number of about 2.4 the entire fuel capacity was used in acceleration to speed and altitude and in accomplishing the 220° combat turn. The radius of the interceptor was correspondingly reduced to about 10 miles. Even for the turbojet with its high specific impulse, the radius decreases with Mach numbers above 2.0 because of the increasing structural weight, engine weight, and fuel weight required to get to speed and to maneuver. At Mach number of 3.0, the combat radius is about 200 miles compared with 360 at a Mach number of 2.0. This result is, of course, somewhat dependent on the state of development assumed for the turbojet. The turbojet engine assumed in this analysis operates in the conventional mode of constant mechanical speed but has a higher thrust-to-weight ratio than exists for current production turbojets, as indicated in appendix B.

The combat radii of several rocket-turbojet combinations of 20,000-pound take-off gross weight at a flight Mach number of 2.0 are shown in figure 12. The bars labeled A and B are the reference turbojet and rocket interceptors, respectively. For Bar C, which represents the reference turbojet with sufficient rocket engine and fuel added to achieve zero length or vertical take-off, the weight of the rocket engine and fuel is assumed to replace an equal weight of turbojet fuel. The resulting reduction in combat radius is 50 nautical miles. 3094

Bar D represents the result when sufficient rocket motor and fuel are added to the reference turbojet interceptor (which has a 2.2-g maneuverability at 50,000 ft) to give it a 4-g maneuverability at 50,000 feet for 220° of turning. The combat radius is reduced to 200 nautical miles, a decrease of 45 percent. The reduction in combat radius would, of course, be less if the rocket power were required for fewer degrees of turning or if smaller increase in maneuverability were required. For comparison, the attainment of 4-g maneuverability at 50,000 feet by means of increasing the turbojet-engine size resulted in an airplane having insufficient fuel to reach combat speed and altitude.

Bar E represents the reference rocket interceptor with sufficient turbojet power added to achieve subsonic cruise. In a combat mission, the rocket flight plan is used and the turbojet is operated at full power for the entire flight (exclusive of the glide). In this case, the small improvement in the specific impulse of the combined propulsion system very nearly compensates for the additional weight of the turbojet engine, so that little change in combat radius results. The primary advantage of adding the turbojet engine is the ability it gives the interceptor to hold or to cruise at subsonic speeds.

The maneuverability of the combination reference turbojet plus rocket (bar D) is compared with the rocket and turbojet alone in figure 13. The curves illustrate the increased maneuverability that results at all altitudes from the addition of sufficient rocket engine and fuel to produce a 4-g maneuverability for 220° of turning at 50,000 feet altitude. At altitudes above 50,000 feet, however, the given quantity of rocket fuel available for turning is consumed in fewer than 220° because of the lower turning rate associated with a lower maneuverability.

SUMMARY OF RESULTS

Under the assumptions of the present study, a rocket-powered interceptor with a 3000-pound fixed load and a take-off gross weight of 20,000 pounds, flying at a Mach number of 2.0 and performing a combat turn of 220°, has a combat radius of about 80 nautical miles. This interceptor takes off vertically and reaches combat speed and altitude in about 1 minute. The high-altitude maneuverability is limited by the maximum permissible wing lift coefficient and pilot tolerance to normal acceleration, rather than by the engine. Above a Mach number of 2.0, the combat radius of the rocket interceptor decreases, approaching 10 miles at about a Mach number of 2.4, because of the large quantities of fuel consumed in accelerating to speed and in combat. Rocket-engine chamber pressures between 300 and 600 pounds per square inch were near optimum for engine thrust-to-weight ratios near 40.

3094

The several methods studied to improve the rocket-interceptor combat radius showed that increasing the take-off gross weight from 20,000 to 30,000 pounds increased the radius from 80 to 115 nautical miles. Staging the interceptor resulted in about the same increase in combat radius (30 nautical miles) for the same gross weight. Changing the propellant combination from gasoline-oxygen to ammonia-fluorine increased the combat radius 50 nautical miles, or over 60 percent.

CX-2

In comparison with the rocket interceptor, a typical turbojet interceptor with a 3000-pound fixed load and a take-off gross weight of 20,000 pounds, flying at Mach number of 2.0, has a combat radius of about 360 nautical miles. The turbojet interceptor takes off in less than 5000 feet and reaches combat speed and altitude in about 5 minutes. The maneuverability (g's without loss of speed or altitude) of this turbojet interceptor is engine-limited and is 2.2 g's at 50,000 feet altitude and 4 g's at 38,000 feet. Relatively large combat radii can be achieved up to a Mach number of 3.0 with the turbojet.

Supplementing the power of a turbojet interceptor, which is capable of a 2.2-g maneuverability at 50,000 feet altitude at a Mach number of 2.0, with rocket power to give it a 4-g maneuverability at the same altitude for a combat turning of 220° reduces the interceptor combat radius about 45 percent to 200 nautical miles. Achieving a 4-g maneuverability at 50,000 feet altitude by increasing turbojet-engine size resulted in an airplane having insufficient fuel to reach combat speed and altitude.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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APPENDIX A

METHODS AND ASSUMPTIONS

This appendix presents the major assumptions and the primary equations used in estimating airplane performance. Examples of significant airplane and performance parameters are also given for the reference turbojet and rocket interceptors.

Symbols 3094

The following symbols are used in this report:

a	speed of sound, ft/sec
C_D	drag coefficient, D/qS
$C_{D,i}/C_L^2$	induced drag coefficient
C_L	lift coefficient, L/qS_w
C_T	thrust coefficient, T/qS_e
D	airplane drag, lb
d_2	distance traversed by bomber between first and second pass by interceptor when first pass is head-on
g	maneuverability; normal load factor that can be sustained by aiprlane without loss of speed or altitude (1 g represents level flight)
gr	acceleration due to gravity, 32.2 ft/sec^2
h	altitude, ft
I	specific impulse based on engine thrust minus engine drag, sec
L	airplane lift, lb
L/D	airplane lift-drag ratio (drag does not include engine drag)
M	Mach number
P_{ch}	rocket chamber pressure, lb/sq in.
p	ambient pressure, lb/sq ft
q	$\frac{\gamma}{2} pM^2$

R	range, nautical miles
S	area, sq ft
T	thrust of engine minus inlet and nacelle drag, lb
T_e/W_e	thrust-to-weight ratio for rocket engine at sea level
t	time, min
W	weight, lb
W_e	weight of engine, including inlet nacelle and exhaust nozzle, lb
W_G	gross weight, lb
γ	ratio of specific heats
θ	flight-path climb angle measured from horizontal, deg
Ω	combat turning angle, deg

Subscripts:

a	available for flight
ar	armament
b	acceleration and climb
c	canopy or canopy cross section
co	combat
cr	cruise
e	engine
ex	exposed
F	fuselage or fuselage cross section
f	fuel
G	gross
g	glide

h	altitude
ho	hold
hor	horizontal
i	induced
in	initial
M	Mach number
r	reserve
ref	reference
t	tail or tail plan form
tot	total
ver	vertical
w	wing or wing plan form
0	at zero lift

Airplane Characteristics

Turbojet-engine characteristics. - The advanced engine used in this report is compared with a typical current production engine at NACA standard sea-level static conditions in the following table:

	Advanced engine used herein	Current production engine
Compressor pressure ratio	5	10
Air flow, lb/(sec)(sq ft compressor frontal area)	27	22
Turbine-inlet temperature, $^{\circ}R$	2000	1940
Engine wt., lb/sq ft compressor frontal area	578	600
Thrust with no afterburning/sq ft compressor frontal area	1600	1350

Further characteristics of the turbojet engine used in this report are:

Maximum afterburner temperature, $^{\circ}$R 3500
Ratio of max. engine nacelle cross-sectional area
to compressor frontal area 1.8
Engine wt. plus inlet and afterburner wt./
sq ft compresssor frontal area 750

3094 The inlet assumed was a single-cone translating-spike type. Critical flow was maintained at the inlet. A 5-percent total-pressure loss was assumed in the subsonic diffuser. The exhaust nozzle was assumed to be completely expanding and continuously variable. The engine mode of operation was constant mechanical rotational speed. At Mach number of 2.0, altitude of 35,000 feet, and afterburner temperature of 3500° R, $C_T M^2 = 4.44$ and $I = 1553$ seconds. At sea-level static conditions and 3500° R afterburner temperature, $C_T M^2 = 0.77$, $I = 1360$ seconds, and $(W_e/W_G)_{ref} = 0.233$.

Rocket-engine characteristics. - The exhaust nozzle of the rocket engine was assumed to be completely expanding and continuously variable. For gasoline-oxygen propellants and a chamber pressure of 400 pounds per square inch, at an altitude h of 70,000 feet, $I = 318$ seconds. At $h = 0$, $I = 260$ seconds and $(W_e/W_G)_{ref} = 0.067$.

In the text of the report, in order to study the effect of rocket chamber pressure, the rocket-engine weight-to-thrust ratio was assumed to vary in the following manner from the reference value of W_e/T_e of 1/40:

$$\frac{W_e}{T_e} = \frac{1}{80} + \frac{1}{80}\frac{P_{ch}}{400} \qquad (1)$$

Airframe characteristics. - The airframe characteristics for turbojet and rocket interceptors are as follows:

	Turbojet	Rocket
Pay load:		
Wt. of armament in form of guided missiles, lb	1000	1000
Wt. of electronic guidance equipment, lb	1000	1000
Wt. of pilot and other fixed equipment, lb	1000	1000
Wing:		
$W_{G,in}/S_W$, lb/sq ft	100	50
Thickness-chord ratio	0.04	0.04
Aspect ratio	3.0	3.0
Tip-root chord ratio	0.5	0.5
Angle of sweep at midchord	0	0
$(W_W/W_{G,in})_{ref}$	0.082	0.094
Tail (similar to wing):		
$(S_t/S_W)_{hor}$	0.1	0.1
$(S_t/S_W)_{ver}$	0.15	0.15
$(W_t/W_{G,in})_{ref}$	0.011	0.014
Fuselage:		
$(S_F/S_W)_{ref}$	0.10	0.055
Length-diameter ratio	10	10
Fuselage denisty, lb/cu ft	25	27
Canopy area, S_c, sq ft	2	2
$C_{D,0,c}/C_{D,0,F}$	2.5	2.5
$(W_F/W_{G,in})_{ref}$	0.045	0.026
Miscellaneous:		
Fuel-tank wt./fuel wt.	0.10	0.05 (integral tanks)
Wt. hydraulic and electrical equipment$/W_{G,in}$	0.04	0.04
Landing-gear wt.$/W_{G,in}$	0.04 (wheels)	0.006 (skids)
Over-all:		
$(W_f/W_{G,in})_{ref}$	0.36	0.59

3094

Performance Calculations

Lift and drag. - The lift and drag of the airplane were calculated by an appropriate summation of the lifts and drags of the component parts:

$$C_L = \frac{W_{G,in}\left(1 - \frac{W_f}{W_{G,in}}\right)g}{qS_w} \tag{2}$$

$$C_{D,O} = C_{D,O,w}\frac{S_{w,ex}}{S_w}\left(1 + \frac{S_{t,ex}}{S_{w,ex}}\right) + C_{D,O,F}\left(\frac{S_F}{S_w} + \frac{C_{D,O,c}}{C_{D,O,F}}\frac{S_c}{S_w}\right) \tag{3}$$

$$C_D = C_{D,O} + \left(\frac{C_{D,i}}{C_L^2}\right)C_L^2 \tag{4}$$

Equation (4) assumes there is no lift on the tail to trim the airplane at either subsonic or supersonic speeds. Following are results of calculations at a Mach number of 2.0 for the reference interceptors:

	Turbojet	Rocket
Cruise lift-drag ratio, $(L/D)_{cr}$	4.3	5.4
Cruise altitude, h_{cr}, ft	55,000	85,000

Questionable whether these figures are attainable in practical interceptors

Acceleration and climb. - The fuel consumed during acceleration and climb was computed by a step-by-step integration of the following types of equations. For example, for the turbojet interceptor,

$$\left(\frac{\Delta W_f}{W_G}\right)_{\Delta M} = \frac{\Delta(Ma)}{\frac{T - D}{T}\ Igr} \tag{5}$$

$$\left(\frac{\Delta W_f}{W_G}\right)_{\Delta h} = \frac{\Delta h}{\frac{T - D}{T}\ IMa} \tag{6}$$

Corresponding equations were used to calculate the time elapsed and range traversed:

$$(\Delta t)_{\Delta M} = \frac{1}{\frac{T - D}{W_G} gr} \Delta(Ma) \tag{7}$$

$$(\Delta t)_{\Delta h} = \frac{\Delta h}{\frac{T - D}{W_G} Ma} \tag{8}$$

$$(\Delta R)_{\Delta M} = (M + 0.5\ \Delta M)a(\Delta t)_{\Delta M} \tag{9}$$

$$(\Delta R)_{\Delta h} = Ma(\Delta t)_{\Delta h} \cos\theta \tag{10}$$

where

$$\sin\theta = \frac{T - D}{W_G} \tag{11}$$

The turbojet interceptor was flown over the following flight path during acceleration and climb: at sea level from Mach number of 0 to 0.8; at Mach number 0.8 from sea level to 30,000 feet altitude; at 30,000 feet from Mach number 0.8 to 2.0; and at Mach 2.0 from 30,000 to 55,000 feet altitude. The rocket interceptor was flown over the following flight path during acceleration and climb: vertical take-off, acceleration from Mach 0 to Mach 0.3 at the rate of 1.0 g; push-over to a climb angle of 45° and continued acceleration to Mach number of 2.0 at the rate of 1.3 g's. The interceptor reaches a Mach number of 2.0 at 32,000 feet and continues to climb at constant Mach number and at 45° to cruise conditions. The rocket-engine thrust is assumed to vary during the flight to satisfy the specific airplane flight conditions. Examples of fuel consumed as a percentage of initial gross weight, time elapsed, and range traversed during acceleration and climb are as follows:

	Turbojet	Rocket
$(W_f/W_{G,in})_b$	0.117	0.442
Time, t_{b}, min	5.1	1.0
Range, R_{b}, nautical miles	56	8.0

3094

CX-3

Fuel reserve (turbojet only). - The fuel reserve was assumed to be 5 percent of the total fuel on board the airplane:

$$\left(\frac{W_f}{W_{G,in}}\right)_a = \left(\frac{W_f}{W_{G,in}}\right)_{tot}\left[1 - \left(\frac{W_f}{W_{f,tot}}\right)_r\right] \tag{12}$$

Hold (turbojet only). - The fuel consumed during the hold period was calculated by the following equations:

$$\left(\frac{W_f}{W_{G,ho}}\right)_{ho} = \frac{e^{\zeta} - 1}{e^{\zeta}} \tag{13}$$

$$\zeta = \frac{t_{ho}}{(L/D)_{ho} I_{ho}} \tag{14}$$

$$\left(\frac{W_f}{W_{G,in}}\right)_{ho} = \frac{\left(\frac{W_f}{W_{G,ho}}\right)_{ho}\left[1 - \left(\frac{W_f}{W_{G,in}}\right)_a\right]}{1 - \left(\frac{W_f}{W_{G,ho}}\right)_{ho}} \tag{15}$$

An example of the fuel consumed for 15 minutes of hold at 5000 feet altitude at the best subsonic Mach number is

$$\left(\frac{W_f}{W_{G,in}}\right)_{ho} = 0.021$$

Glide. - The range in nautical miles that is attainable by gliding or by using the kinetic and potential energy of both the rocket and the turbojet airplanes was estimated by the following equation, where the L/D used was the maximum value at the supersonic Mach number being considered:

$$R_g = \frac{1}{6080}\left[h + \frac{(Ma)^2}{2gr}\right]\frac{L}{D} \tag{16}$$

Combat. - The fuel consumed during combat was calculated by the following equation where the turning angle Ω is 220°:

$$\left(\frac{W_f}{W_{G,co}}\right)_{co} = \frac{e^{\zeta} - 1}{e^{\zeta}} \tag{17}$$

$$\zeta = \frac{g}{\sqrt{g^2 - 1}} \frac{2\pi Ma}{I_{co}(L/D)_{co}\ gr} \frac{\Omega}{360} \tag{18}$$

3094

$$\left(\frac{W_f}{W_{G,in}}\right)_{co} = \left(\frac{W_f}{W_{G,co}}\right)_{co} \left[1 - \left(\frac{W_f}{W_{G,in}}\right)_b - 0.5 \left(\frac{W_f}{W_{G,in}}\right)_{cr}\right] \tag{19}$$

where $\left(\frac{W_f}{W_{G,in}}\right)_{cr}$ is approximated by

$$\left(\frac{W_f}{W_{G,in}}\right)_{cr} = \left(\frac{W_f}{W_{G,in}}\right)_a - \left(\frac{W_f}{W_{G,in}}\right)_b - \left(\frac{W_f}{W_{G,in}}\right)_{ho} - \left(\frac{W_f}{W_{G,co}}\right)_{co} \left[1 - \left(\frac{W_f}{W_{G,in}}\right)_b\right] \tag{20}$$

Examples of the fuel consumed during combat for the reference interceptors for the rocket in a 4-g turn at 50,000 feet and the turbojet in a 4-g turn at 35,000 feet are

	Turbojet	Rocket
$(W_f/W_{G,in})_{co}$	0.024	0.084

Cruise. - The cruise range in nautical miles was calculated by the Breguet range equation:

$$R_{cr} = \frac{1}{6080} I \frac{L}{D} Ma \log_e \frac{1}{1 - \left(\frac{W_f}{W_{G,cr}}\right)_{cr}} \tag{21}$$

where, for a given airplane, the altitude was selected to give maximum range; that is, a maximum product of L/D and I. The fuel available for cruise was approximated by the following equation:

$$\left(\frac{W_f}{W_{G,cr}}\right)_{cr} = \left(\frac{W_f}{W_{G,in}}\right)_{cr} \frac{1}{\left[1 - \left(\frac{W_f}{W_{G,in}}\right)_b - 0.5 \left(\frac{W_f}{W_{G,in}}\right)_{co} - 0.5 \frac{W_{ar}}{W_{G,in}}\right]} \tag{22}$$

where $$\left(\frac{W_f}{W_{G,in}}\right)_{cr} = \left(\frac{W_f}{W_{G,in}}\right)_a - \left(\frac{W_f}{W_{G,in}}\right)_b - \left(\frac{W_f}{W_{G,in}}\right)_{ho} - \left(\frac{W_f}{W_{G,in}}\right)_{co} \tag{23}$$

Total radius. - In general, the total interceptor combat radius $R_{tot}/2$ is given by

$$\frac{R_{tot}}{2} = \frac{R_b + R_{cr} + R_g}{2} \tag{24}$$

An exception occurs when the glide range is greater than the range of acceleration and climb and cruise. The combat radius for this case is

$$\frac{R_{tot}}{2} = R_b + R_{cr} \tag{25}$$

APPENDIX B

DISCUSSION OF INTERCEPTOR MISSION

This appendix discusses several interceptor missions from a point of view that is independent of the engine in an effort to determine the combat radii and maneuverability associated with these missions. Such calculations are an aid in evaluating the results presented in the body of the report. There are two types of mission an interceptor may be required to perform, that of local or point defense, and that of area defense. A local-defense problem is schematically illustrated in figure 14. The warning radar, target of the threat bomber, and interceptor base are located in the same vicinity. The bomber is proceeding from left to right and, if allowed to complete its mission, would release its bombs at point A about 18 miles before it was directly over the target. The interceptor must be capable of making two passes at the bomber, and the second pass must be completed before the bomber reaches the bomb-release point. Consider a possible case where the interceptor has a Mach 2.0 capability and the bomber is flying at Mach 1.5. Based on calculations not presented in this report, the maximum level-flight altitude of the bomber as it approaches its target is expected to be about 50,000 feet. The flight path of the bomber first intersects the field of vision of the radar at a distance of 260 nautical miles, point 0; 5 minutes later the bomber is identified and the interceptor is ready to take-off, point 1. At point 2 the interceptor is ready to start into its combat maneuver. The interceptor fires at the bomber at points 3 and 4, the required two passes. The longest interceptor radius of operation required to accomplish this local defense mission is approximately 90 miles because of the limited radar warning distance. A minimum radius of about 30 miles is required to complete two passes before the bomber reaches the bomb-release point. The significant point is that the relatively short combat radius of 30 nautical miles is useful, while a combat radius of about 90 nautical miles is desirable for a local-defense mission.

The maneuverability required in an interceptor depends on the combat action taken by the bomber and the interceptor. Figure 15(a) illustrates the standard combat maneuver used in most of the interceptor calculations. The interceptor is vectored out so that as it approaches the bomber its flight path is offset horizontally from the bomber flight path. The interceptor then makes a 140° turn to attack the bomber the first time (point 1), crosses the bomber flight path, makes an 80° turn to attack the second time (point 2), a total of 220° of turning. In this case, it was assumed that the bomber takes no evasive action. Assuming adequate ground radar directing, the airplane maneuverability required for this case may be quite low.

Considered in figure 15(b) is the case where the bomber takes an aggressive evasive action (aggressive referring to the fact that the bomber turns toward rather than away from the interceptor), and the first interceptor pass is made head-on to the bomber. By taking aggressive evasive action, the bomber accomplishes two things: (1) presents a low frontal area to the interceptor and gives the interceptor only a short aiming time, thus making it hard to hit on the first pass, and (2) traverses as much distance as possible between the first and second pass. This case places more exacting requirements on the in-
3094 terceptor than the standard case and therefore will be considered in more detail. The distance required to make the second pass is a function of the number of g's (normal load factor) the interceptor "pulls" in the 180° turn and of the velocities of the bomber and the interceptor. For the calculations, the maneuvers are assumed to take place at constant speed for both interceptor and bomber.

The variation of d_2 with interceptor maneuverability is presented in figure 16 in terms of g's. The lower curve is for a Mach 1.5 bomber and a Mach 2.0 interceptor. The horizontal dashed line shows the maximum available distance to make a second pass before the bomber releases its bomb. From the intersection of the dashed line with the lower curve, a maneuverability of 3 or 4 g's appears desirable. The upper curve shows the effect on the distance to make a second pass if the bomber Mach number is 1.8 instead of 1.5. In general, it can be implied that high interceptor speeds and large maneuverabilities are desirable. The maximum interceptor maneuverability that may be utilized, however, is limited by the pilot's tolerance to normal acceleration, which is about 4 g's. The precise maneuverability for which an interceptor should be designed remains a matter of conjecture; consequently, several figures in the body of the report show how the maneuverability requirements affect interceptor design and performance and how maneuverability is affected by altitude. Where one value of maneuverability is required for purposes of illustration and discussion, a value of 4 g's has been selected. This discussion does not imply that the interceptor maneuverability must necessarily exist at the bomber altitude.

A second mission required of an interceptor is that of area defense, illustrated in figure 17. In this case, the interceptor base is located to the rear and/or to one side of a group of targets to be defended, and the radar is located well forward. Again, two passes will be required; however, the distances involved may not be as critical as in the local-defense problem. Economic, tactical, and strategical considerations indicate that to best fulfill the area-defense mission the interceptor should have a combat radius of about 375 nautical miles. The concept of area defense is, of course, compatible with the concept of a two-notch defense system, where the bomber targets are protected by both an area- and a local-defense system. The primary distinction between the local- and area-defense interceptor is the required radius of operation.

This is one reason that radius of operation is used as a dependent variable in the figures concerning the application of turbojet and rocket power plants.

Besides the local- and area-defense missions, there are other considerations that affect the desirability of an interceptor, such as the distance that it can be ferried, its patrol and hold time, its landing and take-off characteristics (such as take-off distance or vertical-take-off capability), and its time to reach combat speed and altitude. Therefore, some of these characteristics are also discussed in the text.

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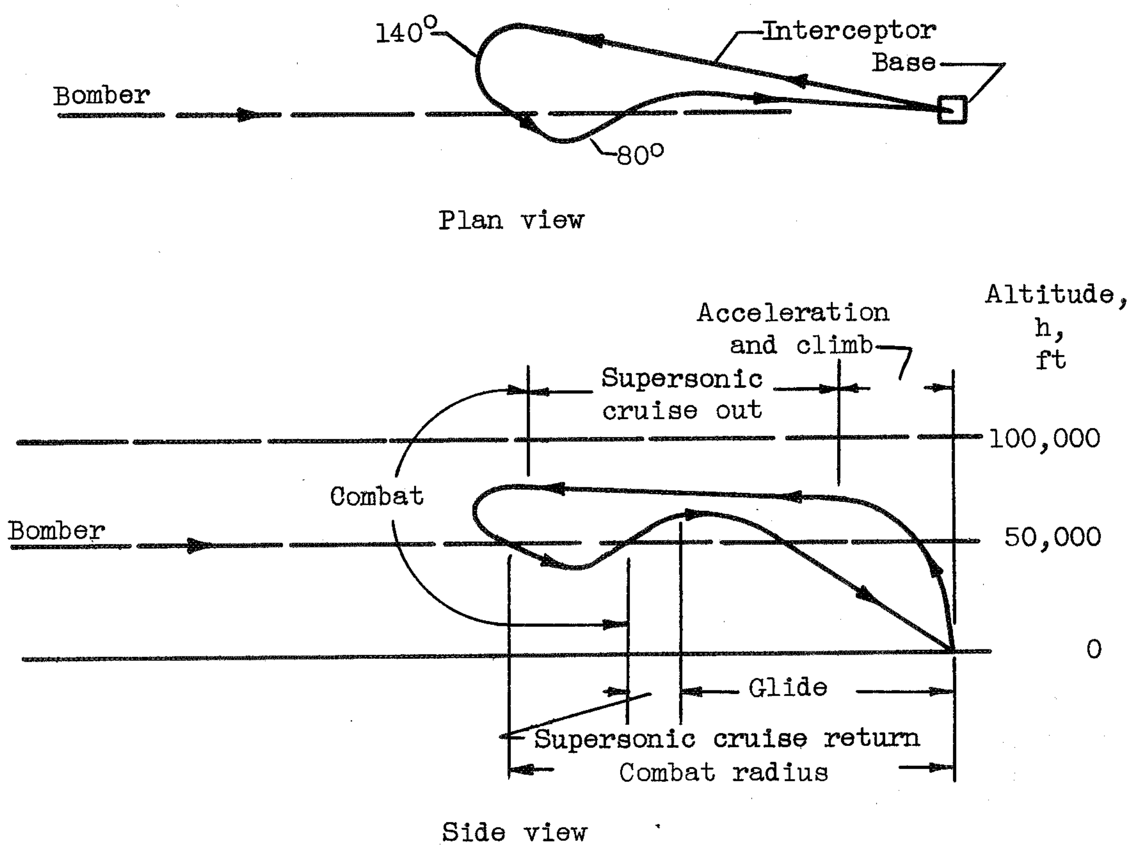
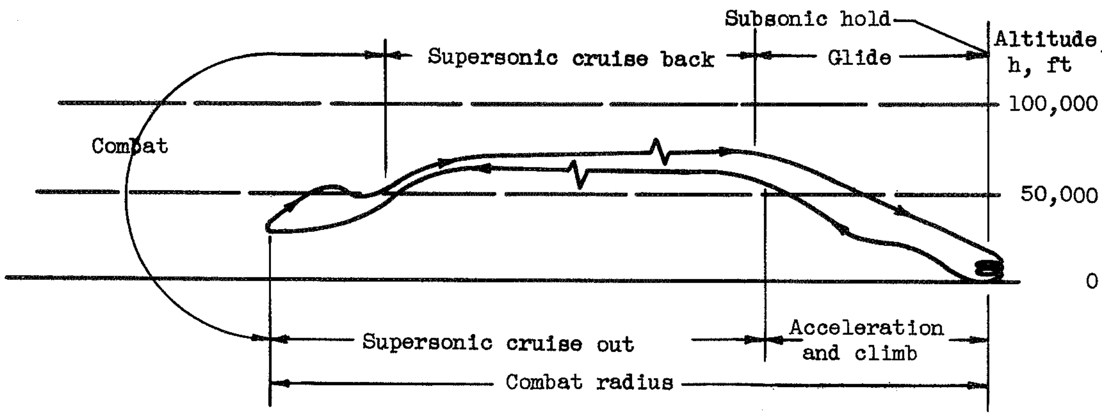
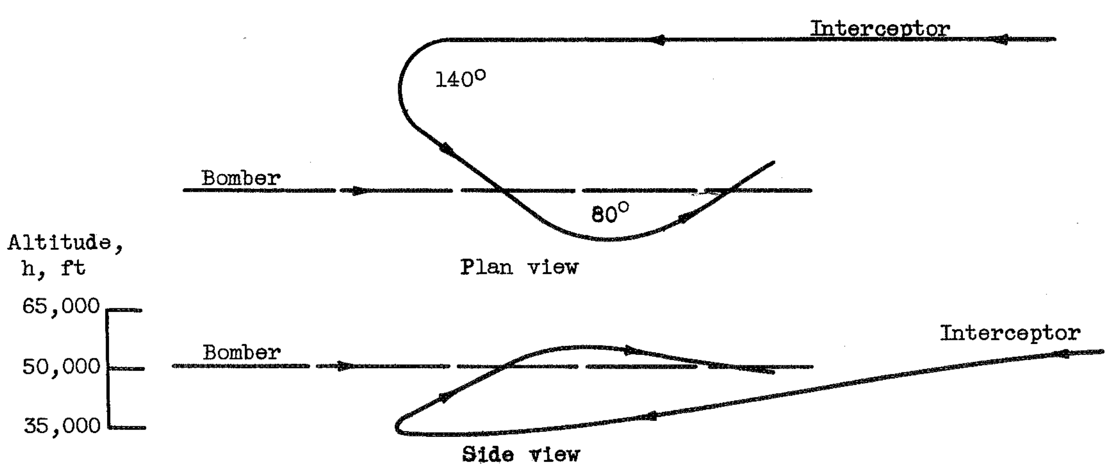


Figure 1. - ~~Standard~~ flight plan for rocket interceptor. Altitudes typical for interceptor Mach number of 2.0.



(a) Over-all flight plan.



(b) Combat maneuver (detail).

Figure 2. - Flight plan for turbojet interceptor. Altitudes typical for interceptor Mach number of 2.0.

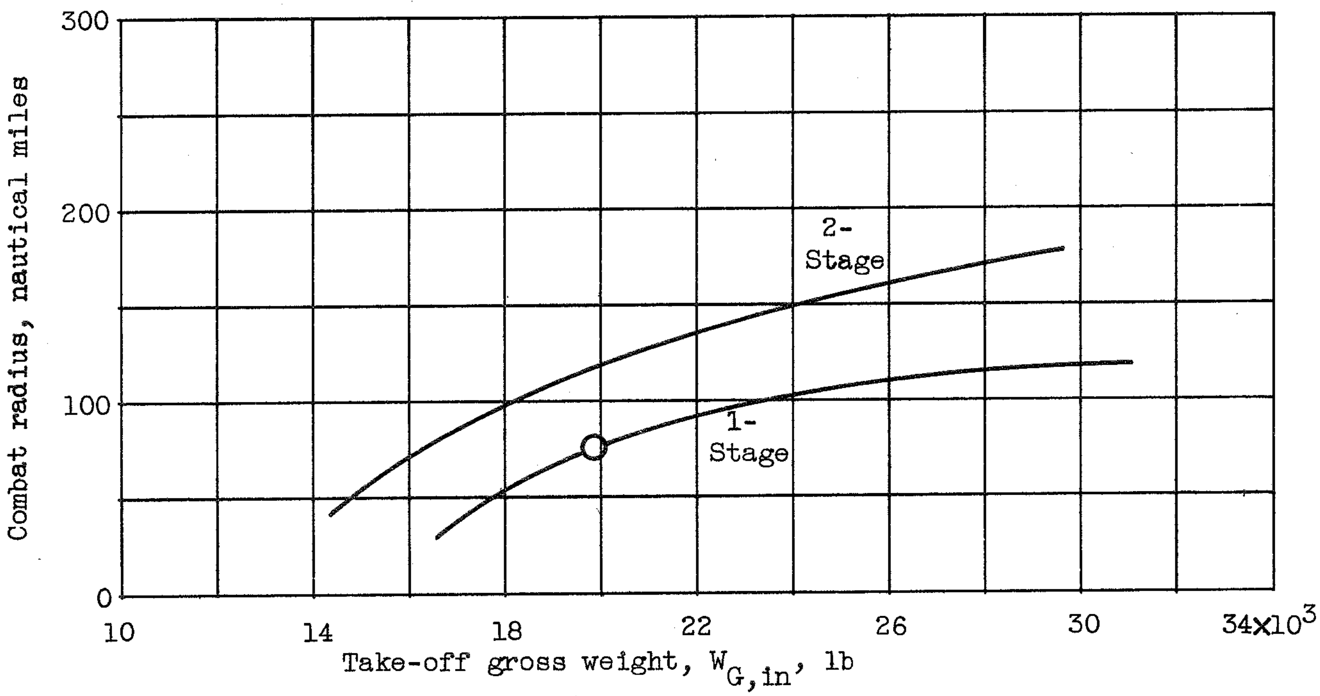


Figure 3. - Variation of combat radius with gross weight for one- and two-stage rocket interceptors at Mach number 2.0. Propellant, gasoline-oxygen.

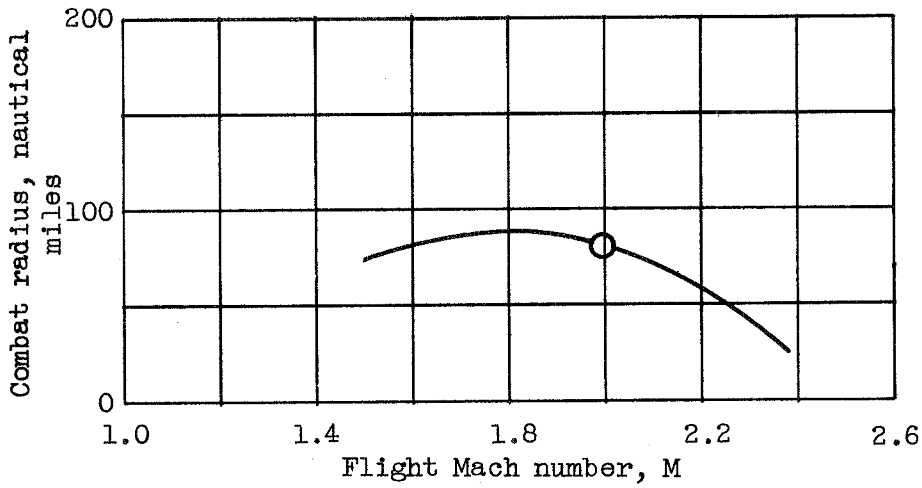


Figure 4. - Variation of single-stage rocket-interceptor combat radius with flight Mach number. Take-off gross weight, 20,000 pounds; propellant, gasoline-oxygen.

3094

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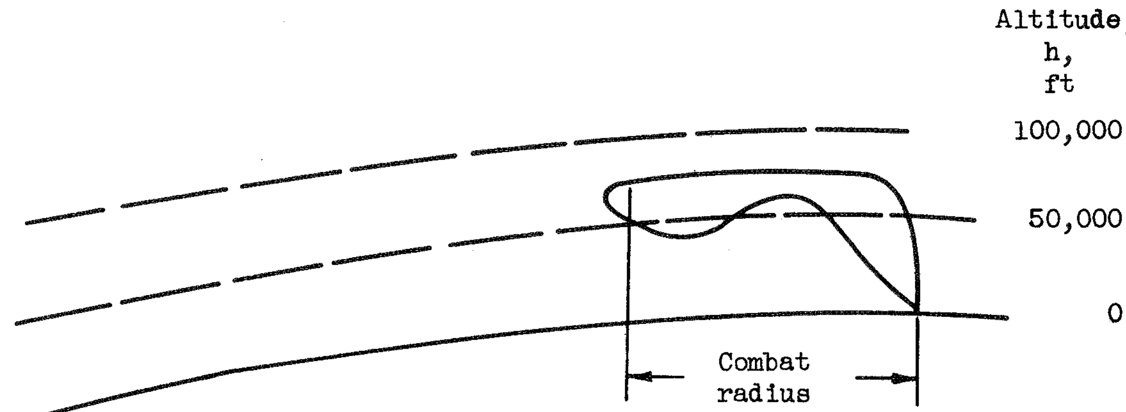
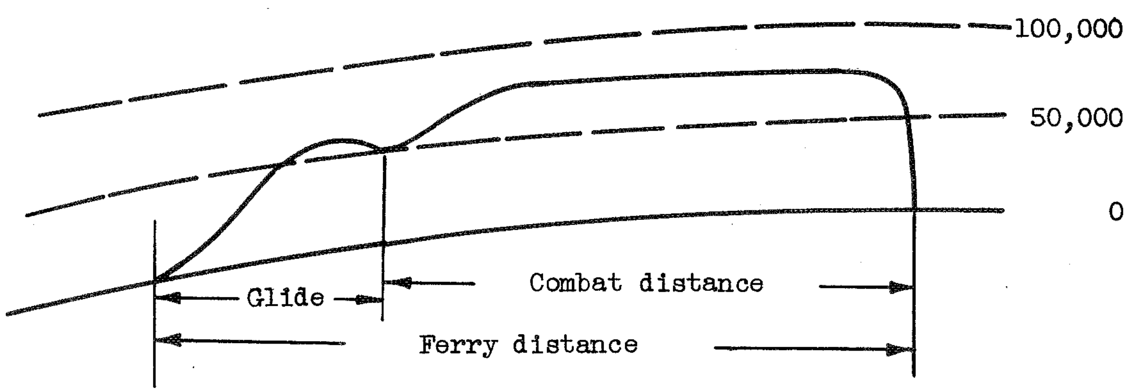


(a) Standard flight plan.



(b) Alternate flight plan.

Figure 5. - Flight plans for rocket interceptor.

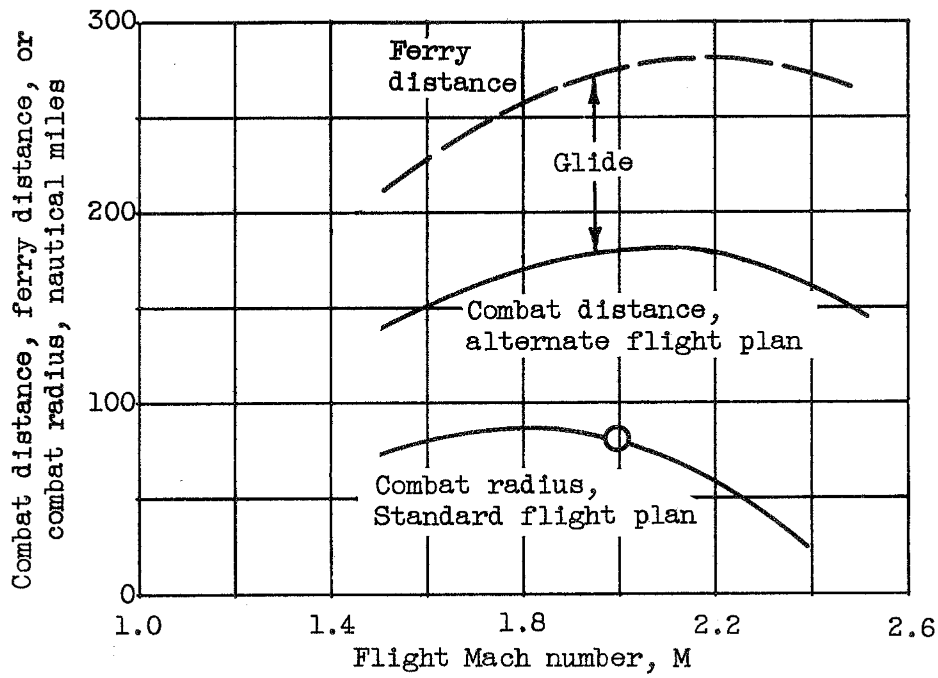


Figure 6. - Variation of single-stage rocket-interceptor radius with flight Mach number for two flight plans. Take-off gross weight, 20,000 pounds; propellant, gasoline-oxygen.

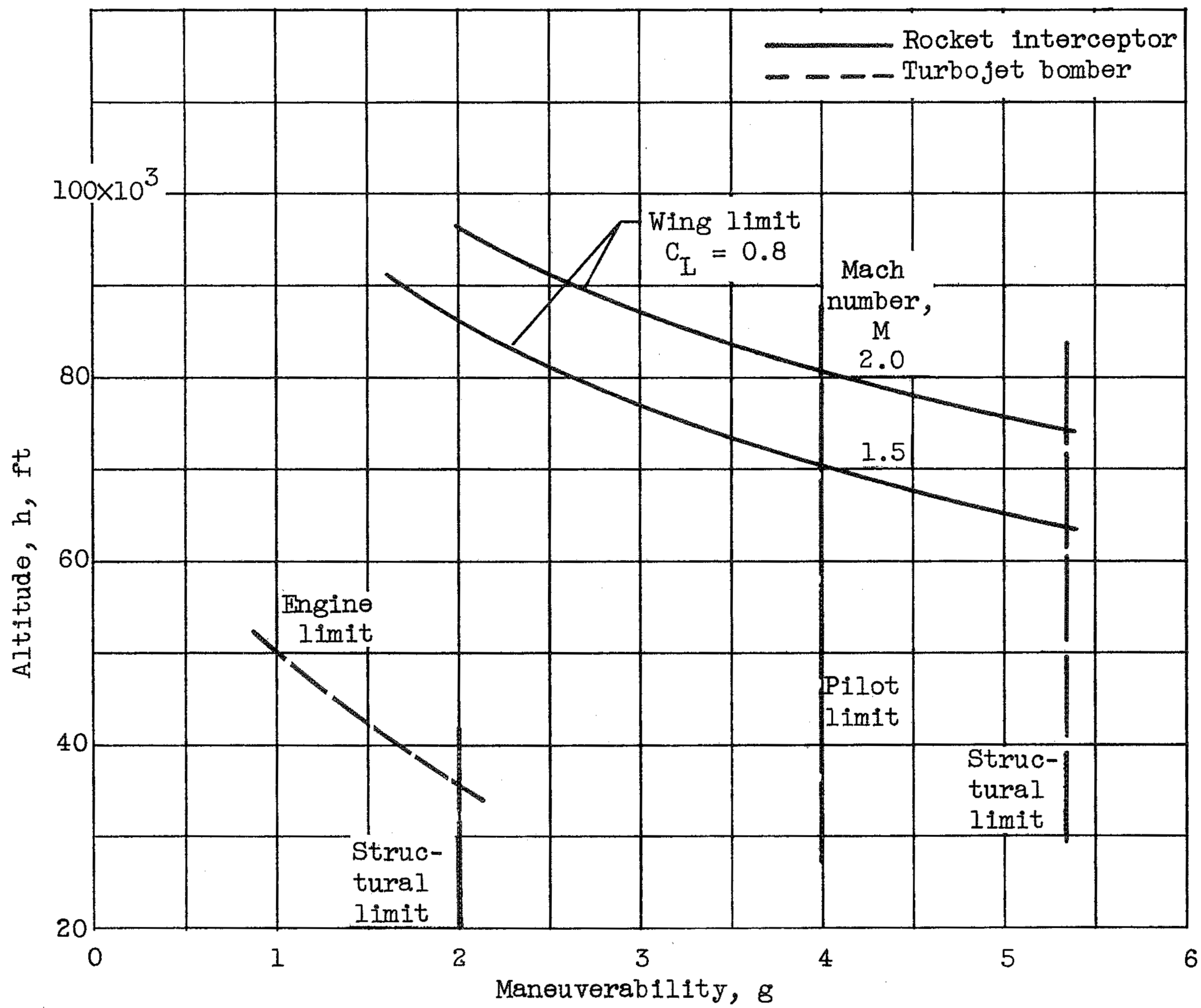


Figure 7. - Comparison of maneuverability of reference rocket interceptor and turbojet-powered threat bomber.

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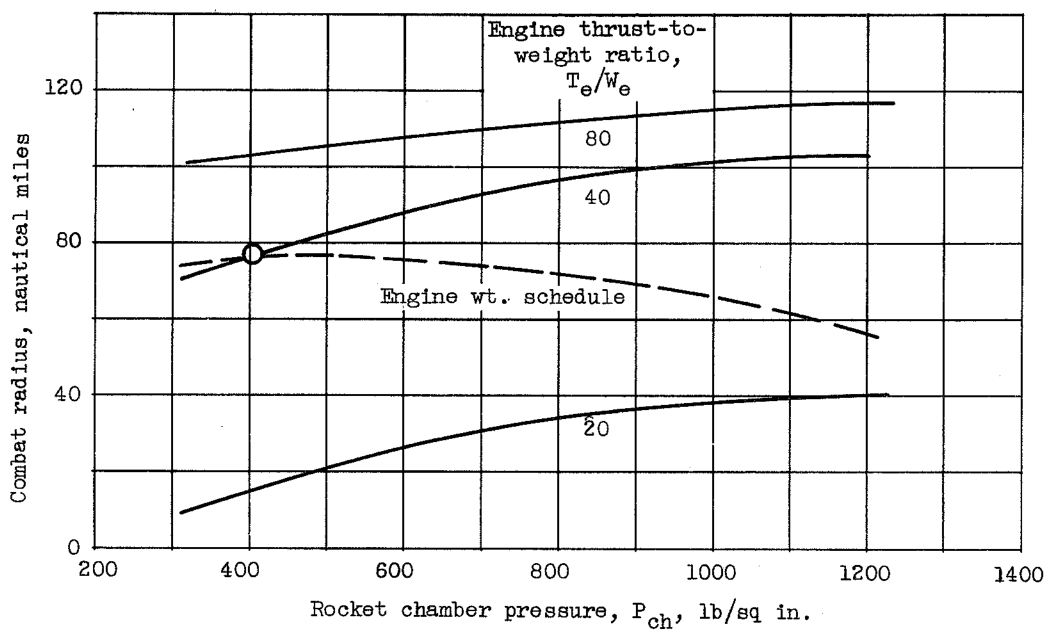
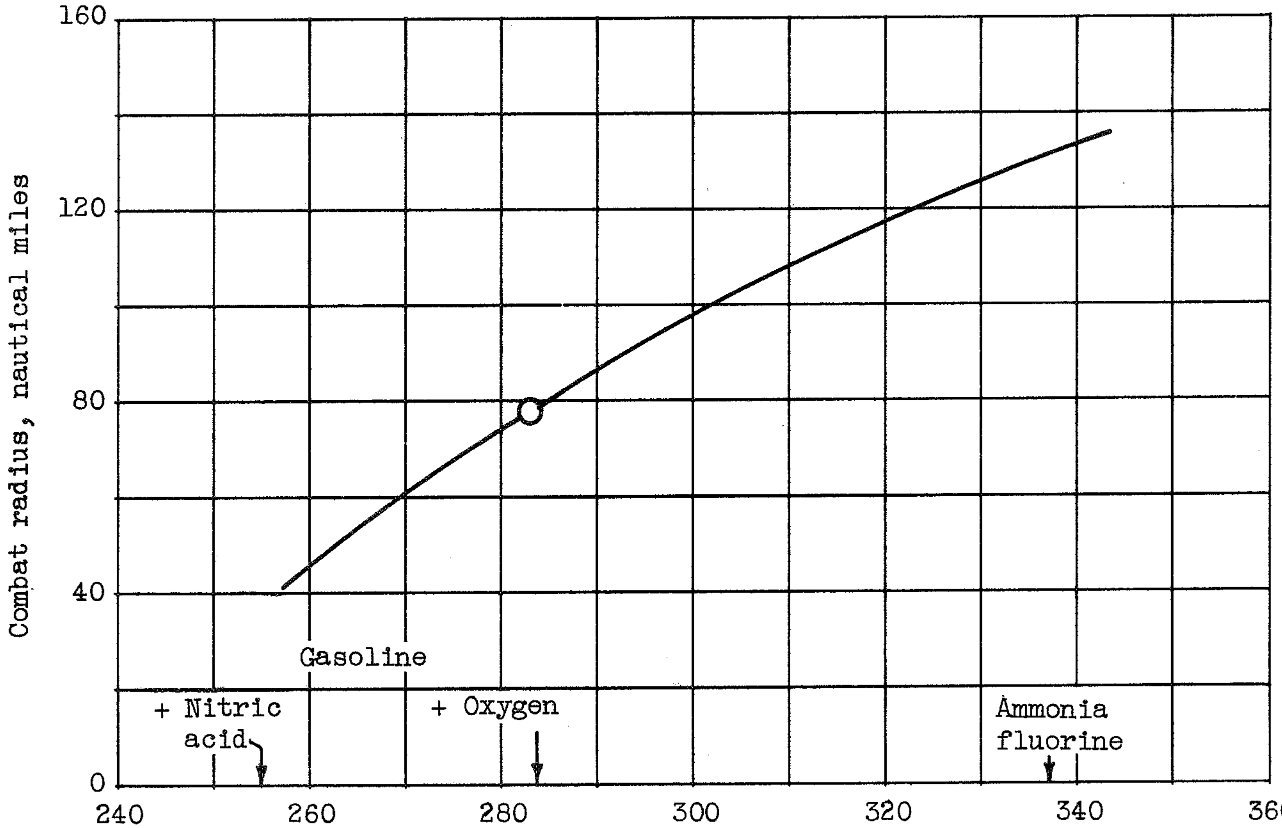


(a) Effect of rocket-engine chamber pressure and thrust-to-weight ratio. Propellant, gasoline-oxygen.

Figure 8. - Effect of engine parameters on rocket-interceptor combat radius. Take-off gross weight, 20,000 pounds; Mach number, 2.0.



(b) Effect of rocket-engine specific impulse. Rocket chamber pressure, 400 pounds per square inch; engine thrust-to-weight ratio, 40.

Figure 8. - Concluded. Effect of engine parameters on rocket-interceptor combat radius. Take-off gross weight, 20,000 pounds; Mach number, 2.0.

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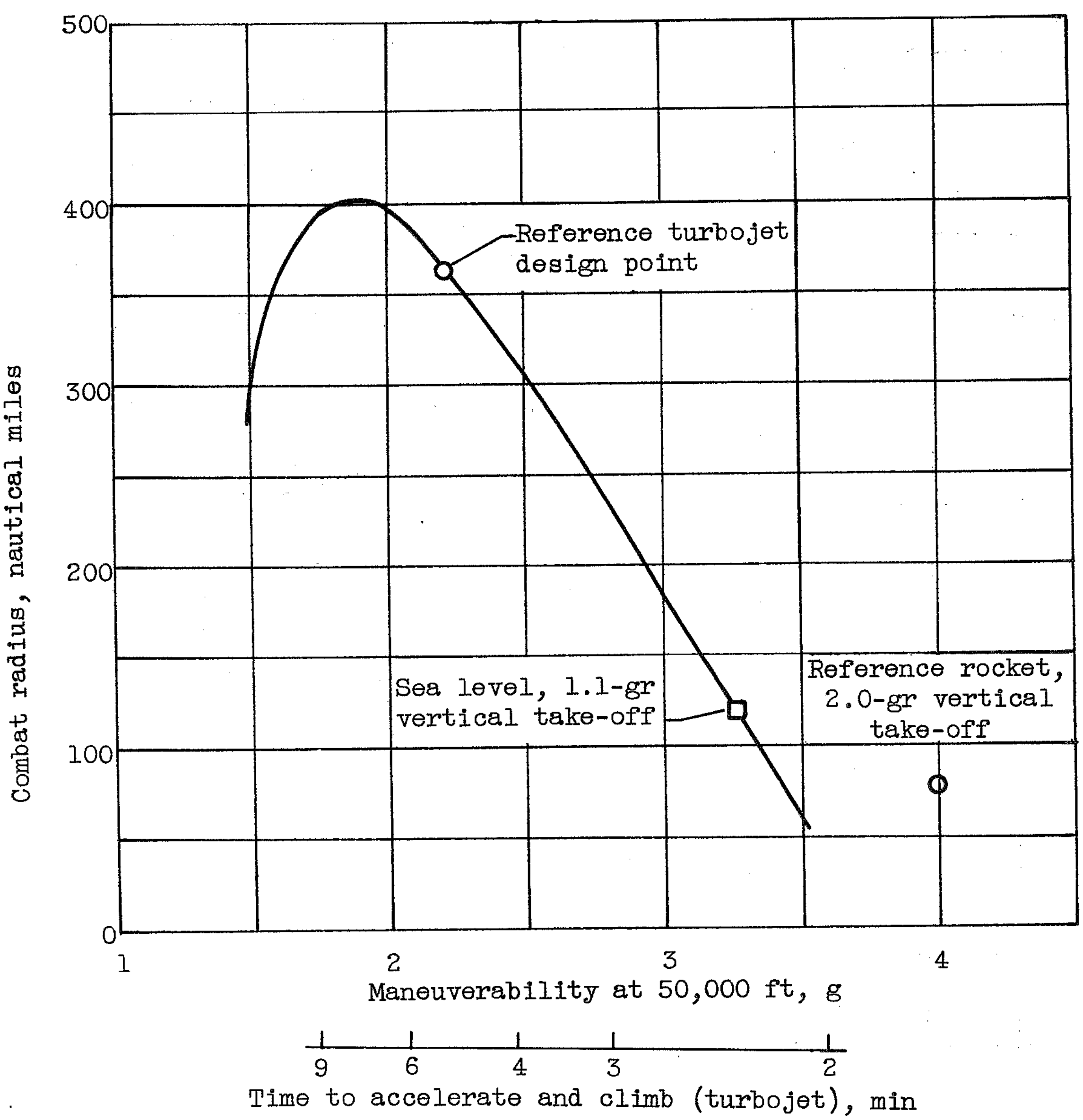


Figure 9. - Variation of turbojet-interceptor combat radius with design maneuverability at 50,000 feet altitude. Take-off gross weight, 20,000 pounds; Mach number, 2.0.

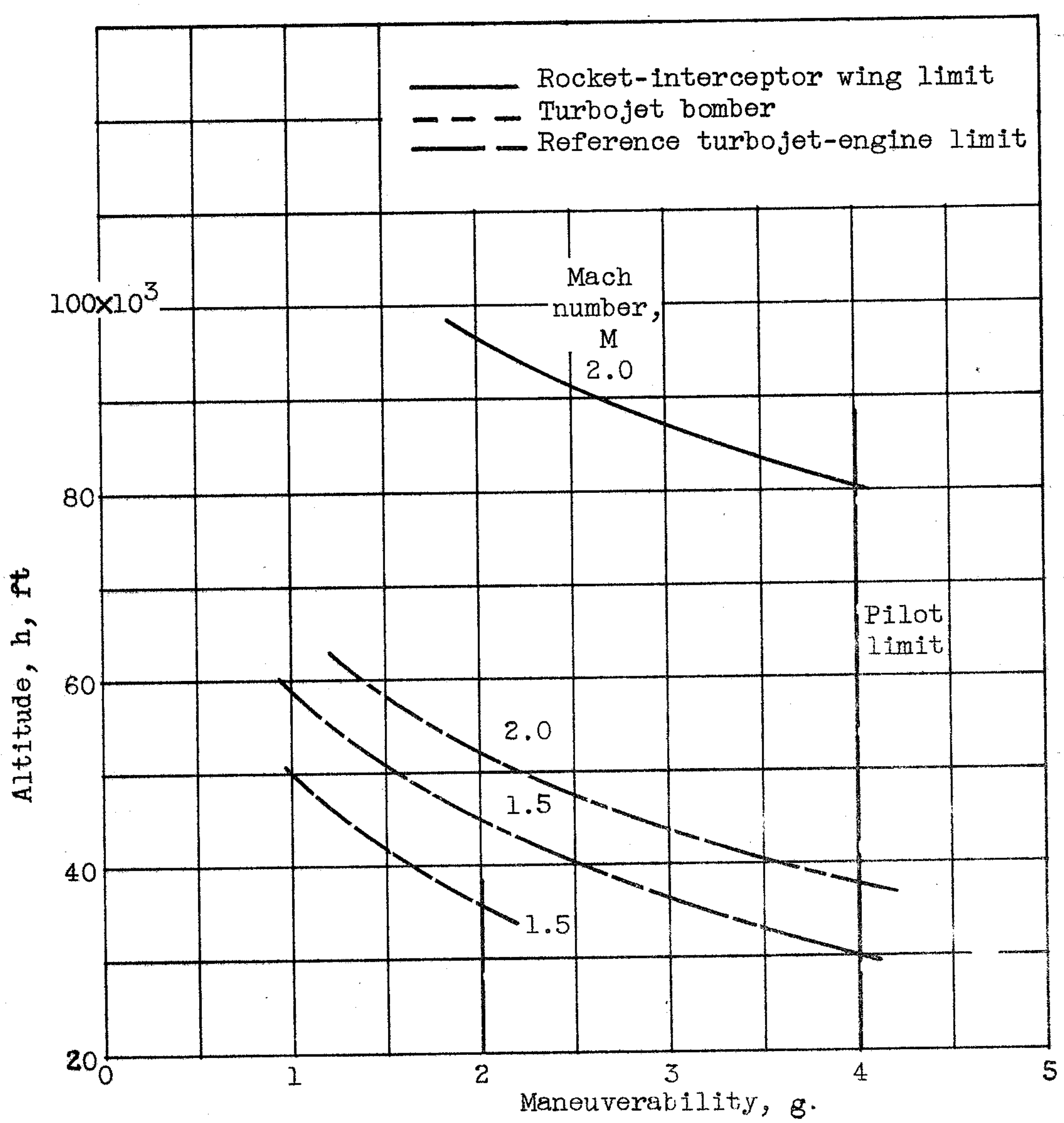
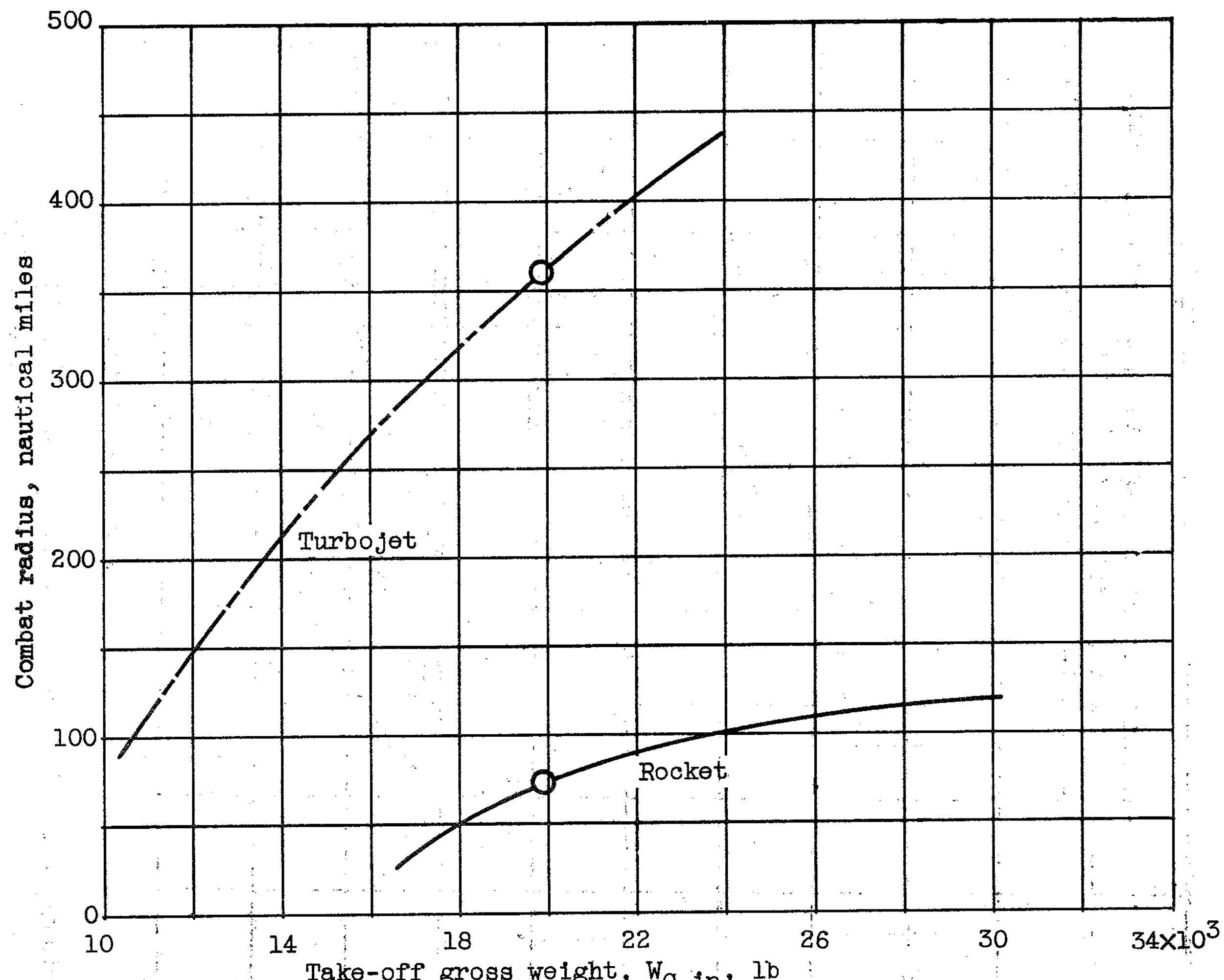
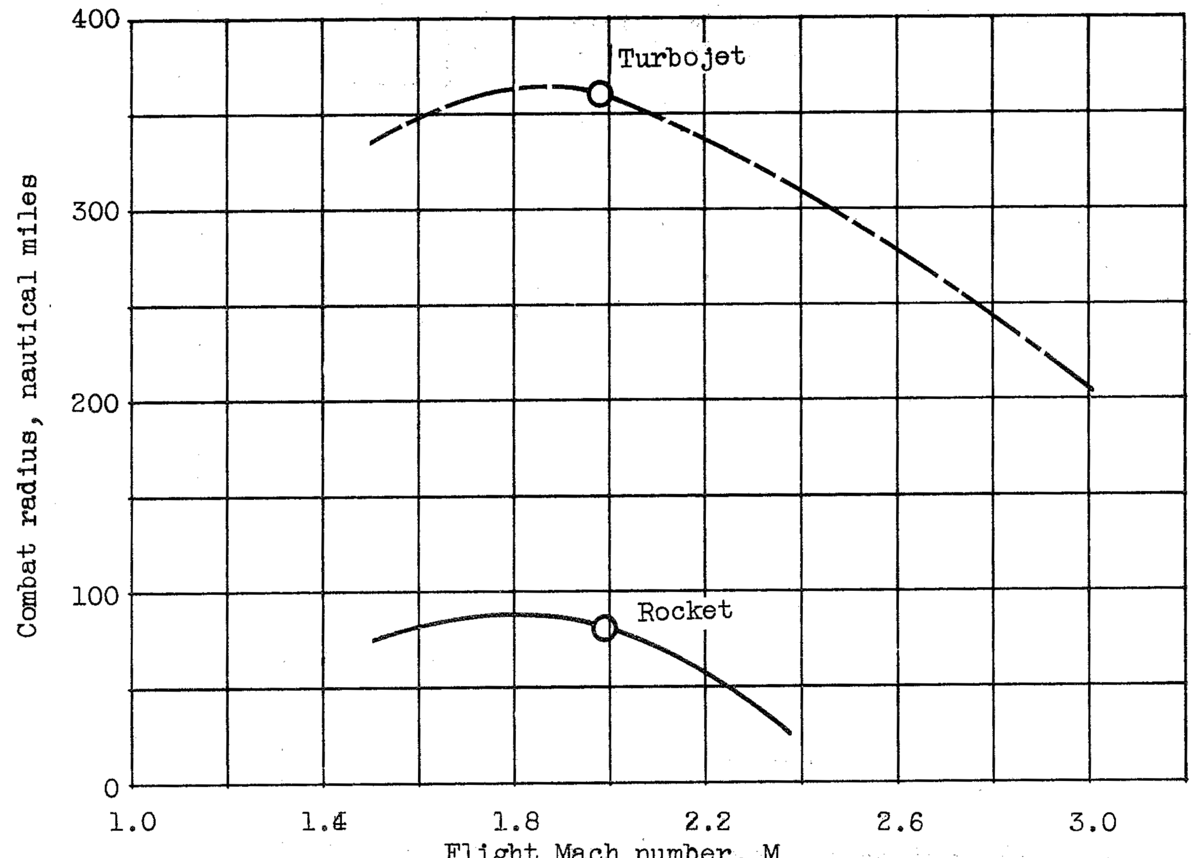


Figure 10. - Comparison of maneuverability of reference rocket interceptor, reference turbojet interceptor, and turbojet-powered threat bomber.



(a) Variation of combat radius with take-off gross weight. Mach number, 2.0.

Figure 11. - Comparison of turbojet and rocket interceptors.



(b) Variation of combat radius with flight Mach number. Take-off gross weight, 20,000 pounds.

Figure 11. - Concluded. Comparison of turbojet and rocket interceptors.

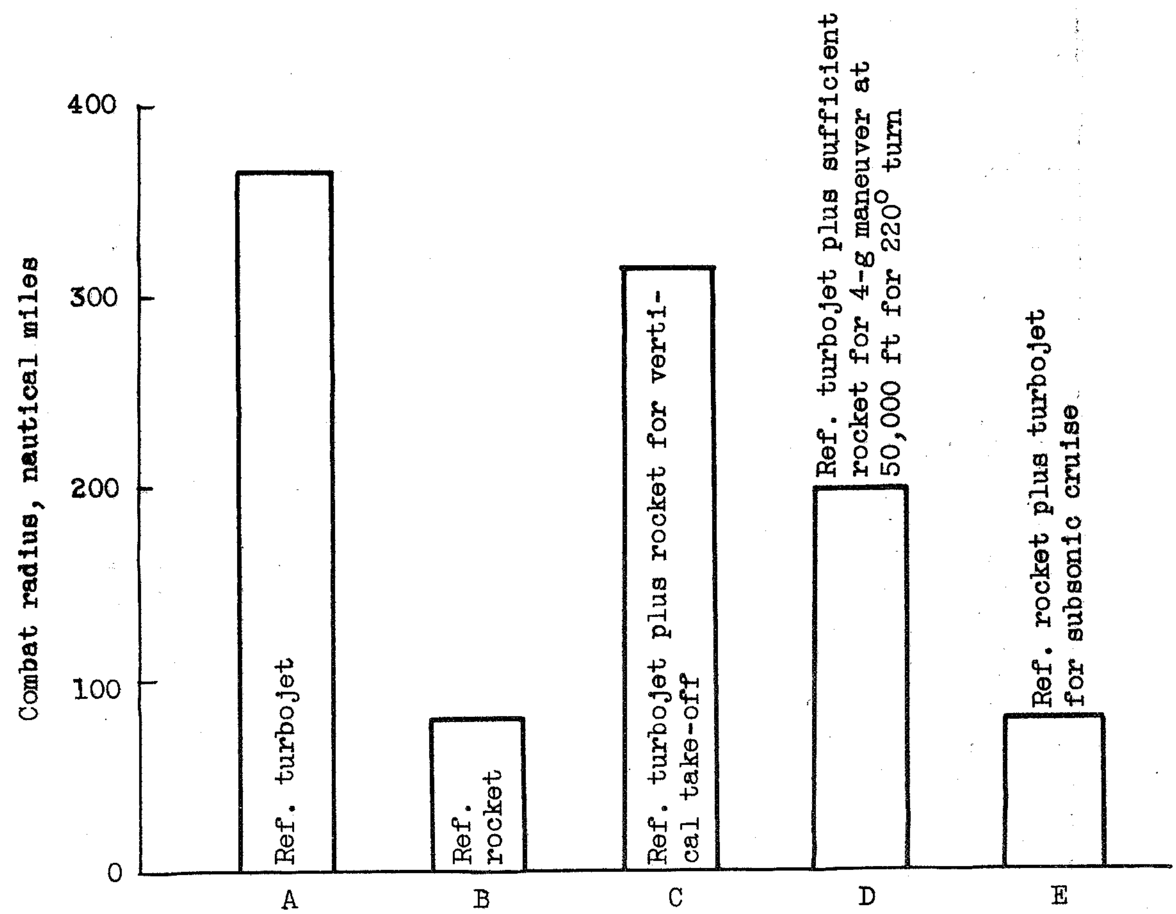


Figure 12. - Comparison of combat radii for several rocket-turbojet combinations. Take-off gross weight, 20,000 pounds; Mach number, 2.0.

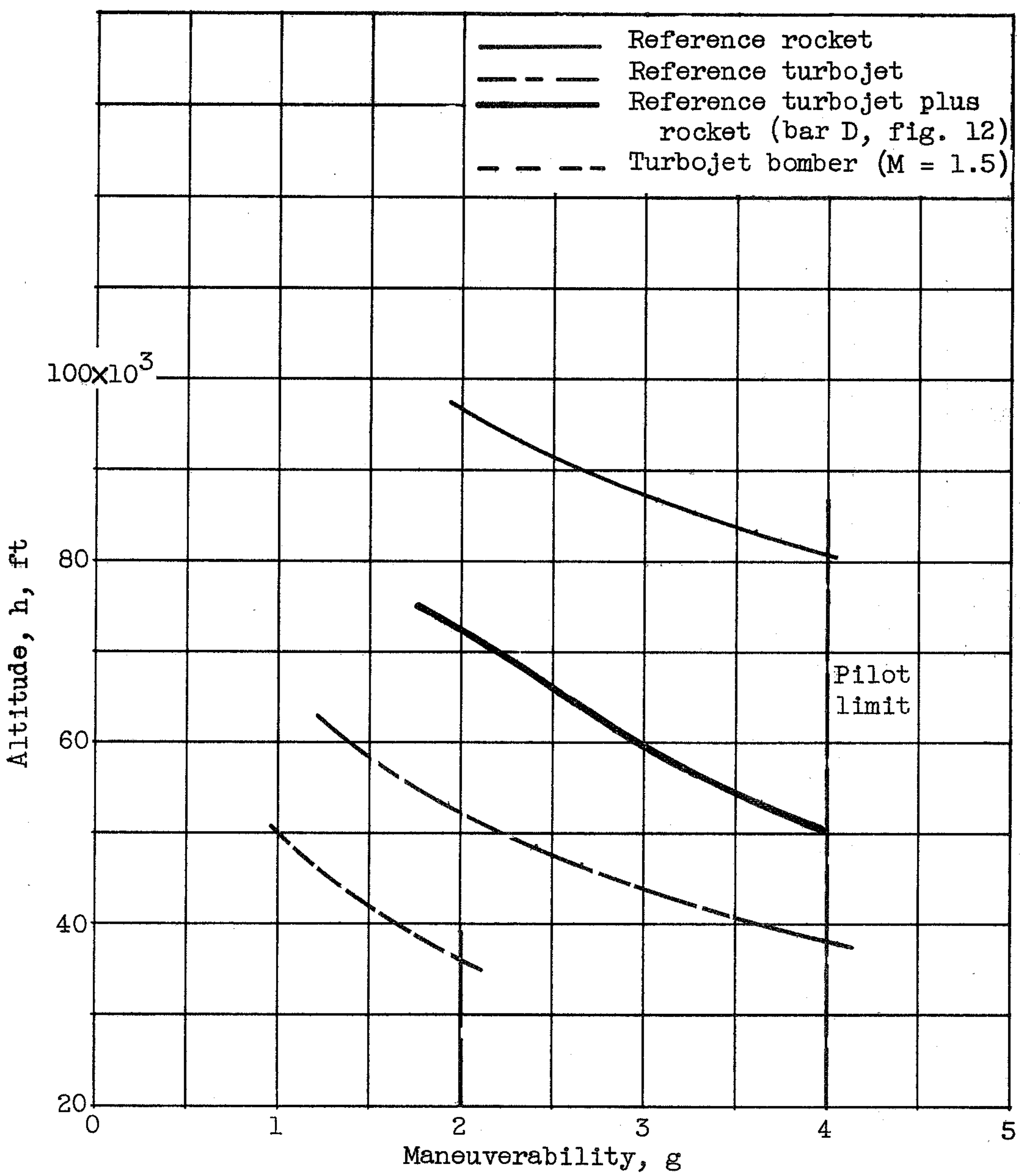


Figure 13. - Comparison of maneuverability of reference rocket interceptor, reference turbojet interceptor, combination reference turbojet interceptor plus rocket, and turbojet-powered threat bomber. Interceptor Mach number, 2.0.

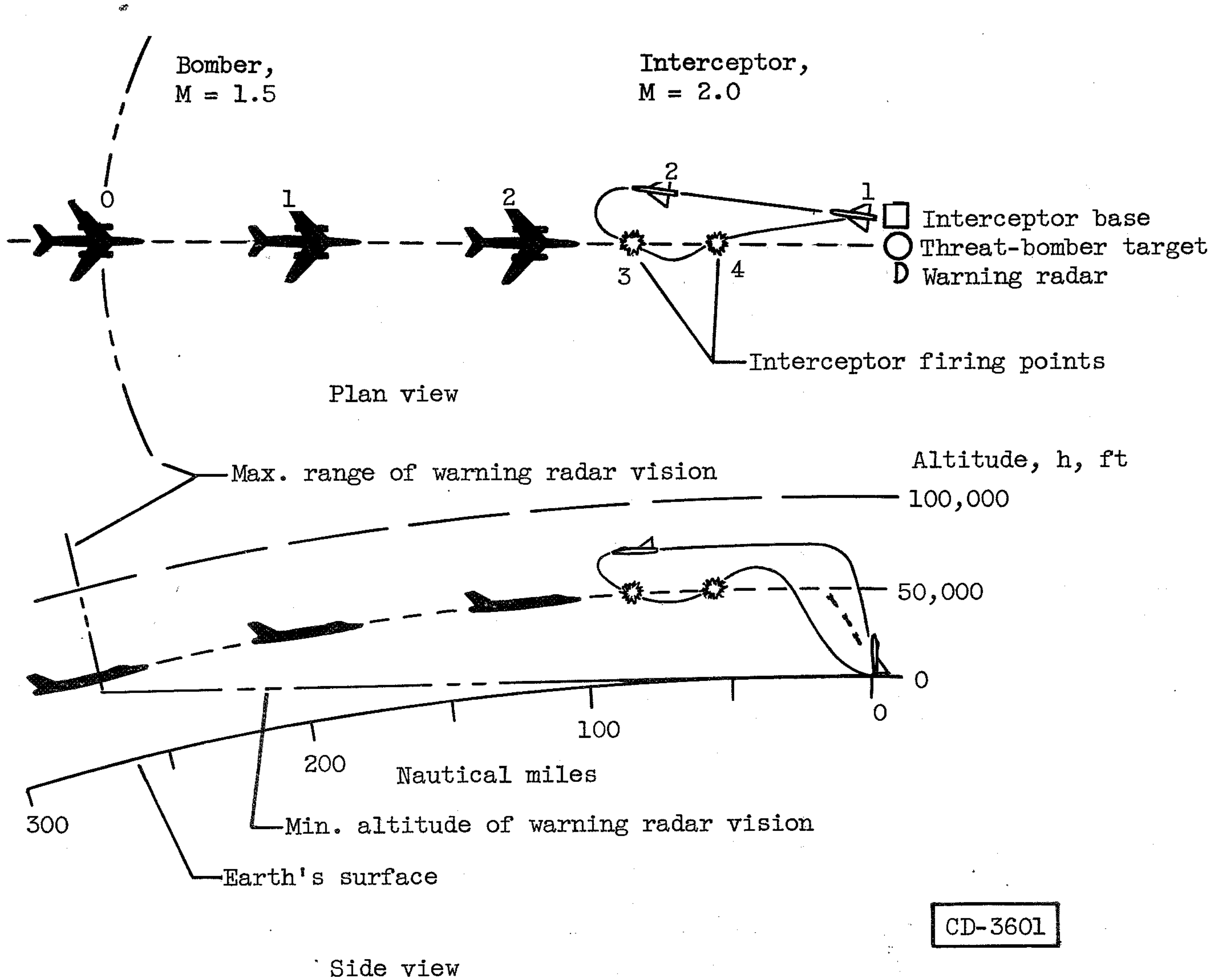
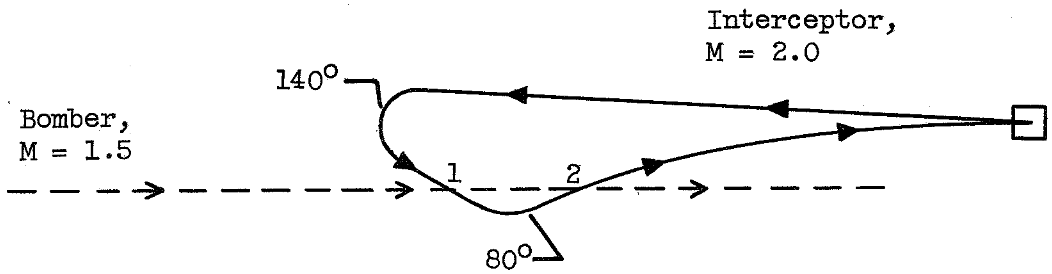
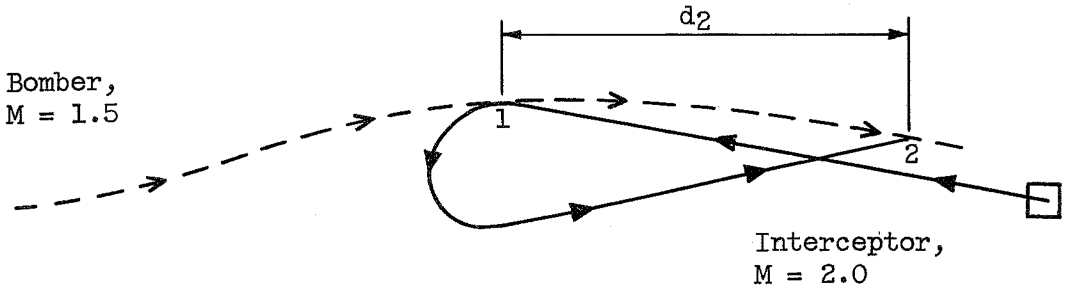


Figure 14. - Schematic illustration of interceptor local-defense mission.



(a) Standard encounter (no bomber evasive action).



(b) Encounter with aggressive bomber evasive action; first interceptor pass head-on.

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Figure 15. - Two possible encounters between interceptor and threat bomber.

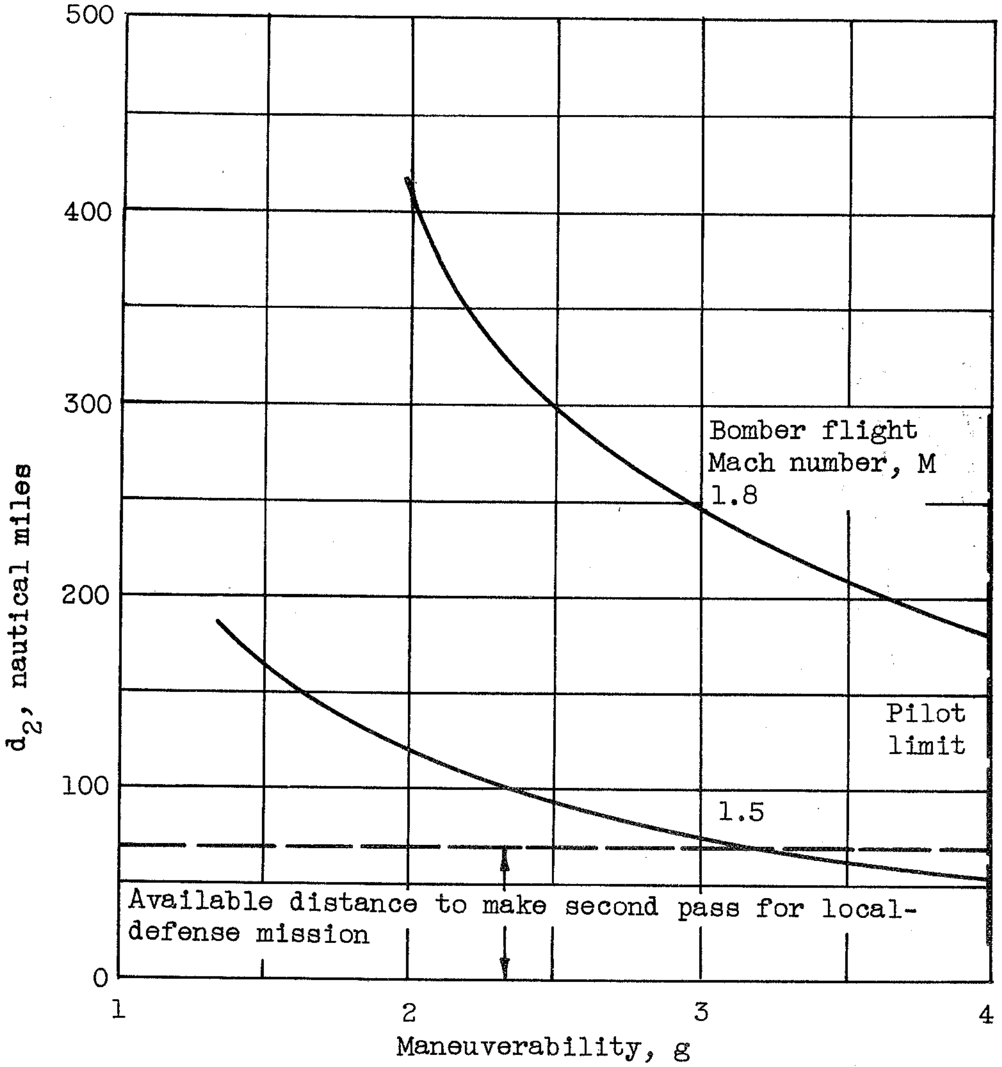

Figure 16. - Distance traversed by bomber between first and second pass of interceptor as function of interceptor maneuverability for encounter with aggressive bomber evasive action. Interceptor flight Mach number, 2.0.

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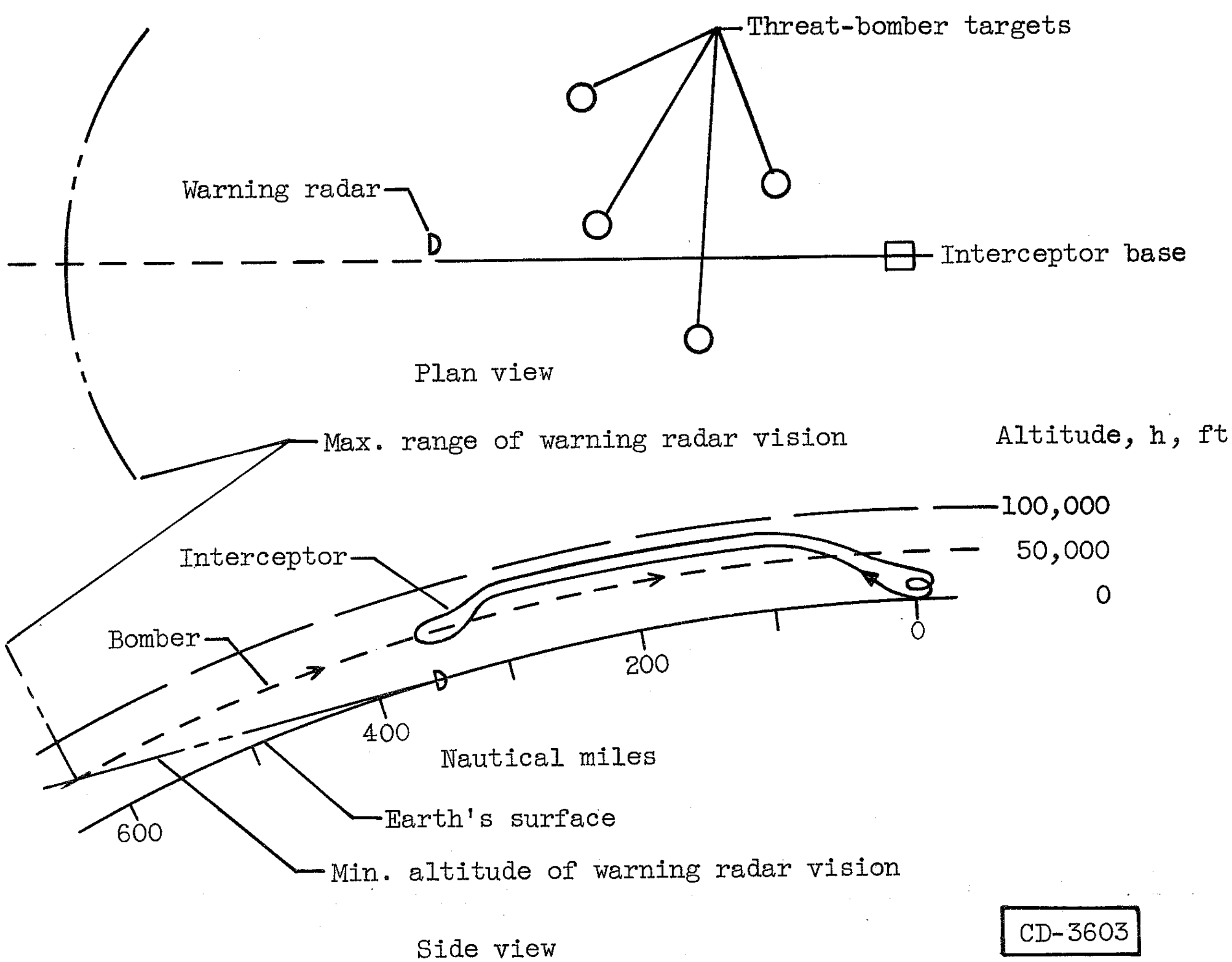

Figure 17. - Schematic illustration of interceptor area-defense mission.

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PERFORMANCE ANALYSIS OF APPLICATION OF ROCKET

ENGINES TO INTERCEPTOR AIRPLANES

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sjt - 4/20/54

Airplanes - Performance	1.7.1.3
Engines, Turbojet	3.1.3
Engines, Rocket	3.1.8
Engine types, Comparison	3.1.12
Rocket Assist	3.3.3
Fuels - Relation to Engine Performance	3.4.3

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Abstract

Missions for which a rocket interceptor is suited and the effect of rocket-engine performance on interceptor performance are discussed. Flight missions for interceptors having rocket and turbojet engines are compared, and circumstances under which a combination of rocket and turbojet may be advantageous are discussed.