NASA Technical Memorandum 78811

(NASA-TM-78811) TRADE STUDIES RELATING TO A LONG RANGE MACH 2.6 SUPERCRUISER (NASA) 20 p HC A02/MF A01 CSCL 01A

N79-15906

Unclas
G3/02 43550

Trade Studies Relating To A Long Range Mach 2.6 Supercruiser

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December 1978

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SUMMARY

A systems study has been conducted on an aircraft concept, representative of a supersonic-cruise military aircraft (supercruiser). The study results indicate that supersonic ranges in excess of 7.5 Mm (4000 n.mi.) at a Mach number of 2.62 are possible with a 222 kN (50000 lbf) class aircraft. Trade studies, to determine the sensitivity of supersonic range to parameters which would improve maneuverability, indicate that thrust-weight ratios of as much as 0.5 can be used without significantly decreasing supersonic range; however, increasing the thrust-weight ratio to 1.0 decreases the range capability by about 2.0 Mm (1100 n.mi.). The range penalty for increasing the aircraft limit load-factor from 4.0 to 9.0 is about 0.93 Mm (500 n.mi.). The increased fuel volume of several configurations improved the subsonic range capability by about 2.2 Mm (1200 n.mi.); but, due to associated losses in supersonic L/D, had an insignificant effect on the range at a Mach number of 2.62.

INTRODUCTION

The National Aeronautics and Space Administration in cooperation with the United States Air Force and with various groups in industry is involved in a study of the feasibility of supersonic-cruise fighter-type aircraft. A number of aircraft concepts are under study at the Langley Research Center. As represented in figure 1, the configuration design philosophies range fr emphasis on maneuver capability at a Mach number of 1.4 to efficient cruise at a Mach number of 2.6. An indication of the scope of the study and some early experimental results may be found in references 1 and 2.

The cruise configuration for a Mach number of 2.6 is of most interest for the present study inasmuch as the Aeronautical Systems Division at Langley has been working on a supersonic demonstrator aircraft concept as part of the Supersonic Cruise Research (SCR) Program. The concept could be used to verify recent relatively dramatic advances in supersonic technology in the areas of aerodynamics, structures and propulsion. With the increase in interest in supersonic-cruise military aircraft (supercruiser), it was decided that a systems study should be conducted on an aircraft concept which would be representative of both a SCR demonstrator and a supercruiser demonstrator. The primary objective of the study was to determine the aircraft gross weight required for a Mach 2.6 cruise mission with range capability on the order of 7.5 Mm (4000 n.mi.). The secondary objective was to conduct trade studies to determine the sensitivity of supersonic range to parameters which would improve maneuverability

Although the configuration selected for this study is similar to the supersonic-cruise configuration of reference 2, the wind tunnel data of that study was not available in time; however, SCR model data was available throughout the Mach number range. It was used in lieu of the fighter data. The basic configuration was laid out in an in-house study. The planform and camber surface of the concept is identical to the arrow-wing supersonic transport shown in figure 2; consequently, the aerodynamic characteristics of the demonstrator aircraft were obtained by incrementing the supersonic-transport data for differences in geometry, wave drag, and skin friction drag. Fuel volumes were calculated for four combinations of body depth and wing thickness. Subsonic cruise missions were calculated at a Mach number of 0.9, and supersonic cruise missions at a Mach number of 2.62. The missions assumed a hot-day atmosphere, 8C above a standard day.

The emphasis in this study was on trade studies which might be useful in formulating supercruiser design philosophy. Performance programs were used to calculate the effect of thrust loading, wing loading, design load-factor, and wing-body volume on range. Takeoff performance calculations were based on preliminary subsonic stability and control data analysis.

SYMBOLS

$\bar{c}$	wing reference chord
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
C_m	pitching moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$
c.g.	center of gravity
L/D	lift-drag ratio
M	Mach number
q	free stream dynamic pressure
S	wing reference area
T/W	thrust loading
W/S	wing loading
α	angle of attack
δ	elevon deflection angle; positive trailing edge down

CONCEPT

Aerodynamic Characteristics. - The basic configuration concept is illustrated in figure 3. The philosophy behind this design was to optimize it to cruise at a Mach number of 2.62 with minimum compromise for other flight regimes. The wing was cambered for minimum drag-due-to-lift at a C_L of 0.08 at cruise speed. The fuselage was area-ruled for minimum wave drag at a Mach number of 2.62. The wing was assumed to have an 0.5-percent leading-edge radius to allow reasonable subsonic performance. Transonic wind tunnel tests have indicated that a lift-to-drag ratio L/D improvement of 1.0 can be achieved by using a Krueger flap on the outboard wing section; thus, variable camber was used on the outboard wing section to improve both subsonic and transonic performance. At subsonic and transonic Mach numbers, the leading edge would be deflected downward 10 to 20 degrees, and at supersonic speeds raised to the best position for that Mach number.

To improve takeoff and subsonic performance, the wing was moved forward on the fuselage until the aircraft was slightly unstable for takeoff and landing; thus, a hard stability-augmentation system is required. This wing location resulted in positive elevon deflection at takeoff and a maximum trimmed lift coefficient C_L of over 0.6.

The results of the subsonic stability and trim analysis are presented in figure 4. These data were derived from wind-tunnel coefficients of the SCR configuration which has an identical wing planform. The data were modified for changes in aerodynamic center and zero-lift pitching moment caused by the differences between the fighter and the SCR fuselages. With a lift coefficient of 0.60 for the climb-out condition, the configuration is 3 percent unstable, and it is trimmed with 5 degrees of downward elevon deflection. For a landing lift-coefficient of 0.55 the aircraft is 6 percent unstable, and it trims with 10 degrees of downward elevon deflection. The data indicate that there is more than adequate trim control for both takeoff and landing.

Figure 5 indicates that, by selectively choosing the tanks from which fuel is burned, the center of gravity can be controlled so that the aircraft cruises with essentially zero trim-drag. The left side of the envelope describes the center-of-gravity variation when fuel is burned from rear to front, and the right side describes the variation when fuel is burned from front to rear. The dotted line indicates the center of gravity position for minimum trim drag.

Structures. - The configuration was conceived to be of all titanium structure with a skin-stringer fuselage and one-inch thick honeycomb-sandwich wing panels. The aircraft weights were estimated using an in-house, statistical weight-estimation technique, based on correlations with advanced aircraft concepts. As a result of using advanced titanium materials, the body weight was reduced by 30 percent and the wing weight was reduced by 10 percent. Table I is a sample group weight statement for the shallow body, thick wing configuration with a limit load factor of 4.0.

Propulsion. - The engine type selected for this study is the Pratt and Whitney VSCE 516 (Variable Stream Control Engine). It is an advanced engine designed for a Mach number of 2.7 on a standard day. It is essentially a duct burning turbofan with variable-area primary and secondary nozzles and with the capability of controlling its air requirements internally so that it has a minimum of spillage and boattail drag. Variations in thrust loading for the airplane concepts of this study were obtained by sizing the engine characteristics in accordance with scaling laws supplied by the manufacturer.

Interior Arrangement. - The general interior arrangement of the aircraft studied is shown in figure 6. Space is provided for a 15 x 61 cm (20 x 24 inch) phased array radar and 5.78 kN (1300 lbf) of avionics in three locations. Space is also provided for an M61 gun and ammunition drum. The cross-hatched area on the upper fuselage (planform view) depicts the assumed location of a missile bay for two 11.12 kN (2500 lbf) missiles. The fuel volume for the wing was calculated by assuming that only 80 percent of the apparent volume was usable for fuel tankage because of the one inch thick honeycomb wing panels. For the skin-stringer fuselage, 92 percent of the internal tank volume was assumed usable. The internal fuselage tank volume was calculated by assuming that there was 3 inches between the external mold line and the inside of the tank.

Variations of Wing and Body. - In an effort to determine the sensitivity of mission range to fuel capacity, four airplane concepts were designed. Fuel volumes were calculated as described above for each concept. The aircraft were combinations of a "shallow" or a "deep" body with a "thin" or a "thick" wing. The basic configuration consists of the shallow body with the thin wing. The deep-body design consisted of increases in cross-sectional area primarily in the region of the fuselage tankage. The cross-sectional areas were enlarged by increasing the height of the upper fuselage centerline by approximately 16 percent. The resulting larger fuselage volume increased the aircraft fuel capacity by about 19 percent, but, it caused a 4.5 percent reduction in the maximum lift-to-drag ratio L/D at a Mach number of 2.62. The thin wing was approximately 3 percent thick at all spanwise locations, whereas the thick wing was 6 percent thick at the body line, and decreased linearly to 3 percent at the vertical fin location (86 percent of semi-span). The thick wing increased the aircraft fuel capacity by about 22 percent, but it resulted in an 11 percent reduction in the maximum lift-drag ratio at a Mach number of 2.62.

Performance Ground Rules. - Performance was calculated for cruise missions at Mach numbers of 0.9 and 2.62, with and without the 22.2 kN (5000 lbf) missile payload (fig. 7). The missiles, when carried, were retained throughout the mission profile thus representing the worst possible case. The takeoff fuel allowance was 570 kg (1250 lbm); a fixed climb profile was used for both missions; climb was continued at cruise Mach number to find the best altitude; and cruise was completed at constant Brequet factor. No descent range credit was given, and the reserve fuel allowance was 5 percent of total fuel.

TRADE STUDIES

Range as a Function of Thrust Loading. - Figure 8 illustrates, for all configurations, the range sensitivity to thrust loading T/W for both the supersonic and the subsonic missions with zero payload. The variations for each airplane were developed by varying the engine size while holding the fuel load constant; that is, by allowing takeoff gross weight to increase with increasing engine size. For the supersonic mission, thrust loadings of up to 0.5 for this augmented engine can be used without significantly reducing the range. Increasing thrust-weight ratio to 1.0 decreases the range by about 2.04 Mm (1100 n.mi.) for the supersonic mission, and it decreases the range at a Mach number if 0.9 by about one-half. The high level of performance suggests that some compromise toward higher T/W would be acceptable if necessary to improve maneuverability.

The solid symbols at or near the maximum range capability for each configuration indicate aircraft with the same engine size (that is; thrust level). These selected aircraft were used as the base aircraft for several subsequent trade studies.

Range as a Function of Both Thrust Loading and Wing Loading. - The sensitivity of mission range to variations in thrust loading (engine size) and wing loading (wing area) for a given aircraft concept can best be shown by a "thumbprint" diagram. Figure 9 is a sample thumbprint for the deep-body, thick-wing airplane flying the supersonic cruise mission. Contours of constant range are shown as a function of thrust loading and wing loading for a constant takeoff weight of 235 kN (52823 lbf). The contours were developed with the aid of the computer program described in reference 3, which generates performance for a matrix of aircraft configurations with varying values of T/W and W/S. For each aircraft, the operating weight empty O.W.E. is adjusted (with respect to the input reference design) for wing loading changes by assuming a constant fuselage weight, and then adjusting the wing weight as a function of wing area. Engine weights are adjusted in accordance with scaling laws supplied by the engine manufacturer. The airplane aerodynamic characteristics are adjusted for the effects of wing area changes and for effects of both flight altitude and nacelle size on skin friction drag.

The symbol at the "eye" of the thumbprint, at a wing loading of 4.79 k Pa (100 lbf/ft^2), represents the maximum range that can be attained for this takeoff weight. Limit lines which represent physical or operational restraints may be superimposed on the range contours. The major restraint for the present study is the fuel-limit line. Aircraft to the left of this line do not have sufficient fuel volume (because of decreased wing size) to obtain the calculated ranges. Aircraft to the right of the line are not full of fuel (excess volume). The takeoff field length shown was selected to intercept the fuel-limit line at the greatest permissable range, since no specific field length was required in this study. The field-length line is included primarily to indicate the typical variation on the thumbprint grid.

The symbol at the intercept of these two overlaid limit lines represents the maximum range that can be obtained within the restraints. The range is 7.82 Mm (4220 n.mi.) which is close to the unrestrained maximum range, being only 0.24 Mm (130 n.mi.) shorter. The thumbprint diagrams for the other aircraft of this study are similar with respect to the range contours; however, as would be expected the range penalty due to the fuel limit restraint is more severe for the aircraft with the shallow body and thin wing. Although maneuverability characteristics are not represented on this figure, the typical approach to increase maneuverability is to increase T/W, decrease W/S, or both. These changes would result in shortening the maximum range.

Effect of Design Load Factor. - Figure 10 shows range as a function of design load factor for the four airplanes studied. It indicates that, if the sole consideration is the supersonic mission, there is little to choose between the four airplanes. Regardless of configuration, if design load-factor is increased from the base value of 4.0 to 9.0 the range penalty is about 0.93 Mm (500 n.mi.). If T/W is also increased, as is usually the case for a maneuvering airplane, there would be an additional range penalty as indicated on figure 8.

Effect of Fuel Volume. - A summary is presented in Table II for the four airplanes studied for a design limit load factor of four. The takeoff gross weight varies by about 35.6 kN (8000 lbf) because of differences in the fuel fraction which varies from 0.50 to 0.59. The engine size and wing are the same for all four aircraft, therefore T/W and W/S vary with changes in takeoff weight. The operating lift-drag ratio in supersonic flight varied from 6.2 for the deep-thick airplane to 7.3 for the shallow-thin airplane; however, the advantage in L/D was offset by reduced fuel fraction resulting from the reduced volume. On the other hand, the configuration with the highest fuel fraction had the greatest range for the subsonic mission because the lower fineness ratio of the large fuel-fraction airplane had little effect on the subsonic aerodynamic characteristics.

The supersonic mission range was also estimated with a 22.2 kN (5000 lbf) payload, consisting of two missiles. It was assumed that the missiles would displace 610 kg (1350 lbm) of fuel and that O.W.E. would increase by 1.56 kN (350 lbf). For each airplane, the range when carrying these missiles over the entire mission was about 1.39 Mm (750 n.mi.) less than the range with zero payload.

CONCLUDING REMARKS

This study of a supersonic cruise military aircraft (supercruiser) concept indicates that,

1. Supersonic ranges in excess of 7.5 Mm (4000 n.mi.) at a Mach number of 2.62 are possible with a 222 kN (50,000 lbf) class aircraft.

2. Thrust-weight ratios of as much as 0.5 (with augmented engines) can be used without significantly decreasing supersonic range; however, increasing thrust-weight ratio to 1.0 decreases supersonic range about 2.0 Mm (1100 n.mi.).

3. The supersonic range penalty for increasing limit load factor from 4.0 to 9.0 is about 0.93 Mm (500 n.mi.).

4. The increased fuel volume (size) of several aircraft studied herein improved the subsonic range by about 2.2 Mm (1200 n.mi.), however, due to associated losses in supersonic L/D, fuel volumes had an insignificant effect on the range at a Mach number of 2.62.

5. The supersonic range penalty for carrying two 11.1 kN (2500 lbf) missiles is about 1.39 Mm (750 n.mi.).

REFERENCES

1. Design Conference Proceedings: Technology for Supersonic Cruise Military Aircraft. Volume I, AFFDL/FX, U. S. Air Force, 1976.

2. Morris, Odell A.: Subsonic and Supersonic Aerodynamic Characteristics of a Supersonic Cruise Fighter Model With a Twisted and Cambered Wing With 74° Sweep. NASA TM X-3530, 1977.

3. Fetterman, David R., Jr.: Preliminary Sizing and Performance Evaluation of Supersonic Cruise Aircraft. NASA TM X-73936, 1976

TABLE I. - GROUP WEIGHT STATEMENT

Configuration with shallow body and thick wing.
Limit Load factor 4.0

ITEM	kN		lbf	
STRUCTURE	42.655		9589	
Wing		17.624		3962
Tail		1.001		225
Body		9.764		2195
Landing Gear		5.783		1300
Surface Controls		5.369		1207
Nacelle		3.114		700
PROPULSION	30.052		6756	
Engines		21.267		4781
Inlet		5.560		1250
Fuel System		2.491		560
Miscellaneous Systems		.734		165
SYSTEMS AND EQUIPMENT	14.567		3275	
Instruments		.818		184
Hydraulic and Pneumatic		1.343		302
Electrical		1.588		357
Avionics/Electronics		5.783		1300
Armament		2.669		600
Furnishings		1.076		242
Air Conditioning/Anti-Ice		1.112		250
Auxiliary Gear		.178		40
WEIGHT EMPTY	87.274		19620	
Basic Operating Items		5.422		1219
BASIC OPERATING WEIGHT	92.696		20839	
Payload (M61 Ammunition)		.756		170
ZERO FUEL WEIGHT	93.452		21009	
Fuel		119.617		26891
TAKE-OFF GROSS WEIGHT	213.069		47900	
DESIGN WEIGHT (.60 Fuel)	165.225		37144	

TABLE II. - AIRPLANE FUEL VOLUME TRADES

All designs with same engine size and wing area.
Limit Load Factor 4.0

CONFIGURATION	Deep-Thick	Deep-Thin	Shallow-Thick	Shallow-Thin
TOGW, kN (lbf)	2350.0 (52823)	217.3 (48846)	213.1 (47900)	195.1 (43850)
O.W.E./TOGW	.41	.46	.44	.50
FUEL/TOGW	.59	.54	.56	.50
THRUST LOADING	.41	.44	.45	.49
WING LOADING, kPa (lbf/ft^2)	3.59 (75)	3.30 (69)	3.26 (68)	2.97 (62)
TAKE-OFF DIST., m (ft)	2520 (8260)	2210 (7260)	2150 (7040)	1860 (6100)
OPERATING L/D, M = 2.62	6.20	6.87	6.51	7.30
RANGE[1], @ M = 2.62, Mm (n.mi.)	7.82 (4220)	8.00 (4320)	7.76 (4190)	7.56 (4080)
RANGE[1], @ M = 0.90, Mm (n.mi.)	10.07 (5440)	8.61 (4650)	9.35 (5050)	7.76 (4190)

[1]Long range cruise mission, zero payload.

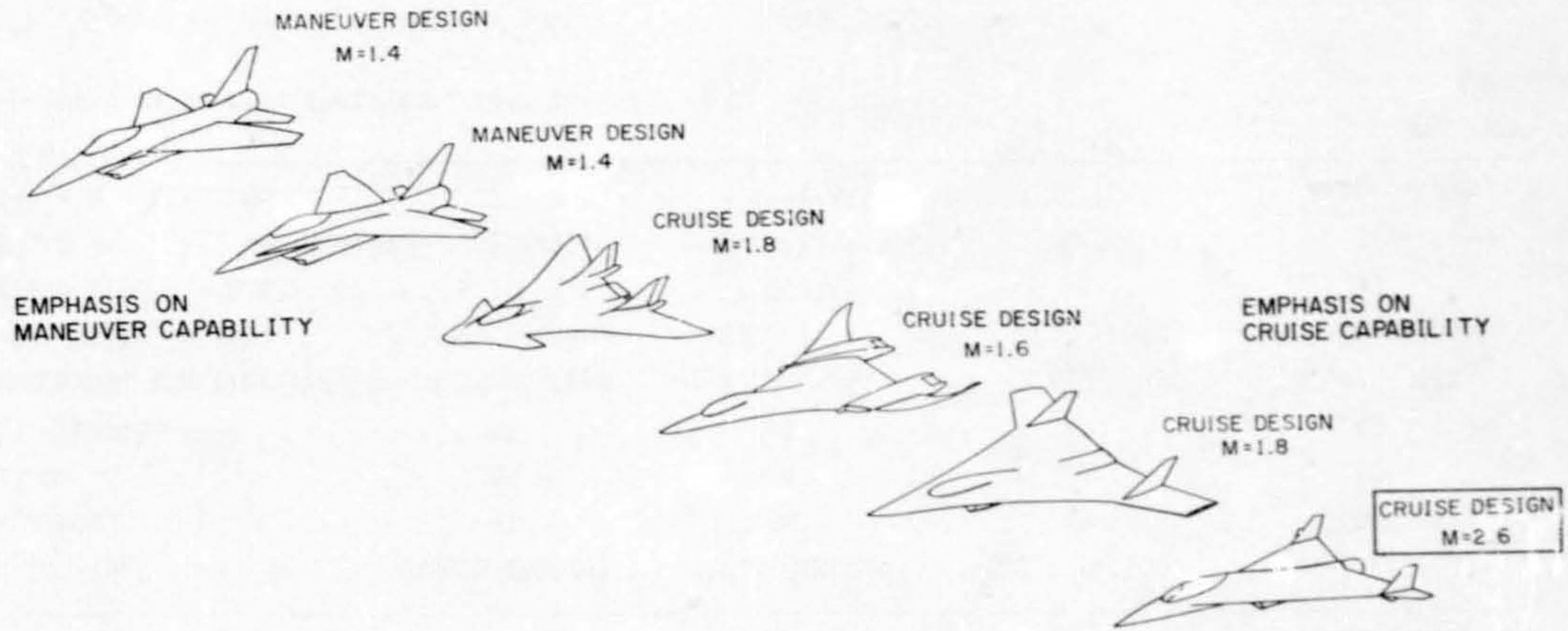

Figure 1. - Supersonic fighter concept program.

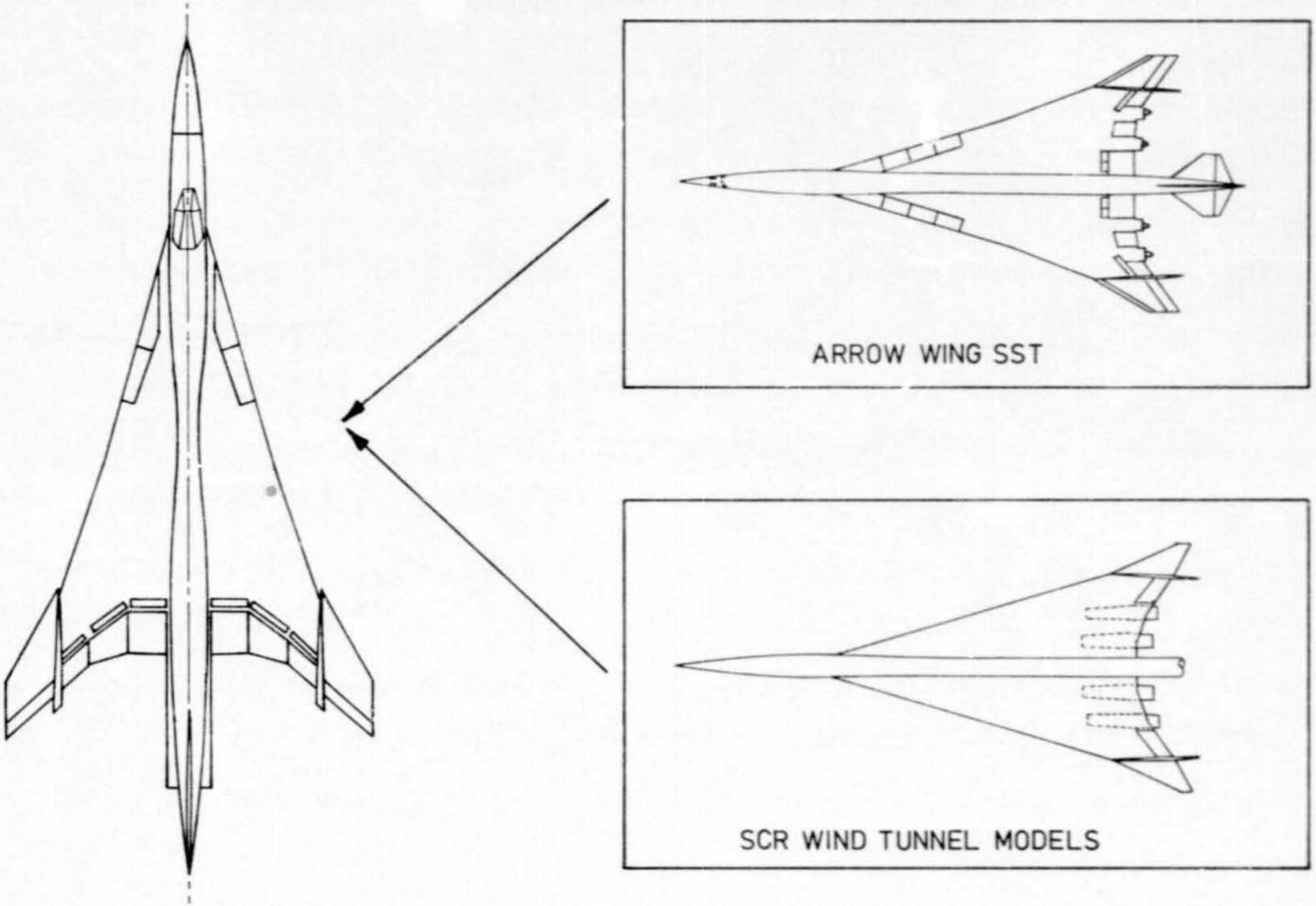

Figure 2. - Relationship of arrow-wing supersonic transport and supersonic cruise research (SCR) wind tunnel models to current study configurations.

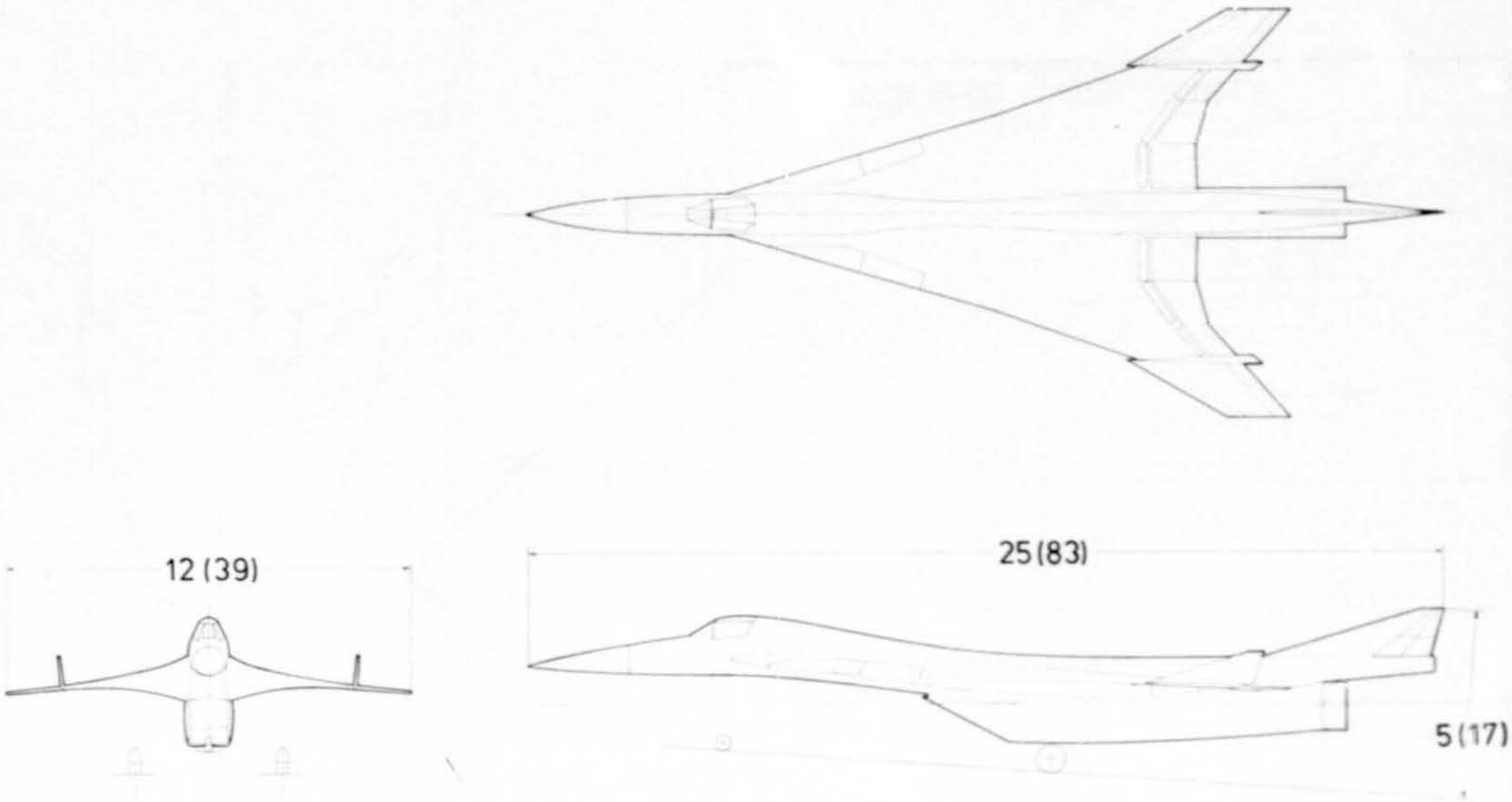

Figure 3. - Configuration concept. All dimensions in meters (feet).

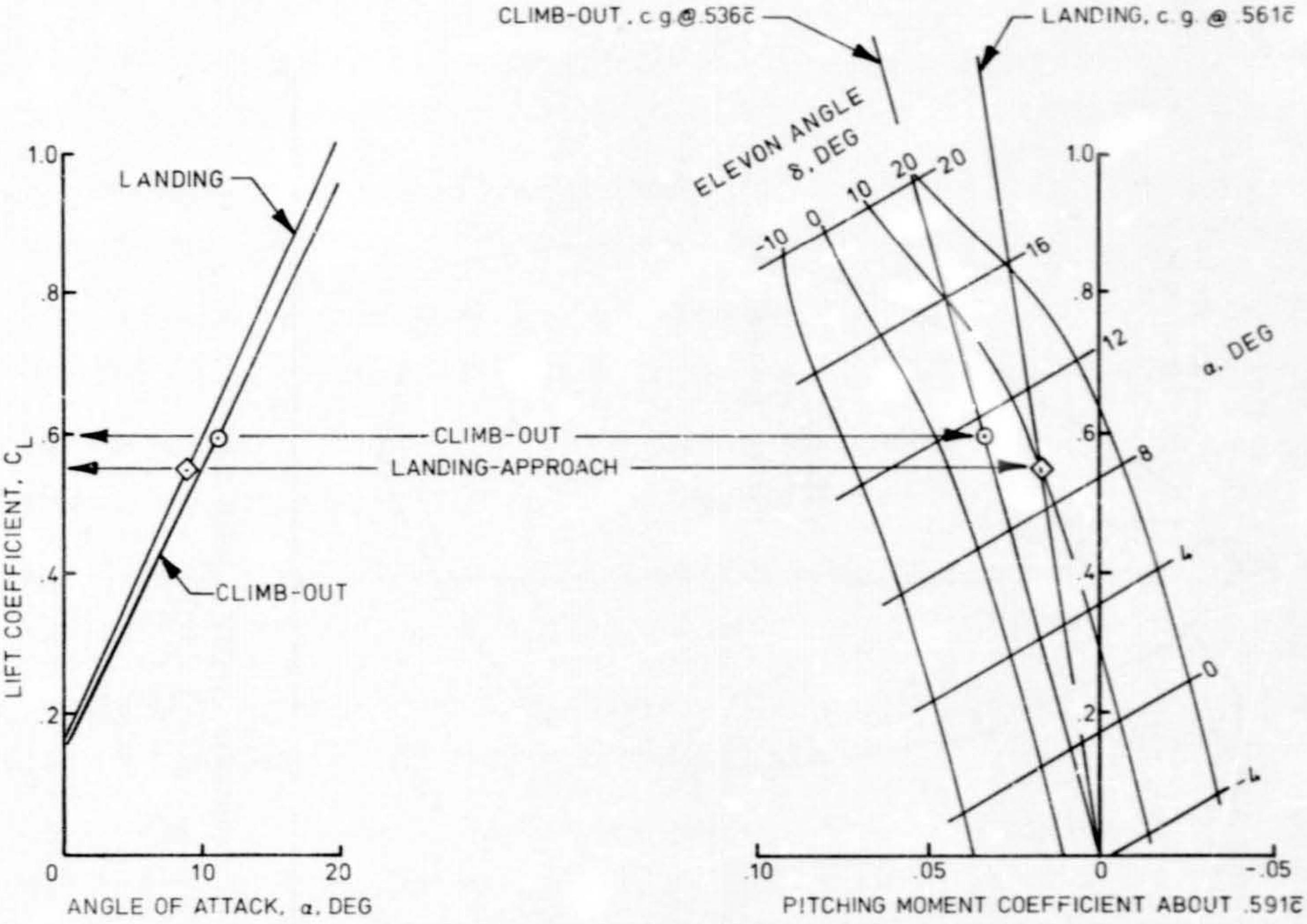

Figure 4. - Low speed static longitudinal stability and trim characteristics.

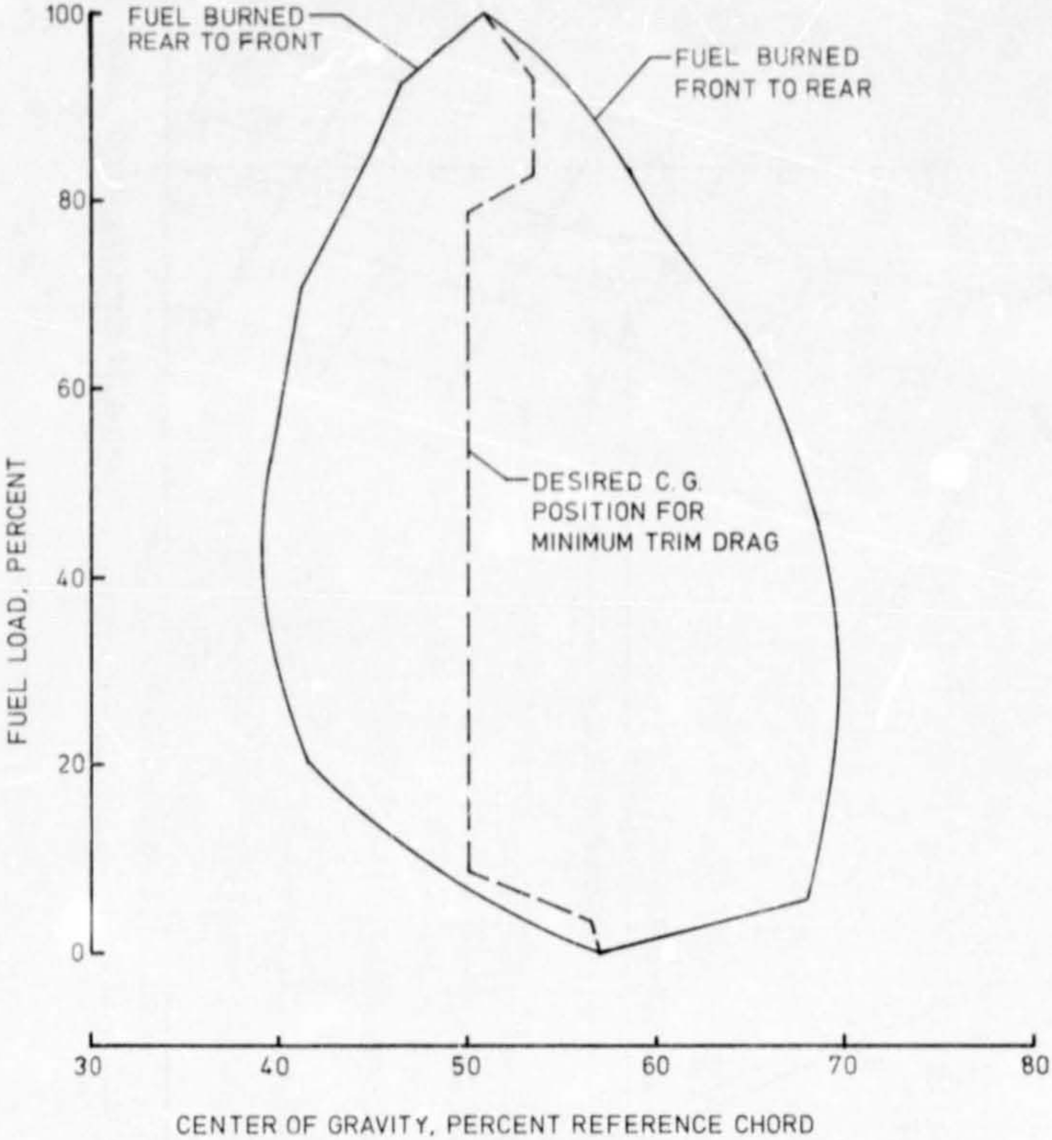

Figure 5. - Center of gravity excursion envelope, with selective fuel burning for minimum trim drag.

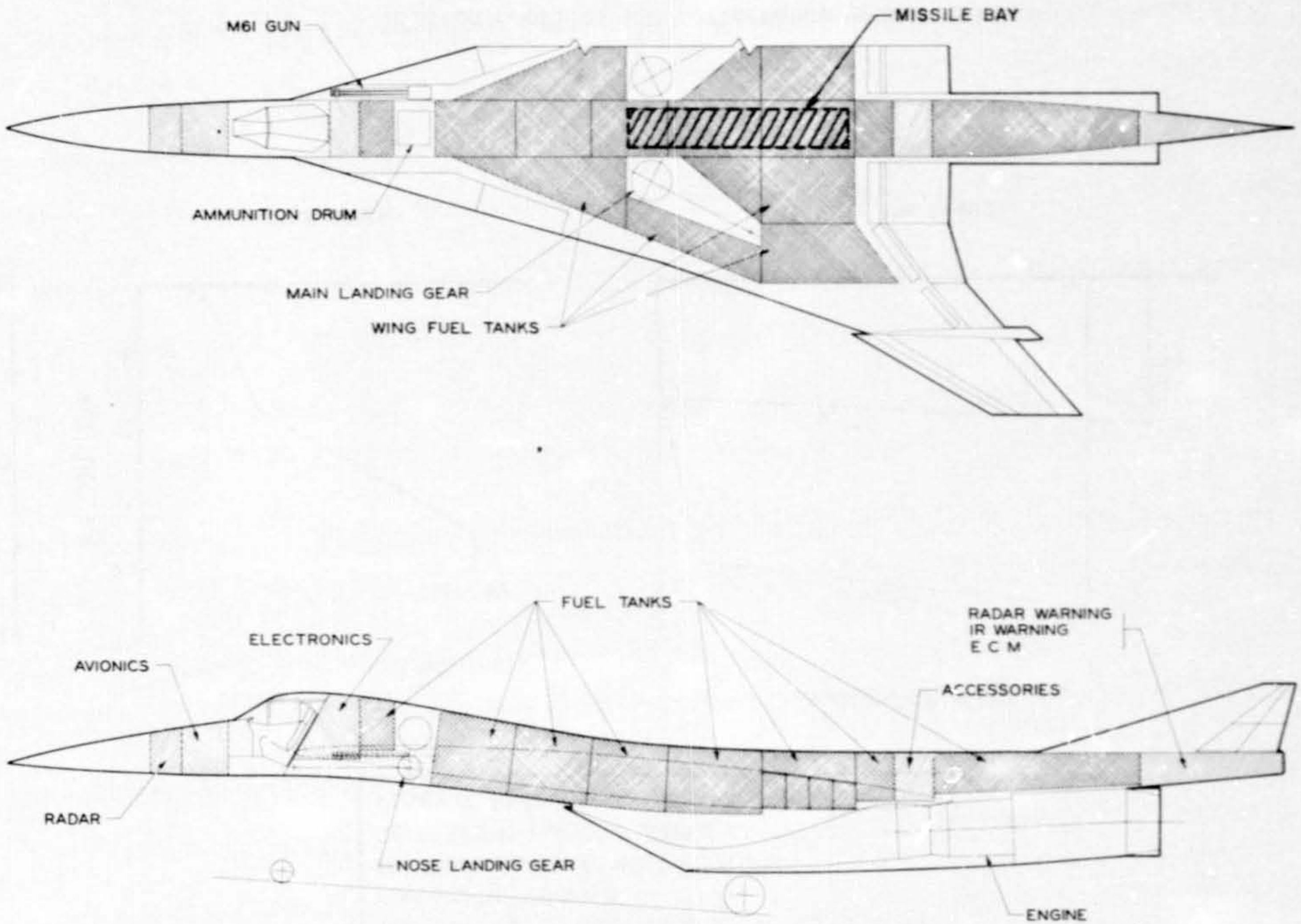

Figure 6. - General interior arrangement.

GROUND RULES

ALL PERFORMANCE FOR HOT DAY (+8 C)
LONG RANGE CRUISE MISSION M = .90 & 2.62
TAKEOFF FUEL ALLOWANCE IS 567 kg (1250 lbm)
FIXED CLIMB PROFILE
CLIMBING CRUISE AT BEST ALTITUDE
NO DESCENT FUEL OR RANGE CREDIT
RESERVE FUEL ALLOWANCE IS 5 % FUEL

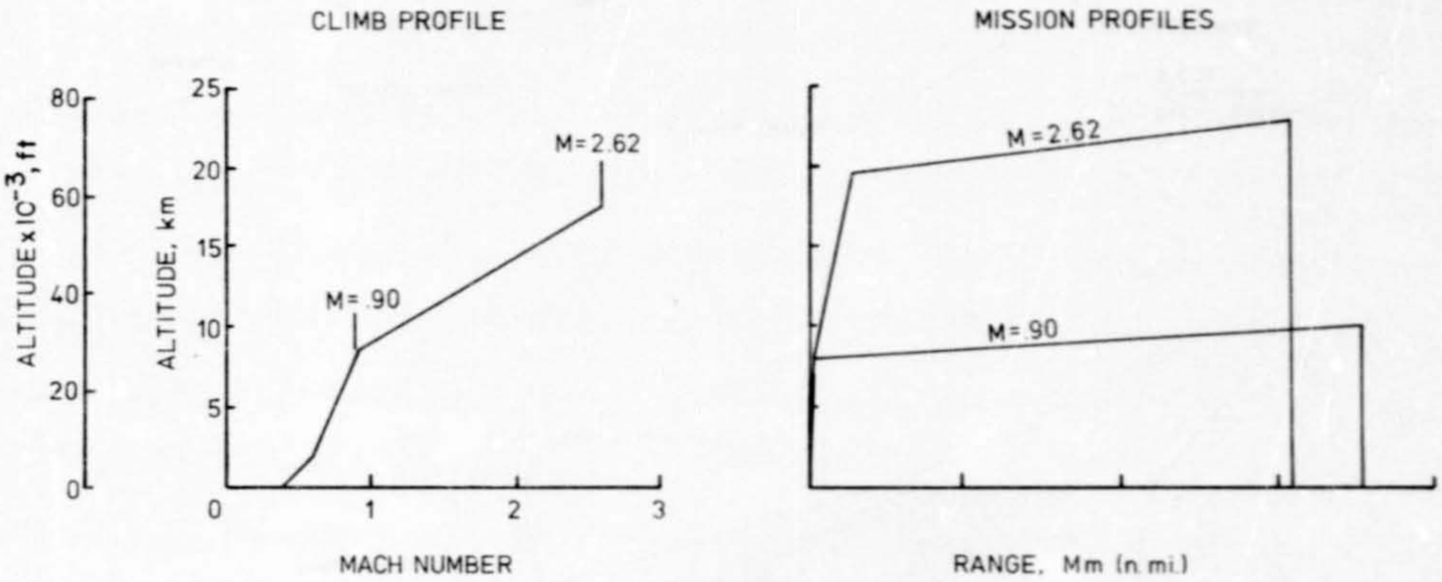

Figure 7. - Mission profiles and performance ground rules.

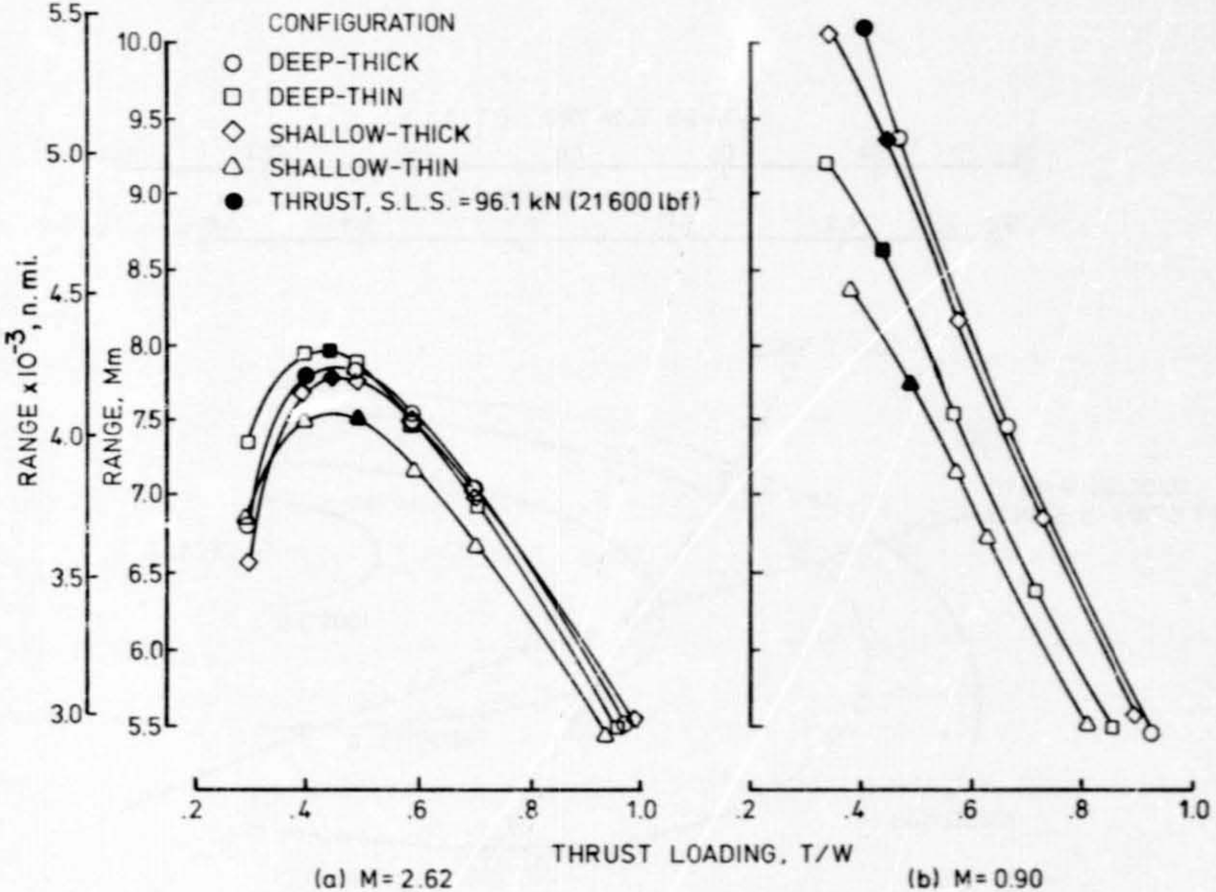

Figure 8. - Range sensitivity to thrust loading. Performance based on constant fuel and zero payload.

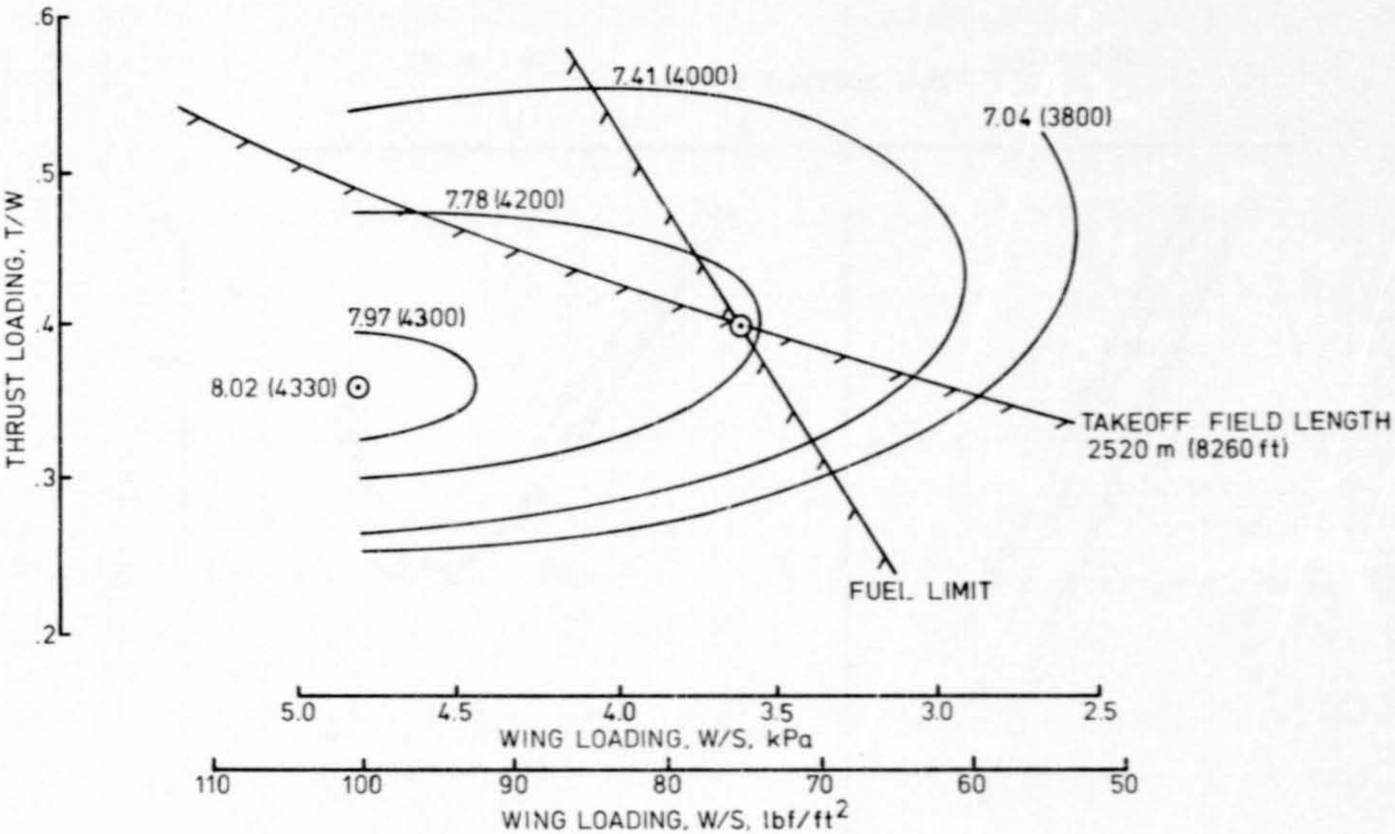

Figure 9. - Thumbprint diagram for the deep-thick configuration with a take-off weight of 235 kN (52823 lbf) for the supersonic mission with zero payload. The contour lines represent range in Mm (n. mi.).

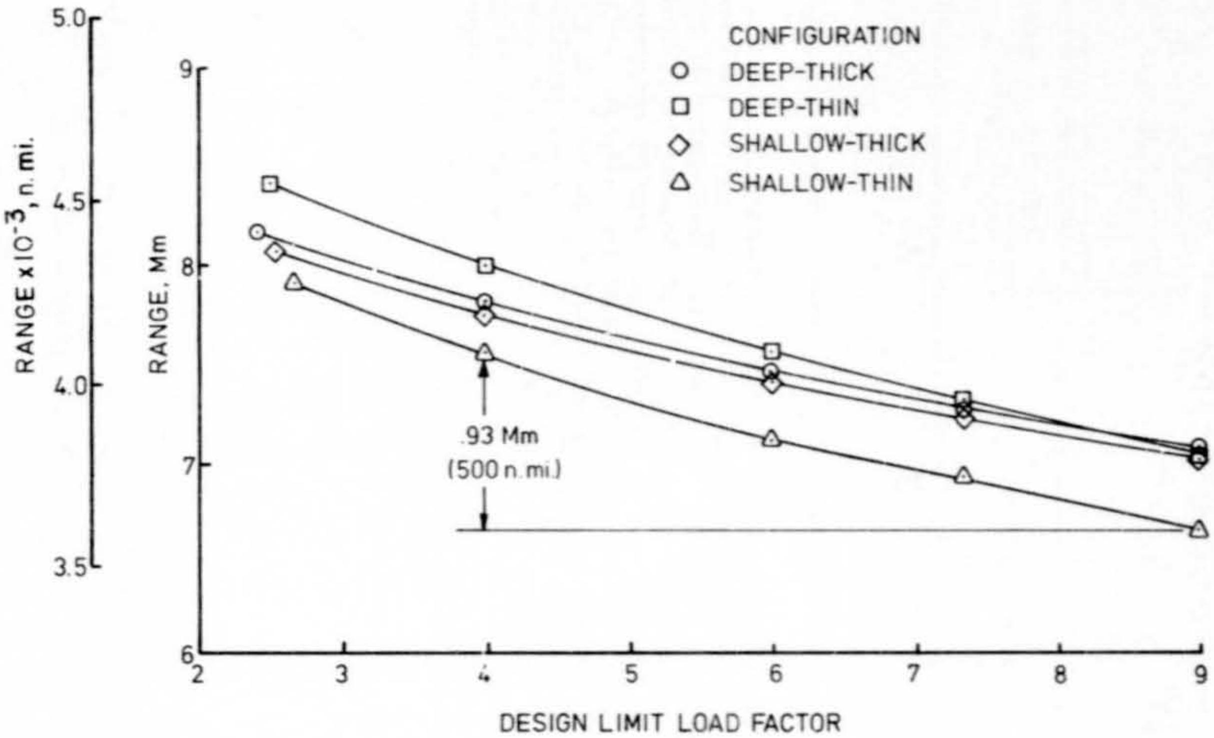

Figure 10. - Effect of design limit load factor on supersonic range. Constant engine thrust of 96.1 kN (21600 lbf).