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DYNA-SOAR AERODYNAMIC PERFORMANCE

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SUMMARY

The aerodynamic performance capabilities of the Dyna-Soar vehicle are summarized below.

The piloted vehicle has a wing area of 330 square feet and weighs 9,720 pounds for the "once-around" mission. This weight includes the pilot and 1,000 pounds of payload.

A test mission has been defined for a "once-around" flight starting at Cape Canaveral and ending at Edwards Air Force Base. The vehicle is launched in a safety boost trajectory to an end-of-boost speed of 105 feet per second above satellite speed at an altitude of 300,000 feet with a flight-path angle of 0°. The vehicle is pitched to a nominal lift coefficient of 0.45 and is held at that lift coefficient to a velocity of Mach 4 at 130,000 feet. It then completes its glide into the landing area at a lower nominal lift coefficient. Range correction, if needed during flight, is made by variation of lift-drag ratio only. Maximum altitude reached is 430,000 feet. For the due East launch, a bank angle of -15° is held during equilibrium glide to cause the vehicle to deviate from its great circle path to proceed to Edwards Air Force Base. Total mission time is 110 minutes.

Energy management studies have been conducted to show an ability to overcome range errors that would have resulted from boost dispersion errors and errors in assumptions of drag coefficient and density.

The vehicle has large maneuver corridors. Even in a banked turn for maximum lateral offset, the vehicle operates with a temperature margin of over 200° F for its most temperature-critical areas.

The vehicle has a large lateral maneuver capability. For an end-of-boost speed of 23,000 feet per second (relative), the vehicle can fly 2,200 nautical miles to the side, down to a speed of 800 feet per second. This side displacement increases to 2,500 nautical miles for an end-of-boost speed of 24,100 feet per second. These values are based on turbulent-boundary-layer assumptions. Additional capability to 2,900 nautical miles would be available if the boundary layer were laminar.

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A landing procedure has been devised to enable development of piloted, nonpowered landing capabilities. Subsonic maximum lift-drag ratio is 4.5. Speed brakes are provided to modulate subsonic aerodynamic characteristics. For down-range flights, a drag chute is provided. This drag chute and high-friction skids materially reduce runout distance.

INTRODUCTION

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The name "Dyna-Soar" is an abbreviation of the words dynamic soaring which are used to describe an equilibrium-flight process wherein a large fraction of the weight of the vehicle is supported by the centrifugal acceleration of high subsatellite velocities. The amount of aerodynamic lift required to maintain equilibrium flight is a small fraction of the weight of the vehicle and this fact results in the following flight characteristics:

1. Equilibrium-flight trajectories take place at extremely high altitudes

2. Vehicle longitudinal deceleration is a small fraction of a g

3. Extremely long ranges can be covered in unpowered gliding flight even when the vehicle has a small lift-drag ratio

4. The actual longitudinal range of the vehicle is directly dependent on its longitudinal deceleration which, in turn, depends directly on its lift-drag ratio. For good range control it is necessary for the vehicle to possess a wide range of lift-drag ratios.

Reliance on extreme speed to obtain longitudinal range imposes serious restrictions on the ability of the vehicle to maneuver in a lateral direction. Large lateral forces are required to make a heading change; however, the vehicle is limited in its ability to develop large lateral forces because of its high-altitude—low-dynamic-pressure glide trajectory.

The resulting ratio of lateral range to longitudinal range for the hypersonic glider is of the order of 1:5 as contrasted to a ratio of 1:1 which is the characteristic of subsonic or low supersonic airplanes. Although the range ratio as mentioned is small, the actual lateral-range capability of the Dyna-Soar is of the order of 2,500 nautical miles, a not inconsiderable amount.

Lateral maneuver control is also dependent directly on the range of lift-drag ratios possessed by the vehicle.

SYMBOLS

C_D	drag coefficient
C_L	lift coefficient
$C_{L,max}$	maximum trimmed lift coefficient
g	gravitational acceleration
h	altitude, ft
$\dot{h}$	rate of climb, fps
L	lift
L/D	lift-drag ratio
M	Mach number
n	maneuver factor, $\left(\frac{V^2}{rg} + \frac{L}{W} - 1\right)$
R	radius
r	flight-path radius of curvature
S	wing area, sq ft
V	inertial velocity, fps
V_i	indicated airspeed, knots
W	weight, lb
W/S	wing loading, lb/sq ft
α	angle of attack, measured from lower surface center line
β	sideslip angle, deg

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γ flight-path angle, deg

ϕ bank angle, deg

Subscripts:

e equilibrium flight

l structural limit

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DISCUSSION

General Arrangement

The general arrangement of the Dyna-Soar glider is shown in figure 1. Some pertinent dimensions are as follows:

Wing area, sq ft	330
Fin area, each, sq ft	31
Elevon area, sq ft	34
Rudder area, each, sq ft	10
Fold-out fin, each, sq ft	9
Forward area uptilt	15 percent S
Angle of tilt, deg	4

The weights and wing loadings of the Dyna-Soar are summarized as follows:

	Step I		Step IIA	
	Weight, lb	W/S, lb/sq ft	Weight, lb	W/S, lb/sq ft
On launch pad	9,280	28.1	9,720	29.4
Reentry	9,190	27.8	9,450	28.7
Landing	8,890	27.0	9,060	27.5

All weights include pilot plus 1,000 pounds of payload. The primary differences for the weights going from Step I to Step IIA are the increased expendable allowances and increased tank sizes to house those expendables.

The center of gravity is located at 63 percent of the reference root chord and varies less than 1/2 percent throughout the flight. The

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reference root chord is 400 inches measured from the theoretical apex of the wing.

Flight Envelope

The flight envelope for the Dyna-Soar launched eastward is shown in figure 2. The recovery ceiling is the locus of points on the h-V diagram at $\gamma = 0^{\circ}$, from which the glider could successfully reenter its flight corridor without violating its structural limits. It is of interest primarily to insure that a terminated boost trajectory would not place the glider into a regime from which it could not recover. The equilibrium glide trajectories are those for hypersonic values of $C_{L,max}$ of 0.69 and of C_L for $(L/D)_{max}$ of 0.15. The minimum flight-altitude line is that where the vehicle becomes structurally limited.

The overall flight corridor at 20,000 feet per second is 60,000 feet. For flight at this speed the dynamic pressure ranges from 15 pounds per square foot at $C_{L,max}$ to 120 pounds per square foot at the minimum flight altitude. Reynolds numbers at these conditions range from 0.2 to 1.2×10^6.

Maneuver Corridors

Maneuver corridors are shown in figure 3 as a function of velocity at three lift coefficients. The maneuver corridor is defined as the altitude difference between the altitude for equilibrium glide at a given lift coefficient and that at which the vehicle is limited structurally at the same lift coefficient.

Of pertinent interest is the fact that large corridors are available at all speeds and lift coefficients for vehicle operation. The smallest corridors are evident at a speed of 20,000 feet per second and this speed will be closely approached during Step I tests.

The importance of the corridor depth can be better understood when it is realized that the vehicle operates at temperatures 100° F lower than its limit for each 6,000 feet of corridor depth. Furthermore, its ability to generate aerodynamic lift doubles for 15,000 to 18,000 feet of depth.

Allowable Maneuver Factors

The maneuver factors available to the Dyna-Soar vehicle at a relative velocity of 20,700 feet per second and the limitations which

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restrict these maneuver factors are shown in figure 4. The ordinate is the altitude and the abscissa is the maneuver factor, described as $\left(\frac{L}{W} + \frac{V^2}{rg} - 1\right)$.

At 20,700 feet per second the value of $\frac{V^2}{rg}$ is approximately 0.73. This is the percent of vehicle weight that would be supported in the absence of aerodynamic lift. For flight at $C_{L,max}$, it is seen that there is no lift contribution to the maneuver factor at 400,000 feet due to extremely low dynamic pressure. For operation at a lower altitude, the aerodynamic lift becomes appreciable. At 258,000 feet, the lift provides equilibrium-flight capability. At still lower altitude the increased lift provides maneuver capability and would increase to very large values if there were no structural limitation imposed on the vehicle for flight at $C_{L,max}$. However, it can be seen that point 2 on the vehicle has met its temperature limit at the altitude of 241,000 feet. Similarly, for flight at $C_L = 0.14$ there is no contribution of lift at high altitudes, but for lower altitude operation the lift contribution again becomes appreciable. Equilibrium glide is established at $h = 223,000$ feet, and, as the vehicle is flown at lower altitudes, significant load factors are developed until the vehicle again becomes structurally limited (due to temperature) along the wing leading edge. The complete boundary of temperature limitations and the maneuver factors that are allowed at various lift coefficients are illustrated in this figure.

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It can be seen that the nose limitation is imposed over a small portion of the h-n diagram and that the dorsal-fin limitation cuts off the low-lift-coefficient operation capability at approximately $C_L = 0.09$ in equilibrium flight. This circumstance makes it possible to fly the vehicle at a lower altitude at $C_L = 0.14$ than at the equilibrium altitude for $C_L = 0.09$ because of temperature relief on the dorsal fin at the higher angle of attack. It can be seen that the maneuver factor required to fly in a 45° banked turn is easily accommodated within the allowable maneuver factors.

For this speed the maneuver factor allowed to the vehicle at $C_{L,max}$ is 0.37; at $C_L = 0.45$, it is 0.6; and at C_L for $(L/D)_{max}$, it is 0.45.

It should be noted that there is an upper limit of C_L that the vehicle cannot surpass when starting at any given C_L in equilibrium glide. This restriction in attitude-change capability becomes important in longitudinal-range control capability, since the full range of lift-drag ratios cannot always be applied. For instance, if the vehicle were in equilibrium at $C_L = 0.14$, the maximum C_L that could be "pulled" would be 0.5.

There is an approximate relationship between the shaded area to the right of the equilibrium line and the shaded area to the left of that line. The upper bound of the shaded area to the left of the equilibrium line is the recovery ceiling of the vehicle at this speed. This relationship follows from the consideration that the maximum vertical velocity of the vehicle attained by starting at the recovery ceiling at $\gamma = 0^{\circ}$ is given by the expression

$$\dot{h} = -\sqrt{2\int_{h_{\text{recovery ceiling}}}^{h_e} n(h)dh}$$

For the vehicle to recover, positive vertical acceleration acting over an altitude depth must be applied to decrease the vertical velocity to zero. The amount available within the bounds of the h-n diagram to the right of equilibrium flight is

$$\dot{h} = \sqrt{2\int_{h_e}^{h_l} n(h)dh}$$

These two values of $\dot{h}$ must be equal and opposite in sign and they are defined by the shaded areas as previously mentioned.

The exact determination of the recovery ceiling is more complex since the horizontal velocity does not remain constant throughout the recovery maneuver.

Drag Polars

The trimmed drag polars for the Dyna-Soar in equilibrium flight are shown for speeds ranging from subsonic to a Mach number of 25 in figure 5. These values are based on turbulent skin friction. At a Mach number of 5, the percent of drag that is skin friction ranges from 15 at $(L/D)_{max}$ to less than 1 at $C_{L,max}$. At a Mach number of 20, this percent ranges from 30.5 at $(L/D)_{max}$ to less than 5 at $C_{L,max}$. There is a small decrease in $(L/D)_{max}$ with increasing hypersonic speed due to the reduction in Reynolds number in the flight corridor and a small reduction in the lift-curve slope. The lift coefficient

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for $(L/D)_{max}$ is essentially constant for the hypersonic speed range as is the angle of attack for $(L/D)_{max}$ which is 15°.

At Mach number 20 the following relationships prevail:

C_L	L/D	α, deg
0.15	2.18	15
.45	1.5	29
.69	.8	50

The ratio of maximum to minimum lift-drag ratios is 2.7, which is an index of equilibrium-glide range-control capability.

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Mission Profile

For the once-around mission from Cape Canaveral to Edwards Air Force Base, the altitude, range, and time are shown in figure 6. The velocity at boost burnout is 105 feet per second above satellite speed at 300,000 feet. This speed is chosen for a nominal flight at $C_L = 0.45$ to be flown to the vicinity of the landing area. This value of C_L and the 300,000-foot injection altitude were chosen so that the vehicle could aerodynamically correct, prior to leaving the sensible atmosphere, boost dispersion errors and errors in the assumptions of vehicle drag coefficient and in density at that tape-line altitude. The nominal mission time is 110 minutes.

Range Control Capability

The range control capabilities during the once-around mission is shown as a function of velocity in figure 7. For a mission which required no range correction the value of C_L would be maintained at 0.45 to approximately 100 miles short of touchdown. In the event that an accumulation of errors requires range correction, there exists a capability to extend the range over 20,000 miles by flying at $(L/D)_{max}$ or to shorten the range by over 10,000 miles by flying at $C_{L,max}$. These range-correction capabilities are significantly greater than conceivable errors that could be made in assumptions in drag coefficient or air density. Most of the range-correction capability exists in the same speed-altitude regime where these errors would have significance. During equilibrium glide the vehicle flies at its proper density altitude;

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consequently, there would be no error introduced by inaccurately known density at a given tape-line altitude. A range-correction capability of ±3,000 miles exists for equilibrium flight.

Lateral-Turn Capability

The maximum lateral-turn capability is shown as a function of velocity at the start of the turn in figure 8. Essentially no lateral-turn capability is available until the vehicle has begun equilibrium flight. The maximum capability is attained by flying at the lift coefficient for $(L/D)_{max}$ and at a bank angle of 45°. It can be seen in the figure that most of the lateral displacement is achieved through turns initiated at the higher velocities. Lateral-turn control extends from zero displacement to those displacements shown.

Terminal Flight Phase

A plan and profile view of the terminal flight phase is shown in figure 9. For the nominal glide trajectory at a little over 300 miles from the landing site, the vehicle is at a Mach number of 7, at 165,000 feet, and 10 minutes from touchdown. At this point the onboard inertial navigator will place the vehicle within an accuracy of ±2 miles in longitudinal range and ±6 miles in lateral displacement. The vehicle longitudinal- and lateral-range correction capabilities are ±100 miles and ±75 miles, respectively. The pilot receives radar-obtained data by radio and updates his inertial navigator readings. He makes range-to-go corrections and proceeds to line up with his landing site. At 30 miles to go he is in visual contact with the landing site at a Mach number of 2 and at 65,000 feet. At this point the vehicle can be landed within a radius of 10 miles of the assumed touchdown point. A pitot-static tube provides the pilot with indicated airspeed and altimeter information starting at a Mach number of 5.

Nominal Landing Profile

The nominal landing profile is shown in figure 10. Although the straight-in approach is pictured, the vehicle can land by using the circular approach developed at Edwards Air Force Base. The landing consists of a high-energy approach using an aiming point short of the runway and starting a moderate flare at an altitude of 1,100 feet. The flare ends 200 feet over the end of the runway and the vehicle decelerates to touchdown at a small rate of sink. Considerably less than the 8,000 feet of runway are used to perform the landing, which allows a high tolerance of touchdown point miss.

During the approach and flare the vehicle configuration is clean except for nominal setting of the speed brakes. At the end of flare, landing skids are extended and the speed brakes are full open. At touchdown a 10-square-foot drag chute is opened.

During the nominal approach the following conditions prevail:

$$\gamma = -22.5^\circ$$

$$\dot{h} = -180 \text{ fps}$$

$$V_i = 280 \text{ knots}$$

$$C_L = 0.10$$

L
1
1
1
2

The flare takes place at $n = 1.5g$ over a 10-second interval with a speed loss of 50 knots. During deceleration the rate of sink is 25 feet per second and time to touchdown is 7 seconds. The velocity at touchdown is 175 knots.

A large tolerance in speed along the nominal glide path exists. The speed may be between 210 knots and 350 knots. Also, there exists a large tolerance in flight-path angle to the aiming point. It could be between -15° and -30° without altering the touchdown point.

CONCLUDING REMARKS

The vehicle designed to perform the Dyna-Soar mission is capable of exploring the effects of hypersonic environment over a wide range of attitudes in a safe manner and can therefore obtain information pertaining to the design of a wide range of possible reentry shapes. It possesses a large longitudinal-range and range control capability, a large lateral-range capability, and can land in a conventional manner, features which will aid in the overall system test and are potentially of military value.

GENERAL ARRANGEMENT

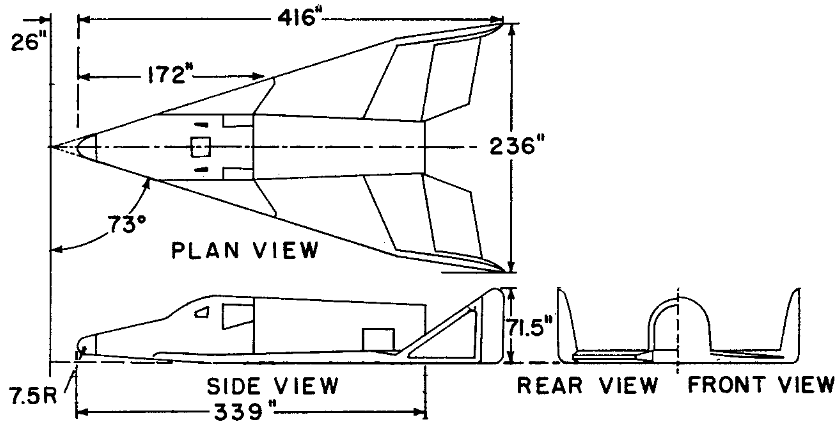

Figure 1

FLIGHT ENVELOPE
W/S=29.0 PSF

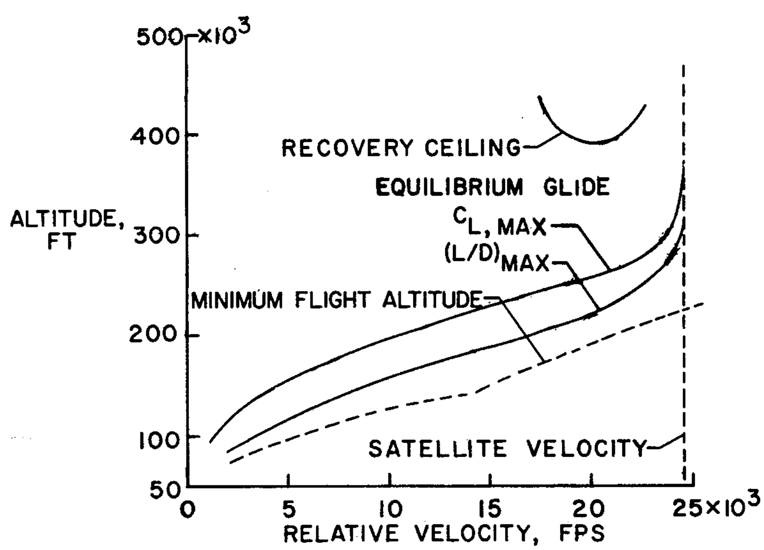

Figure 2

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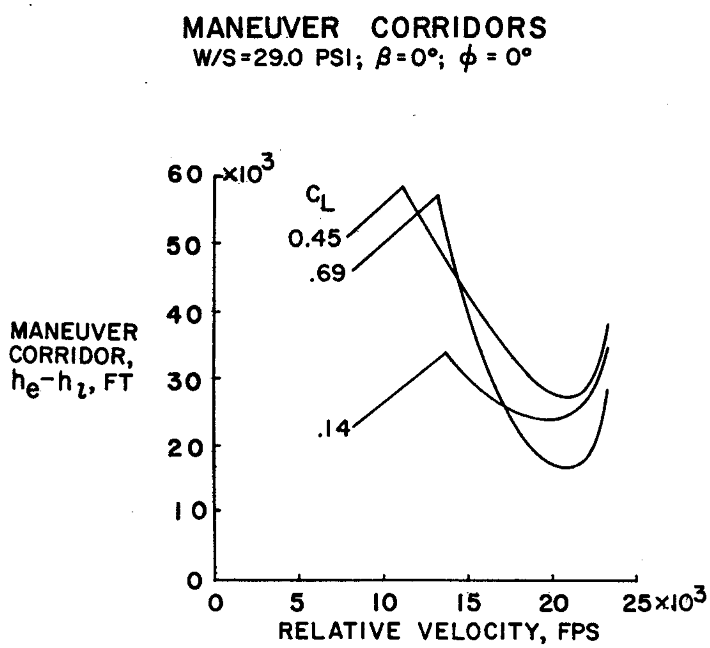

Figure 3

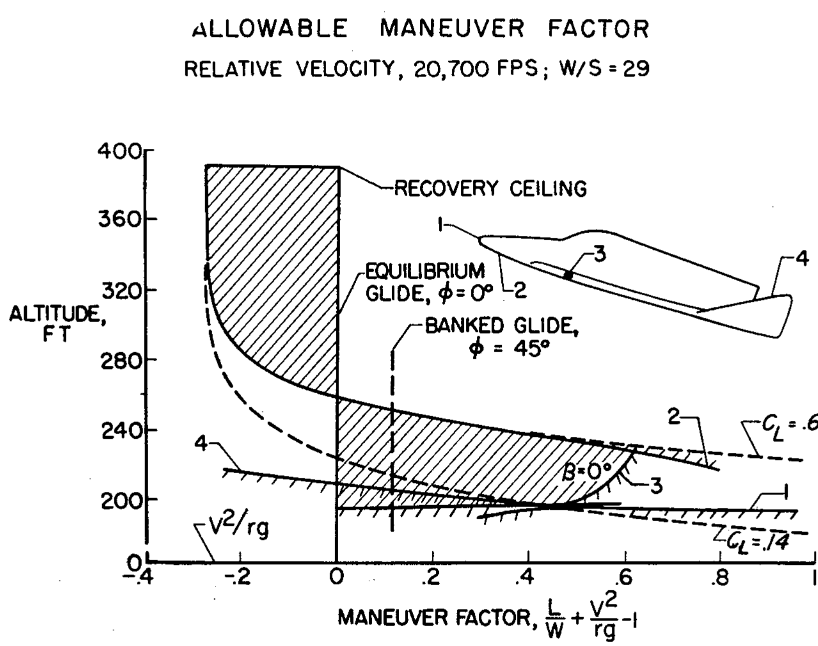

Figure 4

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DRAG POLARS

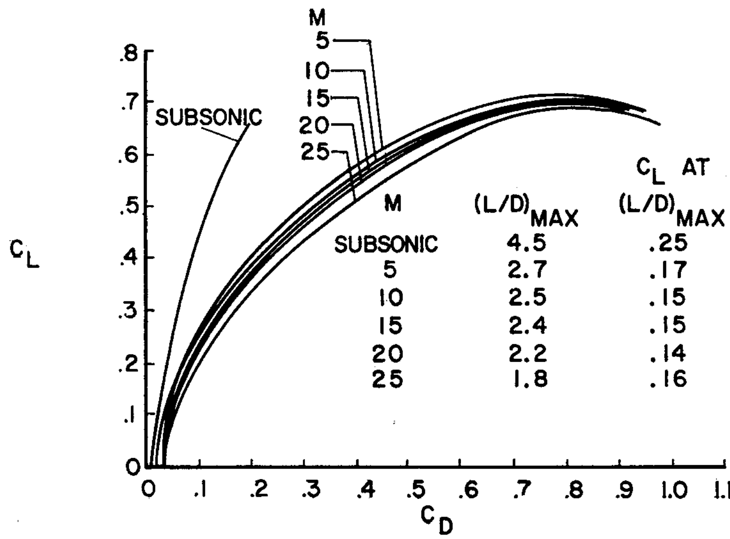

Figure 5

ONCE-AROUND-MISSION PROFILE

$C_L = 0.45$

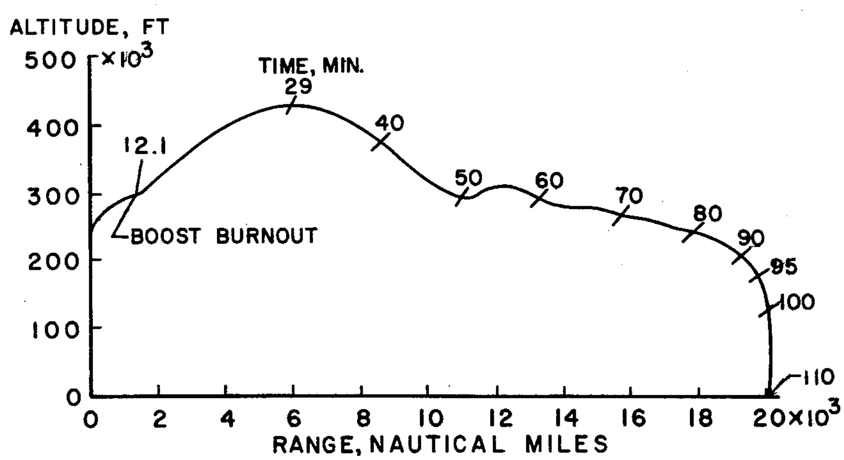

Figure 6

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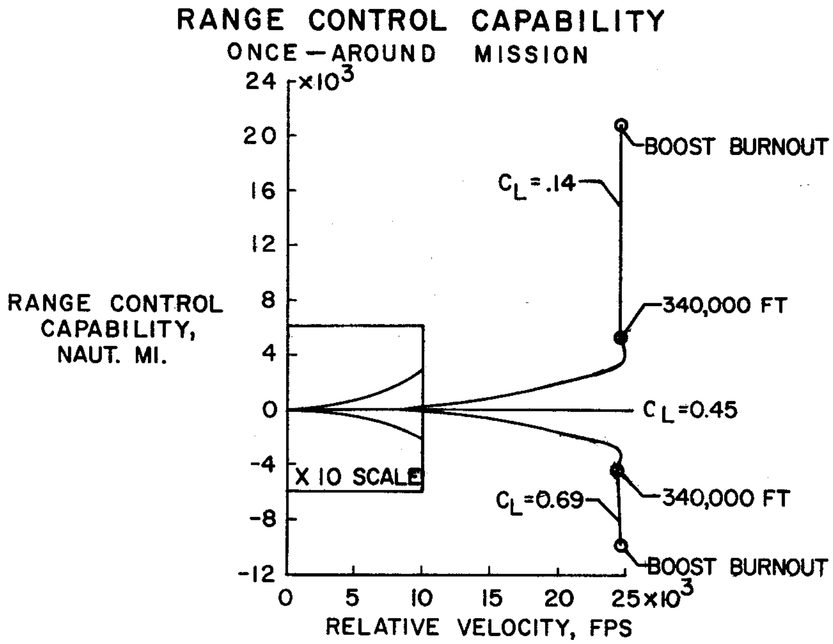

Figure 7

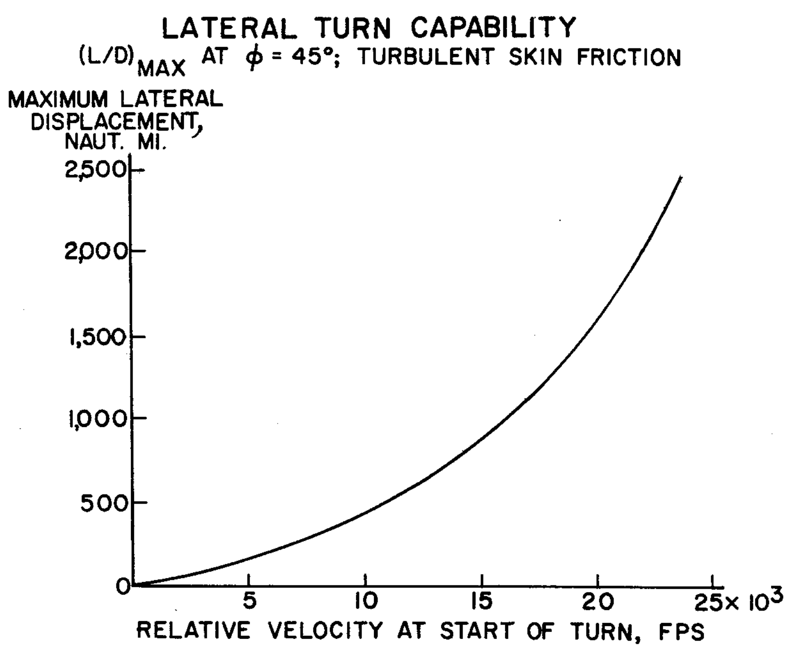

Figure 8

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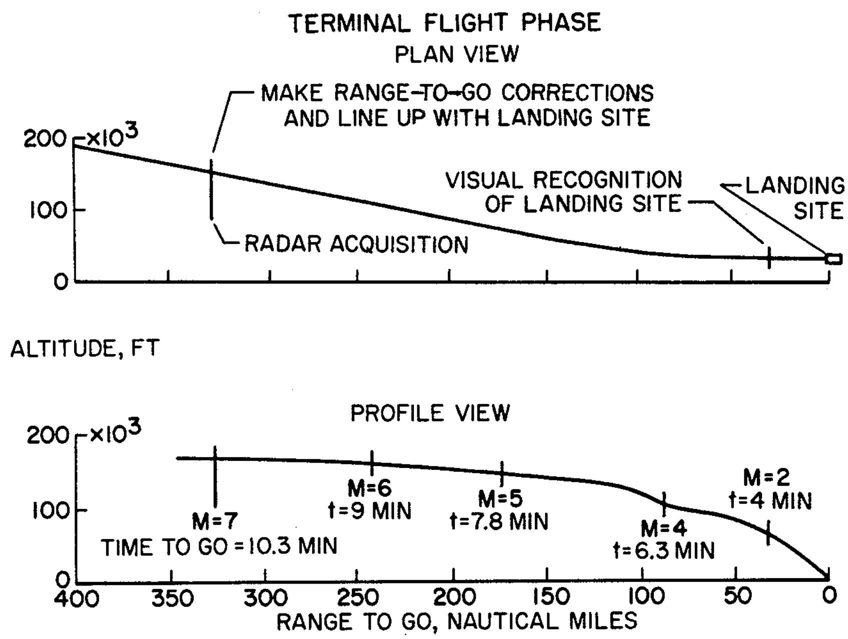

Figure 9

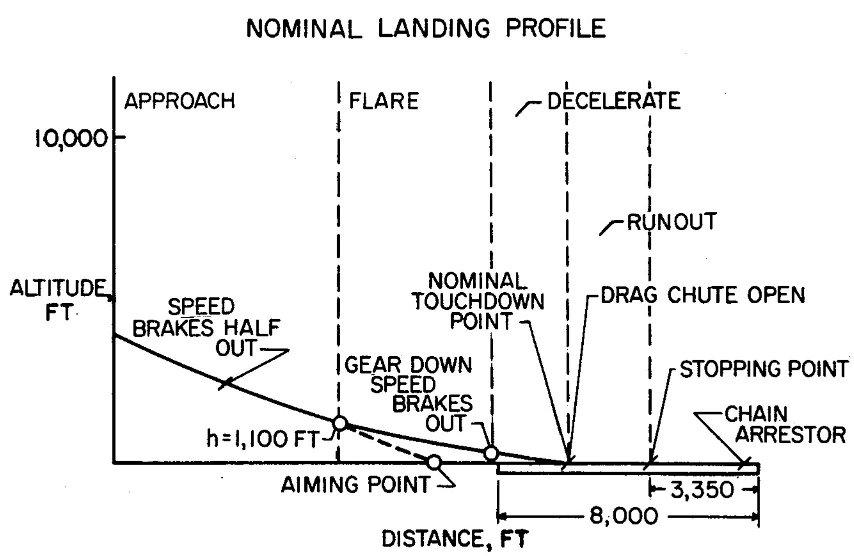

Figure 10

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