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THRUST VECTOR CONTROL REQUIREMENTS FOR SOLID-PROPELLANT LAUNCH VEHICLES

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CONTENTS

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SUMMARY

A study was conducted at the Lewis Research Center to determine the thrust vector deflection requirements for control of solid-based launch vehicles. Two launch vehicles were considered. The first is the Phase II version of the 260-inch solid-SIVB launch vehicle, as described in reference 1. Two payload shroud configurations were studied for this vehicle--those representing the Apollo and the extended Voyager configurations. In addition, a family of shroud shapes and densities was studied to determine the effects of these parameters on control requirements. The second vehicle considered (SSOPM) consists of seven 260-inch solid motors in the first stage, a large spherical solid motor in the second stage, and an orbital propulsion module (OPM) for the third stage. This vehicle was designed to deliver one million pounds of payload to a 100 nm circular orbit.

In the first part of the study, the thrust vector deflection angle (TVDA) required to control the vehicle during peak wind loads was calculated. It was found that approximately 1.6 degrees is required for the Phase II Extended Voyager vehicle and about 1 degree for both Phase II Apollo and SSOPM. In general, the TVDA required is a function of the vehicle and trajectory parameters, as well as payload shroud density and shape. However, for densities not less than 4 pounds per cubic foot

(the density of liquid hydrogen), the TVDA for the Phase II launch vehicle does not exceed about 1.7 degrees, regardless of payload shape. The TVDA required for effects other than winds, such as pitch program, thrust misalignment and dispersions was also calculated. It was found that approximately 0.4 degrees was required for these effects.

The second part of the study effort was concerned with reducing the TVDA requirements through the use of aerodynamic control surfaces. Two types of control surfaces are considered: stationary fins located at the base of the vehicle and movable canards located at the vehicle center of pressure. The effect of these surfaces is shown in the figures as a function of surface area.

RESULTS AND DISCUSSION

The thrust vector deflection angle requirements are calculated for two different launch vehicles--the Phase II 260-inch solid-SIVB and a large solid launch vehicle (SSOPM) designed to deliver one million pounds of payload to a 100 nm circular orbit. Some of the assumptions and groundrules of the study are listed below.

1. The nominal trajectory for each of the vehicles considered was designed by Lewis. Basically, the first (booster) stage was constrained to fly zero angle of attack through the atmosphere, after a rapid initial pitchover phase. The upper stages used a steering program generated by the Calculus of Variations, in order to maximize payload capability into a 100 nm circular orbit. The magnitude of the initial pitchover maneuver, which determines the amount of trajectory lofting, was allowed to be optimized to maximize payload capability, but with the constraint that the dynamic pressure should not exceed 970 psf.

2. Aerodynamic data (center of pressure and normal force coefficients) were obtained both from Lewis and Douglas (reference 1). The Lewis data is analytical, while the

Douglas data is partly analytical and partly based on SIVB flight data and Apollo capsule wind tunnel data.

3. An ETR launch was assumed for both vehicles with a launch azimuth sector of 45 to 120 degrees.

4. The results are mainly theoretical. However, one real wind and one synthetic wind have been simulated along with the Phase II Apollo vehicle on the Lewis six degree of freedom computer program. The results of these cases are presented and compared to the theory, and the agreement is excellent.

5. The autopilot was designed to fly the nominal pitch program (trimmed) regardless of wind disturbances. Other methods such as a load relief autopilot or biased pitch program will be discussed briefly later.

6. The TVDA results are based on a gimbal point located at the base of the aft flare, which corresponds to a liquid injection TVC system. If a gimballed nozzle were used, the gimbal point would be approximately at the nozzle throat, and the TVDA requirements would increase by approximately 15 percent.

The rationale for choosing a trimmed autopilot to calculate TVDA requirements can be seen by referring to figure 1. Assume a triangular shaped wind for which the maximum deflection capability of the vehicle is less than that required to trim at the peak of the wind. The deflection angle increases up to the stop, then remains at the stop until the wind dies down and trim conditions have been re-established. If the maximum deflection angle is less than the solid stability curve, the vehicle will never recover. Actual and analytical results show that divergence is quite rapid, even for δ_{max} about 10 percent less than the stability limit. The parameter β is vehicle and trajectory dependent, and is about $0.5(\text{sec})^{-1}$ for the vehicles studied. Effective wind durations are generally on the order of 8-15 seconds. Therefore, at least 70 percent of trim capability is required for stability.

For square shaped winds, essentially 100 percent of trim capability is required for stability.

Figure 3 presents the results of six degree of freedom trajectory simulations, using the Phase II Apollo vehicle and the synthetic wind profile shown in figure 2. The wind duration is about 8 seconds. Figure 3 shows that about 0.5 degrees of deflection is required to trim at the peak and between 0.3 and 0.4 degrees are required for stability. Both the peak deflection angle and the stability limit are in agreement with the theoretical results.

Figure 4 shows a real wind profile, measured on March 9, 1965, at Cape Kennedy (reference 2). The deflection angle required was again obtained by using a six degree of freedom trajectory program, and is presented on figure 5. The results for this case are also in good agreement with the theory.

The Lewis and Douglas aerodynamic data for the Phase II launch vehicles are presented in figures 6 and 7. The center of pressure data for the Phase II Apollo vehicle are in good agreement in the region of interest (60 to 70 sec.), but Lewis normal force coefficient data are high relative to the Douglas data. For the extended Voyager configuration, the differences in Lewis and Douglas data tend to offset each other, and the overall results are in excellent agreement.

Figures 8 and 9 compare the deflection angle requirements for the Apollo and extended Voyager configurations, using Lewis and Douglas aerodynamic data. The deflection angle trace represents the envelope of deflection angle requirements for a family of winds, each of which peaks at a different time (or altitude). The deflection angle profiles for the various winds are represented by the triangular spikes in figure 8. The peak wind velocity at each altitude corresponds to a 95 percent steady state wind corresponding to the worst monthly period (reference 3). A launch azimuth sector of 45 to 120 degrees was assumed in calculating the maximum deflection angles. Figure 10 summarizes the results for the Apollo and extended Voyager configurations using Lewis and Douglas aerodynamic data. Deflection requirements are about 0.9 degrees for the Apollo configuration, and 1.6 degrees for the extended Voyager. When these results are compared to the Douglas study of reference 1, good agreement is noted for the Apollo configuration, but reference 1 displays a deflection requirement of 3.6 degrees for the extended Voyager configuration. Discussions were subsequently held with appropriate Douglas technical staff members, and the discrepancy has been resolved. The Voyager requirement was re-evaluated by Douglas, and a requirement of 2.6 degrees resulted. This number was based on an omnidirectional wind model, which resulted in higher side wind velocities and, consequently, higher yaw deflection requirements. Since the allowable launch azimuth sector from ETR is approximately 45 to 120 degrees, it seems more reasonable to use the directional wind velocity model presented in reference 3 which results in the lower TVDA requirements quoted in this report.

Figures 11 through 14 demonstrate the possible reduction in deflection angle requirements through the use of stationary base fins or movable canards. These and subsequent data are based on the Lewis aerodynamic data. The normal force coefficients for both types of fins are taken from Lewis wind tunnel data and other experimental results.

The maximum lift coefficient for the canards was also obtained experimentally and is equal to about 0.8 for Mach numbers greater than one. The fin area in the figures corresponds to the total area of two fins in one plane. Actually, four fins would be required, two in each plane. The sketch of the Apollo vehicle in figure 11 is shown with base fins equal to .3 times the base area. The center of pressure of the fins is assumed to be at the gimbal station. The canards (figures 12 and 14) are placed at the center of pressure of the body.

The canard vs. base fin comparison is summarized in figure 15. The canards are more effective on the extended Voyager configuration, because the vehicle center of pressure is higher for this case. The canards would be more effective if they were placed higher on the vehicle. However, a detailed analysis would be required to optimize the location of the canards on the vehicle. This analysis would require consideration of vehicle bending moments and jettison problems as well as canard effectiveness. Both types of fins can be used to reduce the residual deflection angle to a value which could be attained by using a gimballed nozzle or by secondary fluid injection. For example, if 0.5 degrees of TVD is available for the Voyager vehicle, canards of one-half base area or base fins equal to the vehicle area would be required. Canard and base fin data for the SSOPM launch vehicle are shown in figures 16, 17, and 18.

The final part of the analysis determines the deflection angle requirements as a function of shroud density and cone angle for the Phase II launch vehicle. A payload weight of 95,000 pounds was assumed.

For a density of 4.4 pounds per cubic foot, figure 19 shows that the deflection angle required is about 1.2 degrees, for a cone semi-angle of 30 degrees. If payloads with densities lower than 4.4 pounds per cubic foot are encountered, aerodynamic surfaces could be added to the vehicle to maintain the deflection angle at 1.2 degrees for these configurations.

ADDITIONAL CONSIDERATIONS

Two other methods can be employed to reduce the gimbal angle requirement. These are biased pitch programs and load relief autopilots. Both of these methods should reduce deflection requirements somewhat, but more study is required in these areas to develop definitive results.

It should be noted that, in addition to the deflection requirements for winds, additional thrust deflection is required to compensate for such factors as thrust misalignment, pitch program, and vehicle dispersions. The TVDA required to compensate for these effects is summarized in Table 1. The dispersion values for thrust misalignment, thrust and weight were taken from reference 1, and were assumed to be the same for both vehicles studied. The TVDA required for pitchover was obtained from six degree of freedom computer simulations. The total TVDA requirement was calculated by adding the root-sum-square of the thrust misalignment, thrust and weight dispersion to the steady state wind requirement. The wind requirement was added, rather than root-sum-squared, since the wind profile is known at the time of launch. Since deflection angles required for pitchover and for winds occur at different times during the flight, the small pitchover requirement does not contribute to the overall TVDA requirement. Other effects, such as launch release transients and ground winds, have been studied and were found to be negligible compared to thrust misalignment.

If aerodynamic control surfaces are used, TVC must still be supplied to control the vehicle early in flight when these surfaces are ineffective. Simulations have shown that canards can supply enough torque to handle pitchover, but not thrust misalignment. If fixed base fins are used, TVC must be supplied for pitchover, thrust misalignment, and flight control and stability.

CONCLUDING REMARKS

A theoretical study of vehicle response to anticipated wind profiles has indicated that it is necessary to trim or nearly trim the vehicle to retain control after penetration into the high wind region.

Some discrepancies between LeRC and Douglas aerodynamic data have been uncovered. In spite of this, compensating circumstances have resulted in good agreement between the final results of the two studies.

Either movable canards or fixed fins are effective in providing aerodynamic forces and reducing thrust vector deflection requirements.

To provide control in the wind shear region, thrust vector deflection angles of 1.0 and 1.6 degrees are required for the Phase II vehicle with Apollo and Voyager payloads, respectively. Wind shear thrust vector deflection requirements for a very large solid-boosted vehicle were found to be small. Deflections of less than 1.0 degrees were required for the solid-solid-OPM vehicle capable of boosting one million pounds to orbit. For all the booster configurations of this report, an additional 0.4 degrees is required for effects such as thrust misalignment, ground winds, launch transients, and dispersions in thrust and weight. The pitchover requirement of 0.6 degrees is already available.

Total thrust vector deflection angles of 1.4 and 2.0 degrees are required for Phase II vehicles with Apollo and Voyager payloads, respectively. A total TVDA of 1.4 degrees is required for the SSOPM vehicle. These deflection angles can be reduced to less than 0.5 degree by the use of aerodynamic surfaces.

Thrust vector deflection requirements depend critically on payload density and shape. It appears reasonable to design the thrust vector control system for conventional payloads with densities of 4 to 20 pounds per cubic foot. Subsequently, if peculiar payloads are encountered which exceed the capabilities of the thrust vector control system, aerodynamic surfaces can be added to stabilize the vehicle without increasing deflection angles.

REFERENCES

1. Douglas Missile and Space Systems Division: Saturn IB Improvement Study (Solid First Stage), Phase II, Final Detailed Report, March 30, 1966.

2. Scoggins, James R. and Susko, Michael: Radar/Jimsphere Wind Data Measured at the Eastern Test Range, FPS-16, NASA TMX-53290, July 9, 1965.

3. Smith, O. E. and Daniels, G. E.: Directional Wind Component Frequency Envelopes, Cape Kennedy, Florida, Atlantic Missile Range, NASA TMX-53009, February 21, 1964.

Table 1

Thrust Vector Deflection Angle Requirements

		Deflection Angle (Deg.)		
Parameter	Variation	Phase II Apollo Configuration	Phase II Extended Voyager Configuration	SSOPM
Steady State Winds	95%	1.0	1.6	1.0
Thrust Misalignment	.25 Deg.	0.25	0.25	0.25
Thrust	2%	0.14	0.14	0.14
Weight	0.5%	0.05	0.05	0.05
Pitchover	Maximum	0.6	0.6	0.5
Total		1.4	2.0	1.4

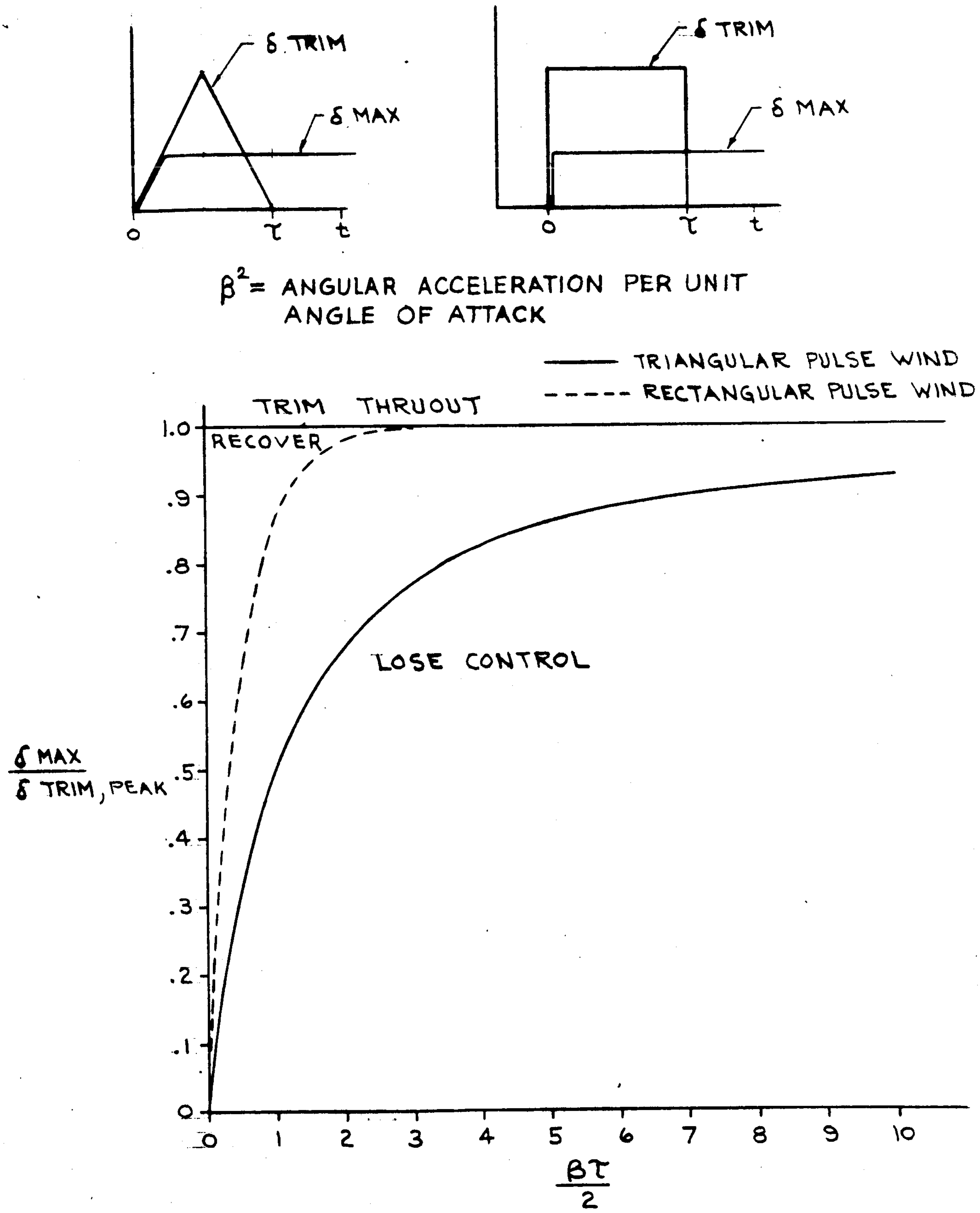

FIGURE 1. STABILITY LIMITS

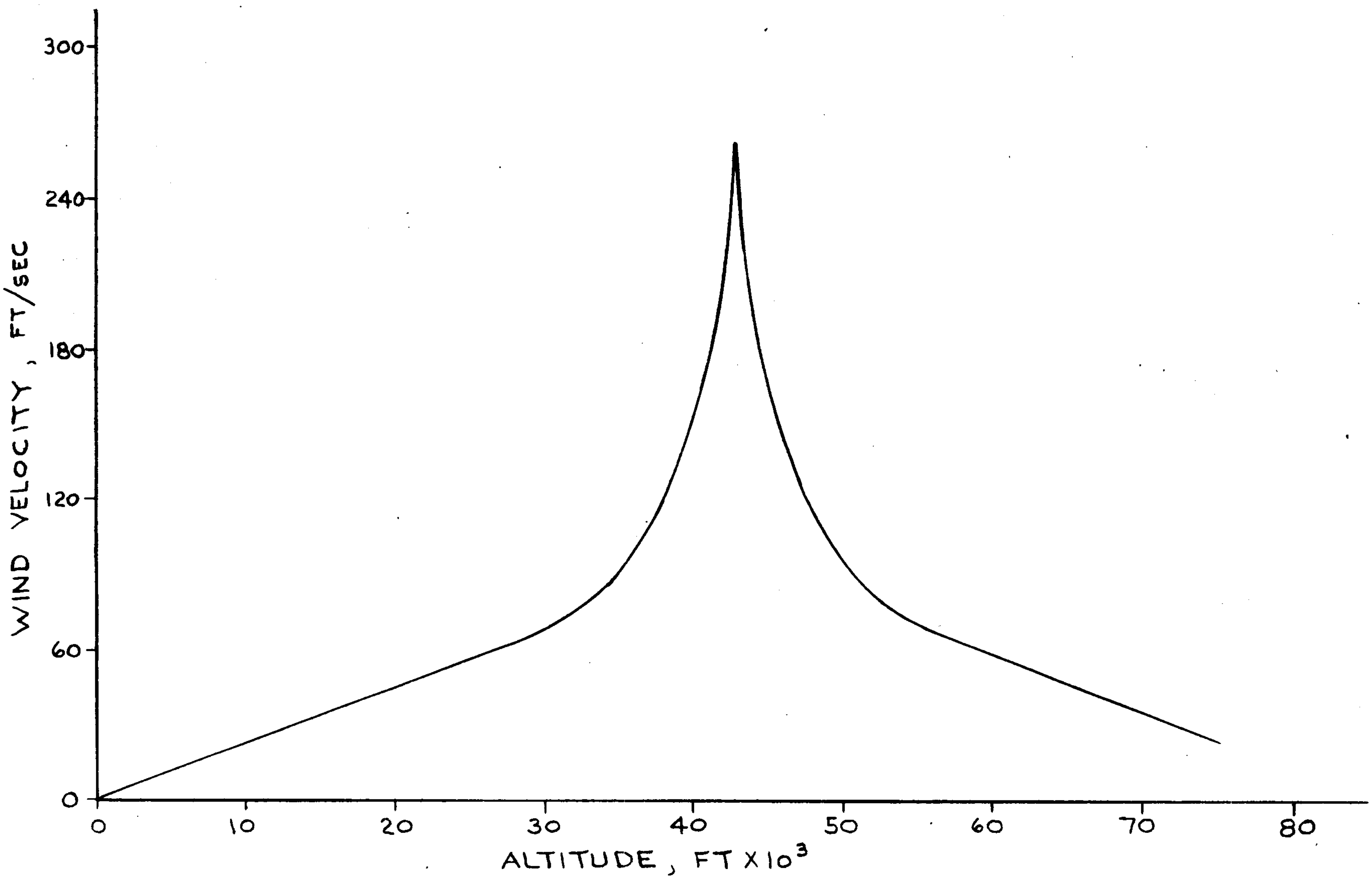

FIGURE 2. SYNTHETIC WIND PROFILE

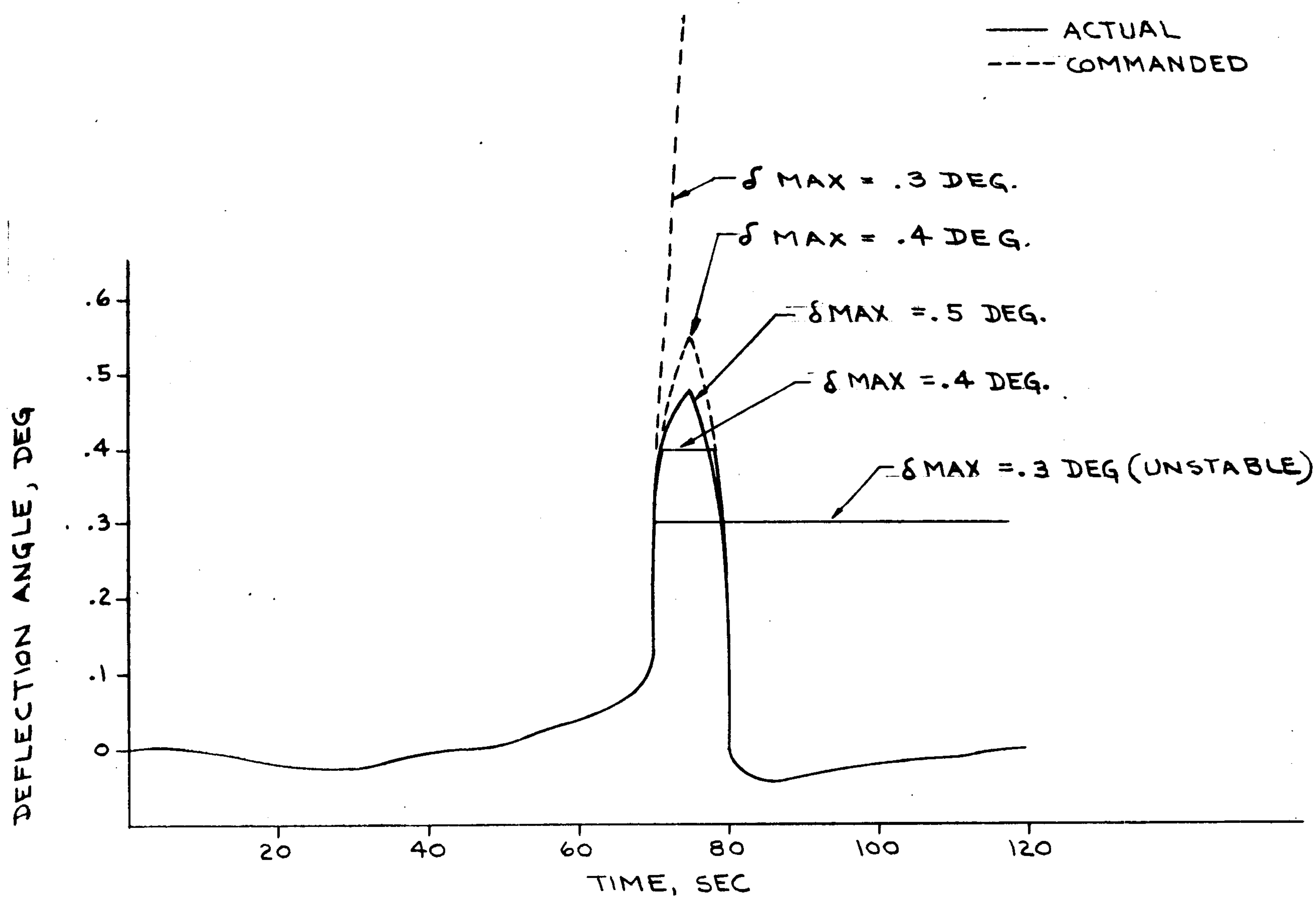

FIGURE 3. REQUIRED DEFLECTION ANGLE, SYNTHETIC WIND PROFILE, PHASE II - APOLLO LAUNCH VEHICLE

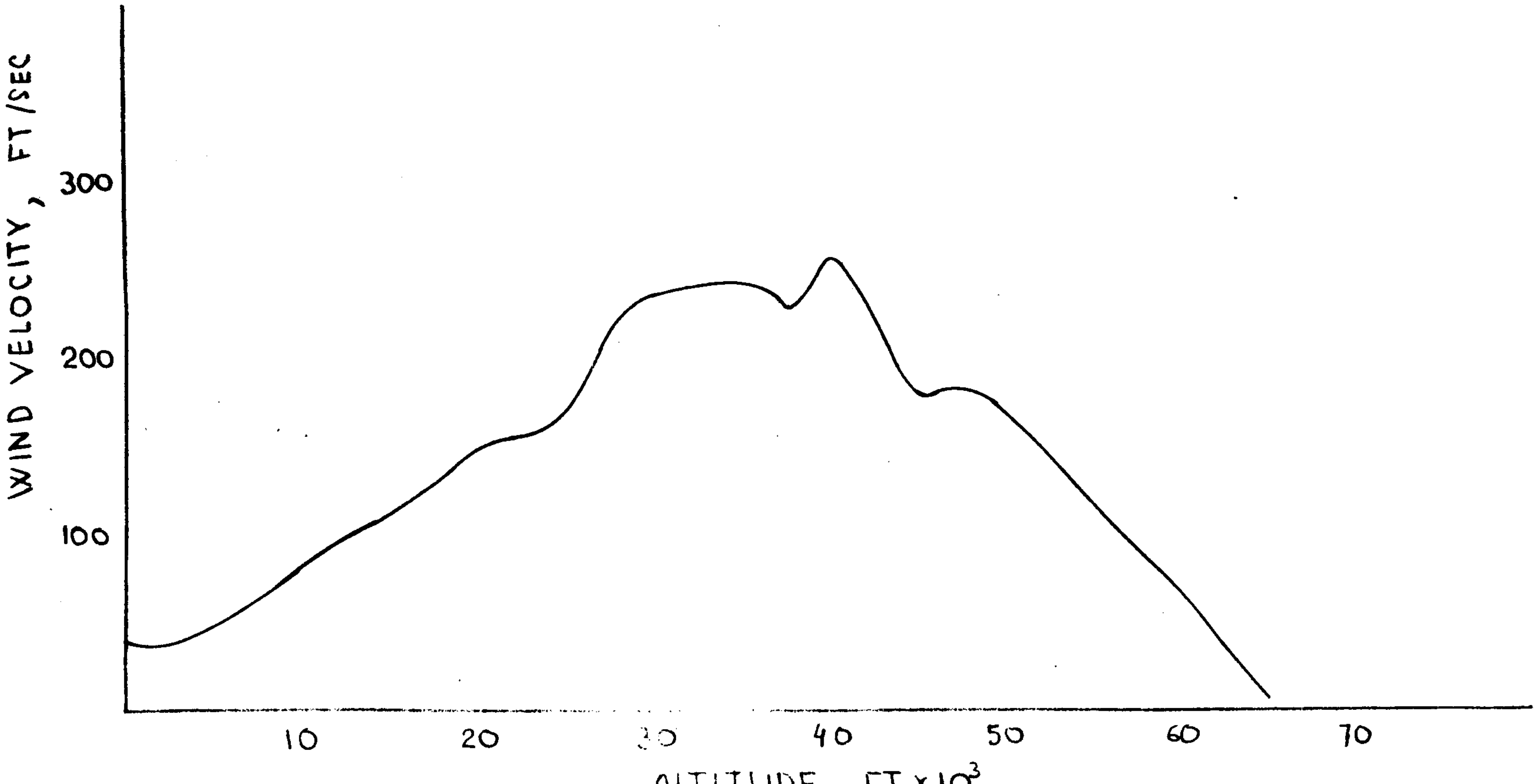

FIGURE 4 REAL WIND PROFILE

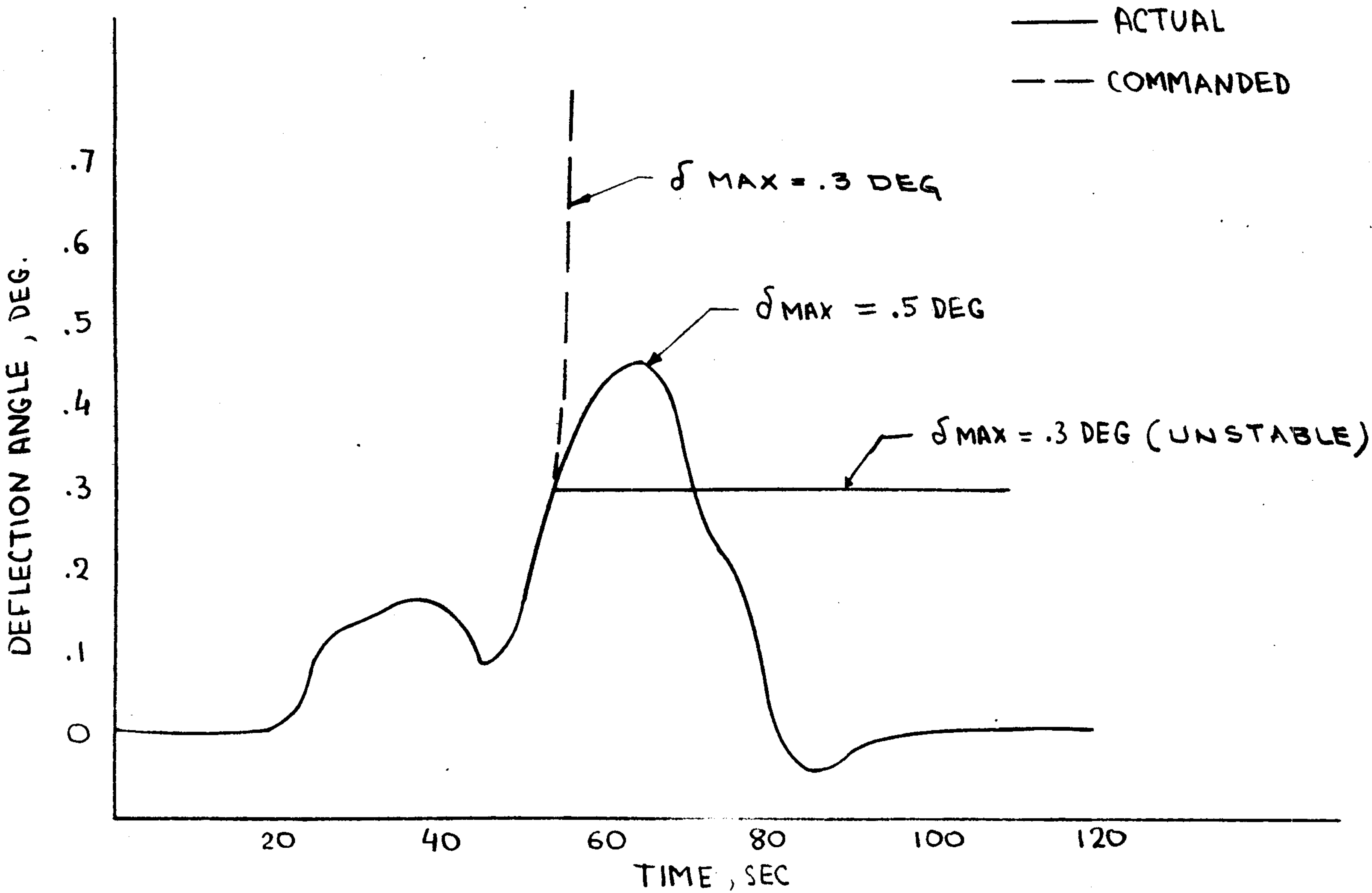

FIGURE 5 REQUIRED DEFLECTION ANGLE REAL WIND PROFILE.
PHASE II - APOLLO LAUNCH VEHICLE

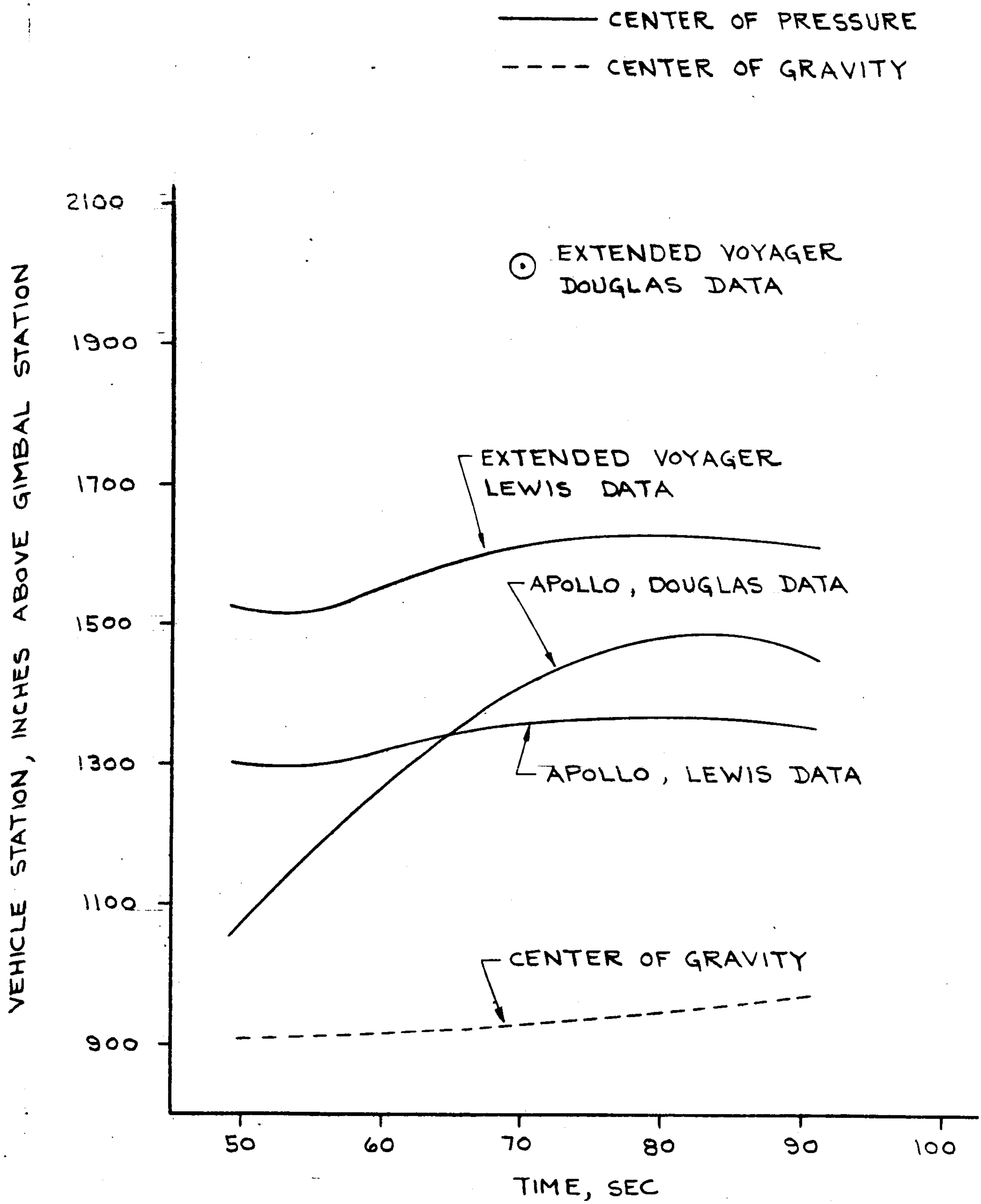

FIGURE 6. AERODYNAMIC DATA
PHASE II LAUNCH VEHICLE

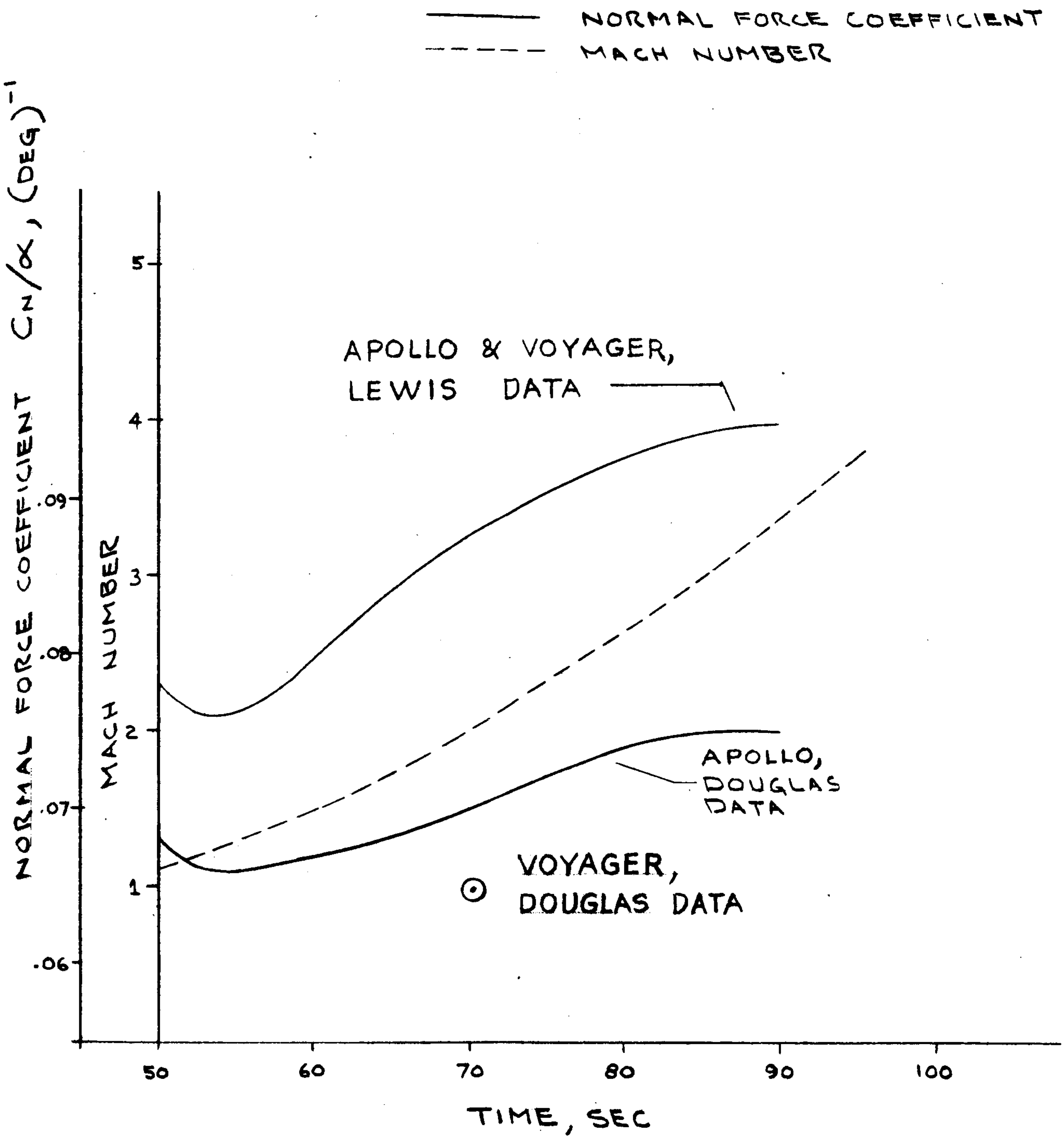

FIGURE 7. AERODYNAMIC DATA
PHASE II LAUNCH VEHICLE

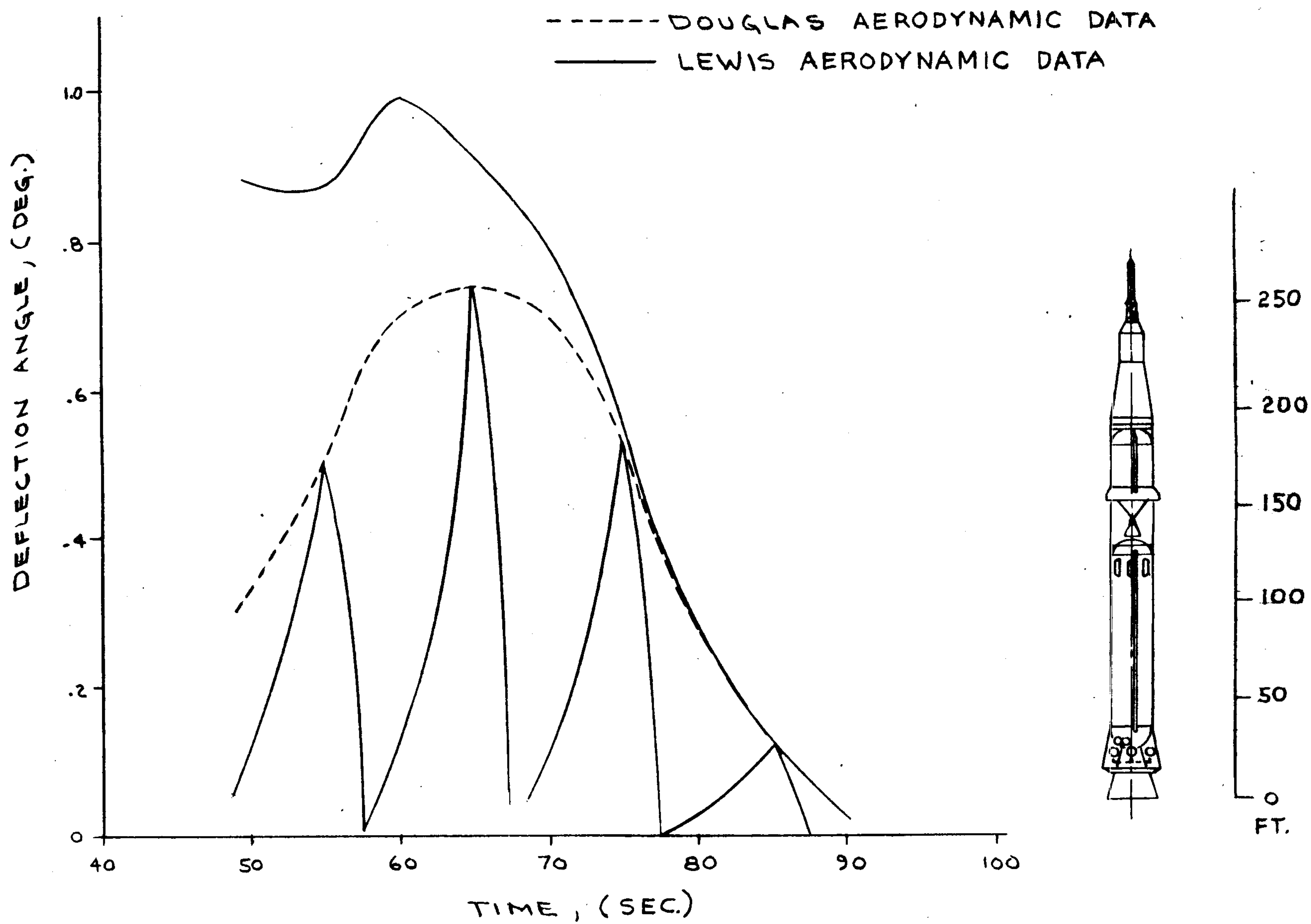

FIGURE 8. REQUIRED DEFLECTION ANGLE
PHASE II - APOLLO LAUNCH VEHICLE

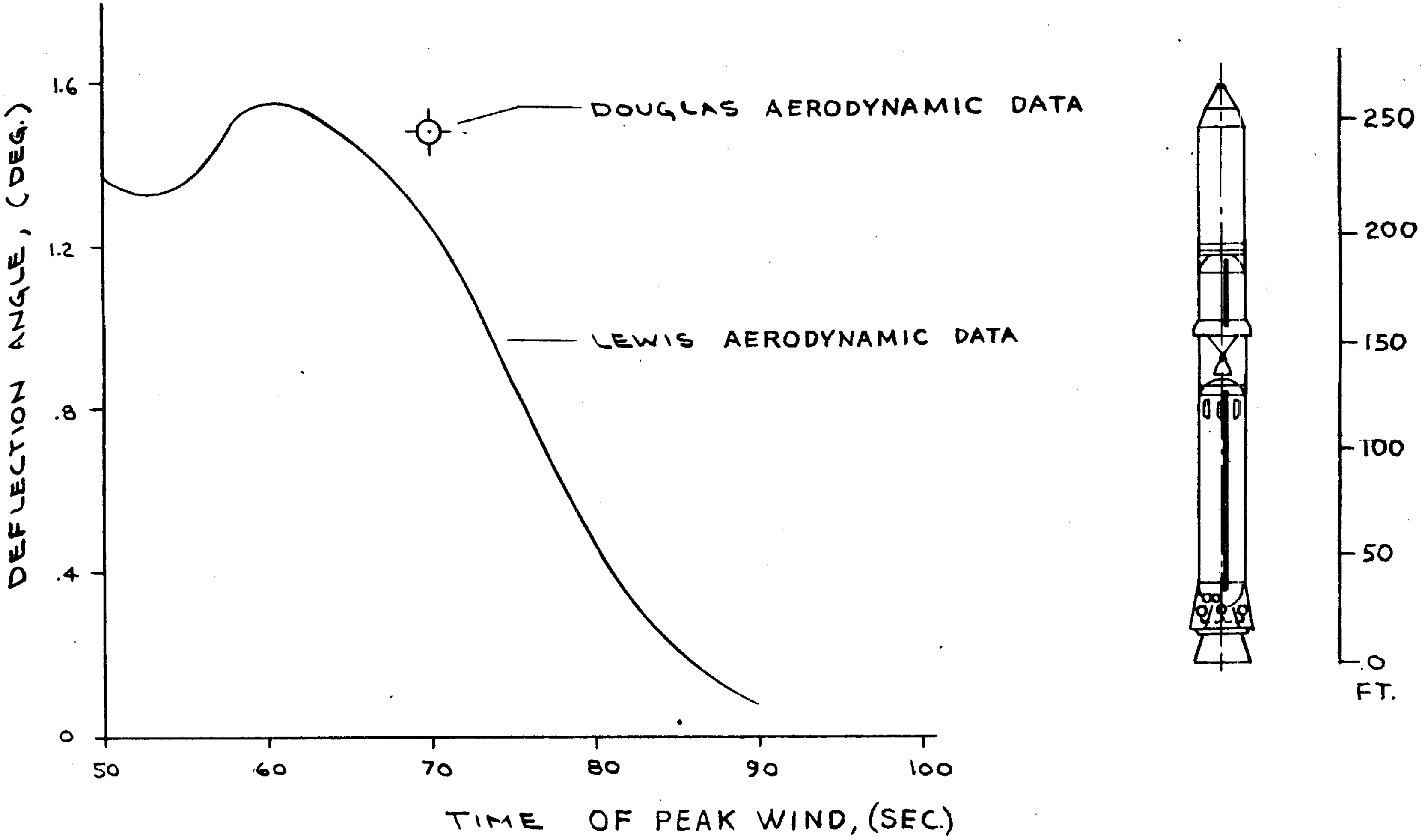

FIGURE 9. ENVELOPE OF REQUIRED DEFLECTION ANGLE
PHASE II - EXTENDED VOYAGER LAUNCH VEHICLE

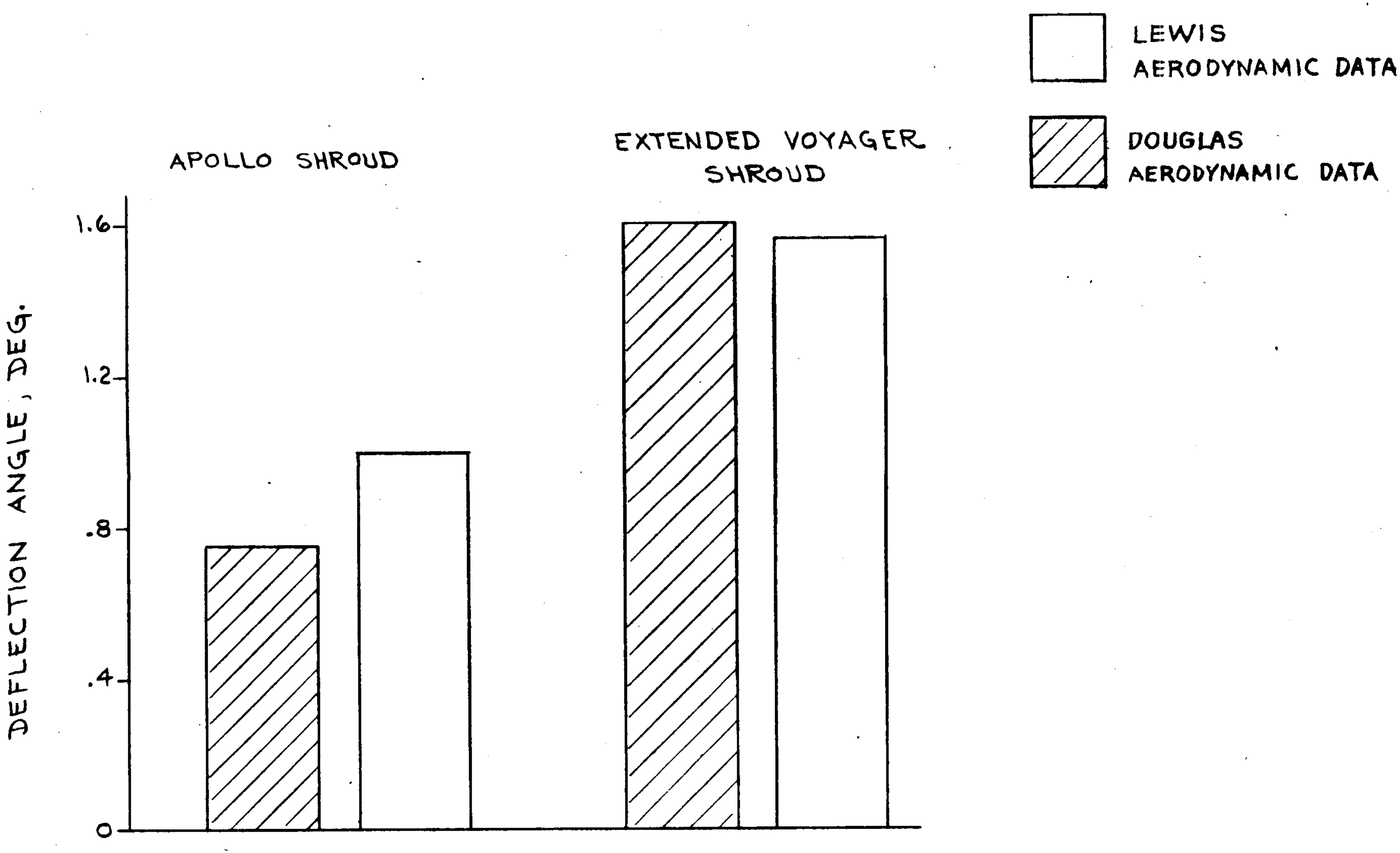

FIGURE 10. REQUIRED DEFLECTION ANGLE PHASE II
260" SOLID, SIV B LAUNCH VEHICLE

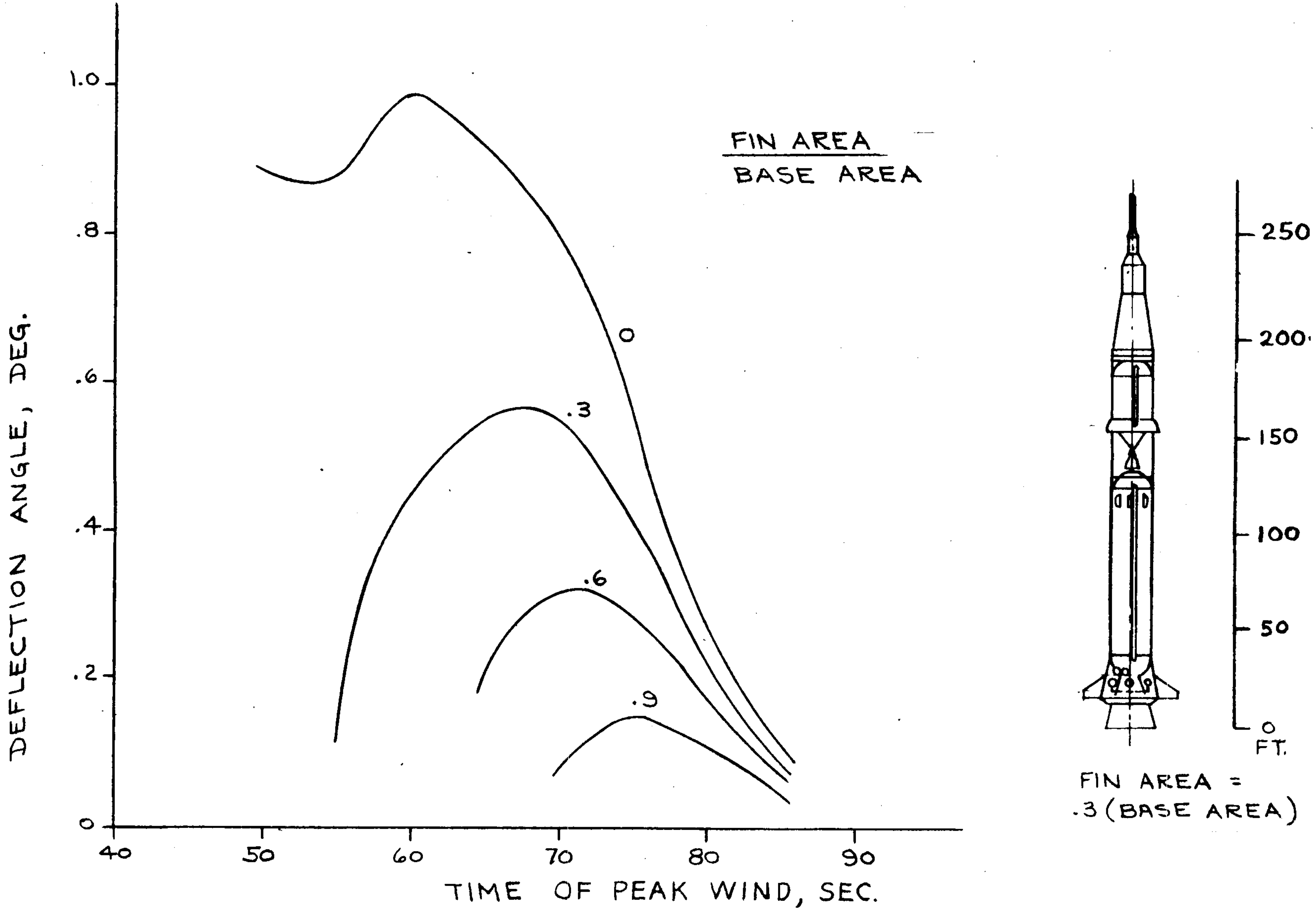

FIGURE 11. ENVELOPE OF DEFLECTION ANGLE REQUIREMENTS FOR VARIOUS FIN AREAS. PHASE II APOLLO LAUNCH VEHICLE

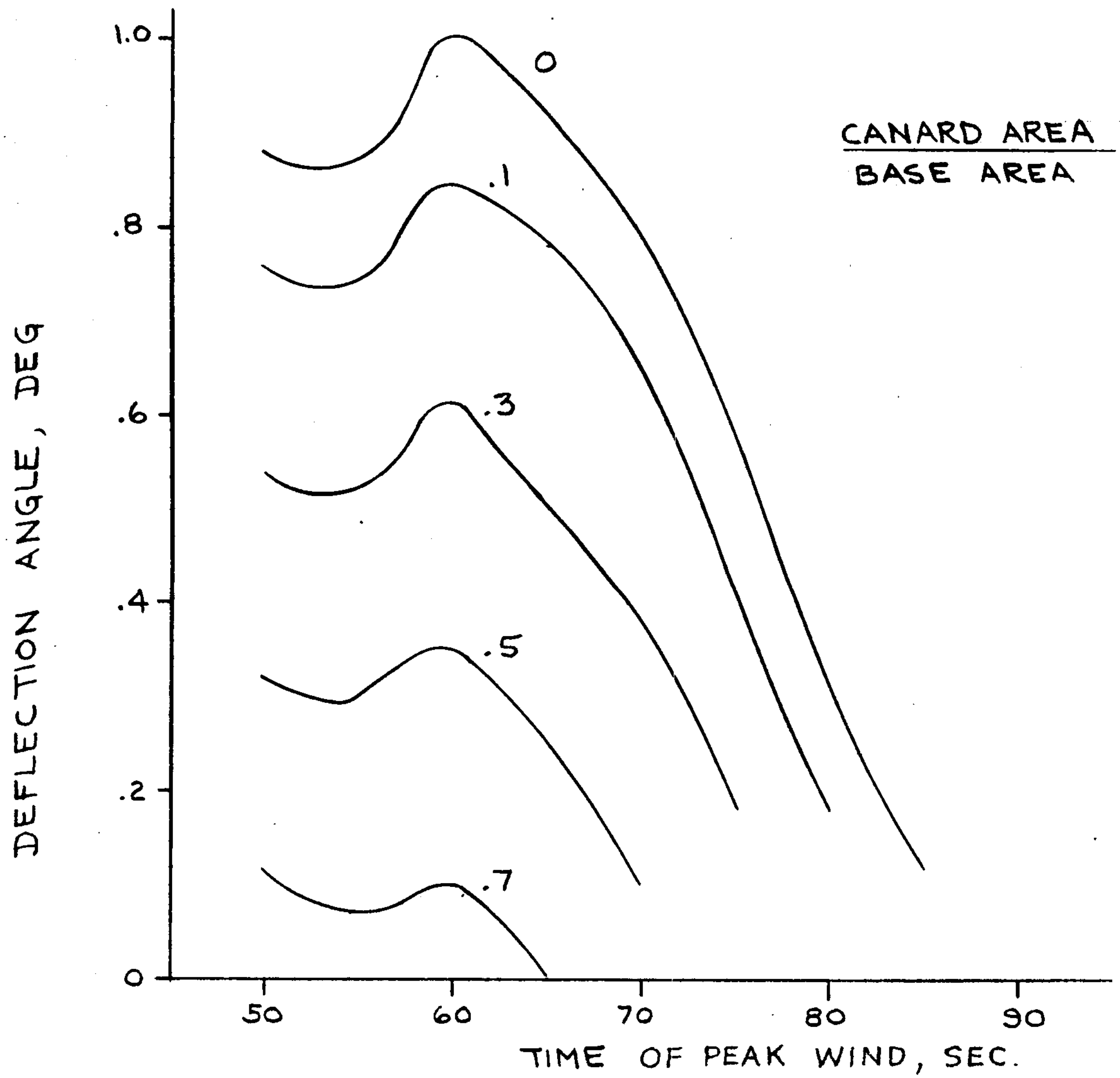

FIGURE 12. ENVELOPE OF DEFLECTION ANGLE REQUIREMENTS FOR VARIOUS CANARD AREAS. PHASE II APOLLO LAUNCH VEHICLE

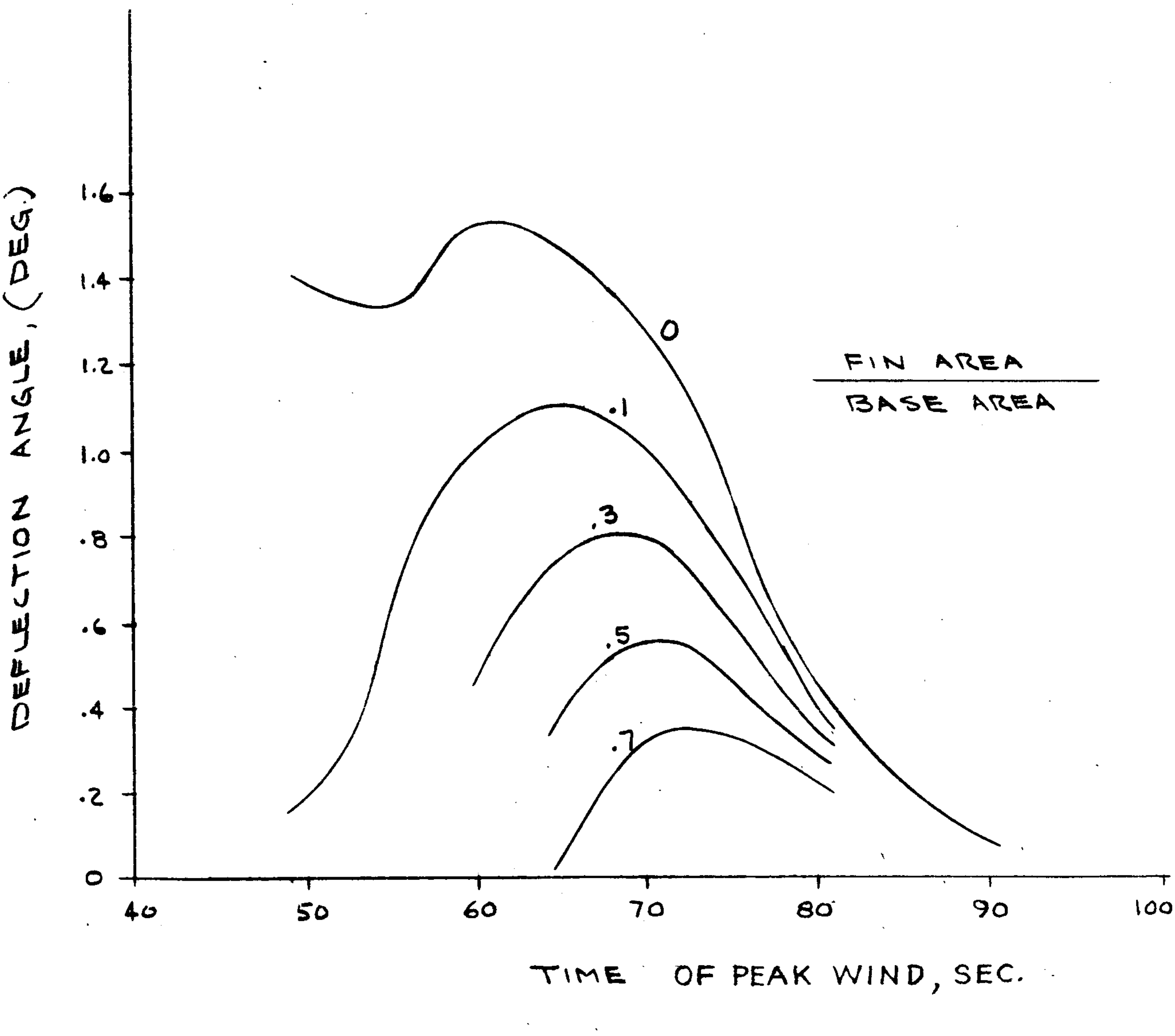

FIGURE 13. ENVELOPE OF DEFLECTION ANGLE REQUIREMENTS FOR VARIOUS FIN AREAS. PHASE II EXTENDED VOYAGER LAUNCH VEHICLE.

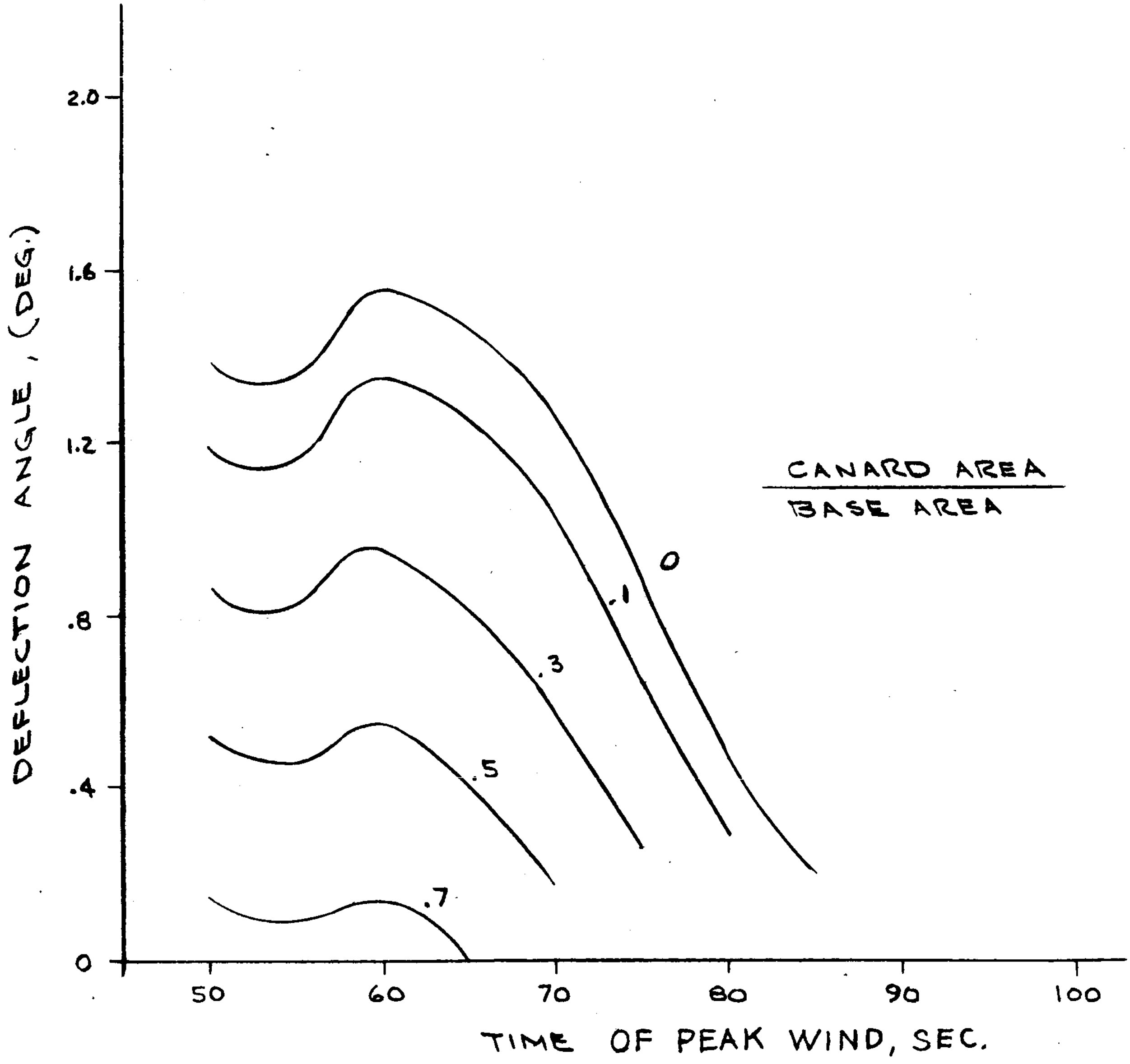

FIGURE. 14 ENVELOPE OF DEFLECTION ANGLE REQUIREMENTS FOR VARIOUS CANARD AREAS.

PHASE II EXTENDED VOYAGER LAUNCH VEHICLE.

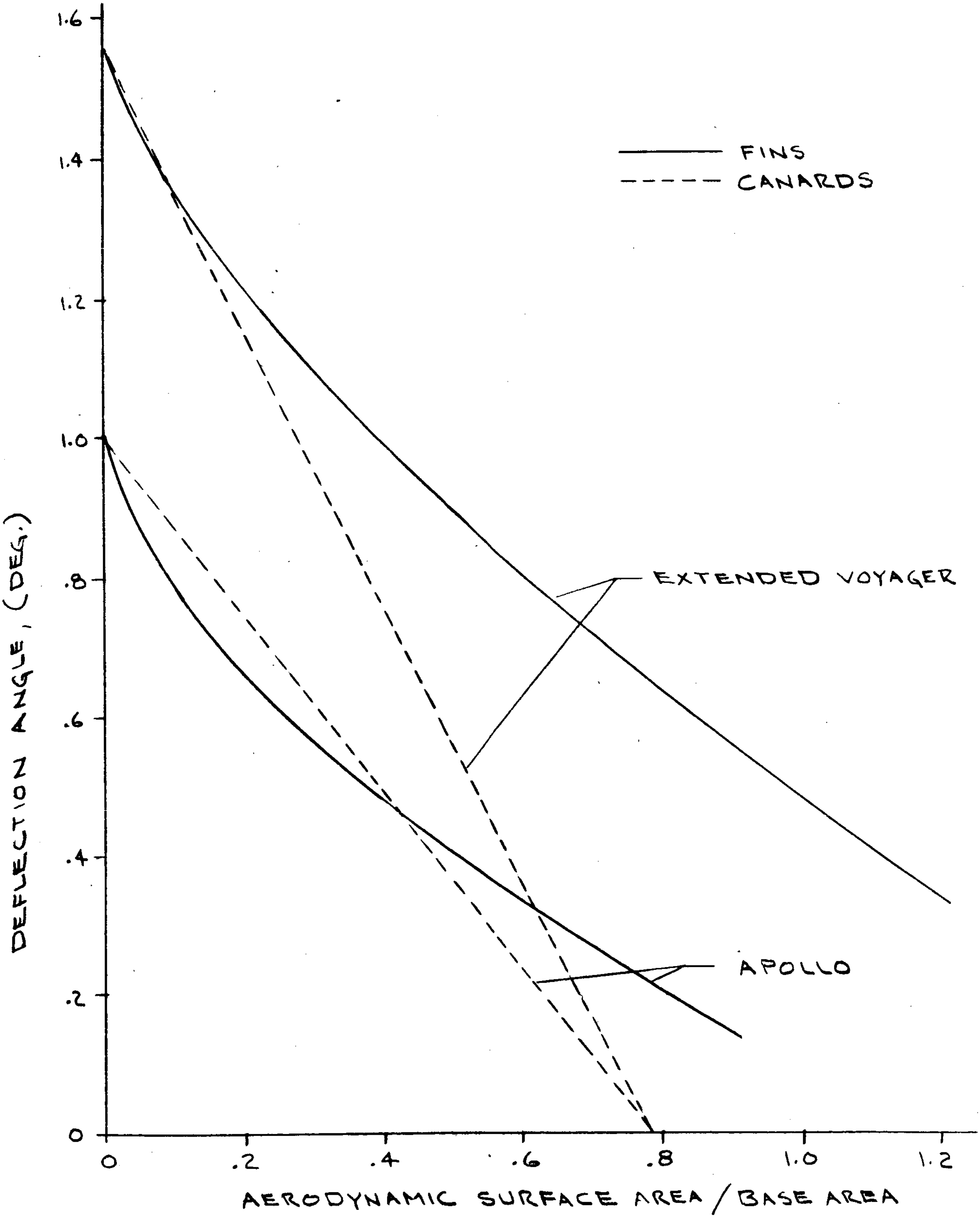

FIGURE 15. REDUCTION IN DEFLECTION ANGLE REQUIREMENTS VS AREA OF AERODYNAMIC SURFACE PHASE II LAUNCH VEHICLE

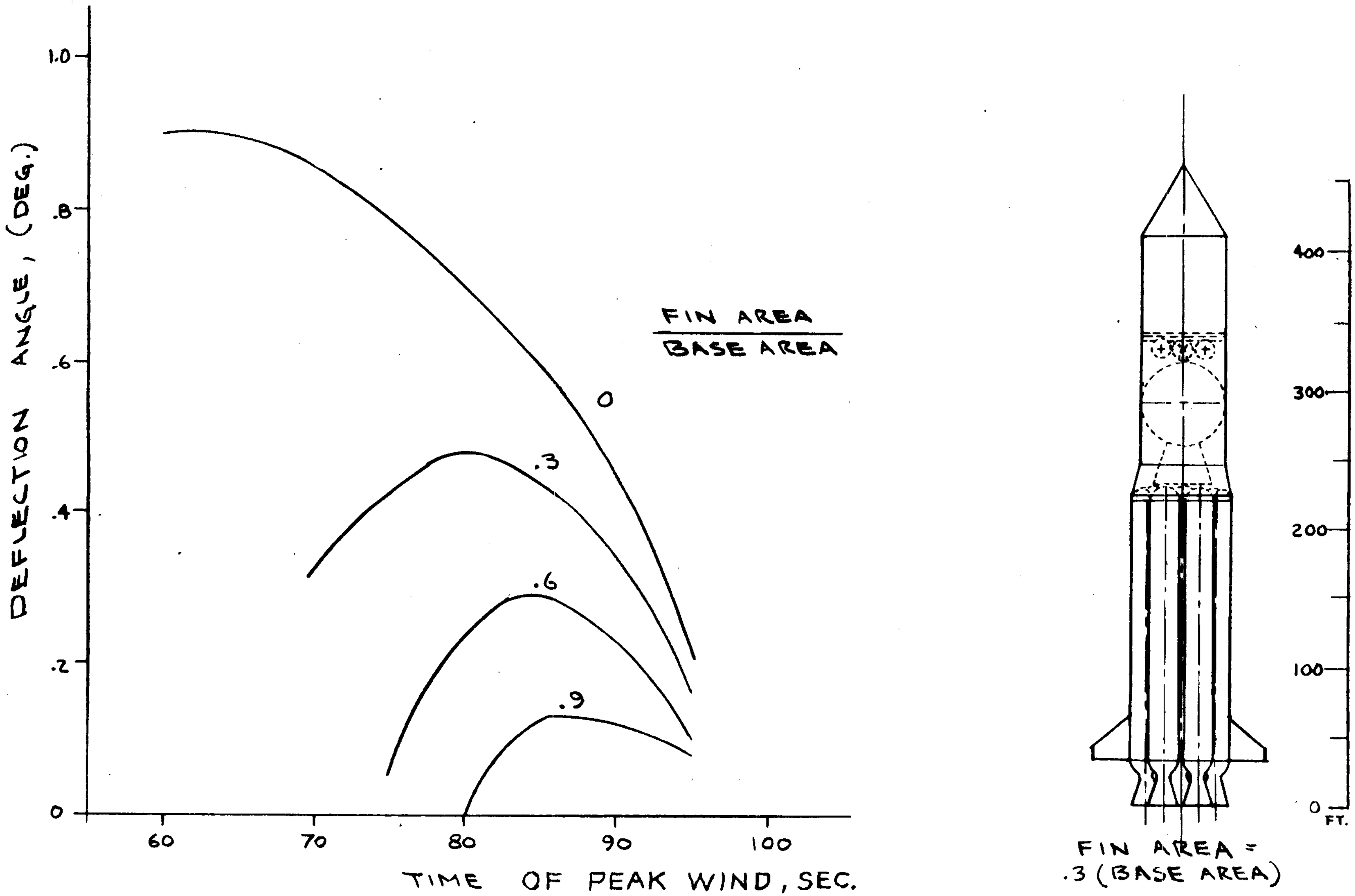

FIGURE 16 ENVELOPE OF DEFLECTION ANGLE REQUIREMENTS FOR VARIOUS FIN AREAS.
SOLID-SOLID-OPM LAUNCH VEHICLE

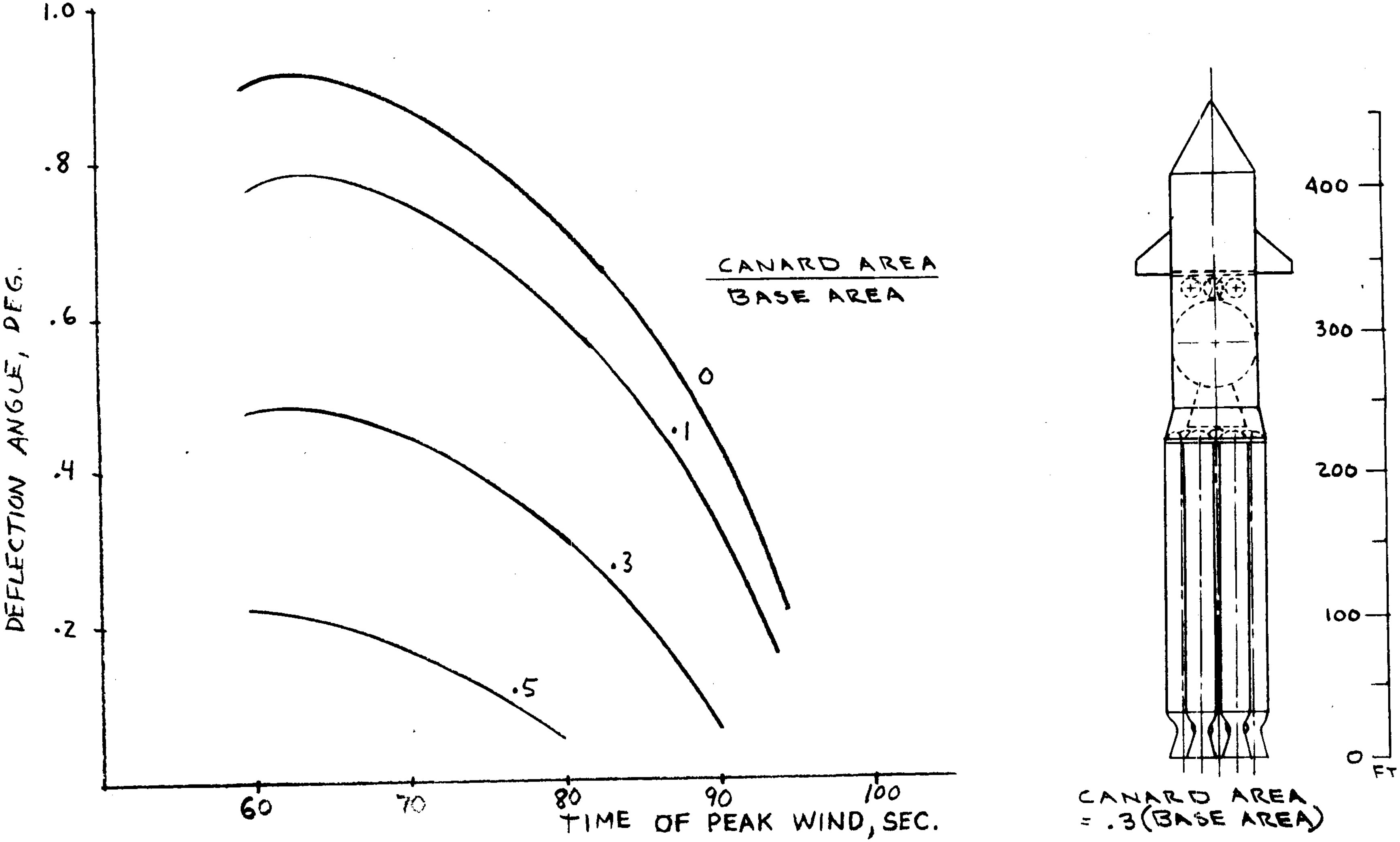

FIGURE 17. ENVELOPE OF DEFLECTION ANGLE REQUIREMENTS FOR VARIOUS CANARD AREAS.
SOLID- SOLID-OFM LAUNCH VEHICLE

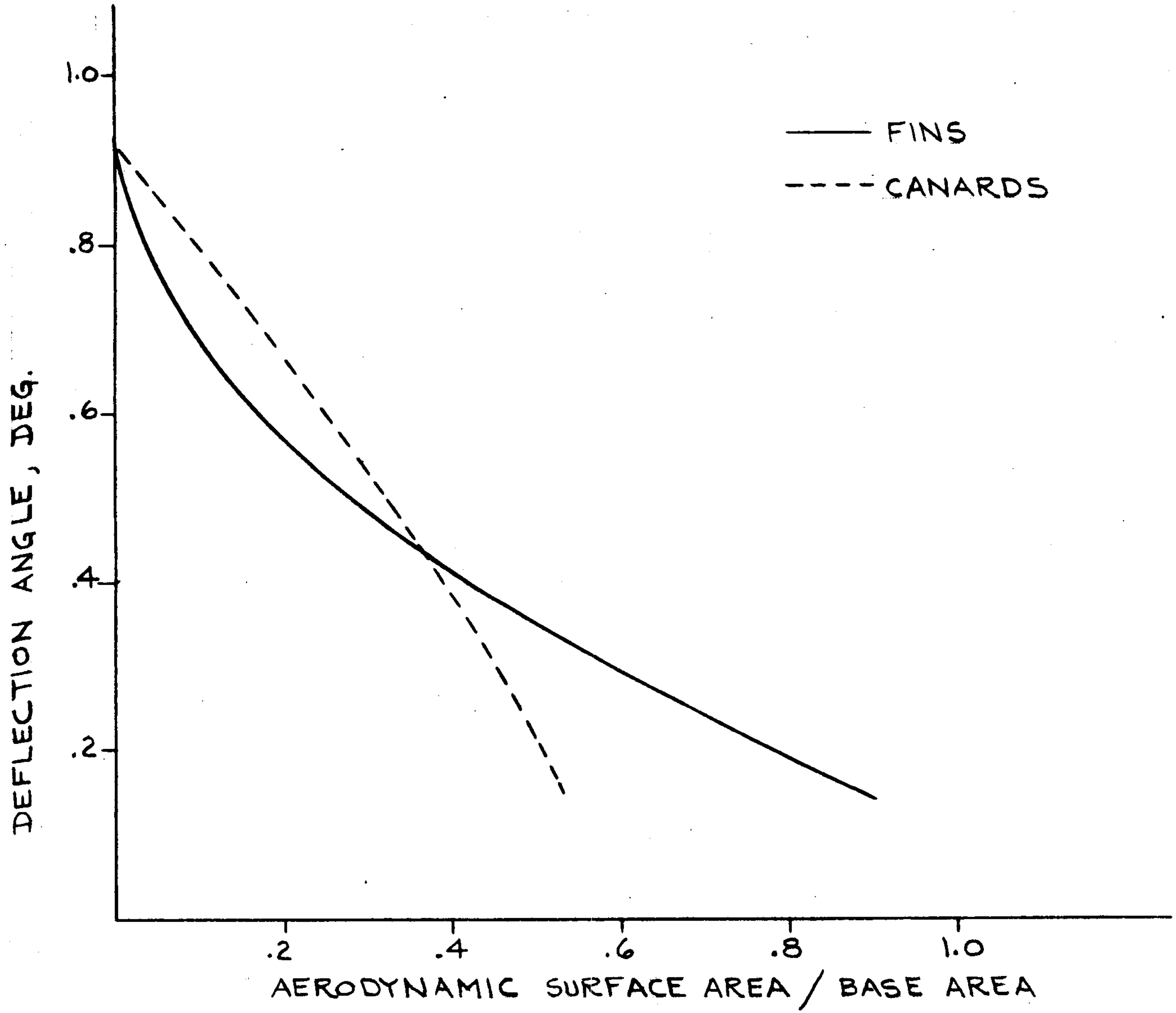

FIGURE 18. REDUCTION IN DEFLECTION ANGLE REQUIREMENTS VS. AREA OF AERODYNAMIC SURFACE SOLID-SOLID-OPM LAUNCH VEHICLE

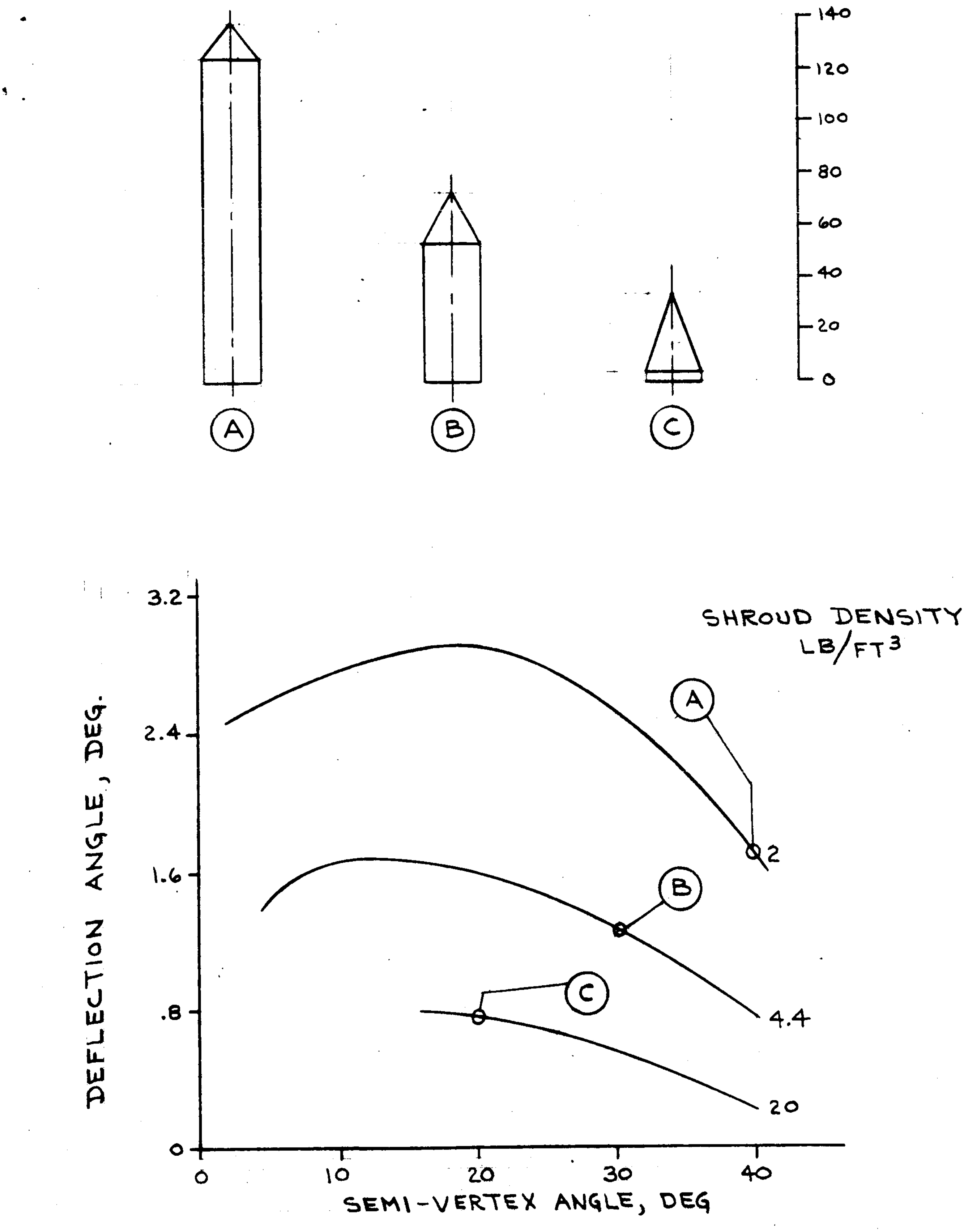

FIGURE 19. DEFLECTION ANGLE REQUIREMENTS VS. SHROUD DENSITY AND SHAPE PHASE II 260" SOLID ~ S IV B LAUNCH VEHICLE PAYLOAD WEIGHT = 95,000 LBS