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ANALYSIS OF SURFACE PRESSURE
ON A 5° CONE IN FREE FLIGHT
NEAR MACH 20 (REENTRY F)

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ANALYSIS OF SURFACE PRESSURE ON A 5° CONE IN FREE FLIGHT NEAR MACH 20 (REENTRY F)*

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SUMMARY

Pressure measurements were made at 13 locations on a 396-cm-long (156-inch) 5° half-angle conical spacecraft during reentry at a free-stream Mach number near 20. The cone surface was beryllium except for the graphite nose which had an initial tip radius of 0.25 cm (0.10 inch). The angle of attack was less than 1° during the entry from 30.48 km to 15.24 km (100 000 feet to 50 000 feet).

Comparison of theory with data measured along the spacecraft indicated that sharp cone pressure existed over the rearward two-thirds of the cone. In most cases theoretical pressures in this region, computed with the tangent cone concept, were within the accuracy band of the measured data. The nose radius history indicated from the analysis of measured pressure data was different from that predicted by an ablation analysis. The trends and magnitude of the circumferential pressure data are represented reasonably well by the theory of High and Blick.

INTRODUCTION

The Reentry F flight test was conducted to obtain experimental turbulent heat-transfer data at conditions of simultaneous high Mach number, Reynolds number, total enthalpy, and low ratios of wall temperature to total temperature. Surface pressure measurements were made to aid in the definition of the flow field around the conical spacecraft. These data are presented herein.

Although the experiment was designed so that the flow conditions over most of the body were essentially those for a sharp cone, factors such as nose tip radius growth, angle of attack, thermal distortion, and boundary-layer growth influenced the experimental pressure distributions. Theoretical pressures have been computed with consideration of the aforementioned factors and transition location for comparison with the surface measurements. Nose radii have been computed that are compatible with the pressures at the most forward measurement locations, where the pressure is significantly influenced by nose radius.

*Title, Unclassified.

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SYMBOLS

The data presented herein were obtained in the U.S. Customary Units but are presented in both International Units (SI) and U.S. Customary Units.

C_p	coefficient of pressure, $\frac{p - p_\infty}{q_\infty}$
h	altitude
M_∞	free-stream Mach number
p	local static pressure
$p_{t,2}$	stagnation pressure behind normal shock
p_∞	free-stream static pressure
q_∞	free-stream dynamic pressure
r_b	base radius
r_n	nose radius
$r_{n,A}$	nose radius predicted from ablation analysis
V_∞	free-stream velocity
x	axial distance from stagnation point
x_{tr}	axial distance from stagnation point to beginning of transition
α	angle of attack
α_m	mean angle of attack
α_{td}	incremental local angle of attack due to thermal distortion
β	angle of sideslip



η	total angle of attack
δ^*	boundary-layer displacement thickness
θ	local flow angle relative to free-stream velocity vector
θ_c	cone half-angle
θ_{δ^*}	incremental local flow angle due to displacement thickness
ω	bluntness ratio, r_n/r_b
ϕ	circumferential angle

EXPERIMENT

Spacecraft and Launch Vehicle

The test spacecraft was a 5° half-angle cone, 396 cm (156 inches) long with an initial nose tip radius of 0.25 cm (0.10 inch). The primary structure aft of station 21.8 cm (8.6 inches) consisted of a 1.52-cm-thick (0.60-inch) beryllium cone fabricated from seven individual frustums. An ATJ graphite nose tip was mounted forward of station 21.8 cm (8.6 inches). A sketch of the spacecraft is shown in figure 1.

The nose-tip assembly shown in figure 2 consisted of an ATJ graphite shell with an initial tip radius of 0.25 cm (0.10 inch), a porous carbon insulator inner shell, and a tungsten-alloy insert for attaching the nose tip to the spacecraft. Note that the nose-tip half-angle was $5^\circ 23'$ whereas the afterbody was a 5° half-angle cone.

Additional pertinent information concerning design considerations can be found in references 1 and 2. It should be noted that in this paper the primary instrumented ray is designated $\phi = 0^\circ$ rather than $\phi = 352.5^\circ$ as in reference 2.

The experiment was launched with a modified three-stage Scout. The launch vehicle provided the spacecraft with a roll rate of 62 revolutions per minute prior to separation. At an altitude of 60.96 km (200 000 feet) the spacecraft had a velocity of 6014 m/sec (19 730 ft/sec) and a reentry flight-path angle of -21° .

Instrumentation

Thirteen pressure orifices were located on the conical surface at the stations shown in figure 1. The primary instrumentation ray is defined herein as $\phi = 0^\circ$. Data from the low and high range gages were recorded at 20 and 40 samples per second, respectively.

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The installation at each of the 13 orifices consisted of a beryllium plug through the spacecraft skin with a 0.229-cm (0.090-inch) inside diameter nylon tube connected to a potentiometer type of pressure transducer. Each plug had a 0.152-cm (0.060-inch) orifice as is shown by the typical pressure port connection in figure 3. The length of tubing from orifice to transducer was approximately 38 cm (15 inches) at the four rearmost stations and 137 cm (54 inches) at the two forwardmost stations. A preflight experimental test simulating the instrumentation arrangement and utilizing a pressure history simulating zero-angle-of-attack reentry indicated that this system would not introduce significant lag in the pressure data. From consideration of telemetry accuracy analyses and the gage calibration, the pressure data are believed to be accurate within about ± 4 percent of the full-scale value.

Other instrumentation on board the spacecraft but not reported herein included thermocouples installed in the beryllium wall at 21 locations (including 13 located close to the pressure orifices) from which the heating rates, the prime objective of the experiment, were determined. Also included were base pressure and base heat flux sensors, accelerometers and rate gyros for measurement of body motions, and various diagnostic sensors.

Entry Trajectory and Environment

The altitude, free-stream velocity, and free-stream Mach number time histories during the test portion of the Reentry F trajectory are presented in figure 4. Reference 3 gives detailed explanations and graphical presentations for the complete space flight trajectory including locations of receiving stations, radar equipment used, and so forth.

Meteorological measurements of atmospheric properties were obtained with sonde payloads carried by high-altitude sonde balloons to about 36.58 km (120 000 feet) and by Arcas rockets to 60.96 km (200 000 feet). Free-stream properties were derived from these data, combined into continuous variations, and employed in computing free-stream conditions for the flight. The ambient pressure and the dynamic-pressure time histories are presented in figure 5.

Local Angle of Attack

The spacecraft experienced small angles of attack during the data-measuring portion of the flight as is evidenced by the angle-of-attack component histories presented in figure 6. Note that the mean β is small during the primary data period and, therefore, was neglected for the present analysis. These histories were determined from onboard measurements of normal and transverse accelerations and pitch, yaw, and roll rates. Reference 4 from which figure 4 was obtained presents the analysis of the spacecraft body motions.

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During reentry the spacecraft experienced thermal distortion along the longitudinal axis because of differences in temperature on opposite sides of the body. Below an altitude of about 25.91 km (85 000 feet) the measured temperatures along the secondary ray were higher than at diametrically opposite locations along the primary ray. The distortion occurred primarily in the α -plane and the local distortion angles computed for the pressure measurement stations in the α -plane are shown in figure 7. The thermal distortion histories presented herein are results from unpublished analyses conducted at the Langley Research Center.

The orientation of the spacecraft with the angle-of-attack and thermal-distortion components is shown in figure 8. Note that α_{td} changes algebraic sign at the center-of-gravity location. In the angle-of-attack analysis in reference 4, the tangent to the center line of the distorted body was assumed to be parallel to the center line of the undistorted body at the center-of-gravity station, that is, $(\alpha_{td})_{cg} = 0$.

FLIGHT DATA AND ANALYSIS

Flight Data

Typical pressure measurements (station number 2, $\phi = 0^\circ$) are shown in figure 9. Note that although the high-range gage recorded data throughout the test period, these data are not shown prior to the low range gage nearing its full scale. The pressure data for all the measurement locations are presented in figure 10 in the form of pressure coefficients.

Longitudinal Pressure Distribution Analysis

A modified tangent cone or equivalent cone concept was utilized to compute theoretical pressures on hemispherically capped cones (see appendix A) for comparison with the flight data. This modified tangent cone concept is identical to the tangent cone concept (ref. 5) beyond $\frac{x}{r_n} \approx 300$. The modification consisted of assuming that the pressure on the blunt-body section of the spacecraft was that which occurs on a blunted cone whose half-angle was the local flow inclination angle at a desired x/r_n location. An assessment of the tangent cone method by comparison with pressure measurements from high Mach number wind-tunnel experiments is presented in appendix B.

The local flow angle θ was determined at each measurement station by the contributions shown in equations (1) and (2):

$$\theta_{\phi=0^\circ} = \theta_c + \theta_{\delta^*} - \alpha_m - \alpha_{td} \quad (1)$$

$$\theta_{\phi=180^\circ} = \theta_c + \theta_{\delta^*} + \alpha_m + \alpha_{td} \quad (2)$$

[REDACTED]

Since the angle of attack and pressure time histories oscillate during the experiment, mean values of α in figure 6 were used in the computation of theoretical pressures for comparison with mean values of measured surface pressure. The thermal distortion component α_{td} was obtained from figure 7. The boundary-layer contribution θ_{δ}^* was obtained by determining the slope at the pressure-measuring stations of theoretical distributions of δ^* . The δ^* values were obtained from unpublished computations at the Langley Research Center of boundary-layer parameters and local flow conditions with the transition location as determined from experimental heat-transfer distributions. (See ref. 1.) A representative δ^* distribution is shown in figure 11 and a typical θ_{δ}^* plot, in figure 12. The values of local θ with the various contributions are shown in table I.

Normalized theoretical pressure distributions were found to vary by less than 1 percent over the range of velocity and altitude conditions of this experiment. Therefore, a family of curves of $p/p_{t,2}$ as a function of x/r_n for the range of local θ given in table I was established to determine theoretical pressures for comparison with the measured data. Lomax and Inouye's flow field analysis described in reference 6 was used to produce the pressure distributions shown in figure 13. Note that pressure levels associated with sharp cone conditions ($x/r_n > 300$) are only dependent on flow angle whereas in the body region influenced by nose bluntness ($x/r_n < 300$), surface pressure is dependent on x and r_n as well as on flow angle. Linear interpolation was used between angles shown in figure 13, since pressure variation is almost linear with θ over one-half-degree intervals as shown in figure 14.

A typical plot of experimental data and theoretical predictions from figure 13 with various local flow contributions is presented in figure 15. The ± 4 -percent accuracy band of the data is denoted by the vertical bars. It is readily seen that taking all the local flow components into consideration provides the best agreement with the measured longitudinal data.

Experimental data and theoretical predictions from figure 13 are presented in figure 16 for several altitudes. The ± 4 -percent accuracy band of the data is denoted by the vertical bars. Nose radii required to produce theoretical pressures falling within the accuracy band of the measured data were determined for each altitude as indicated in figure 16. Theoretical predictions are also shown at the two forwardmost stations based on nose radii predicted from an ablation analysis. The predictions based on $r_{n,A}$ are higher than the data and accuracy band at the higher altitudes and below the measured data and the accuracy band at the lower altitudes. Surface pressure at the four rearmost measuring stations on the primary ray and at all measurement stations on the secondary ray were found to be essentially independent of nose radius. In most cases the theoretical pressures are in very good agreement with the measured data on the primary ray. On the

secondary ray the agreement is also reasonable in both the magnitude and trend; except at the lower altitudes, the data from the rearmost station becomes progressively lower than the predictions.

The nose radii values that are compatible with the pressure measurements are presented in figure 17 and are indicated by the vertical bars. The lower curve in figure 17 resulted from an ablation analysis considering thermochemical equilibrium at the surface and the higher curve was a postulation of the largest nose radius possible based on nose tip thermocouple data. (See ref. 1.) As can be readily seen from figure 17, the nose radius history indicated from the analysis of measured pressure data was different from that predicted by the ablation analysis. This difference is not understood and the performance of the nose tip cannot presently be precisely defined from the limited onboard measurements pertinent to an analysis of the nose tip history. However, this analysis of the pressure data indicates that the postulated largest nose radii possible (upper curve of fig. 17) did not occur.

Circumferential Pressure Distribution Analysis

The surface pressure measured at the four circumferential locations at station number 7 and the three locations at station number 4 were compared with the theory of High and Blick (ref. 7). Since High and Blick's theory assumes that all body motion occurs in the angle-of-attack plane, the local angle of attack for the analysis herein was computed from

$$\eta_{\text{local}} = \left[(\alpha + \alpha_{\text{td}})^2 + \beta^2 \right]^{1/2}$$

and the cone angle, from $\theta = \theta_c + \theta_\delta^*$. The most windward ray was determined by the components $\alpha + \alpha_{\text{td}}$ and β .

The measured data are presented in figure 18, the theory being denoted by the solid line and the ± 4 -percent accuracy bands, by the vertical bars. The circumferential trends and magnitude of the data are represented reasonably well by the theory, except for station number 7, $\phi = 180^\circ$ which appears to be consistently low at the lower altitudes. Data from this same location are noted to be lower than theory in the longitudinal distribution analysis.

CONCLUSIONS

Flight measurements at Mach 20 of surface pressure on a 5° half-angle cone 396 cm (156 inches) long are presented for reentry down to an altitude of 12.19 km (40 000 feet). The data were compared with theory based on a modified tangent cone method. Angle of

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attack, thermal distortion, boundary-layer growth, and transition location were considered. The following conclusions are noted:

1. The theoretical predictions were in general within the accuracy band of the longitudinal data.

2. The nose radius history indicated from the analysis of measured pressure data was different from that predicted by an ablation analysis.

3. The trends and magnitude of the circumferential pressure data are represented reasonably well by the theory of High and Blick.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 13, 1971.



APPENDIX A

BICONIC INVESTIGATION

The graphite nose tip half-angle was $5^{\circ}23'$ as shown in figure 2, whereas the beryllium body of the flight vehicle was a 5° half-angle cone. Therefore, an investigation was conducted to determine whether a biconic model was required for the pressure analysis. Theoretical pressure values were obtained from a computer program which employs the method of characteristics for the supersonic part of the inviscid flow field coupled with an inverse blunt body subsonic flow field solution (Lomax and Inouye, ref. 6).

The pressure distributions for a 5° half-angle hemispherically tipped conical body and for a hemispherically tipped biconic body are presented in figure 19 in nondimensionalized form $p/p_{t,2}$ as a function of x/r_n . Since the nose-tip radius growth history was uncertain, this analysis was conducted by assuming several different nose radii, two of which are shown in figure 17. The results indicate that the expansion corner has no appreciable effect on the surface pressures at or rearward of the forwardmost pressure measuring station; a conical model was therefore used for theoretical analysis purposes.

APPENDIX B

TANGENT CONE CONCEPT

A modified tangent cone concept has been used herein to determine theoretical pressures on the spacecraft at angle of attack. Pressures on the tangent cone have been computed by use of the Lomax and Inouye inverse blunt-body flow field solution (ref. 6) extended in the supersonic region by method of characteristic solutions. This procedure was assessed by comparison with the experimental data of reference 8.

The data from reference 8 were taken on 5.6° cones at an angle of attack of 1° with bluntness ratios of 0.00, 0.05, 0.10, and 0.30 in a Mach 14 wind tunnel. The experimental data from the leeward ray are shown in figure 20 along with the theoretical distribution computed as noted by employing the tangent cone concept. The sharp cone value from Sims (ref. 9) for $\theta = 4.6^\circ$ is also shown. The theoretical prediction is ≈ 15 percent lower than the measured values when the flow has expanded to approximately sharp cone conditions ($x/r_n = 190$).

Reference 8 correlates the measured and inviscid pressures by adding to the tangent cone angle $\theta_c - \alpha$ a boundary-layer-induced increment θ_{δ^*} evaluated near the base of the $\omega = 0.05$ model. Lomax and Inouye's program was again used to compute sharp cone pressure on this effective cone, $\theta = \theta_c - \alpha + \theta_{\delta^*}$. The result is indicated by the dashed line in figure 20. With the boundary-layer-induced increment, the theoretical pressure is within 6 percent of the measured data at the 190 nose radii location.

The boundary-layer-induced pressure contribution to the local flow angle increases on the forward part of the body. The theoretical prediction should, therefore, agree with data within 5 percent for $x/r_n < 190$ in figure 20. Thus, it is believed that the tangent cone or equivalent cone concept can be satisfactorily employed for the pressure analysis at small angle of attack as long as the local flow angle is accurately defined.



REFERENCES

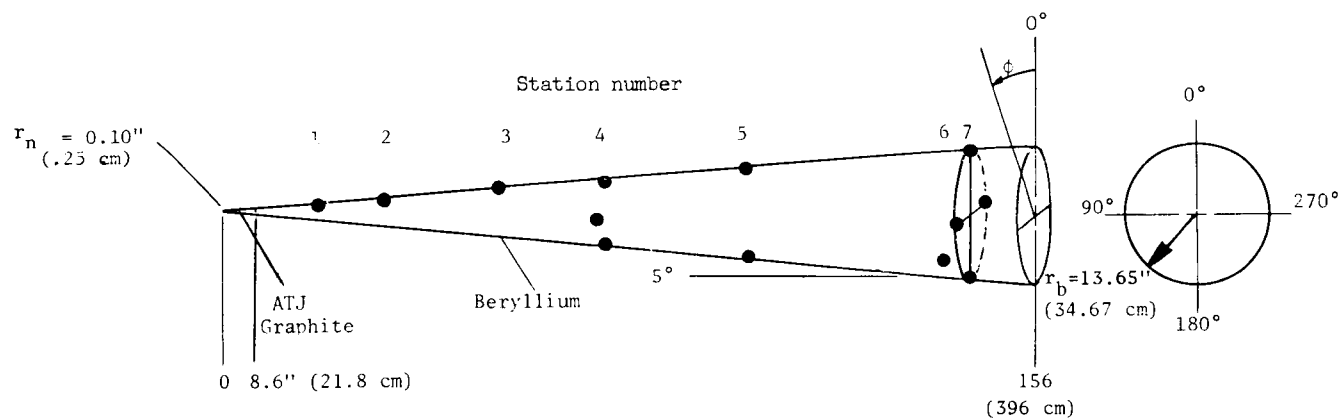
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TABLE I.- LOCAL FLOW ANGLE WITH VARIOUS CONTRIBUTIONS

Station number	θ_c , deg	θ_δ^* , deg	α_m , deg	α_{td} , deg	$\theta_\phi=0^\circ$, deg	$\theta_\phi=180^\circ$, deg
Time, 453.21 sec; altitude, 30.48 km (100 000 ft)						
1	5.0	0.104	-0.070	0	5.174	
2	5.0	.083	-.070	0	5.153	
3	5.0	.050	-.070	0	5.120	
4	5.0	.050	-.070	0	5.120	4.980
5	5.0	.039	-.070	0	5.109	4.969
7	5.0	.295	-.070	0	5.365	5.225
Time, 453.89 sec; altitude, 28.96 km (95 000 ft)						
1	5.0	0.092	-0.075	0	5.167	
2	5.0	.074	-.075	0	5.149	
3	5.0	.054	-.075	0	5.129	
4	5.0	.045	-.075	0	5.120	4.970
5	5.0	.036	-.075	0	5.111	4.961
7	5.0	.308	-.075	0	5.383	5.233
Time, 454.58 sec; altitude, 27.43 km (90 000 ft)						
1	5.0	0.082	-0.085	0	5.167	
2	5.0	.067	-.085	0	5.152	
3	5.0	.053	-.085	0	5.138	
4	5.0	.042	-.085	0	5.127	4.957
5	5.0	.036	-.085	0	5.121	4.951
7	5.0	.268	-.085	0	5.353	5.183
Time, 455.27 sec; altitude, 25.91 km (85 000 ft)						
1	5.0	0.071	0.065	-0.020	5.026	
2	5.0	.060	.065	-.010	5.005	
3	5.0	.049	.065	-.010	4.994	
4	5.0	.038	.065	.002	4.971	5.105
5	5.0	.115	.065	-.002	5.052	5.178
7	5.0	.276	.065	-.020	5.231	5.321
Time, 455.95 sec; altitude, 24.38 km (80 000 ft)						
1	5.0	0.065	0.140	0.002	4.923	
2	5.0	.054	.140	0	4.914	
3	5.0	.045	.140	0	4.905	
4	5.0	.037	.140	.015	4.882	5.192
5	5.0	.086	.140	-.015	4.961	5.211
7	5.0	.270	.140	-.040	5.170	5.370

TABLE I. - LOCAL FLOW ANGLE WITH VARIOUS CONTRIBUTIONS - Concluded

Station number	θ_c , deg	θ_δ^* , deg	α_m , deg	α_{td} , deg	$\theta_\phi=0^\circ$, deg	$\theta_\phi=180^\circ$, deg
Time, 456.64 sec; altitude, 22.86 km (75 000 ft)						
1	5.0	0.056	0.415	0.070	4.571	
2	5.0	.050	.415	.050	4.585	
3	5.0	.041	.415	.035	4.591	
4	5.0	.139	.415	.030	4.694	5.584
5	5.0	.345	.415	-.020	4.950	5.740
7	5.0	.221	.415	-.060	4.866	5.576
Time, 457.34 sec; altitude, 21.34 km (70 000 ft)						
1	5.0	0.040	0.652	0.190	4.198	
2	5.0	.045	.652	.140	4.253	
3	5.0	.059	.652	.080	4.327	
4	5.0	.159	.652	.060	4.447	5.871
5	5.0	.302	.652	-.020	4.670	5.934
7	5.0	.197	.652	-.070	4.615	5.779
Time, 458.03 sec; altitude, 19.81 km (65 000 ft)						
1	5.0	0.034	0.680	0.410	3.944	
2	5.0	.034	.680	.270	4.084	
3	5.0	.054	.680	.160	4.214	
4	5.0	.255	.680	.080	4.495	6.015
5	5.0	.247	.680	-.030	4.597	5.897
7	5.0	.179	.680	-.080	4.579	5.779
Time, 458.74 sec; altitude, 18.29 km (60 000 ft)						
1	5.0	0.012	0.690	0.720	3.602	
2	5.0	.028	.690	.450	3.888	
3	5.0	.050	.690	.250	4.110	
4	5.0	.065	.690	.100	4.275	5.855
5	5.0	.075	.690	-.035	4.420	5.730
7	5.0	.054	.690	-.095	4.459	5.649
Time, 459.45 sec; altitude, 16.76 km (55 000 ft)						
1	5.0	0.011	0.785	1.000	3.226	
2	5.0	.026	.785	.630	3.611	
3	5.0	.048	.785	.330	3.933	
4	5.0	.064	.785	.120	4.159	5.969
5	5.0	.074	.785	-.040	4.329	5.819
7	5.0	.054	.785	-.110	4.379	5.729



Station		Station number	$\phi = 0$, deg	$\phi = 90$, deg	$\phi = 135$, deg	$\phi = 180$, deg	$\phi = 270$, deg
inch	cm						
20.9	53.1	1	X				
32.5	82.6	2	X				
53.5	135.9	3	X				
74.5	189.2	4	X	X		X	
100.5	255.3	5	X			0	
142.0	360.7	6			X		
145.5	369.6	7	X	X		X	X

X Gages with 0 to 3 and 0 to 20 psia (0 to 21 and 0 to 138 kN/m²) ranges

0 Gage with 0 to 50 psia (0 to 345 kN/m²) range

Figure 1. - Spacecraft with pressure measurement locations.

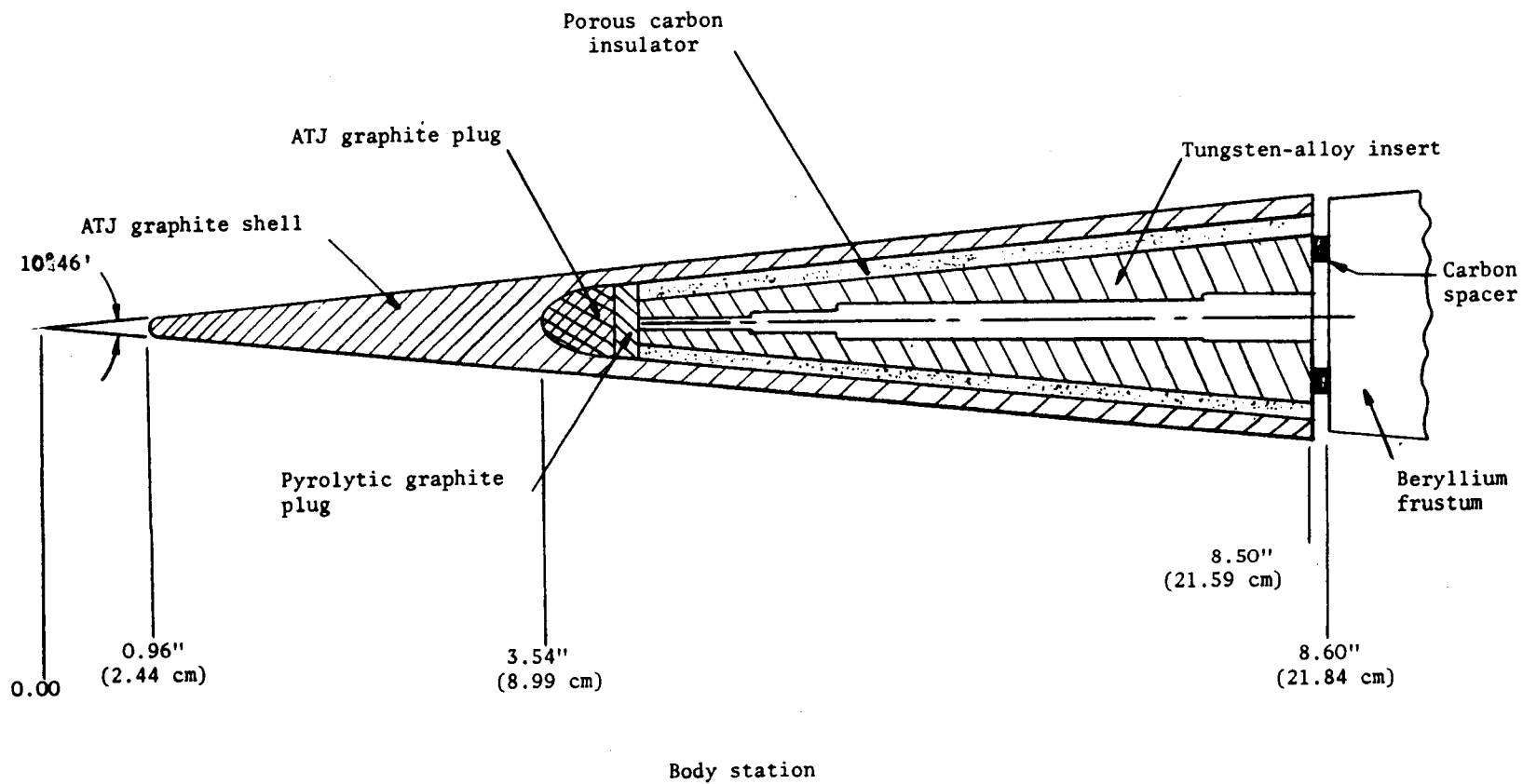


Figure 2. - Nose-tip assembly.

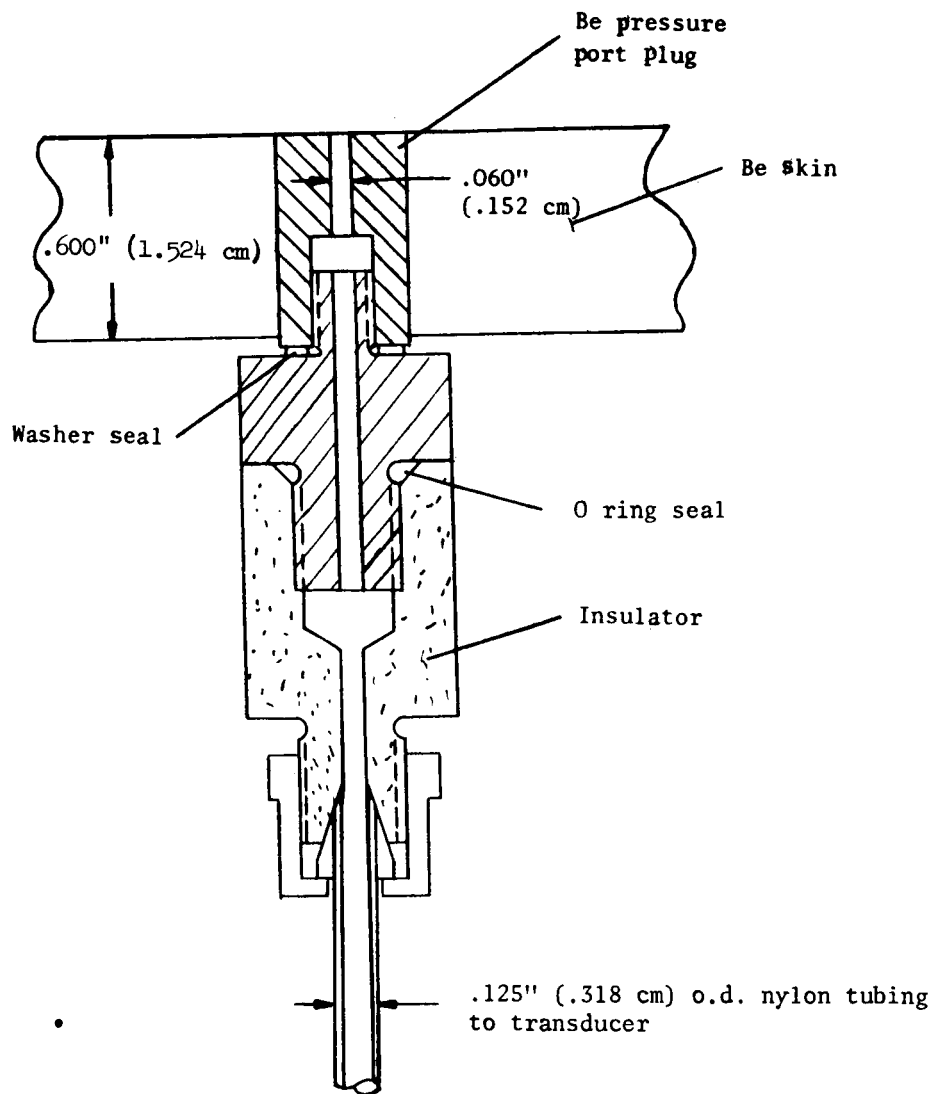


Figure 3.- Typical pressure port connection.

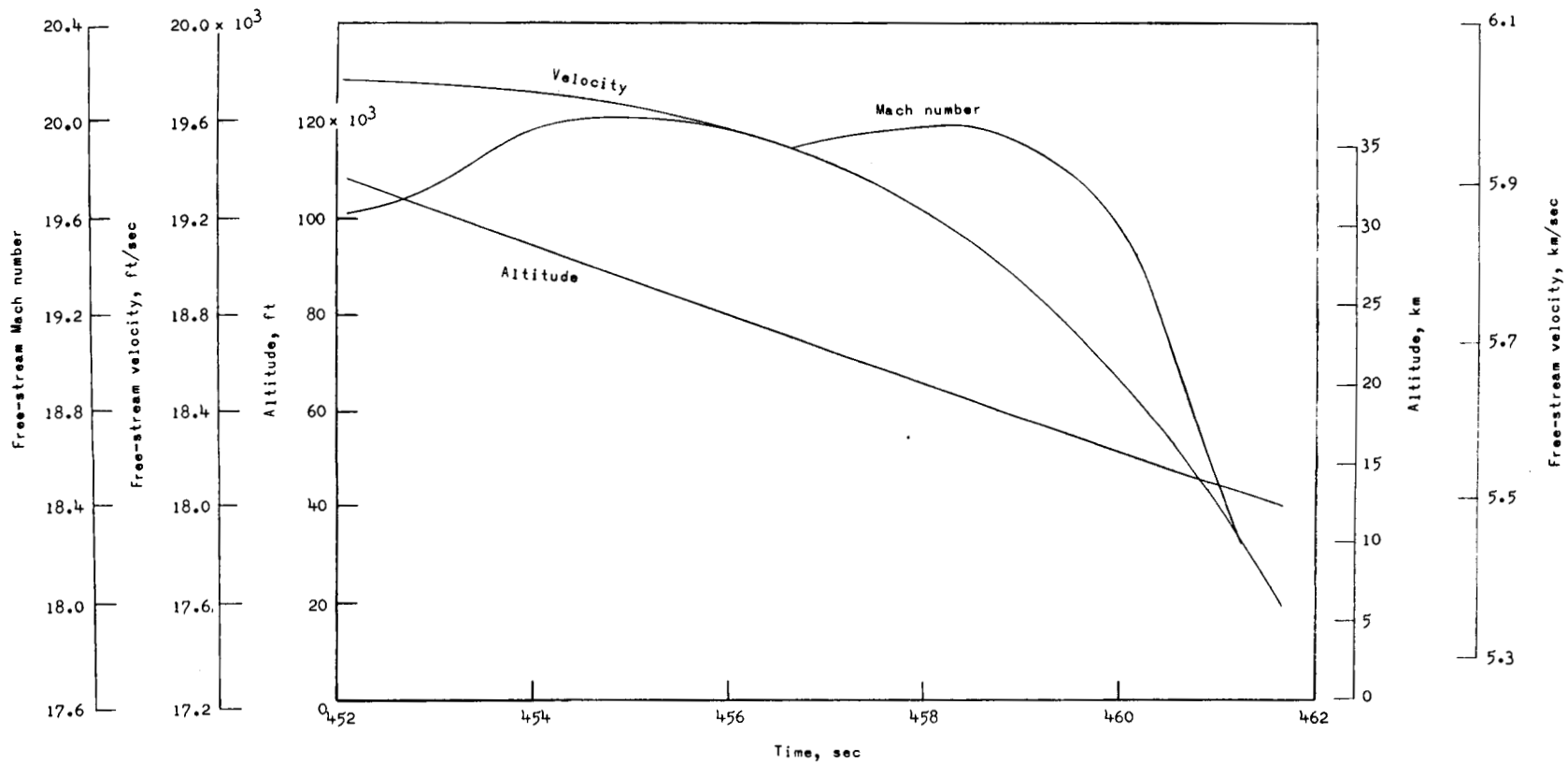


Figure 4.- Altitude, free-stream velocity, and free-stream Mach number during reentry.

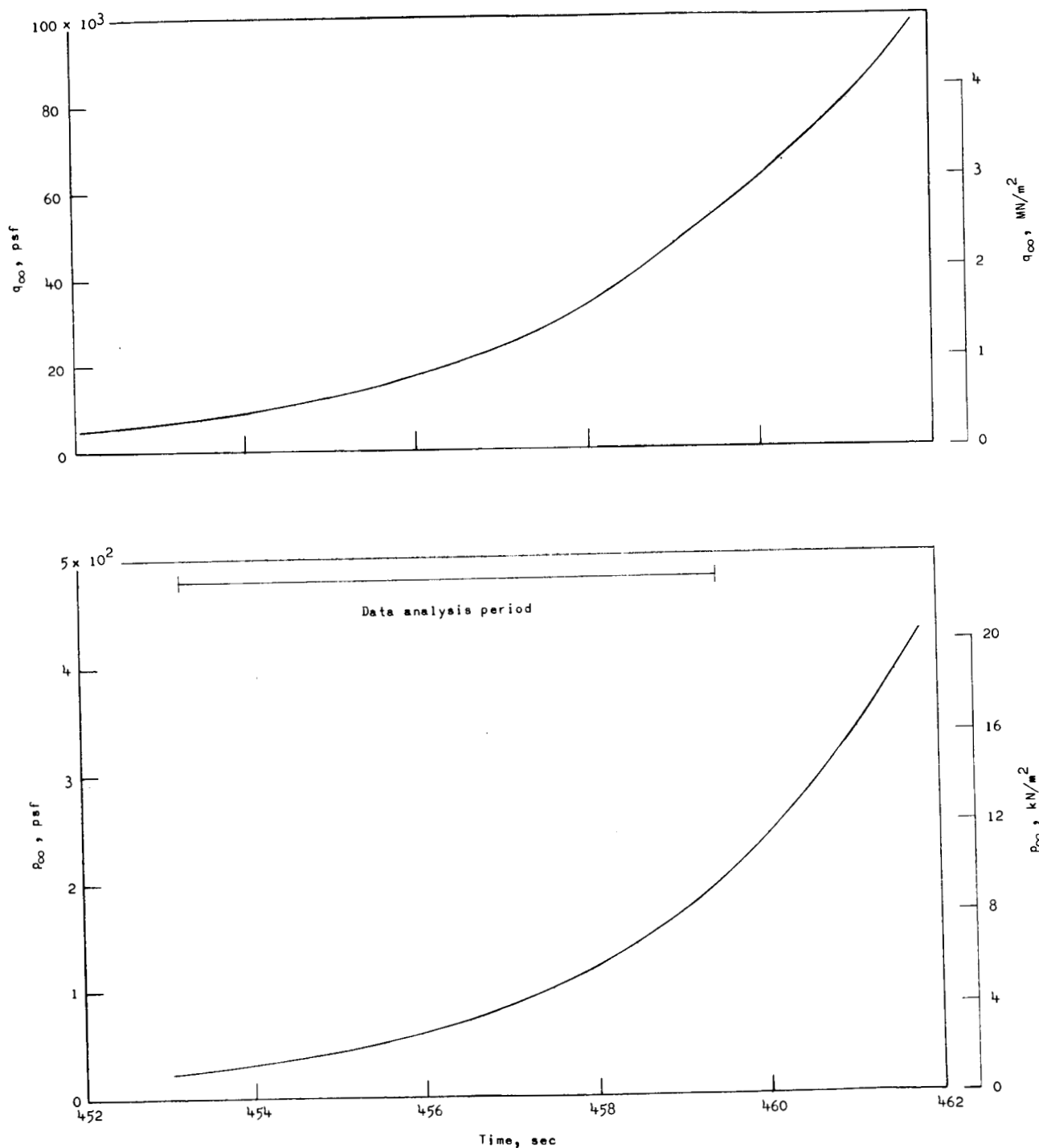


Figure 5.- Variation of free-stream dynamic pressure and ambient pressure during reentry.

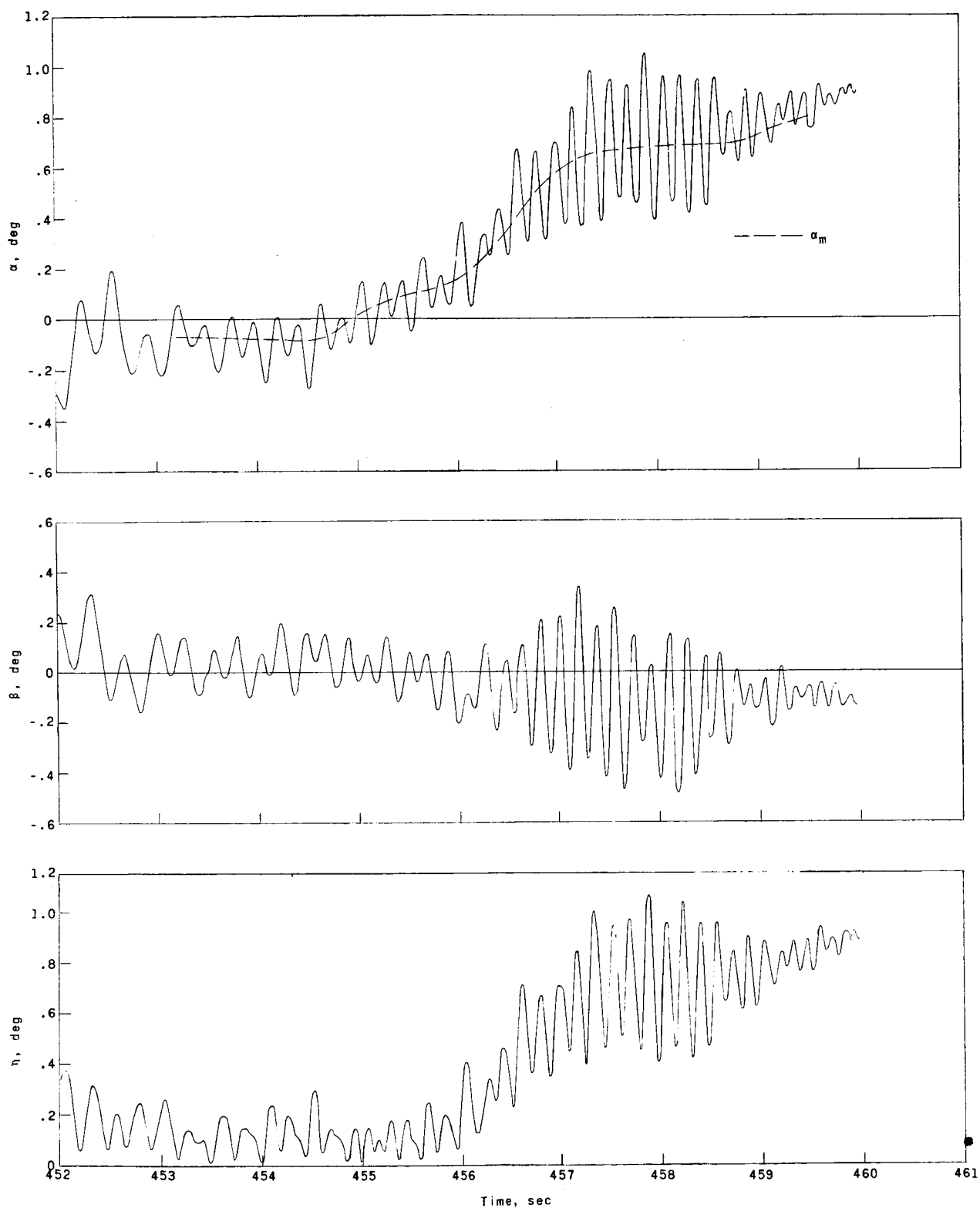


Figure 6.- Angle of attack, angle of sideslip, and total angle of attack as a function of time.

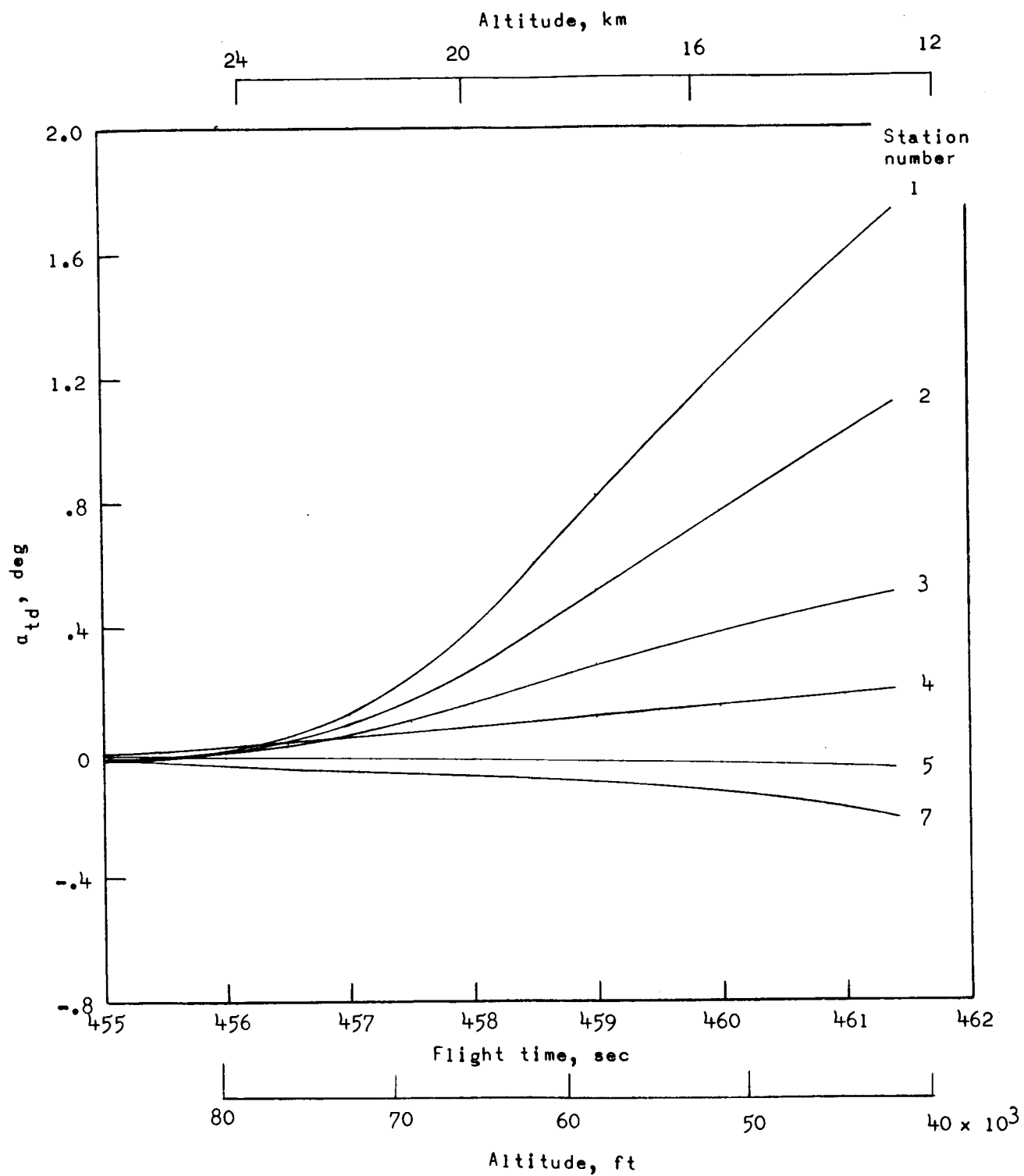


Figure 7.- Thermal distortion at pressure-measuring stations during reentry.

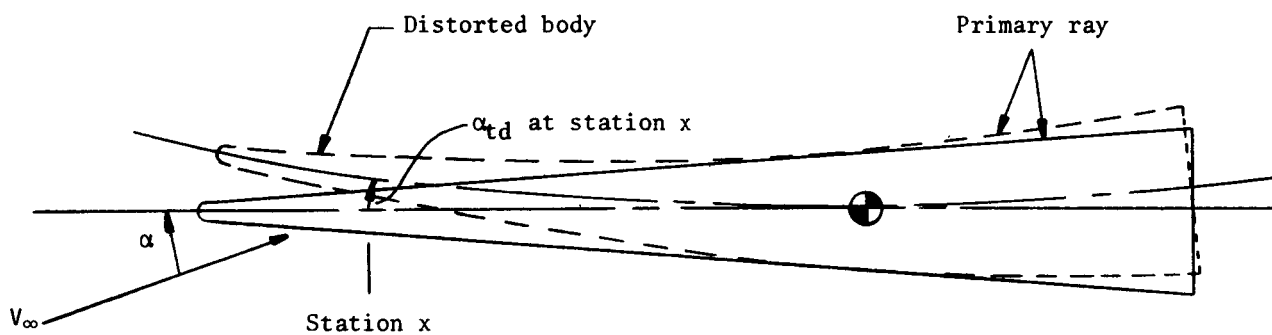


Figure 8.- Sketch of spacecraft showing orientation for angle of attack and thermal distortion. Figures not to scale.

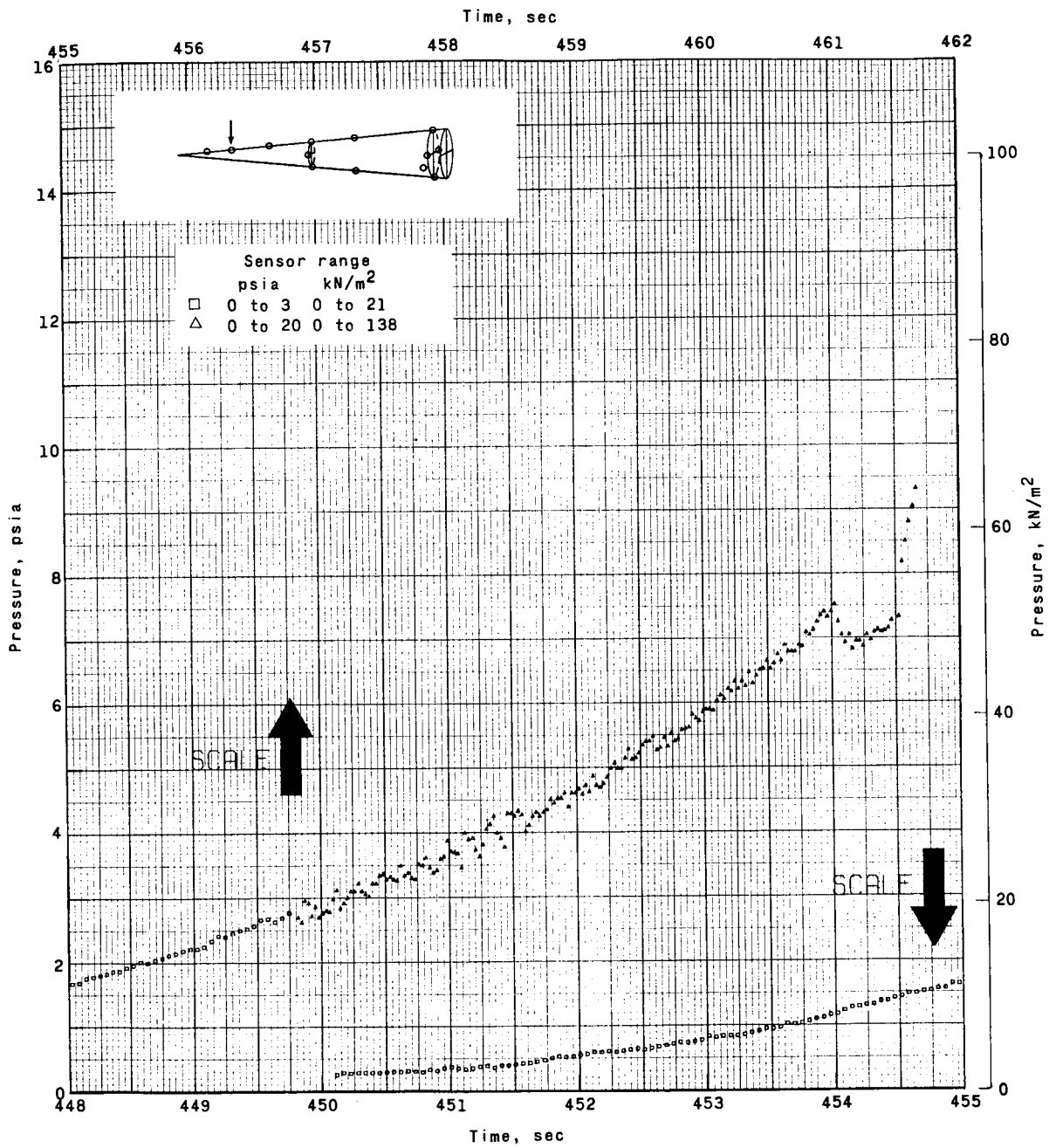
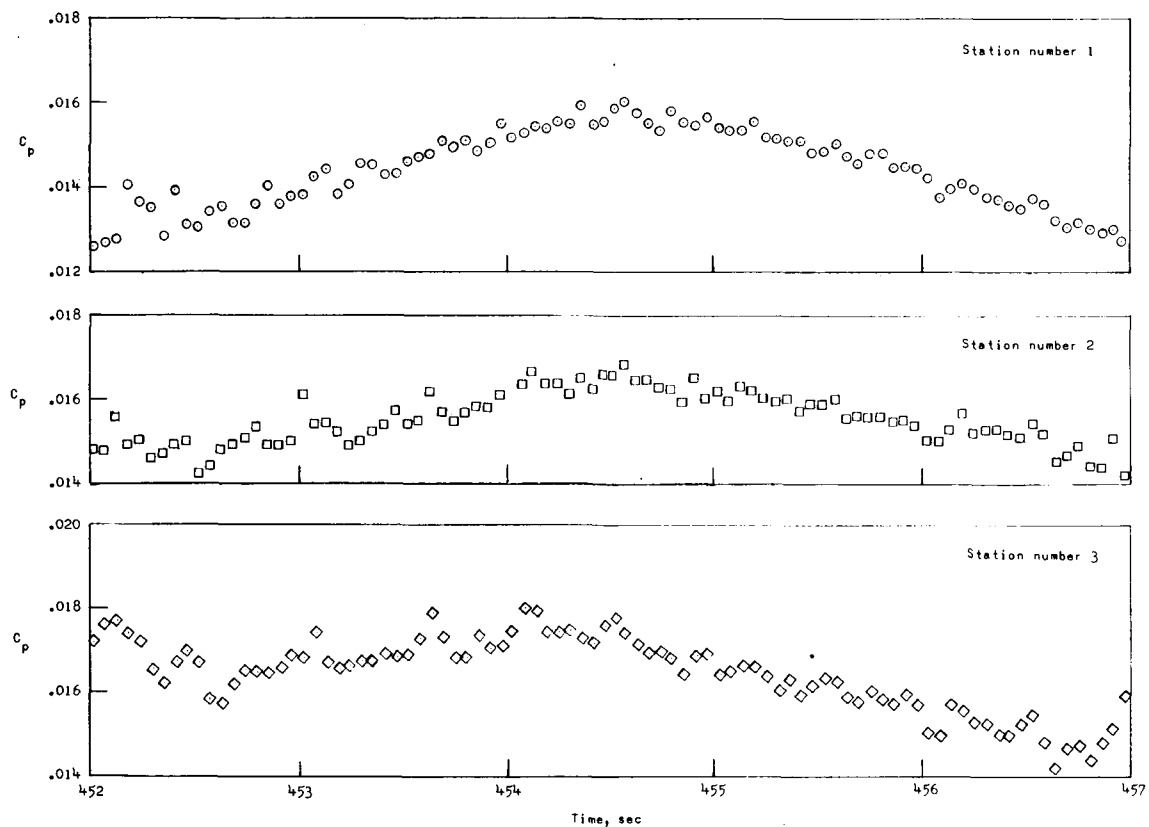
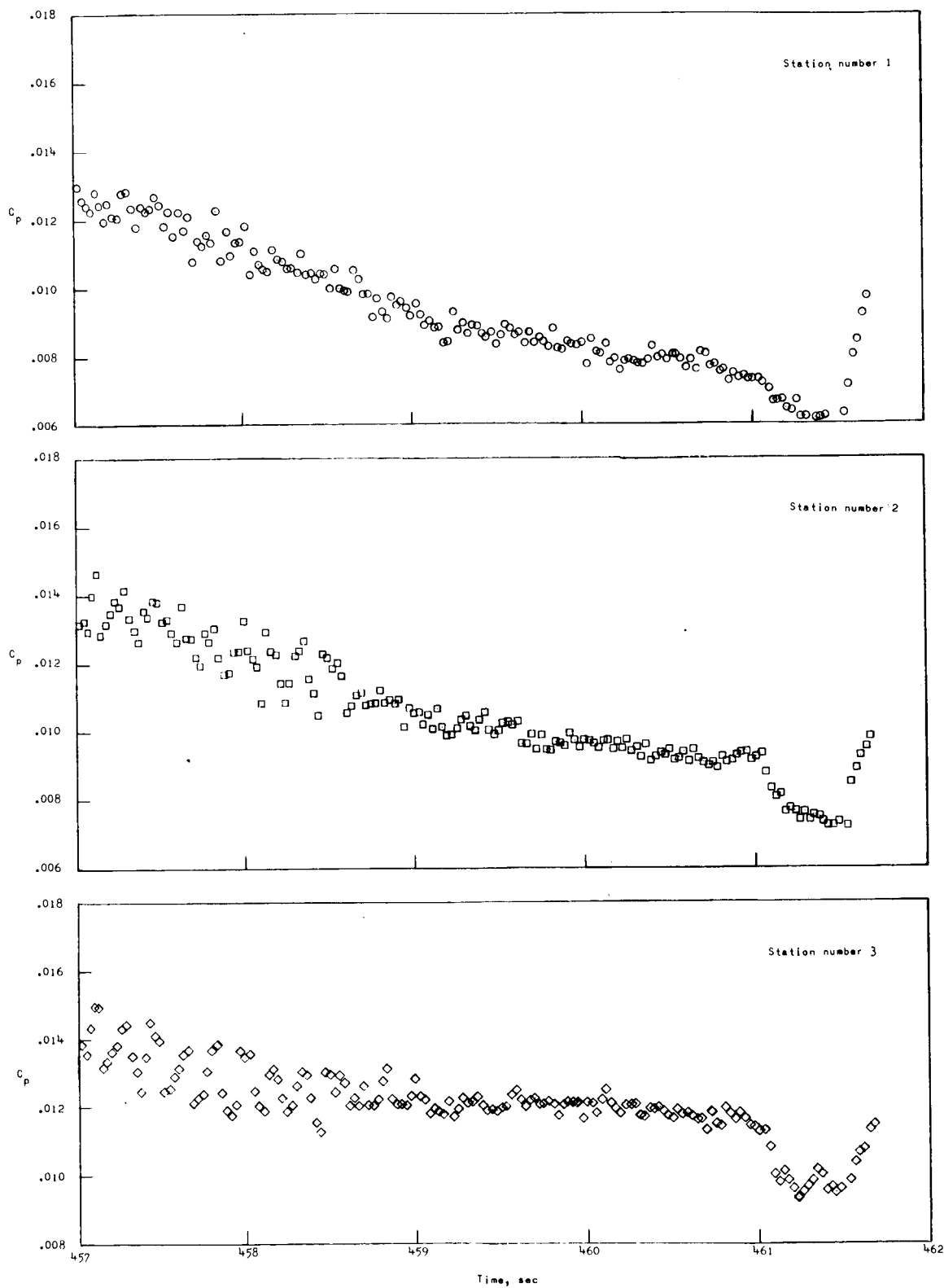


Figure 9.- Typical pressure time history. Station number 2; $\phi = 0^\circ$.



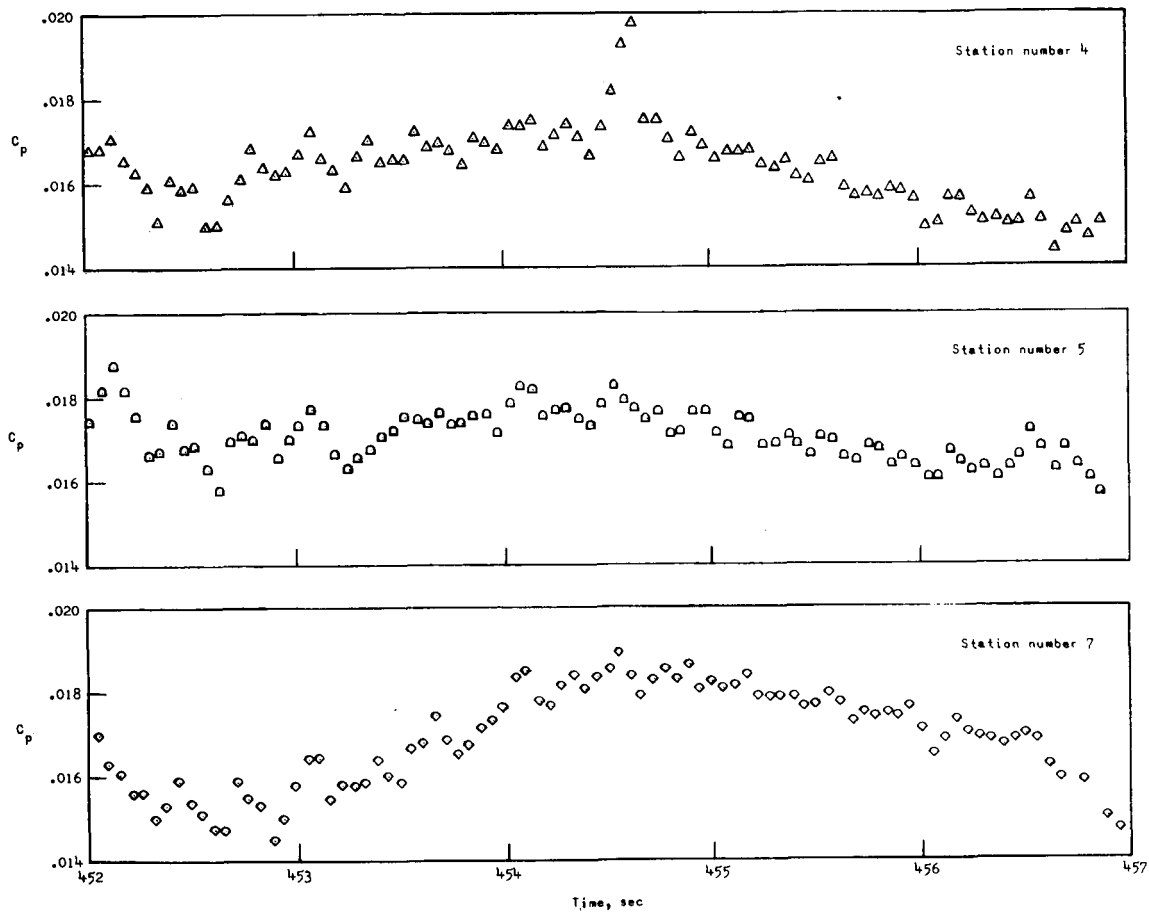
(a) $\phi = 0^\circ$; 0 to 21 kN/m² (0 to 3 psia) gage.

Figure 10.- Surface pressure coefficient time history.



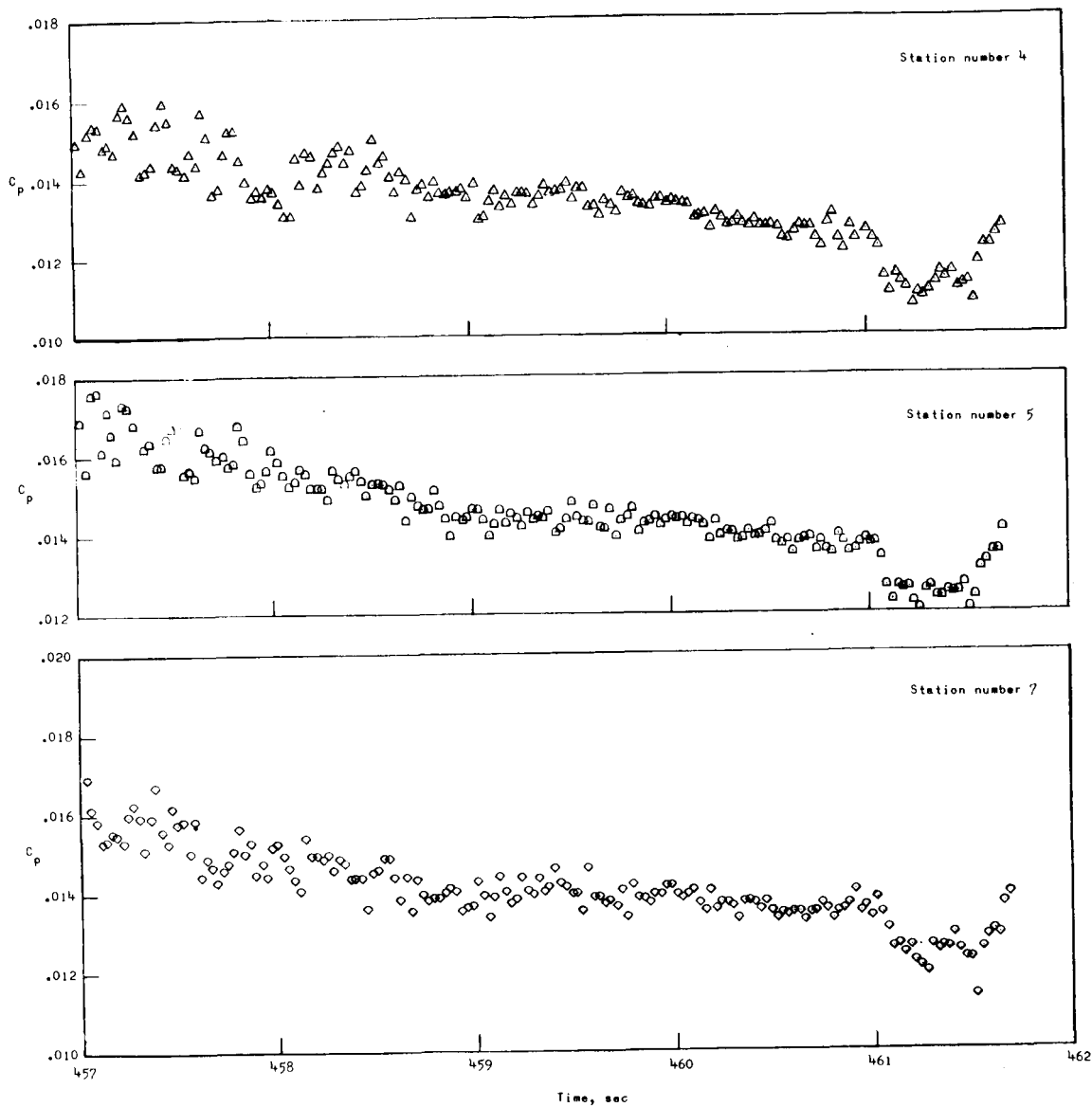
(b) $\phi = 0^\circ$; 0 to 138 kN/m² (0 to 20 psia) gage.

Figure 10.- Continued.



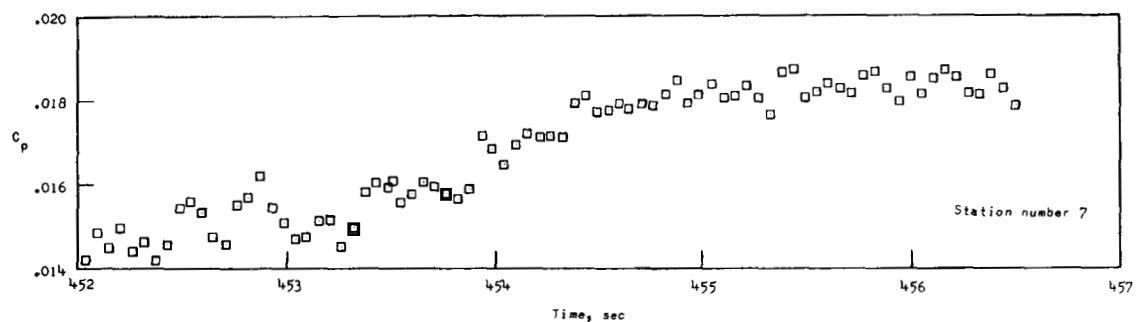
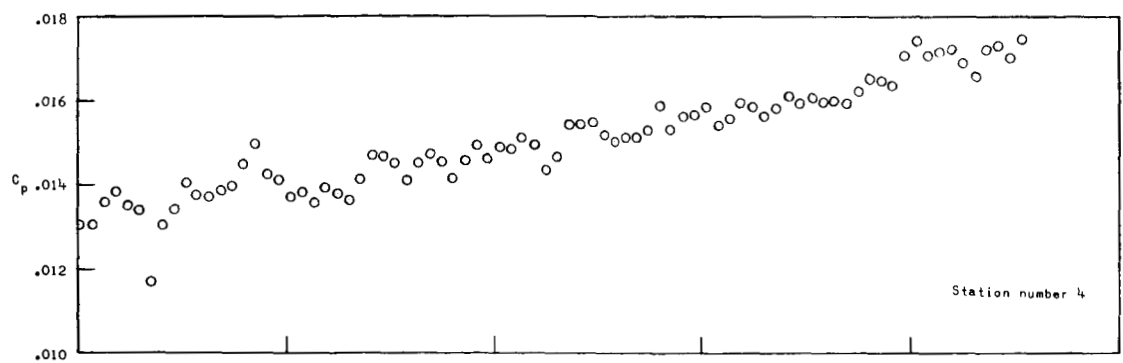
(c) $\phi = 0^\circ$; 0 to 21 kN/m² (0 to 3 psia) gage.

Figure 10.- Continued.

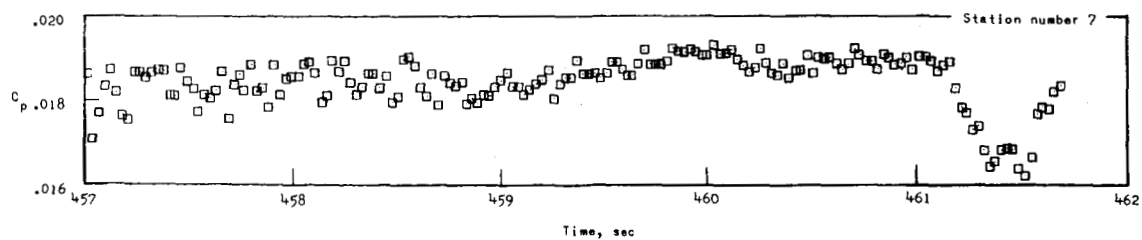
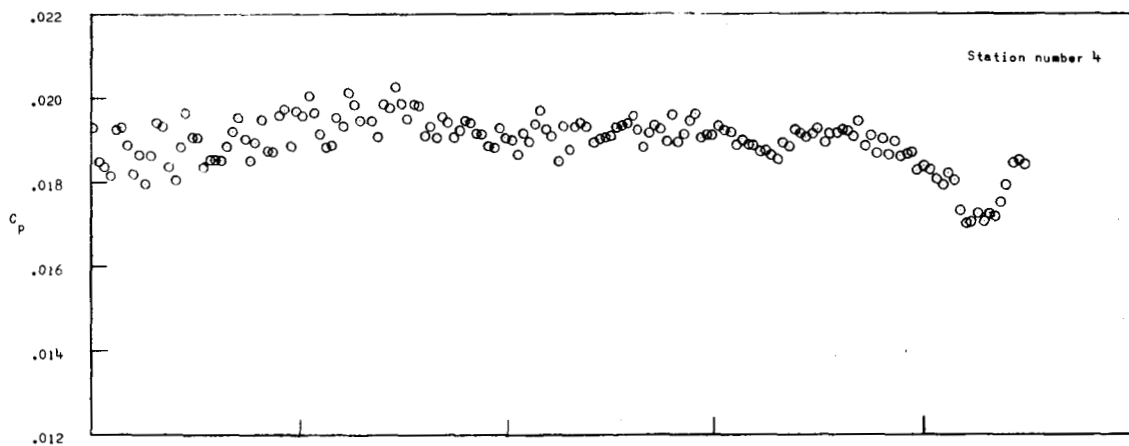


(d) $\phi = 0^\circ$; 0 to 138 kN/m² (0 to 20 psia) gage.

Figure 10.- Continued.

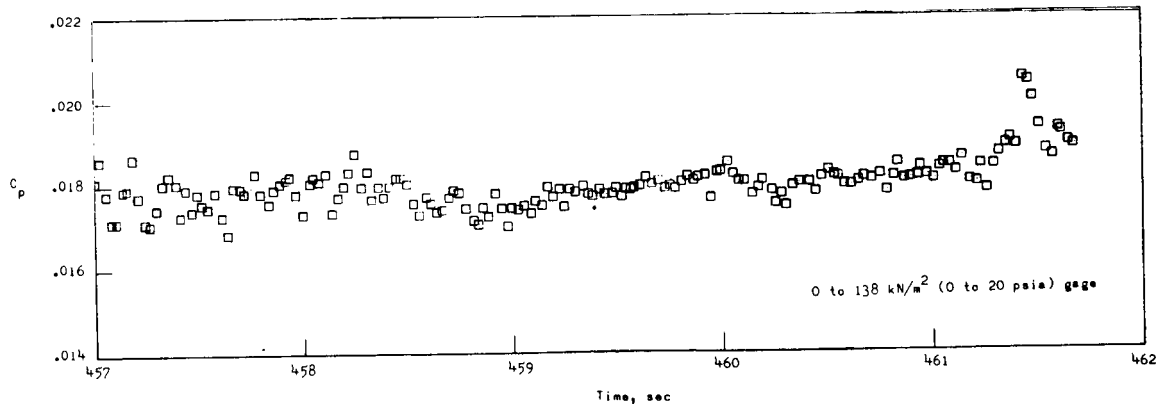
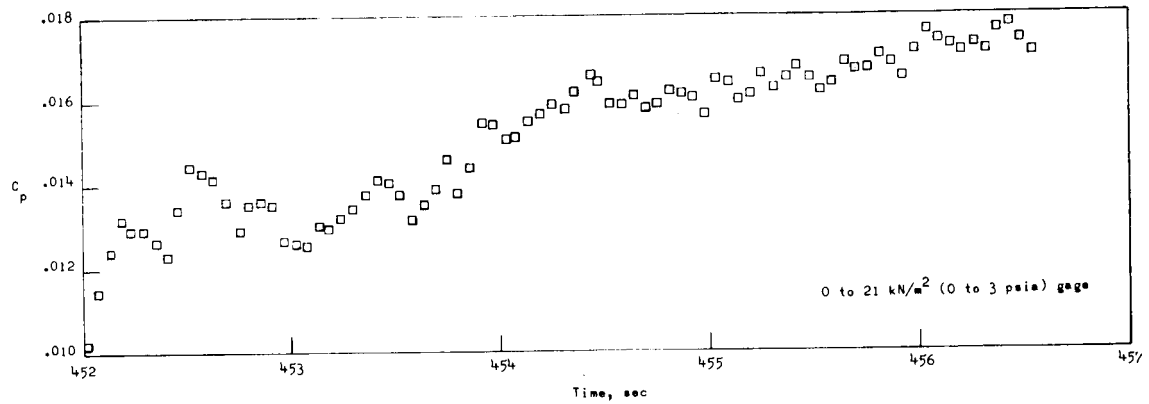


(e) $\phi = 90^\circ$; 0 to 21 kN/m² (0 to 3 psia) gage.



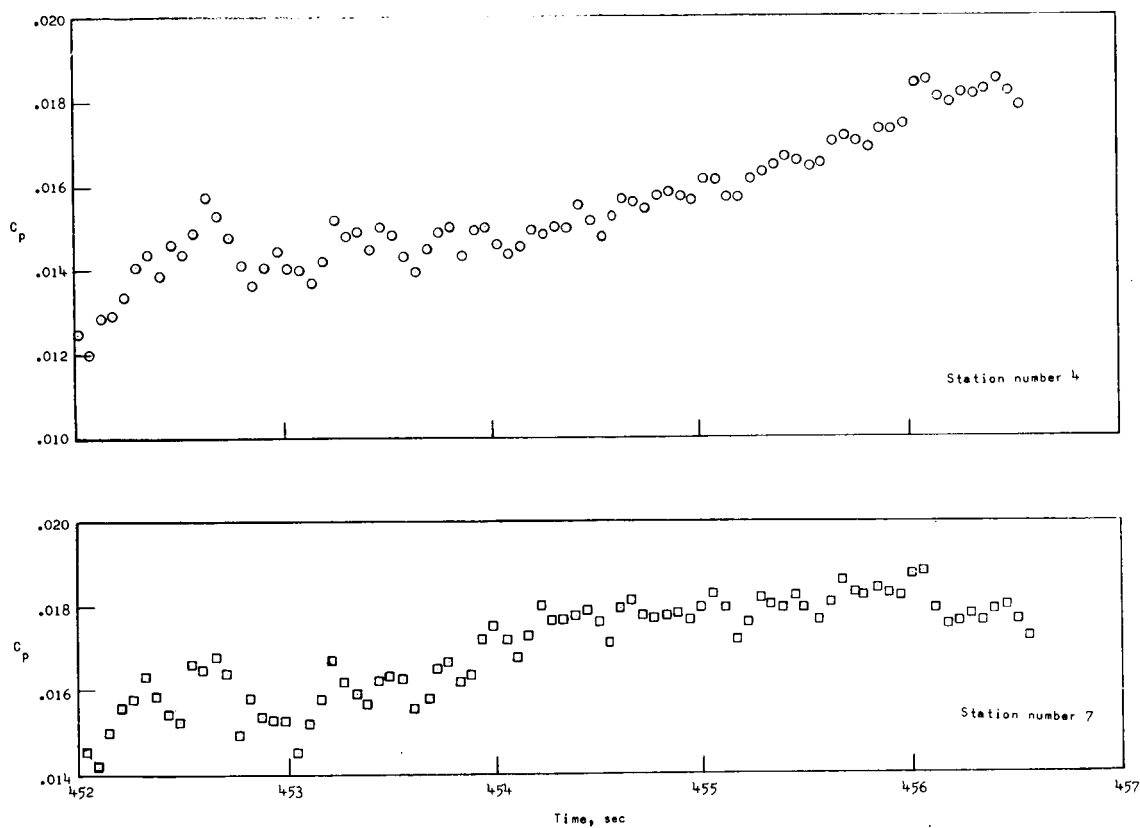
(f) $\phi = 90^\circ$; 0 to 138 kN/m² (0 to 20 psia) gage.

Figure 10. - Continued.



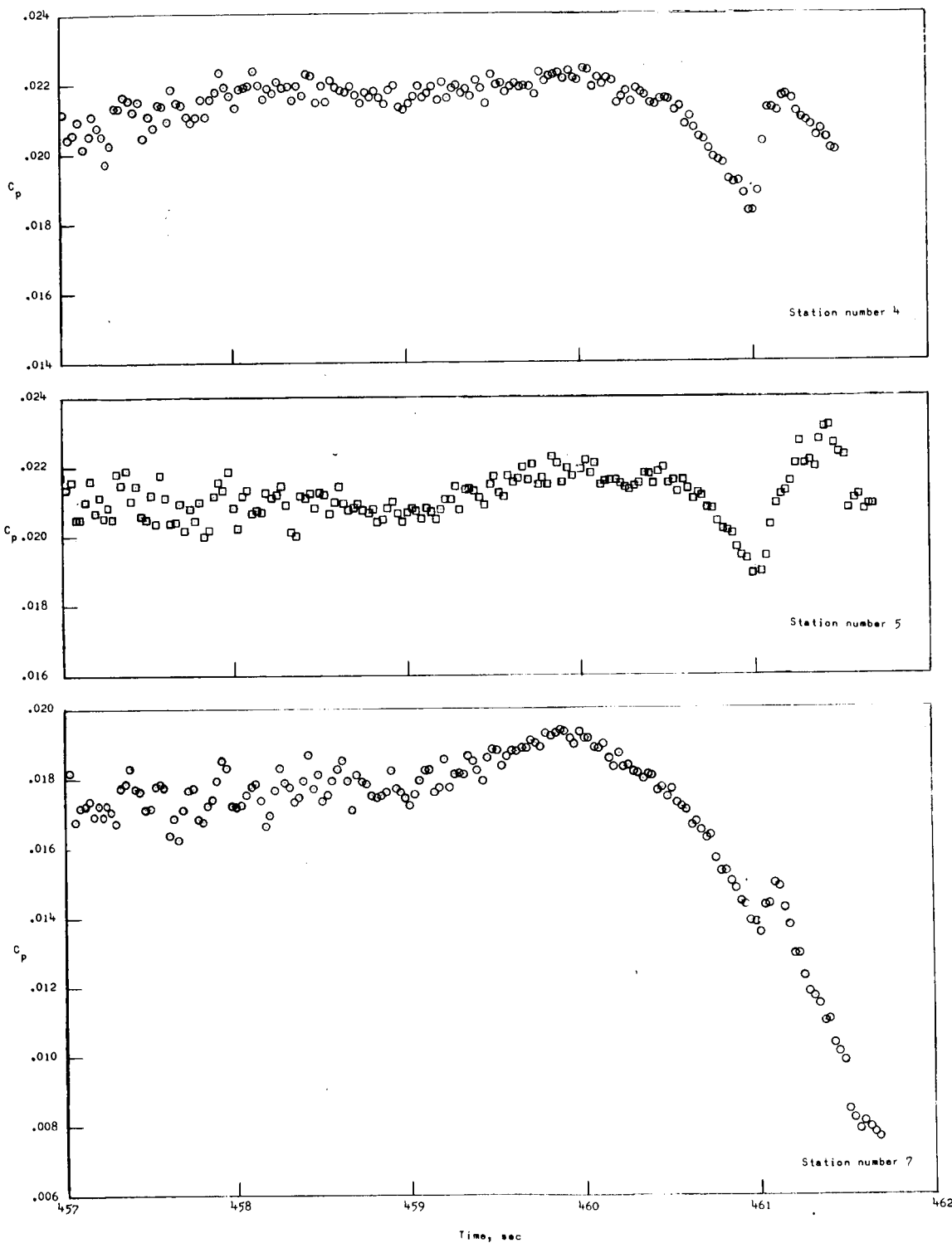
(g) $\phi = 135^\circ$; station number 6.

Figure 10.- Continued.



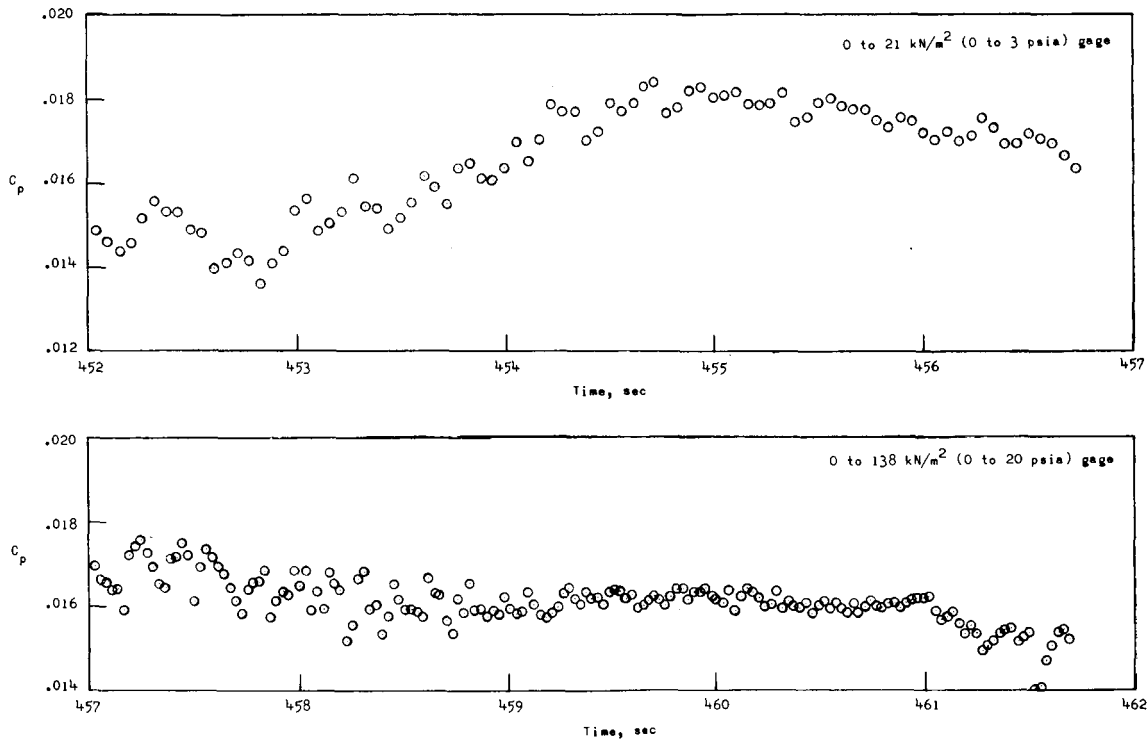
(h) $\phi = 180^\circ$; 0 to 21 kN/m² (0 to 3 psia) gage.

Figure 10.- Continued.



(i) $\phi = 180^\circ$; 0 to 138 kN/m² (0 to 20 psia) gage.

Figure 10.- Continued.



(j) $\phi = 270^\circ$; station number 7.

Figure 10.- Concluded.

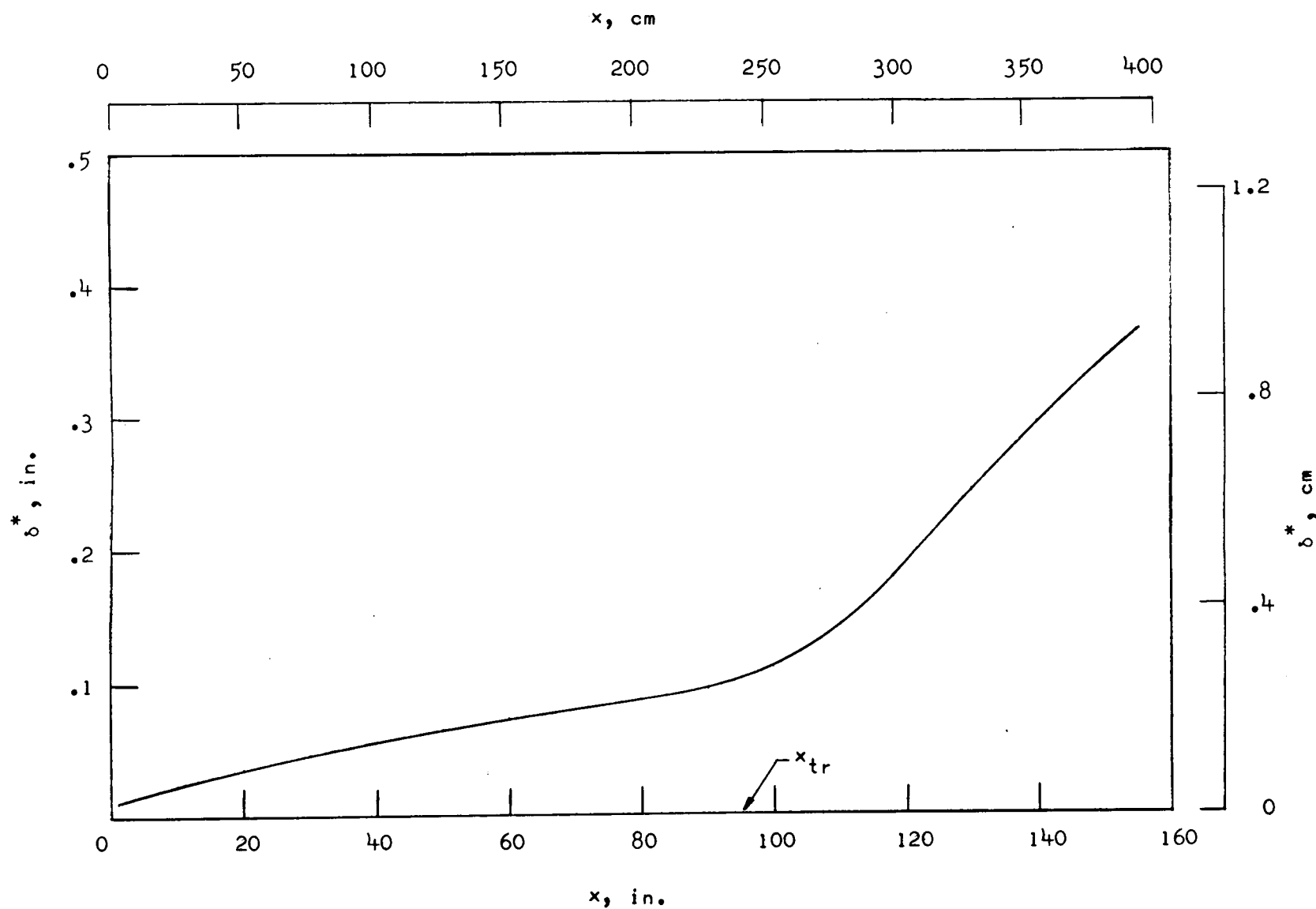


Figure 11.- Typical displacement thickness distribution on spacecraft. $h = 25.9$ km (85 000 ft).

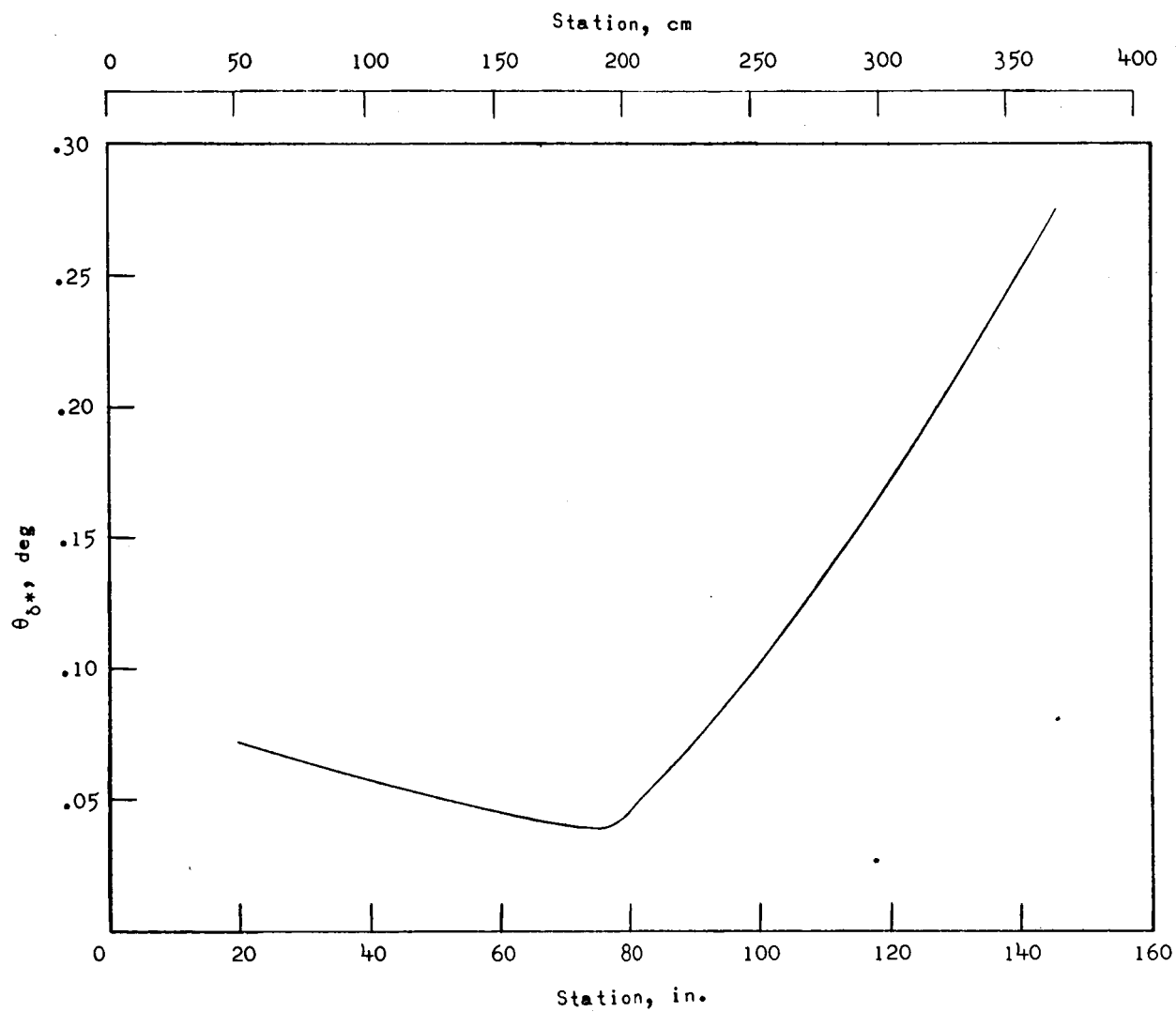


Figure 12.- Variation of flow angle due to displacement thickness.
 $h = 25.9 \text{ km (85 000 ft)}$.

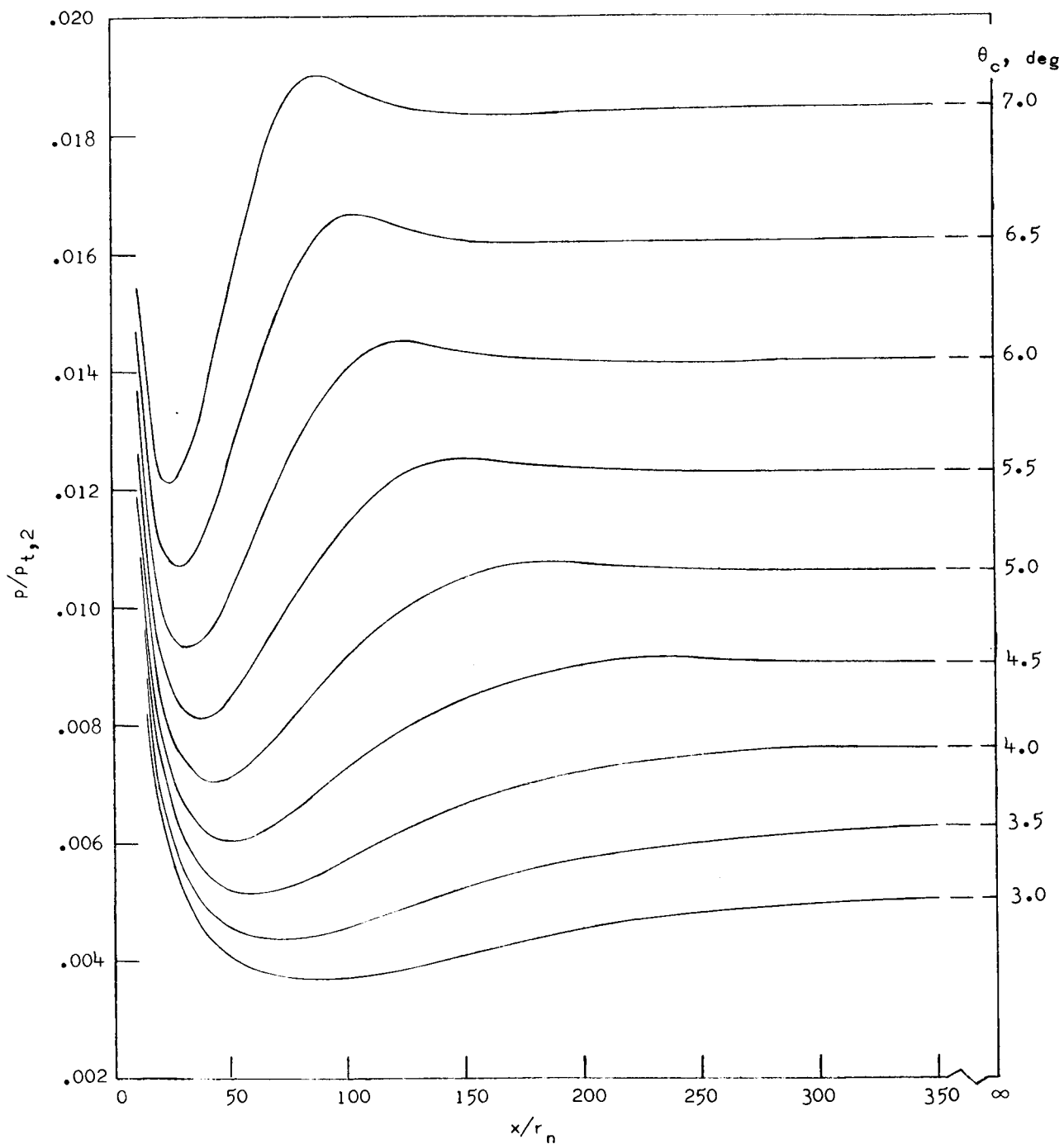


Figure 13.- Pressure distributions for several hemispherically capped cones computed with Lomax and Inouye's flow field solution.

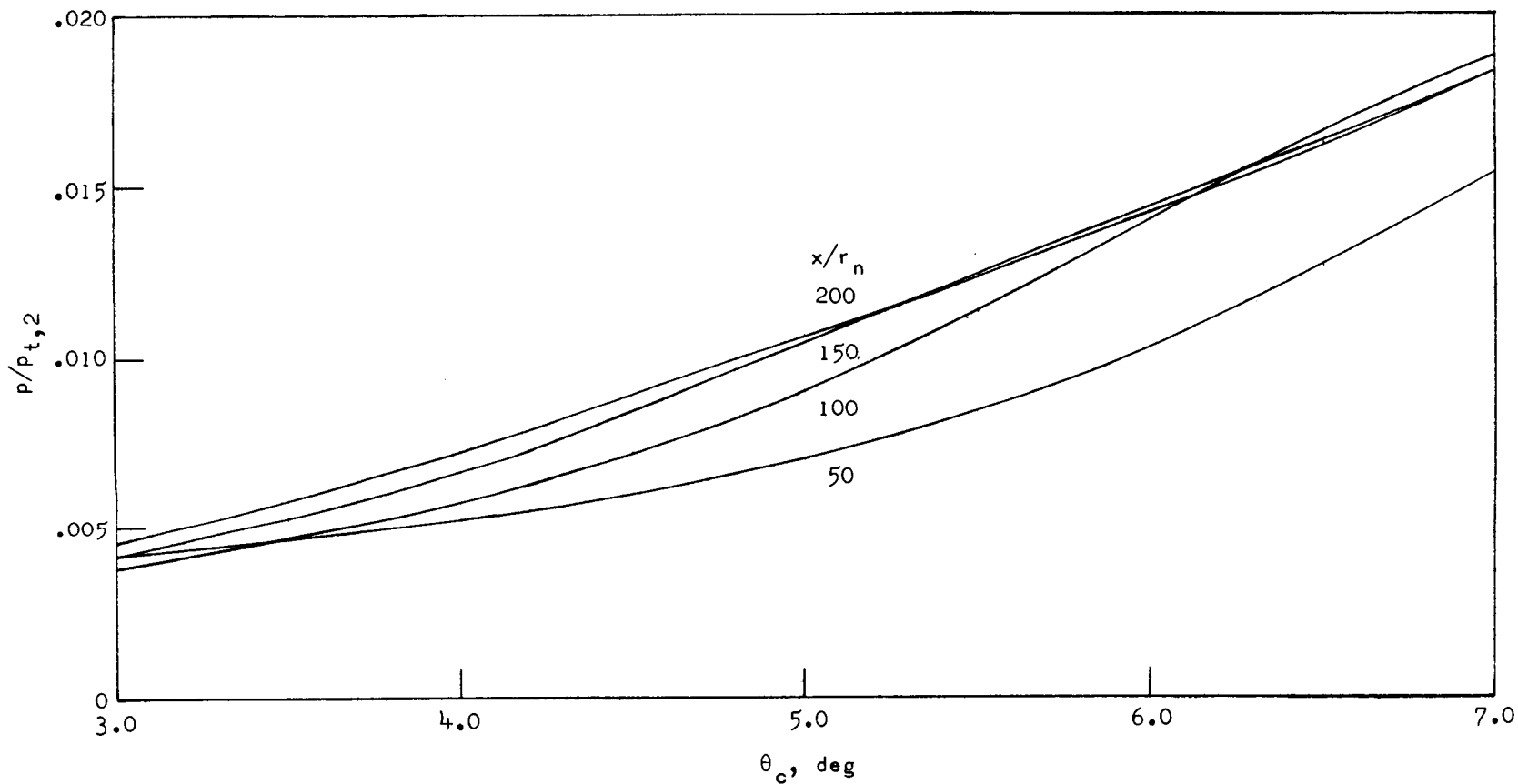


Figure 14.- Variation of local to total pressure ratio with cone half-angle from cross plot of figure 13.

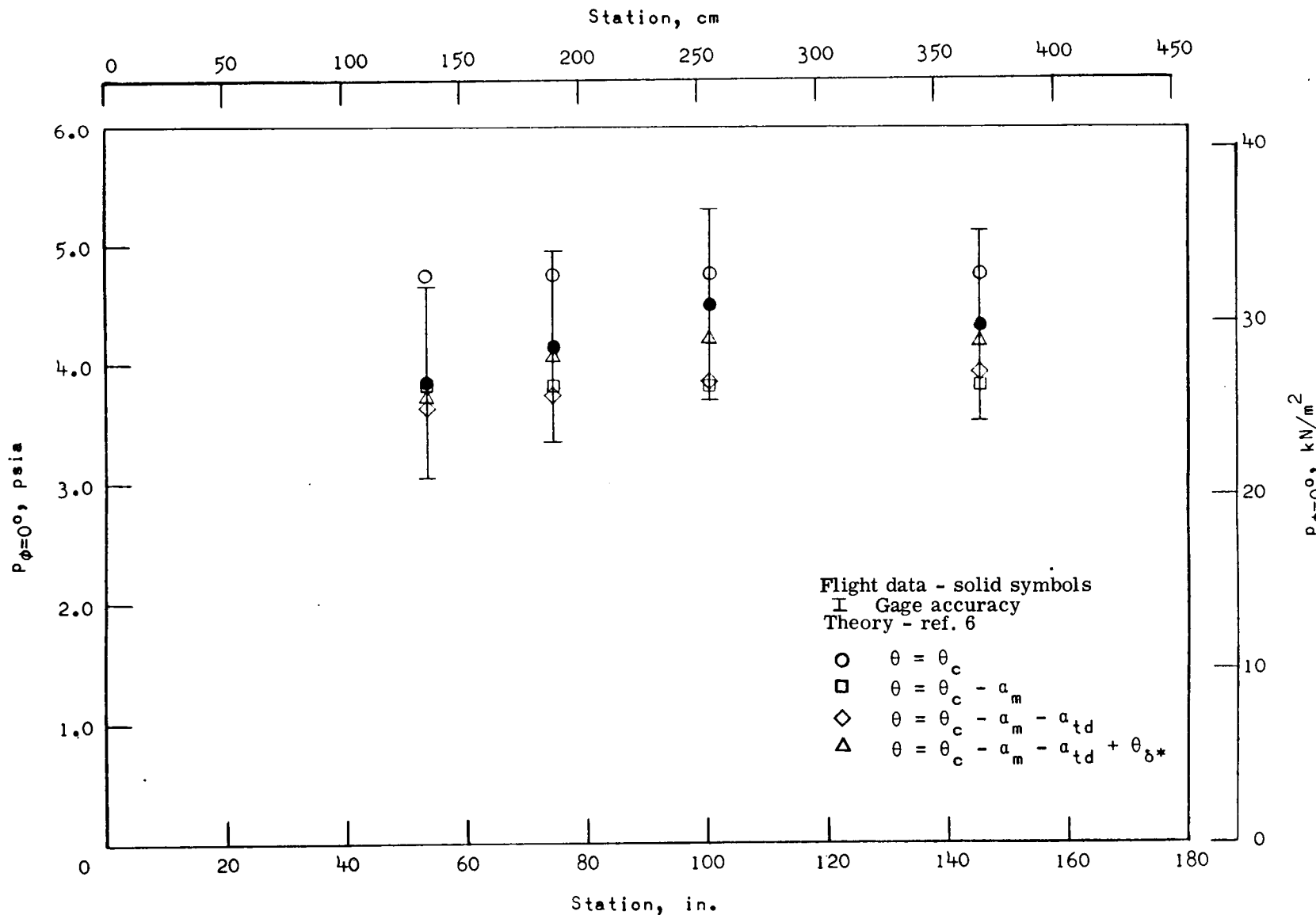
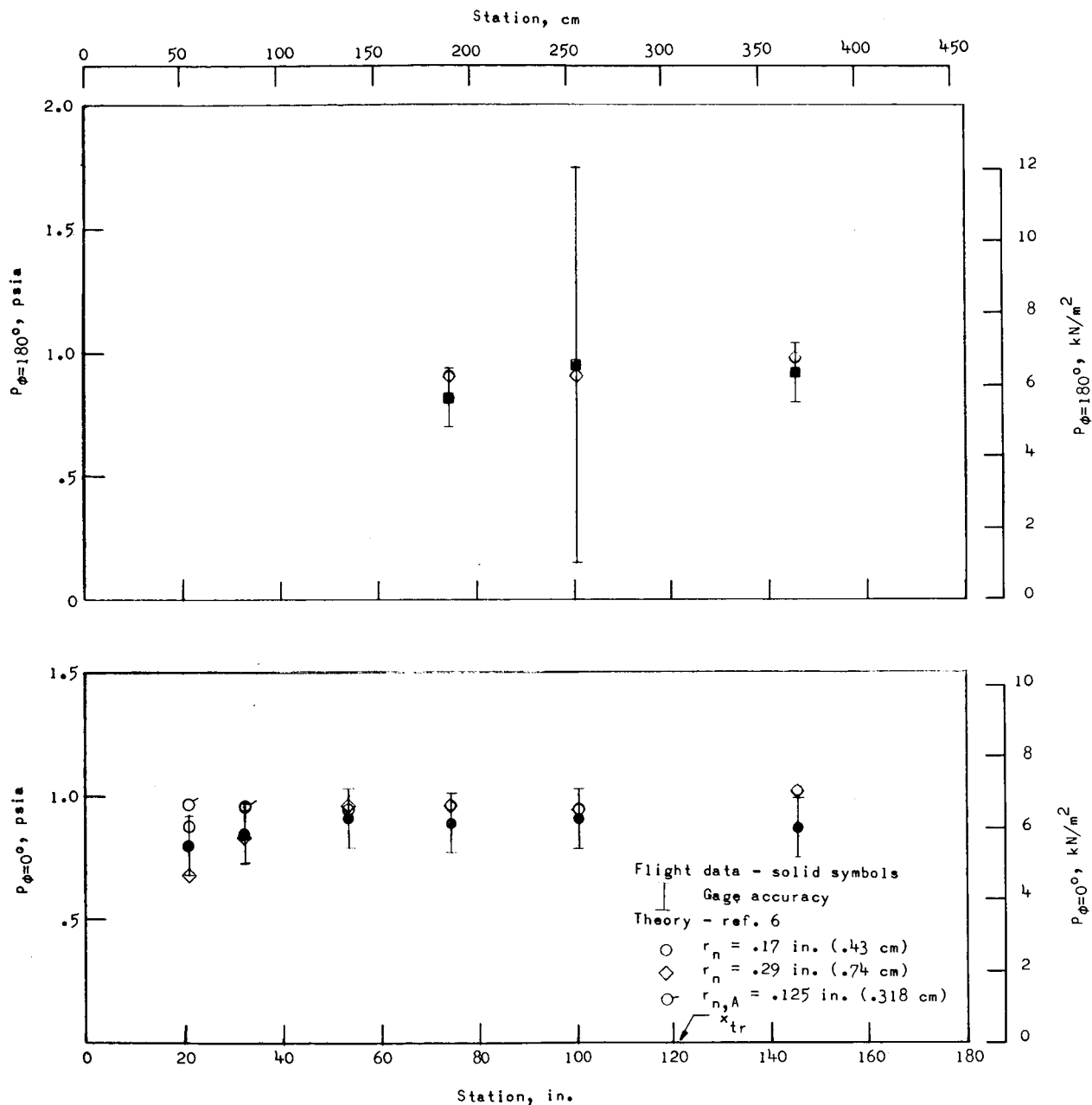
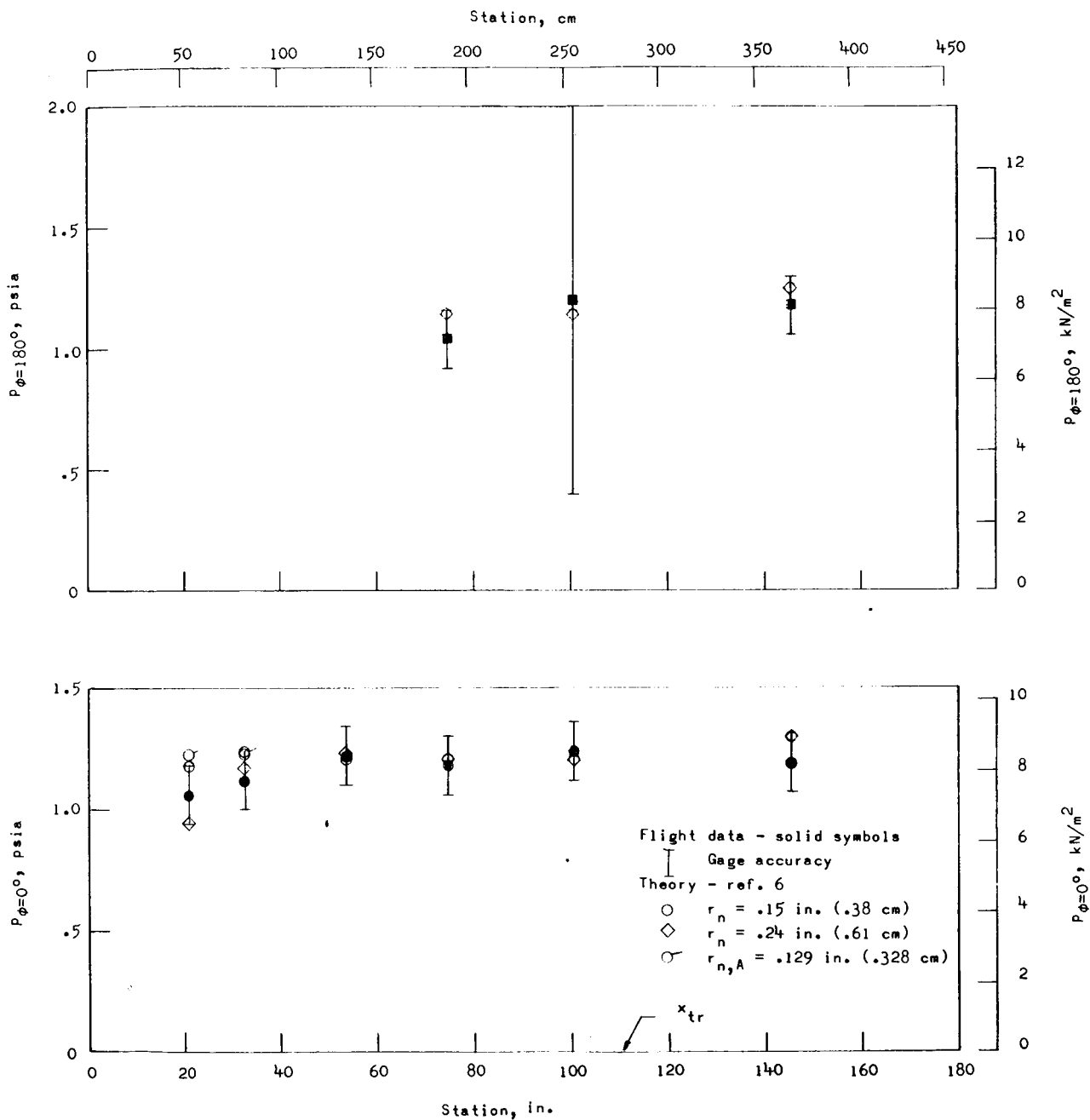


Figure 15.- Typical theoretical and experimental pressure distribution on spacecraft showing effects of local flow angle (19.81 km (65 000 ft)).



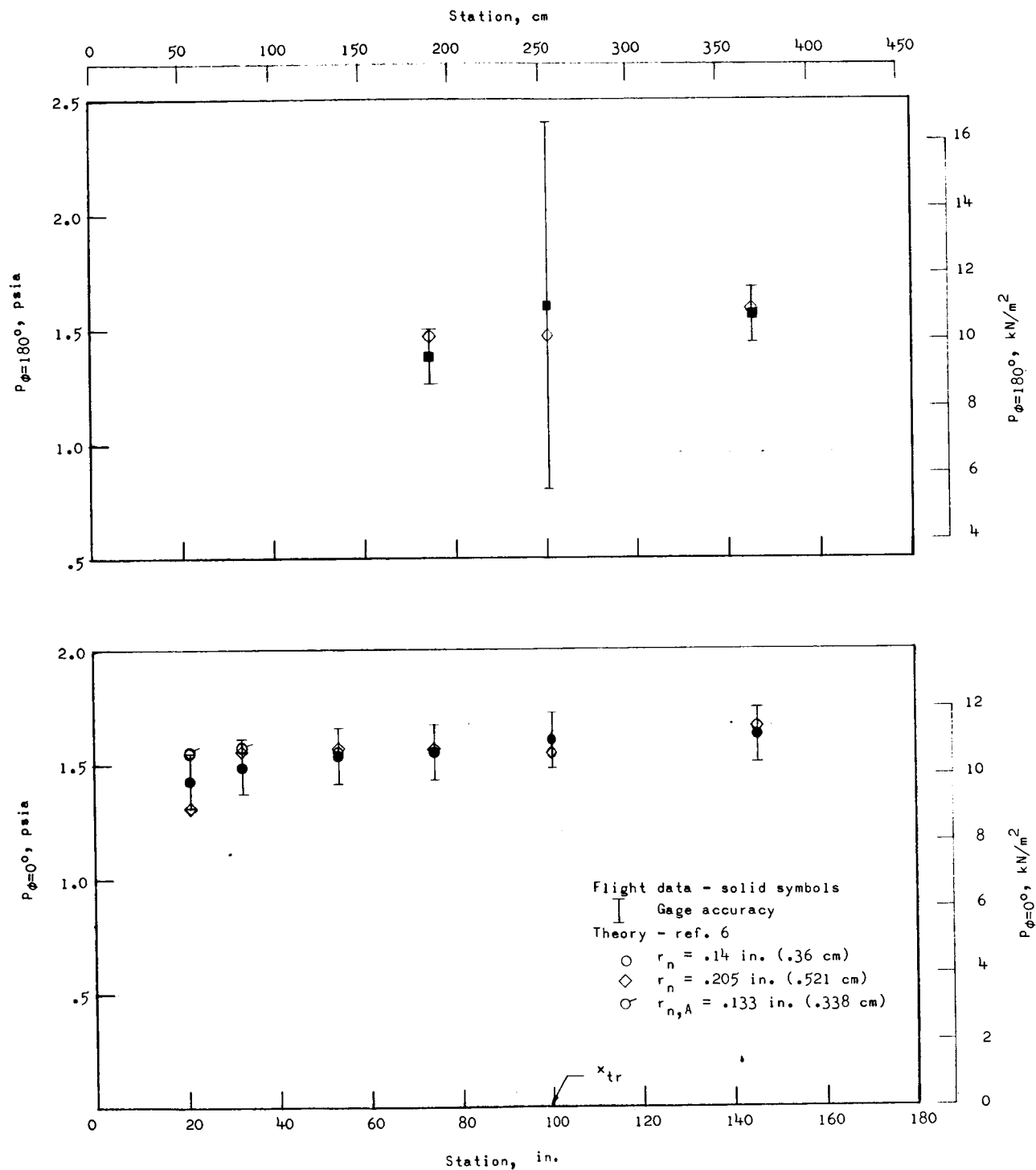
(a) $h = 30.5$ km (100 000 ft); $p_{t,2} = 5.9$ atm.

Figure 16.- Theoretical and experimental pressure distribution on spacecraft.



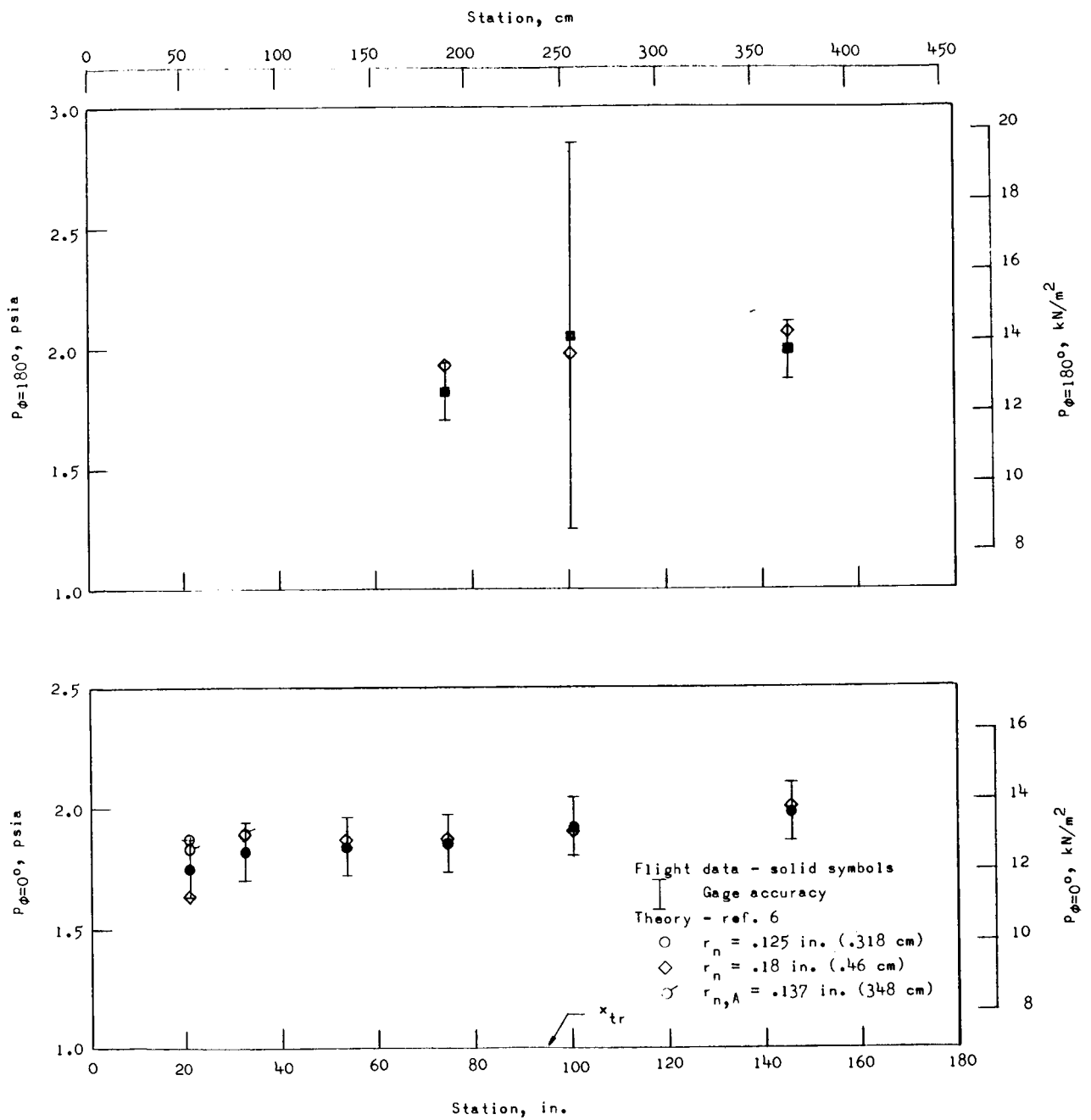
(b) $h = 29.0$ km (95 000 ft); $p_{t,2} = 7.5$ atm.

Figure 16.- Continued.



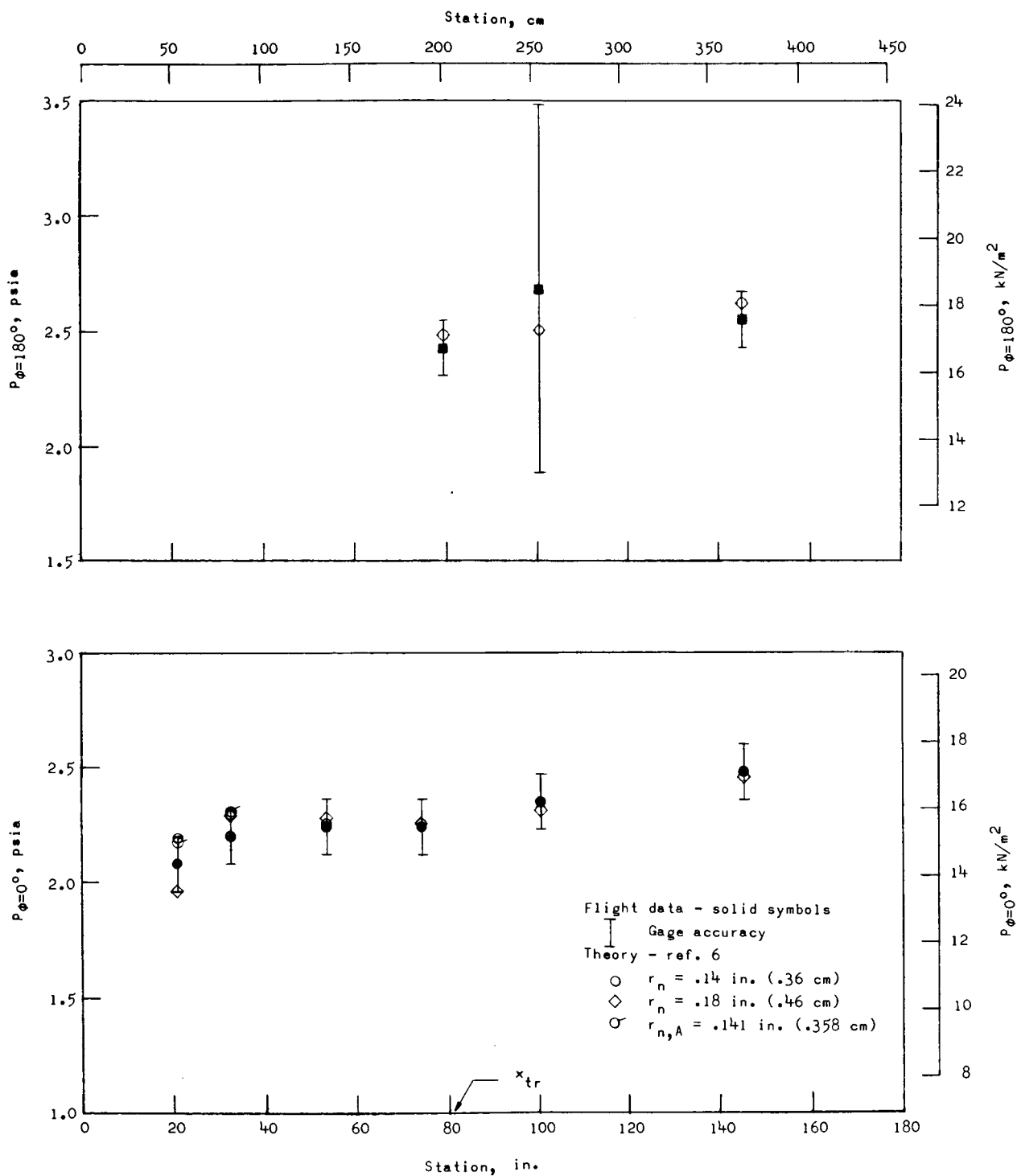
(c) $h = 27.4$ km (90 000 ft); $p_{t,2} = 9.6$ atm.

Figure 16.- Continued.



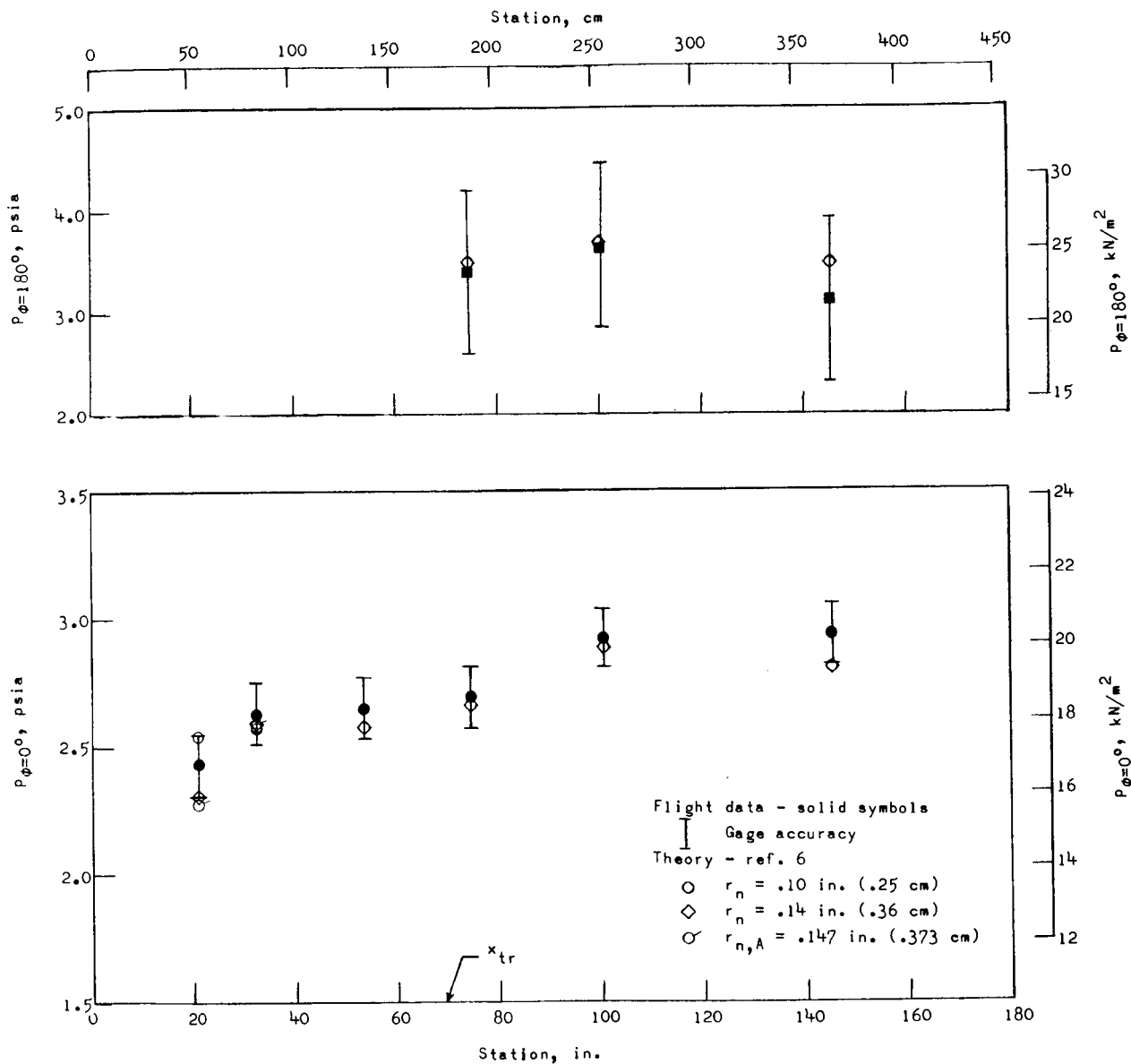
(d) $h = 25.9$ km (85 000 ft); $p_{t,2} = 12.1$ atm.

Figure 16.- Continued.



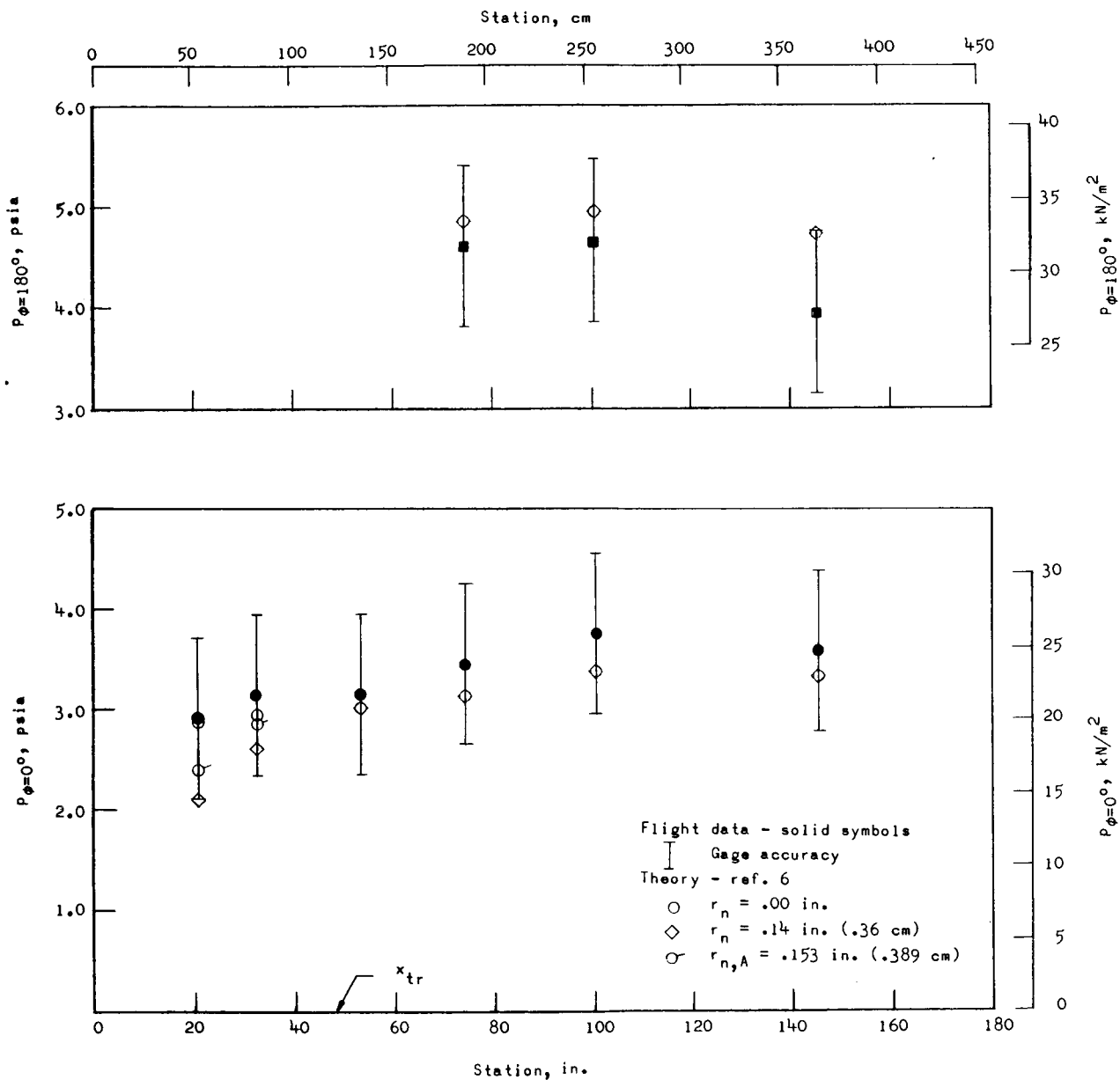
(e) $h = 24.4$ km (80 000 ft); $p_{t,2} = 15.1$ atm.

Figure 16.- Continued.



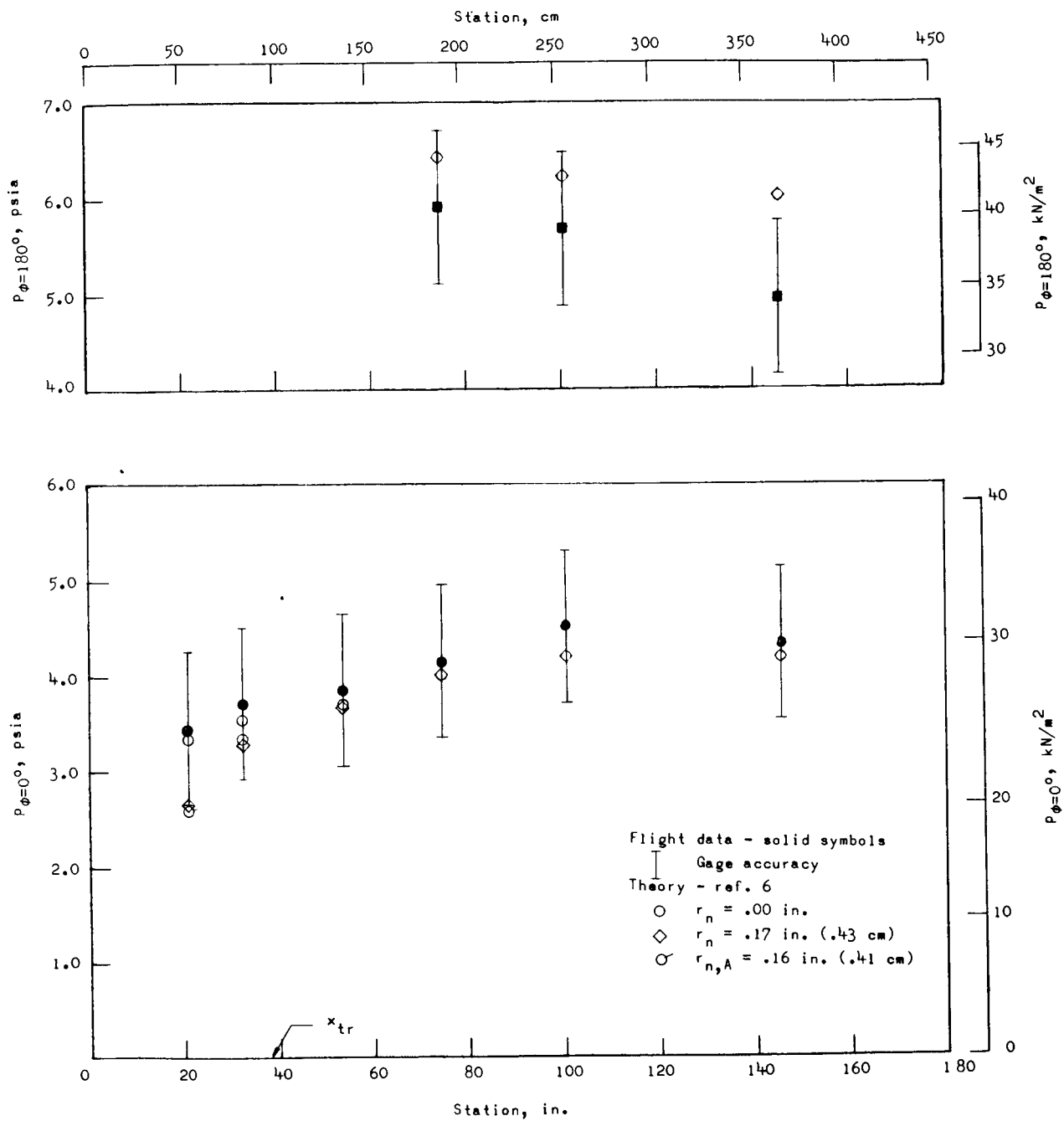
(f) $h = 22.9$ km (75 000 ft); $p_{t,2} = 18.9$ atm.

Figure 16.- Continued.



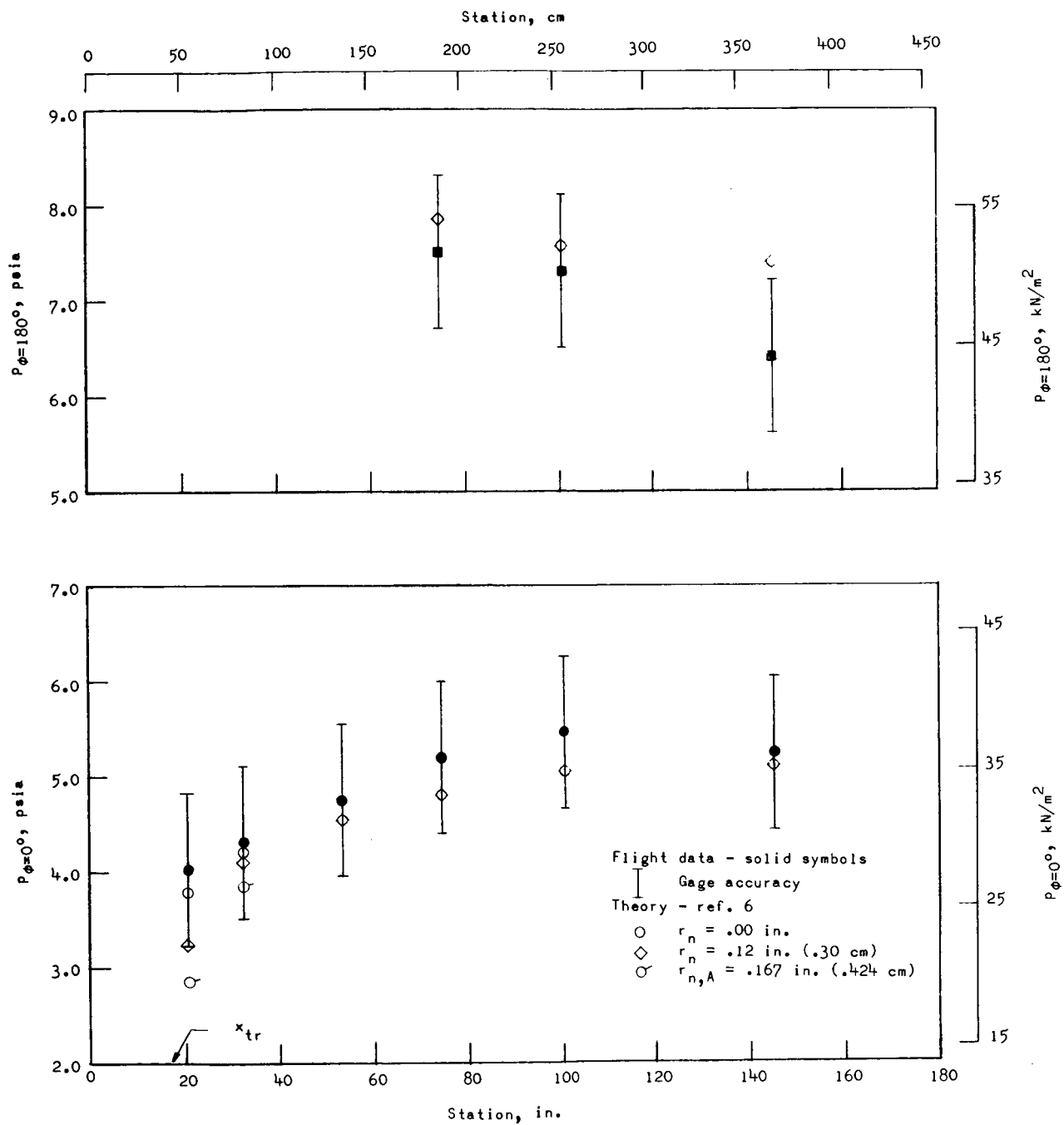
(g) $h = 21.3$ km (70 000 ft); $p_{t,2} = 24.1$ atm.

Figure 16.- Continued.



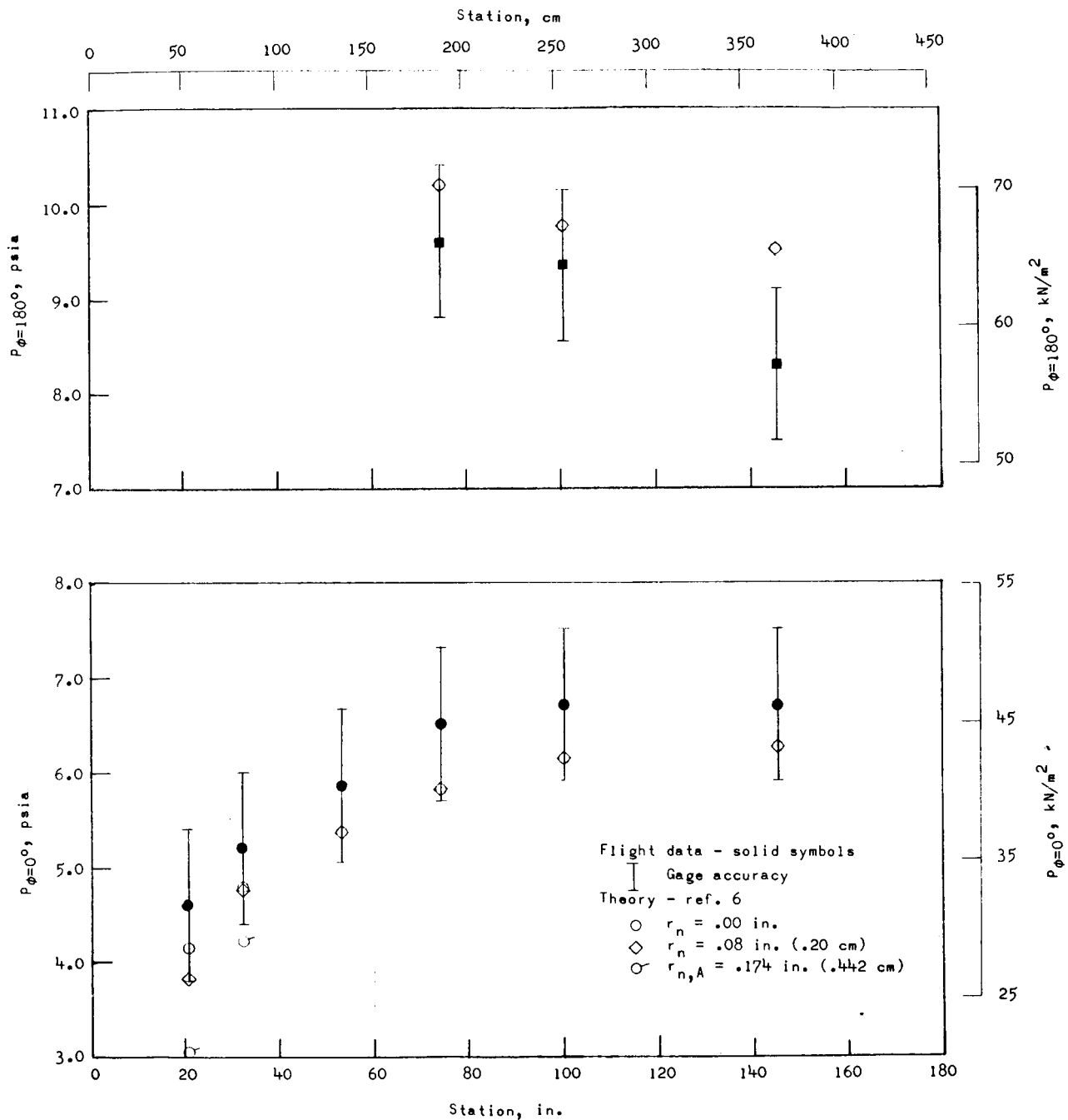
(h) $h = 19.8$ km (65 000 ft); $p_{t,2} = 30.7$ atm.

Figure 16.- Continued.



(i) $h = 18.3$ km (60 000 ft); $p_{t,2} = 39.1$ atm.

Figure 16.- Continued.



(j) $h = 16.8$ km (55 000 ft); $p_{t,2} = 49.2$ atm.

Figure 16.- Concluded.

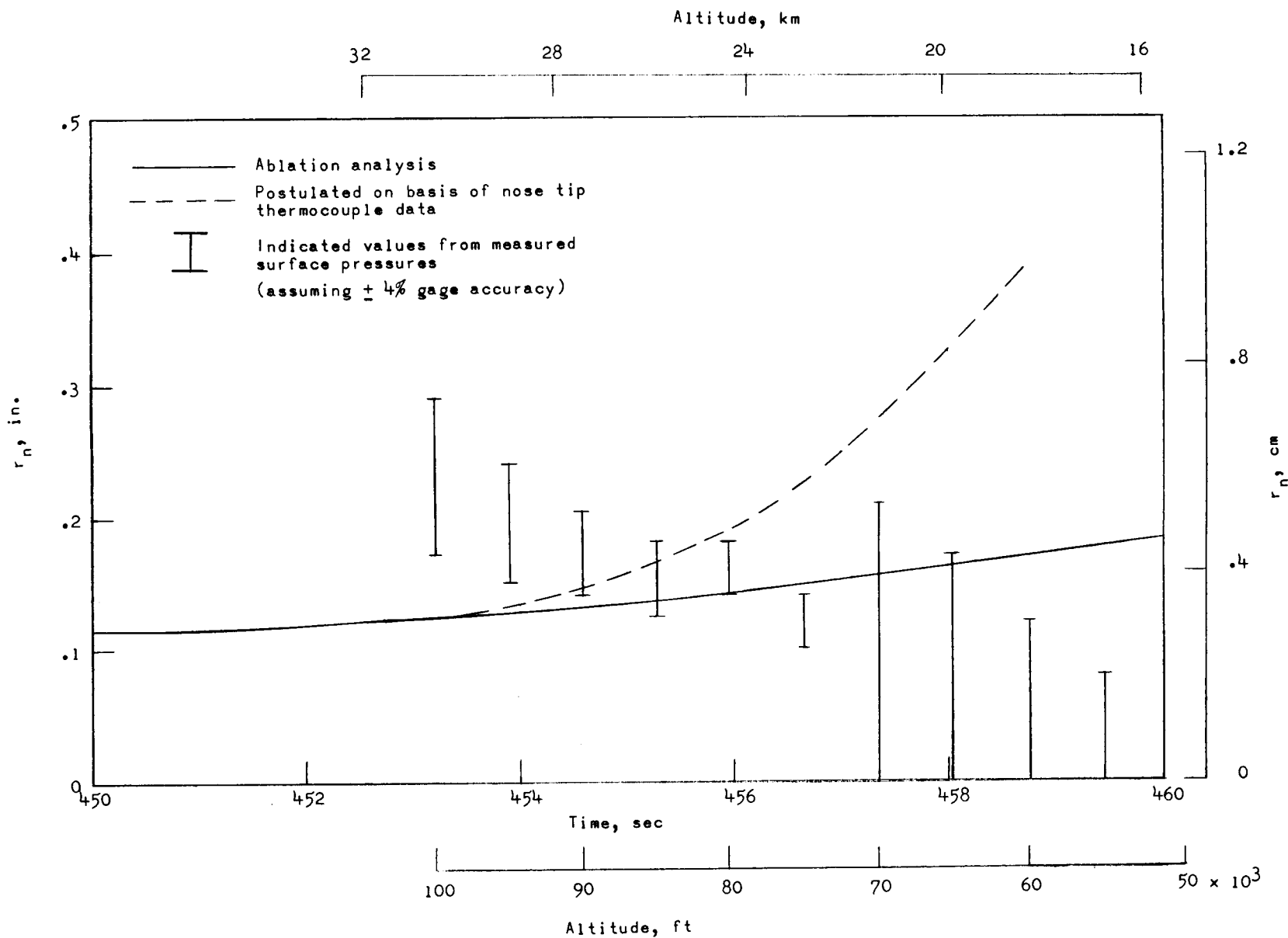
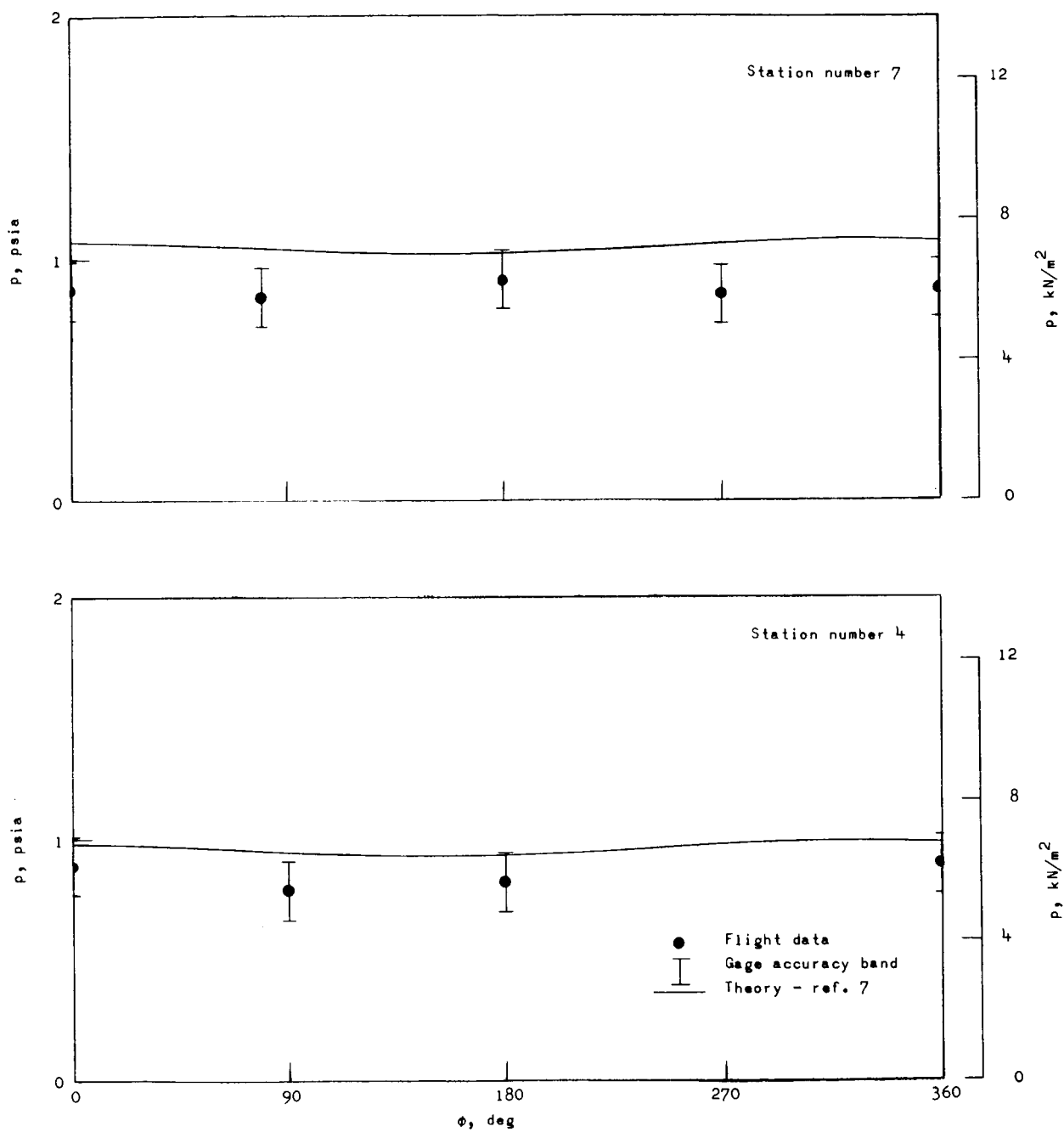
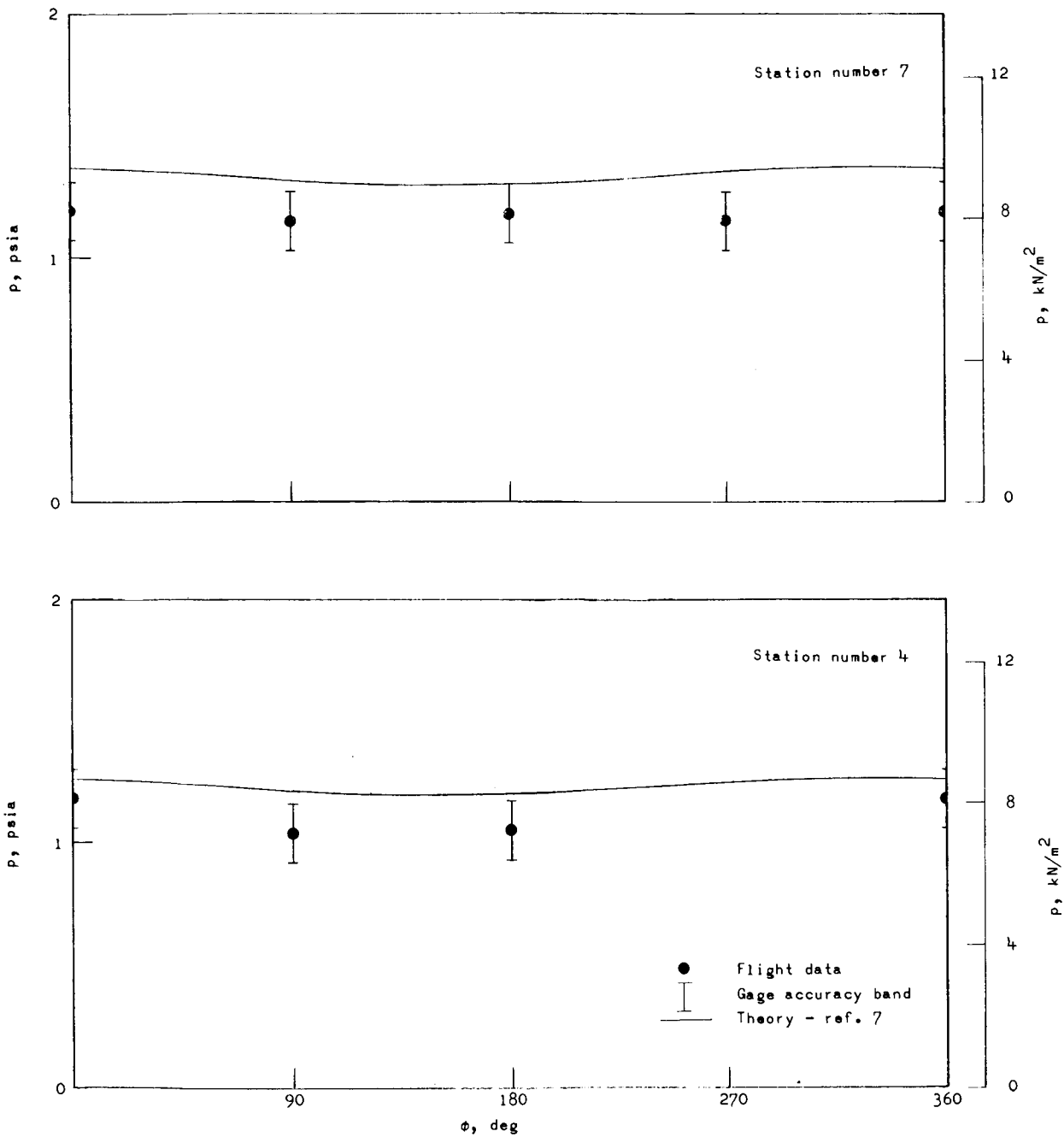


Figure 17.- Nose radius time history during reentry.



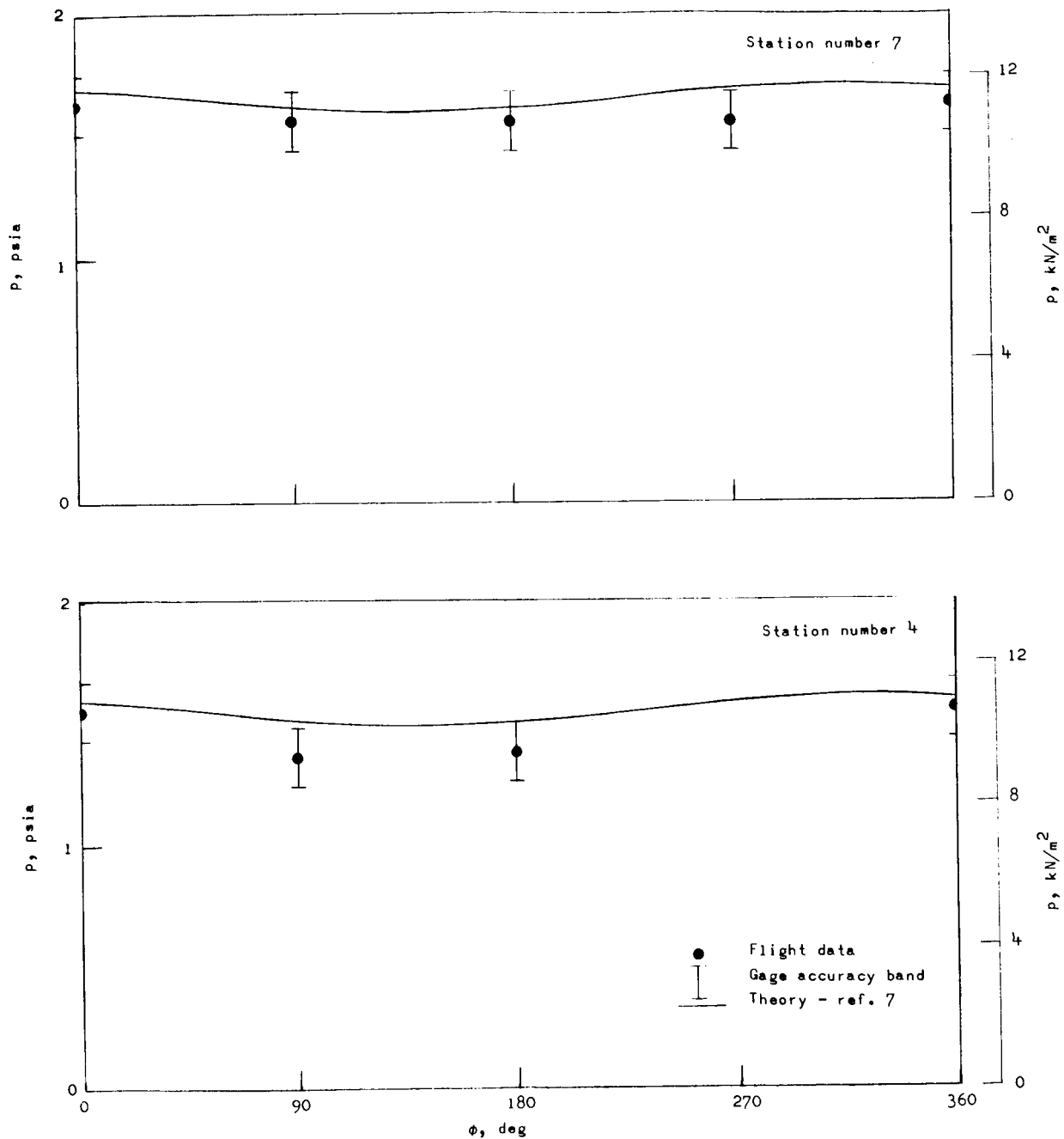
(a) $h = 30.5 \text{ km (100 000 ft)}$.

Figure 18.- Circumferential pressure distribution.



(b) $h = 29.0 \text{ km (95 000 ft)}$.

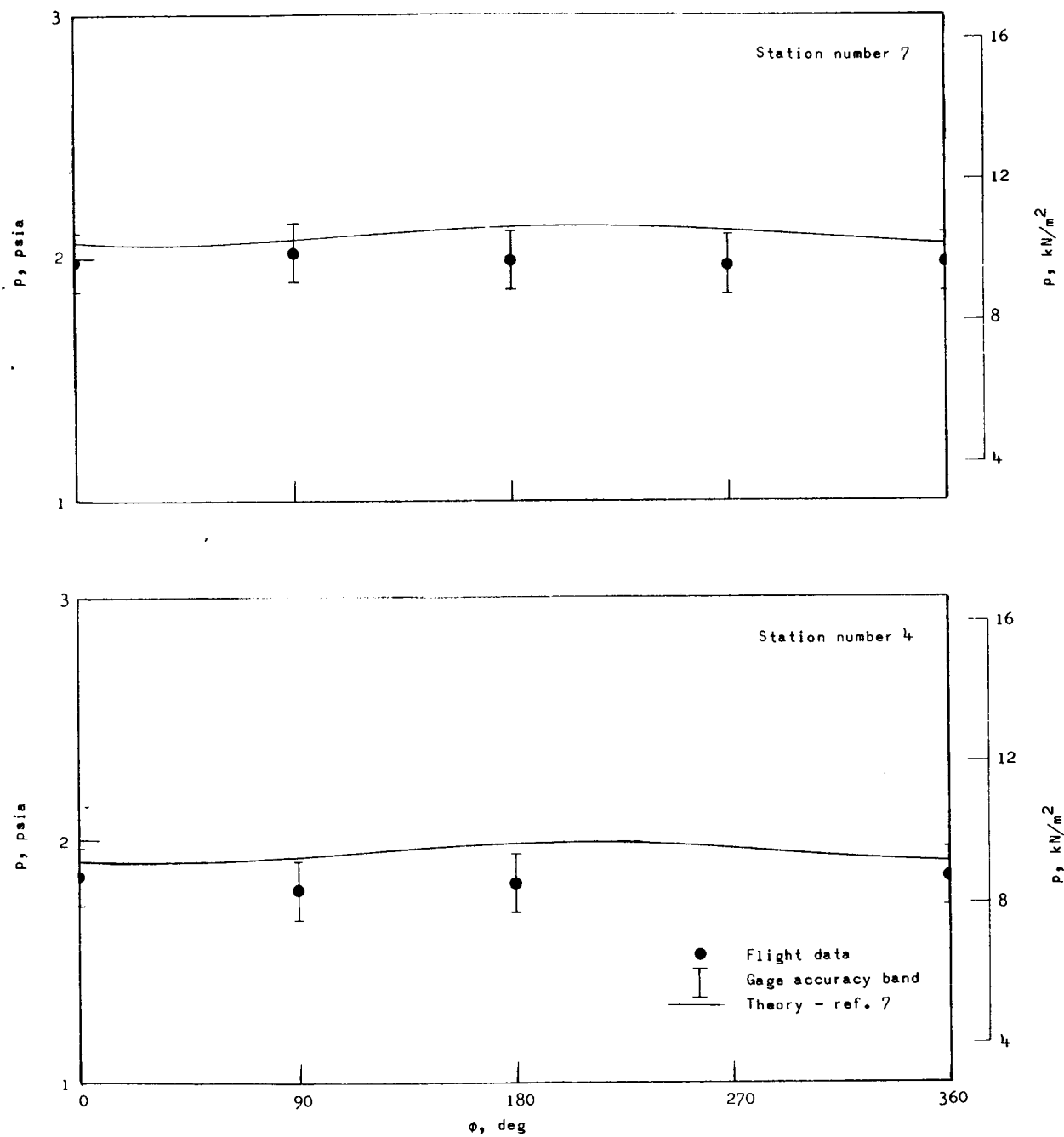
Figure 18.- Continued.



(c) $h = 27.4 \text{ km (90 000 ft)}$.

Figure 18.- Continued.

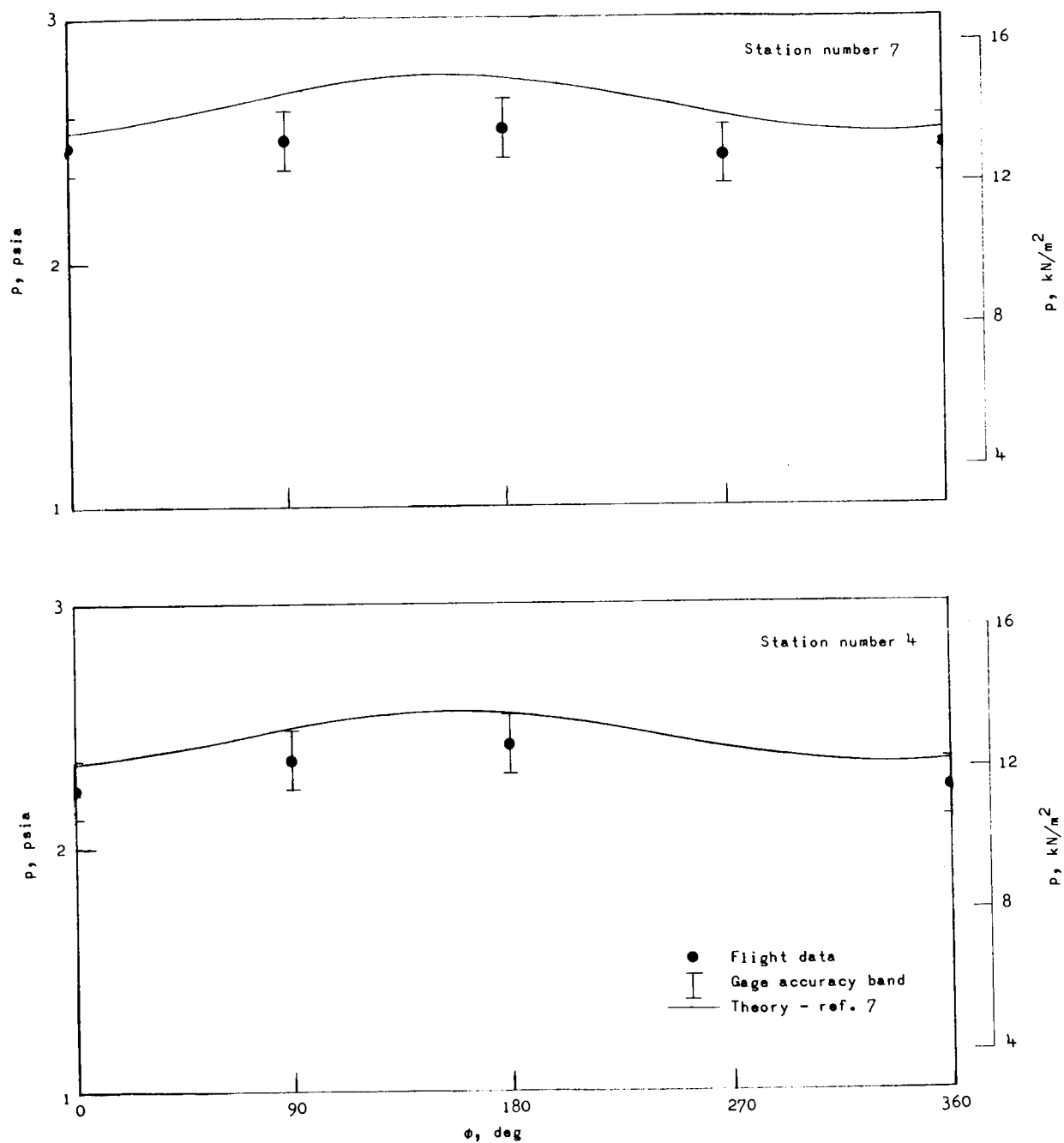
[REDACTED]



(d) $h = 25.9$ km (85 000 ft).

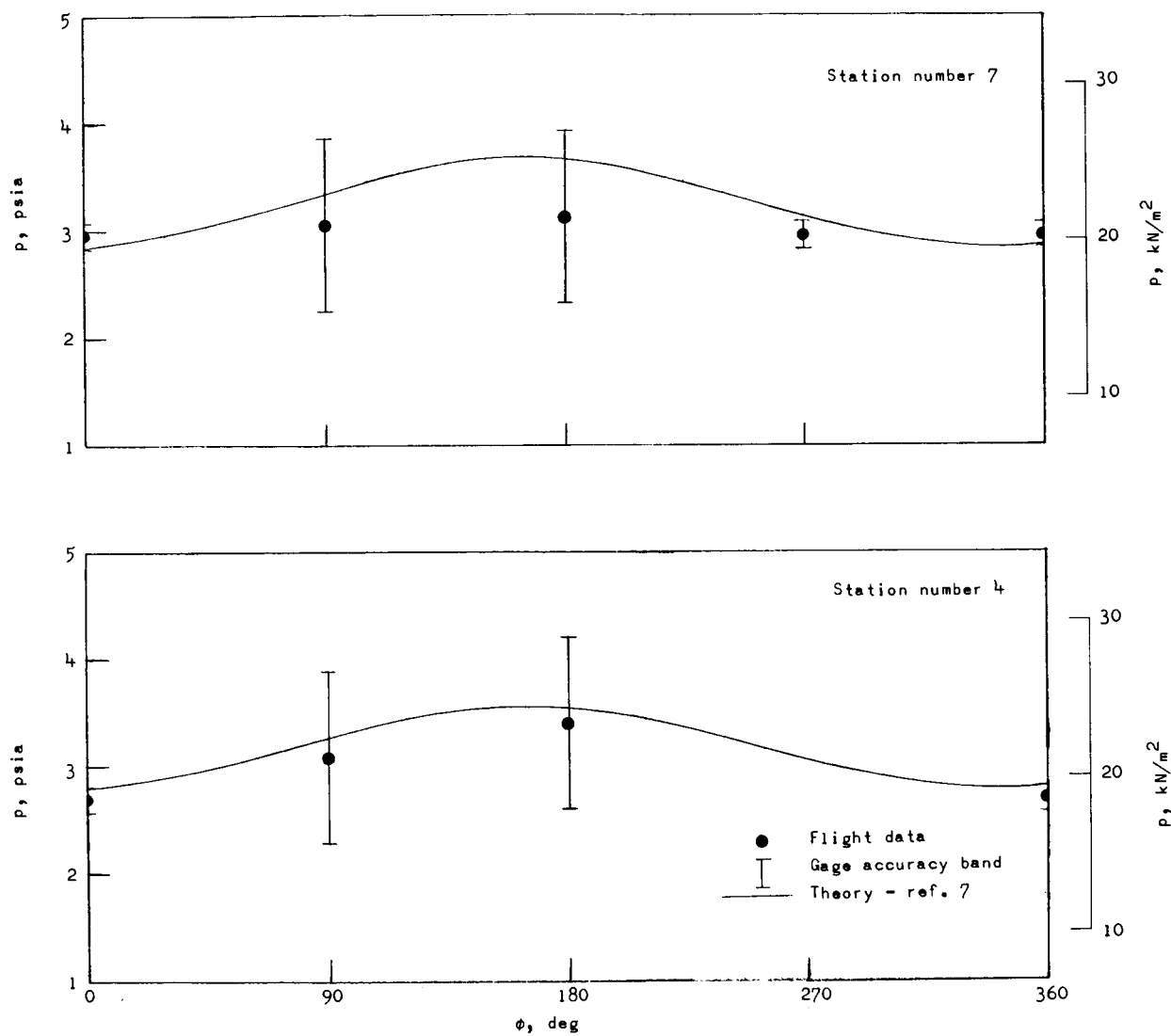
Figure 18.- Continued.

[REDACTED]



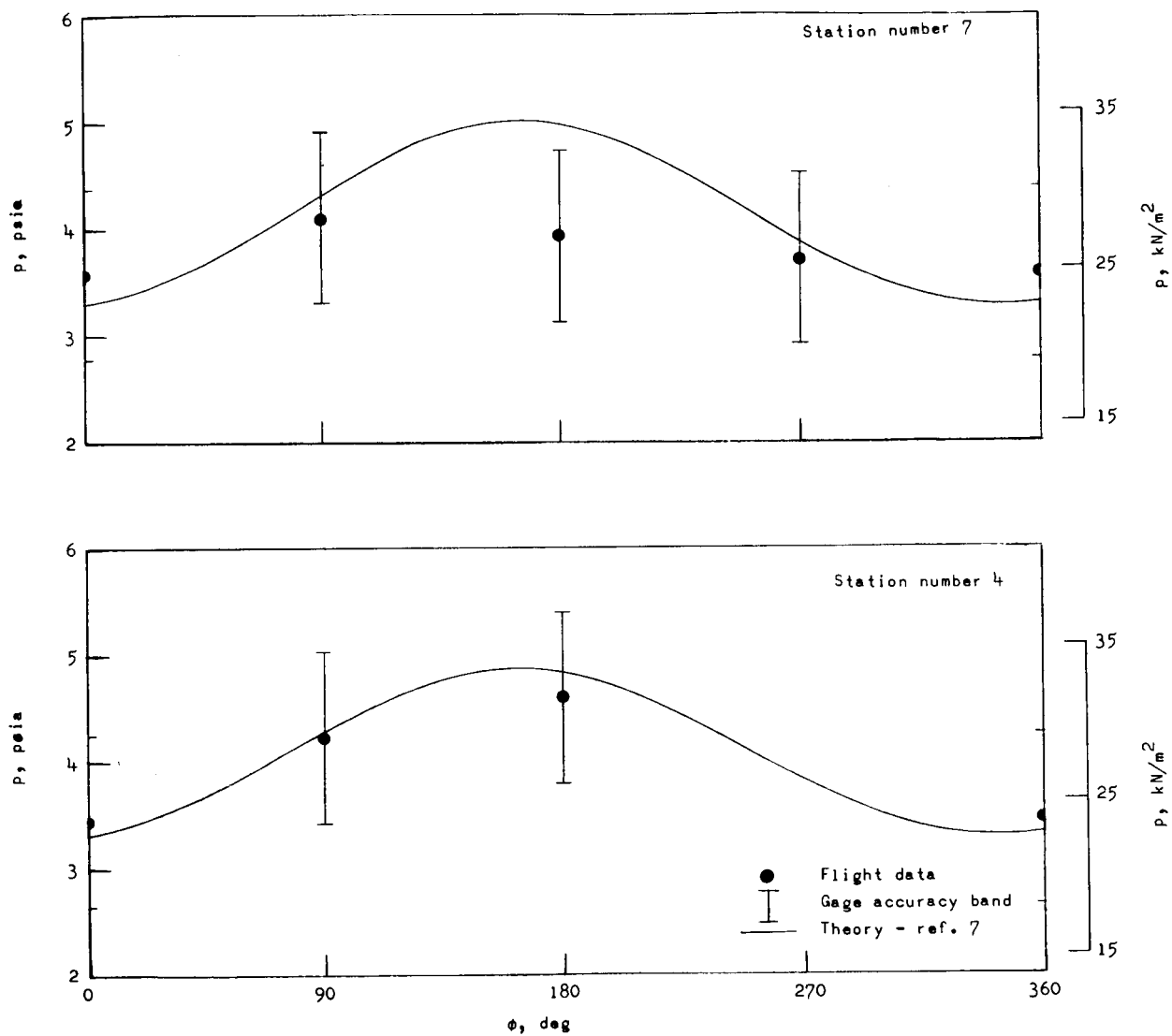
(e) $h = 24.4$ km (80 000 ft).

Figure 18.- Continued.



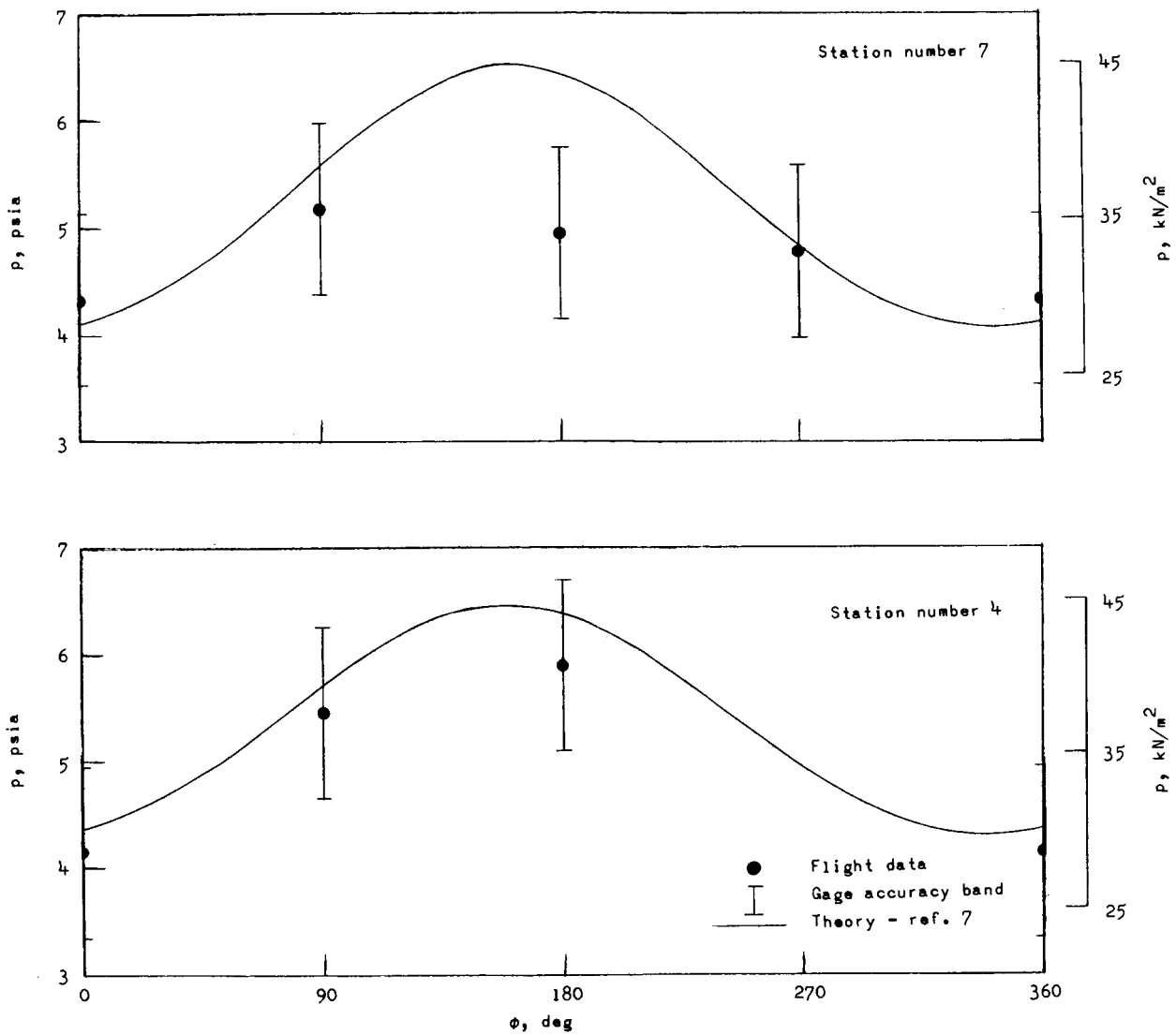
(f) $h = 22.9 \text{ km (75 000 ft.)}$.

Figure 18.- Continued.



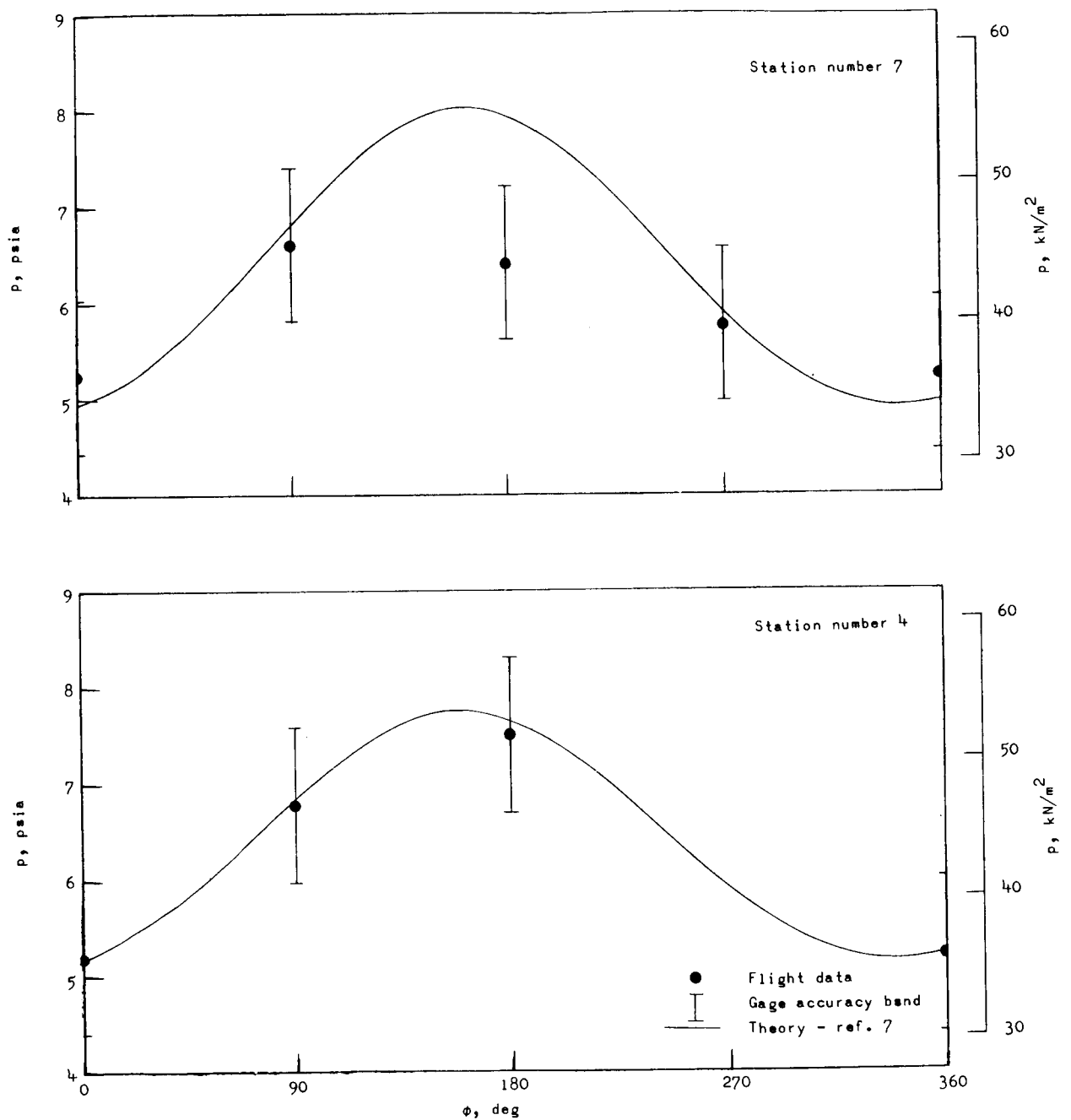
(g) $h = 21.3 \text{ km (70 000 ft)}$.

Figure 18.- Continued.



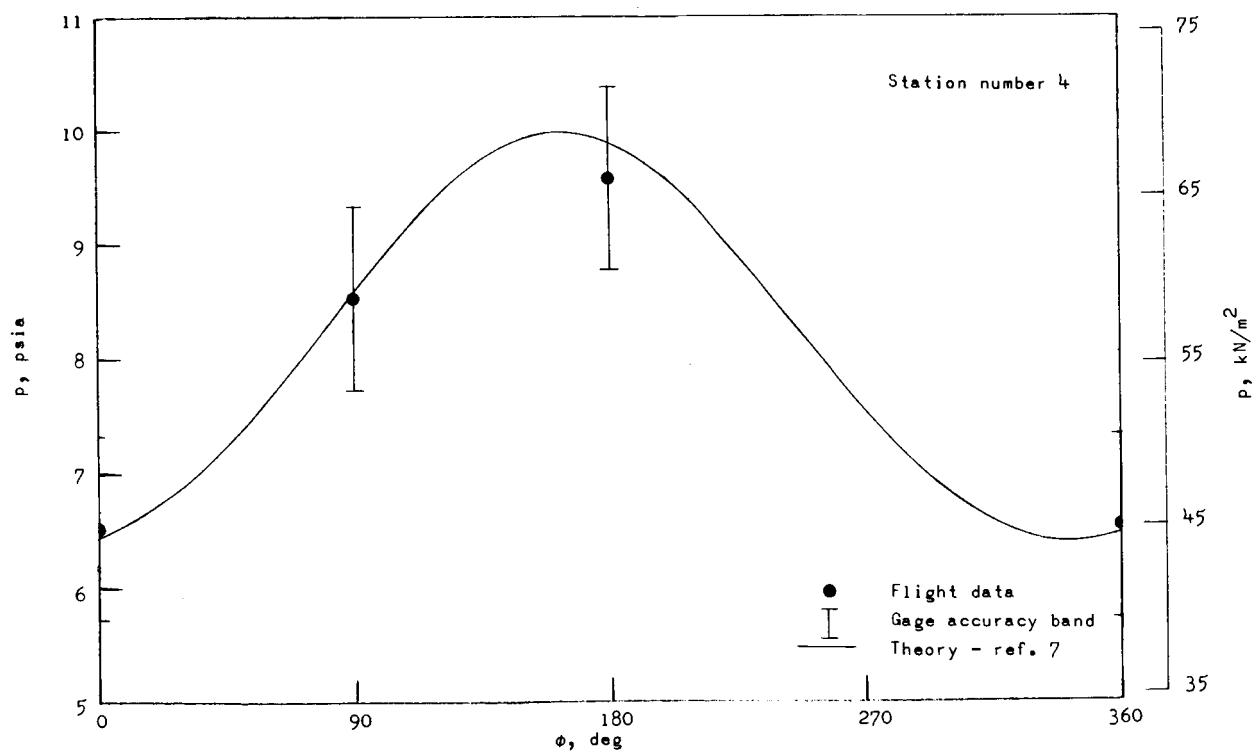
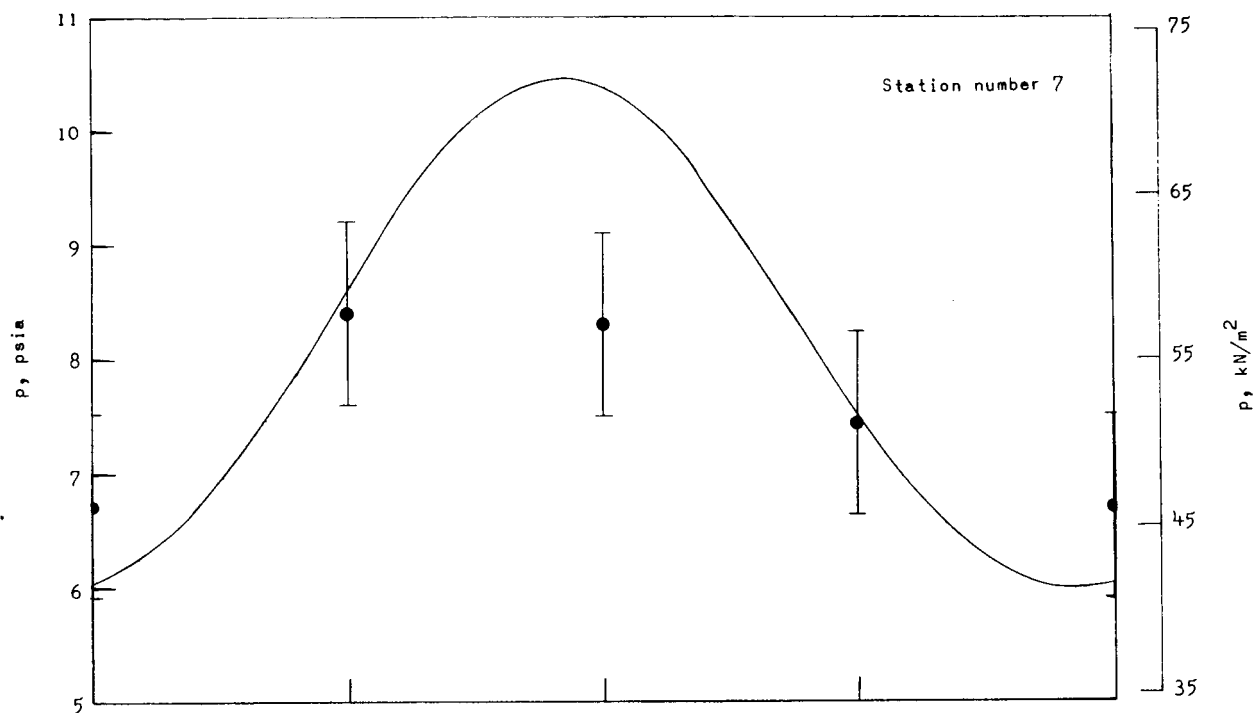
(h) $h = 19.8 \text{ km (65 000 ft)}$.

Figure 18.- Continued.



(i) $h = 18.3 \text{ km (60 000 ft.)}$

Figure 18.- Continued.



(j) $h = 16.8 \text{ km}$ (55 000 ft).

Figure 18.- Concluded.

[REDACTED]

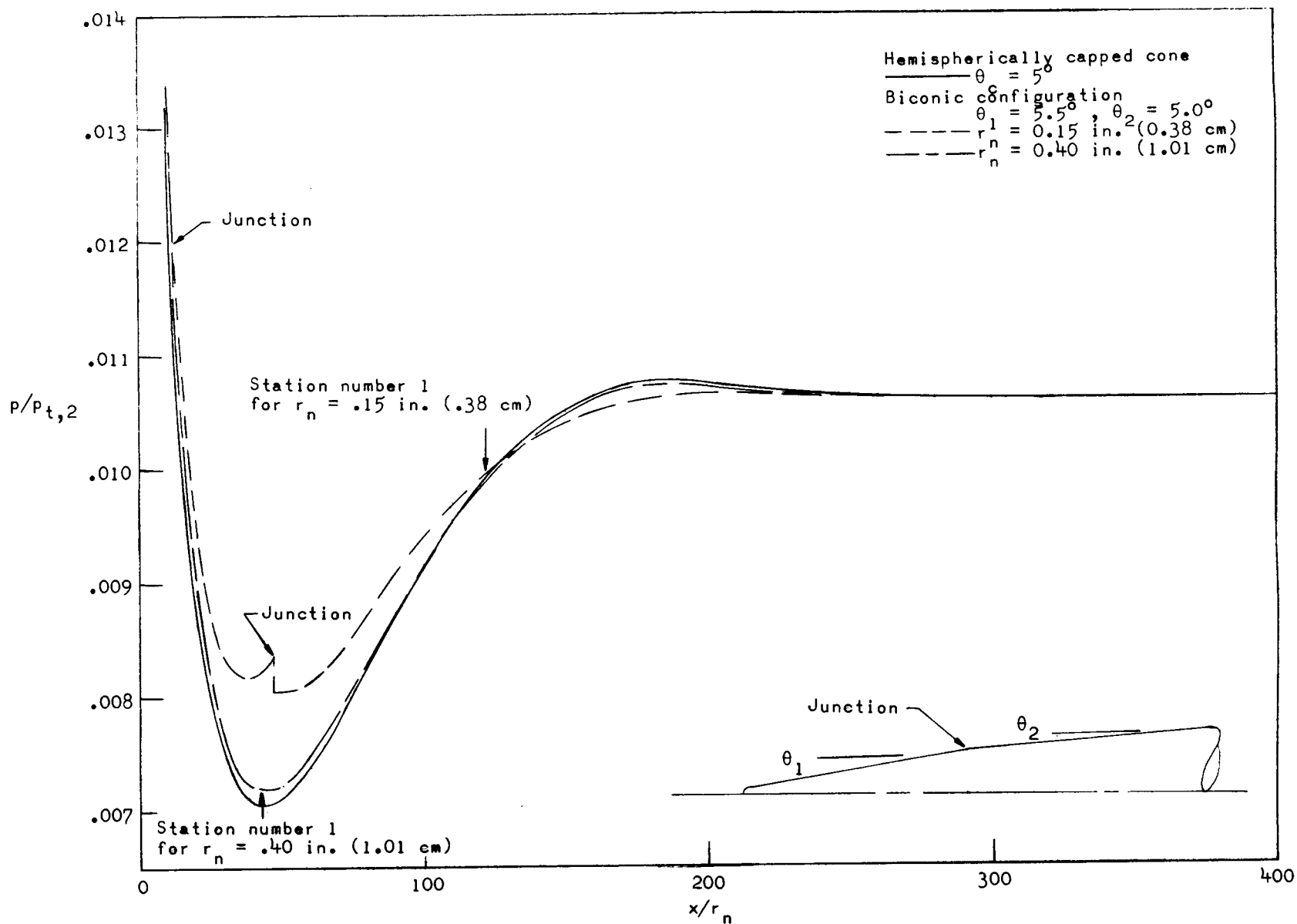


Figure 19.- Pressure distribution showing effects of biconic configuration.

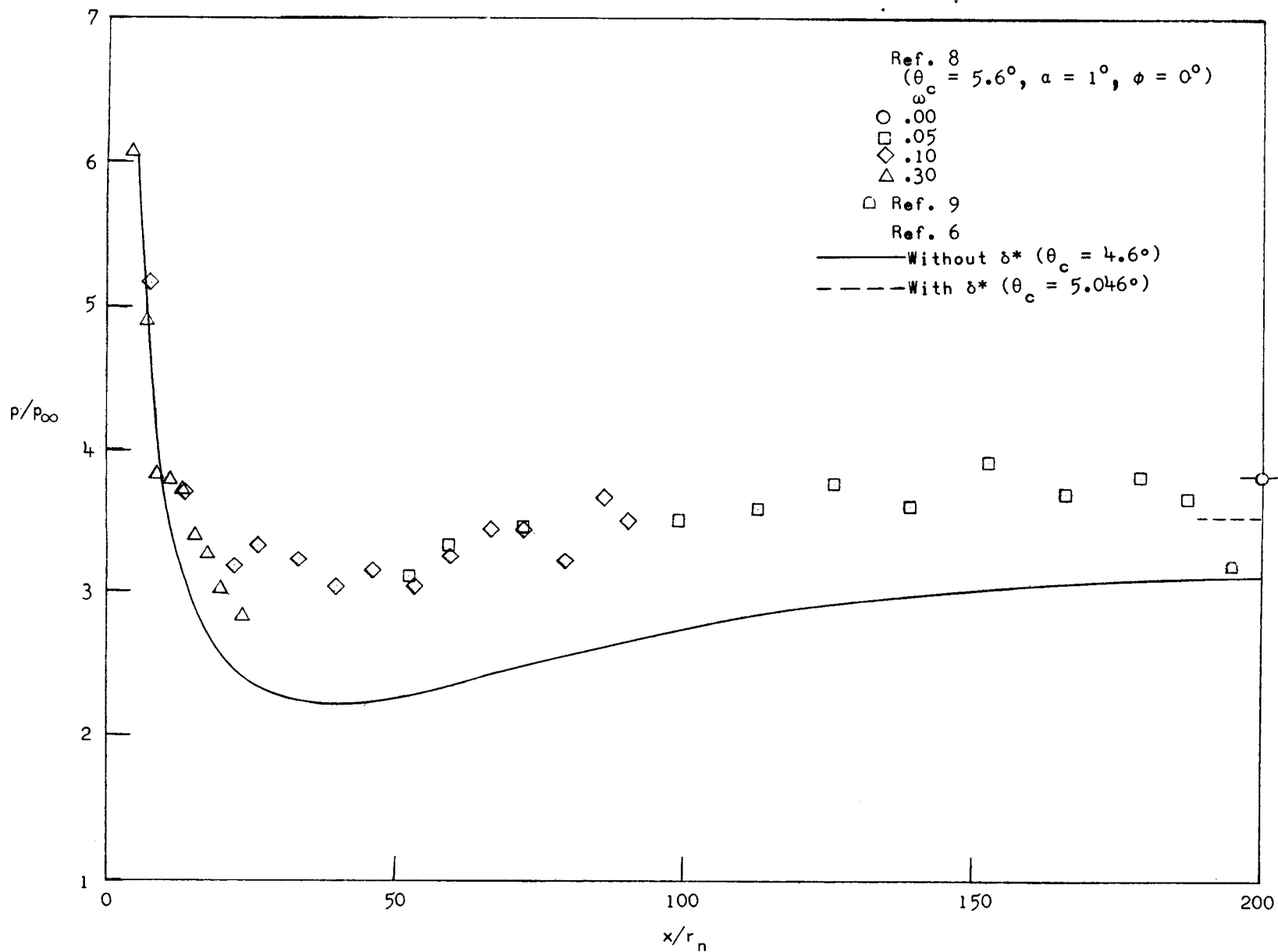


Figure 20.- Pressure distribution on the leeward ray of a 5.6° cone at 1° angle of attack. $M_\infty = 14$.

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