BOEING

CR-151672

D180-22876-8

NAS9-15196
DRL T-1346
DRD MA-664T
LINE ITEM 3

Volume VIII
SPS Launch Vehicle Ascent and Entry Sonic Overpressure and Noise Effects

(NASA-CR-151672) SOLAR POWER SATELLITE SYSTEM DEFINITION STUDY. PART 2, VOLUME 8: SPS LAUNCH VEHICLE ASCENT AND ENTRY SONIC OVERPRESSURE AND NOISE EFFECTS (Boeing Aerospace Co., Seattle, Wash.) 70 p
N78-20163
Unclas
G3/15 11821

Solar Power Satellite

SYSTEM DEFINITION STUDY
PART II

D180-22876-8

CONTRACT NAS9-15196
DRL T-134-6
DRD MA-664T
LINE ITEM 3

Solar Power Satellite

SYSTEM DEFINITION STUDY
PART II

VOLUME VIII
SPS LAUNCH VEHICLE ASCENT AND ENTRY SONIC OVERPRESSURE AND NOISE EFFECTS

D180-22876-8
DECEMBER 1977

Submitted To
The National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
in Fulfillment of the Requirements
of Contract NAS9-15196

Supervised By: H. A. Di Ramio
H. A. DiRamio

Approved:
G. R. Woodcock
Study Manager

BOEING AEROSPACE COMPANY
MISSILES AND SPACE GROUP-SPACE DIVISION
P.O. BOX 3999
SEATTLE, WASHINGTON

FOREWORD

The SPS system definition study was initiated in December 1976. Part I was completed on May 1, 1977. Part II technical work was completed October 31, 1977.

The study was managed by the Lyndon B. Johnson Space Center (JSC) of the National Aeronautics and Space Administration (NASA). The Contracting Officer's Representative (COR) was Clarke Covington of JSC. JSC study management team members included:

Dickey Arndt	Microwave System Analysis	Andrei Konradi	Space Radiation Environment
Harold Benson	Cost Analysis	Jim Kelley	Microwave Antenna
Bob Bond	Man-Machine Interface	Don Kessler	Collision Probability
Jim Cioni	Photovoltaic Systems	Lou Leopold	Microwave Generators
Hu Davis	Transportation Systems	Lou Livingston	System Engineering and
R. H. Dietz	Microwave Transmitter and Rectenna	Jim Meany	MPTS Computer Program
		Stu Nachtwey	Microwave Biological Effects
Bill Dusenbury	Energy Conversion	Sam Nassiff	Construction Base
Bob Gundersen	Man-Machine Interface	Bob Ried	Structure and Thermal Analysis
Alva Hardy	Radiation Shielding		
Buddy Heineman	Mass Properties	Jack Seyl	Phase Control
Lyle Jenkins	Space Construction	Bill Simon	Thermal Cycle Systems
Jim Jones	Design	Fred Stebbins	Structural Analysis
Dick Kennedy	Power Distribution		

The study was performed by the Boeing Aerospace Company. The Boeing study manager was Gordon Woodcock. Boeing Commercial Airplane Company assisted in the analysis of launch vehicle noise and overpressures. Boeing technical leaders were:

Ottis Bullock	Structural Design	Don Grim	Electrical Propulsion
Vince Caluori	Photovoltaic SPS's	Henry Hillbrath	Propulsion
Bob Conrad	Mass Properties	Dr. Ted Kramer	Thermal Analysis and Optics
Eldon Davis	Construction and Orbit-to-Orbit Transportation	Frank Kilburg	Alternate Antenna Concepts
		Walt Lund	Microwave Antenna
Rod Darrow	Operations	Keith Miller	Human Factors and Construction Operations
Owen Denman	Microwave Design Integration		
		Dr. Ervin Nalos	Microwave Subsystem
Hal DiRamio	Earth-to-Orbit Transportation	Jack Olson	Configuration Design
		Dr. Henry Oman	Photovoltaics
Bill Emsley	Flight Control	John Perry	Structures
Dr. Joe Gauger	Cost	Scott Rathjen	MPTS Computer Program Development
Jack Gewin	Power Distribution		
Dan Gregory	Thermal Engine SPS's		

The General Electric Company Space Division was the major subcontractor for the study. Their contributions included: Rankine cycle power generation, power processing and switchgear, microwave transmitter phase control and alternative transmitter configurations, remote manipulators, and thin-film silicon photovoltaics.

Other subcontractors were Hughes Research Center—gallium arsenide photovoltaics; Varian—klystrons and klystron production; SPIRE—silicon solar cell directed energy annealing.

This report was prepared in 8 volumes as follows:

I – Executive Summary
II – Technical Summary
III – SPS Satellite Systems
IV – Microwave Power Transmission Systems
V – Space Operations
VI – Evaluation Data Book
VII – Study Part II Final Briefing Book
VIII – SPS Launch Vehicle Ascent and Entry Sonic Overpressure and Noise Effects

This volume, "SPS Launch Vehicle Ascent and Entry Sonic Overpressure and Noise Effects" addresses the anticipated sonic overpressures and launch noise for the candidate SPS launch vehicles. The sonic overpressure and launch noise investigations were conducted by the Aerodynamics and Acoustics Preliminary Design staff of the Boeing Commercial Airplane Company. The principal contributors were

Larry J. Runyan – Sonic Overpressure Analysis
Frank Klujber – Launch Noise Analysis

The NASA monitor for this portion of the study was Herb Patterson.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Recoverable launch vehicle concepts for the Solar Power Satellite program have been identified which have a payload capability in the 400 metric ton range. These large launch vehicles are powered by proposed new engines in the F-1 thrust level class. In comparison to the Saturn V, these vehicles are much larger in size (by a 1.5-3.0 factor) and use 16 of the F-1 class engines rather than the 5 on the Saturn V.

Both ballistic and aerodynamic winged recovery versions of the launch vehicle have been identified in a previous portion of the SPS study (Ref. 1-1). Due to the large size of the vehicles and the magnitude of the installed thrust, investigations into the prediction of the launch noise and sonic overpressures during ascent and reentry were undertaken.

This volume includes:

- o Description of the candidate launch vehicles and their operating mode.
- o Predictions of the sonic overpressures during ascent and entry for both types of vehicles.
- o Prediction of launch noise levels in the vicinity of the launch site.
- o Overall assessment and criteria for sonic overpressure and noise levels.

1.1 REFERENCE OPERATING MODE

The analysis of predicting the sonic overpressures and noise levels in the vicinity of the launch site and also in the landing zone was conducted for both the 2-stage ballistic recoverable and 2-stage winged recoverable vehicles.

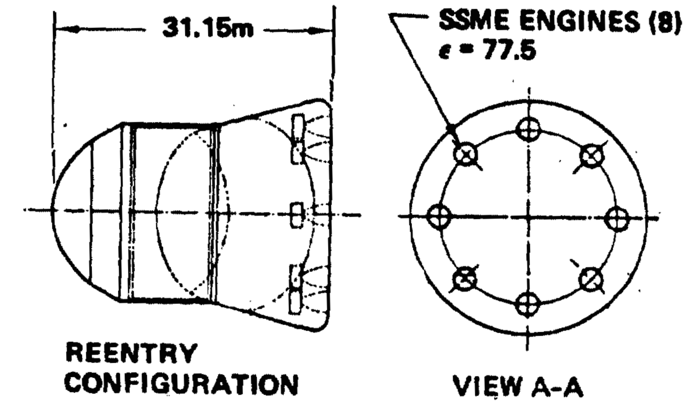
The operational mode for both vehicles is a launch to a 477.5 km circular orbit at 31° inclination assuming a launch site at 28.5°N. The first stages of either vehicle are recovered downrange with sea recovery for the ballistic booster and land recovery for the winged booster. The upper stages, in both cases, circularize the payload and deorbit approximately 24 hours after launch to return to the launch site area. A nominal zero degree (0°) angle of attack has been assumed for the ballistic reentering stages. Winged stages are at a 60° angle of attack until they perform the subsonic transition. The transition occurs usually between 20 km and 24 km altitude.

1.2 BASELINE VEHICLES DESCRIPTION

2-Stage Ballistic Vehicle

The reference concept for the ballistic recoverable vehicle is shown in Figure 1.2-1. Main propulsion is provided by sixteen (16) RP-1/LO_2 gas generator cycle engines which use liquid hydrogen (LH_2) for engine cooling.

SPS-164



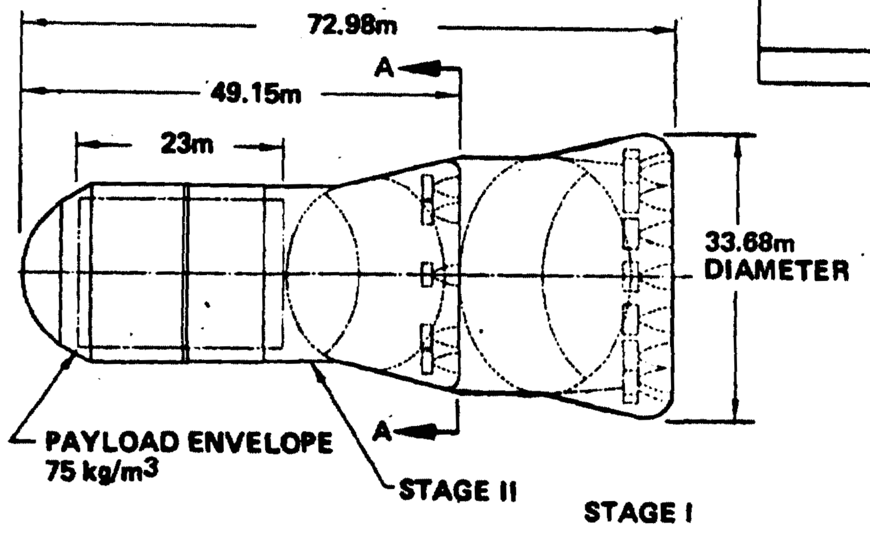
VEHICLE CHARACTERISTICS

GLOW	10.472×10^6 kg	(23.087×10^6 lbm)
BLOW	8.243×10^6 kg	(18.173×10^6 lbm)
W_{P_1}	7.456×10^6 kg	(16.437×10^6 lbm)
ULOW	1.838×10^6 kg	(4.051×10^6 lbm)
W_{P_2}	1.479×10^6 kg	(3.261×10^6 lbm)
PAYLOAD	0.391×10^6 kg	(0.863×10^6 lbm)

T/W AT LIFTOFF 1.30

MAIN PROPULSION

STAGE	ϵ	NUMBER/TYPE	THRUST/ENGINE (VACUUM)		EXHAUST VELOCITY		I_{sp} - SEC
			10^6 N	10^6 lb_f	MPS	FPS	
1ST	42.5	16-LO_2/RP-1	9.060	2.037	3441	11290	350.7
2ND	77.5	8/STD SSME	2.091	0.470	4466	14660	455.3



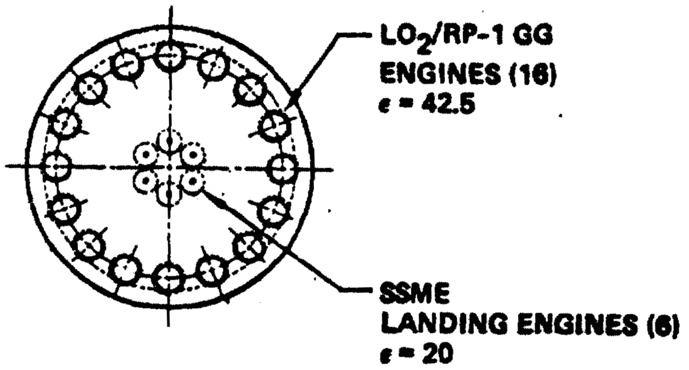


Figure 1.2.1 SPS Launch Vehicle—Cargo Version

The baseline engine is a scaled up version of the Alternate Mode 1 engine defined by Aerojet Liquid Rocket Company under contract NAS3-19727 to NASA Lewis Research Center. The following main engine characteristics were used in the analysis.

Propellants	RP-1/LO_2/LH_2	
Thrust–Vacuum	9.059×10^6N	(2.037×10^6 lbf)
Chamber Pressure	29300 kpa	(4250 psia)
Mixture Ratio	2.9:1	
Specific Impulse (SL/Vac.)	323.5/350.7 sec.	
Total Flow Rate/Engine	2635 kg/sec	(5808 lbm/sec)

Engine overall length is 5.44m and the power head and exit diameters are 3.51m and 2.97m, respectively.

The ascent trajectory chacacteristics for the vehicle are shown in Figure 1.2-2. The major characteristics are summarized as follows:

First Stage
- T/W @ Ignition = 1.30
- Maximum Dynamic Pressure = 32.125 kpa
- Maximum Acceleration = 4.90 g's
- Stage Burn Time = 176.89 sec.
- Dynamic Pressure at Staging = 405 pa

Second Stage
- T/W @ Ignition = 0.76
- Maximum Acceleration = 2.28 g's
- Stage Burn Time = 394.84 sec.

At main engine cutoff (MECO) the trajectory characteristics are as follows:

Altitude = 110948m
Relative Velocity = 7540 m/sec
Burnout Mass = 749583 kg

The significant trajectory parameters for the sonic overpressure analysis are the mach number, altitude, and flight path angle (γ) as a function of distance along the ground track. These parameters are plotted for the ballistically recoverable vehicle or stages in Figure 1.2-3 through Figure 1.2-5. The vehicle ascent characteristics are shown in Figure 1.2-3 and the reentry characteristics for both the booster and second stage are shown in Figures 1.2-4 and 1.2-5, respectively.

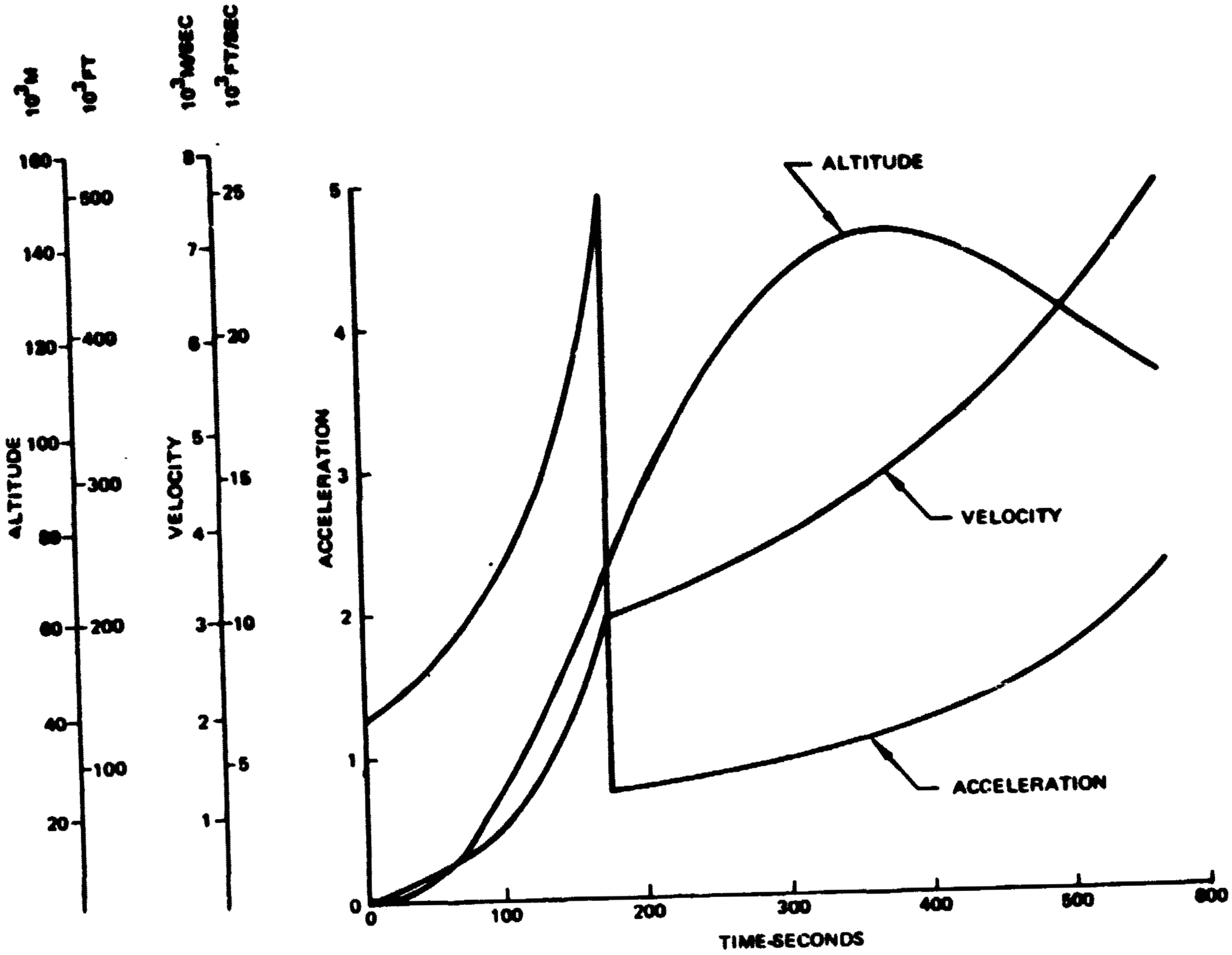


Figure 1.2-2 2-Stage Ballistic Vehicle Ascent Performance Characteristics

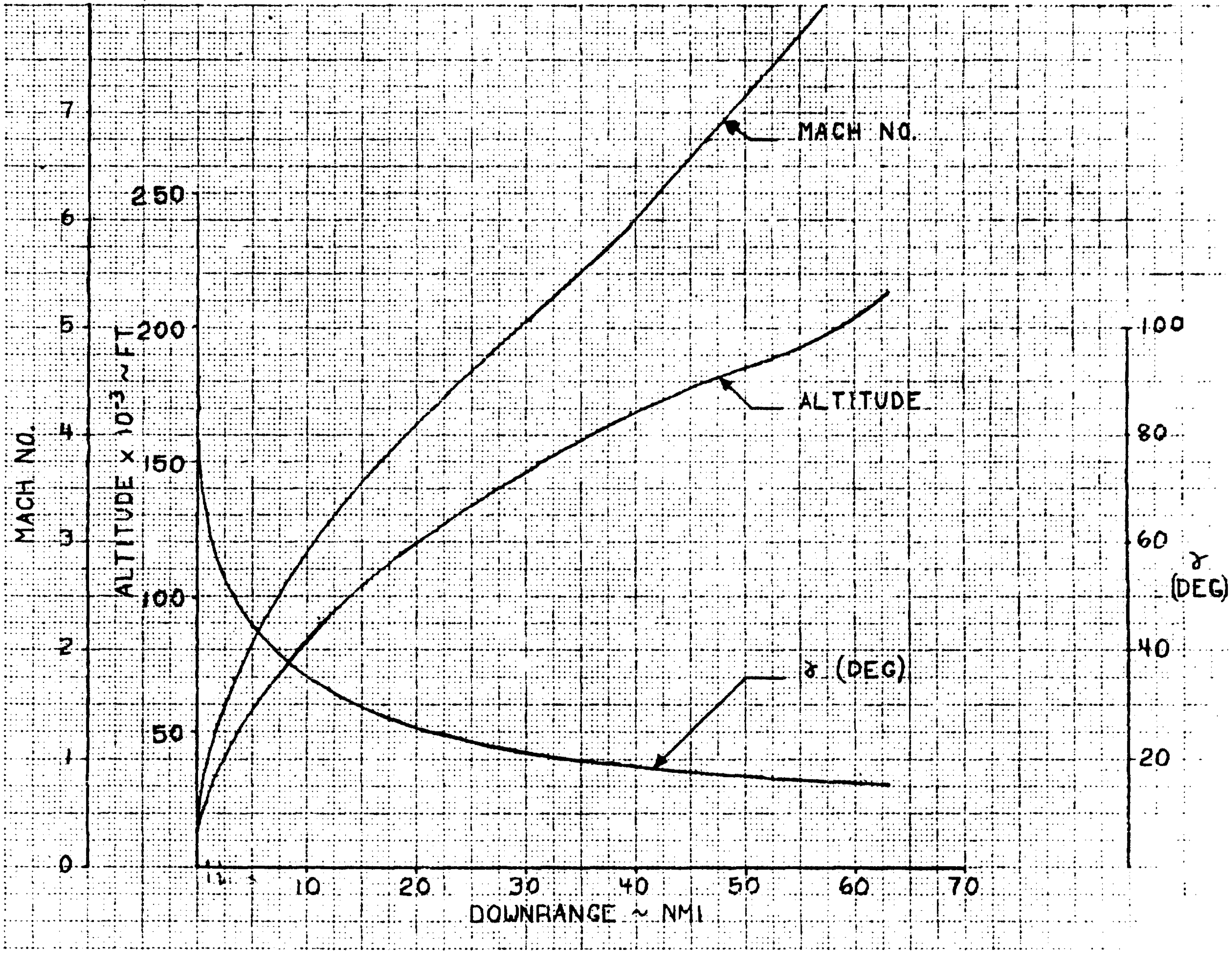


Figure 1.2-3 Ballistic Vehicle Ascent Trajectory

ORIGINAL PAGE IS
OF POOR QUALITY

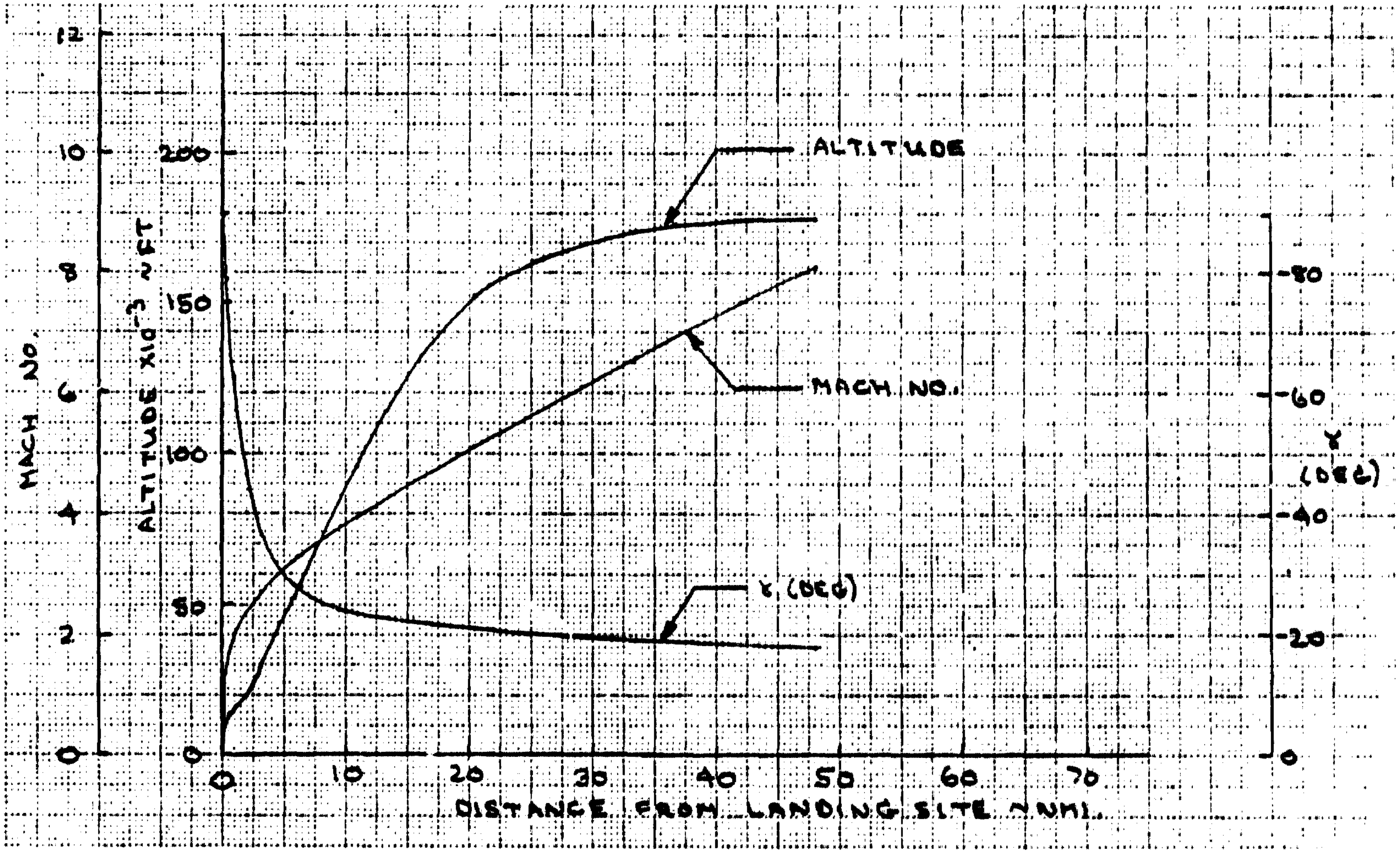


Figure 1.2-4 Ballistic Booster Reentry Trajectory

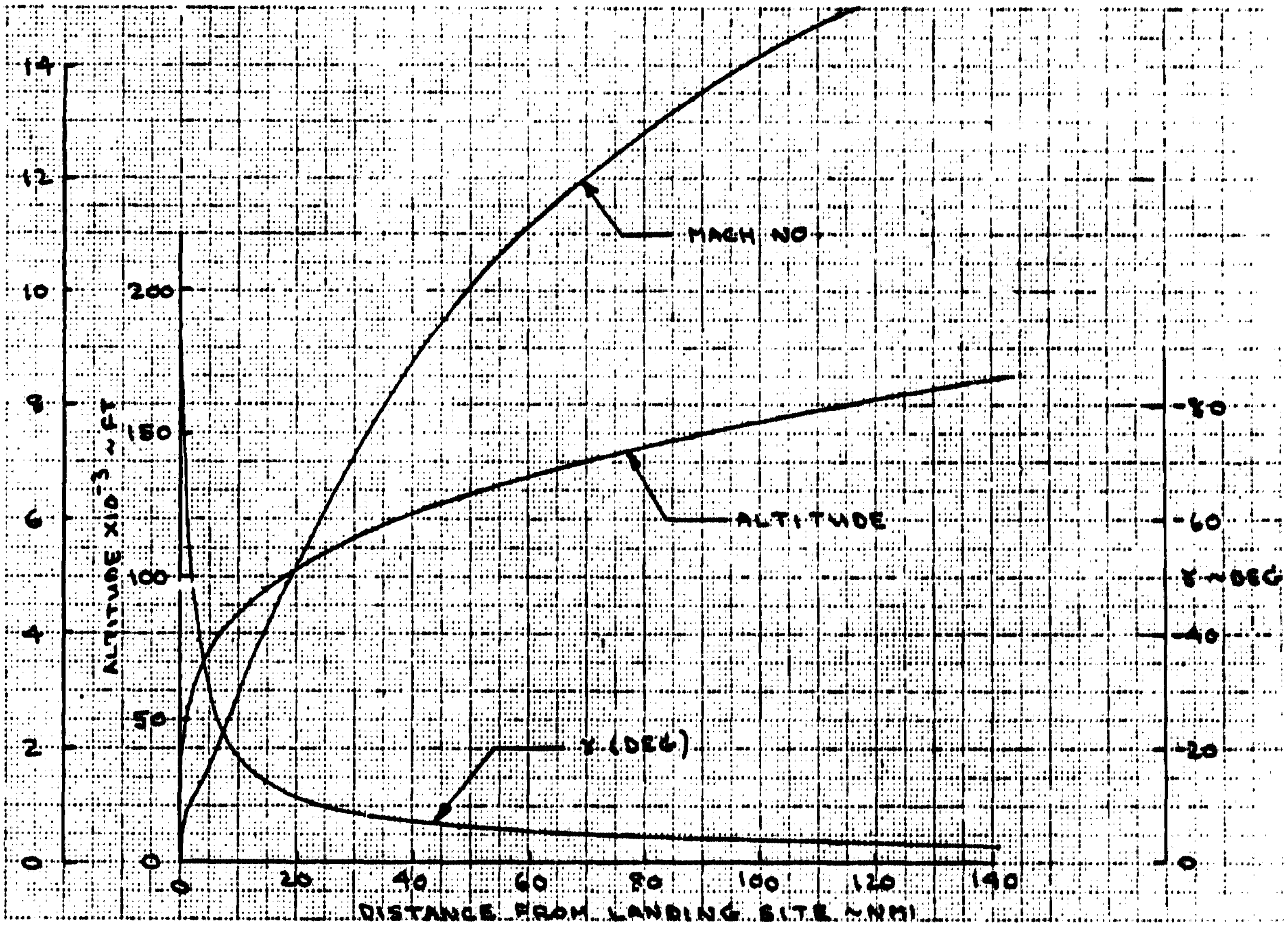


Figure 1.2-5 Ballistic Second Stage Reentry Trajectory

ORIGINAL PAGE IS
OF POOR QUALITY

2-Stage Wing Vehicle

The reference concept for the winged recoverable vehicle is shown in Figure 1.2-6. Main propulsion is provided by sixteen (16) RP-1/LO_2/LH_2 gas generator cycle engines similar to those on the 2-stage ballistic vehicle. The following engine characteristics were used in the analysis:

Propellants	RP-1/LO_2/LH_2
Thrust–Vacuum	8.275×10^6N
Chamber Pressure	29300 kpa
Mixture Ratio	2.9:1
Specific Impulse (S.L./Vac)	323.5/350.7 sec.

The ascent trajectory characteristics for the vehicle are shown in Figure 1.2-7. The major characteristics are summarized as follows:

First Stage
- TW @ Ignition = 1.30
- Maximum Dynamic Pressure = 34.446 kpa
- Maximum Acceleration = 3.49 g's
- Stage Burn Time = 147.96 sec.
- Dynamic Pressure at Staging = 1819 pa

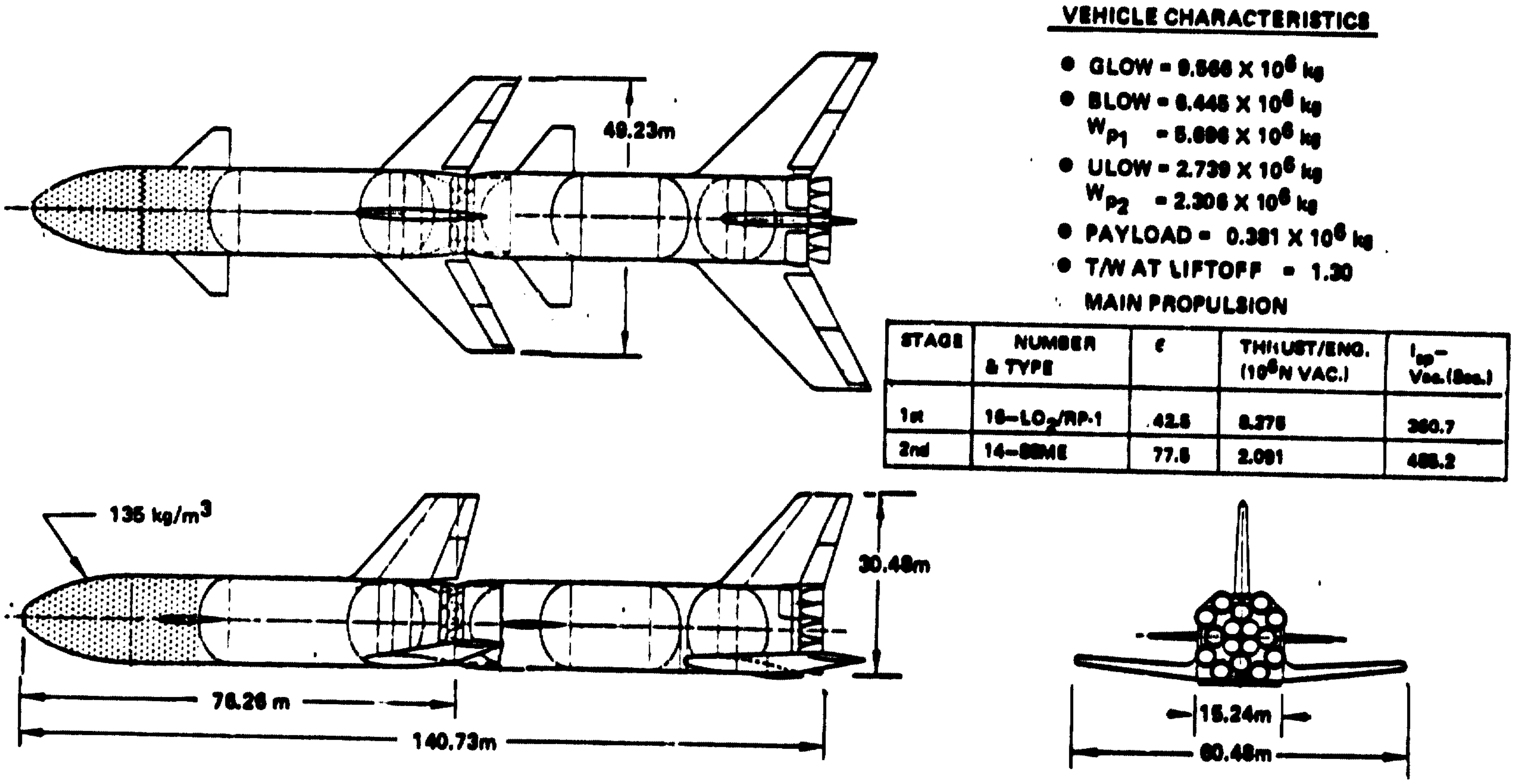
Second Stage
- TW @ Ignition = 0.95
- Maximum Acceleration = 3.67 g's
- Stage Burn Time = 351.78 sec.

The mach number, altitude, and flight path as a function of distance along the ground track for the winged vehicle and stages are shown in Figures 1.2-8 through 1.2-10. The winged vehicle ascent characteristics are shown in Figure 1.2-8 and the reentry characteristics for the booster and second stage are shown in Figures 1.2-9 and 1.2-10, respectively.

References

1-1 SPS Transportation: Representative System Descriptions. D180-20689-5. Part 1 of Contract NAS9-15196.

ORIGINAL PAGE IS
OF POOR QUALITY



VEHICLE CHARACTERISTICS

- GLOW = 9.566 X 10^6 kg
- BLOW = 6.445 X 10^6 kg
  W_{P1} = 5.696 X 10^6 kg
- ULOW = 2.739 X 10^6 kg
  W_{P2} = 2.306 X 10^6 kg
- PAYLOAD = 0.381 X 10^6 kg
- T/W AT LIFTOFF = 1.30
- MAIN PROPULSION

STAGE	NUMBER & TYPE	ε	THRUST/ENG. (10^6N VAC.)	I_{sp}– Vac.(Sec.)
1st	16–LO_2/RP-1	42.5	8.375	360.7
2nd	14–SSME	77.5	2.091	455.2

Figure 1.2-6 2-Stage Winged SPS Launch Vehicle

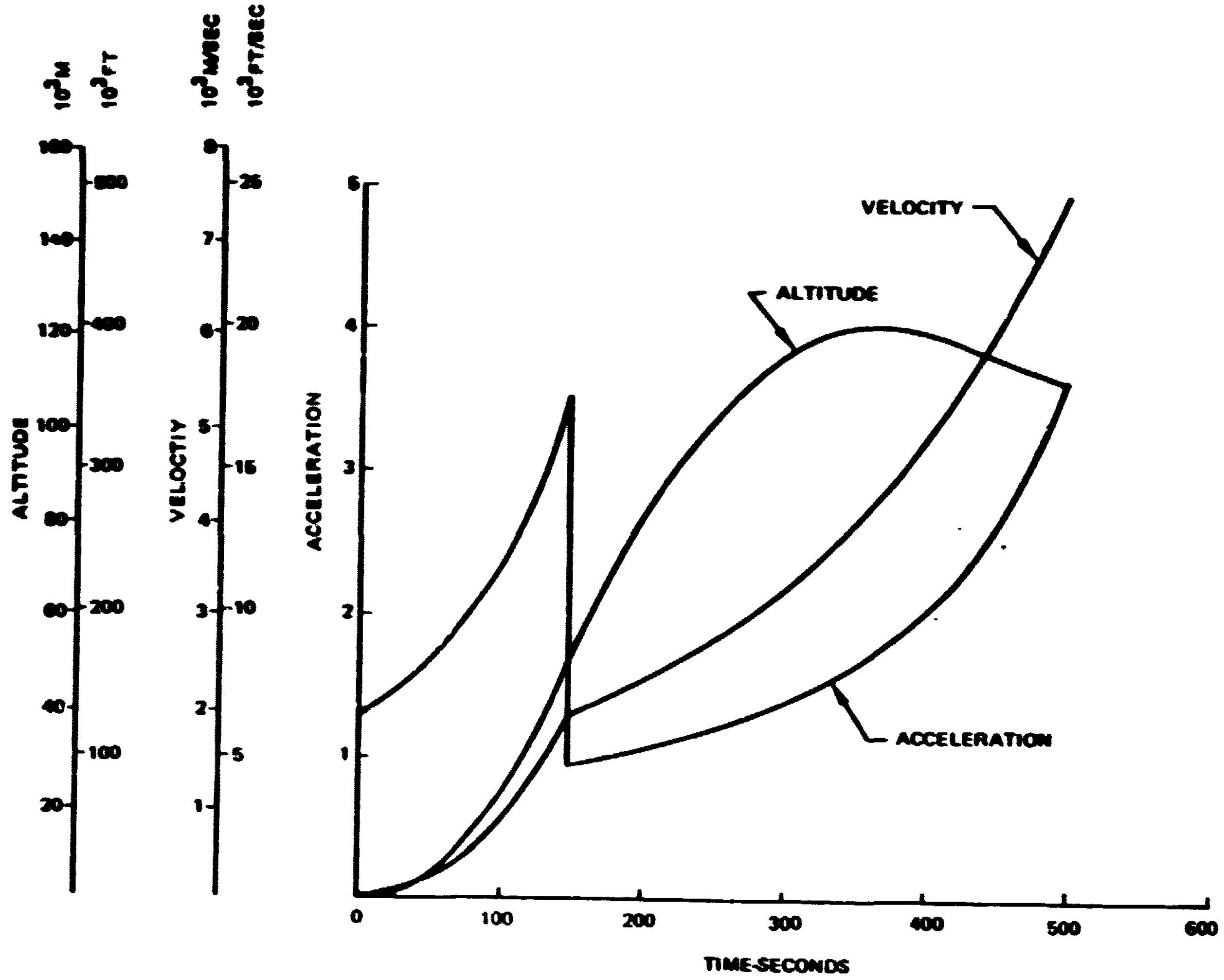


Figure 1.2-7 2-Stage Winged Vehicle Ascent Performance Characteristics

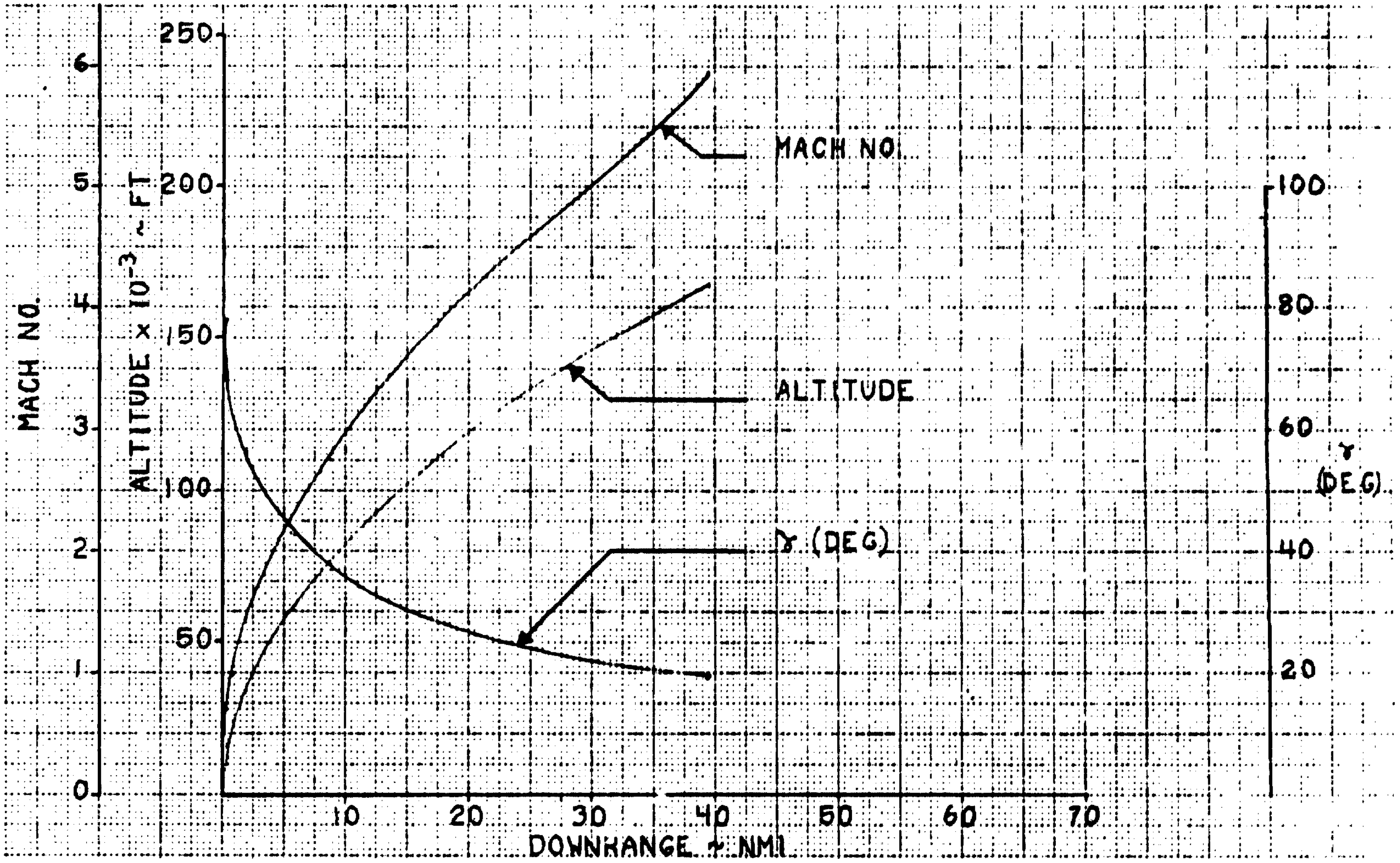


Figure 1.2-8 SPS Winged Vehicle Ascent Trajectory

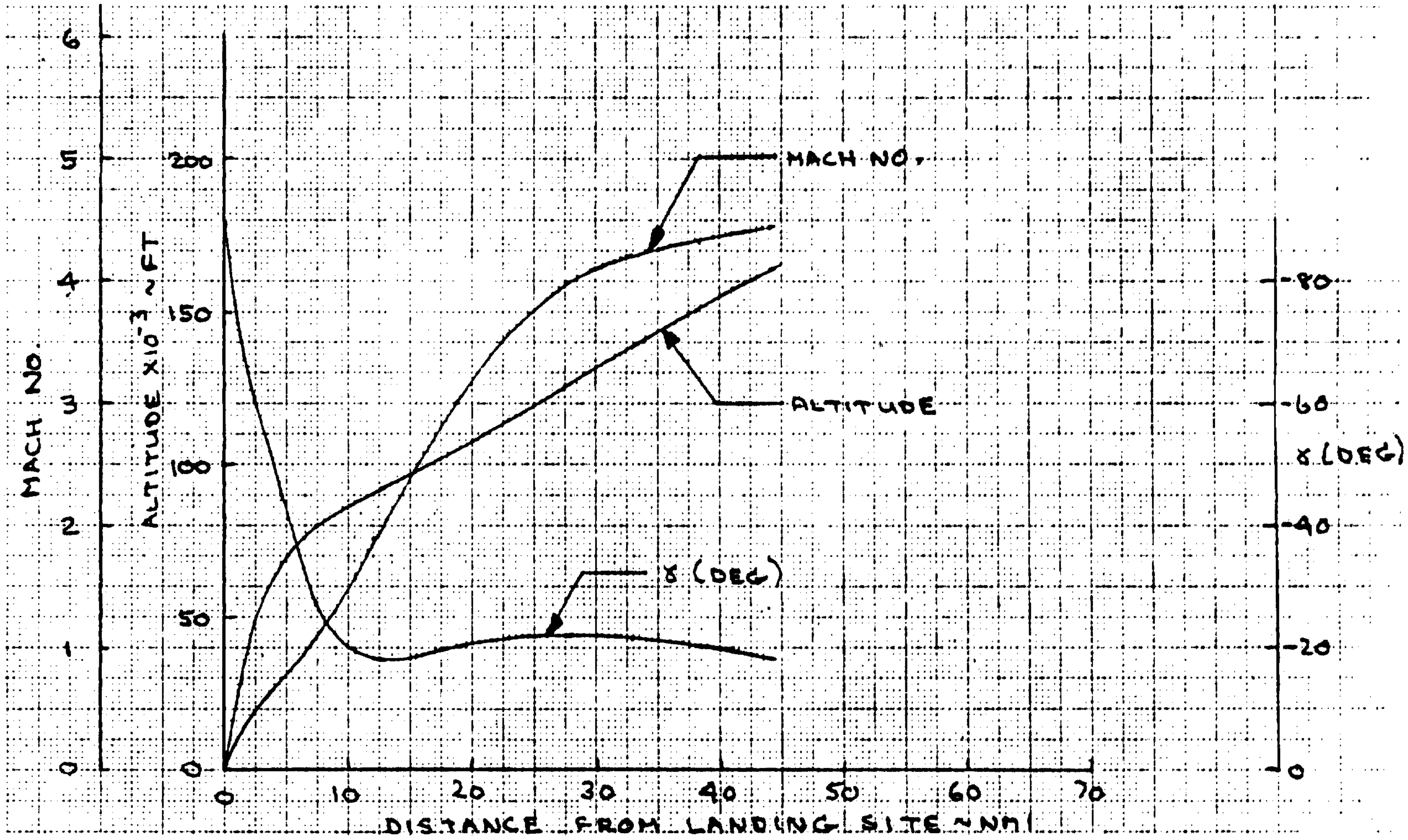


Figure 1.2-9 Winged Booster Reentry Trajectory

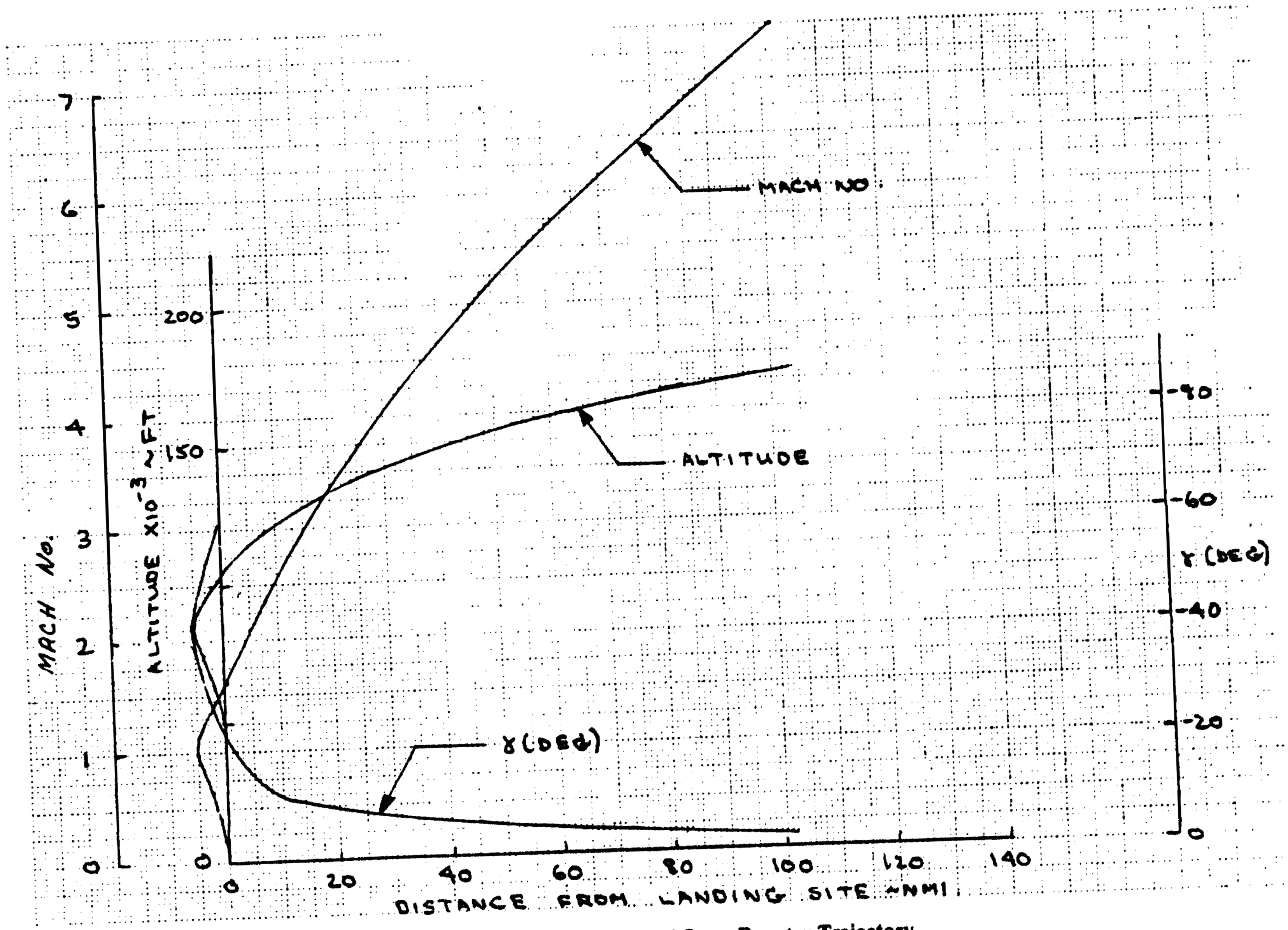


Figure 1.2-10 Winged Second Stage Reentry Trajectory

ORIGINAL PAGE IS
OF POOR QUALITY

2.0 LAUNCH AND ENTRY OVERPRESSURE ANALYSIS

The sonic boom characteristics have been developed for the candidate SPS launch vehicles during both ascent and reentry. During ascent the main engine plumes are a significant factor in the overall sonic overpressures. The vehicle reentry characteristics, particularly the subsonic transition altitude, influence the magnitude and the area impacted by the sonic overpressure.

2.1 MAIN ENGINE PLUME CHARACTERISTICS

During ascent, it is the vehicle exhaust plume which determines the magnitude of the sonic boom that is generated. This is because the plume is so much larger than the vehicle itself. Therefore, good estimates of the plume size are essential.

To estimate the plume characteristics of the SPS launch vehicle, the following approach was used. The Saturn V plume characteristics were first estimated by assuming a plume length of 1.5 times the vehicle length (as suggested in Reference 2-1) and a plume diameter which resulted in an estimated linearized theory sonic boom overpressure which matched the measured overpressure for the Saturn V at flight altitude of 107,000 feet. The estimated Saturn V plume length and diameter at 107,000 feet were then multiplied by 16/5, which is the ratio of the number of F-1 thrust class rocket engines on the SPS launch vehicle to the number of F-1 rocket engines on the Saturn V. The justification for this approach is that the ratio of the Saturn V plume length and diameter to the plume length and diameter of a single F-1 engine is fairly close to the ratio of the number of engines (5:1). This results in a plume length of 1744 feet and a plume diameter of 1024 feet for the SPS launch vehicle at an altitude of 107,000 feet. The plume length and diameter were assumed to vary with altitude in the same ratio as that of the F-1 engine (Reference 2-2). The resulting SPS ascent vehicle estimated plume characteristics are shown in Figure 2.1-1.

2.2 SONIC OVERPRESSURE CALCULATION METHODS

Sonic boom calculations for typical supersonic airplane configurations are based upon linearized supersonic aerodynamics. However, the accuracy of these methods begins to decrease for mach numbers greater than 3.5 and for non-slender vehicles. Therefore, it was questionable whether this approach could be used to calculate the sonic booms generated by the SPS vehicles. However, comparisons between linearized theory estimates and measured Apollo 17 ascent data and measured Apollo 15 command module reentry data for mach numbers as high as 4.8 have shown fairly good agreement. Figure 2.2-1 summarizes these comparisons and gives the equation used to make the calculations. This equation is a modification of Whitham's equation for the bow shock overpressure (pressure rise through the shock) of a slender, pointed body of revolution (Reference 2-3) and is given in Reference 2-4. These results show that linearized theory can be expected to give good estimates of the sonic boom characteristics of the SPS launch and reentry vehicles for the mach number and altitude ranges which produce significant overpressures at ground level. This conclusion is in agreement with the results of a study by Carlson and Mack (Reference 2-5) which demonstrated

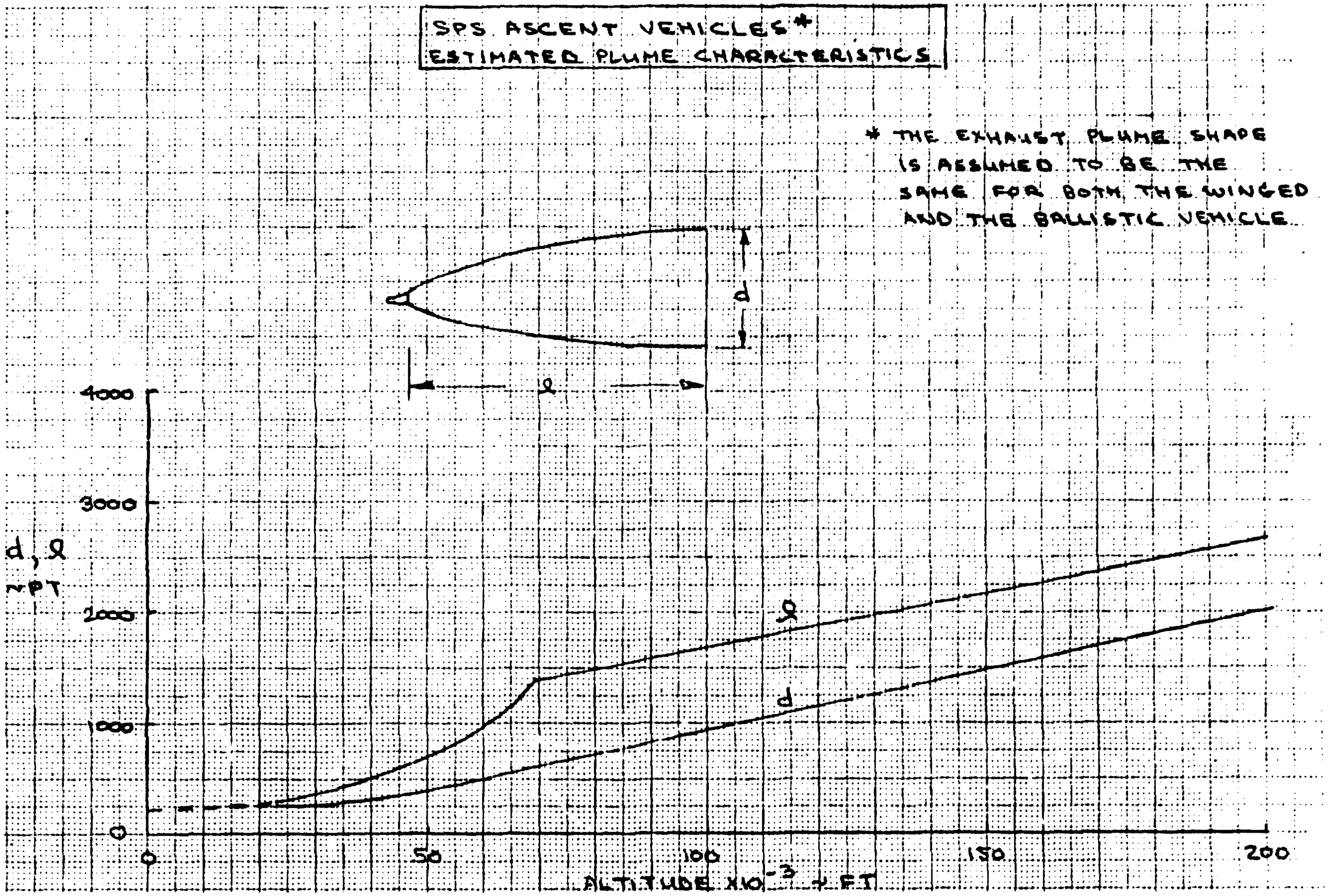


Figure 2.1-1 SPS Ascent Vehicles Estimated Plume Characteristics

The following equation was used to make the linearized theory estimates:

$$\Delta P = \frac{\sqrt{P_A P_G}}{h^{3/4}} \cdot K_R \cdot (M^2 - 1)^{1/8} \cdot \frac{d}{\ell^{1/4}} K_v$$

where: ΔP = Bow shock overpressure in psf
P_A = Atmospheric pressure at vehicle altitude in psf
P_G = Atmospheric pressure at ground level in psf
h = Perpendicular distance from vehicle flight path in feet
K_R = Reflection factor (usually about 2.0)
M = Vehcile Mach number
d = Vehicle diameter
ℓ = Vehicle length
K_v = Vehicle volume shape factor ($.54 \leq K_v \leq .81$); assumed to be 0.8 for this study

This equation is called the modified "Whitham Equation" and is given in Reference 6.

FLIGHT DATA
VS
LINEARIZED THEORY ESTIMATES

CASE #	Vehicle	Altitude (ft)	Mach	Measured ΔP (psf)	Estimated ΔP (psf)
CASE 1	Saturn V (Apollo 17)	107,400	3.78	4.5	4.5
CASE 2	Saturn V (Apollo 17)	115,500	4.00	4.1	4.4
CASE 3	Saturn V (Apollo 17)	149,400	4.84	1.3	2.1
CASE 4	Command Module (Apollo 15)	110,000	4.57	0.4	0.6

Figure 2.2-1 Validation of Linearized Sonic Boom Theory at High Mach Numbers

that linear theory sonic boom methods gave good agreement between test and theory for bodies with ratios of diameter to length as great as two and for mach numbers as high as 4.14.

The modified Whitham equations was used to estimate the sonic boom overpressures of the SPS vehicles. However, in order to determine shock wave locations on the ground, caustic locations, and the location of the "cut-off" which occurs at the edge of the region affected by the sonic boom, it was necessary to use TEA-251 (Reference 2-6). This is the Boeing version of a computer program developed by Hayes (Reference 2-7) which calculates sonic boom propagation in a stratified atmosphere.

Whitham Overpressures Under Flight Track

The overpressures predicted by the modified Whitham equation along the vehicle flight track are shown in Figures 2.2-2 through 2.2-4, as a function of vehicle altitude. These overpressures were used together with data from program TEA-251 to determine sonic boom overpressure patterns lateral to the ground track.

2.3 SONIC BOOM OVERPRESSURE PATTERNS

Figures 2.3-1 through 2.3-8 show the sonic boom overpressures as a function of ground location for each of the SPS vehicle configurations, as determined using the TEA-251 ground shock patterns together with the Whitham overpressures.

Figure 2.3-1 shows the overpressures for the winged vehicle ascent and booster reentry. The combination of vehicle trajectory and acceleration results in the generation of a caustic or "focal zone" in which the sonic boom overpressures are much larger than they would be for steady flight. Overpressures in this very localized region will be about 25 psf. The beginning of the caustic is located 31 nmi downrange from the launch site. The overpressure under the flight track decreases rapidly to 10 psf at a point 35 nmi downrange from the launch site. It has dropped to 2 psf 66 nmi downrange from the launch site. These overpressures are about three times as large as those generated by the Saturn V. The overpressures generated by the reentry of the booster reach a maximum of 4 psf in the vicinity of the landing site.

Figure 2.3-2 shows the overpressures generated by the ballistic vehicle ascent and booster reentry. The ascent overpressures are very similar to those of the winged vehicle. However, the booster reentry overpressures are much larger than those of the winged vehicle, reaching a maximum of 11 psf in the vicinity of the landing site. This is caused by the difference in trajectory between the winged booster and the ballistic booster. The ballistic booster maintains supersonic velocity to a much lower altitude than the winged booster resulting in the higher overpressures. The difference in trajectories, primarily the higher staging velocity, also results in the ballistic booster landing site being much further downrange than that of the winged booster.

ORIGINAL PAGE IS
OF POOR QUALITY

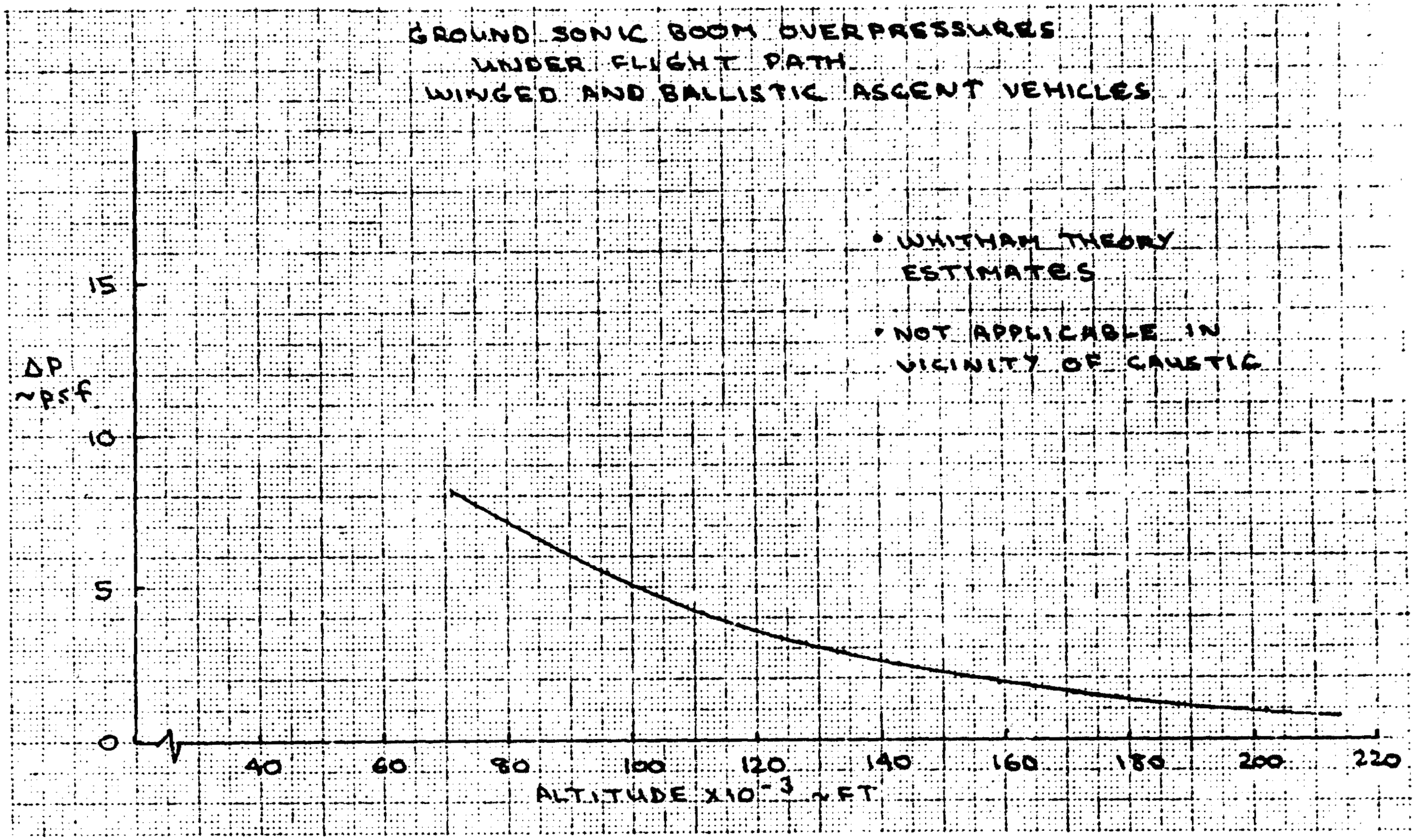


Figure 2.2-2 Sonic Boom Overpressures under Flight Track of Winged and Ballistic Ascent Vehicles

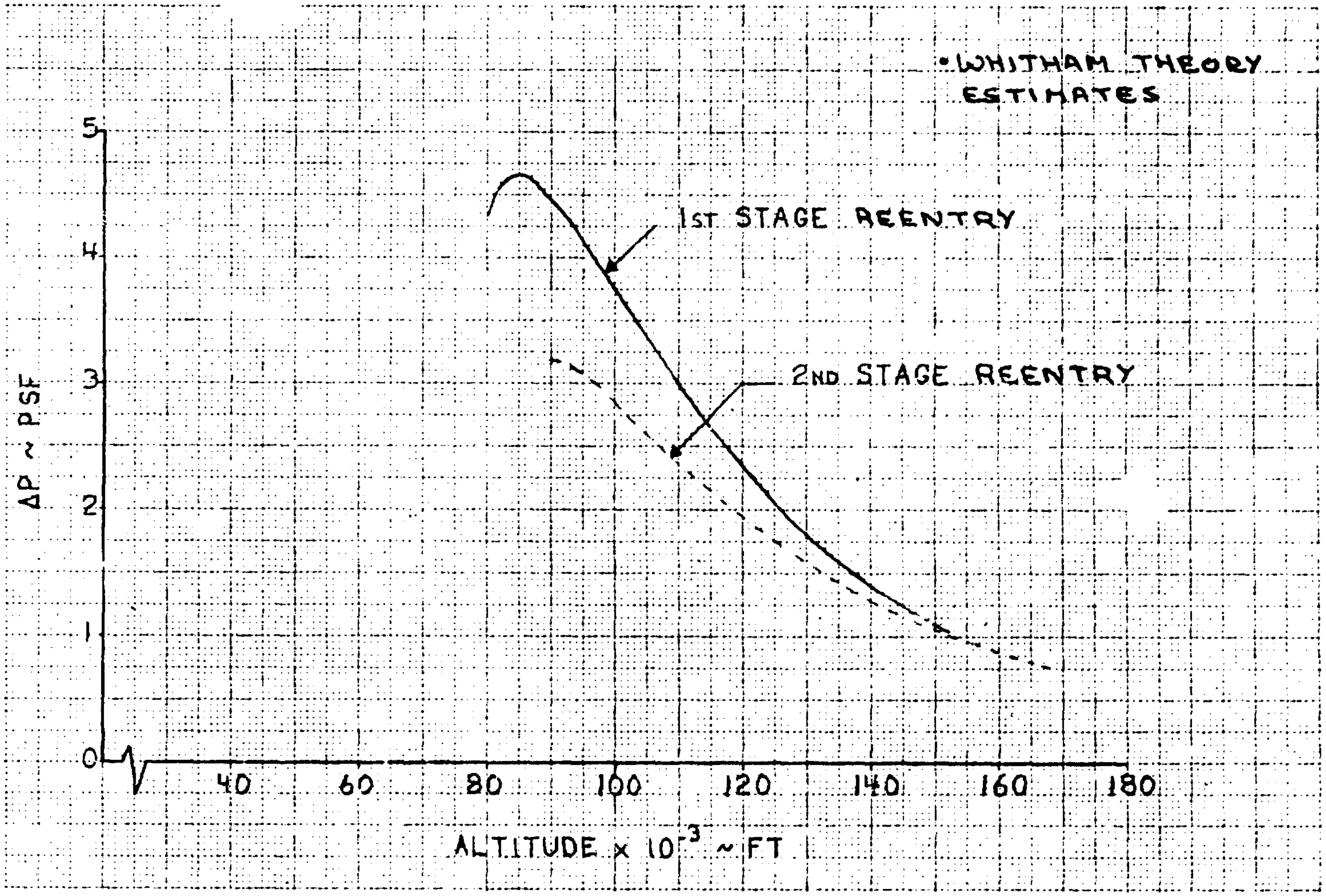


Figure 2.2-3 Ground Sonic Boom Overpressures under Flight Track–Winged Vehicle Reentry

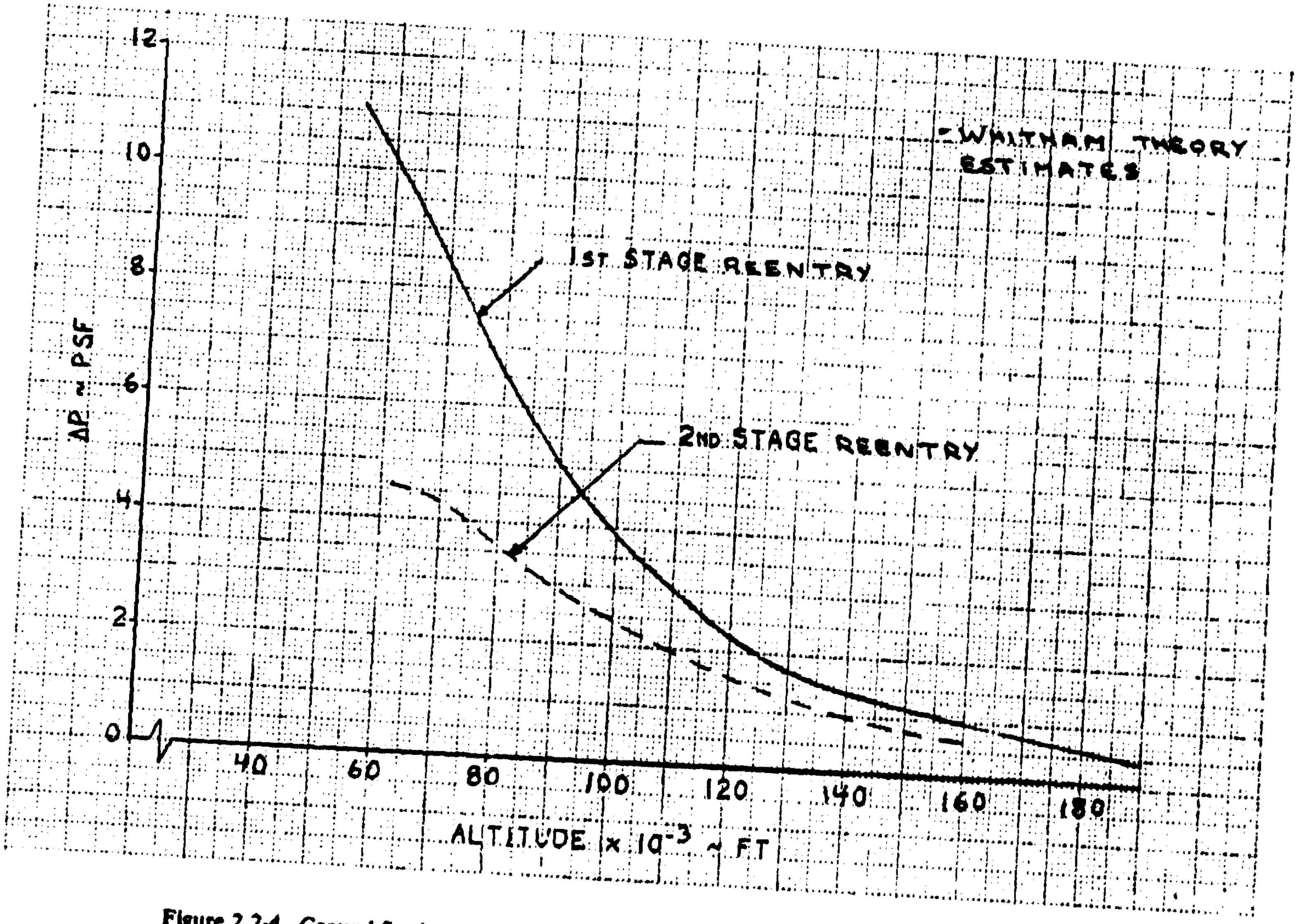


Figure 2.2-4 Ground Sonic Boom Overpressures under Flight Track—Ballistic Vehicle Reentry

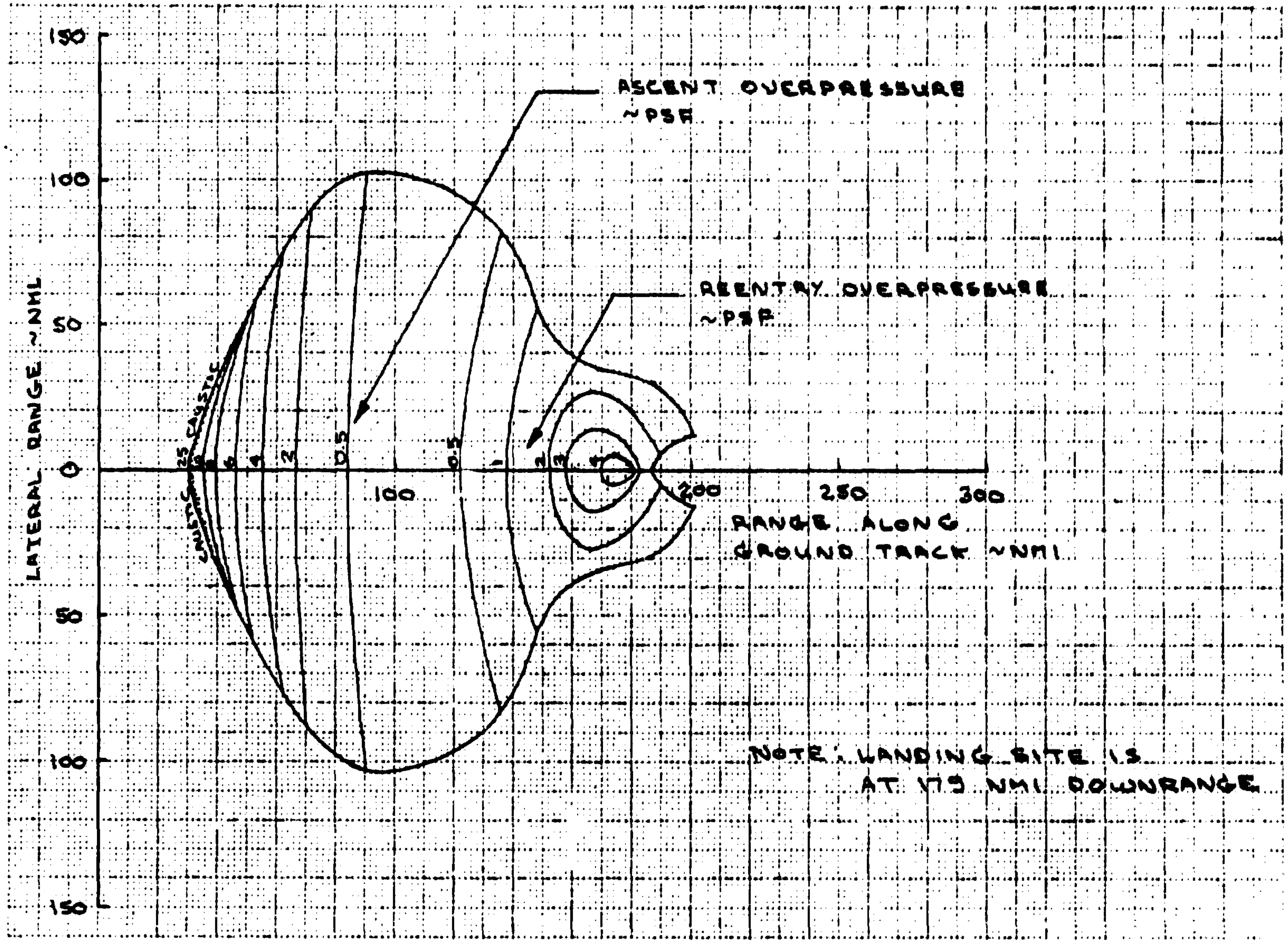


Figure 2.3-1 Winged HLLV Ascent and Booster Reentry Sonic Boom Overpressures

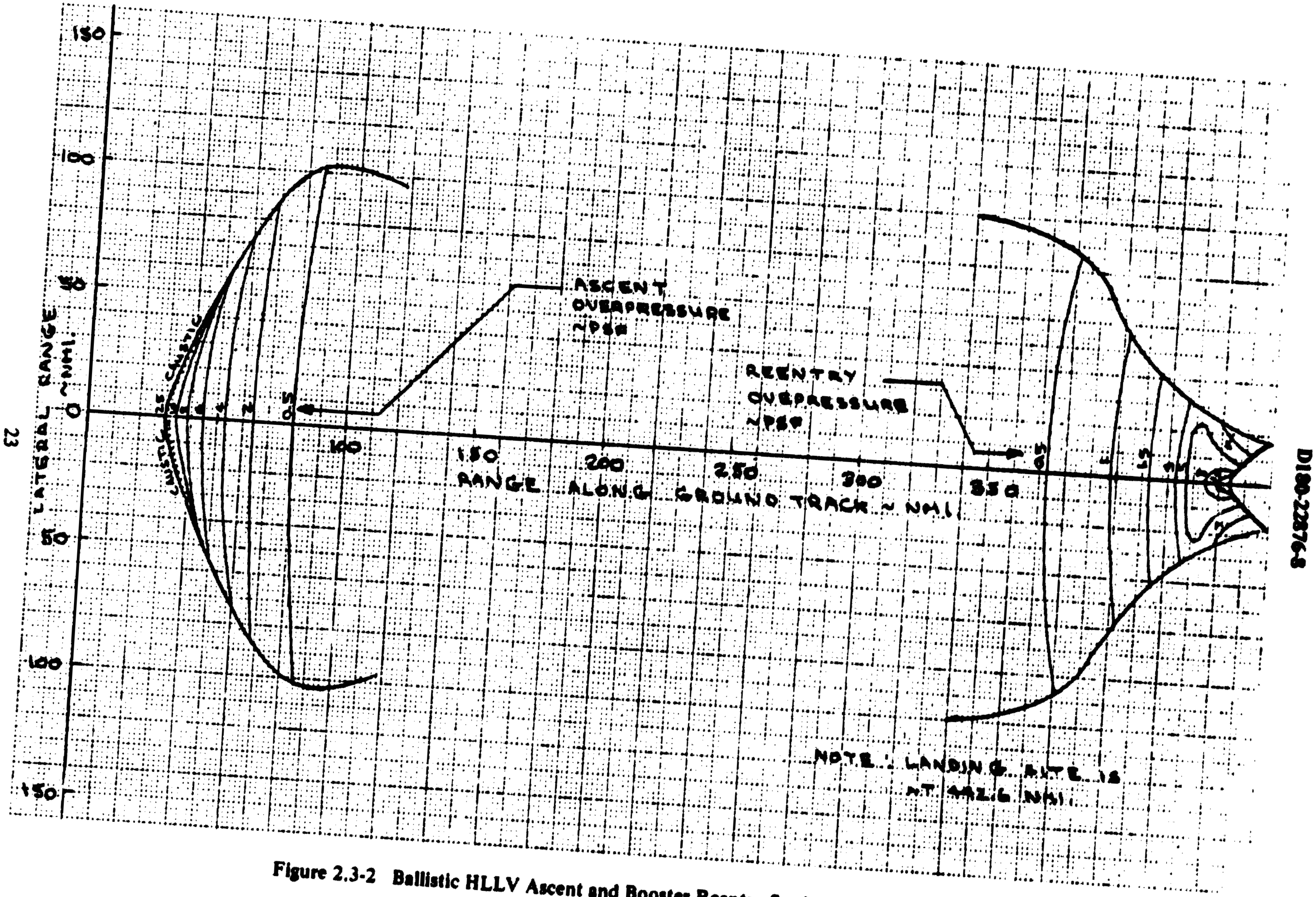


Figure 2.3-2 Ballistic HLLV Ascent and Booster Reentry Sonic Boom Overpressures

Figures 2.3-3 and 2.3-4 show the winged vehicle ascent and booster reentry overpressures in greater detail. Figure 2.3-5 shows the sonic boom overpressures resulting from the reentry of the second stage of the winged vehicle. The overpressures reach a maximum of 3 psf in the vicinity of the landing site.

Figures 2.3-6 and 2.3-7 show the ballistic vehicle ascent and booster reentry overpressures in greater detail than was shown in Figure 2.3-2. Figure 2.3-8 shows the sonic boom overpressures resulting from the reentry of the second stage of the ballistic vehicle. The overpressures reach a maximum of 4 psf in the vicinity of the landing site. The lateral extent of the region affected by the second stage of the ballistic vehicle is less than that of the second stage of the winged vehicle because it has a lower trajectory.

2.4 PRESSURE SIGNATURES

Figures 2.4-1 through 2.4-5 show the positive portions of the sonic boom pressure signatures for each of the SPS vehicle configurations. A pressure signature is the variation of sonic boom overpressure with time that an observer at a fixed point would experience. Only the positive pressure portions of the pressure signature were calculated in the present study.

Figure 2.4-1 shows sonic boom pressure signatures at two points along the flight track of the SPS ascent vehicle. These signatures are applicable to both the winged ascent vehicle and the ballistic ascent vehicle. The first pressure signature is that which occurs 32 nmi downrange from the launch site. This signature was generated when the vehicle was at an altitude of 92,000 feet and a mach number of 3.2. The maximum overpressure is 21 psf and the duration of the positive portion of the pressure signature is 2.3 seconds. The second pressure signature occurs 39 nmi downrange. It has a maximum overpressure of 8.4 psf and a positive lobe duration of 2.65 seconds.

The pressure signatures shown in Figures 2.4-2 through 2.4-5 have much shorter durations than those of the ascent vehicles because the reentry vehicles are much shorter than the exhaust plumes of the ascent vehicles. The duration of the positive lobe for the reentry vehicles is about 0.7 sec.

2.5 EFFECT OF ASCENT VEHICLE SIZE

The effect of ascent vehicle size on the magnitude of the sonic boom overpressures is shown in Figure 2.5-1. Ascent vehicle size was varied by varying the number of F-1 class engines and, thereby, the plume size. The overpressure at the caustic decreases from 25 psf to 15 psf when the number of engines is reduced from 16 to 10 and from 25 psf to 8 psf when the number of engines is reduced from 16 to 5. These peak overpressures are the limit in the focal zone.

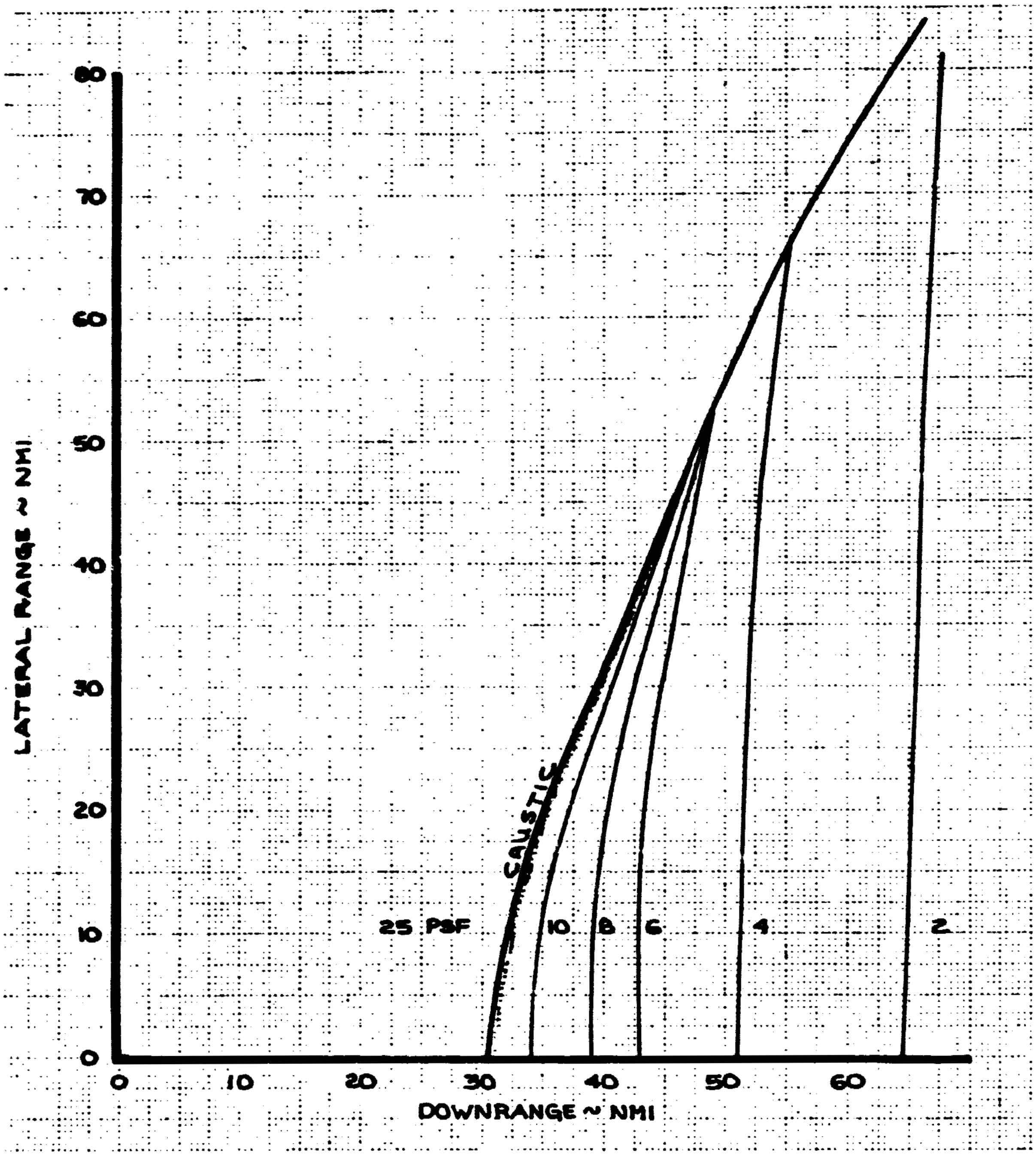


Figure 2.3-3 Winged HLLV Ascent Sonic Boom Overpressures

ORIGINAL PAGE IS
OF POOR QUALITY

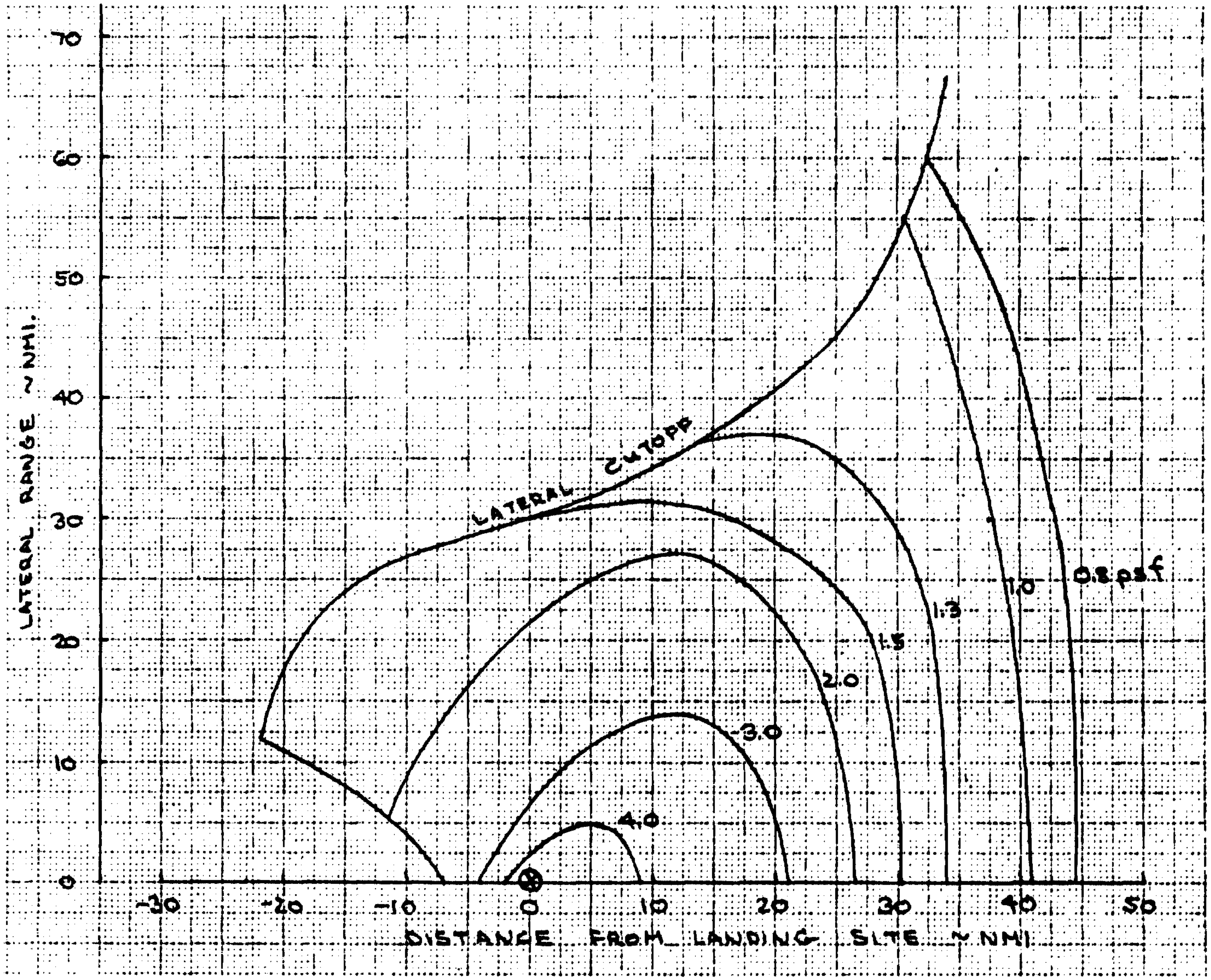


Figure 2.3-4 Winged HLLV Booster Reentry Sonic Boom Overpressures

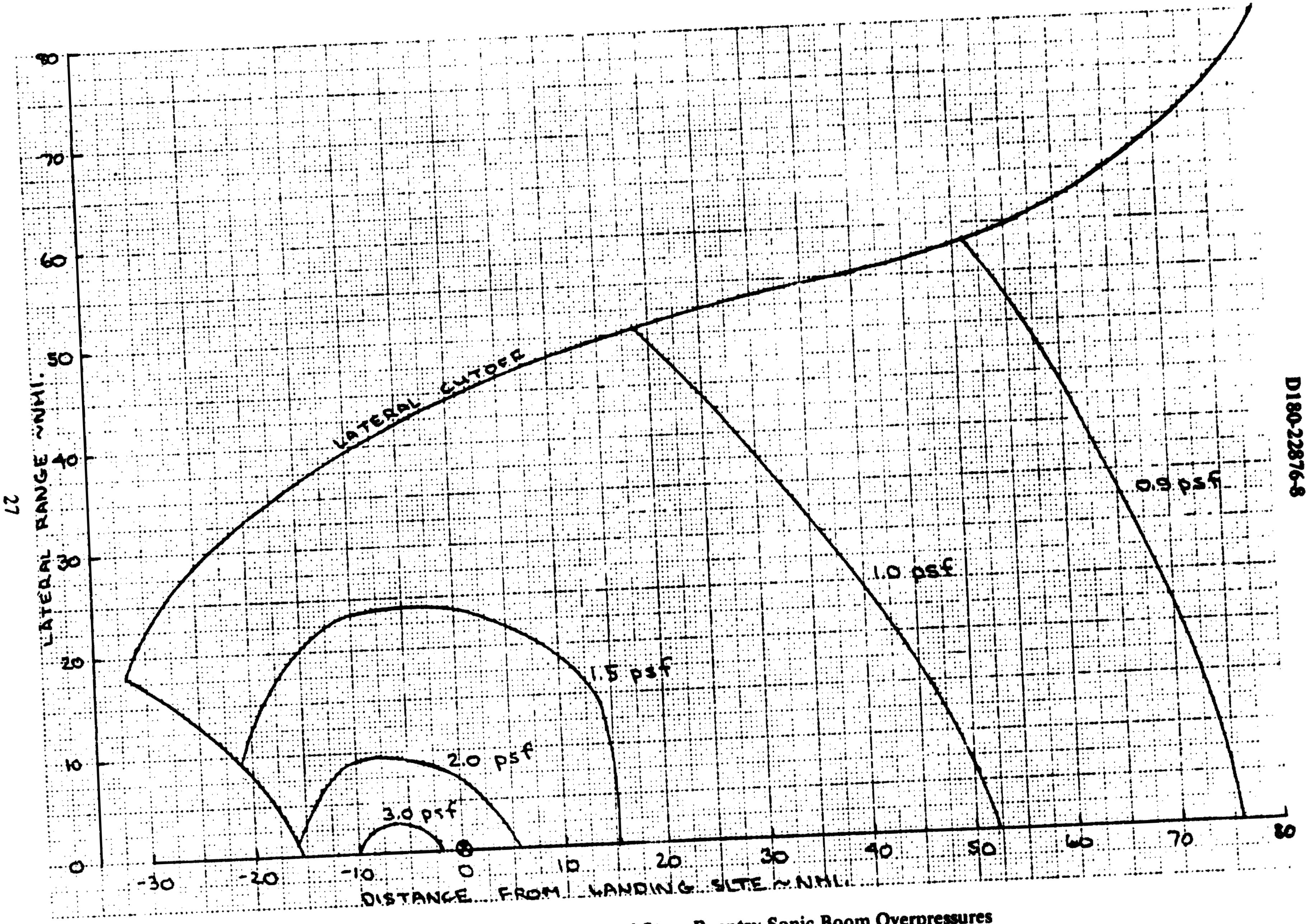


Figure 2.3-5 Winged HLLV Second Stage Reentry Sonic Boom Overpressures

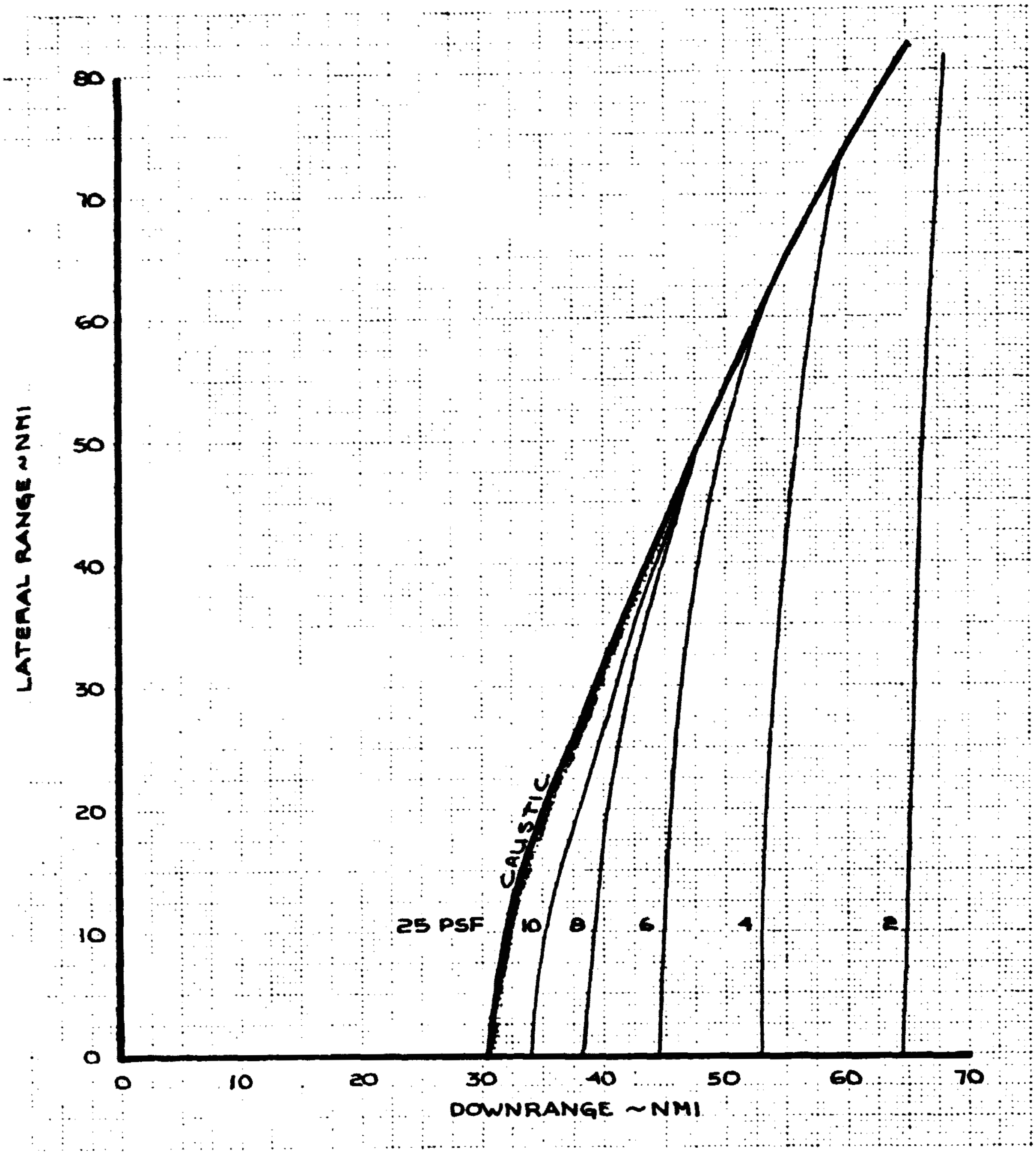


Figure 2.3-6 Ballistic HLLV Ascent Sonic Boom Overpressures

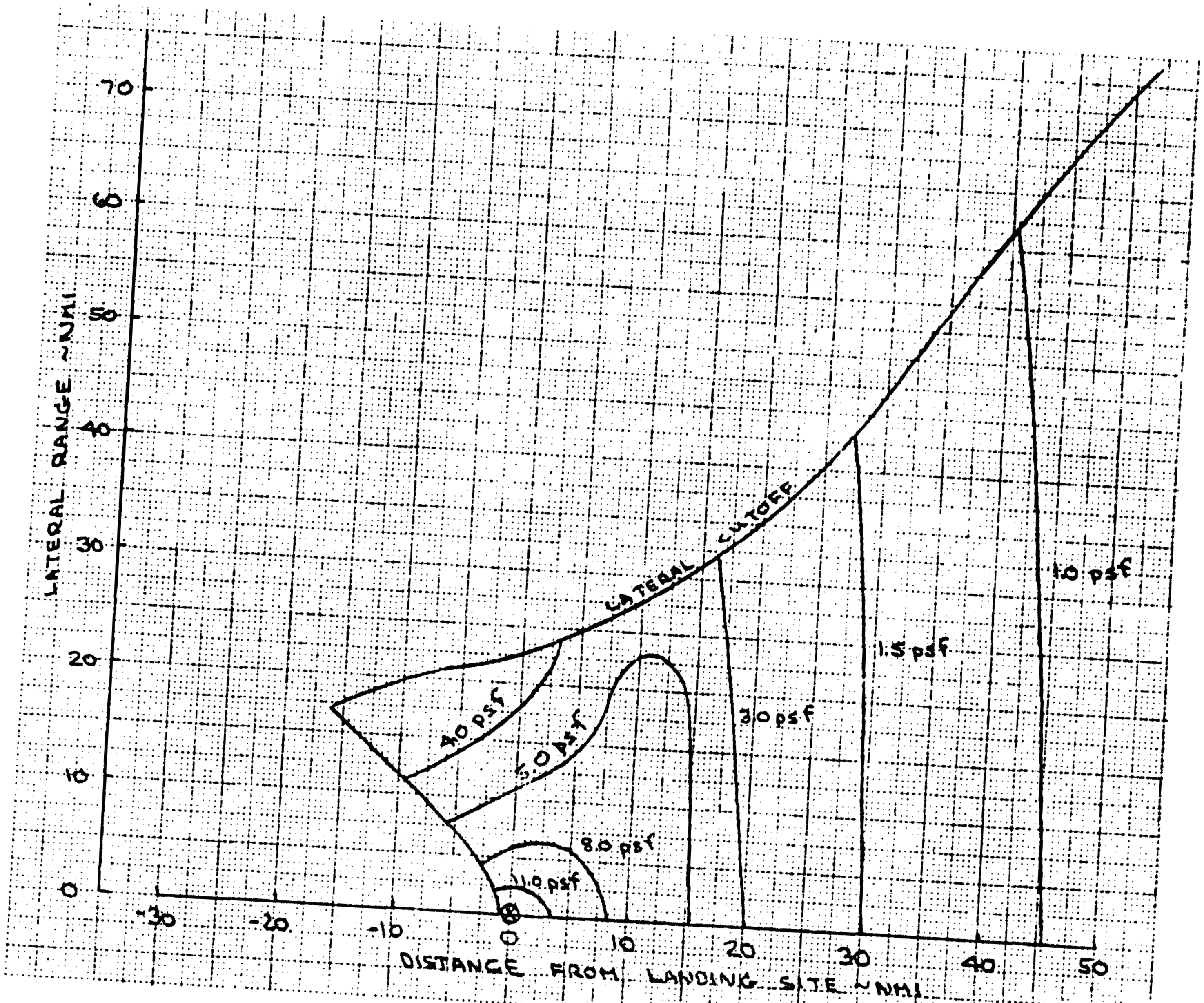


Figure 2.3-7 Ballistic HLLV First Stage Reentry Sonic Boom Overpressures

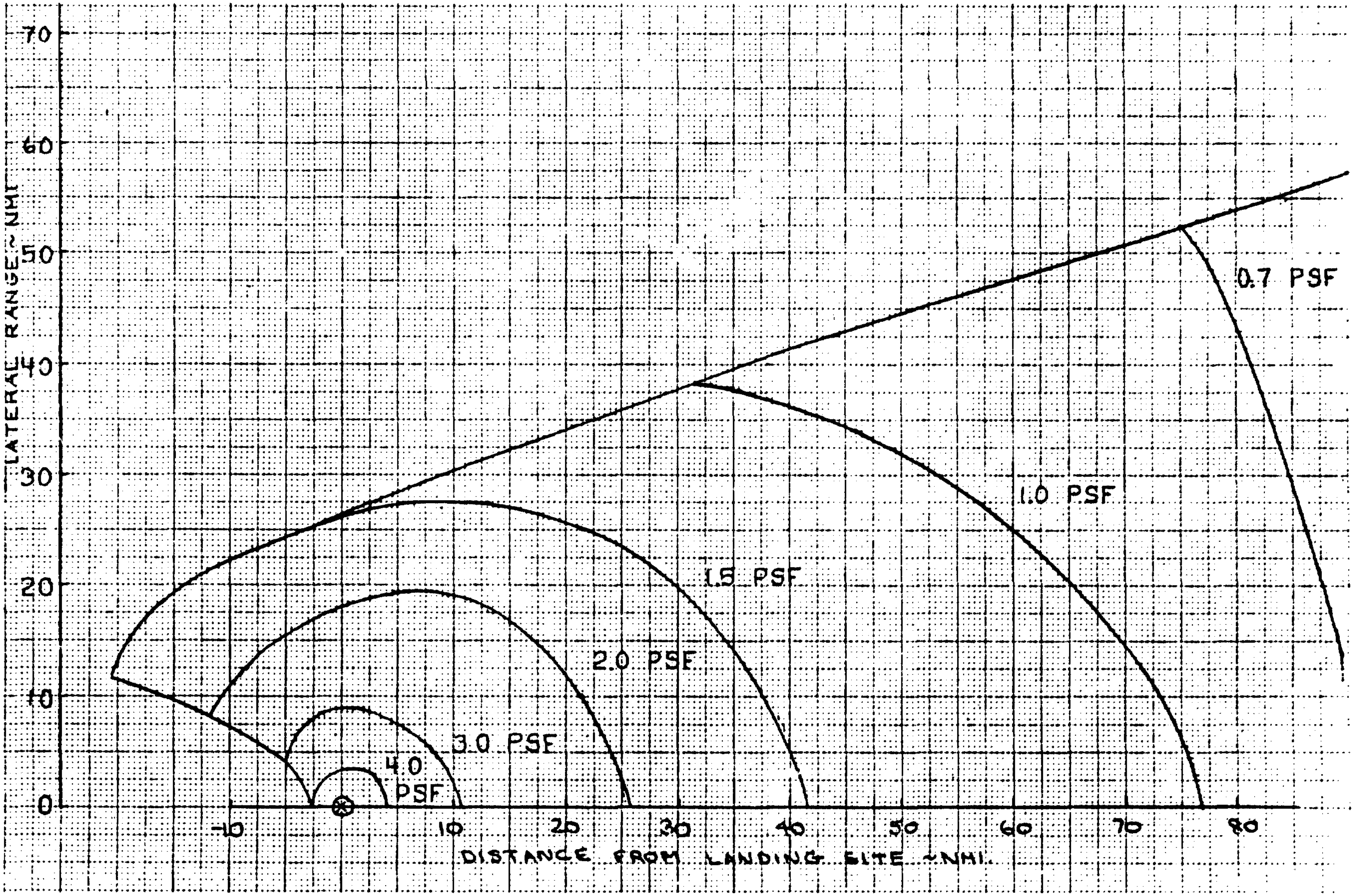


Figure 2.3-8 Ballistic HLLV Second Stage Reentry Sonic Boom Overpressures

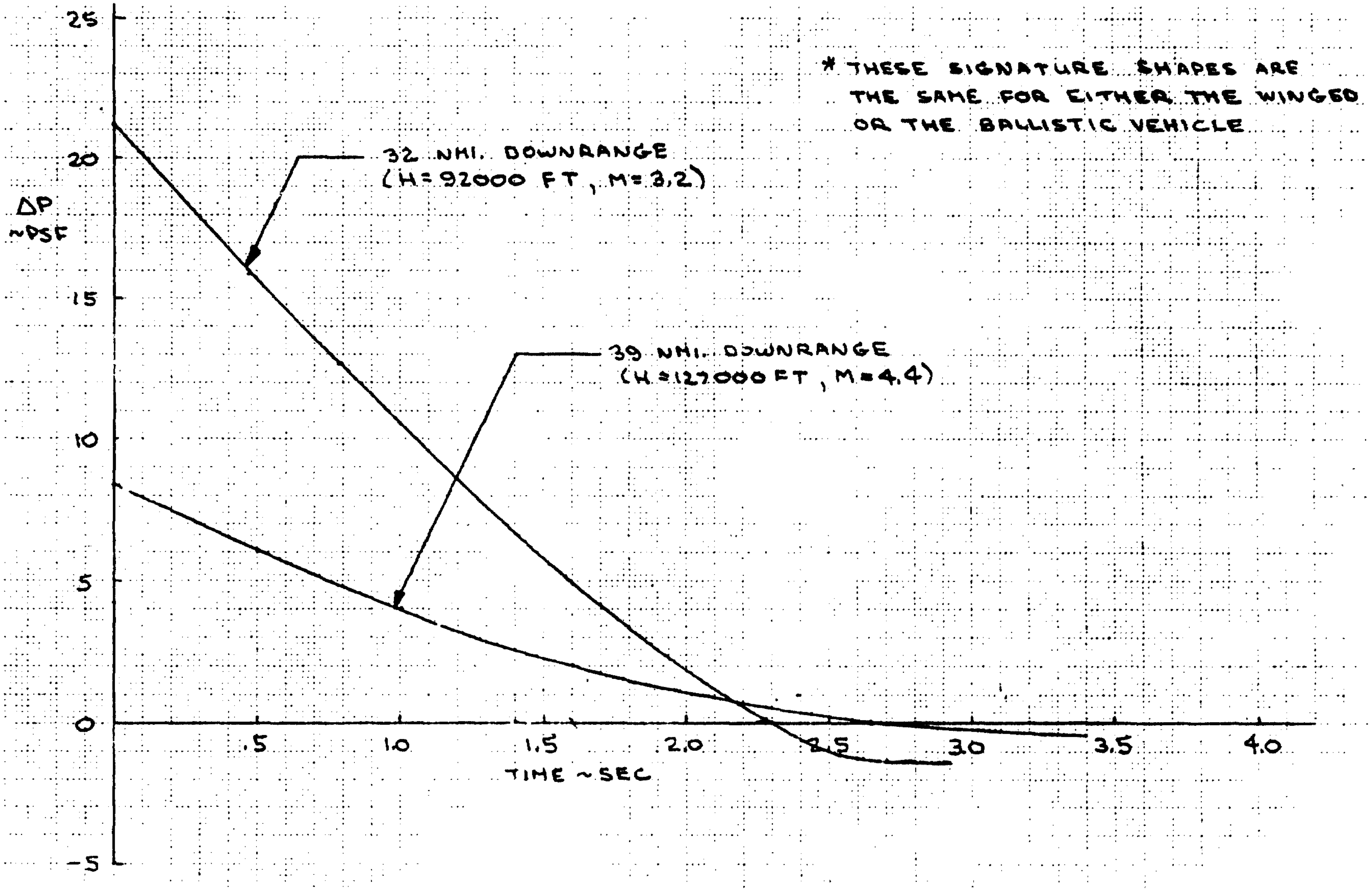


Figure 2.4-1 HLLV Ascent Sonic Boom Pressure Signatures

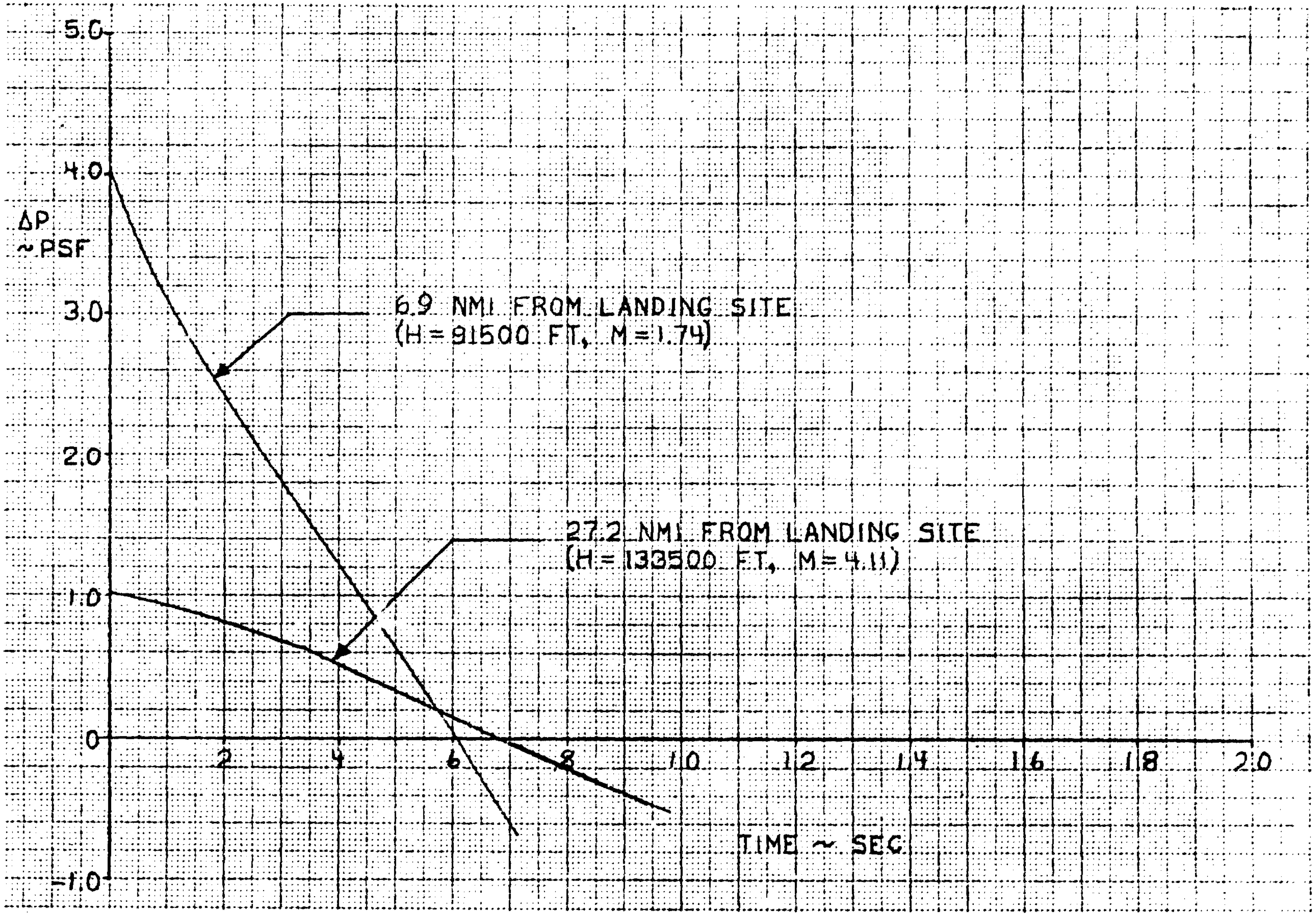


Figure 2.4-2 Winged HLLV Booster Reentry Sonic Boom Pressure Signatures

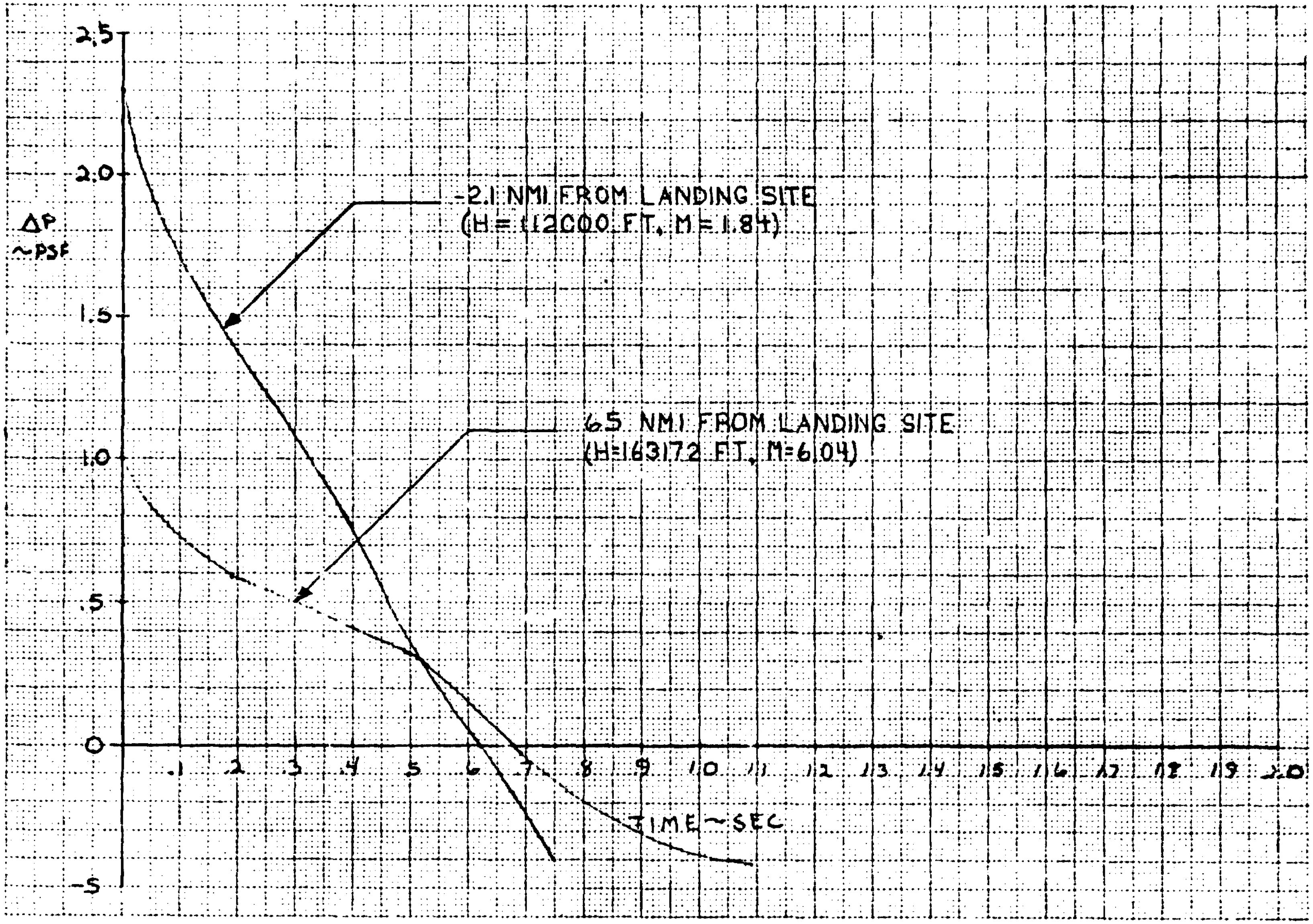


Figure 2.4-3 Winged HLLV Second Stage Reentry Sonic Boom Pressure Signatures

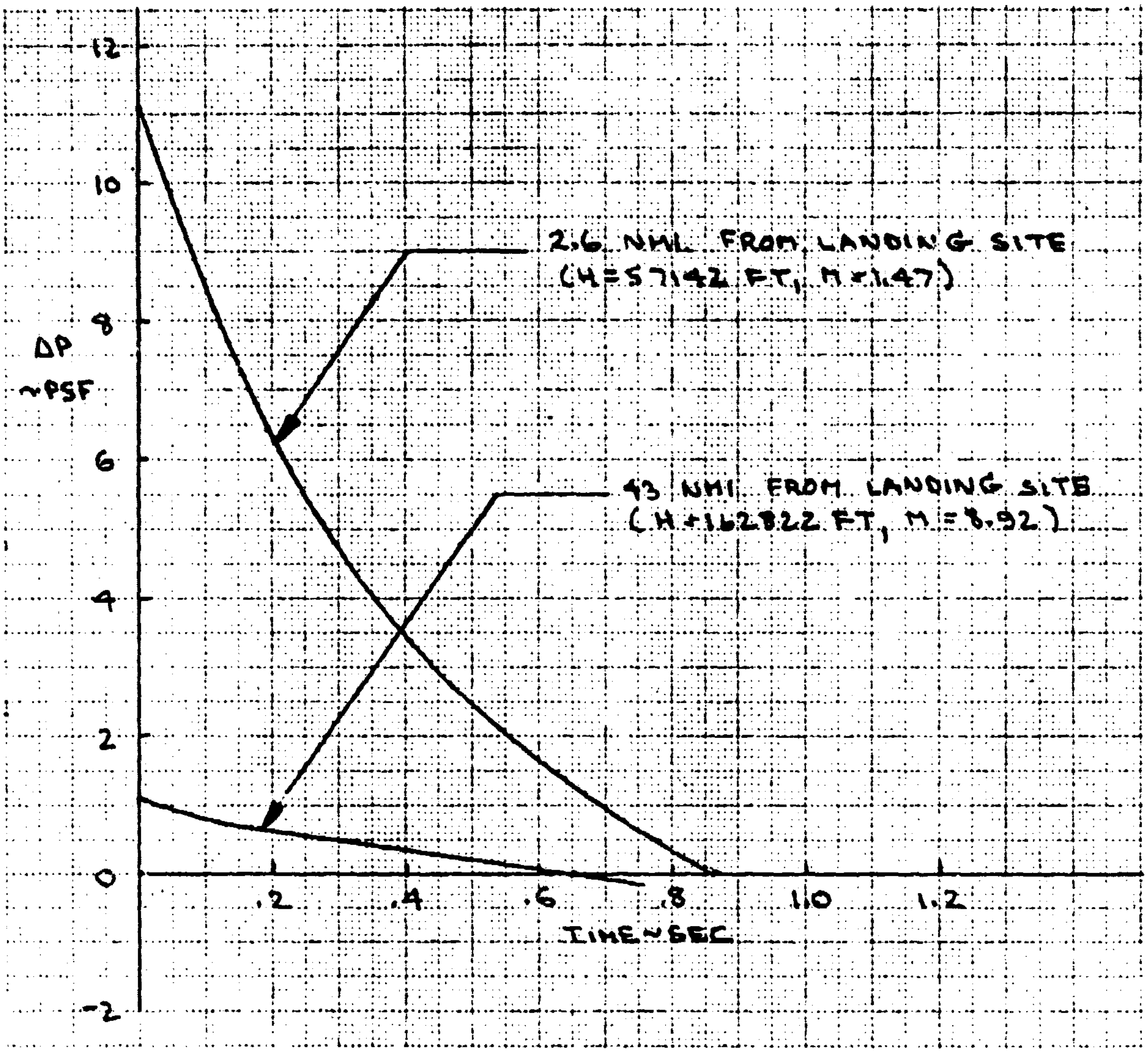


Figure 2.4-4 Ballistic HLLV First Stage Reentry Sonic Boom Pressure Signatures

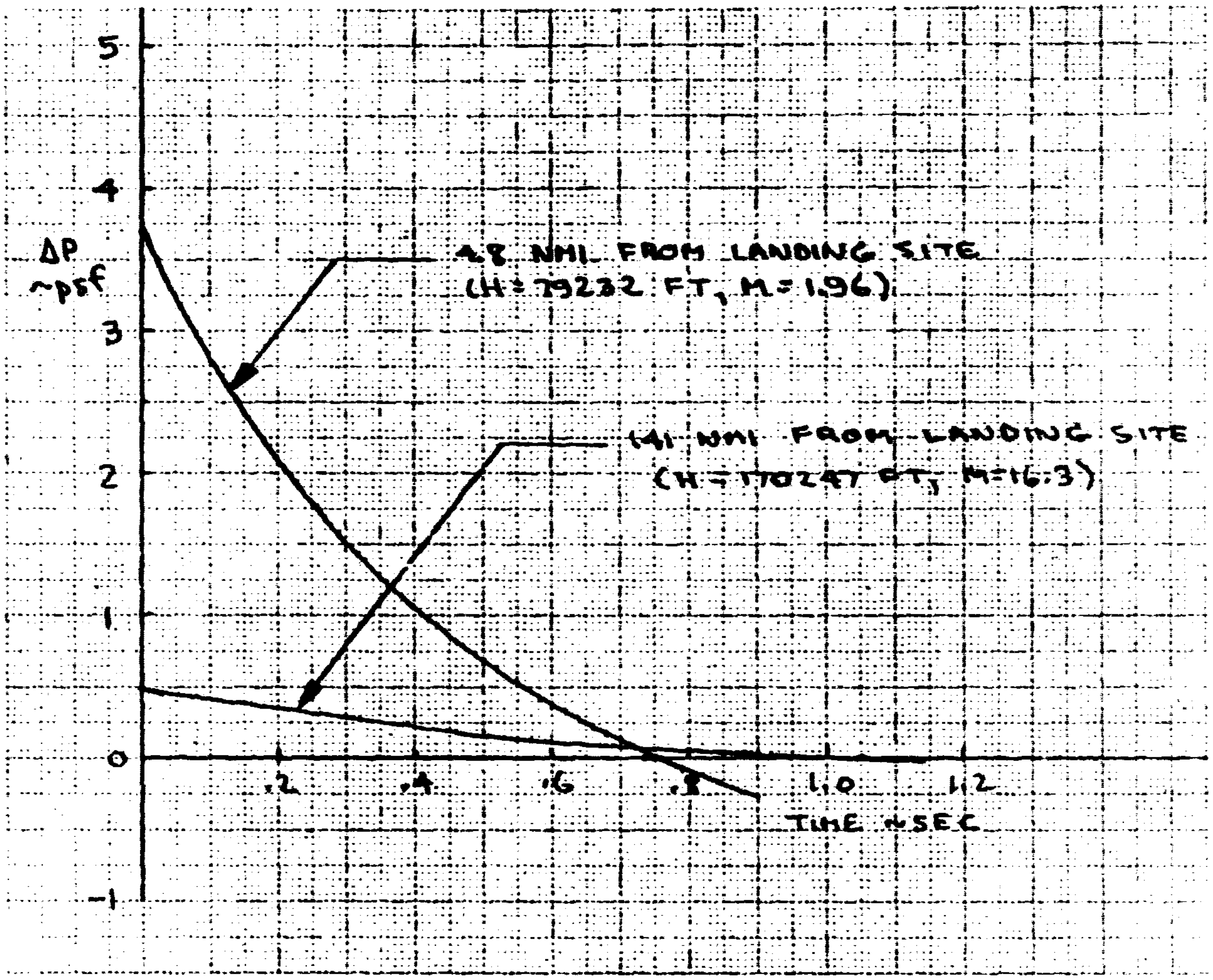


Figure 2.4-5 Ballistic HLLV Second Stage Reentry Sonic Boom Pressure Signatures

ORIGINAL PAGE IS
OF POOR QUALITY

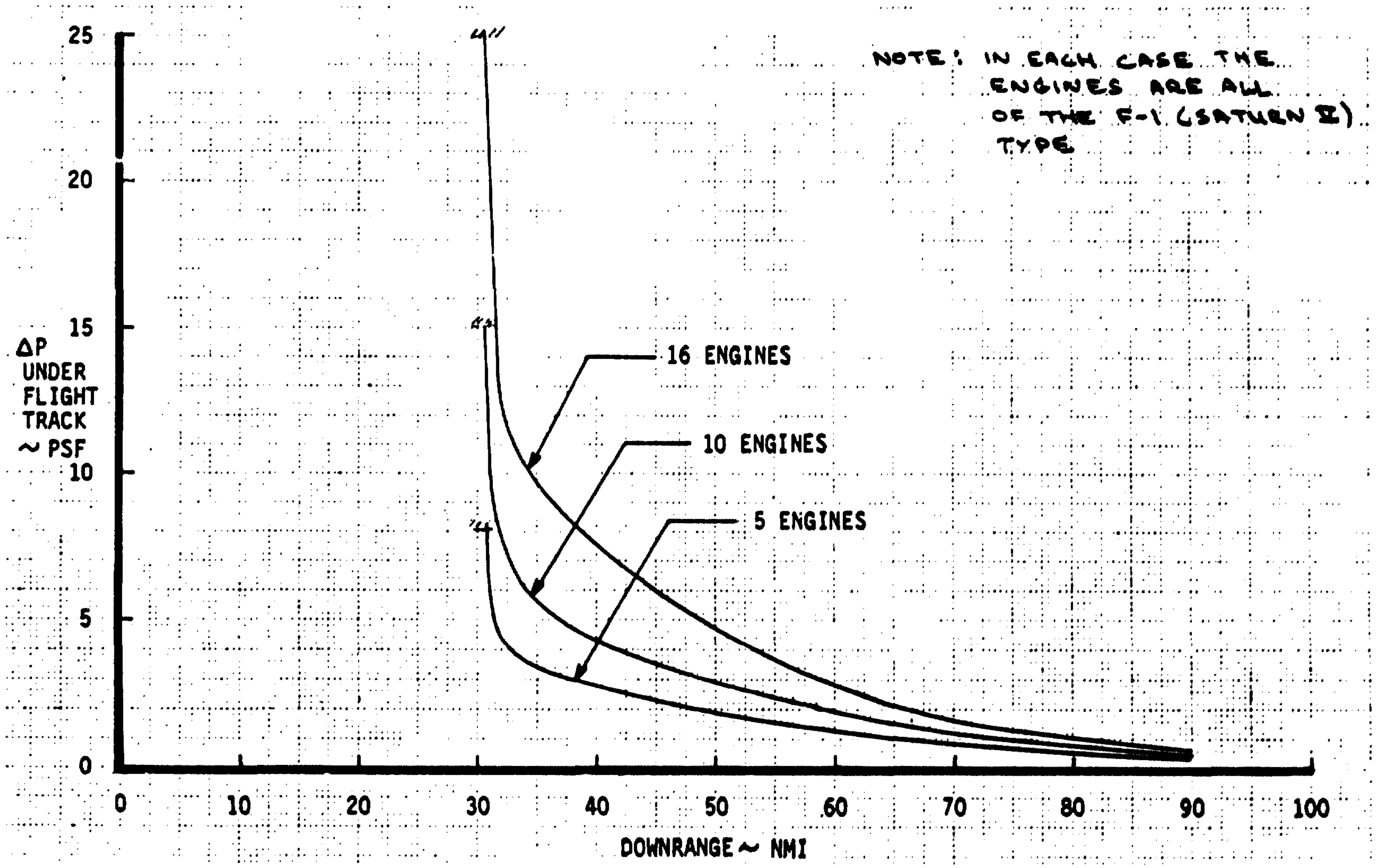


Figure 2.5-1 Sensitivity of HLLV Ascent Sonic Boom Overpressures to Vehicle Size

2.6 CONCLUSIONS

It is estimated, based upon the correlation obtained between the linear theory estimates and the Apollo 17 data, that the estimated overpressures for the SPS vehicles are within 30% of the actual values. The caustic and lateral cutoff locations are probably within 10% of the actual locations.

The following are some general conclusions that can be drawn from the results of this study:

(1) For the ascent vehicles maximum overpressures of 25 psf will occur in the vicinity of the caustic.

(2) Overpressures at the caustic are reduced from 25 psf to 15 psf when the number of F-1 engines is reduced from 16 to 10 and to 8 psf when the number of F-1 engines is reduced to 5.

(3) For the reentry vehicles maximum overpressures of 3-4 psf will occur in the vicinity of the landing site except for the first stage of the ballistic vehicle, in which case the maximum overpressures in the vicinity of the landing site will be 11 psf.

(4) For the ascent vehicles the duration of the positive lobe of the pressure signature will be about 2.5 seconds.

(5) For the reentry vehicles the duration of the positive lobe of the pressure signature will be about 0.7 seconds.

(6) The only significant difference between the sonic boom characteristics of the winged and ballistic vehicles is that the ballistic booster reentry overpressures are much higher than the winged booster reentry overpressures, and the ballistic booster landing site is much farther downrange than the winged booster landing site.

References

2-1 "Shuttle Sonic Boom–Technology and Predictions," Paul F. Holloway, Gilbert A. Wilhold, Jess H. Jones, Frank Garcia Jr., and Raymond M Hicks, AIAA Paper 73-1039, October 1973

2-2 "Saturn Base Heating Data," C. R. Mullen, et al., NASA CR 61390, May 1, 1972

2-3 "The Flow Pattern of a Supersonic Projectile," G. B. Whitham, Communications on Pure and Applied Mathematics, Vol. V, 1952, pp. 301-348

2-4 "The Shock Wave Problem of Supersonic Aircraft in Steady Flight," Domenic J. Maglier and Harry W. Carlson, NASA Memo 3-4-59L, April 1959

2-5 "A Study of the Sonic Boom Characteristics of a Blunt Body at a Mach Number of 4.14." Harry W. Carlson and Robert J. Mack, NASA Technical Paper 1015, September 1977

2-6 "Study Covering Calculations and Analysis of Sonic Boom During Operational Maneuvers: Vol. III—Description of Computer Program "Sonic Boom Propagation in a Stratified Atmosphere" and Estimation of Limitation Near Caustics," G. T. Haglund and Dennis L. Olson, Boeing Document No. D6A12108-3, July 1971

2-7 "Sonic Boom Propagation in a Stratified Atmosphere with Computer Program," Wallace D. Hayes, Rudolph C. Haefeli, and H. E. Kulsrud, NASA CR-1299, April 1969

3.0 LAUNCH NOISE ANALYSIS

A preliminary investigation was conducted on the Solar Power Satellite (SPS) launch vehicle noise to provide basic noise information to assess the environmental impact on a launch facility and to facilitate preliminary launch site selection. The investigation included rocket launch noise prediction, a limited literature survey on past experience, and a review of present prediction capability to assess technology development requirements and recommendations. Each of the above items will be discussed in some detail in the following sections.

3.1 ROCKET LAUNCH NOISE

The basic launch noise for rockets is created by the rocket engine exhaust. The high velocity exhaust contacts the stationary ambient air and a mixing of the two gas masses takes place. Two basic noise generating mechanisms have been identified as being the main contributors to noise generation in this process. Jet mixing noise is generated by turbulent pressure fluctuations in the mixing region. In addition to this mixing noise, shock cell generated noise is also present in jets with supersonic nozzle exit velocities. Both of the above noise sources have been a subject of considerable past investigation. Jet mixing noise has been investigated in connection with subsonic aircraft and supersonic aircraft propulsion systems. Procedures for aircraft type power plant jet noise prediction have been developed and computerized computation procedures were available. These available prediction procedures were modified to extend the prediction range to jet velocities that are characteristic of the SPS launch vehicle propulsion engines. The basic prediction method is documented in References 3-1 and 3-2. The prediction procedure utilizes the basic jet noise generation influencing parameters (jet velocity, density, massflow, temperature and nozzle area) and predicts the sound spectrum generated by the jet. Spectral information is obtained at 10° intervals around the jet axis. Distance extrapolations are also handled by the computer program accountings for the effect of spherical divergence and atmospheric attenuation as a function of distance. Overall Sound Pressure Levels (OASPL) and Perceived Noise Level (PNL) are also computed from the predicted spectral information. The computer program is equipped to handle jets with the effect of vehicle forward motion taken into account.

This option has not been used in these predictions because the forward flight velocities are small compared to the jet velocities in the initial stages of the flight. Due to the limited scope of this investigation, noise prediction was limited to the static case.

The predicted launch Overall Sound Pressure Level (OASPL) contour map is shown on Figure 3.1-1. The predicted launch Perceived Noise Level contour is shown on Figure 3.1-2. The contour maps represent the maximum noise emitted by the launch vehicle at the site. As a measure of relative comparison, it is suggested that for building damage estimates the OASPL levels should not exceed 147 dB and for habitation the PNL levels should not exceed 108 dB. The building damage limit level is suggested on the basis of literature survey results and the PNL level limit is based on criteria

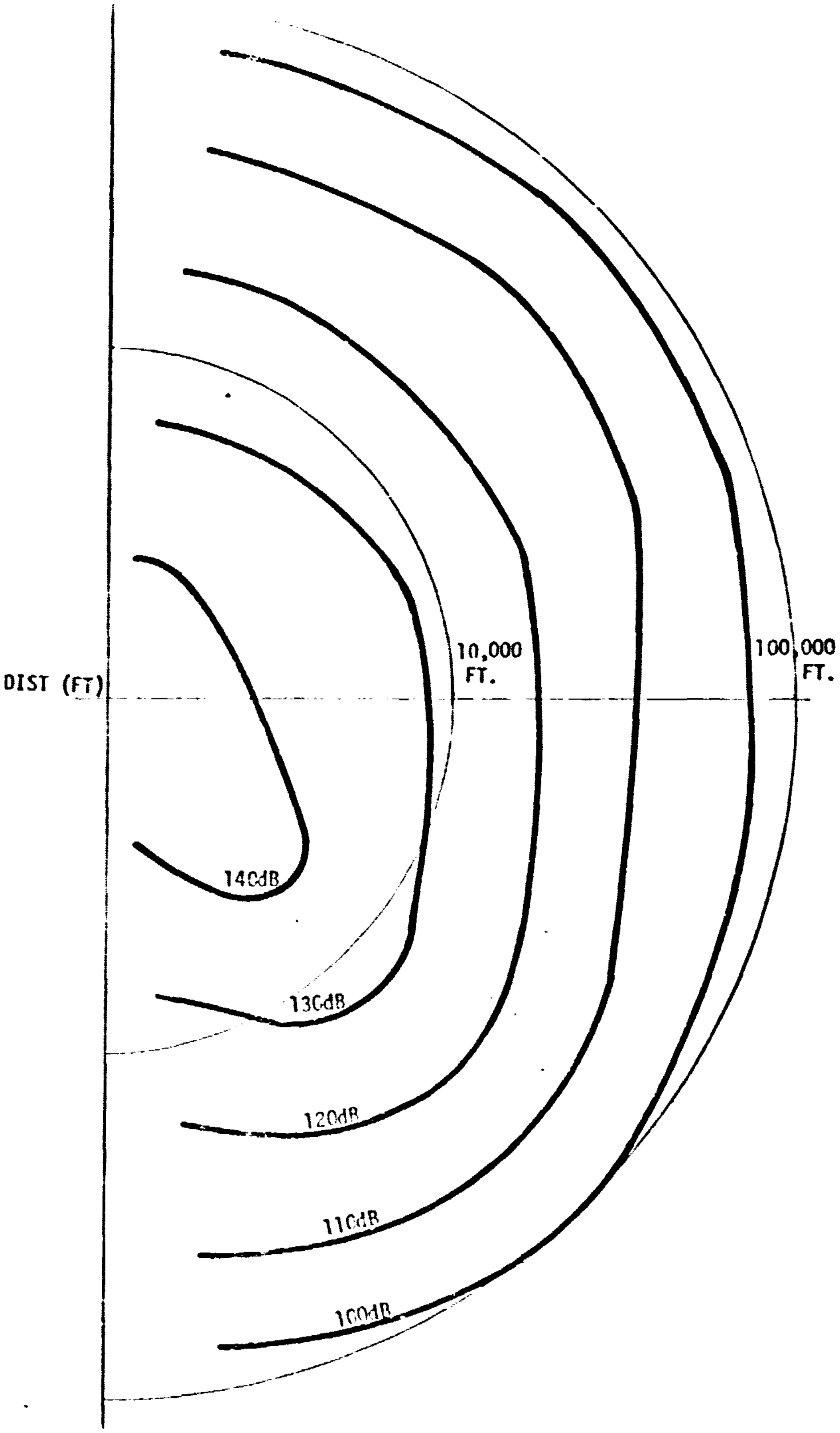


Figure 3.1-1 SPS Predicted Overall Sound Pressure Levels–OASPL-dB

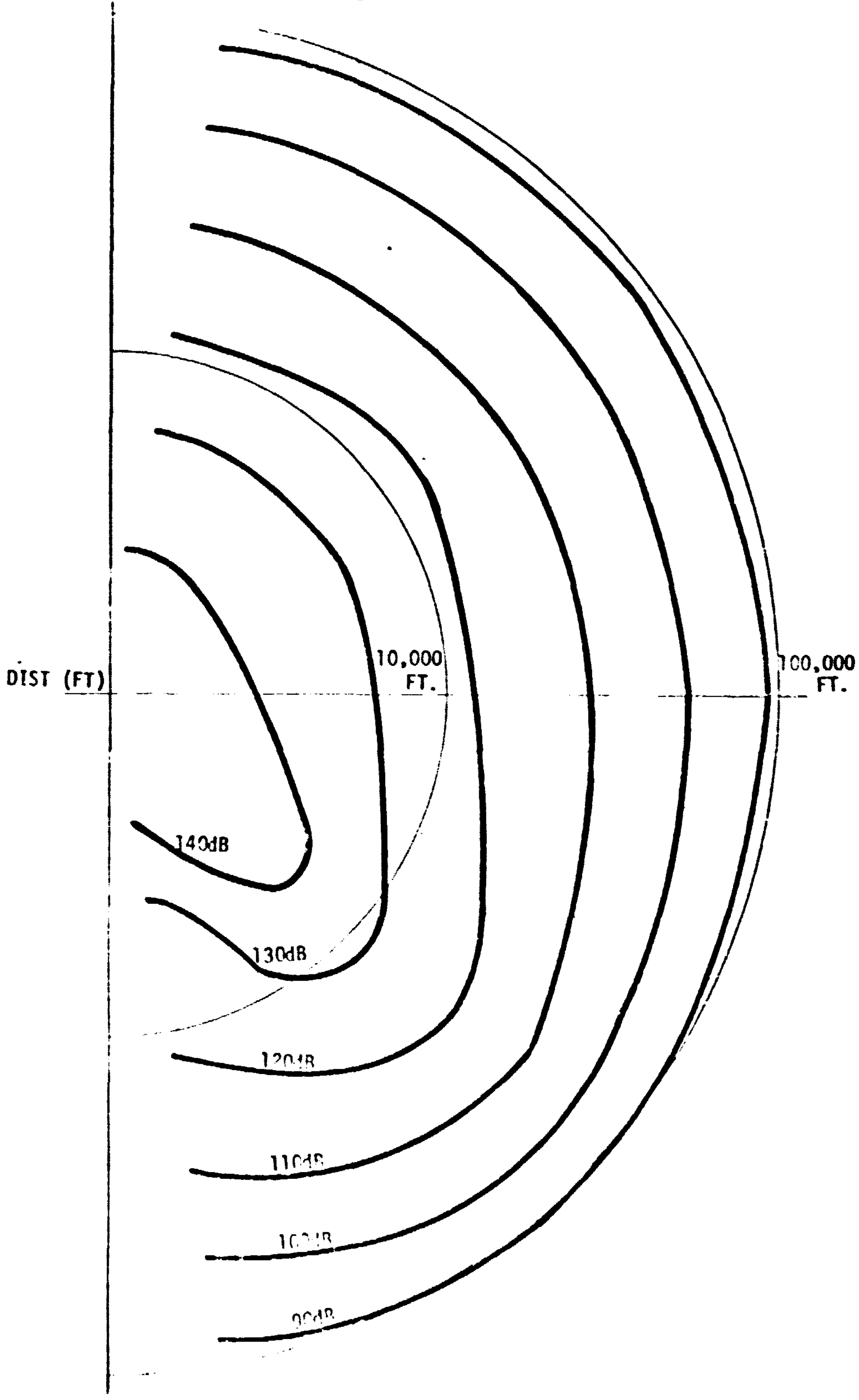


Figure 3.1-2 SPS Predicted Perceived Noise Levels–PNL-dB

established as maximum for commercial aircraft in any category on takeoff or landing approach (at the measureing point per Reference 3) in the United States. (The 108 dB PNL levels assume a 10 second time duration for the noise level to decay 10 dB from the peak.)

Figure 3.1-3 shows the OASPL and PNL levels for the SPS launch vehicle as a function of radial distance along the ground surface ($\theta=90^{\circ}$). From this curve, it can be seen that the maximum OASPL level for building damage occurs at 1000 ft from the launch vehicle and the PNL limit 108 dB takes place at 32,000 ft from the launch axis. Figures 3.1-4 through 3.1-6 present the polar plot of the predicted OASPL for 1000, 10,000 and 100,000 ft distances and the PNL prediction for the same distances is shown on Figures 3.1-7 through 3.1-9. Figures 3.1-10 through 3.1-12 show the sound spectrum along the ground plane for the above distances.

3.2 LITERATURE SURVEY AND PAST EXPERIENCE

A review of applicable data on rocket noise has identified a number of information sources. The majority of available material on rocket noise that is available is from 1964, 1968 and 1972. A summary of this material is provided in the following paragraphs:

(1) Determination of Rocket Engine Noise Damage to Community Dwellings Near Launch Sites–1964.

Volume I is a discussion of the study.
Volume II is a presentation of the data.

Both volumes deal with the tests on windows and walls. Tests were conducted to check structural damage. There was no glass damage below 120 dB. Wall damage (dry wall type) occurred above 147 dB.

The post-Saturn booster created no glass damage and some plaster damage when weather conditions were such that the noise focused on the building with the plaster walls.

Weather conditions cause "acoustical focusing" that could cause damage. The weather conditions are hard to predict. The velocity of the wind plays an important part in acoustical focusing and it is hard to measure.

This report is concerned with the dynamic response to windows and wall damage caused by rocket noise. It also specifies that the authors feel that the psychological damage possibility is remote.

(2) Analysis of Potential Community Response to Test Operations of Rocketdyne/Santa Susana facility 1968.

Structural damage was not predicted. Complaints occurred when noise got to be about 120 dB or windows rattled. Very few claims were paid although a lot were filed.

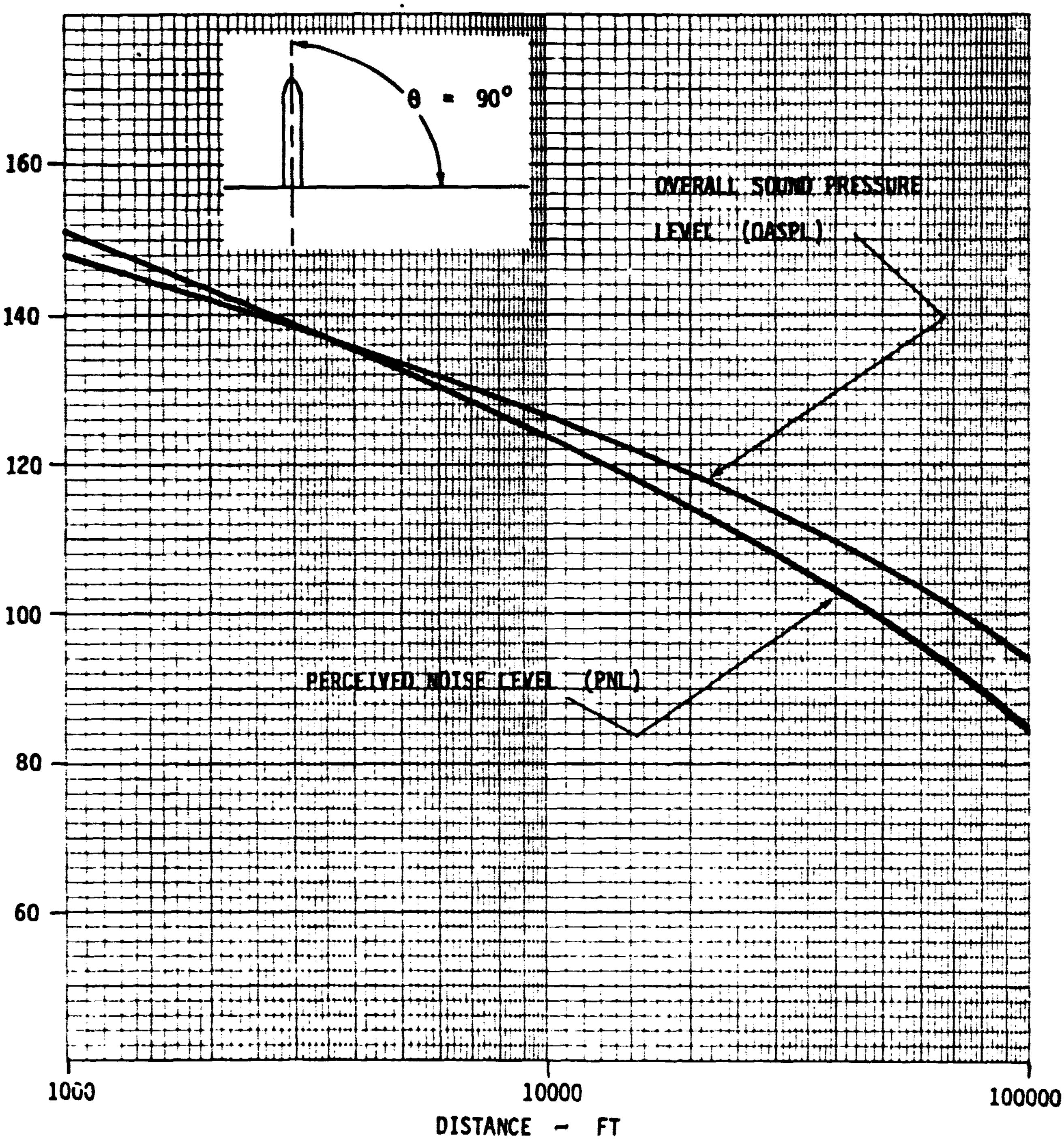


Figure 3.1-3 Launch Site Ground Surface Noise Levels (θ = 90°)

ORIGINAL PAGE IS
OF POOR QUALITY

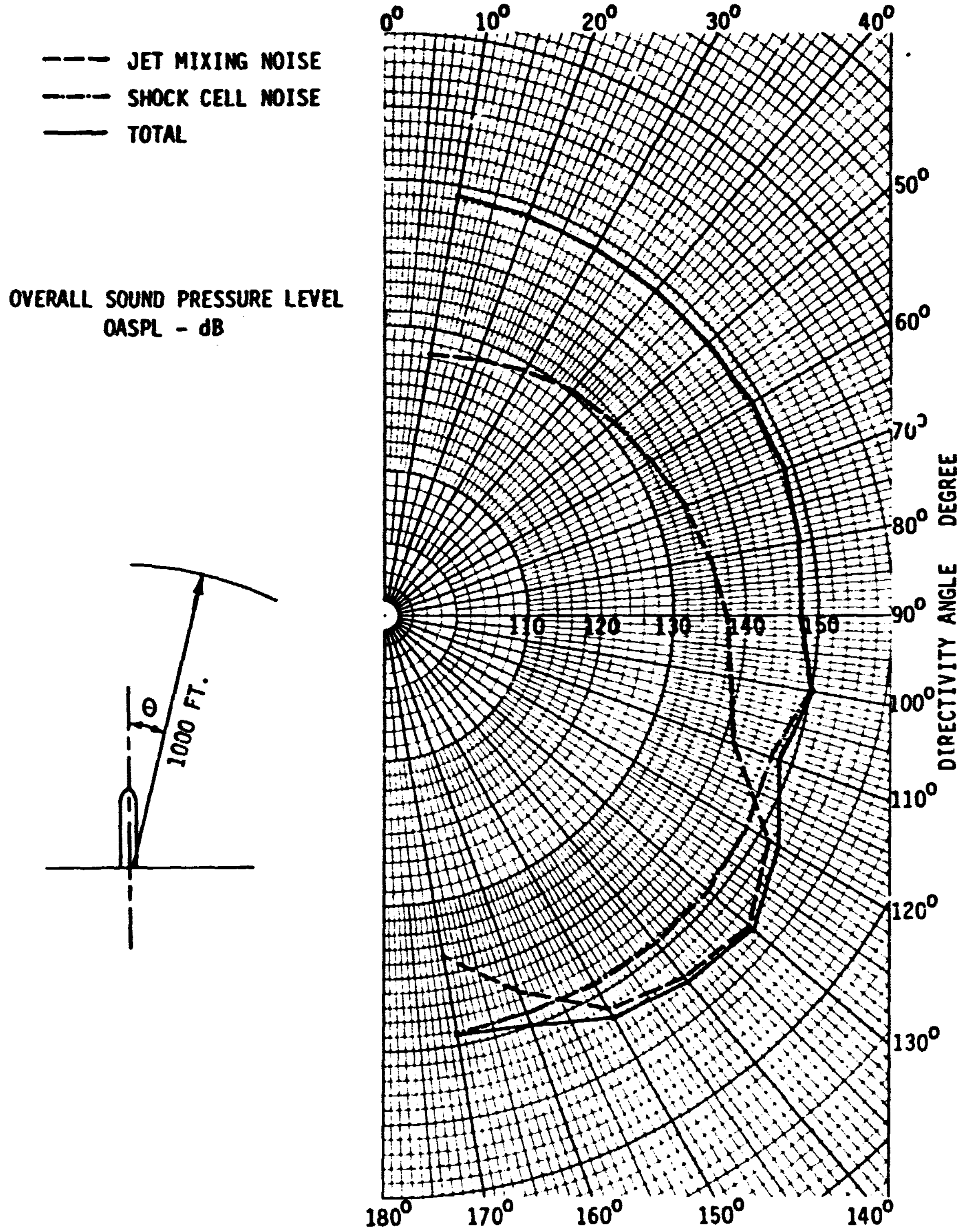


Figure 3.1-4 SPS Launch Vehicle Overall Sound Pressure Level-dB (1,000 ft. Sideline Distance)

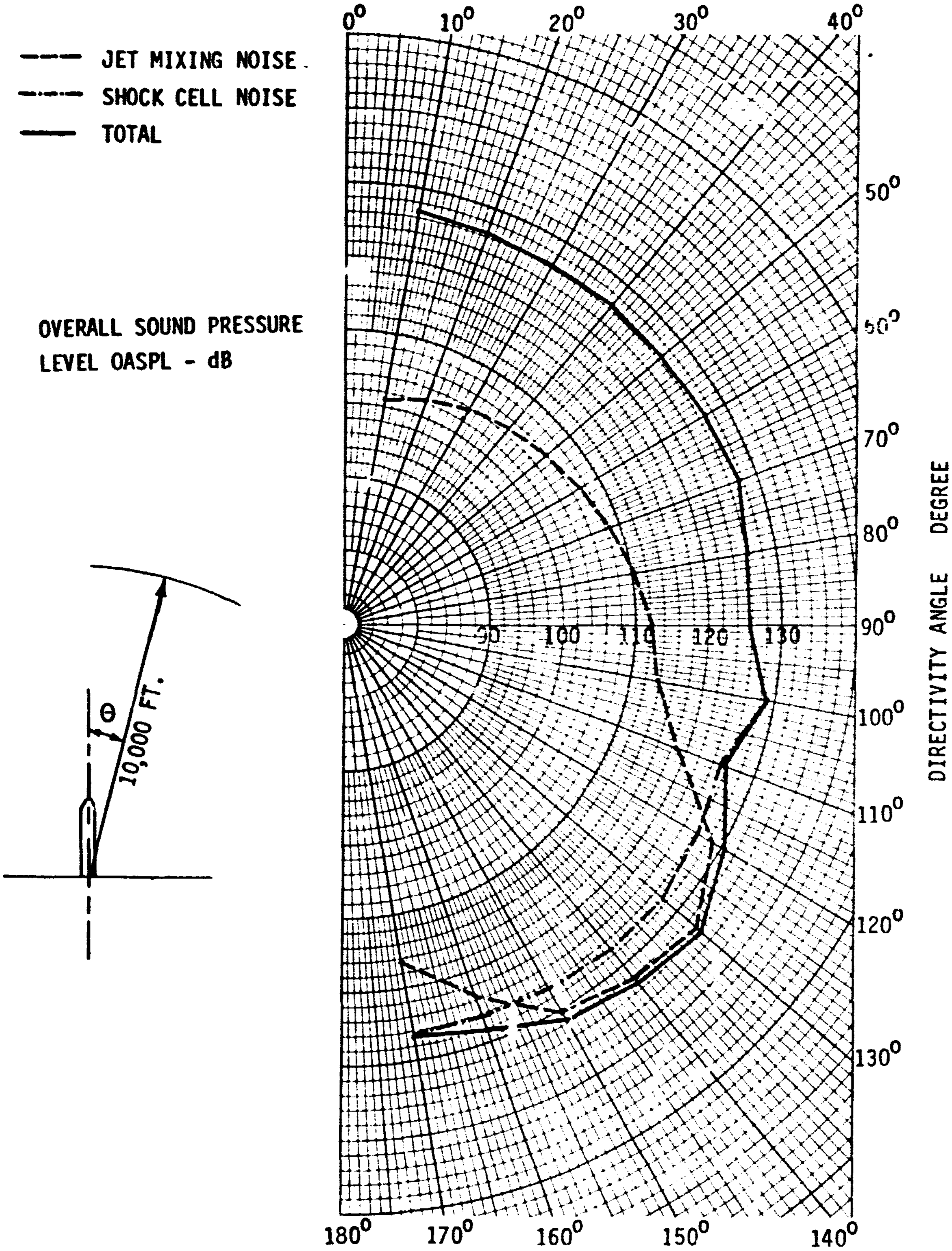


Figure 3.1-5 SPS Launch Vehicle Overall Sound Pressure Level-dB (10,000 ft. Sideline Distance)

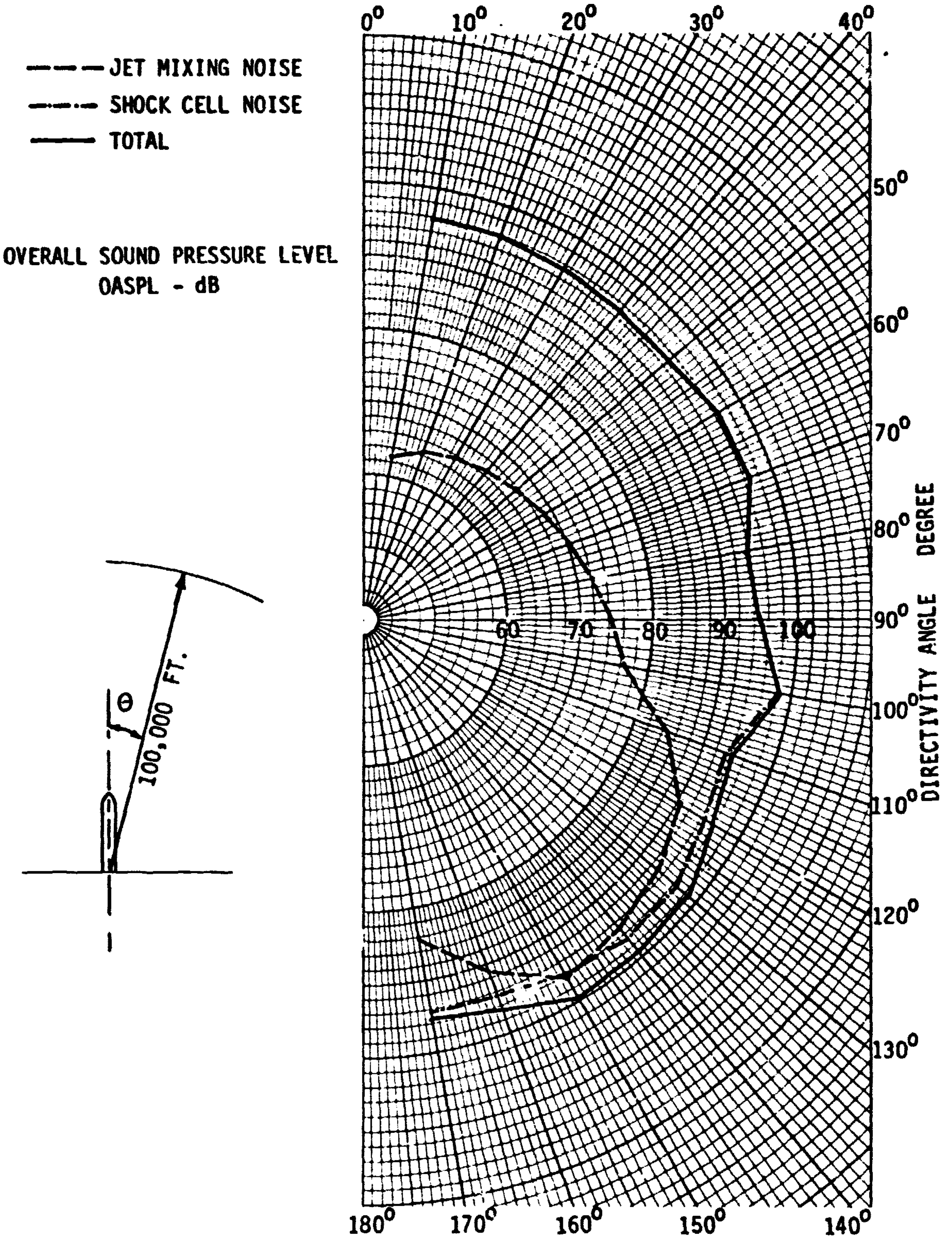


Figure 3.1-6 SPS Launch Vehicle Overall Sound Pressure Level-dB (100,000 ft. Sideline Distance)

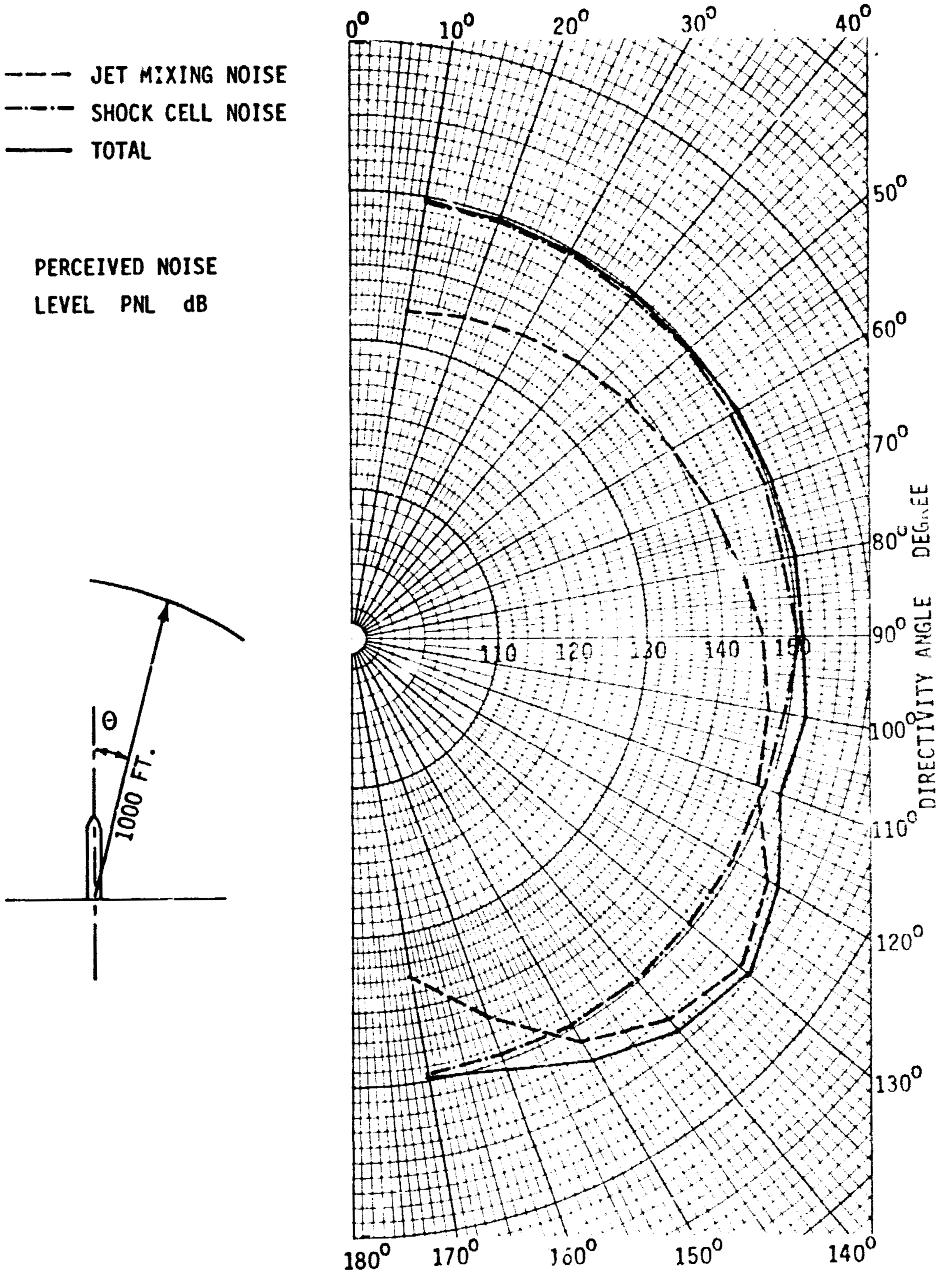


Figure 3.1-7 SPS Launch Perceived Noise Level-dB (1,000 ft. Polar Distance)

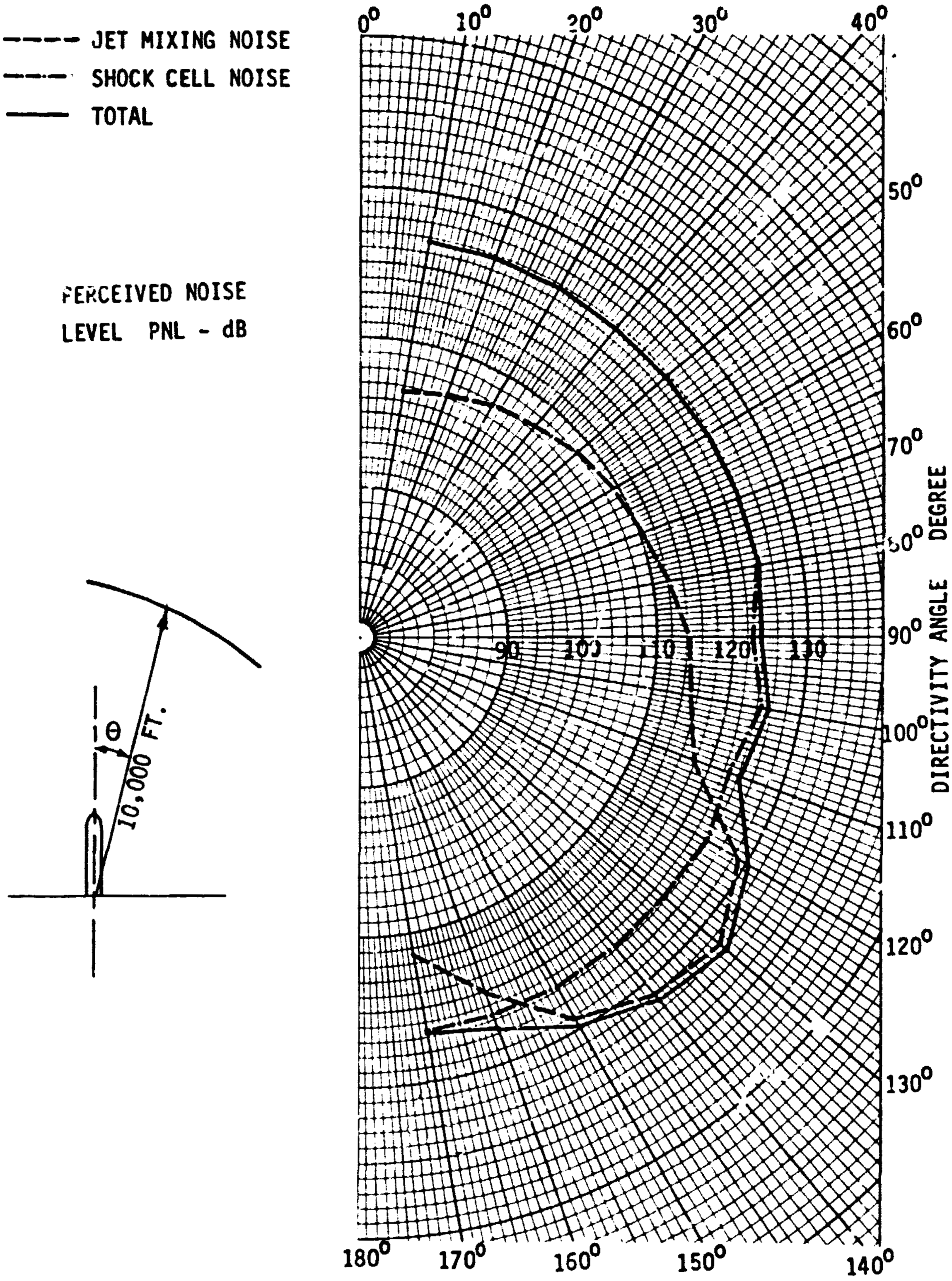


Figure 3.1-8 SPS Launch Perceived Noise Level-dB (10,000 ft. Polar Distance)

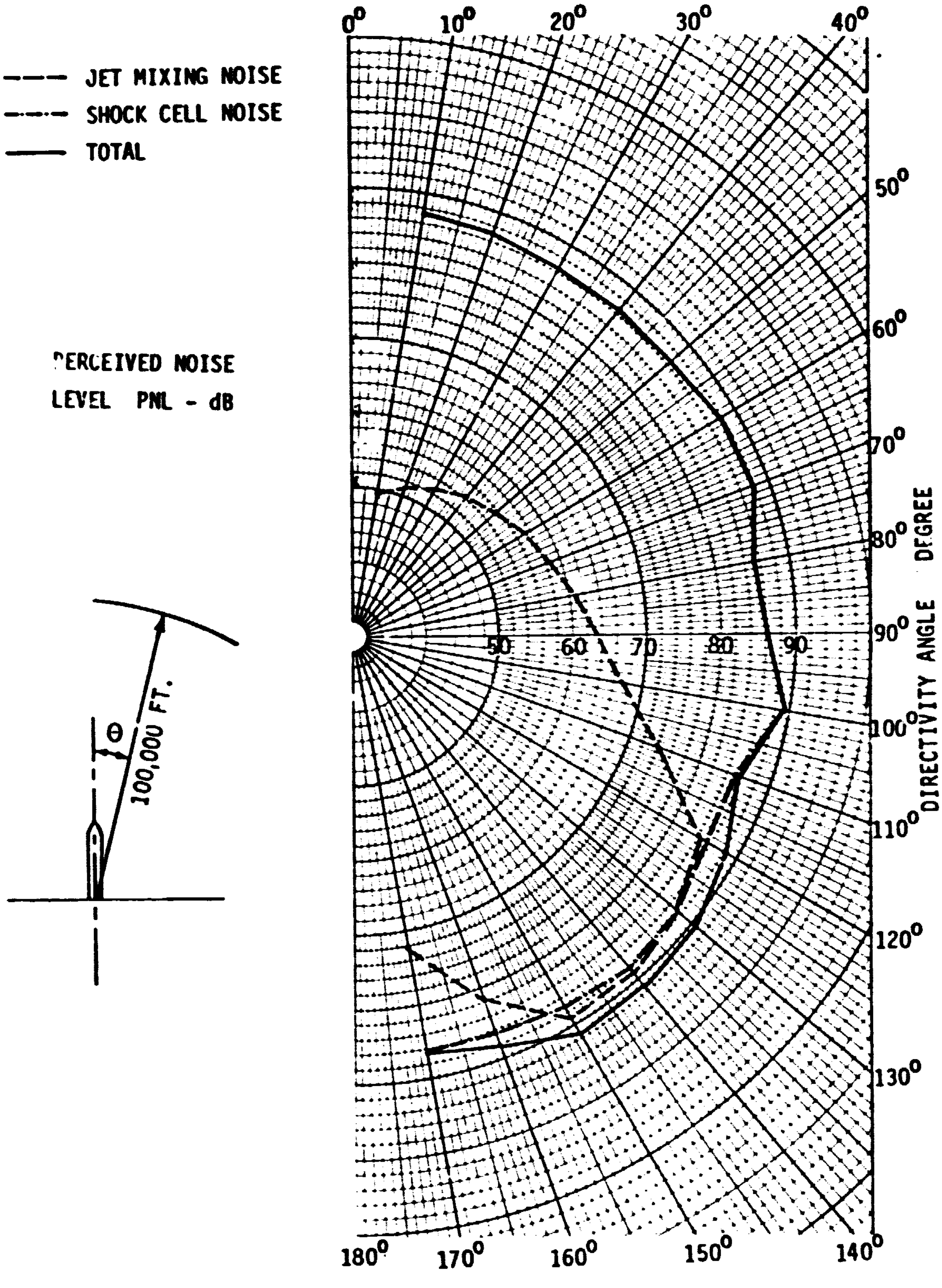


Figure 3.1-9 SPS Launch Perceived Noise Level-dB (100,000 ft. Polar Distance)

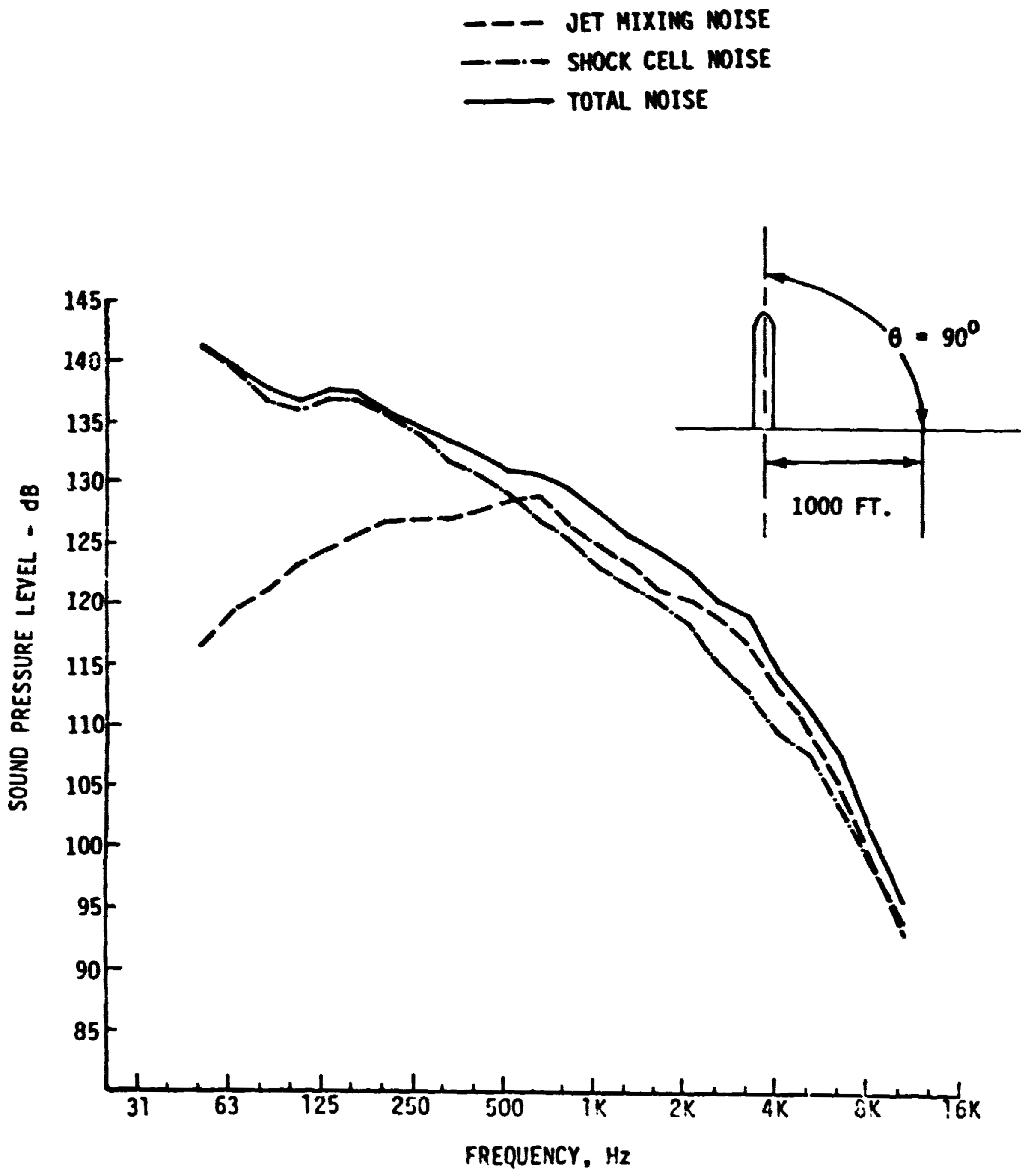


Figure 3.1-10 SPS Sideline Noise Spectrum—1,000 ft. Sideline Distance

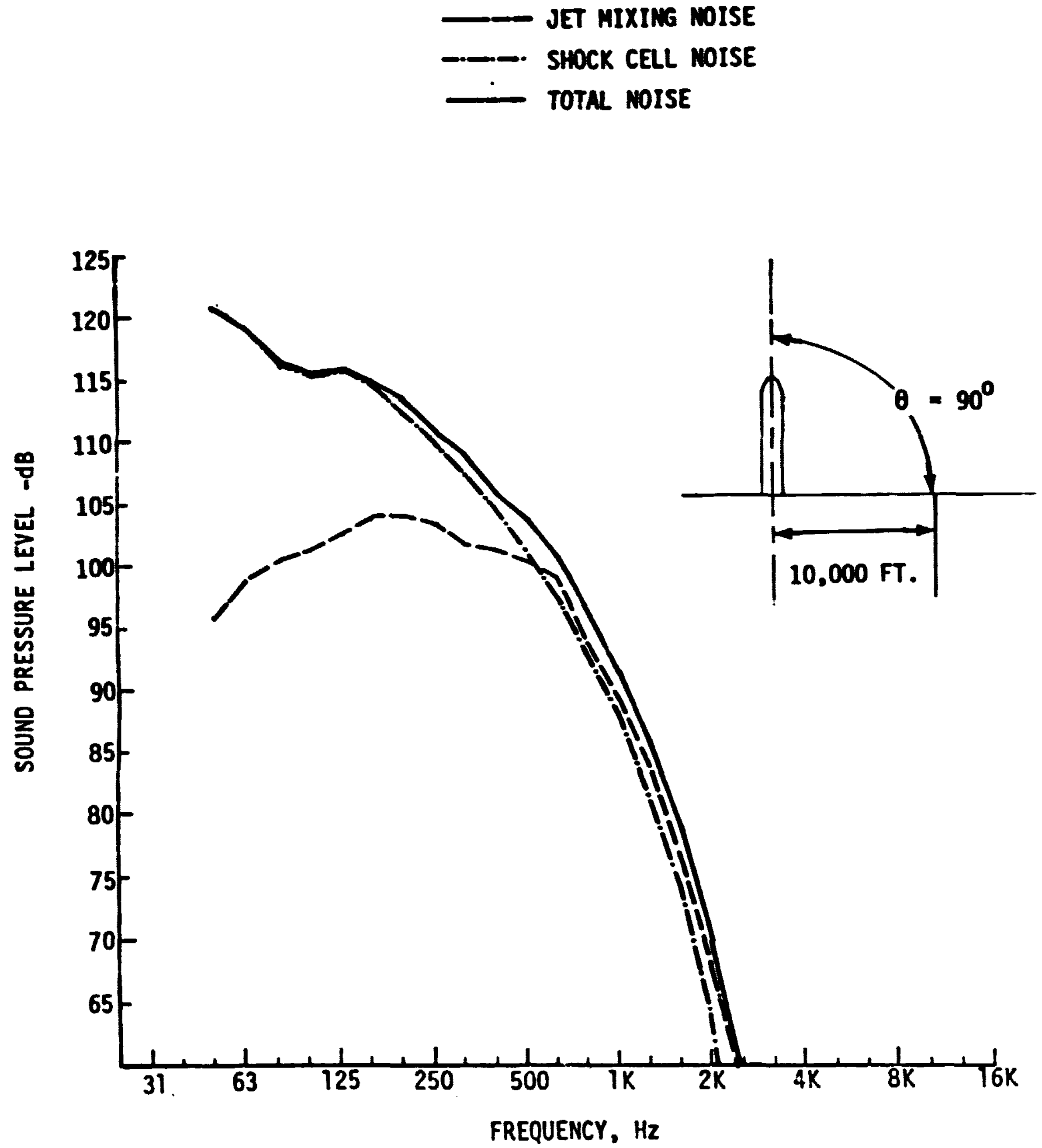


Figure 3.1-11 SPS Sideline Noise Spectrum–10,000 ft. Sideline Distance

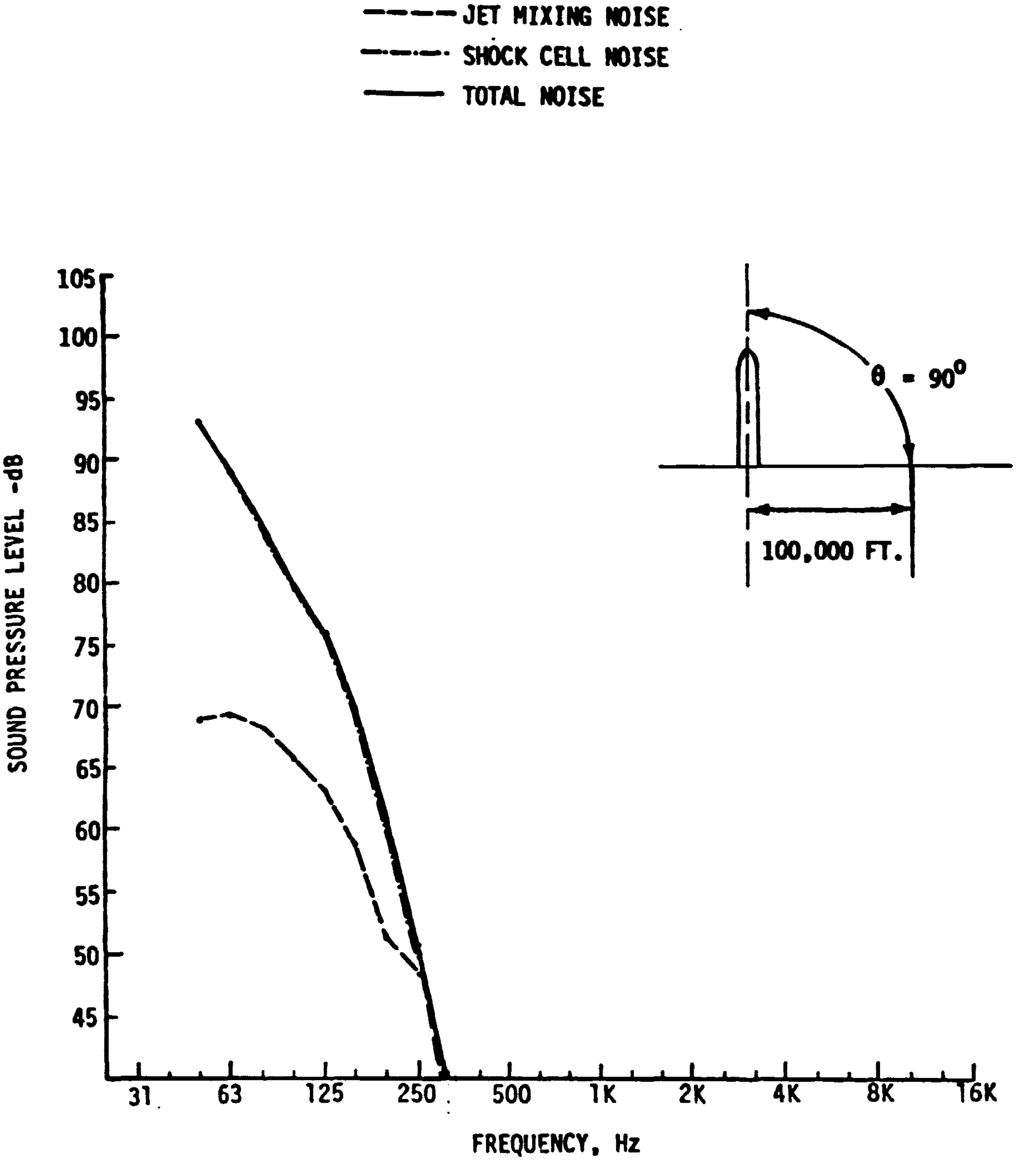


Figure 3.1-12 SPS Sideline Noise Spectrum–100,000 ft. Sideline Distance

(3) Structural Damage Claims Resulting from Acoustical Environments Developed During Static Test Firing of Rocket Engines–1972.

  (a) Data measured from about 1 Hz and higher. Highest OASPL values at about 10 Hz.

  (b) Weather plays an important part. "Less favorable" days gave higher sound pressure level values and therefore more complaints.

  (c) "Acoustic damage" is referred to as the basis for claim remuneration but what the damage consists of was never mentioned.

  (d) Number of complaints increased with increase in OASPL.

Conclusions

No information is available in these documents on the effect of the low frequency noise on humans. One document states that they feel that there is no effect on humans. Other information does not mention any words about the subject. All were concerned with glass and wall damage rather than human annoyance. The loudness (over 120 dB) of the noise was the reason for the complaints.

References

3-1 C. L. Jaeck, "Empirical Jet Noise Predictions for Single and Dual Flow Jets With and Without Suppressor Nozzles." Boeing Document No. D6-42929-1. April 1976.

3-2 M. Harper-Bourne and M. J. Fisher. "The Noise from Shock Waves in Supersonic Jets in AGARD CP-131, 1973."

3-3 Part 36–Noise Standards: Aircraft Type Certification: Federal Aviation Regulations.

..0 PRELIMINARY LAUNCH SITE SELECTION CRITERIA

Establishment of preliminary launch site selection criteria from a standpoint of sonic overpressures and launch noise required a review of present standards, reports on the impact of noise on structures (buildings, etc.) and humans. In addition to the sonic overpressure and launch noise problem, the explosive hazard of the large launch vehicles must be considered.

4.1 EXPLOSIVE HAZARD DUE TO THE PROPELLANT COMBINATIONS

The explosive hazard of the propellant combinations used in the SPS launch vehicle was estimated using the procedures of the Air Force Explosives Safety Manual (Reference 4-1). The first stage propellants include liquid oxygen (LO_2), liquid hydrogen (LH_2) and a hydrocarbon rocket propellant (RP-1). The equivalent mass of TNT for these combinations is as follows:

LO_2 + RP-1 = 20% of the loaded mass in equivalent mass of TNT
LO_2 + LH_2 = 60% of the loaded mass in equivalent mass of TNT

Using these proportions the total vehicle explosive hazard is the equivalent of 2806 metric tons (6.2×10^6 lbm) of TNT, with 51% on the first stage and 49% on the second. The predicted overpressures from an on-pad explosion are shown in Figure 4.1-1 and were developed using the methodology in Reference 4-1. The required minimum separation distances as established in Reference 4-1 for this explosion hazard is:

2840m (9330 ft) for inhabited buildings
1700m (5600 ft) for public highways

The safety manual (Reference 4-1) also provides some examples of overpressures (of short time duration) on structural elements. These effects are summarized below:

BLAST OVERPRESSURE EFFECTS

Structural Element	Failure	PSI Side On Overpressure
Aircraft	Damage to control surfaces and other minor repair	1.0–2.0
	Major repair	2.0–3.0
Glass windows, large and small	Shattering occasional frame failure	0.5–1.0
Corrugated asbestos siding	Shattering	1.0–2.0
Corrugated aluminum or steel paneling	Connection failure followed by buckling	1.0–2.0
Brick wall panel 8 to 12 in. thick (not reinforced)	Shearing and flexure failure	7.0–8.0
Wood siding panels standard housing construction	Usual failure at main connections allowing panel to be blown in	1.0–2.0
Concrete or cinderblock wall panel 8 to 12 in. thick (not reinforced)	Shattering of the wall	2.0–3.0
Steel frame buildings	Sides blown in distortion	8.6
Steel towers	Blown down	30.0

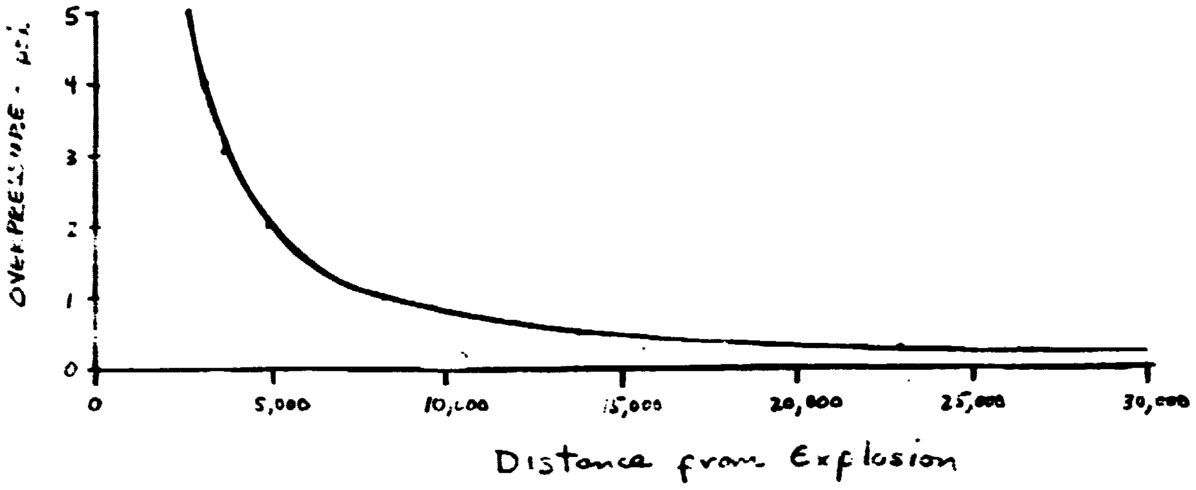


Figure 4.1-1 Predicted Overpressures per an On-Pad Explosion

Overpressures in the range of 1 to 2 psi are sufficient to dish in panels and buckle stiffeners/stringers on adjacent vehicles. Therefore, using a *minimum pad separation distance of 2 miles will limit the overpressures to less than 0.75 psi on adjacent pads and will minimize any potential damage.*

4.2 EFFECTS OF SONIC OVERPRESSURES

The effects of sonic overpressures on humans, due to the operation of supersonic aircraft structures, etc., has been investigated by many researchers in the past. An overall summary to the effects can be found in Reference 4-2, "Sonic Boom Literature Survey." The following paragraphs will summarize some of these findings.

Human Effects

Transient overpressures of considerable magnitude can be experienced under certain circumstances without significant discomfort. For example, the overpressures inside a car when the door is closed are up to 245N/m^2 (4 psf) for standard sedans and station wagons up to 425 N/m^3 (8.5 psf) for compact cars. Overpressures of 600 N/m^2 (12 psf) have been measured in public viewing areas during firework displays.

Limits for physical damage to humans due to sonic booms have been reported by H. E. von Gierke (Reference 4-3). A summary of these results are shown below:

(1) Rupture of the tympanic membrane
- o None expected below 720 #/ft^2
- o None observed up to 144 #/ft^2

(2) Aural pain
- o None observed up to 144 #/ft^2

(3) Short temporary fullness, tinnitus
- o Reported above 95 #/ft^2

(4) Hearing loss–temporary
- o None measured
  - – 3-4 hours after exposure up to 120 #/ft^2
  - – immediately after booms up to 30 #/ft^2

(5) Stapedectomy
- o No ill effects reported after booms up to 3.5 #/ft^2

(6) Hearing aids
- o No ill effects reported after booms up to 3.5 #/ft^2

The most probable objection by humans to sonic boom is the behavioral effects rather than physical damage, since the anticipated overpressure levels are much lower than those which can cause damage or discomfort.

The International Civil Aviation Organization (ICAO) sonic boom panel published a report (Reference 4-4) on the behavioral effects on humans due to sonic boom. The observations noted by the ICAO panel are shown below:

Sonic Boom Overpressure N/m^2	(PSF)	Behavioral Effects
16	(0.33)	– Orienting, but no startle response – Eyeblink response in 10% of subjects – No arm/hand movement
30 to 111	(0.63 to 2.32)	– Mixed pattern of orienting and startle responses – Eyeblink in about half of the subjects – Arm/hand movements in about a quarter of subjects; no gross bodily movements
130 to 310	(2.72 to 6.47)	– Predominant pattern of startle response – Eyeblink response in 90% of subjects – Arm/hand movements in more than half of the subjects; gross body flexion in about a fourth of subjects
340 to 640	(7.1 to 13.37)	– Arm/hand movements in more than 90% of subjects

The Oklahoma City test (Reference 4-2) for the 6 month period of February to July 1964 where the populace was exposed to 1253 sonic booms between 1.13 to 1.60 psf in magnitude resulted in about 73% to 90% feeling they could accept eight booms per day of this magnitude. A number of the people who actually complained to the FAA, during this test series, were the most intensely annoyed and most hostile toward the SST (Supersonic Transport).

Structural Damage Effects

Sonic booms of varying magnitude can cause various degrees of damage to dwellings and other structures. A number of test series have been conducted to measure the effect of sonic boom at varying levels of overpressure on selected structures and materials. One of these test series was conducted at the White Sands Missile Range from November 18, 1964 through February 15, 1965 and is reported in Reference 4-5. The observed results of this test program has provided the data to establish 1) the maximum safe predicted or recorded overpressure for representative building materials and bric-a-brac other than glass (see Table 4.2-1) and 2) the maximum safe predicted or measured average ground overpressure for plate and window glass (see Figure 4.2-1).

Recommended Sonic Overpressure Criteria

A maximum allowable overpressure of 2.0 psf outside of the government reservation perimeter shall not be exceeded in populated areas for SPS launch vehicle operations. The Space Shuttle is expected to produce a 2.1 psf sonic overpressure during a typical return to Kennedy Space Center.

Table 4.2-1 Maximum Safe Predicted[1] or Recorded Peak Overpressures–for Representative Building Materials and Bric-a-Brac–Other Than Glass

	White Sands	
Material	Minor[2]	Major[3]
Interior Walls and Ceilings		
1. plaster on wood lath	3.3	5.6
2. plaster on gyp lath	7.5	16.
3. plaster on expanded metal lath	16.	16.
4. plaster on concrete block	16	16.
5. gypsum board (new)	16	16.
6. gypsum board (old)	4.5	16.
7. nail popping (new)	5.4	16.
8. bathroom tile (old)	4.5	8.5
9. damaged suspended ceiling (new)	4.0	16
10. stucco (new)	5.0	16
Bric-a-brac		
1. extremely precariously placed or unstable items	NA	3.1
2. normally stable or placed items	NA	5.6
Miscellaneous		
1. brick stacked	19	–
2. glass door loosened	19	–
3. twisted mullions	9	–
4. popped molding	19	–

1. Less than one chance in 10,000 when within five miles of flight track. This value corresponds to a 99.99 percent confidence that damage will not occur.

2. Small (less than three inches) hairline cracks extensions or pre-damaged paint chipping or spalling.

3. Falling plaster or tile, etc.

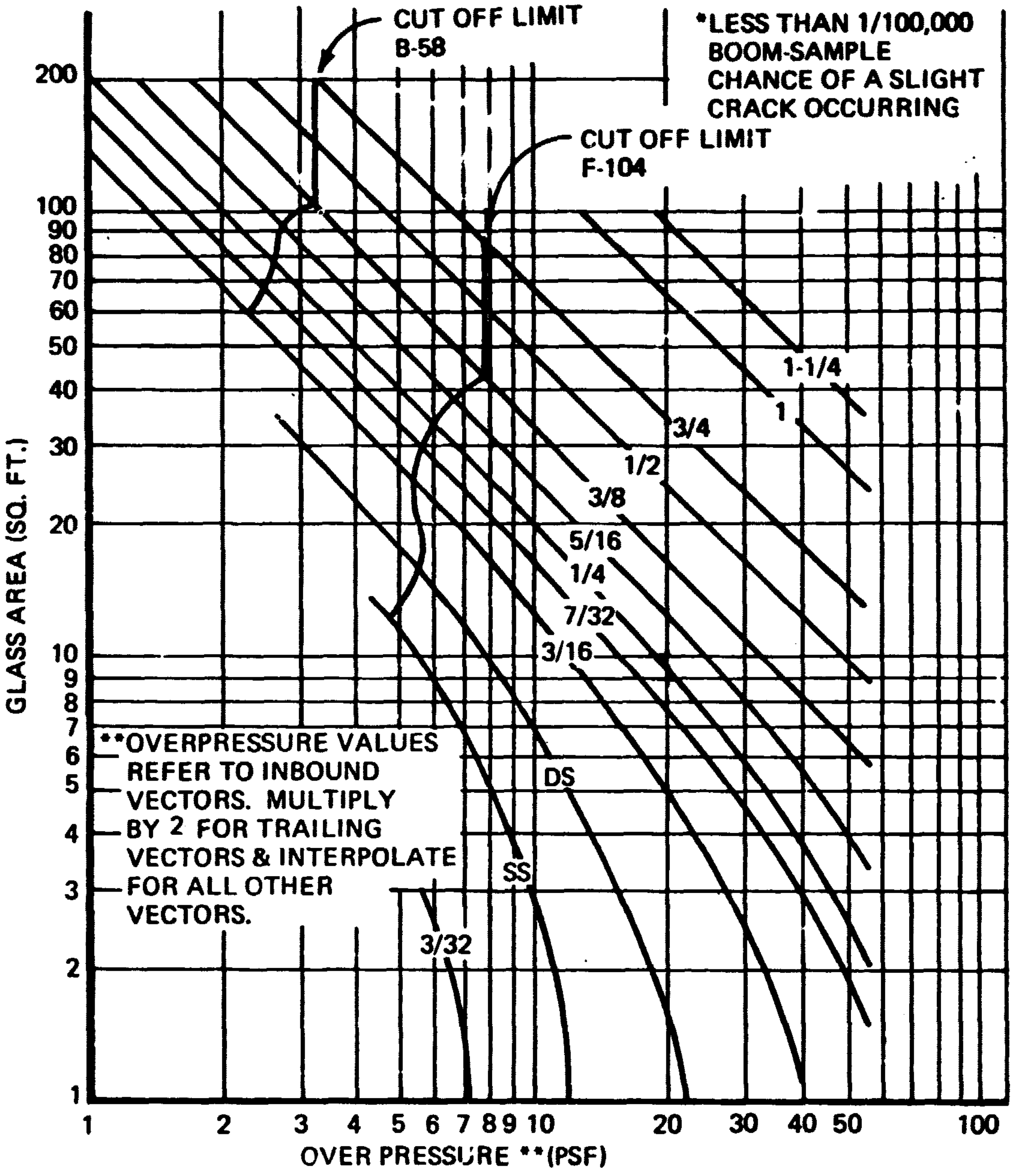


Figure 4.2-1 Maximum Safe Predicted or Measured Average Ground Overpressure for Plate and Window Glass

4.3 LAUNCH NOISE EFFECTS

The Occupational Safety and Health Administration (OSHA) noise standards for exposure levels and allowable duration are shown in Table 4.3-1. A maximum of 140 dB peak sound noise level is acceptable for a very short duration (impact noise). The safe limit appears to be 147 dB for building damage as a result of a literature survey. A perceived noise level (PNL) of 108 dB for habitation is the maximum allowable for commercial aircraft in any category on takeoff or landing approach in the United States (Part 36–Noise Standards: Aircraft Type Certification: Federal Aviation Regulations). The 108 dB PNL levels assure a 10 second duration for the noise level to decay 10 dB from the peak.

References

4-1 Air Force Manual 127-100, Explosives Safety Manual, dated October 3, 1975

4-2 Sonic Boom Literature Survey, Volumes 1 and 2, Report No. FAA-RD-73-129-1 and -2, prepared by Larry J. Runyan and Edward J. Kane (Boeing Commercial Airplane Company), September 1973

4-3 Effects of Sonic Boom on People: Review and Outlook, Henning E. von Gierke, Proceedings of the Sonic Boom Symposium, The Journal of the Acoustical Society of America, Vol. 39, No. 5, Part 2, 1966, pp S43-S50

4-4 Report on the Sonic Boom Phenomenom, The Ranges of Sonic Boom Values Likely to be Produced by Planned SST's, and the Effects of Sonic Booms on Humans, Property, Animals, and Terrain–Attachment A of ICAO Document 8894, SBP/II, Report of the Second Meeting of the Sonic Boom Panel, Montreal, October 12 to 21, 1970

4-5 The Effects of Sonic Boom on Structural Behavior–A Supplementary Analysis Report, John H. Wiggins, Jr., Federal Aviation Agency SST Report No. 65-18, October 1975

Table 4.3-1 OSHA Noise Standards for Occupational Noise Exposure

Sound Level–dB [1]	Allowable Exposure Time (hours)
115 dB	1/4 hour or less
110 dB	1/2 hour
105 dB	1 hour
102 dB	1-1/2 hours
100 dB	2 hours
97 dB	3 hours
95 dB	4 hours
92 dB	6 hours
90 dB	8 hours

[1] If these levels must be exceeded minimization procedures must be undertaken (ear plugs, acoustic helmets, etc.)

5.0 SUMMARY AND RECOMMENDATIONS

Summary

The SPS launch vehicles are expected to produce peak sonic overpressures of 25 psf during ascent primarily due to the plume effect and total thrust of the vehicle. These peak pressures occur downrange about 30 miles from the launch site due to the focusing phenomena. Winged vehicle concepts are expected to produce a peak overpressure in the 3 to 4 psf range during reentry. Ballistic recoverable vehicles are expected to produce reentry overpressures of between 4 and 11 psf. It is expected that the launch noise will be 140 PNL dB in the vicinity of the launch pad and 108 PNL dB at a distance of 32,000 ft from the pad. The explosive hazard due to the on-board propellant combinations is expected to produce an overpressure less than 0.75 psi two miles away from the launch pad.

Based on the above, the following criteria are proposed for inhabited areas along the ground track.

(1) Maximum allowable overpressure of 2.0 psf

(2) Maximum noise level of 108 PNL dB

In addition, it is recommended that a launch pad separation distance of at least 2 miles be used.

Recommendations

In order to enhance the confidence level in the accuracy of the predictions and the ef[illegible]ic overpressure and noise the following items are recommended for future effort:

(1) The accuracy of the sonic boom overpressure estimates made in this study could [illegible] improved upon by conducting a wind tunnel test using models of the SPS vehicles. The results of this test would be near-field sonic boom pressure signatures which could then be extrapolated to flight coordinations. This is a well-known technique used by NASA (Reference 2-1) to predict the Space Shuttle sonic boom characteristics.

(2) It is recommended that a detailed study be undertaken to review the validity of the analytical tools currently available in terms of existing rocket noise data. This study should include review of data quality and measurement technology by which such data had been acquired. Extrapolation techniques should be verified where prediction techniques based on supersonic transport aircraft engine noise are extended to the relatively high velocity range of rocket engines.

(3) A study should also be undertaken to establish subjective noise limits to be set for valid assessment of rocket noise on human subjects. Building damage assessment should also be improved by a comprehensive assessment of past experience.