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LIQUID BOOSTER MODULE (LBM) PLUME FLOWFIELD MODEL

FINAL REPORT

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Marshall Space Flight Center, Alabama 35812

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FOREWORD

This document presents the results of work performed by Lockheed's Huntsville Research & Engineering Center. This work was carried out under Contract NAS8-33976, "Liquid Booster Module (LBM) Plume Flowfield Model," for NASA-Marshall Space Flight Center. The NASA Contracting Officer's Representative for this study was Dr. T.F. Greenwood, ED33. This document, along with previous delivered reports, constitutes fulfillment of Contract NAS8-33976.

SUMMARY

This report describes the analysis and exhaust plume structure of the Liquid Booster Module (LBM) motors at sea level through LBM separation. A complete definition of the LBM plume is important for many Shuttle design criteria. The exhaust plume shape has a significant effect on the vehicle base pressure. The LBM definition is also important to the Shuttle base heating, aerodynamics and the influence of the exhaust plume on the launch stand and environment. For these reasons and perhaps others, a knowledge of the LBM exhaust plume characteristics is necessary.

This document presents a definition of the sea level LBM plume as well as at several points along the Shuttle trajectory to LBM burnout.

CONTENTS

1. ANALYSIS AND CALCULATION PROCEDURE

This section discusses the methodology and calculational procedures which were used to define the LBM exhaust plume characteristics. The assessment of the LBM plume effects on the Space Shuttle base radiation is given in Ref. 1.

1.1 INVISCID NOZZLE/PLUME

The inviscid nozzle and plume solutions were calculated using the Lockheed-Huntsville Method-of-Characteristics (MOC) Program (Ref. 2). The nozzle/plume solution was initiated at the throat assuming a Mach number of 1.01, an oxidizer to fuel ratio of 2 and a chamber pressure of 809 psia. The LBM motor is the Aerojet LR87-11 with a 15:1 area ratio. The nozzle contour is given in Table 1. The propellants of this motor are N_2O_4/MMH. The chemistry of the propellant was taken to be equilibrium to a pressure of 32 psia at which point the exhaust products were assumed to be frozen. The thermodynamic properties of the combustion products were determined using the NASA-Lewis TRAN72 code (Ref. 3). A tabulation of the NASA-Lewis results which was used by the MOC program in the inviscid analysis are presented in Table 2.

1.2 VISCOUS PLUME

A viscous plume was calculated at sea level only. The viscous LBM plume was calculated using the LAMP program (Ref. 4). The method used to calculate the viscous plume is the same as described in Refs. 5 and 6 except that the jet properties were determined be expanding the average flow properties at the exit to 1 atm using the method of Sukanek (Ref. 7). The viscous results were then superimposed on the inviscid plume out to approximately 37 ft from the exit at which point the plume became totally viscous.

Table 1
LIQUID BOOSTER MODULE ENGINE NOZZLE CONTOUR

Axial Distance from Throat (in.)	Radial Coordinate (in.)	Wall Angle (rad.)
.00000	.76260+01	.00000
.15964+00	.76288+01	.34907-01
.31948+00	.76372+01	.69813-01
.47874+00	.76511+01	.10472+00
.63741+00	.76706+01	.13963+00
.79531+00	.76956+01	.17453+00
.95223+00	.77261+01	.20944+00
.11080+01	.77620+01	.24435+00
.12624+01	.78034+01	.27925+00
.14153+01	.78502+01	.31416+00
.15664+01	.79022+01	.34907+00
.17157+01	.79595+01	.38397+00
.18628+01	.80220+01	.41888+00
.20077+01	.80895+01	.45379+00
.20729+01	.81219+01	.46967+00
.90480+01	.11662+02	.46967+00
.97570+01	.12022+02	.46757+00
.10478+02	.12385+02	.46408+00
.11209+02	.12748+02	.45815+00
.11956+02	.13116+02	.45448+00
.12706+02	.13480+02	.44942+00
.13477+02	.13849+02	.44366+00
.14246+02	.14212+02	.43755+00
.15043+02	.14582+02	.43145+00
.15840+02	.14946+02	.42464+00
.16646+02	.15307+02	.41801+00
.17478+02	.15673+02	.41137+00
.18307+02	.16032+02	.40474+00
.19139+02	.16386+02	.39828+00
.20012+02	.16749+02	.39165+00
.20881+02	.17105+02	.38502+00
.21748+02	.17453+02	.37874+00
.22629+02	.17800+02	.37210+00
.23551+02	.18157+02	.36530+00
.24954+02	.18678+02	.35360+00
.26000+02	.19060+02	.34662+00
.28000+02	.19768+02	.33336+00
.30000+02	.20446+02	.32097+00
.32000+02	.21098+02	.30927+00
.34000+02	.21725+02	.29758+00
.36000+02	.22327+02	.28728+00
.38000+02	.22908+02	.27733+00
.40000+02	.23471+02	.26808+00
.43000+02	.24272+02	.25412+00
.46000+02	.25029+02	.24120+00
.49000+02	.25747+02	.22846+00
.53000+02	.26643+02	.21223+00
.57000+02	.27471+02	.19635+00
.61000+02	.28234+02	.18099+00
.65000+02	.28934+02	.16581+00
.69150+02	.29595+02	.15010+00

Table 2

LIQUID BOOSTER MODULE ENGINE EQUILIBRIUM CHEMISTRY THERMODYNAMICS

S (ft^2/sec^2 ^{o}R)	V (ft/sec)	R (ft^2/sec^2 ^{o}R)	GAMMA	T (^{o}R)	P (psfa)
.00000					
	.00000	.22071+04	.11416+01	.60264+04	.11650+06
	.37646+04	.21821+04	.11406+01	.56944+04	.67137+05
	.42037+04	.21760+04	.11406+01	.56113+04	.58248+05
	.62309+04	.21409+04	.11454+01	.50882+04	.23299+05
	.67622+04	.21303+04	.11503+01	.48969+04	.16642+05
	.72984+04	.21207+04	.11585+01	.46902+04	.11650+05
	.83870+04	.21058+04	.11928+01	.41222+04	.46598+04
	.95707+04	.21058+04	.12333+01	.31919+04	.11650+04
	.10497+05	.21058+04	.12549+01	.23290+04	.23299+03
	.10795+05	.21058+04	.12664+01	.20182+04	.11650+03
	.11317+05	.21058+04	.12967+01	.14175+04	.23299+02
	.11485+05	.21058+04	.13099+01	.12063+04	.11650+02
	.11776+05	.21058+04	.13361+01	.81387+03	.23299+01
.62264+04					
	.00000	.22652+04	.11252+01	.54995+04	.72000+04
	.36297+04	.22349+04	.11232+01	.52485+04	.41753+04
	.40774+04	.22271+04	.11228+01	.51822+04	.36000+04
	.60623+04	.21818+04	.11228+01	.47364+04	.14400+04
	.66069+04	.21669+04	.11241+01	.46447+04	.10286+04
	.71197+04	.21521+04	.11269+01	.44943+04	.72000+03
	.82162+04	.21212+04	.11465+01	.40901+04	.28800+03
	.94197+04	.21212+04	.12359+01	.31599+04	.72000+02
	.10356+05	.21212+04	.12580+01	.22989+04	.14400+02
	.10656+05	.21212+04	.12697+01	.19893+04	.72000+01
	.11180+05	.21212+04	.13003+01	.13925+04	.14400+01
	.11348+05	.21212+04	.13134+01	.11833+04	.72000+00
	.11639+05	.21212+04	.13391+01	.79597+03	.14400+00

2. RESULTS

2.1 SEA LEVEL LBM PLUME

Figures 1 through 5 present the flow properties of the inviscid/viscous sea level LBM plume. Figures 1 through 4 present radial distributions of flow properties at various axial stations downstream of the nozzle exit plane. Figure 1 presents Mach number distribution. Figure 2 shows static pressure distribution. Figure 3 gives static temperature distribution, and Fig. 4 shows pitot total pressure distribution. Figure 5 presents the centerline pitot pressure distribution from 50 to 500 ft from the nozzle exit plane.

2.2 ALTITUDE PLUME EFFECTS

Figures 6 through 9 present the results of altitude variations on the LBM exhaust plume. Plumes were generated at 50,000, 100,000, 145,000 ft (SRB separation) and 160,000 ft (.BM cutoff). Each plume was generated assuming that the plume boundary conditions were quiescent (back pressure = ambient pressure) as well as the inclusion of the dynamic pressure contribution. For applications in which the near field plume is the design driver then the quiescent plume plume should be used. For plume problems that are dominated by far downstream properties than the plume that includes the dynamic pressure contribution in its boundary conditions should be used. Figure 6 presents the plume boundary shapes and shock locations at each of four altitudes for a single LBM exhaust plume assuming the freestream static pressure as a boundary condition. Figure 7 shows the same data except the freestream dynamic pressure is included in the boundary conditions. Figure 8 presents the plume boundary shapes and shock locations for an equivalent LBM motor assuming the freestream static pressure as a boundary condition. The LBM concept uses two motors. An equivalent motor is a single engine having the same mass flow as two engines. The

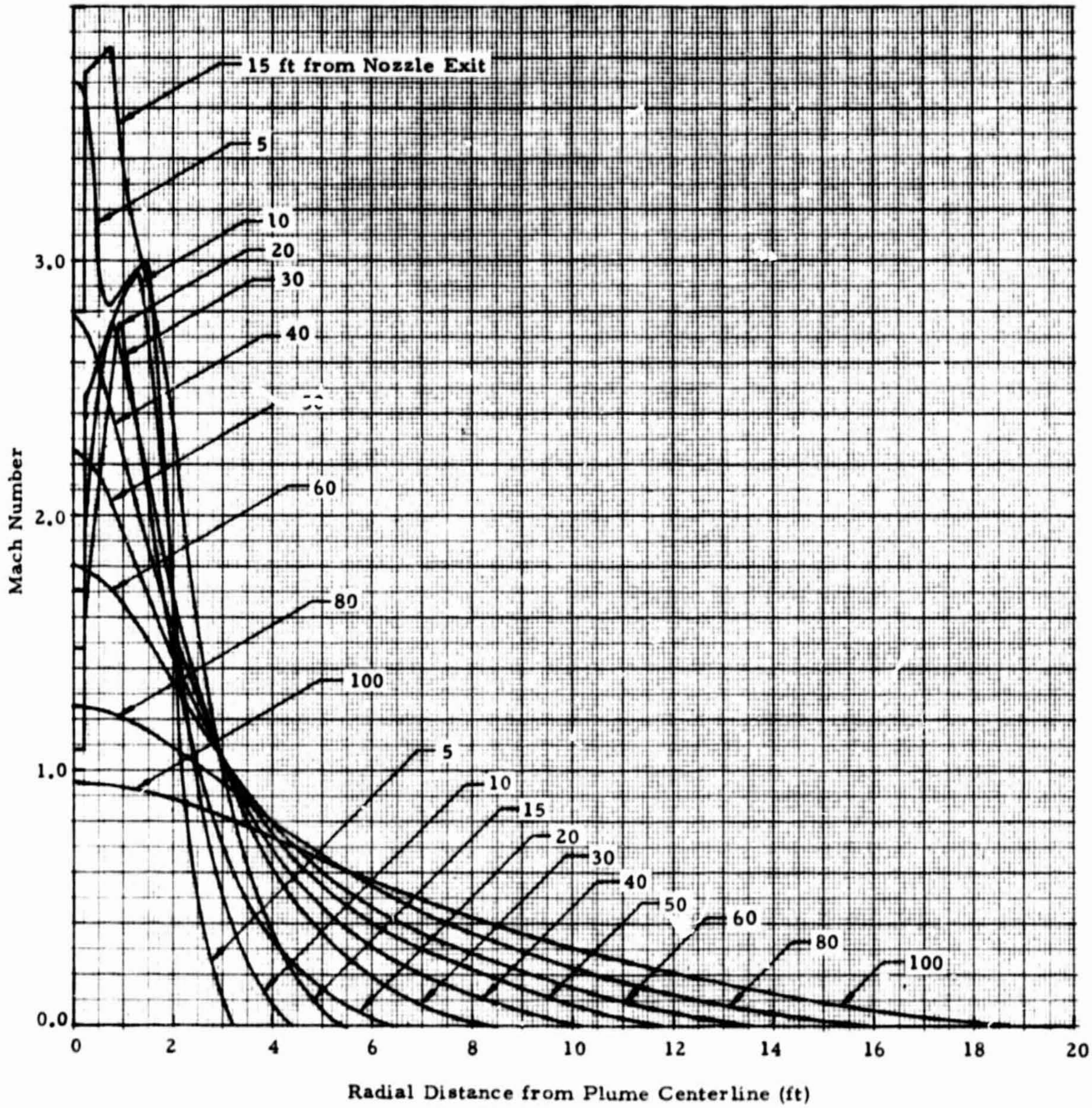

Fig. 1 - Sea Level Liquid Booster Module Engine Exhaust Plume Radial Mach Number Distribution

Note: Beyond 37 ft the static pressure
is constant at 1 atm.

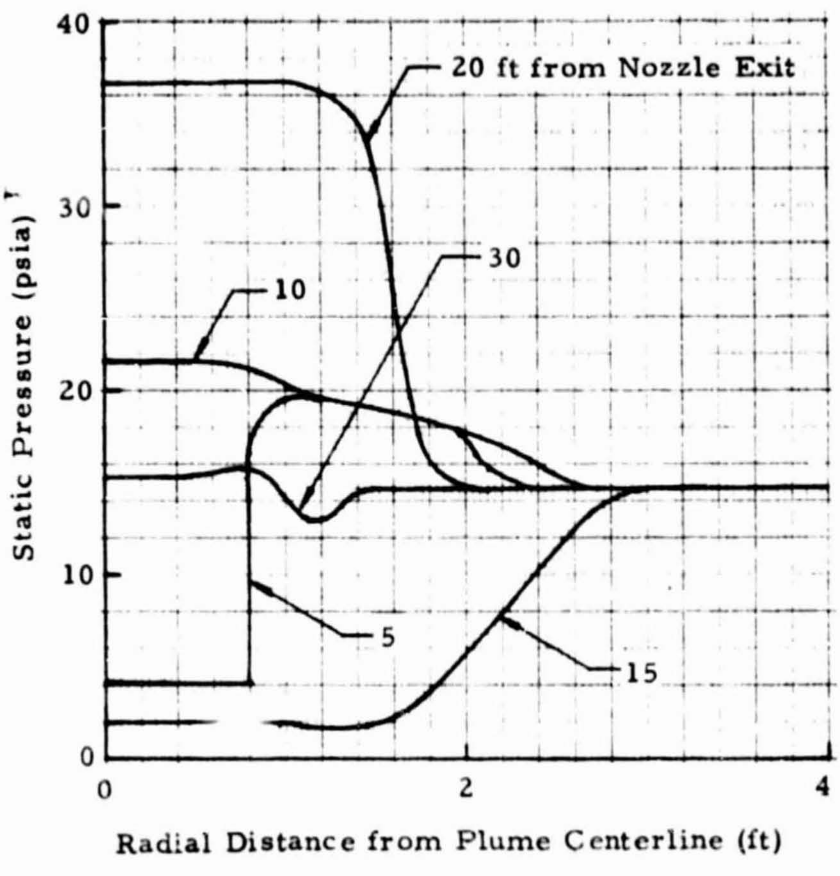

Fig. 2 - Sea Level Liquid Booster Module Engine Exhaust Plume
Radial Static Pressure Distribution

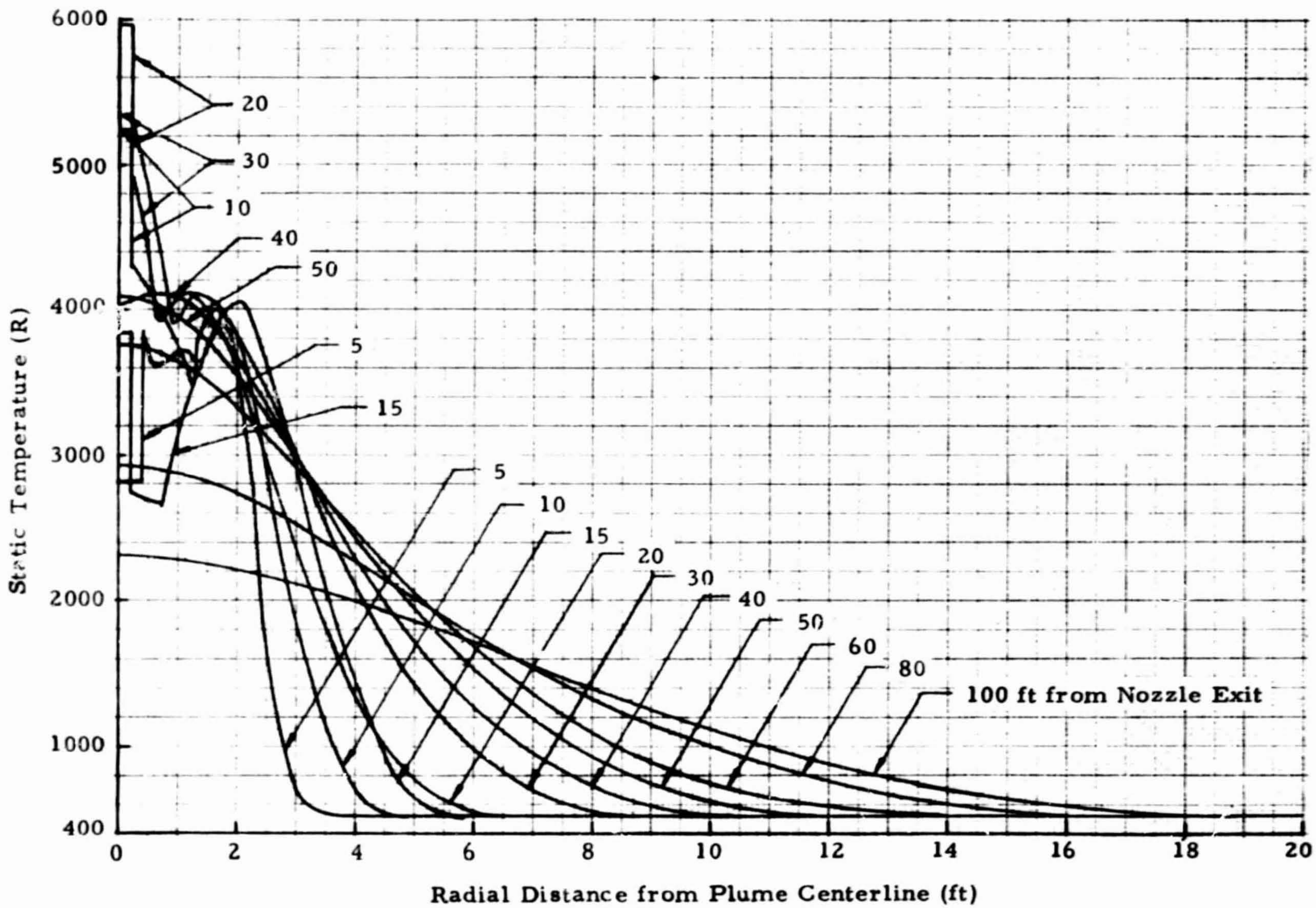

Fig 3 - Sea Level Liquid Booster Module Engine Exhaust Plume Radial Static Temperature Distribution

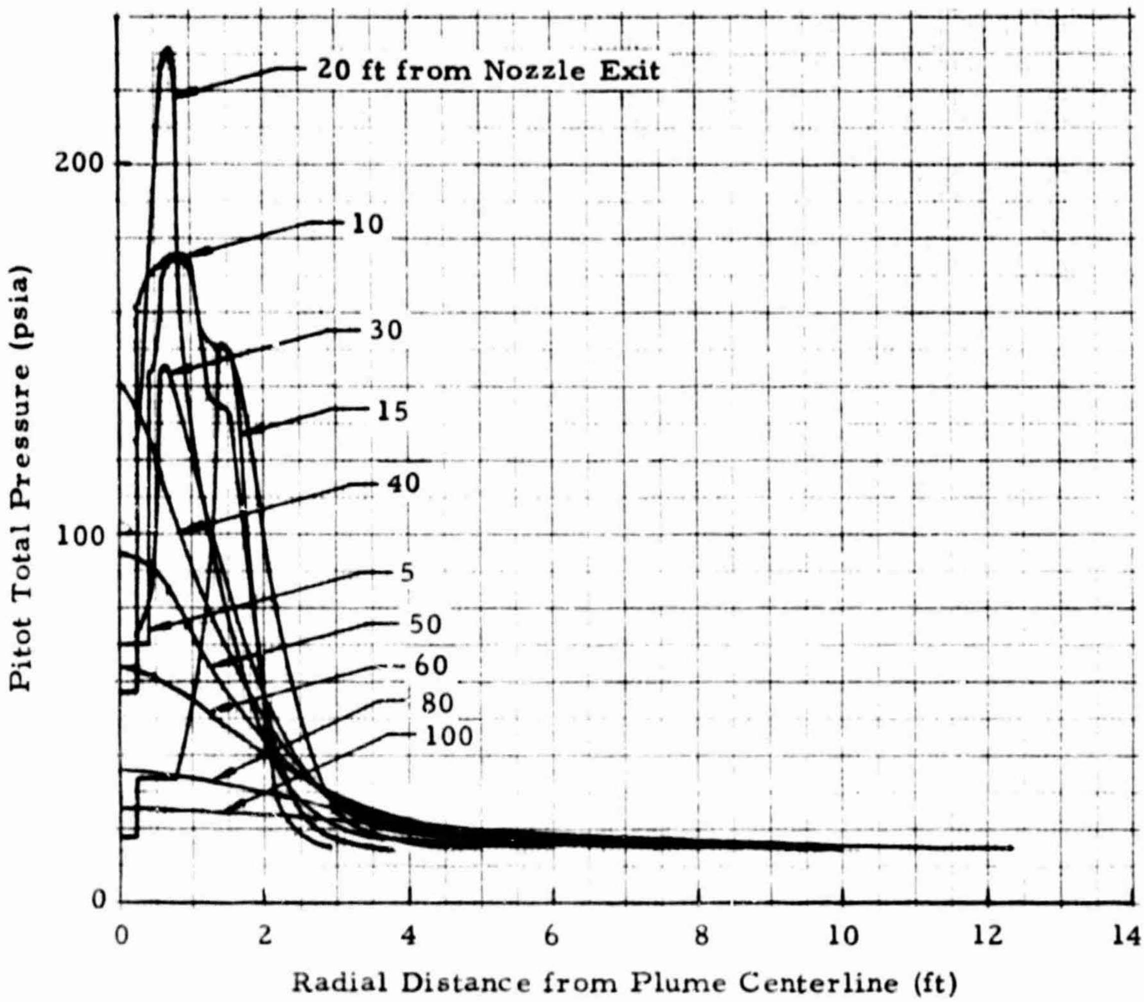

Fig. 4 - Sea Level Liquid Booster Module Engine Exhaust Plume Radial Pitot Total Pressure Distributions

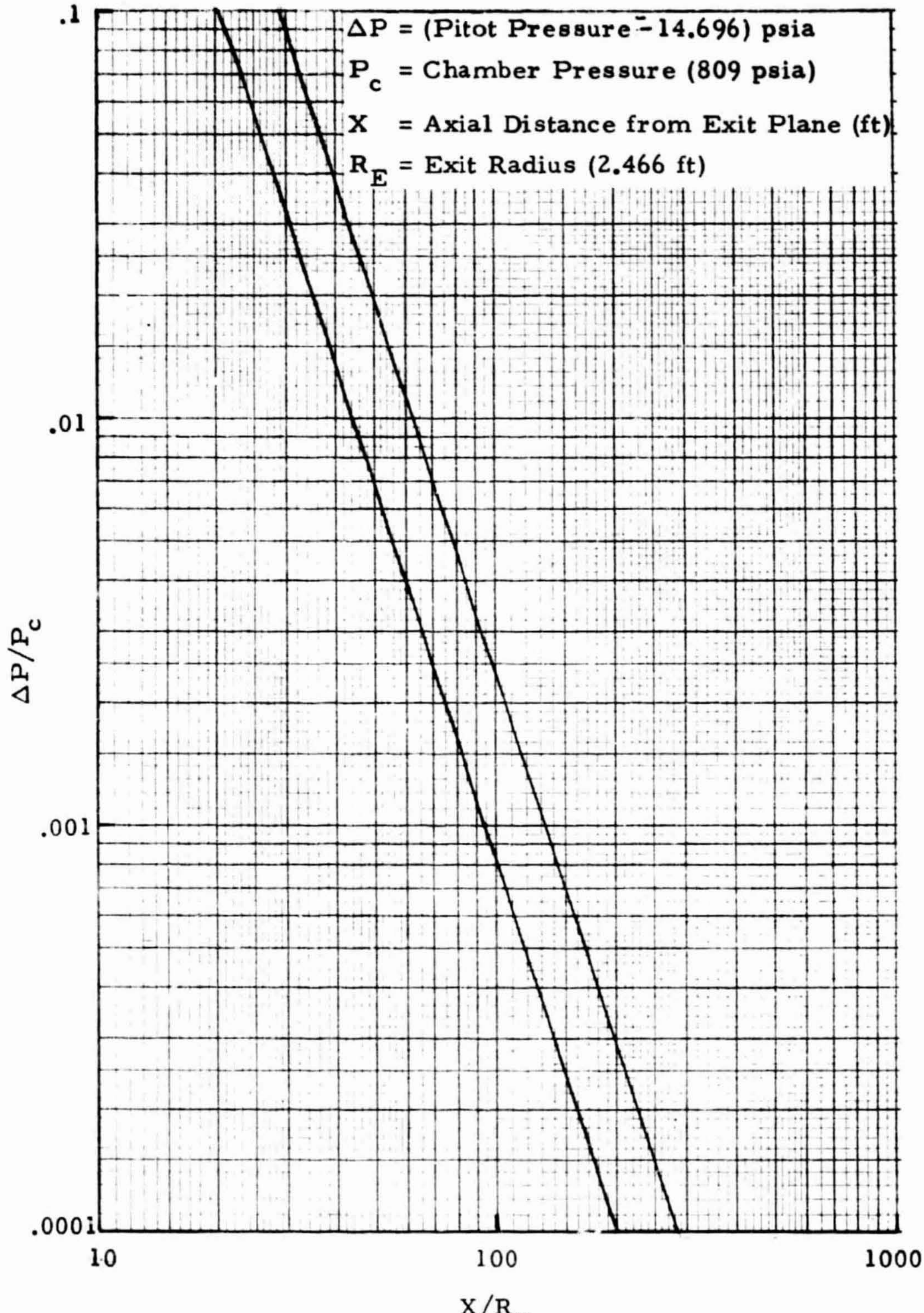

Fig. 5 - Sea Level Liquid Booster Module Engine Centerline Pitot Total Pressure Distribution

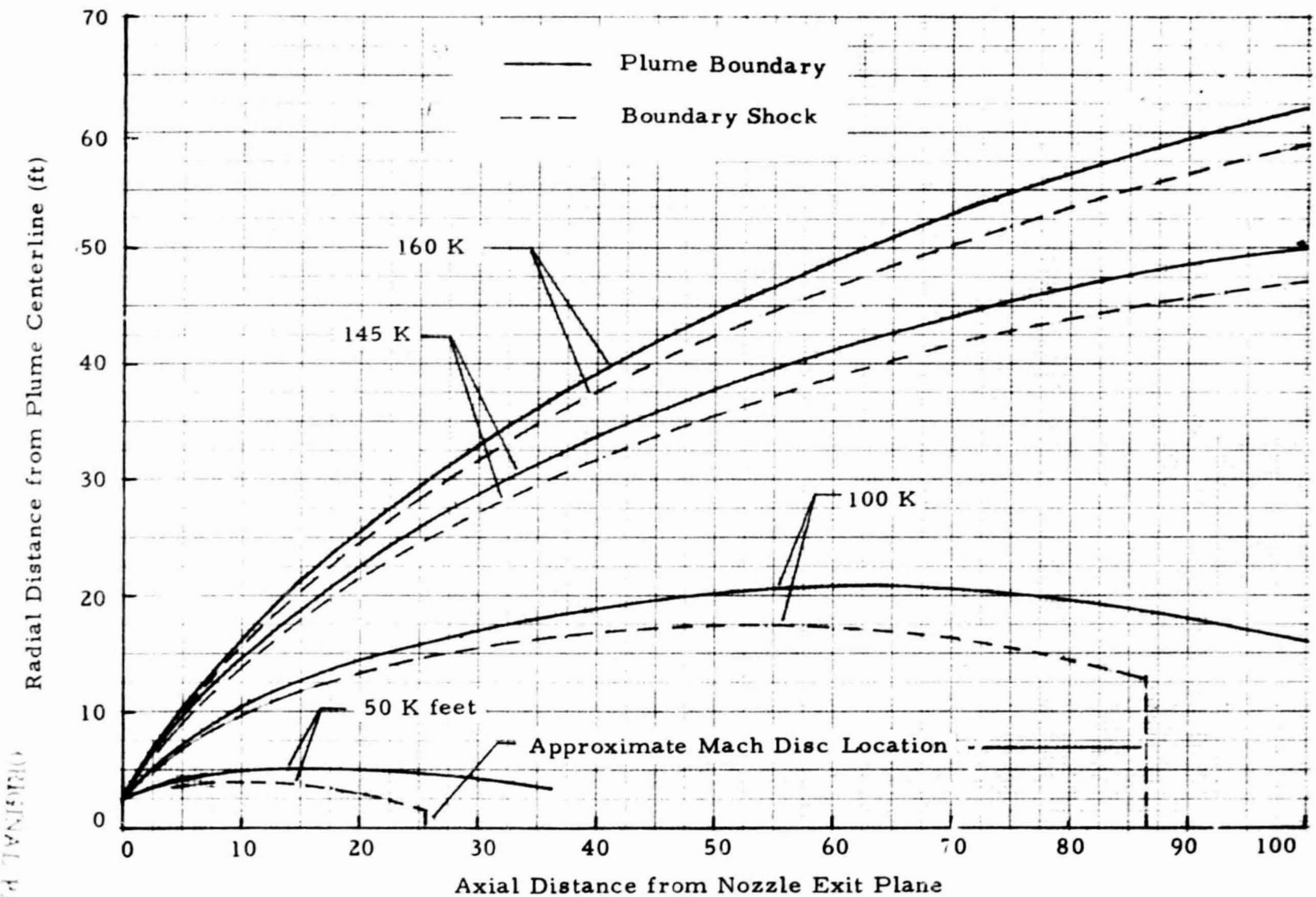

Fig. 6 - Liquid Booster Module Single Engine Plume Boundaries at Several Altitudes Assuming Quiescent Boundary Conditions

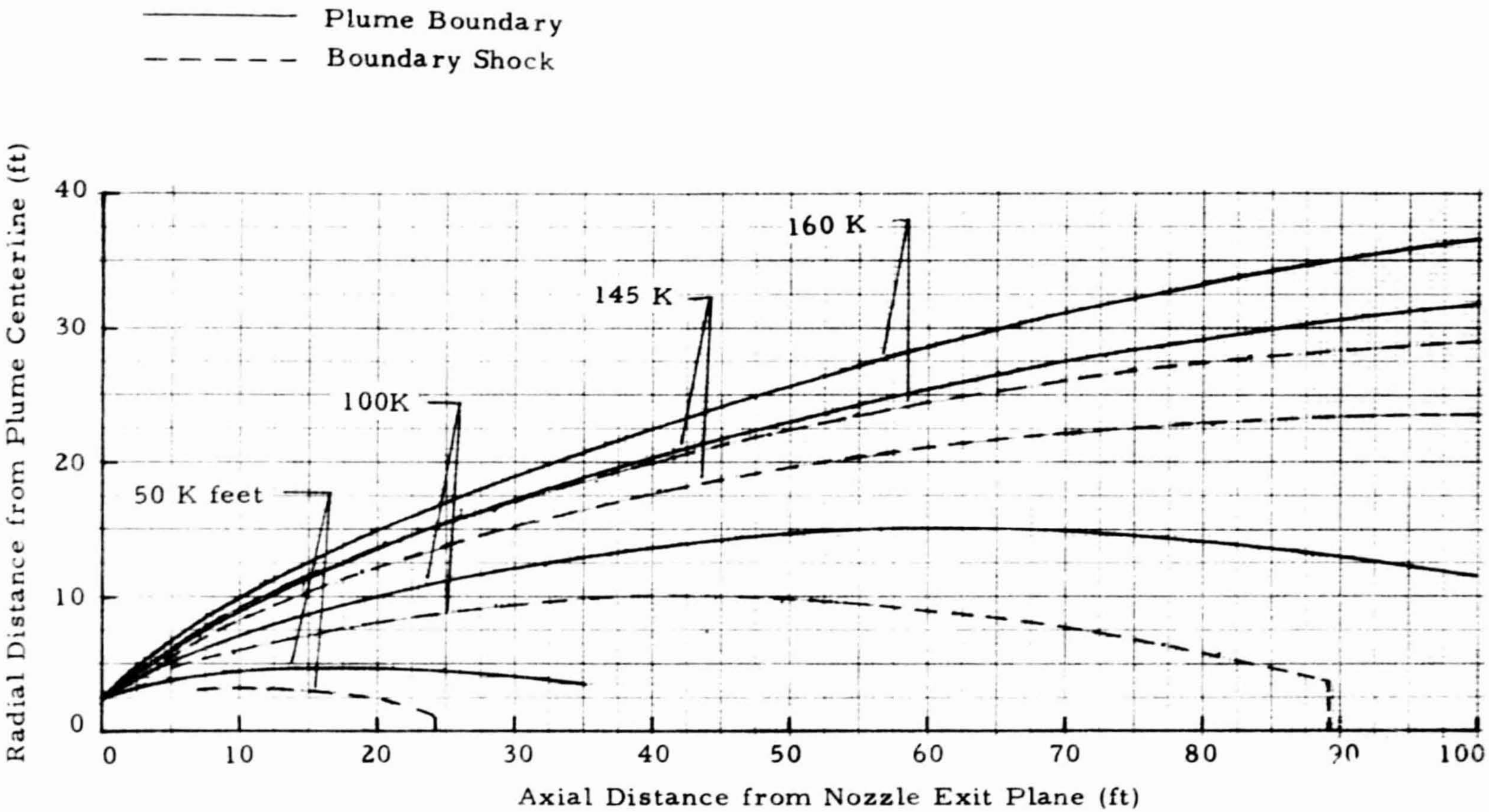

Fig. 7 - Liquid Booster Module Single Engine Plume Boundaries at Several Altitudes Assuming Dynamic Boundary Conditions

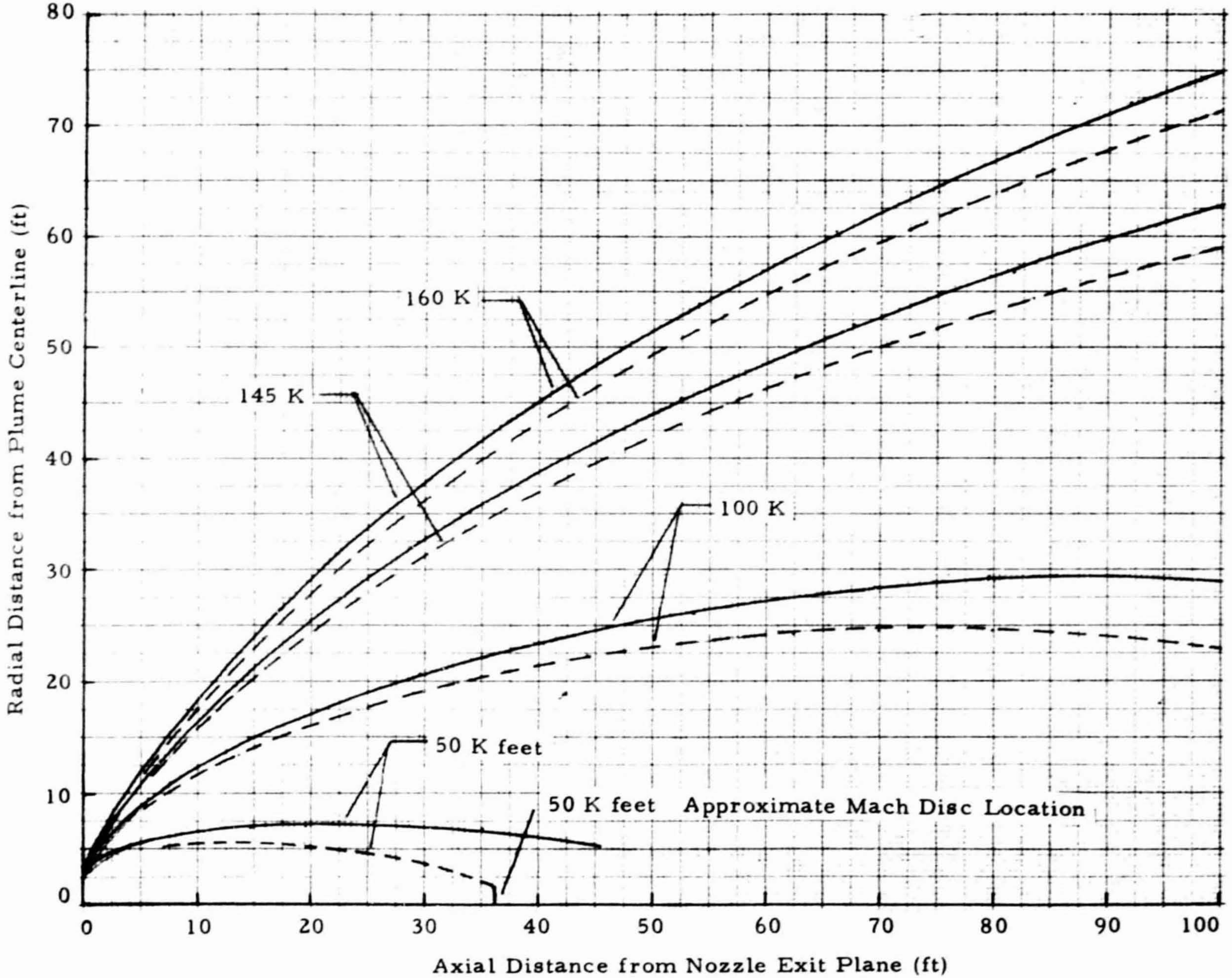

Fig. 8 - Liquid Booster Module Equivalent Engine Plume Boundaries at Several Altitudes Assuming Quiescent Boundary Conditions

equivalent motor concept has been used in previous Shuttle studies that address multiple engine effects on the exhaust plumes. Figure 9 presents the same plumes as Fig. 8 except the freestream boundary conditions include the dynamic pressure. Figures 10 and 11 present centerline distributions of plume properties. Figure 10 presents centerline pitot total pressure, static pressure and density distributions. Figure 11 presents centerline Mach number and static temperature distributions.

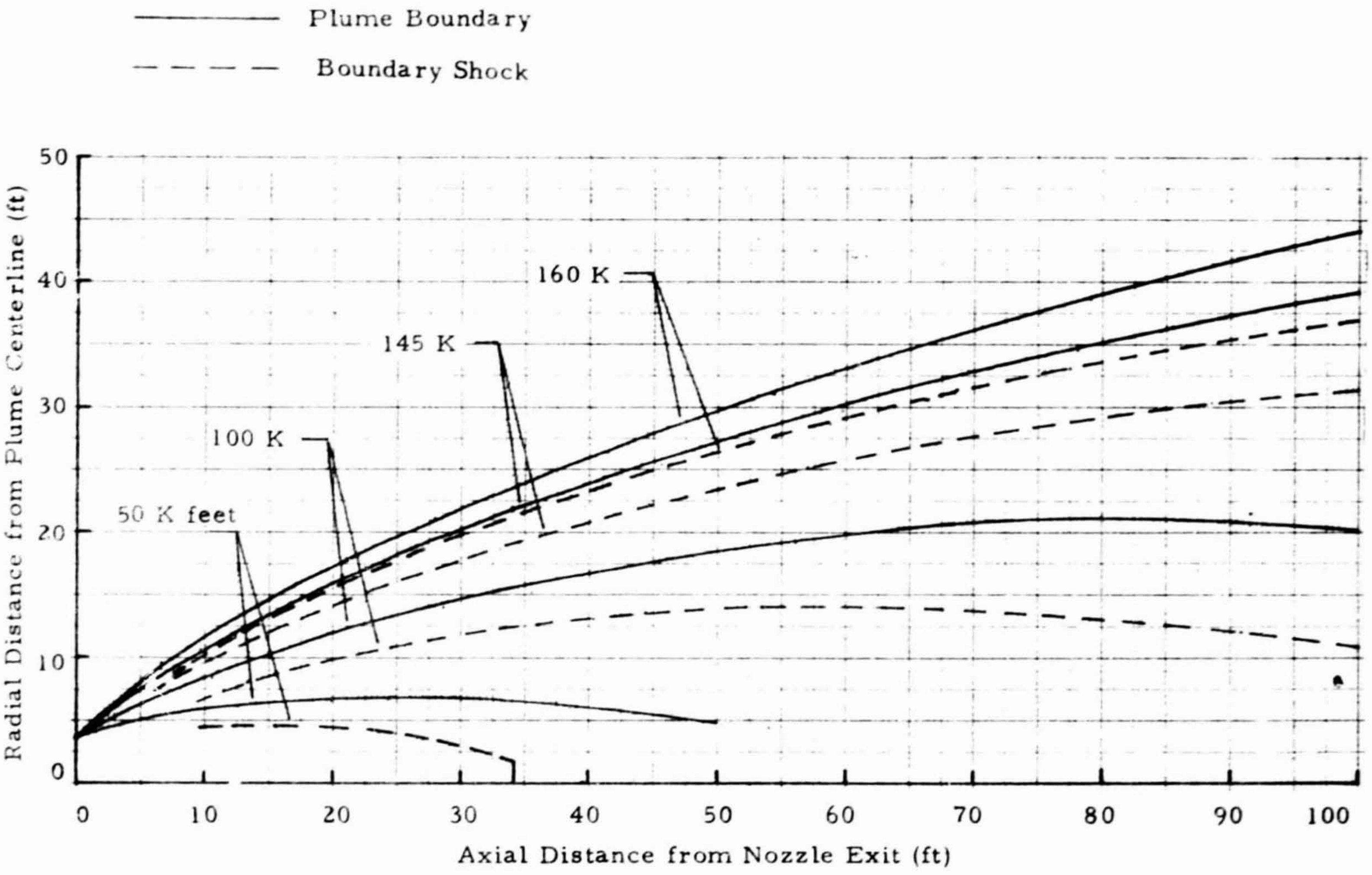

Fig. 9 - Liquid Booster Module Equivalent Engine Plume Boundaries at Several Altitudes Assuming Dynamic Boundary Conditions

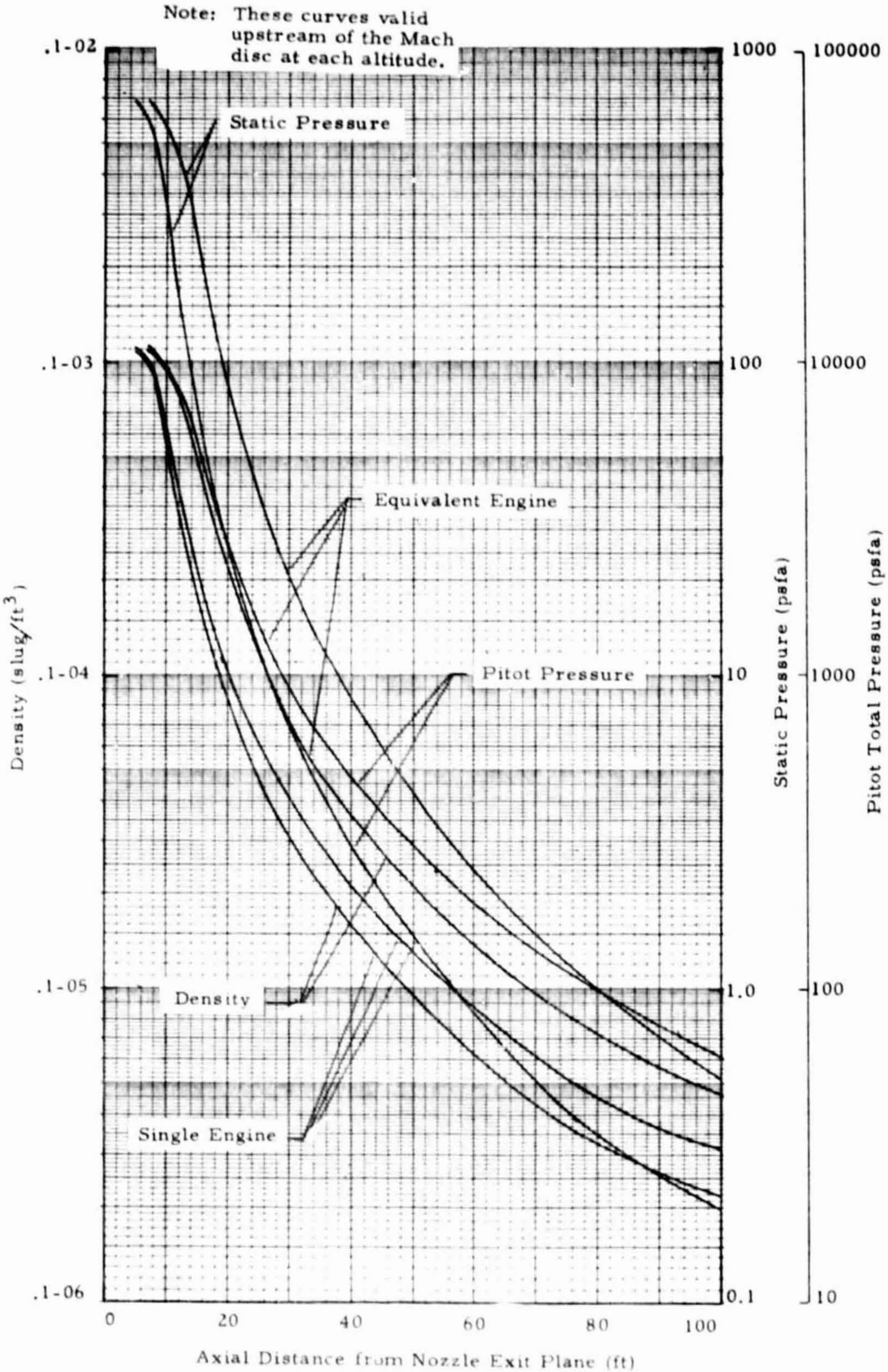

Fig. 10 - Liquid Booster Module Single and Equivalent Engine Centerline Distributions of Static Pressure Density and Pitot Total Pressure

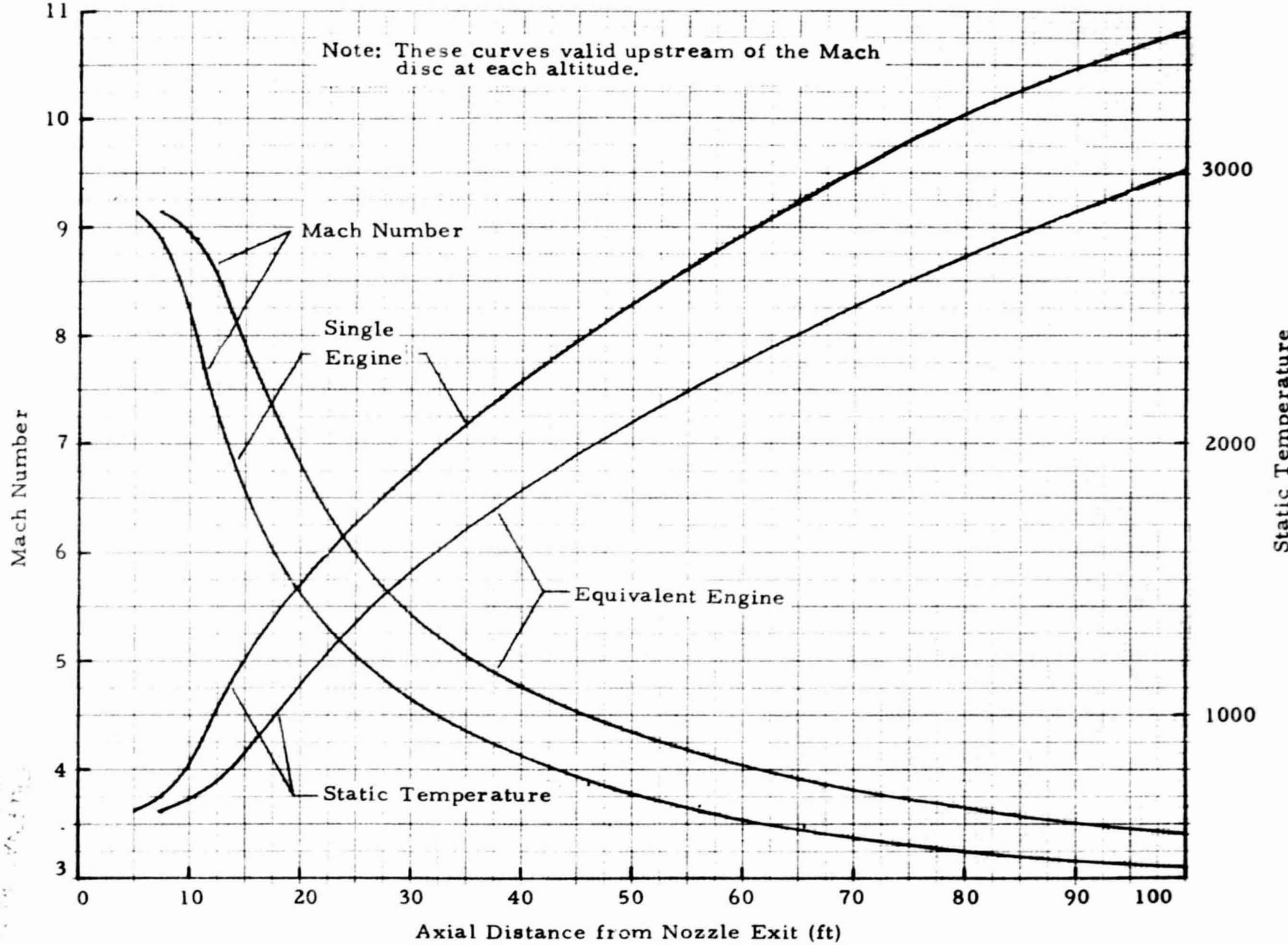

Fig. 11 - Liquid Booster Module Single and Equivalent Engine Centerline Distributions of Mach Number and Static Temperature

3. CONCLUSIONS AND RECOMMENDATIONS

This report has presented a definition of the LBM exhaust plumes at sea level and four additional altitudes to LBM cutoff. These data will aid in determining the impact of the LBM exhaust plume on Space Shuttle vehicle design environments. It is recommended that any Shuttle design studies use these data to assess the LBM exhaust plume effects on the Space Shuttle design environment.

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