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RTR 016-5

(NASA-CR-150848) SPACE SHUTTLE PLUME SIMULATION EFFECT ON AERODYNAMICS Final Report (Remtech, Inc., Huntsville, Ala.) 66 p HC A04/MF A01 CSCL 22B G3/16 N79-11103 Unclas 37184

SPACE SHUTTLE PLUME SIMULATION EFFECT ON AERODYNAMICS

Final Report

Contract NAS8-29751

October 1978

by
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Prepared for
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FOREWORD

This document summarizes the test data generated and gathered during a series of wind tunnel tests related to plume simulation on Space Shuttle. The work was performed for NASA Marshall Space Flight Center, Huntsville, AL. The NASA Technical Coordination for this study was provided by Mssrs. Kenneth L. Blackwell and Joseph L. Sims of Systems Dynamics Laboratory.

SUMMARY

At the initiation of the SSLV program, technology for simulating plumes in wind tunnel tests was not adequate to provide the required confidence in test data where plume-induced aerodynamic effects might be significant. A broad research program was undertaken to correct this deficiency. Four tasks within this broad program are reported on herein. Three of these tasks involve conducting experiments, related to three different aspects of the plume simulation problem: base pressures, lateral jet pressures, and plume parameters. The fourth task involves collecting all of the base pressure test data generated during the program.

Task 1 measured base pressures on a classic cone-ogive-cylinder body as affected by the coaxial, high temperature exhaust plumes of a variety of solid propellant rockets. Valid data were obtained at supersonic freestream conditions but not at transonic. Task 2 produced pressure data related to lateral (separation) jets at $M_\infty = 4.5$, for multiple clustered nozzles canted to the freestream and operating at high dynamic pressure ratios, q_j/q_∞ (up to 450). All program goals were met although the model hardware was found to be large relative to the wind tunnel size so that operation was limited to $q_j/q_\infty \approx 250$ for some nozzle configurations. Task 3 was a program of parametric measurements in the exhaust plumes of solid propellant rockets, and generated the largest parametric set of such data to date. Tests were performed at static backpressure conditions corresponding to altitudes of 50 kft, 100 kft, and 112 kft for propellants containing 2%, 10%, and 15% Aluminum. Task 4 produced a compact, but comprehensive, collection of test data from 10 test series of plume simulation effects on base pressure.

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NOMENCLATURE

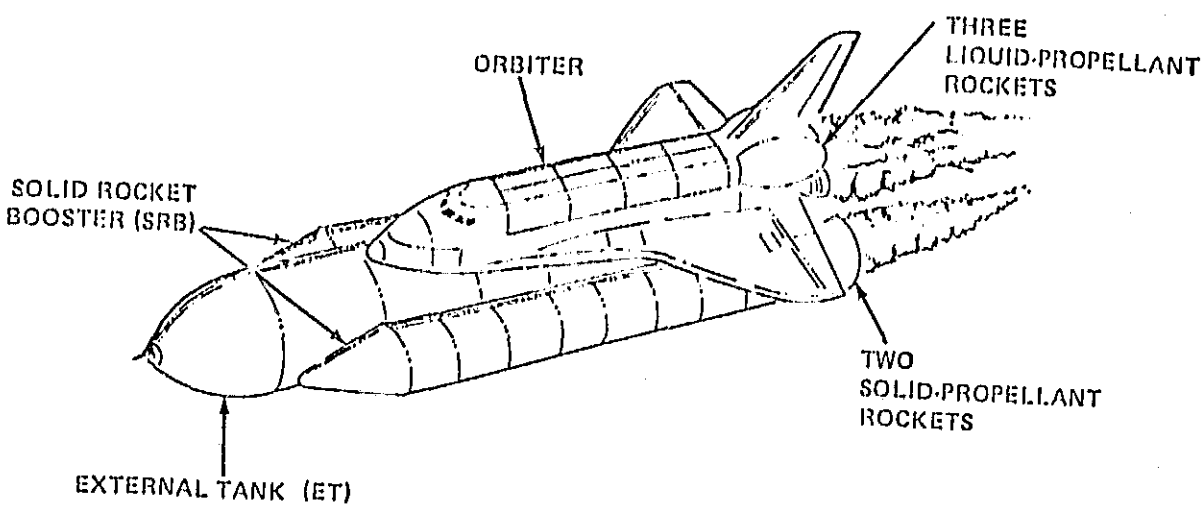
A	Area
AP	Ammonium Perchlorate
B.L.	Boundary Layer
c.l.	Center Line
CTPB	Carboxy Terminated PolyButadiene
D, dia	Diameter
ET	External Tank
HTPB	Hydroxyl Terminated PolyButadiene
JANNAF	Joint Army Navy NASA Air Force
M	Mach Number
M.O.C.	Method of Characteristics
P	Pressure
PBAN	PolyButadiene Acrylonitrile
q	Dynamic Pressure
R	Gas Constant
S/N	Serial Number
SRB	Solid Rocket Booster
SSLV	Space Shuttle Launch Vehicle
SSME	Space Shuttle Main Engine
T	Temperature
γ	Isentropic Exponent (Ratio of Specific Heats)
δ	Plume Slope
ε	Nozzle Area Ratio
Θ	Nozzle Wall Angle
ψ	Plate Inclination - See Figure 14

Subscripts:

amb	Ambient
b	Base
c	Chamber
ex	Exit
j	Jet
n or w	Nozzle Wall
t	Total (Stagnation)
*	Throat (Sonic)
∞	Freestream

Section 1
INTRODUCTION

The development and operation of space launch vehicles may be considerably influenced by the aerodynamic effects induced by the various propulsive rockets. It is important to be able to accurately predict these effects, so that data can be generated for vehicle performance, stability and control, and structural design. Aerodynamic design data for such vehicles are usually obtained from wind tunnel tests of scaled models, where the propulsive rocket engine exhaust plumes are simulated by flowing a gas (such as air or some product of combustion) through model nozzles. At the initiation of the Space Shuttle Launch Vehicle (SSLV) program, the technology for simulating plumes was not adequate to provide the required confidence in model test data. Significant plume-induced effects were anticipated as the SSLV configuration, sketched below, has five major plume-producing rockets. A research program was undertaken to correct this deficiency.



The basic approach of the research program was to conduct a series of parametric wind tunnel tests with sufficient controls to allow independent assessment of the pertinent variables: vehicle type, nozzle geometry, propellant gas type, nozzle conditions, and wind tunnel freestream conditions. The total program was divided so that NASA personnel were in charge of one group of experiments; REMTECH, Incorporated was contracted to perform another group of experiments; and a third group was contracted to other industrial concerns. This document summarizes the work performed by REMTECH, Incorporated.

There were four tasks performed during this contract. Three of these involved performing experiments, and one involved collecting related published experimental data:

Task 1 High Temperature Exhaust Plume Effects on Base Pressure Simulation

Task 2 Lateral Jet Simulation

Task 3 Parametric Measurements in Solid Propellant Plumes

Task 4 Plume Simulation Data Summary

Task 1 was a two-phase effort which measured base pressures on a classic cone-ogive-cylinder body as affected by the coaxial, high temperature exhaust plumes of a variety of solid propellant rockets. The first phase was conducted in the NASA MSFC 14 x 14-Inch Trisonic Wind Tunnel (TWT) and primarily covered the supersonic speed range: M = 1.5 - 3.5. The second phase was conducted in the NASA ARC 6 x 6-Foot Supersonic Wind Tunnel and covered the transonic speed range: M = 0.9 - 1.5. Task 2 was an investigation of lateral jet simulation parameters. It was performed in the MSFC TWT using cone-ogive-cylinder and flat plate models at M = 4.5, using three different gases: air, CF_4, and He. A special high pressure gas heater (developed for an earlier test in the overall program) was used to supply these gases. Task 3 was a test to measure selected parameters in the exhaust plumes of a variety of solid propellant rockets, exhausting into a quiescent, high-altitude condition. This experiment was a comprehensive and parametric investigation utilizing the 50 ft diameter sphere that had been built as the exhaust receiver for the MSFC High Reynolds Number Wind Tunnel (HRWT). Task 4 consisted of collecting and summarizing all of the test data generated in the complete NASA Plume Technology program. There was a total of ten tests in that program, and after evaluation, the data from seven tests were chosen for publication.

All of the hardware used on these experimental efforts were developed specifically for each respective test (except for the gas heater mentioned above on Task 2). The following sections of this document present a brief discussion of each task. For the three experimental tasks, this discussion includes descriptions of model hardware, auxiliary equipment, instrumentation, results, and examples of the data. For Task 4, the discussion includes a summary of the various tests and hardware from which data are summarized. Detailed discussions of all aspects of each task are presented in separate documents. Table 1 is a guide to these detailed documents along with other related documents generated on this contract, keyed to the tasks and associated test identification numbers.

TABLE 1. PROGRAM SUMMARY

Task	Test		Documentation		
	NASA Id.	Test Site Id.	Test Data Report	Pretest Info. Memo	Other Memo
1	MA10F	TWT-586	RTR 016-1[1]	RM 016-1[6]	
	FA7	066-33	RTR 016-2[2]	RM 016-2[7]	RM 016-3[8]
2	FA13	TWT-612	RTR 016-3[3]	RM 016-4[9]	RM 016-5[10]
3	FA21	HRWT-38	RTR 016-4[4]	RM 016-6[11]	
4			NASA Technical Paper[5]		RM 016-7[12]

1. Superscripts denote reference identification numbers.

2. Some results of Ref. 4 were given at the 10th JANNAF Plume Technology Conference: Ref. 13.

Section 2

HIGH TEMPERATURE EXHAUST PLUME EFFECTS ON BASE PRESSURE SIMULATION

It is important to accurately predict the aerodynamic characteristics of the Space Shuttle during ascent to provide the data required for structural and control systems design. Recent studies have shown that induced effects, due to the plumes of the propulsion engines, can have a significant effect on the aerodynamic characteristics during the portion of the flight where aerodynamic forces are large relative to inertial forces. At the initiation of this program, the technology for simulating the Space Shuttle propulsion system plumes in a wind tunnel was not adequate to provide the required confidence in aerodynamic data obtained from model tests where plume induced effects are significant. In order to advance plume simulation technology, a test program was initiated.

Task 1 was conducted to measure the aerodynamic effects of plumes from high temperature gases in the presence of an external flowfield. This investigation provided data to compare with the effects observed using cold gas plumes. The first test phase was conducted in the MSFC 14 x 14-Inch Trisonic Wind Tunnel (Ref. 14) during December 1973 (MSFC TWT-586; MA11F). The second phase was conducted in the ARC 6 x 6-Foot Supersonic Wind Tunnel (Ref. 15) during August 1974, (ARC 066-33; FA7). For these tests, a wind tunnel model which included a solid propellant combustor was built. The specific objective of these tests was to measure combustor, nozzle, and base region pressures using two types of solid propellant, operated at four values of chamber pressure, for two nozzle area ratios, at four freestream Mach numbers. Propellants with 16 percent and 2 percent Aluminum were used to assess the effects of particles on plume aerodynamic interactions, at chamber pressures from 400-1800 psia. Conical nozzles of 15° half-angle with area ratios of 4 and 8 were used to vary the plume shape. These nozzles were calibrated using cold air. The wind tunnels were run at Mach numbers of 0.9, 1.2, 1.5, and 3.5. In addition to the pressures measured, Schlieren photographs were taken for all of the second phase tests, for the first phase tests at Mach 3.5, and for the nozzle air calibration tests. Reference 1 presents the data acquired during the first test phase, along with detailed definition of the hardware and tests conditions; Reference 2 is a similar document for the second test phase.

For the first phase, a total of 31 rocket firings were accomplished in 11 days of operation, with 3 days of nozzle calibration and model installation preceeding the main test period. The average operational rate was 2 hours per run in the blowdown MSFC tunnel. For the second phase, a total of 23 firings were accomplished in 14 shifts, after 5 shifts of model installation. Average operational rate was 5 hours per run in the continuous-flow ARC tunnel. A capsule summary of the Task 1 test series is presented in Table II.

Design and instrumentation of the model is shown in Figure 1. The pressure transducers were mounted in the support strut, for closest proximity to the pressure port and thus, minimum response lag. Characteristics of the solid-propellant-burning gas generator (Ref. 16), which produced the high temperature gas for the exhaust plume, are presented in Figure 2. This device was designed as an integral part of the model so that the combustion chamber outside wall formed the outer mold lines of the aerodynamic surface. Ignition was provided by a single, head-end mounted electric squib. Typical operation is shown in Figure 3.

The nature of this test was such that the gas generator chamber pressure was not explicitly controllable. Once the igniter fired, the propellant burned, and the resulting chamber pressure varied with time in response to irregularities in manufacturing tolerances in the various gas generators. Nozzle and base pressures were directly affected by the chamber pressure. Typical time histories of selected pressures are shown in Figure 4.

TABLE II

CAPSULE OF TASK 1 TEST SERIES

a. Type of Tests

Internal Flow (thru nozzle)	External Flow $M_\infty = 0$	External Flow $M_\infty > 0$
None	-	Tare Runs
Air	Nozzle Calibration	-
Exhaust Products from Solid Propellant Gas Generator	Outside Demonstration	Basic Hot Firing

b. Chronology

Date	Event
Sep-Oct 73	Gas Generator Development at Calspan Corp. (NAS8-26701)
26 Nov.	Gas Generator Delivery to MSFC
3-4 Dec.	Air Calibration of Nozzles S/N 1,3 in MSFC TWT Special Test Section
5-19 Dec.	Tare Runs & Basic Hot Firings in MSFC TWT Transonic & Supersonic Test Sections
16 Jan. 74	Air Calibration of Nozzle S/N 2, Recalib. of Nozzle S/N3: in MSFC TWT Special Test Section
1 Aug.	Gas Generator Delivery to ARC
21-28 Aug.	Tare Runs & Basic Hot Firings in ARC 6 x 6-Foot SWT

c. Test Accomplished (Design Values)

A_{ex}/A_*	% Al	M_∞	Pc (psia) 0	200	400	600	800	1200	1600
4	Air	0		1	1	1			
	2	.9			2				
		1.2			1				
		1.5			1				
		3.5			1				
	16	.9					2		
		1.2			1		1		
		1.5			1		1,2		
		3.5			1		1		
8	Air	0		1	1	1			
	2	.9			2		2		2
		1.2			1,2		1,2	1	2
		1.5			1		1	1	
		3.5			1		1	1	
	16	.9			2		1,2	2	1,2
		1.2			1,2		1,2	1,2	1,2
		1.5			1,2		1,2	1,2	2
		3.5			1		1	1	1
		.9	1,2	1 = Phase 1 2 = Phase 2					
		1.2	1,2						
		1.5	1,2						
		3.5	1						

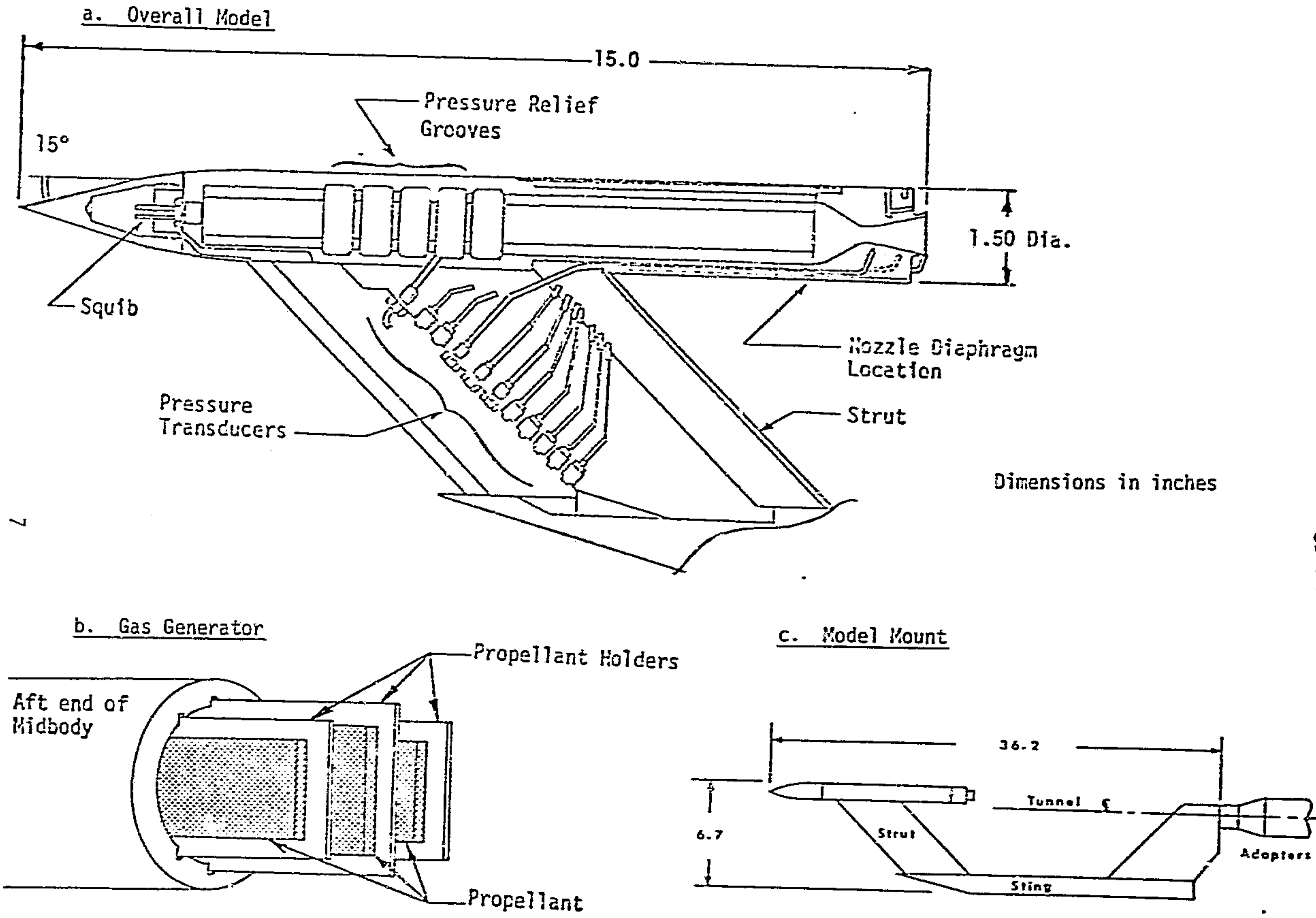


Figure 1 Task 1 Model Design

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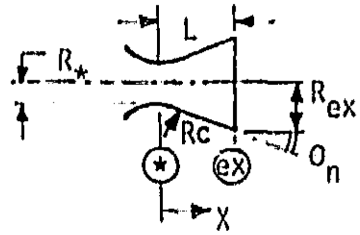
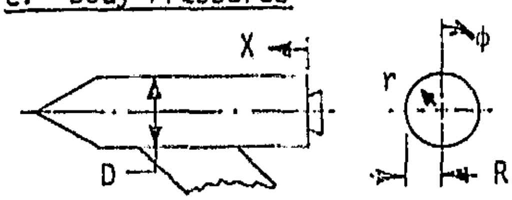
d. Nozzles



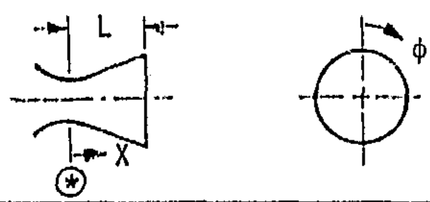
Nozzle	Design R_c/R_*	Design θ_n	Design ϵ	Design D_{ex} (in.)	Measured R_c/R_*	Measured θ_n	Measured ϵ	Measured D_{ex} (cm)	Measured D_* (cm)	Measured L (cm)	Measured D_{ex} (in.)	Measured D_* (in.)	Measured L (in.)
1	4.0	15°	8.0	.700	3.63	14.9°	7.88	1.77	.630	2.26	.696	.248	.891
2					3.63	14.7°	7.88	1.77	.630	2.52	.696	.248	.994
5					3.59	15.0°	7.92	1.77	.630	2.30	.698	.248	.905
6					3.44	15.0°	7.97	1.79	.635	2.33	.706	.250	.918
3			4.0		3.79	15.2°	4.05	1.78	.884	1.88	.700	.348	.740
7					3.82	15.0°	4.09	1.78	.879	1.85	.700	.346	.730

e. Body Pressures



ϕ=0° X/D	ϕ=0° r/R	ϕ=60° X/D	ϕ=60° r/R
0	.52	0	.52
	.84		.84
.03	1.0		
.33			
.67			

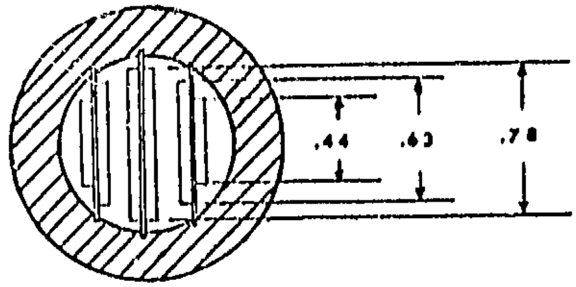
f. Nozzle Pressures



Nozzle	Upstream Tap Id.	Upstream Tap ϕ	Upstream Tap X/L	Upstream Tap A/A_*	Middle Tap Id.	Middle Tap ϕ	Middle Tap X/L	Middle Tap A/A_*	Downstream Tap Id.	Downstream Tap ϕ	Downstream Tap X/L	Downstream Tap A/A_*
1	2	180°	.155	1.40	3	120°	.569	3.92	4	240°	.943	7.27
2	2	180°	.236	1.44	3	120°	.622	4.04	4	240°	.952	7.33
5	2	180°	.181	1.47	3	120°	.608	4.19	4	240°	.963	7.53
6	2	180°	.191	1.52	3	120°	.612	4.25	4	240°	.967	7.62
3	2	180°	.268	1.36	3	120°	.644	2.56	4	240°	.942	3.78
7	2	180°	.304	1.53	3	120°	.655	2.67	4	240°	.959	3.91

Figure 1. Concluded

(All Dimensions in inches)



a. Complete Assemblies

Propellant	ε	Design P_c (psia)	Propellant Length Side	Propellant Length Center	Diaphragm Thickness	Quantity Fab.	Approx. Burn Time (msec)
ANB-3335-1 (2%Al) (.079 Thick)	8	400	1.50	5.60	.005	7	350
		800	1.60	9.50	.007	9	200
		1200	9.50	1.50	.009	13	50-100
	4	400	8.75	1.50	.005	10	350
UTP-3001 (16%Al) (.090 Thick)	8	400	1.50	3.15	.005	9	300
		800	1.50	6.20	.007	12	200
		1200	1.50	8.60	.009	11	100-150
		1600	7.80	1.50	.011	8	100
	4	400	1.50	8.55	.005	8	250
		800	9.50	1.50	.007	9	100-200

b. Propellant Properties

Designation	UTP-3001	ANB - 3335-1
Manufacturer	United Technology Center San Jose, Calif.	Aerojet Solid Propulsion Co. Sacremento, Calif.
Batch No.	-	VBM-70-009
Al Content	16%	2%
Oxidizer	AP	AP
Binder	PBAN	CTPB
Flame Temperature	6100°R (at P_c = 300 psia)	5340°R (at P_c = 510 psia)

c. Operational Events

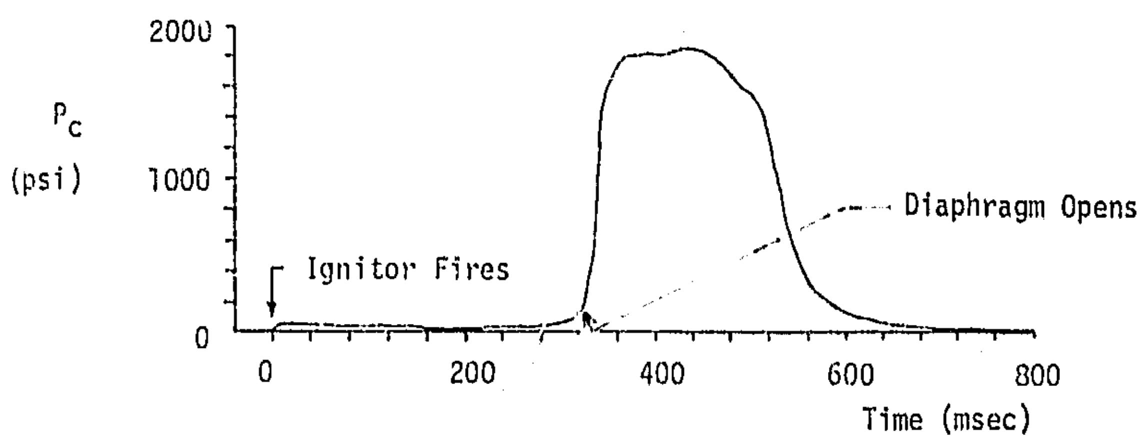


Figure 2. Task 1 Gas Generator Characteristics

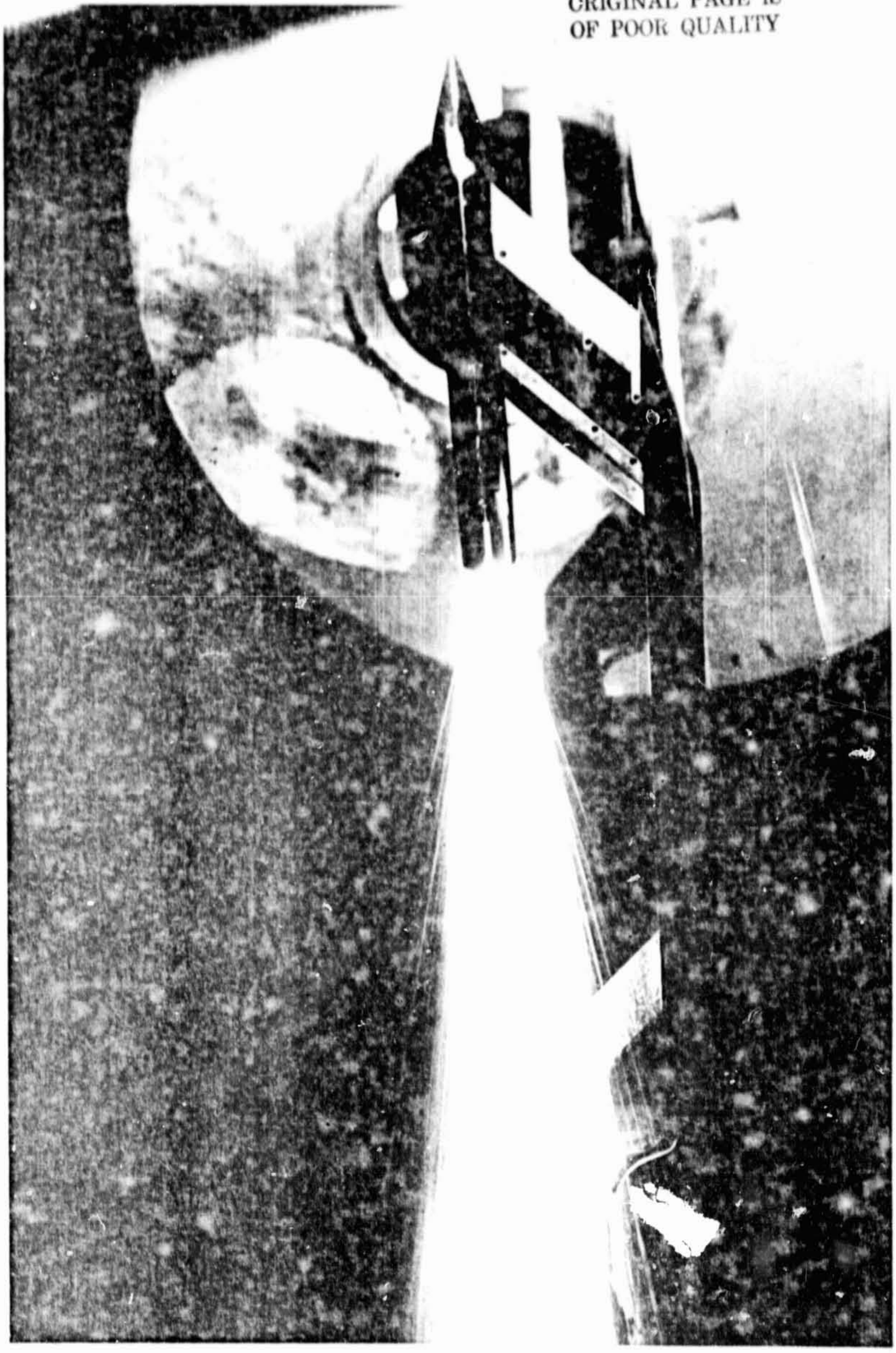


Figure 3. Typical Task 1 Model Operation

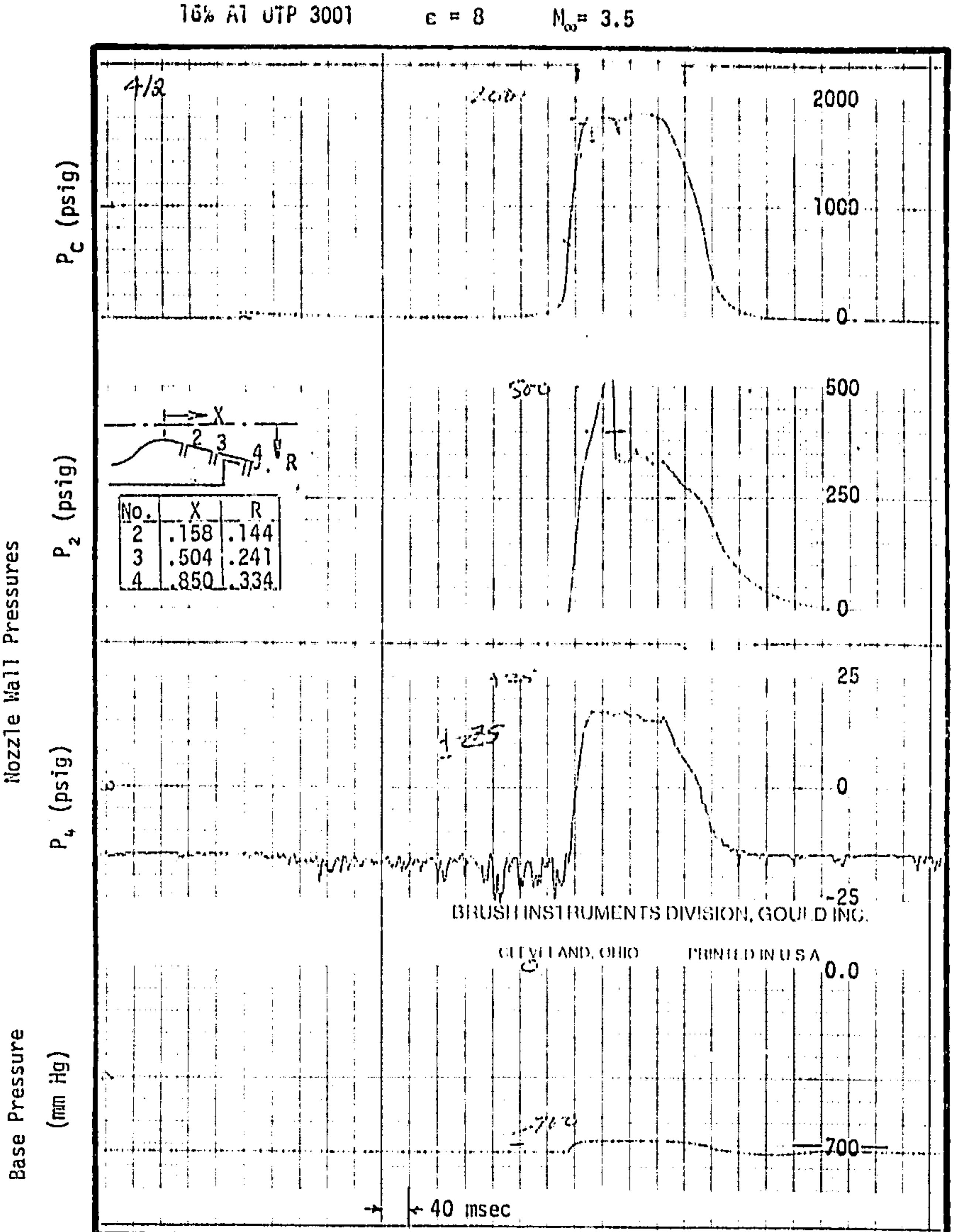


Figure 4. Typical Task 1 Time History of Pressures

For the time histories, digital data were recorded every 2 msec, producing a total of approximately 100,000 digital data points (along with 6-8 channels of analog data on each run). Useful schliern flow visualization photographs were obtained for 12 hot firings, 40 nozzle calibrations, and 9 tare (wind on, plume off) runs. For each run, the time histories were examined, and the period was identified of least variation in P_c. The values of all parameters were recorded for that period. Examples of the data selected by this process are presented in Figures 5 and 6. Figure 5 shows base pressure, the parameter of primary interest in this study. Figure 6 shows nozzle wall pressures compared to two theoretical values. The degree of agreement of theory to test data within the nozzle strongly affects the confidence placed in theoretically-predicted plume shapes downstream of the nozzle.

The supersonic ($M_\infty \geq 1.5$) data generated on this task have been accepted. The transonic ($M_\infty \geq 1.2$) have not been regarded with high confidence. In the Phase 1 transonic test, Mach number was controlled via tunnel plenum pressure. The tunnel control system could not respond rapidly enough to compensate for the large plume-induced pressure transient during the brief rocket motor operation, so steady-state tunnel conditions were not obtained. (In the supersonic phase, no such problem arose because Mach number was controlled by the nozzle area ratio and the pressure ratio across the nozzle.) In the Phase 2 test, the pressure transducers exhibited significant zero-drifts during the 1-2 hour period between closing the wind tunnel and reaching the desired test conditions. It was suspected that this drift was caused by temperature changes during the protracted tunnel operation. However, no satisfactory corrective technique was devised, so that Phase 2 data could not be used.

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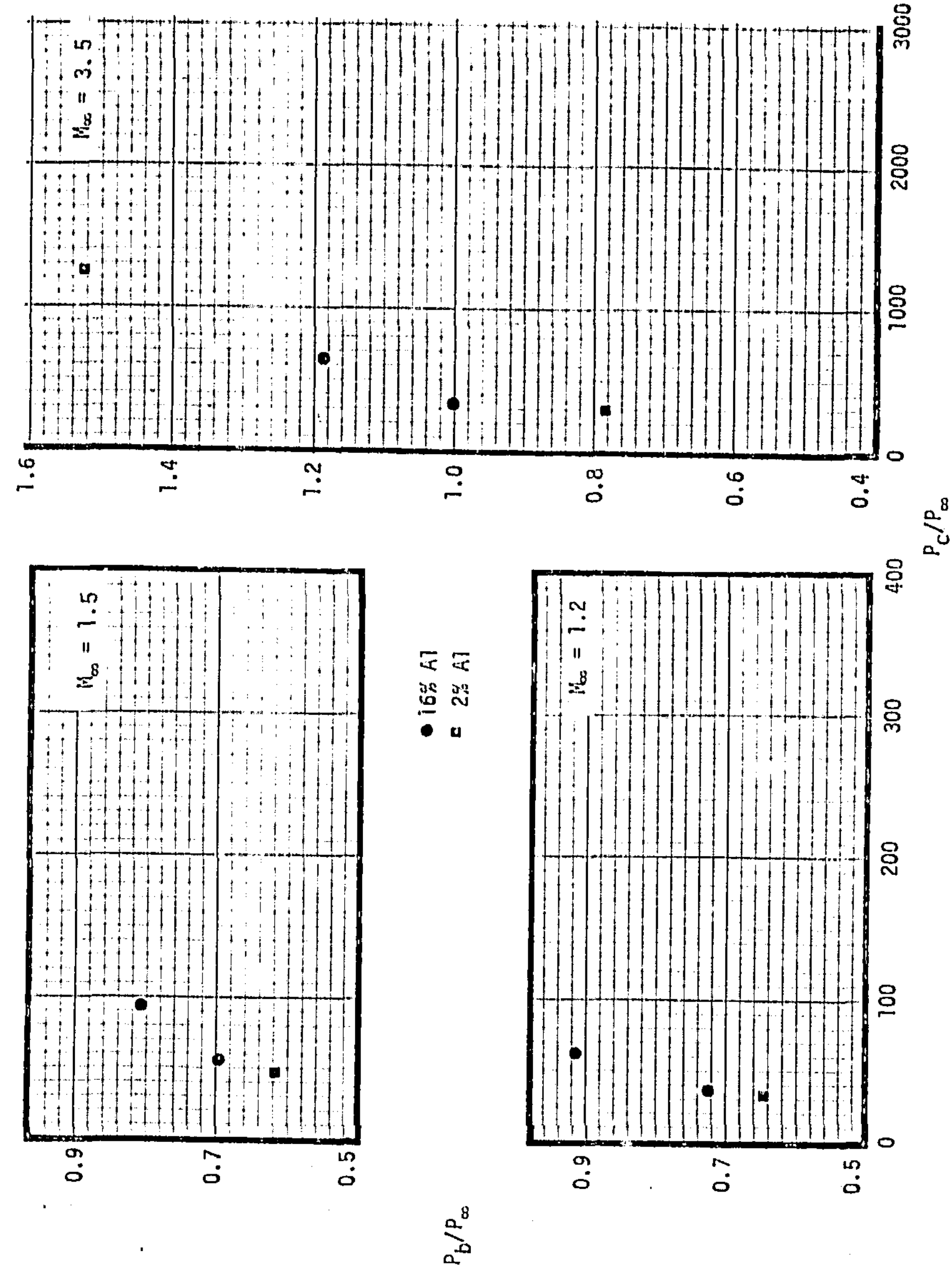

Figure 5. Example of Task 1 Base Pressure Data (ε = 4)

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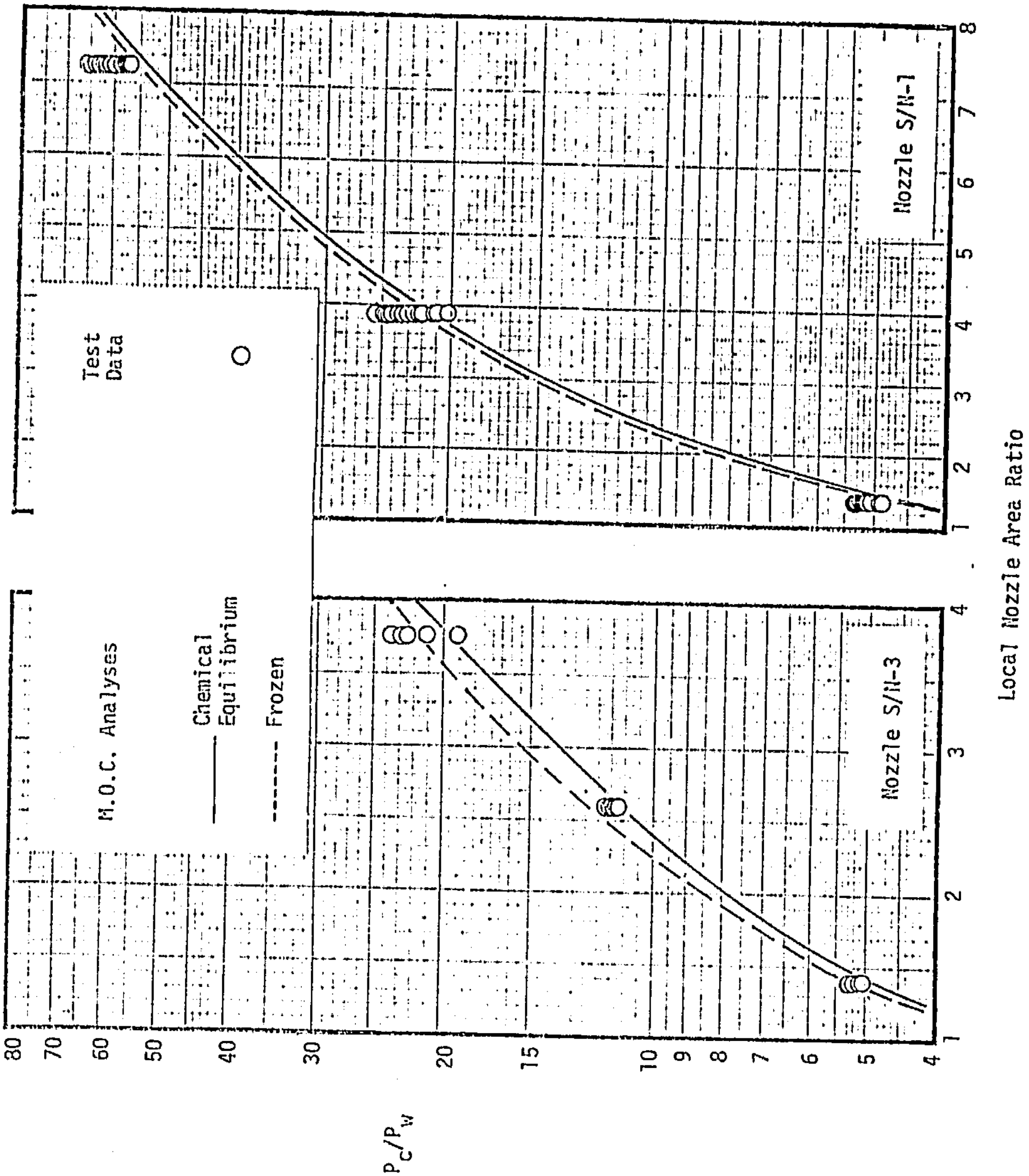


Figure 6. Example of Task 1 Nozzle Pressure (16% Al UTP-3001)

Section 3

LATERAL JET SIMULATION

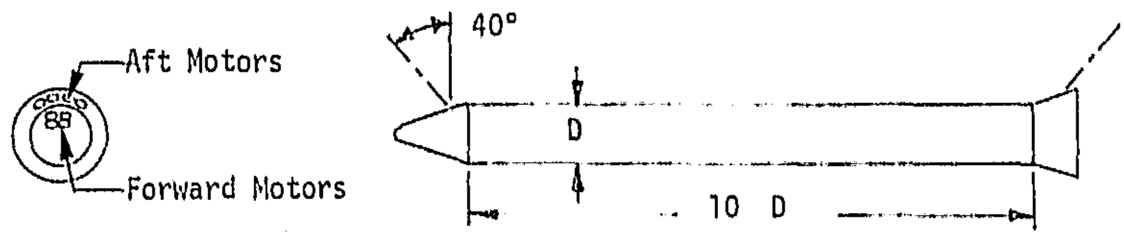
Small solid propellant rocket motors are used on the Space Shuttle SRB to provide positive separation from the orbiter and external tank (ET). The plumes from these small motors impinge on the orbiter/ET combination and cause induced aerodynamic effects, which can be a significant factor in the overall aerodynamic forces on the vehicle. Because of the importance of these separation motor effects, the plumes of the motors must be simulated during aerodynamic tests of the separation. Although there has been testing to characterize the effects of small motors firing normal to the boundary flow past a vehicle, there are significant differences between previous research and the conditions which will exist on the Space Shuttle. In this case, the ratio of exhaust plume to freestream dynamic pressure is higher, and multiple clustered nozzles are used, canted relative to the freestream. Because the available technology for simulating the Space Shuttle separation system plumes in a wind tunnel was not adequate to provide the required confidence in aerodynamic data, a test program was initiated. This test would determine if the presently accepted simulation - nozzle contouring to produce an air plume shape to match the prototype plume shape - were suitable for this application. Suitability would be evaluated by schlieren visualization of the complex interacting flowfield of the nozzle jet and the freestream, and by pressures produced on both the nozzle-mounting body and on a flat plate in proximity to the nozzles.

To achieve these results, the following set of pressure models and instrumentation was built and tested in the MSFC 14 x 14-Inch Trisonic Wind Tunnel:

Flat plate model
Cone-cylinder model - short
Cone-cylinder model - long
Nozzles
Impingement pressure plate

The models accomodated several nozzle configurations. Each nozzle was calibrated with air by measuring exit pitot pressure in a quiescent backpressure environment. A heater and gas supply system was used to control the temperature and pressure of the test gases. Three gases were used: air, CF_4, and He. The target chamber temperature was 1000°R for all cases. Model surface pressures, schlieren flow visualization, and impingement plate surface pressures were obtained. Tests were conducted at $M_\infty = 0$ and $M_\infty = 4.45$. Variations were made in model nozzle chamber pressure (from 50 to 2000 psia) and tunnel total pressure (from 20 to 70 psia). Variations of pitch or yaw were not made. A plate was mounted in the lateral jet plumes to investigate impingement pressures produced by the plumes. Pressures were measured on the model and impingement plate surfaces, and schlieren photographs of the complex interaction flowfield were made. A total of 202 runs were accomplished in 21 days of operation; 4 days of model installation preceeded the test period. Thus, the average run rate after installation was about 9.6 per day. The greatest number of runs per day was 18, and 16 runs were accomplished on each of two days. A capsule summary of the Task 2 test series is presented in Table III.

The SRB configuration is a cone-cylinder-frustum with four separation motors mounted on the cone and four on the frustum, as sketched below:



The models and nozzles for this test were designed to approximate this configuration but limitations of wind tunnel size and arrangement did not permit exact scaling. Details of the models and nozzles are given in Figure 7. There were three basic models. The cylindrical models qualitatively represented the SRB, with the short

TABLE III

CAPSULE OF TASK 2 TEST SERIES

a. Hardware Use

Gas	Element: Nozzle Calibration	Element: Schlieren Only	Element: Impingement Plate
Air	Flat (1) Short (12)	Flat (1) Short (4) Long (7)	Short (3) Long (3)
He		Flat (1) Long (1)	
CF_4		Short (2) Long (2)	Short (2) Long (2)

b. Test Matrix (showing number of runs)

Gas	Model	Instr.	Nozzle Mounting (or): ε = 2.42, No. = 1, Id. = (1-M-1-0)	3.15, 1, (7-M-1-0)	2.42, 4, (1-M-4-45)	3.15, 4, (7-M-4-45)	1.1, 4, (11-M-4-45)	1.99, 4, (9-M-4-45)	2.42, 4, (1-M-4-45)	3.15, 4, (7-M-4-45)	1.1, 4, (11-M-4-45)
Air	Long	-	7	8	6	1	8		5		4
↓	↓	Plate	8	7			10				
CF_4	↓	↓		6		6					
↓	↓	-				5				5	
↓	Short	-		5		5					
↓	↓	Plate		6		4					
Air	↓	↓	8	6			11				
↓	↓	-		5	6	5	12				
He	↓	-						6			
↓	Flat	-	5								
Air	↓	-	5								

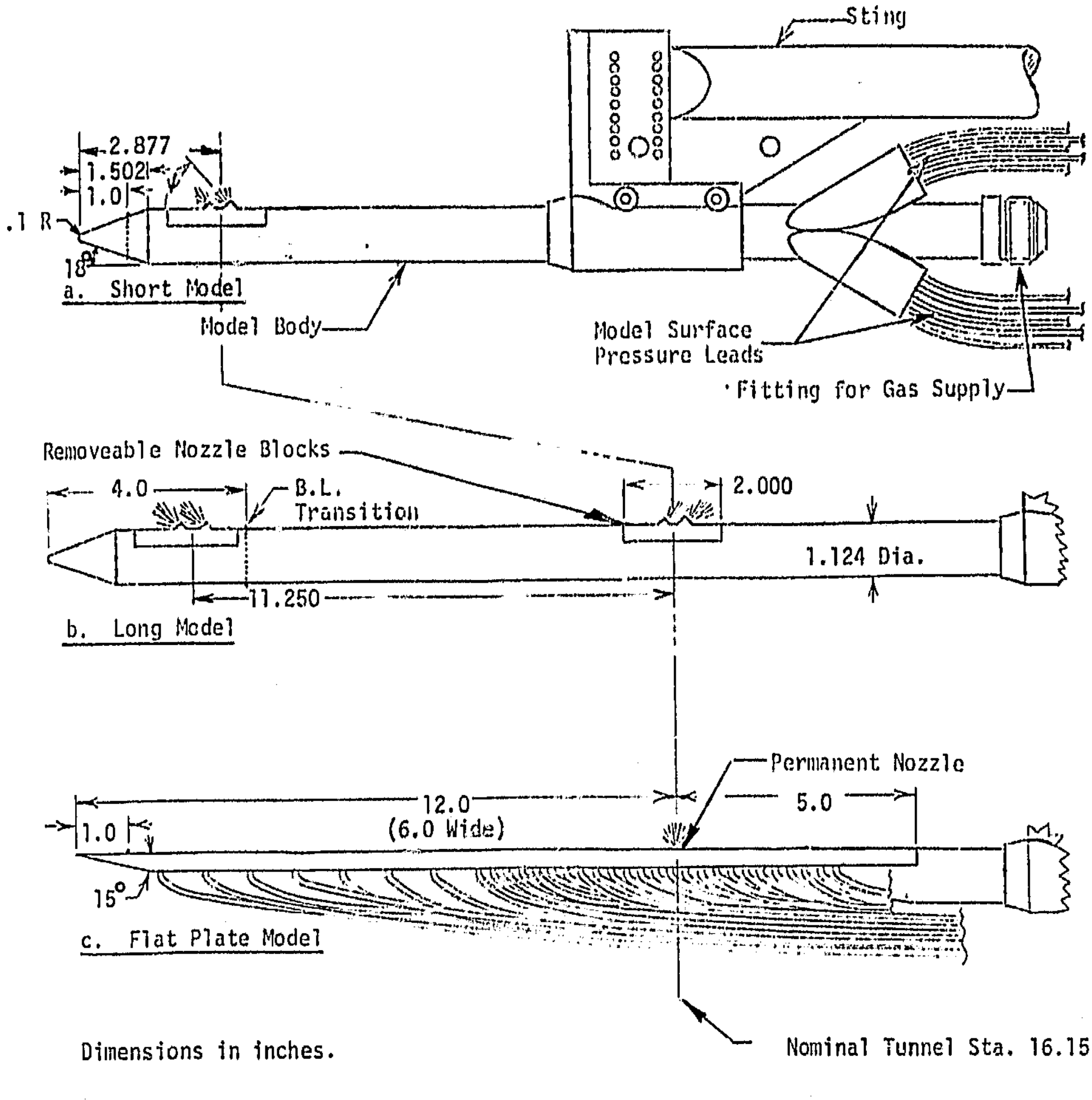
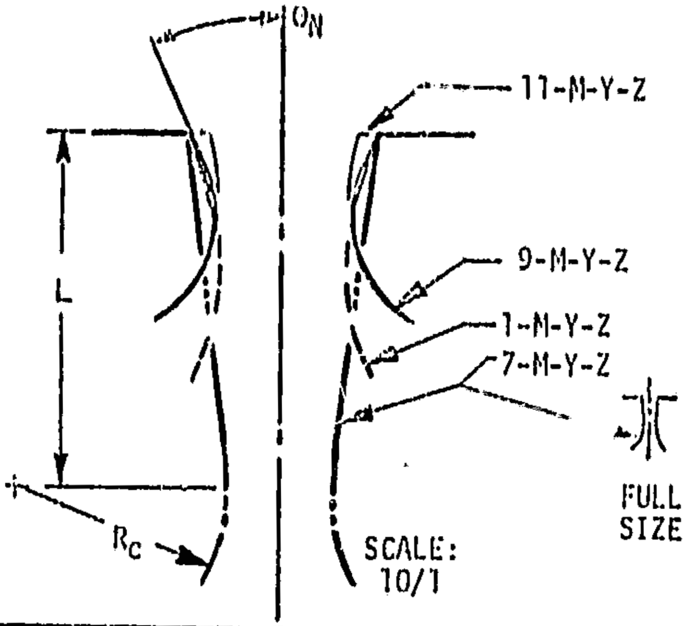


Figure 7. Task 2 Model Designs

Dimensions in inches



DESIGN VALUES				Part No.	Id. No. ③	Quan. Avail.	Schematic
$\varepsilon = A_{ex}/A_*$	D_{ex}, D_*	θ_N	L, R_c ①				
2.42	.1000, .0643	18.4°	.0746, .1290	80M51417 18 19	1-M-1-0 ④ 1-M-1-45 1-M-4-45	1 1 2	
1.1	.0788, .0751	8°	.0235, .150	27	11-M-4-45	2	
3.15	.1000, .0563	7°	.1847, .1126	20 21 22	7-M-1-0 7-M-1-45 7-M-4-45	1 1 2	
1.99	.1000, .0709	27°	.0427, .0591 ②	23	9-M-4-45	2	

Notes: ① $R_c/R_* = 4.0$ unless noted
② $R_c/R_* = 1.67$
③ In Nozzle Plate Id. No. "X-M-Y-Z",
Y = number of nozzle holes, and
Z = degrees of inclination of c.l. off normal.
④ This nozzle profile also used in Flat Plate Model.

d. Nozzles

Figure 7. Concluded

model positioning the forward nozzles in the schlieren visualization field, and the long model positioning the aft nozzles there. A classic flat plate configuration was included so that data from this test could be directly compared to previous data. Nozzle patterns provided a parametric variation from the classic single, normal design through a single, inclined design to the SRB-type of inclined, four-nozzle configuration. All nozzle profiles were conventional conical shapes. Wall angles and expansion ratios were selected to match initial plume shapes (δ_j) for the various test gases.

To qualitatively represent the Shuttle FT, which is in close proximity to the SRB separation motors, a flat plate was provided upon which the model nozzle exhausts would impinge. Installation arrangements of this impingement pressure plate are shown in Figure 8. Locations of all of the pressure instrumentation ports are shown in Figure 9.

To supply heated, high pressure gases to these model, an extant heater (Ref. 17) was used. A schematic of this heater is presented in Figure 10. There were three close-coupled tanks. Pneumatically driven compressors pumped low pressure gas to the cold tank. This tank was used as the controlled supply for the heater tank, where the gas could be electrically heated as desired. A mixing valve was used to control the temperature of the gas delivered to the model. Gases could be delivered to the model at 2000 psia and 1060°R, at flow rates up to 4 lb/sec for 10 seconds. A small relief tank permitted operational flexibility, especially in preventing loss of expensive CF_4 gas.

It was crucial to investigate plume simulation at the high jet dynamic pressure/ambient dynamic pressure ratios(q_j/q_∞) associated with SSLV: $q_j/q_\infty > 400$. The maximum obtainable value of q_j was limited by the gas heater capability, so to achieve this high ratio of q_j/q_∞ the value of q_∞ was reduced by operating the tunnel at minimum stagnation pressure (20 psia). Unfortunately, at this condition, it was not possible to verify a turbulent boundary layer on the short model.

Dimensions in Inches

Model	Run No.	h (in.)	X_1 (in.)	X (in.)
Long	47-61	~1.00	2.038	12.087
	62-71	.799	3.816	10.309
	72-83/1	1.002	2.032	12.093
Short	102-125	.992	2.588	.289
	126-136	.800	~2.977	~ -.10

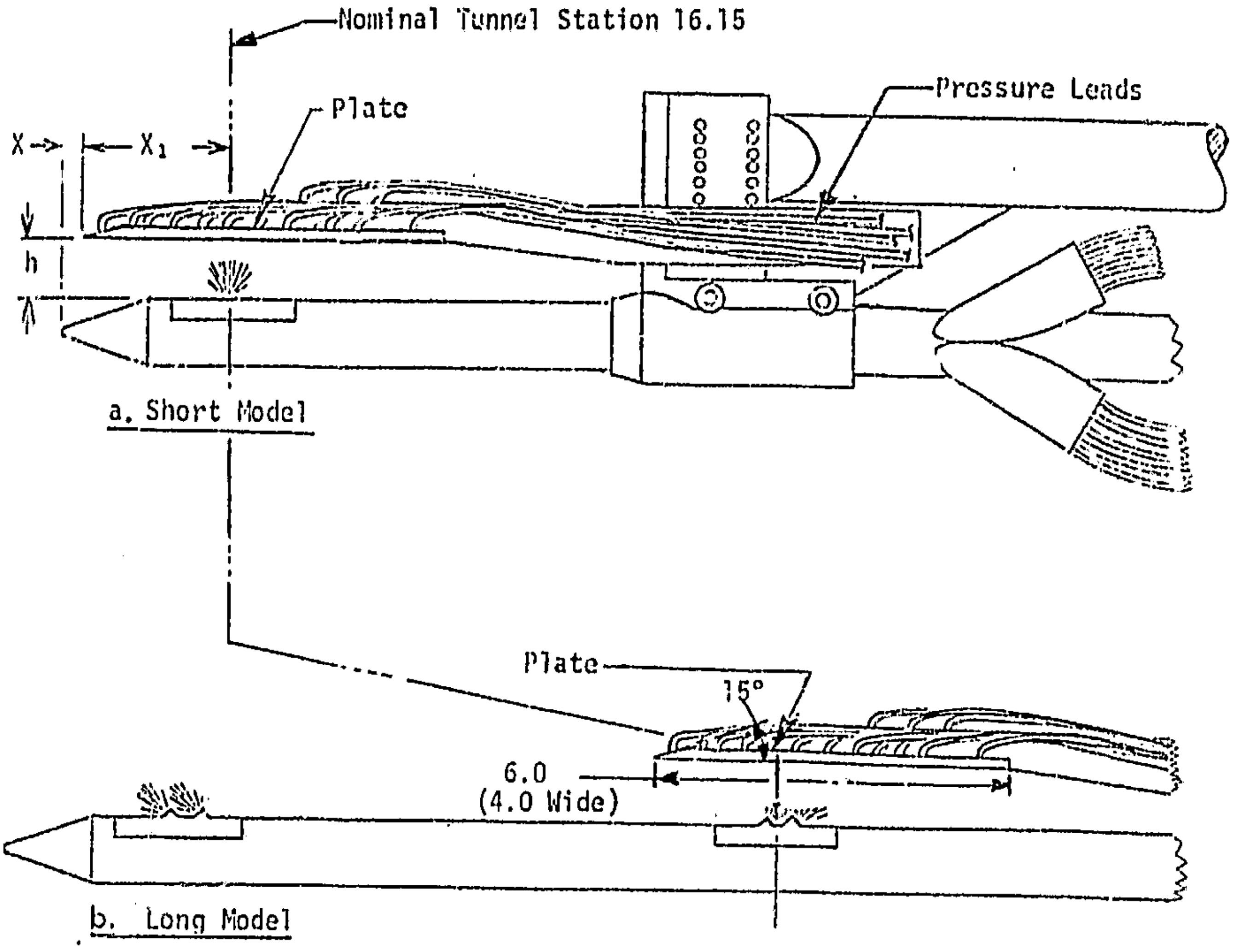
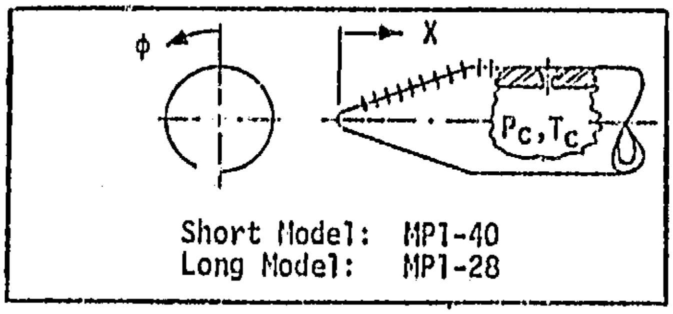
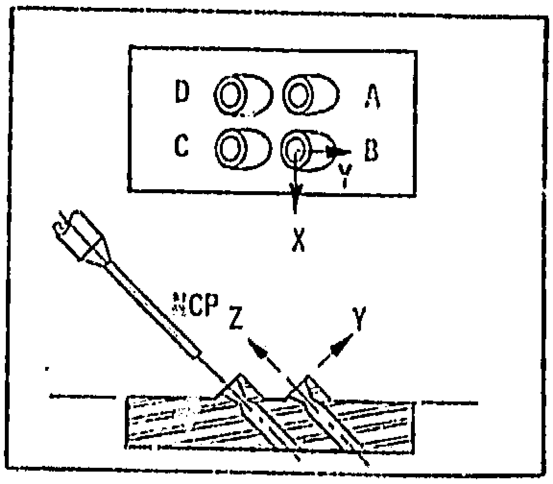


Figure 8. Task 2 Impingement Pressure Plate Installations



X(in.)							
Short Model						Long	
φ = 0°		φ = 30°		φ = 60°		(φ = 0°)	
MP1	.502					MP1	.575
2	.601					2	.671
3	.701					3	.766
4	.803					4	.859
5	.903					5	.951
6	1.002					6	1.049
7	1.102					7	1.144
8	1.202	MP9	1.204	MP10	1.202	8	1.238
11	1.304					9	1.332
12	1.404	13	1.406	14	1.404	10	1.429
	(1.502)		(Shoulder)				(1.508)
15	1.596	16	1.598	17	1.596	11	1.609
18	1.689					12	1.711
19	1.820	20	1.823	21	1.821	13	1.832
	(2.877)		(Jet, P_c,T_c)				(2.882)
22	3.936	23	3.939	24	3.936	14	4.384
25	4.066					15	4.881
26	4.159	27	4.158	28	4.158	16	5.381
29	4.312	30	4.312	31	4.310	17	6.387
32	4.412					18	7.385
33	4.512	34	4.512	35	4.511	19	8.385
36	4.612					20	9.385
37	4.711					21	10.385
38	4.810					22	10.885
39	4.910					23	11.382
40	5.011					24	11.885
						25	12.385
						26	12.881
					(Jet, P_{c2},T_{c2})		14.125
						27	15.183
						28	15.309

a. Cylinder Models



b. Nozzle Calibration

Figure 9. Task 2 Instrumentation Locations and Nomenclature

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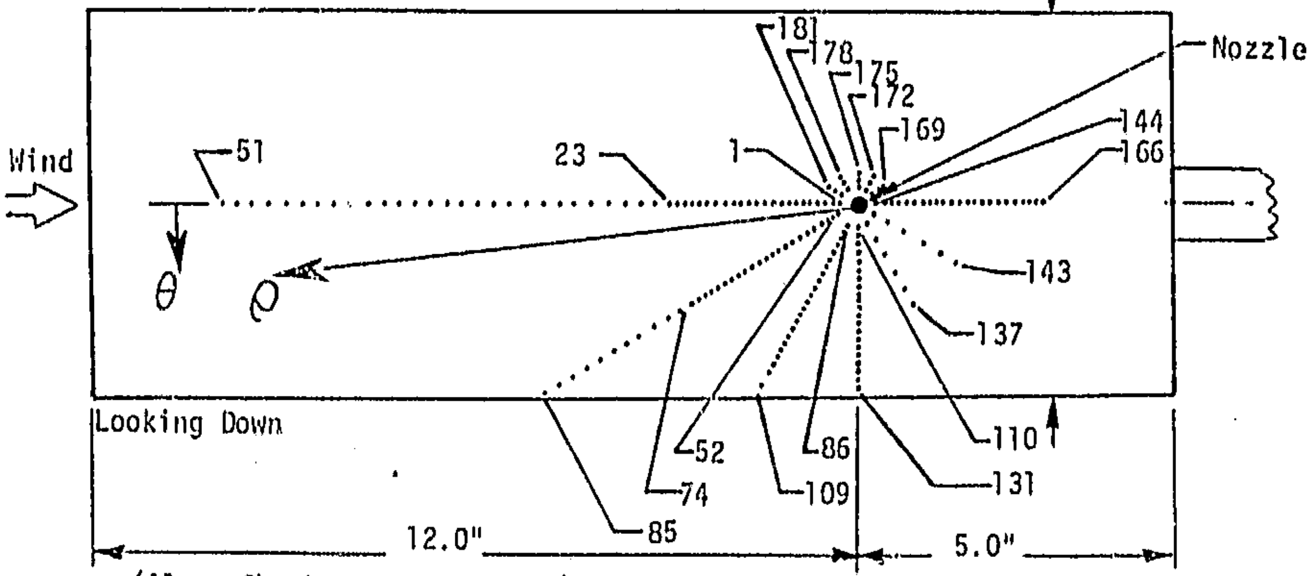
Flat Plate Pressures FP1-181



(Also, Chamber Pressure FPC)

ρ (in.)	θ 0°	30°	60°	90°	120°	150°	180°	-150°	-120°	-90°	-60°	-30°
.250	1	52	86	110	132	138	144	167	170	173	176	179
.375	2	53	87	111			145	168	171	174	177	180
.500	3	54	88	112	133	139	146	169	172	175	178	181
.625	4	55	89	113			147					
.750	5	56	90	114	134	140	148					
.875	6	57	91	115			149					
1.000	7	58	92	116	135	141	150					
1.125	8	59	93	117			151					
1.250	9	60	94	118	136	142	152					
1.375	10	61	95	119			153					
1.500	11	62	96	120	137	143	154					
1.625	12	63	97	121			155					
1.750	13	64	98	122			156					
1.875	14	65	99	123			157					
2.000	15	66	100	124			158					
2.125	16	67	101	125			159					
2.250	17	68	102	126			160					
2.375	18	69	103	127			161					
2.500	19	70	104	128			162					
2.625	20	71	105	129			163					
2.750	21	72	106	130			164					
2.875	22	73	107	131			165					
3.000	23	74	108				166					

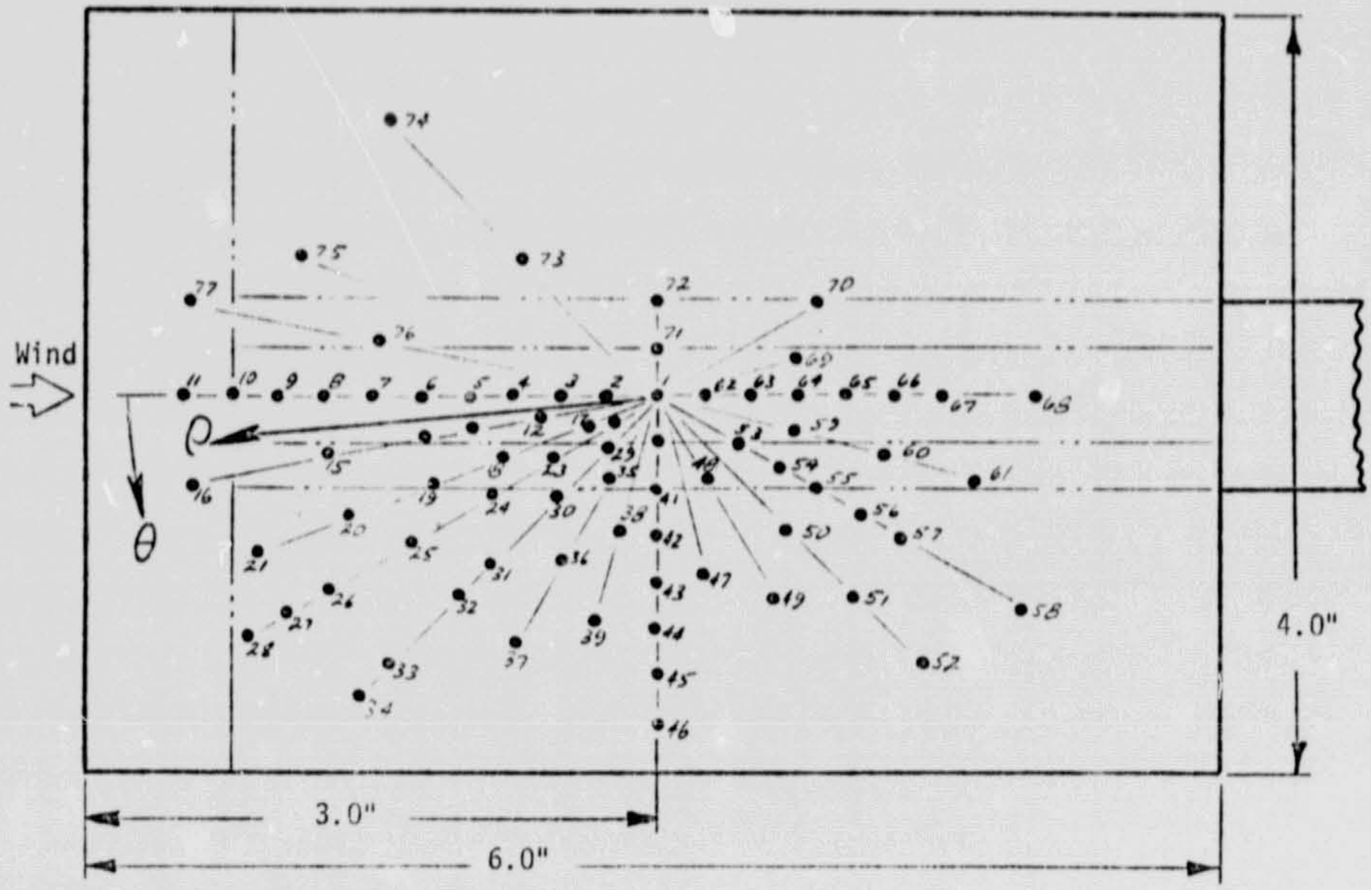
ρ (in.)	θ 0°	30°	60°
3.250	24	75	109
3.500	25	76	
3.750	26	77	
4.000	27	78	
4.250	28	79	
4.500	29	80	
4.750	30	81	
5.000	31	82	
5.250	32	83	
5.500	33	84	
5.750	34	85	
6.000	35		

ρ (in.)	θ 0°
6.25	36
6.50	37
6.75	38
7.00	39
7.25	40
7.50	41
7.75	42
8.00	43
8.25	44
8.50	45
8.75	46
9.00	47
9.25	48
9.50	49
9.75	50
10.00	51

c. Flat Model

Figure 9. Continued

Plate Pressures: PP1-77



ρ (in.)	θ 0°	10°	20°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	±180°	-165°	-150°	-90°	-45°	-20°	-10°
0	PP1																			
.250	2			22				(40)						62			(71)			
.375			17		29															
.500	3					35		(41)		48		53		63			(72)			
.625		12		23																
.750	4				30		38	42				54	(59)	64	(69)					
.875			18																	
1.000	5	13		24		36		43	47		50	(55)		65		(70)		73		
1.250	6	14	19		31		39	44		49		56	60	66						
1.500	7			25	32	37		45			51	57		67						76
1.750	8	15	20					46					61							
2.000	9			26	(33)						52			68				(74)	75	
2.250	10		21	27	34							58								
2.500	11	(16)		28																(77)

d. Impingement Plate

Circled numbers denote left-hand-to-right-hand mirror images.

Figure 9. Concluded

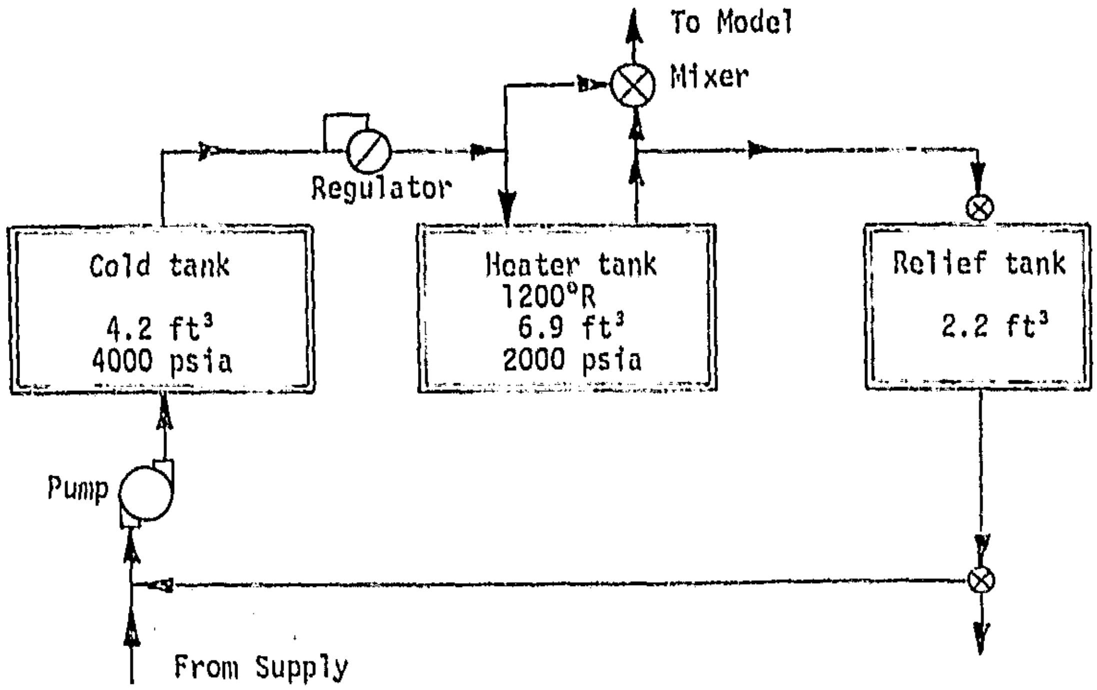


Figure 10. Task 2 Heater Schematic

Another problem affecting this goal of high values of q_j/q_∞ was that a number of tunnel unstarts occured, especially with four-hole nozzles on the short model at high q_j/q_∞. The maximum allowable q_j/q_∞ value was determined for each nozzle by trial and error. An example of the flowfield produced by a four-hole nozzle on the short model at an intermediate value of q_j/q_∞ (≈ 240) is shown in Figure 11, along with typical pressure data. In the early stages, several repeat runs were made. The indicated repeatability was adequate to preclude further repeat points in the program. It also became apparent that schlieren photographs of the $M_\infty = 0$ runs were not useful, and were not attempted after Run 55.

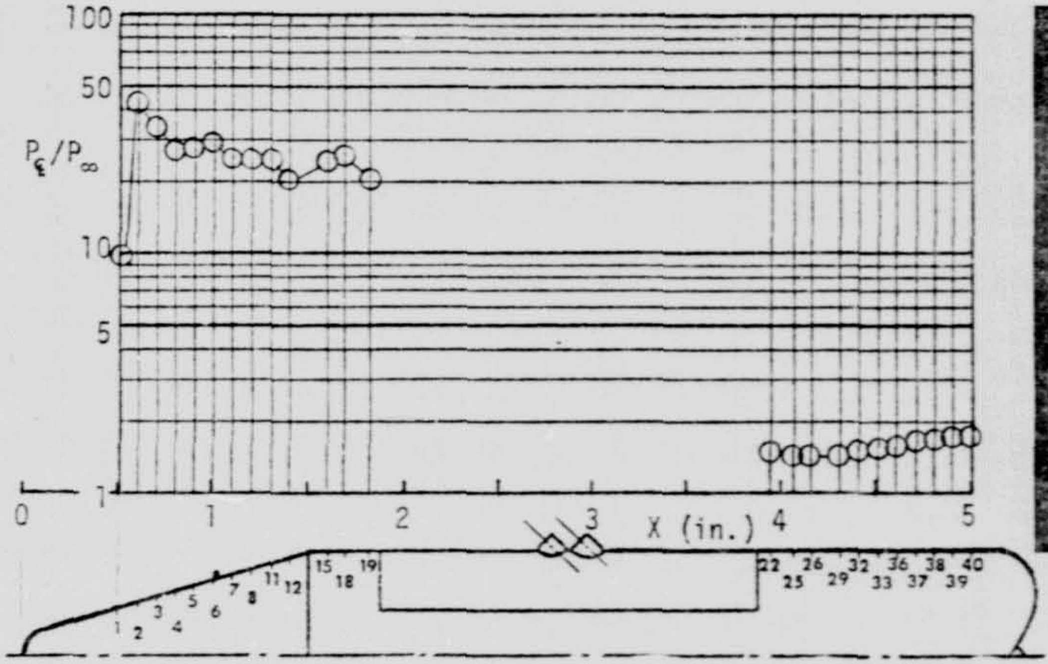
Of the 202 runs completed, 194 gave useful results representing approximately 14,000 digital data points and 156 schlieren flow visualization photographs.

SEPTEMBER 9, 1975 — MSFC TRISONIC WIND TUNNEL — HUNTSVILLE, ALABAMA
TEST 612 — RUN 99/0 — PLUME TECHNOLOGY---SHORT MODEL

Gas = CF_4
Nozzle ID = 7-M-4-45 S/N = 2

FR	PC (PSIA)	TC (F)	QJ/Q(INF)	MP(I)/P(INF) 1-20	MP(I)/P(INF) 21-40
1	1969.0	405.	239.71	9.655	5.082
2	1973.5	425.	239.16	43.897	1.584
3	1975.5	437.	239.46	33.820	1.268
4	1982.0	443.	240.43	27.534	1.242
5	1985.0	447.	240.25	28.732	1.432
6	1989.0	451.	241.26	28.977	1.451
7	1992.0	455.	241.74	25.473	1.340
8	1995.5	457.	242.07	25.893	1.316
9	1996.5	461.	242.19	22.841	1.467
10	1996.5	464.	242.21	14.933	1.394
11	1998.0	466.	242.37	25.275	1.356
12	2000.0	469.	242.79	25.414	1.537
13	2001.0	471.	242.74	20.431	1.570
14	2001.0	474.	242.55	11.931	1.489
15	2003.5	476.	243.22	25.508	1.420
16	2006.0	479.	243.53	15.875	1.642
17	2005.0	481.	243.22	5.692	1.689
18	2007.0	484.	243.46	26.288	1.728
19	2007.0	486.	243.46	20.375	1.776
20	2010.0	488.	243.83	9.070	1.808

AVERAGE VALUES--- PC= 1994.8 QJ/QI= 241.94 PTA= 33.16 PSA= 0.1228 MACH.= 4.450 R/L= 2.5 Q= 1.69



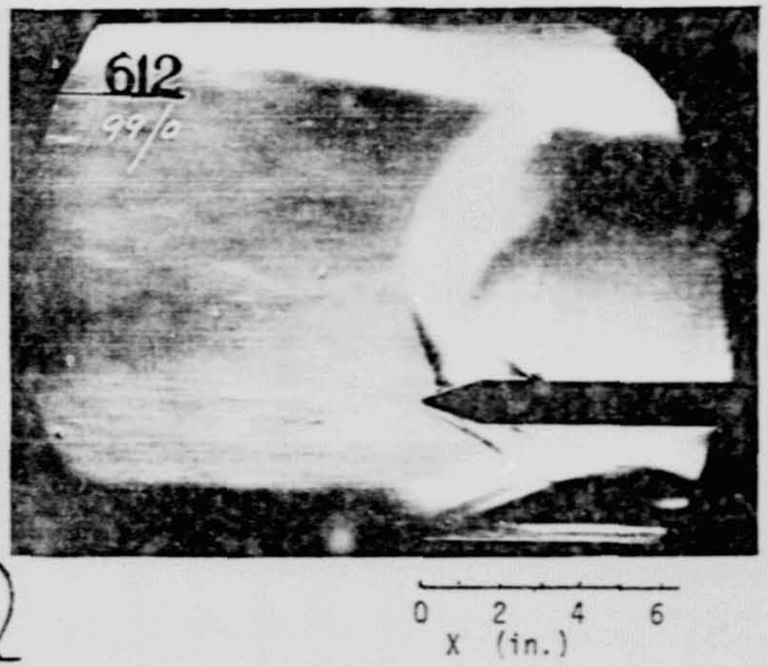


Figure 11. Example of Task 2 Test Data

Section 4

PARAMETRIC MEASUREMENTS IN SOLID PROPELLANT PLUMES

Solid propellant rocket motors are common items on space vehicles. There has been continuing effort to produce more accurate analyses of plumes of such rocket motors. The traditional method for evaluating the utility of analyses is to compare analytically-predicted properties with measured values and, of course, this method has been applied to these analyses. However, there have been several shortcomings regarding this approach:

1. Measured values of plume properties are scarce.
2. Measured values have not been acquired with enough repeat cases to provide high confidence in their reliability.
3. Data are not available for parametrically varied conditions.

An experimental program was conducted to overcome many of these shortcomings. The specific aim of this program was to increase confidence in a particular recently developed analysis of solid propellant rocket motor exhaust plumes (Ref. 18) for Space Shuttle applications. The overriding consideration was to acquire parametric data of the utmost reliability. Extensive use was made of repeat data points to enhance reliability. A new facility was provided by adding a vacuum capability, supplying instrumentation, and enhancing personnel access for the 50 ft diameter sphere which is the exhaust receiver for the MSFC High Reynolds Number Wind Tunnel (HRWT) (Ref. 19).

One rocket nozzle geometry representative of the shuttle SRB (ε = 7.6, θ_n = 15°) and one design chamber pressure (1000 psia) were used throughout. The test variables were propellant aluminum content and pressure altitude, encompassing Shuttle usage. Plume measurements included pressures, temperatures, forces, heat transfer rates, particle sampling, and high-speed movies. Approximately

210,000 digital data points and 15,000 movie frames were acquired in 90 firings. Measurements were made in the plumes via rake-mounted probes, and on the surface of a large plate impinged upon by the exhaust plume. Parametric variations were made in pressure altitude (50K, 100K, 112K feet), propellant aluminum loading (2%, 10%, 15%), impinged plate incidence angle (30°, 45°, 60°, 90°), and distance from nozzle exit to plate or rake (X/D = 5, 12, 16, 20). A nozzle calibration phase (with air, in the MSFC 14 x 14-Inch TWT) proceeded the basic test of rocket motors in the HRWT 50 ft sphere. A capsule summary is given in Table IV.

The basic test setup incorporated an array of plume instrumentation located in the exhaust plume of a small solid propellant rocket motor (Fig. 12). The rocket motors to produce the plumes were of a design which had been used frequently in U. S. Army Missile Research and Development Command Programs, Fig. 13. The motor was mounted onto the motor support for alignment with the plume instrumentation equipment. The propellant composition was 11.35% HTPB binder, 84% solids (AP and Aℓ), and 4.65% of specialized agents and plasticizer. Three aluminum contents were used: 2%, 10%, and 15%. The propellant (weighing approximately 0.3 lb.) was bonded to the case. The igniter was a separate component installed in the nozzle entrance during the motor assembly procedure. Peak thrust was less than 400 lb. Because of the brief motor operating time, ~200 msec, instrumentation required rapid response characteristics. Rocket nozzle and P_C transducers were located in close proximity to the measuring port to preclude response lags.

The plume instrumentation is shown in Fig. 14. The rake or plate could be positioned at any longitudinal location, and the plate could be rotated to several inclinations. The rake could accommodate pressure, heat rate, temperature, and force gage probes at 0.50 in. increments. The force gage was positioned with greater spacing so that its large bow shock would not interfere with adjacent gages. The purpose of this force gage was to confirm that the pitot pressure measured in this two-phase flow environment truly represents gas-phase pressure without spurious

TABLE IV

CAPSULE OF TASK 3 TEST SERIES

a. Summary (Showing Altitudes in Feet)
(No. of runs in parentheses)

	X/D = 5	X/D = 12	X/D = 16	X/D = 20	
Plate (ψ = 45°)	50K (6) 100K (6)	100K (6)		100K (26) (+ψ=30°,60°,90°)	6 38
Rake	50K (7) 100K (4)	100K (5) 112K (6)	100K (5)	100K (7) 112K (2)	7 21 8
Particle		100K (4)		100K (6)	10
	23	21	5	41	90

b. Details

Design P_c = 1000 psia

	X/D=5			X/D=12			X/D=16		X/D=20		
	2%	10%	15%	2%	10%	15%	2%	10%	2%	10%	15%
Plate ψ = 30°									●●●	●●	●●
ψ = 45°	●● ▲▲	●● ▲▲	●● ▲▲	●●	●●	●●			●●	●●	●●
ψ = 60°									●●	●●	●●
ψ = 90°									●●	●●	●●●
Rake	▲▲	●● ▲▲	●● ▲▲▲	6 ●●	66 ●	666 ●●	●●	●●●	6 ●●●	6 ●●	●●
Particle				●●	●	●			●●	●●	●●

6 112,000 feet pressure altitude
● 100,000 feet pressure altitude
▲ 50,000 feet pressure altitude

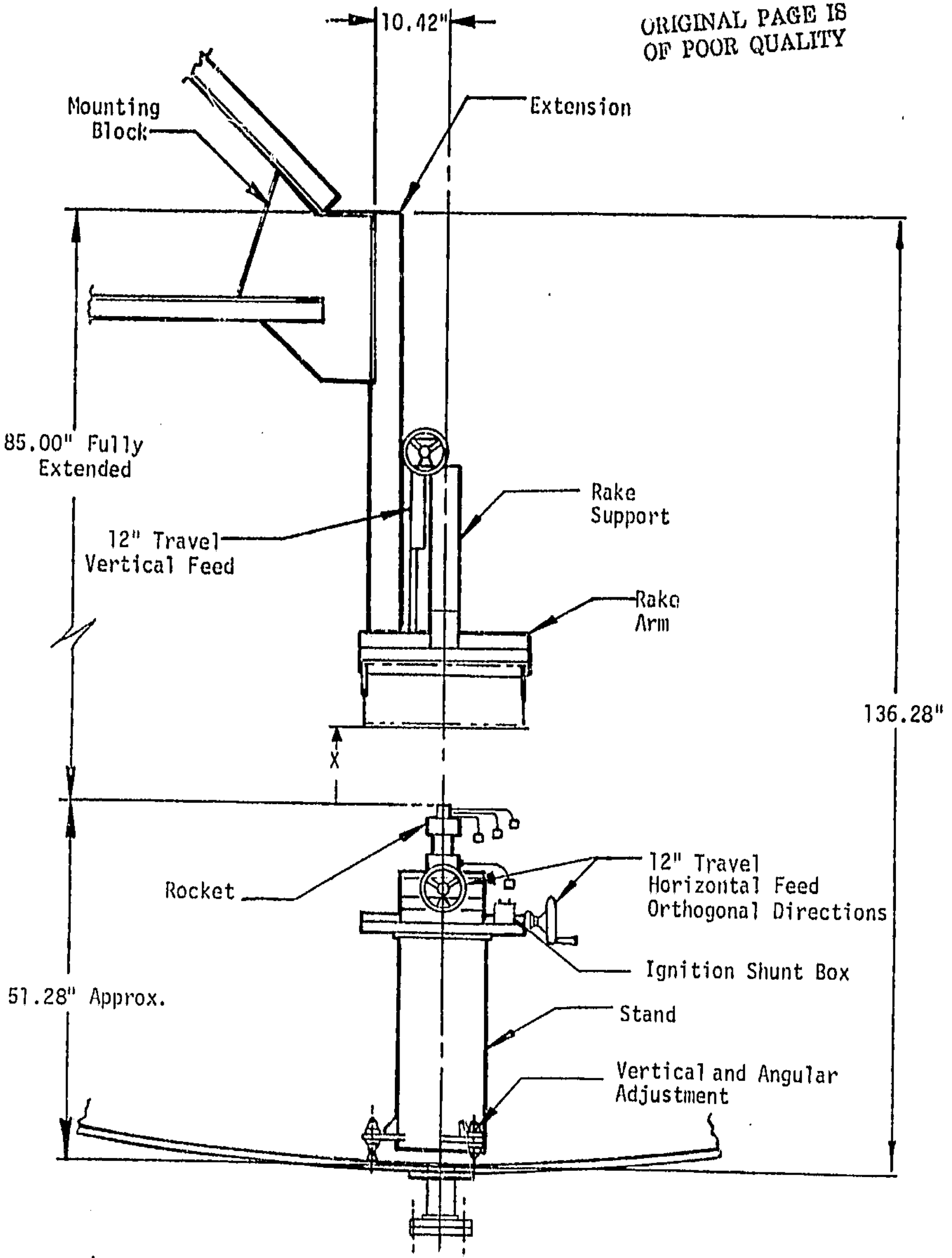


Figure 12. Task 3 Test Setup

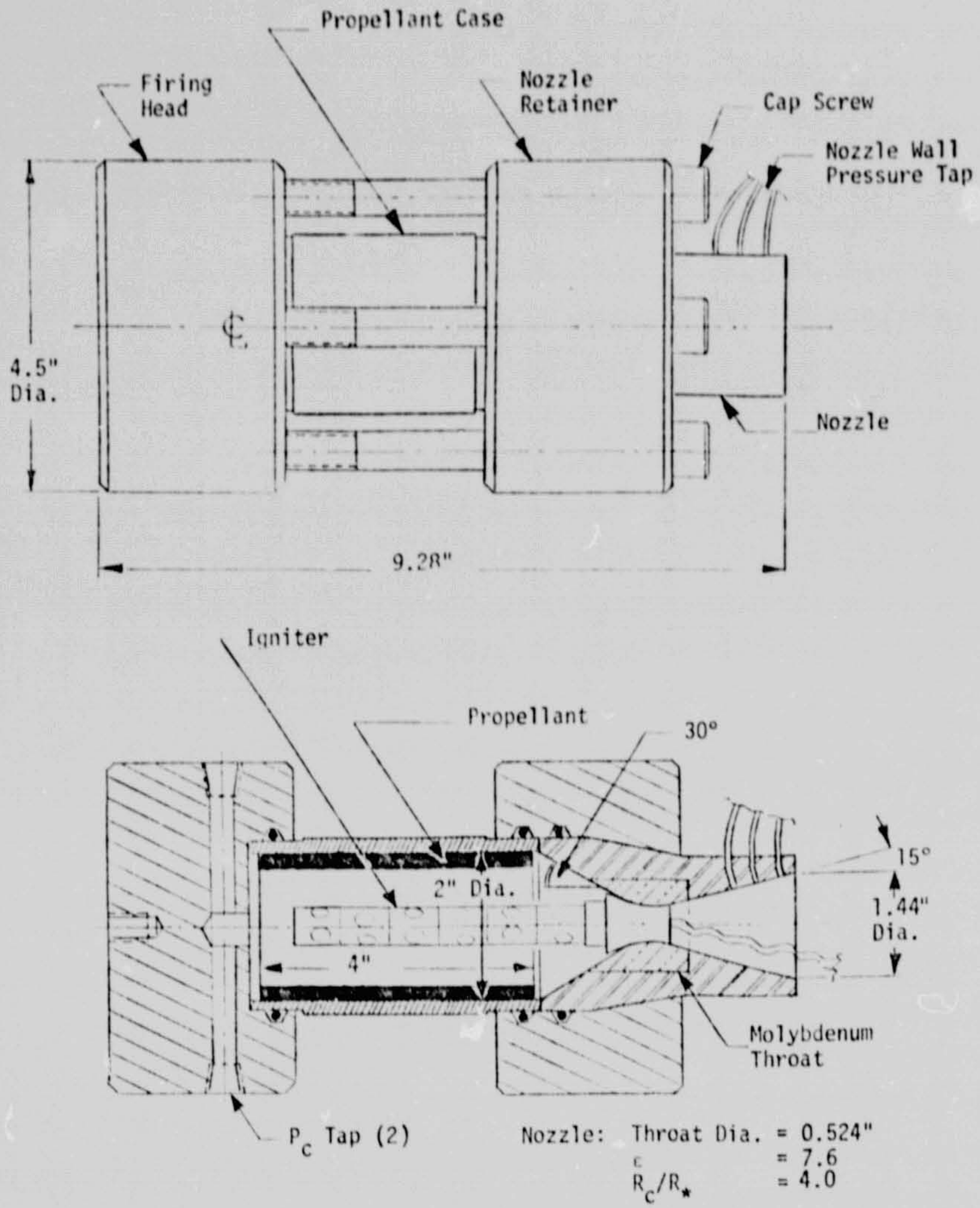


Figure 13. Task 3 Rocket Motor

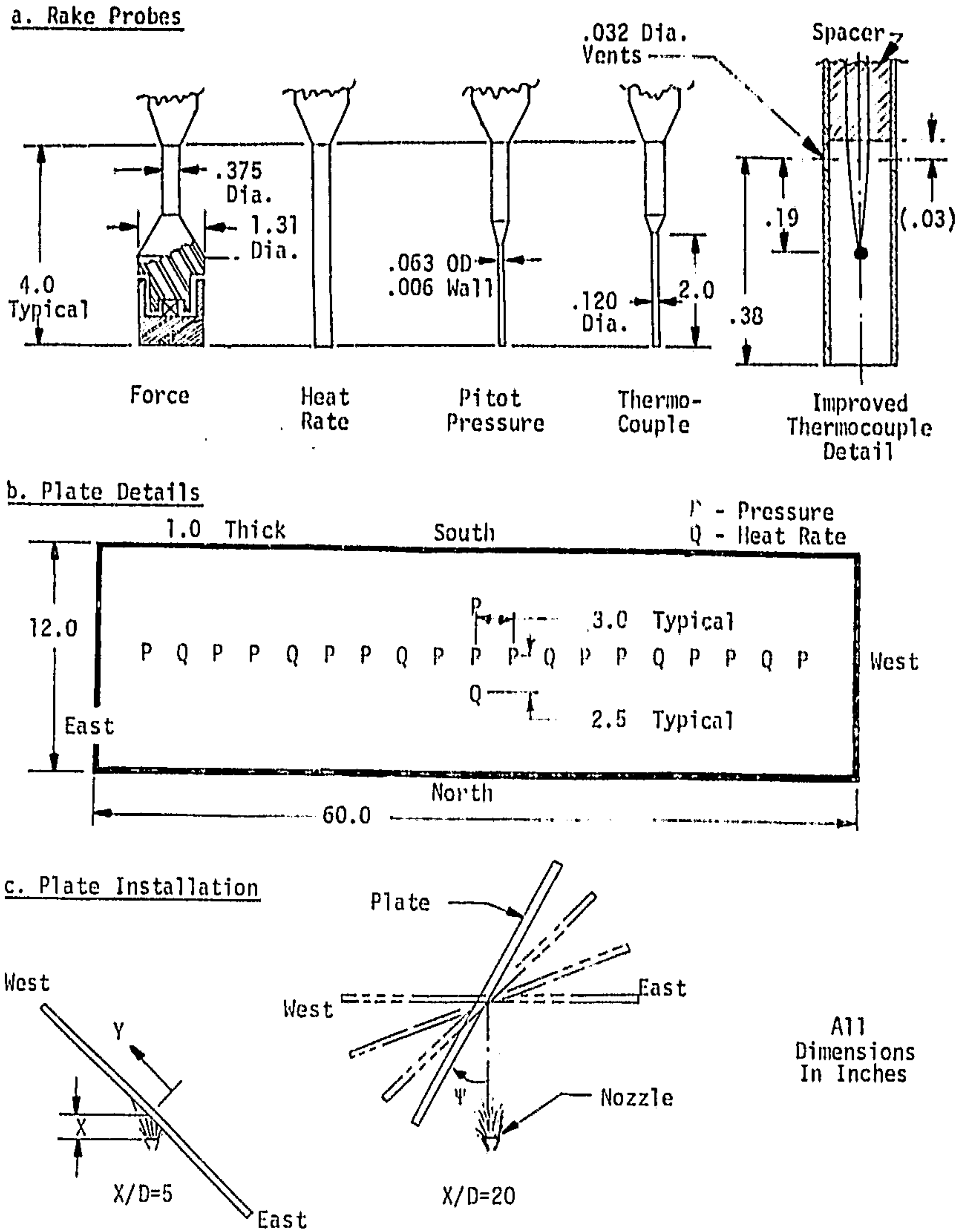


Figure 14. Task 3 Plume Instrumentation

d. Particle Sampler

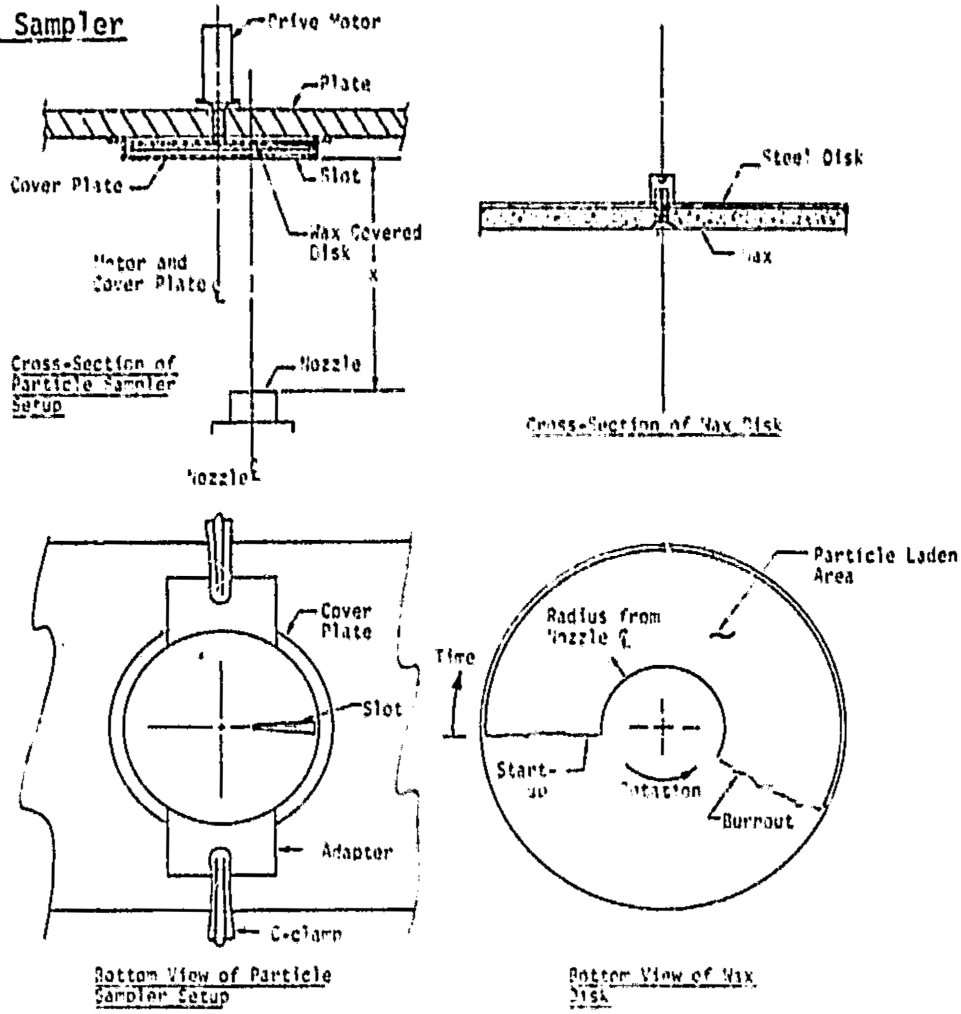


Figure 14. Concluded

particle-induced effects. The plate incorporated pressure and heat rate gages. Alignment and spacing of gages were fixed. Plate incidence angles (Ψ) were available at 15° increments. Plume pressures were measured with commercial transducers located in close proximity to the pitot tube face, approximately 10 in., to preclude response lags. The temperature measuring device was a W-.05Re/W-.26Re thermocouple, of 0.001 in. diameter wire, installed in a special probe. Heat rate measurement came from copper slug calorimeters with a nominal upper flux level of 600 Btu/ft^2/sec. The force gage incorporated a piezoelectric crystal.

Other instrumentation included movies and particle sampling. High speed color motion pictures (approximately 1500 frames/sec) were acquired using a camera in the sphere. The particle sampling equipment was intended to quantify the particle size distribution using a rotating wax disk (on a steel backplate) shielded by a slotted cover to limit the spatial extent of sampling. Particles arriving at the shield entered the slot and impinged the wax. Rotation of the disk behind this slot arrayed the particles on the wax in an arc which produced a time history, and the length of the slot produced a radial distribution. The disk was rotated at a speed such that the rocket motor start-up and tail-off particles would not overlap, yet still be arrayed over most of the disk.

Figure 15 shows photographs of typical installed instrumentation. Figure 16 shows test operations for several typical instrumentation setups, as photographed by the high speed movie camera. Typical time histories of test data are presented in Figure 17. As with the Task 1 test series, P_c was not explicitly controllable. The time histories were evaluated to identify an interval of 50 msec during which P_c was acceptably smooth. The data were then averaged over this identified interval. Data selected by this process are presented in Figures 18-20.

Equipment durability was excellent, although there was instrumentation deterioration at X/D = 5. The motors had adequately constant chamber pressure characteristics, although P_c was less than design for the 2% and 10% Aℓ propellants. However, the program goal was satisfied and 90 runs were performed in 46 working days. A routine operation of 3-4 runs/day was developed. At least one repeat point was made for each test condition. (The original plan called for 3 runs at each condition to provide highest confidence in the data, but demonstrated repeatability was found to be adequate with only 2 runs.) Measurements of stagnation temperatures were not reliable nor was particle number density counting successful, but the repeatability of pressure and heat rate measurements was excellent. The resulting parametric matrix of pressure and heat rate data is the most complete set of solid propellant rocket exhaust plume and plume impingement data available to date.

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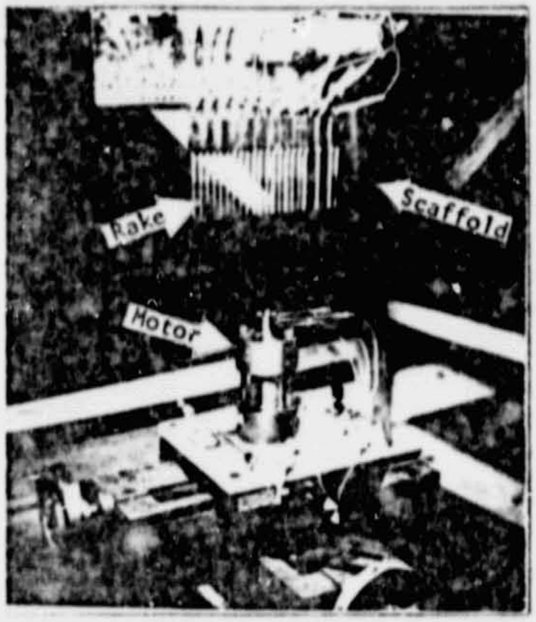
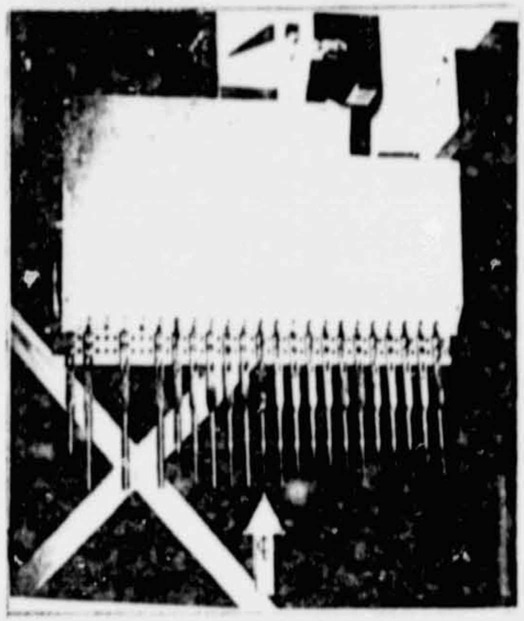
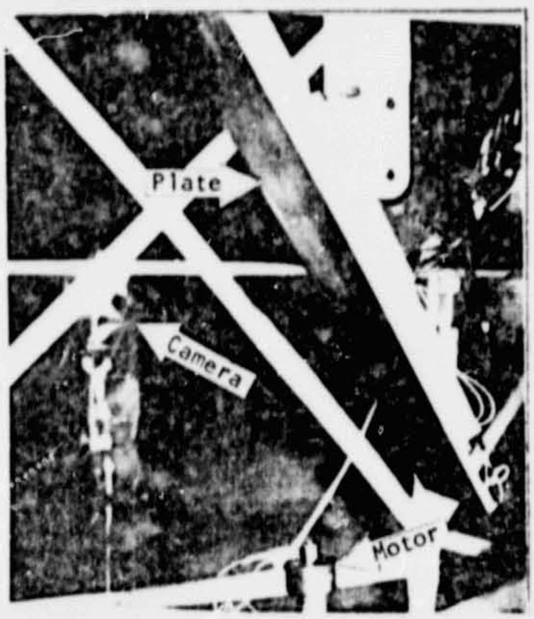
a. Overall View (looking North-East)



b. Rake (looking South)



c. Plate (looking South)



d. Particle Sampler (on Plate)

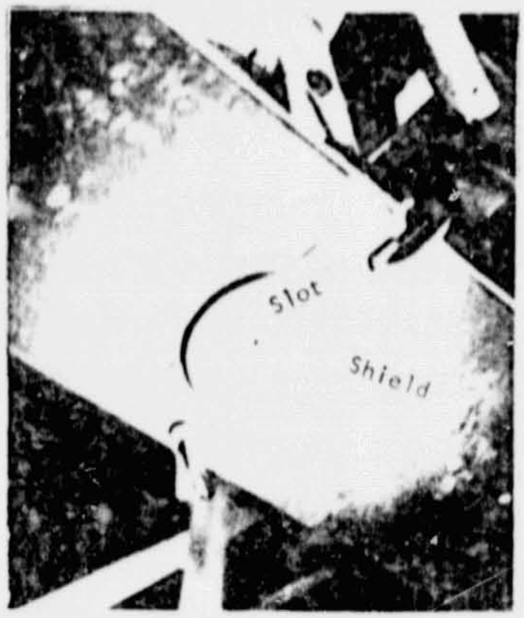


Figure 15. Task 3 Installations

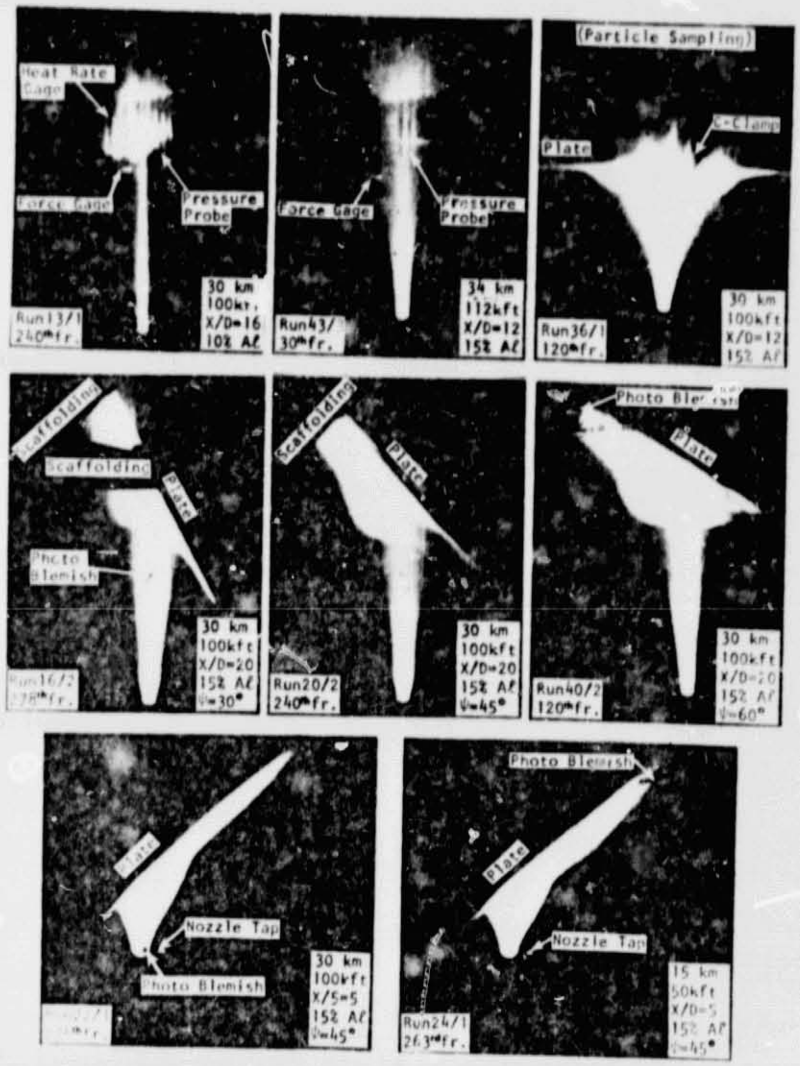


Figure 16 Typical Task 3 Operations

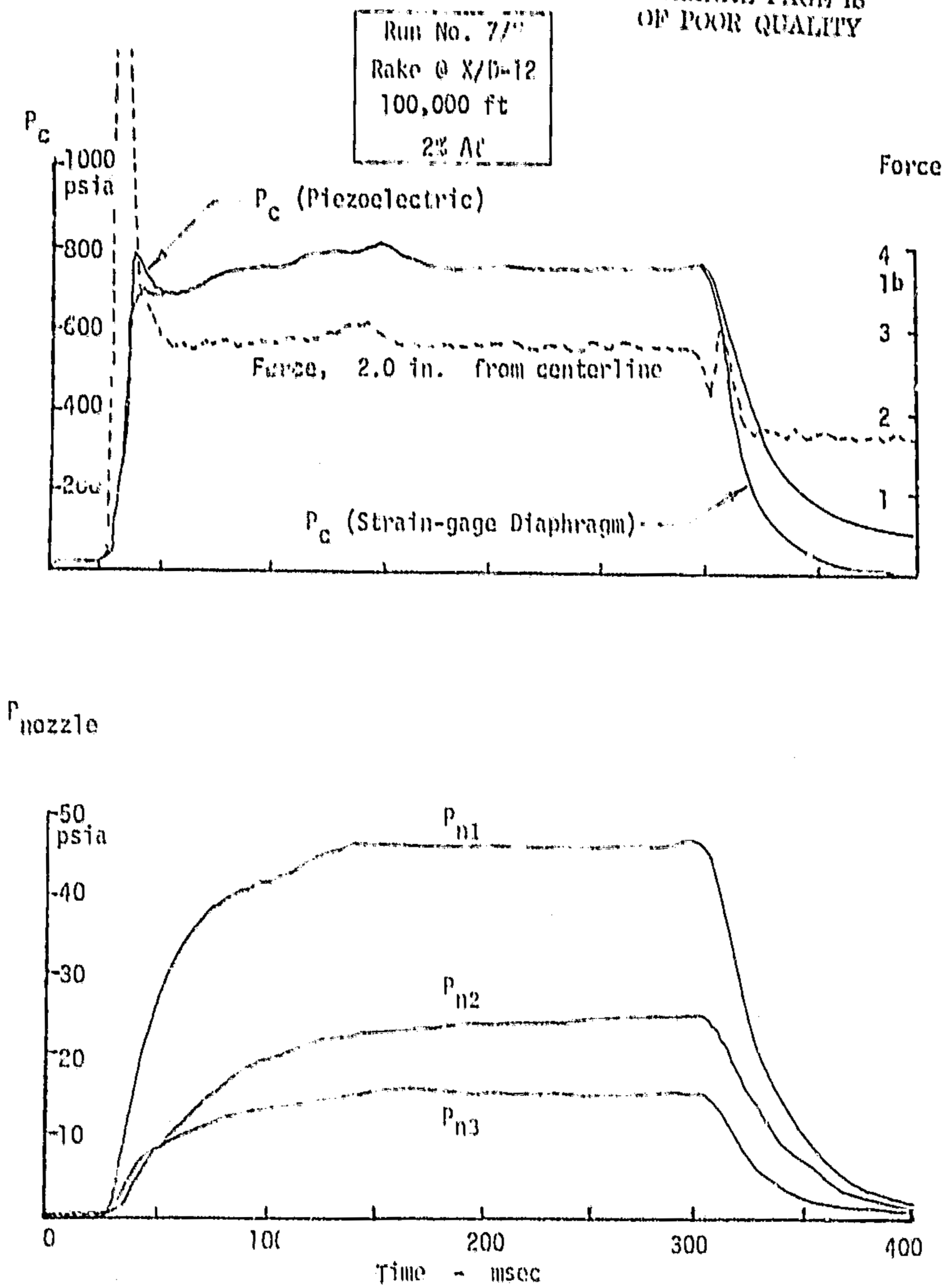


Figure 17. Task 3 Time Histories of Data.

Radial Position in inches from centerline

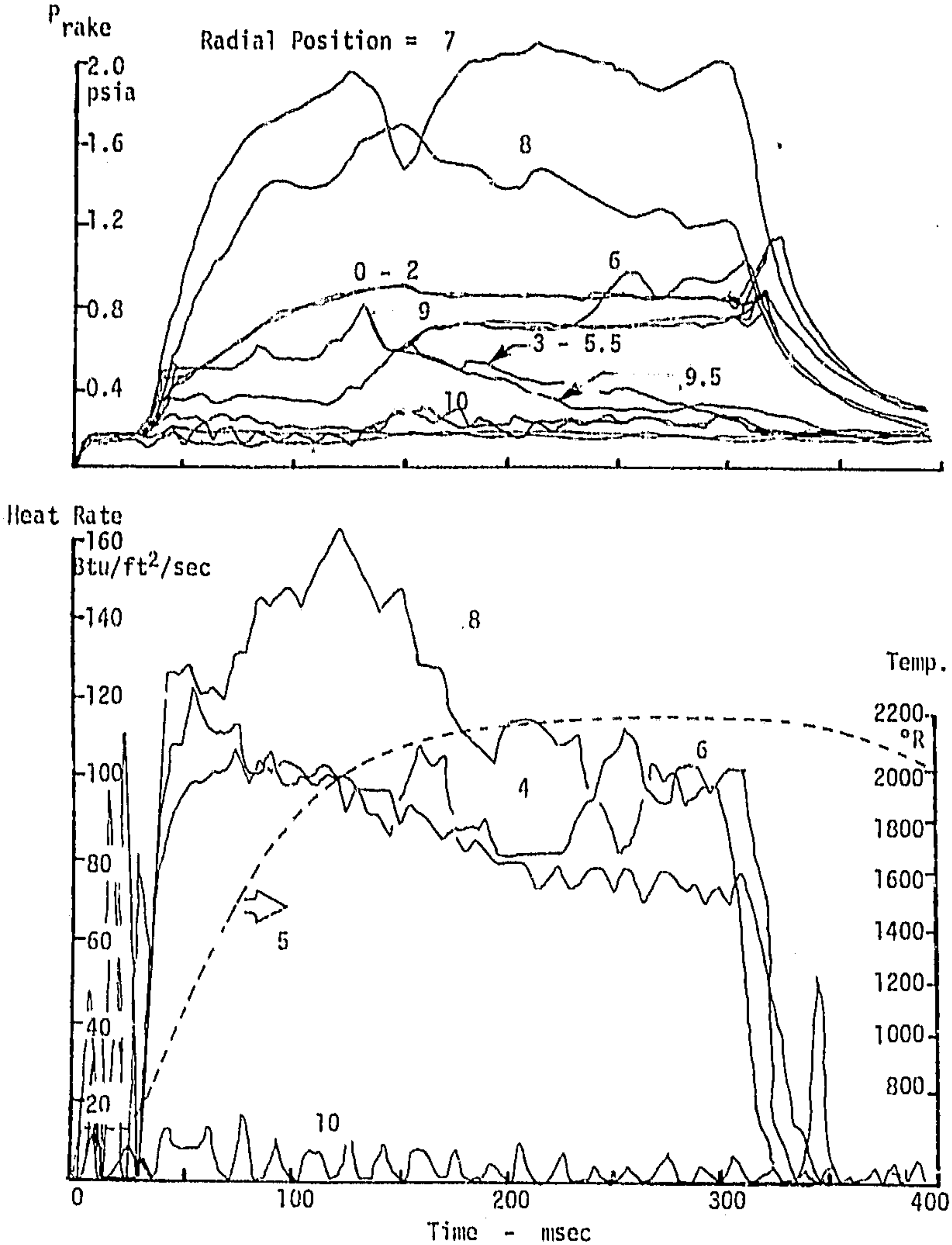


Figure 17. Concluded

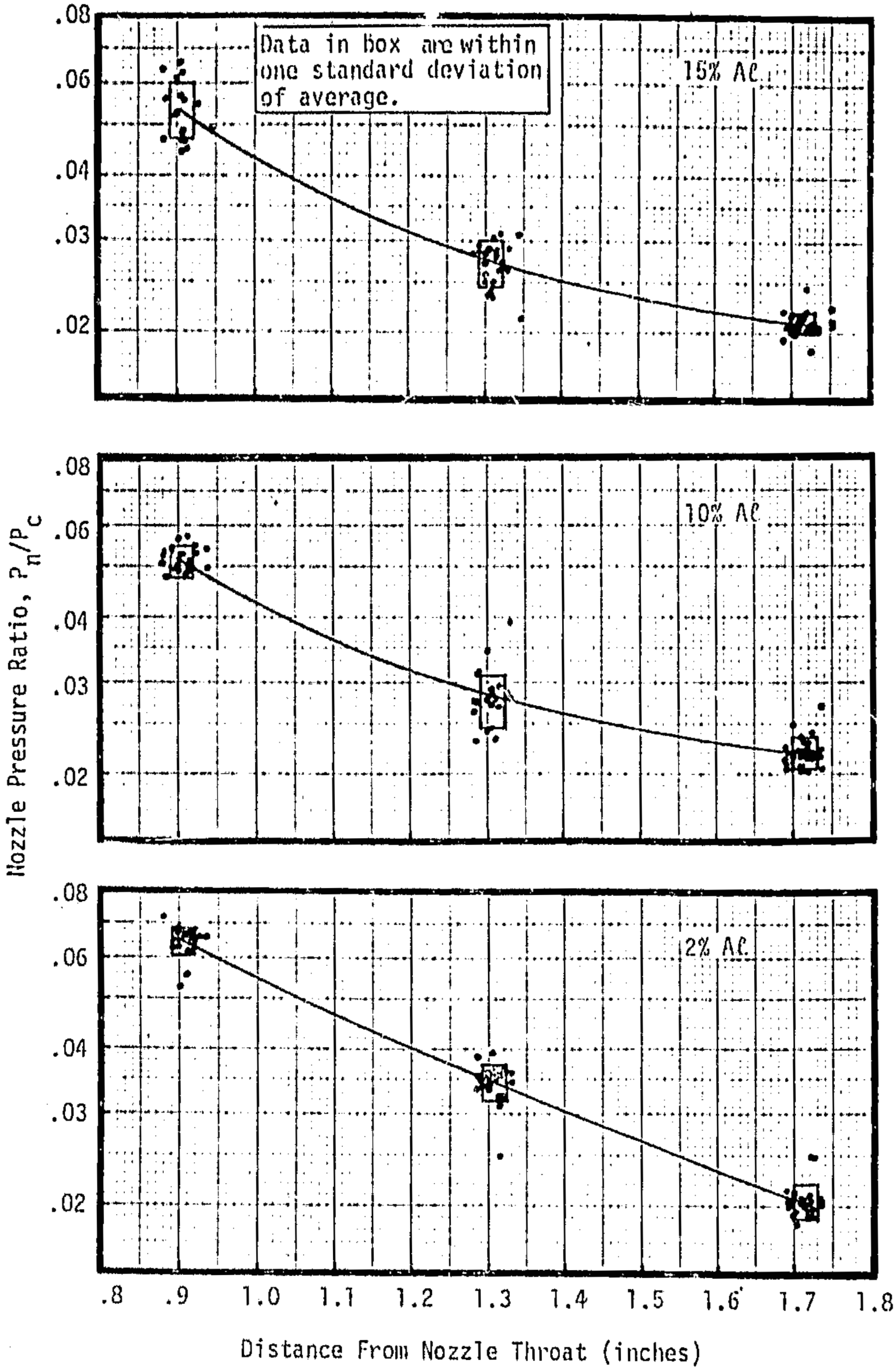


Figure 18. Task 3 Nozzle Data Summary

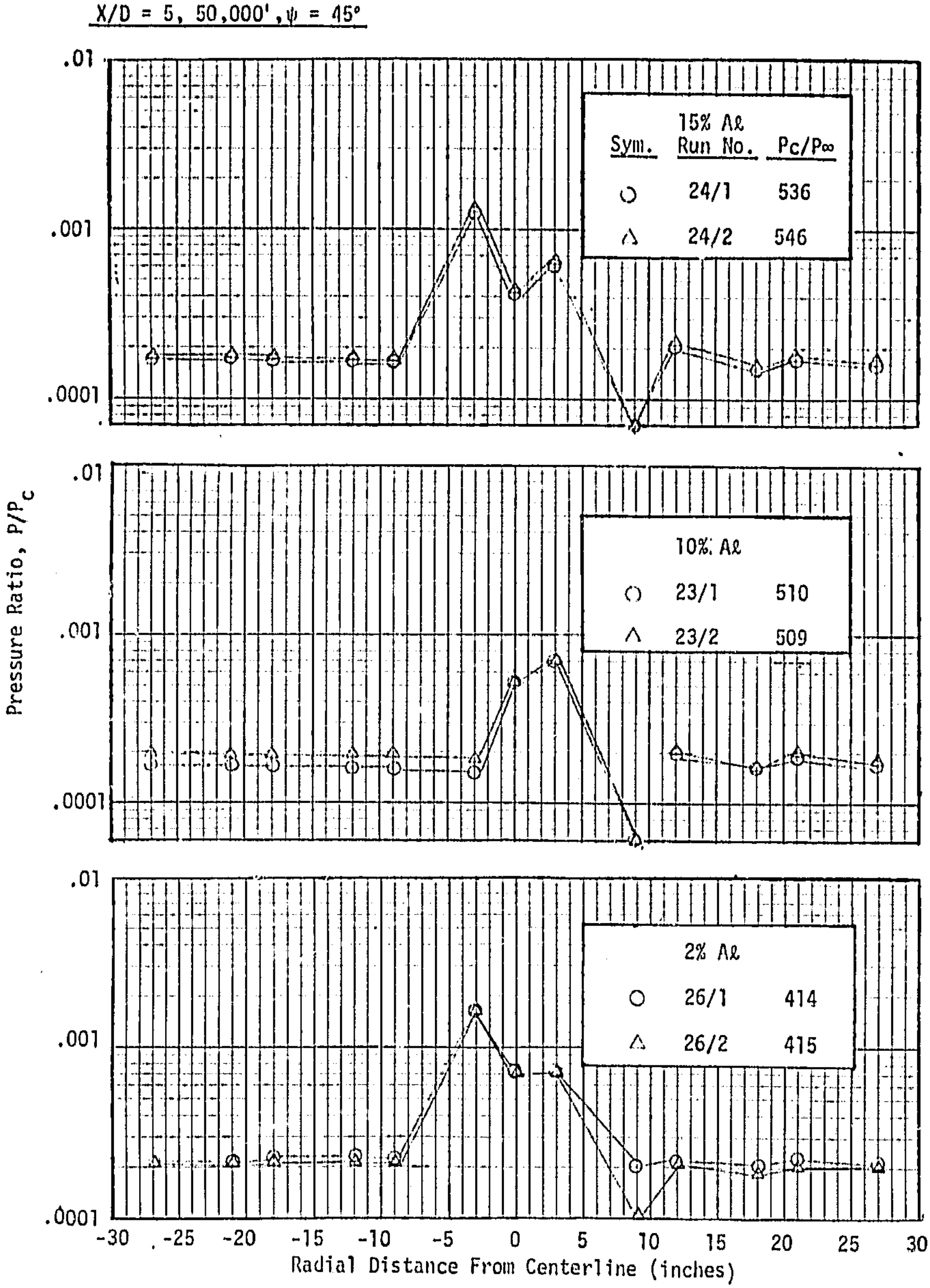


Figure 19. Example of Task 3 Plate Data Summary

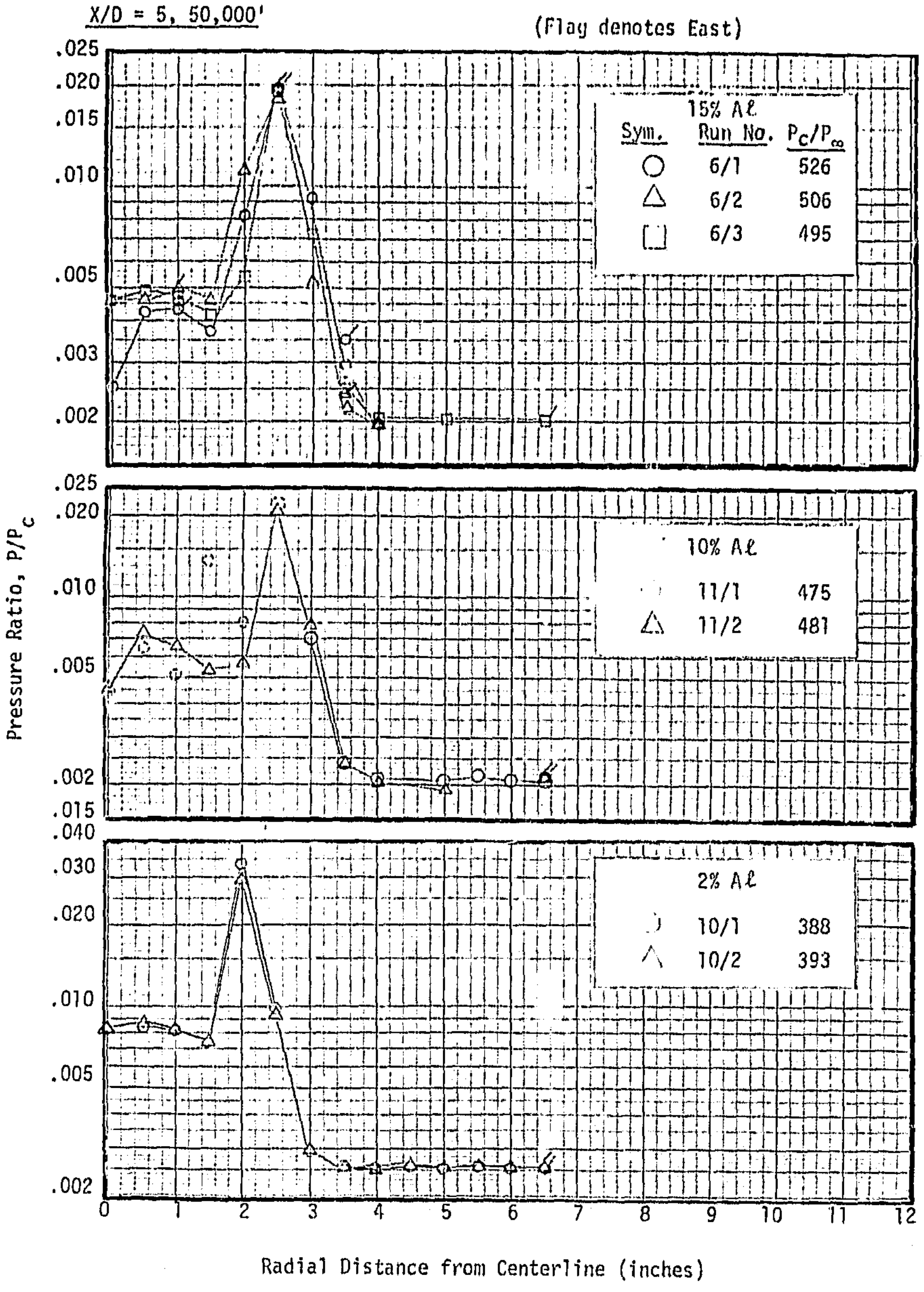


Figure 20. Example of Task 3 Rake Data Summary

Section 5

PLUME SIMULATION DATA SUMMARY

Design of rocket powered vehicles such as Saturn I & V, Space Shuttle, and large military rockets is considerably influenced by the aerodynamic effect induced by the main propulsion rocket engines. Aerodynamic design data for these vehicle types are usually obtained from wind tunnel tests of scaled vehicle models where the main propulsion engine plumes are simulated by flowing gases such as air or some product of combustion through model nozzles. A multi-element study was begun to develop an improved plume simulation procedure for use in design of the Space Shuttle Launch Vehicle (SSLV). Task 4 consisted of gathering and summarizing all of the wind tunnel test data generated on that study.

The basic plan of that overall study called for conducting a series of parametric wind tunnel tests that had sufficient controls to allow independent assessment of the pertinent variables. Variables included nozzle geometry, propellant gas type, chamber pressure, and chamber temperature for fixed model external geometry and wind tunnel freestream conditions. That matrix of variables was then repeated for configuration types which are important to the SSLV such as multiple nozzles and multiple bases. The propellant gases were chosen to encompass both air and SSLV prototype gasdynamic characteristics. Then, correlations could be tried until one was found which would reasonably overlay the base pressure effects using either air or prototype propellant gases. This approach could also be attempted for the various external configuration types and freestream Mach numbers to determine their applicability over the range of conditions that would be encountered with the SSLV. It was believed that for a plume simulation program to be a success, it would be necessary to fully understand the model and prototype nozzle and plume flowfields, and to conduct the wind tunnel tests with some parametric variations. To attack the simulation problem in a parametric fashion it would be required to know the measurable parameters considered for this investigation: Model external geometry; external flow conditions (M_∞, P_{t_∞}, P_∞, T_{t_∞} - air assumed); nozzle internal geometry; and internal flow conditions (P_c, T_c, γ, R, etc. - thermochemical characteristics which are fixed for each exhaust gas). From the outset, it was decided to use a simple classic configuration (Fig. 21) such as the cone-ogive-cylinder as a baseline for investigation of the plume-to-freestream interaction in the base region. Initially, the base geometry was limited to two configurations, a classic single nozzle and a triple nozzle arranged symmetrically on the base (orbiter class). In both cases, the exit planes were aft of the base. Using these configurations as baselines, the remaining parameters were varied. As illustrated in Figure 21, two gases were chosen as prototypes: CF_4 for its variable γ characteristics at medium temperatures, and an aluminized solid propellant for its two-phase and high temperature characteristics. Air was used as the primary simulant gas . Later, helium was used to obtain a different constant-γ flow. The table below illustrates the matrix of gases and configurations that was accomplished during this test series. Figure 22 details the overall test program matrix. Note that data from three tests were omitted because of their questionable quality.

GENERAL TEST MATRIX

Gas	Model Configuration			
	Classic Geometry (Single Nozzle)	Orbiter Class (Triple Nozzle)	ET/SRB Class (Triple Body)	SRB Class (Flare)
Helium	√	√		
Air	√	√	√	√
CF_4	√	√	√	√
2% Aℓ (a)	√			
16% Aℓ (b)	√		√	

a Combustion products of ammonium-perchlorate-based solid propellant with 2% Aℓ in CTPB binder

b Combustion products of ammonium-perchlorate-based solid propellant with 16% Aℓ in PBAN binder

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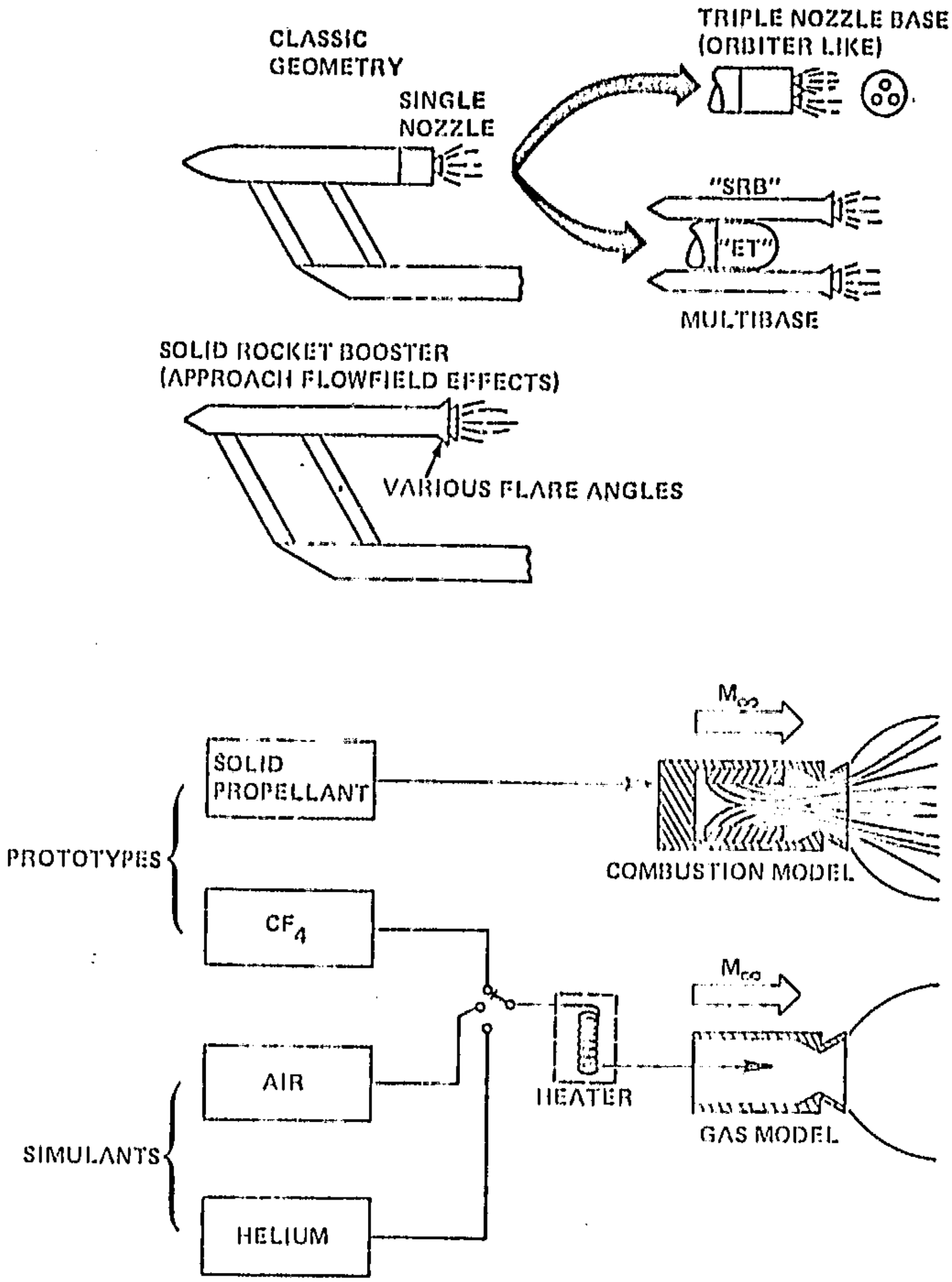


Figure 21. Experimental Concept for Data in Task 4

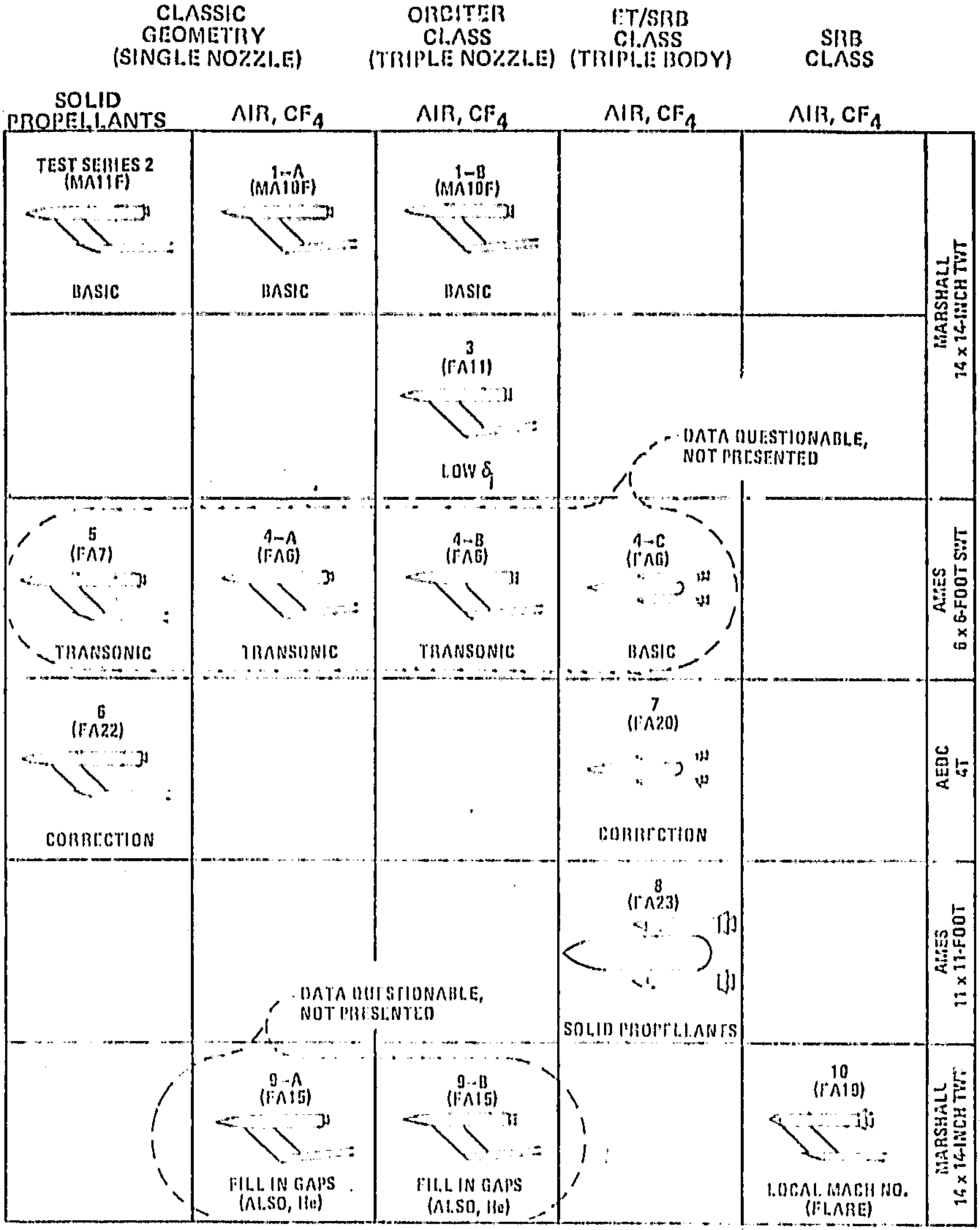


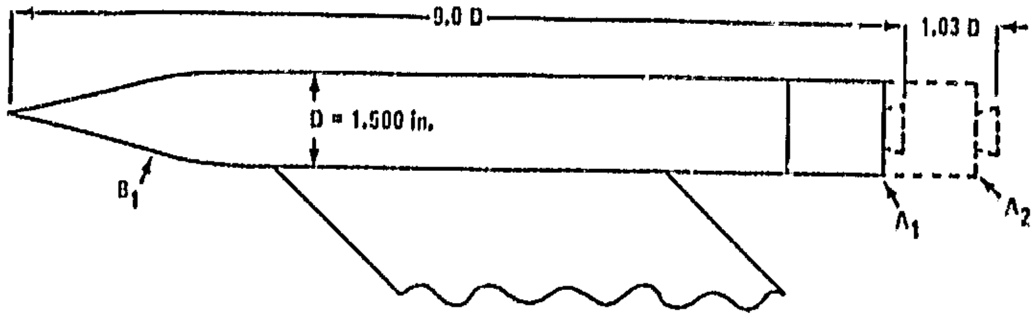
Figure 22. Overall Program Schematic for Data in Task 4

Fundamental to this program was the understanding of the model nozzle performance to the exit plane. It was believed that errors between flight and wind tunnel data on previous programs may have been due in part to lack of understanding of the flow in both prototype and model nozzles. To conduct the parametric program as planned it would be imperative to accurately quantify parameters that would possibly be used in a simulation equation, such as temperature and pressure (and thus γ or other thermodynamic properties). Therefore, great care was taken to provide instrumentation from which the nozzle performance could be determined. Furthermore, each nozzle was calibrated under quiescent external flow conditions.

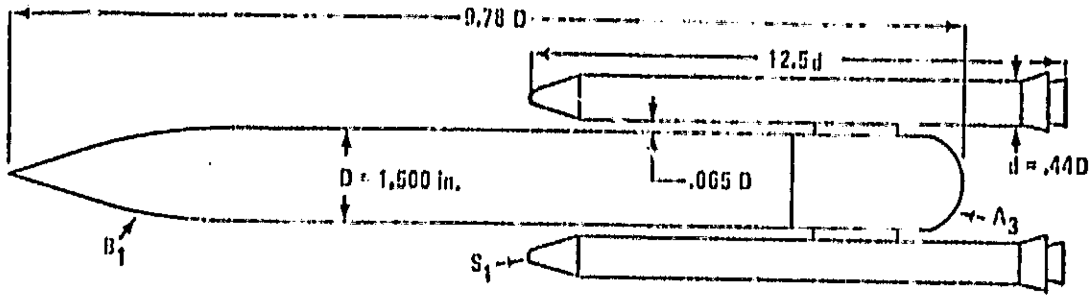
There was a wide variety of apparatus used: four wind tunnels and five model assemblies (with attendent instrumentation) plus some auxiliary equipment such as the gas generator and heater mentioned on Tasks 1 and 2, respectively, above. Details of all of this equipment are given in Ref. 5. A summary of the models and nozzles is given in Figure 23.

A total of 10 test series were performed. The general quality of these tests is presented in Table V. There were seven tests for which the bulk of the data were acceptable. Table VI summarizes the conditions of these tests. A great deal of model pressure data were acquired, for model chamber, nozzle wall, and model base regions. The base pressure is affected by plume flow in the base region, and the size of the plume is a first order parameter to be considered in performing simulation analyses. Further, the initial plume angle (δ_j) is a good indicator of relative plume size. The range of plume sizes available in the data, as a function of M_∞, gas type, and configuration class, are shown in Figure 24.

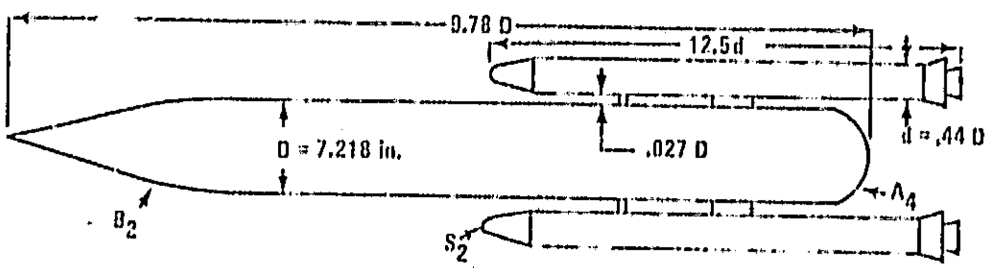
The data gathered and summarized in Task 4 were grouped into three categories. The first category was the (single) base pressure of primary interest to development of a simulation parameter, along with the model chamber and wind tunnel freestream conditions. The location of these pressures on the various models is



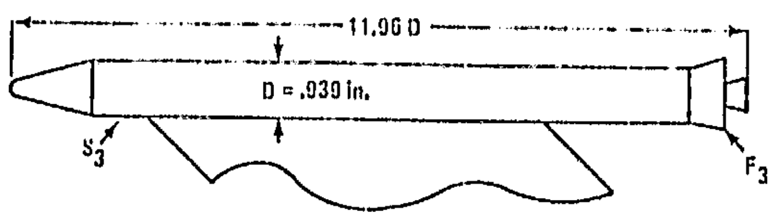
(a) CLASSIC AND ORBITER CLASS FOR GASES AND SOLID PROPELLANTS



(b) ET/SRB CLASS FOR GASES

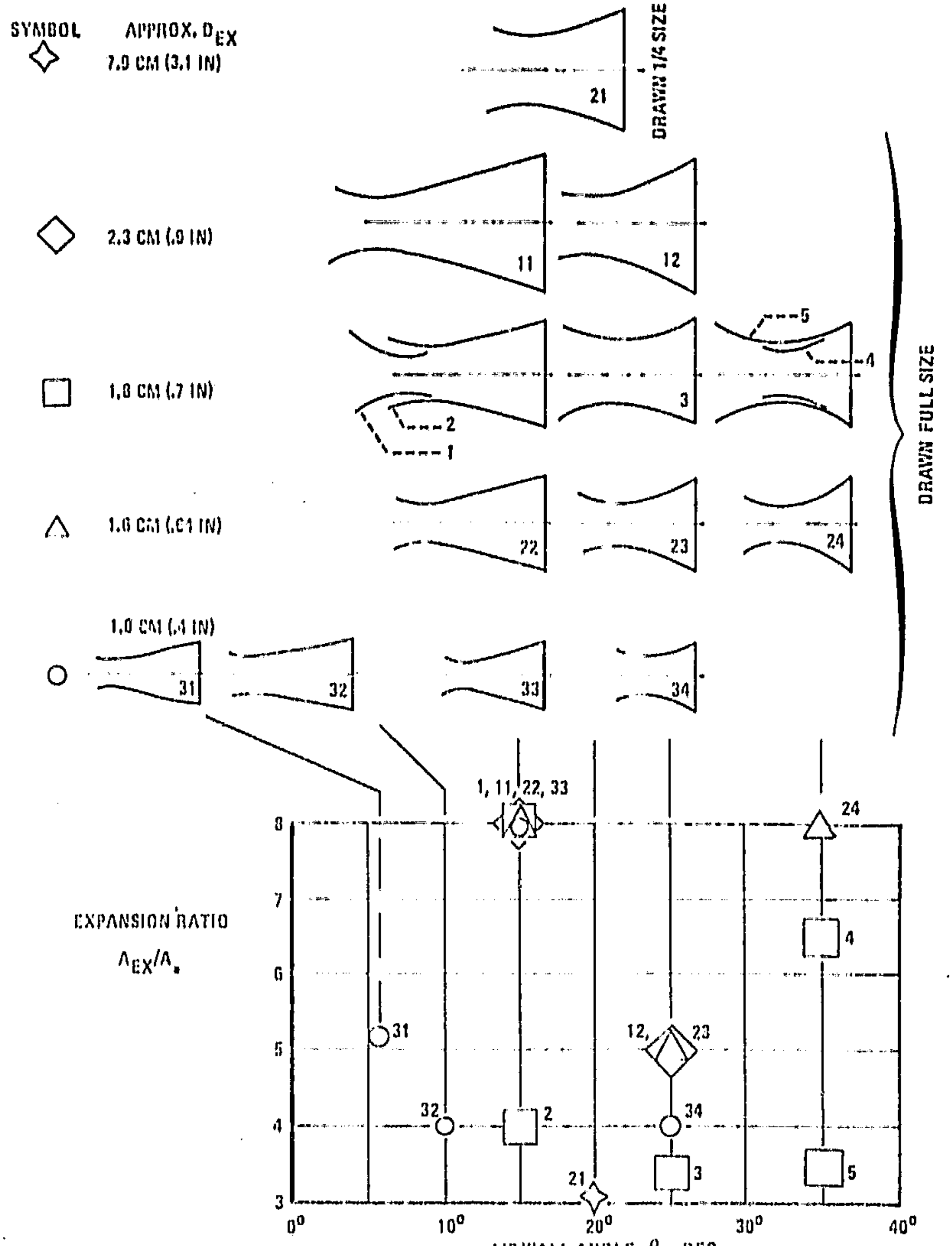


(c) ET/SRB CLASS FOR SOLID PROPELLANTS



(d) SRB CLASS FOR GASES

Figure 23. Summary of Models and Nozzles for Data in Task 4



(e) NOZZLES

Figure 23. Concluded

TABLE V - SUMMARY OF QUALITY OF TESTS INCLUDED IN TASK 4

Test	Data Usability
1 (MA10F)	Acceptable, some discrepancies in nozzle wall pressures.
3 (FA11)	Acceptable, some discrepancies in nozzle wall pressures.
6 (FA22)	Low confidence in P_c values due to propellant contamination.
7 (FA20)	Acceptable
2 (MA11F)	Subsonic and low supersonic data not usable due to tunnel being too slow to respond to plume-induced pressure transient before motor termination; quality of pressure transducers questionable for supersonic data.
8 (FA23)	Transonic portion acceptable; unresolved question about which serial no. nozzle was used on left and right SRB.
10 (FA19)	Acceptable for qualitative comparisons within this data set, but tunnel interference precludes quantitative comparison with data from other sources.

TABLE VI - SUMMARY OF TEST CONDITIONS FOR DATA IN TASK 4

Class	Model	Nozzle	Gas	δ_{jb} (0, 20, 40, 60)	M_∞ (0.5, 1.0, 1.5, 2.0, 3.5)	Test Series
Classic	B_1A_1	3	Air			1
		4				
		5				
		1A	CF_4			
	B_1A_2	1B,1C	a,b			2
		1D,1E				6
		2A				2
		2B				6
Orbiter	B_1A_1	31	Air			3
		32				
		33				
		34				
		33	CF_4			
ET/SRB	$B_1A_3S_1$	23	Air			7
		24				
		22	CF_4			
	$B_2A_4S_2$	21	b			8
SRB	S_3F_1	12	Air			10
		11	CF_4			
	S_3F	12	Air			

a 2% Aℓ Solid Propellant
b 16% Aℓ Solid Propellant

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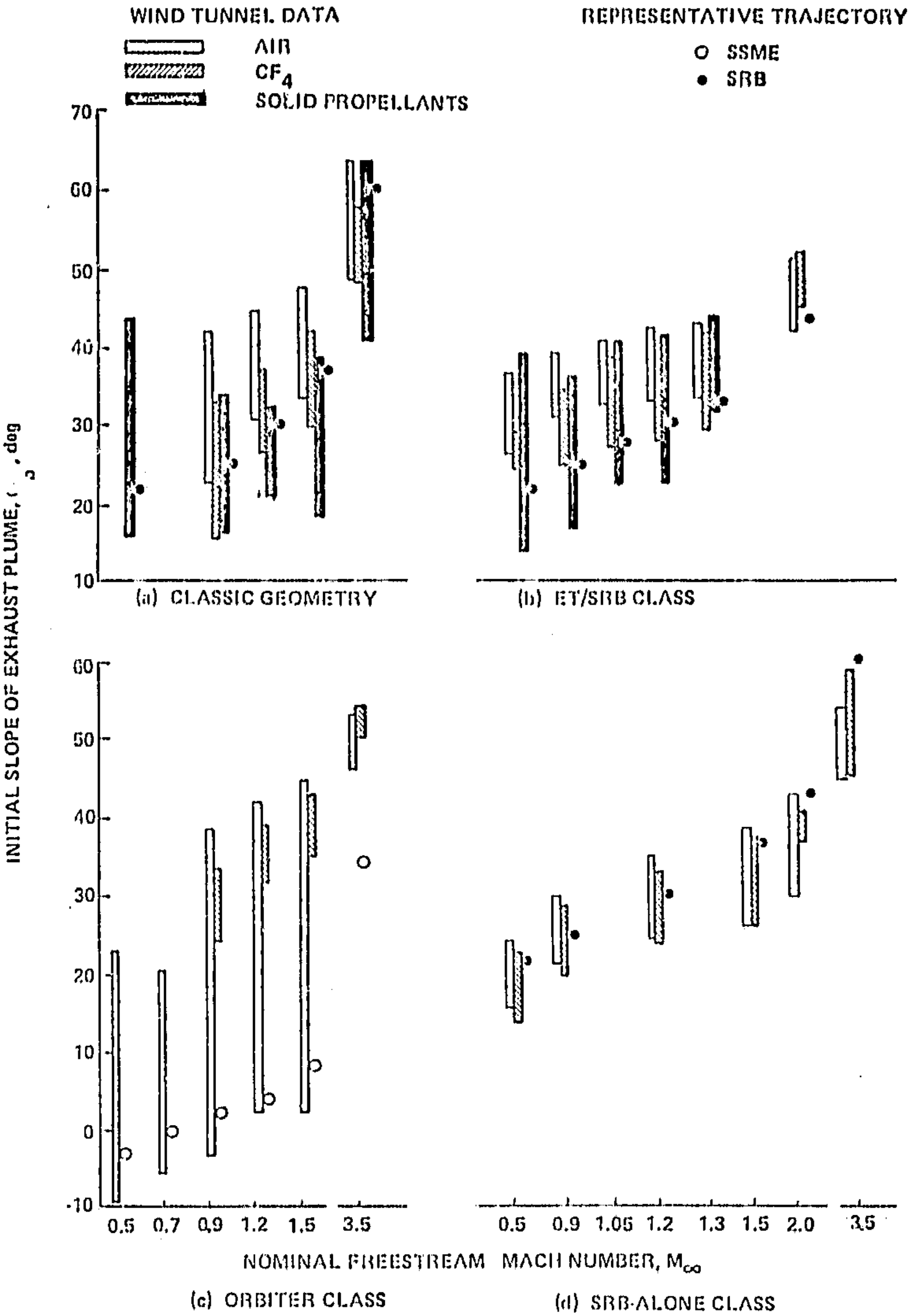
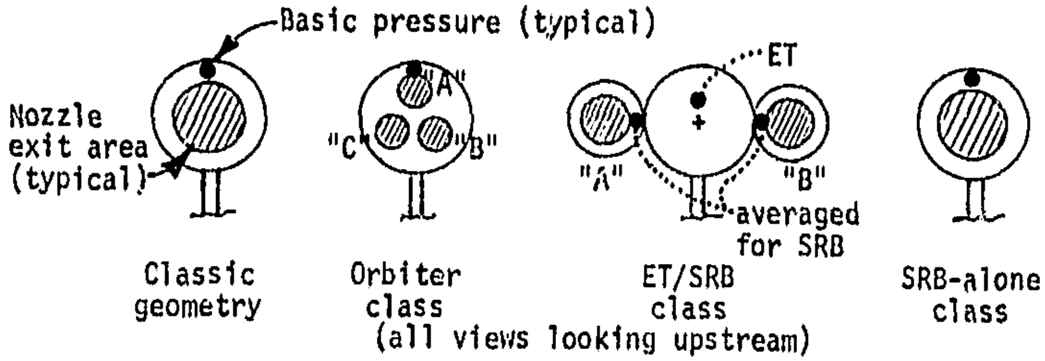


Figure 24. Range of Plume Sizes for Data in Task 4

sketched below:



An example of this category of data is presented in Figure 25. The second category was the complete set of base, body, and nozzle pressures. An example of this category of data is presented in Figure 26. The third category was the nozzle calibration data, of which an example is shown in Figure 27.

The complete set of ten test series spanned a three-year period, representing approximately 8 months of wind tunnel occupancy. There were approximately 1200 runs producing 300,000 digital data points. After the Task 4 screening, there remained 661 valid runs comprising about 21,000 digital data points, all of which were compactly presented in Ref. 5.

TEST DATA OF PRIMARY INTEREST - CLASSIC GEOMETRY

ID.	FREESTREAM				CHAMBER		BASE		
RUN/ RERUN	M	P (PSFA)	TT (°R)	RE/L (M/FT)	PC (PSIA)	TC (°R)	PB/P	PC/PB	PC/P
TEST 1	---			G1,N3	(AIR, A/A=3.5, 25 DEG.)				
372/0	.889	1553	563	5.0	0	0	.948	0	0
356/0	.888	1553	563	5.0	466	958	.846	51	43
323/0	.903	1528	562	5.1	472	518	.841	53	44
357/0	.901	1531	564	5.0	837	966	.933	84	79
354/0	.906	1524	561	5.1	865	702	.939	87	82
322/0	.908	1520	562	5.1	952	510	.967	93	90
353/0	.905	1525	561	5.1	1217	708	.994	116	115
358/0	.901	1532	562	5.1	1234	989	.995	117	116
321/0	.910	1516	563	5.1	1422	510	1.047	129	135
359/0	.902	1530	562	5.1	1501	983	1.029	137	141
352/0	.907	1523	561	5.1	1584	712	1.037	144	150
320/0	.909	1517	563	5.1	1746	504	1.087	152	166
373/0	1.194	1078	562	5.4	0	0	.913	0	0
363/0	1.194	1075	563	5.4	451	950	.709	85	60
316/0	1.208	1059	563	5.4	519	571	.741	95	71
362/0	1.194	1073	562	5.4	854	984	.864	132	114
349/0	1.206	1062	561	5.4	856	704	.873	133	116
317/0	1.206	1061	563	5.4	1054	511	.967	143	143
350/0	1.203	1066	561	5.4	1211	711	.979	167	164
329/0	1.189	1086	562	5.4	1251	883	.993	167	166
361/0	1.211	1055	562	5.4	1224	1004	.994	168	167
328/0	1.186	1089	562	5.4	1502	890	1.057	188	199
318/0	1.207	1060	563	5.4	1545	507	1.138	184	210
351/0	1.203	1066	562	5.4	1616	708	1.074	203	218
360/0	1.208	1058	561	5.4	1619	1021	1.092	202	220
319/0	1.207	1060	562	5.4	1808	508	1.207	204	246
374/0	1.459	749	564	5.2	0	0	.962	0	0
347/0	1.459	750	563	5.2	461	737	.766	116	89
364/0	1.468	741	566	5.2	460	931	.770	116	89
315/0	1.459	749	563	5.2	510	512	.801	122	98
365/0	1.484	723	566	5.2	847	961	.924	182	169
346/0	1.479	728	561	5.2	857	730	.919	184	170
314/0	1.477	731	563	5.2	983	510	.985	197	194
345/0	1.482	725	560	5.3	1202	717	1.012	236	239

Figure 25. Example of Task 4 Base Pressure Data of Primary Interest

BASE AND BODY SURFACE PRESSURE RATIOS (P/P_∞) FOR CLASSIC GEOMETRY
(A) 51A1

X/D	R/R	Ø=0	=60	=180	Ø=0	=60	=180	Ø=0	=60	=180	Ø=0	=60	=180
		TEST 1, RUN 372/0			TEST 1, RUN 356/0			TEST 1, RUN 323/0			TEST 1, RUN 357/0		
0	.52	.915	.898		.850	.854		.845	.849		.940	.948	
0	.64	.948	.964	.902	.846	.847	.856	.841	.843	.851	.933	.936	.948
.03	1.0	.935	.919	.935	.892	.875	.906	.891	.875	.903	.952	.939	.966
.22	1.0	.948	.963		.000	.949		.000	.948		.000	.979	
.40	1.0	.976	.978		.968	.966		.966	.962		.987	.965	
.58	1.0	.980	.979		.973	.973		.973	.975		.987	.968	
.76	1.0	.979	.986	1.015	.976	.982	1.013	.977	.985	1.014	.987	.993	1.027
.94	1.0	1.013	.999		1.011	.992		1.013	.997		1.019	.999	
1.12	1.0	.978	.992	1.022	.978	.992	1.019	.976	.991	1.023	.983	.998	1.026
1.30	1.0	.983	.989		.986	.991		.983	.989		.990	.995	
1.48	1.0	.973	.972		.972	.972		.970	.970		.976	.975	
1.84	1.0	.966			.970			.967			.971		
2.20	1.0	.962	.948	1.042	.968	.956	1.044	.963	.949	1.043	.967	.954	1.041
2.56	1.0	.956			.961			.955			.958		
2.92	1.0	.963	.963		.971	.969		.964	.965		.969	.967	
3.22	1.0	.979			.980			.977			.980		
		TEST 1, RUN 354/0			TEST 1, RUN 322/0			TEST 1, RUN 353/0			TEST 1, RUN 358/0		
0	.52	.943	.954		.973	.982		1.000	1.015		1.003	1.012	
0	.84	.939	.946	.951	.967	.970	.981	.994	1.002	1.006	.995	1.000	1.010
.03	1.0	.959	.951	.969	.920	.966	.991	1.005	1.000	1.012	1.005	.996	1.015
.22	1.0	.000	.984		.000	.993		.000	1.011		.000	1.011	
.40	1.0	.983	.993		.996	.993		1.007	1.010		1.008	1.007	
.58	1.0	.991	.993		.994	.996		1.003	1.007		1.003	1.003	
.76	1.0	.991	1.000	1.026	.993	1.000	1.031	1.002	1.010	1.036	.998	1.006	1.038
.94	1.0	1.023	1.007		1.023	1.007		1.030	1.014		1.027	1.010	
1.12	1.0	.985	1.000	1.030	.984	1.002	1.033	.992	1.006	1.036	.991	1.004	1.031
1.30	1.0	.989	.996		.991	.996		.995	1.001		.995	1.000	
1.48	1.0	.977	.979		.977	.977		.981	.982		.981	.950	
1.84	1.0	.972			.971			.976			.974		
2.20	1.0	.970	.955	1.042	.963	.951	1.042	.970	.953	1.044	.969	.955	1.043
2.56	1.0	.958			.954			.960			.959		
2.92	1.0	.966	.972		.963	.964		.969	.971		.969	.967	
3.28	1.0	.986			.977			.985			.980		

Figure 26. Example of Task 4 Complete Pressure Data

NOZZLE CALIBRATION DATA FOR CLASSIC GEOMETRY

Run/ Rerun	P_{amb} (psia)	P_c (psia)	T_c (°R)	P_c/P_w at Tap No. 44	48	45	46	47
Test 1 ---			G1 N3		(AIR, A/A = 3.5, 25 DEG.)			
301/0	2.610	181.3	941	17.02	22.14	26.28	26.55	26.51
302/0	2.610	408.1	984	16.71	21.66	26.34	26.13	26.32
303/0	2.610	639.2	996	17.12	22.12	27.02	26.77	26.86
304/0	2.610	923.9	987	17.54	24.11	26.89	27.07	26.98
306/0	2.610	1267.6	1023	17.36	31.75	27.24	27.36	27.14
307/0	2.610	1467.1	1043	17.41	32.53	27.29	27.47	27.30
Test 1 ---			G1 N4		(AIR, A/A = 6.5, 35 DEG.)			
101/0	1.089	115.9	542	63.69	81.04	99.11	89.85	90.58
102/0	.762	274.4	557	57.47	77.88	95.79	89.53	89.21
103/0	.587	472.4	563	55.71	77.52	97.85	89.85	89.53
104/0	.500	936.6	577		80.19	102.46	92.68	91.83
105/0	.467	1295.0	575		81.83	104.28	93.63	91.91
106/0	.369	1654.4	567	57.50	84.82	103.73	97.38	94.43
107/0	.330	1820.3	918	56.56	84.25	102.15	98.14	94.79
108/0	.533	210.3	897	56.43	77.16	92.42	87.80	86.66
109/0	.570	412.9	928	56.92	81.17	96.99	94.79	93.28
110/0	.454	666.1	932	55.31	81.17	97.75	94.97	92.59
111/0	.572	818.7	969	55.22	81.43	98.33	95.15	92.42
112/0	.531	960.3	970	55.01	81.63	98.72	95.06	92.59
113/0	1.175	1298.2	993	54.59	80.78	98.62	94.88	91.83
114/0	.356	1716.6	1008	55.40	82.78	100.30	95.69	93.37
219/0	.579	194.0	629	57.80	78.68	94.34	89.13	87.95
220/0	.642	373.4	714	57.05	80.06	96.34	92.76	91.41
221/0	.564	546.1	739	56.31	79.74	97.56	92.76	89.85
222/0	.413	810.8	809	56.24	80.65	99.30	93.55	91.24
223/0	.435	1014.4	852	55.07	81.43	100.50	94.79	92.17
224/0	.371	1278.2	904	55.07	81.63	100.00	95.42	92.25
Test 3 ---			G1 N4		(AIR, A/A = 6.5, 35 DEG.)			
151/0	.567	979.6	609	63.44	85.37			111.93
152/0	.993	981.1	630	63.63	85.62			112.39
153/0	2.141	983.0	637	63.50	85.45			112.03
154/0	4.059	981.9	642	63.58	85.57			112.09
155/0	5.912	984.4	643	63.66	85.69			112.20
156/0	.567	1484.0	596	65.15	88.02			114.84
157/0	1.016	1491.4	615	65.18	88.15			114.96
158/0	1.901	1472.7	638	65.24	88.22			115.04
159/0	4.001	1478.7	631	65.14	88.06			114.77
160/0	7.656	1479.9	632	65.21	88.13			114.79
161/0	.544	1453.1	973	63.60	87.57			113.74
162/0	.939	1462.5	997	62.95	86.84			112.43
163/0	1.836	1463.6	998	63.02	87.00			112.54
164/0	3.986	1467.0	992	63.52	87.66			113.76
165/0	7.586	1471.1	984	63.76	87.98			114.61
166/0	.540	1460.7	863	63.54	87.49			113.55

Figure 27. Example of Task 4 Nozzle Calibration Data

Section 6

CONCLUSIONS AND RECOMMENDATIONS

Four tasks were performed to improve the technology base for predicting ascent plume-induced aerodynamic effects on the SSLV over that available from Saturn development. The three experimental tasks produced an extensive set of valid data: approximately 320,000 digital data points, 15,000 optical movie frames, and 200 schlieren still photographs. The data collection/summarizing task inspected 290,000 digital data points from 1200 runs and retained 21,000 points from 661 runs for publication. Each of these tasks was completed within budget, and was documented within an adequate time period after test completion. As with most aerodynamic experimental programs, there were some delays encountered in getting access to the various wind tunnel facilities, and some minor requirements for occupancy of the facilities longer than initially expected. However, in general, the three experimental tasks were performed in expedient fashion.

The High Temperature Exhaust Plume Effects on Base Pressure Simulation Task (1) was the first use of solid propellants at the MSFC TWT and ARC SWT facilities and as such was relatively exploratory in nature. Good performance was experienced for the basic model, but the pressure instrumentation needed more protection from the heat of the rocket. The Lateral Jet Simulation Task (2) met the program goals although the model hardware was found to be large relative to the MSFC TWT. The Parametric Measurements in Solid Propellant Plumes Task (3) produced the most extensive and parametric set of plume data to date. The Plume Simulation Data Summary Task (4) condensed the results of ten test series into a compact and readily usable form.

Those shortcomings in the transonic data obtained in Task 1 were corrected in a subsequent NASA test at AEDC, and no recommendations are envisioned regarding that aspect. The size of the MSFC TWT constrained some of the Lateral Jet Simulation testing to operation at q_j/q_∞ less than SSLV ranges. It would be desirable to obtain at least a limited data set in a larger wind tunnel, where the SRB separation condition could be performed. REMTECH envisions that such a test would use the existing "long cylinder" model plus high pressure gas heater, with air and CF_4. The NASA Langley UPWT would be a promising candidate wind tunnel. These data would complete the verification of the dynamic pressure ratio as an adequate correlator for the SSLV separation motor configuration (4 nozzles) at flight staging condition: $q_j/q_\infty \approx 450$. This verification was not completely achieved in the MSFC TWT, with the size model required to mount the various nozzles originally tested.

In the original plan for the Parametric Plume Measurements test, the effect of motor scale was of concern. That effect was not addressed in that test due to the expense involved, although there were discussions of "piggy-backing" instrumentation on a ground test firing in the SRB development (or a related program). However, this has not come to pass. It is recommended that an investigation be undertaken of the practicality of quantifying the motor scale effect by "piggy-backing" pressure and heat rate instrumentation in the exhaust plume of a medium or large size solid propellant rocket. REMTECH envisions that such a scheme could be made to be achievable within reasonable resource allotments, if competent and thorough pretest planning is completed. The data thus acquired would permit the extensive parametric data base already obtained at small scale to be extended with high confidence to SSLV full scale values.

The recommendations just identified as a result of analyzing the Space Shuttle Plume Simulation Effect on Aerodynamics are summarized as follows:

1. Conduct a limited test of the Lateral Jet Simulation hardware in a larger wind tunnel.

2. Perform an investigation to establish the practicality of mounting pressure and heat rate instrumentation in the exhaust plume of an SRB developmental motor.

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JAN 10 1979