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RESULTS OF A M = 5.3 HEAT TRANSFER
TEST OF THE INTEGRATED VEHICLE
USING PHASE-CHANGE PAINT TECHNIQUES
ON THE 0.0175-SCALE MODEL 56-OTS
IN THE NASA/AMES RESEARCH CENTER
3.5-FOOT HYPERSONIC WIND TUNNEL
(IH-42)

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SPACE SHUTTLE AERODYNAMIC DATA REPORT

Data Management Services

Michoud Engineering Office Chrysler Corporation

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by

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Prepared under NASA Contract Number NAS9-17179

by

Data Management Services
Chrysler Military-Public Electronic Systems
Michoud Engineering Office
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for

Systems Engineering Division

Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Wind Tunnel Test Specifics:

Test Number: ARC 3.5-ft HWT - 218
NASA Series Number: IH-42
Model Number: 56-OTS (0.0175-Scale)
Test Dates: April 27 through May 26, 1976
Occupancy Hours: 218

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ABSTRACT

An experimental investigation was performed in the NASA/Ames Research Center 3.5-foot Hypersonic Wind Tunnel during April and May 1976 to obtain supersonic heat-distribution data in areas between the orbiter and external tank using phase-change paint techniques. The tests used Novamide SSV Model 56-OTS in the first and second-stage ascent configurations.

Data were obtained at a nominal Mach number of 5.3 and a Reynolds number per foot of 5×10^6, with angles-of-attack of $0°$, $\pm 5°$, and sideslip angles of $0°$ and $\pm 5°$.

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INTRODUCTION

An experimental investigation (IH-42) was conducted to obtain supersonic heat-distribution data in areas between the orbiter and external tank using phase-cha ge paint technqiues. These heat transfer profiles we obtained in order to acquire data that could not be obtained using thermocouple instrumentation.

Test IH-42 was conducted in the NASA/Ames Research Center 3.5-foot Hypersonic Wind Tunnel from April 27 through May 26, 1976. The model used for this test was SSV Model 56-OTS, a 0.0175-scale representation of the orbiter and tank/SRB configuration 5. Data were obtained for the first and second-stage ascent configurations at $M = 5.3$ and R_e per foot of 5×10^6 which simulated ascent flight conditions.

Data were recorded at angles-of-attack of zero degree and ± 5 degrees. This was the second test that the Rockwell provided photographic system and data redu on program were used at the ARC 3.5-foot HWT.

All test objectives were successfully met, as well as six additional oil-flow visualization runs. This report contains information on the conduct of the test, details of the model, a summary of the test schedule and conditions, and typical phase-change paint photographs of the model.

NOMENCLATURE

Symbol	Computer Symbol	
C		Specific heat of model skin material - BTU/lb_m - °R
Cp, cp		Specific heat of airstream (perfect gas value) - BTU/lb_m - °R
CHAN	CHAN	Recording-system channel
deg		Degrees
°F		Degrees Fahrenheit
ft		Foot or feet
H_{aw}	HAW	Adiabatic wall enthalpy - BTU/lb_m
H_t	HT	Freestream total enthalpy - BTU/lb_m
H_{w_i}	HW	Enthalpy based on model wall temperature at initial time - BTU/lb_m
h	H	Heat-transfer coefficient at model wall lb_m/ft^2-sec
h_s	HS	Stagnation-point heat-transfer coefficient for reference sphere lb_m/ft^2-sec
h/h_s(X.XXX)	H/HS(X.XXX)	Ratio of model heat-transfer coefficient to heat-transfer coefficient of reference sphere for H_{aw}/H_t = X.XXX
K		Thermal conductivity
L	LENGTH	Model reference length - ft
lb_m		Pounds mass
M, M_∞	MACH	Freestream Mach number
m		Meter(s), unit of length
mm		Millimeter(s), unit of length
Nr		Nose radius
PR		Prandtl Number
psi		Pounds per square inch
psia		Absolute pressure in pounds per square inch

NOMENCLATURE (Continued)

Symbol	Computer Symbol	
P_t	PT	Freestream total pressure psia
$\dot{q}_i$	Q	Heat-transfer rate at model wall at initial time - BTU/ft^2-sec
$\dot{q}_s$	QS	Stagnation-point heat-transfer rate for reference sphere at initial time
^oR		Degrees Rankine
R_s	RS	Reference sphere radius at model scale equivalent to 0.305 m (1 ft) for full-scale vehicle - ft
Re_∞	RE/FT	Freestream Reynolds number per foot
$Re_{\infty, L}$	REL	Freestream Reynolds number based on model reference length, L
sec		Seconds, unit of time
T		Temperature - ^oR
T_{in}		Initial temperature - ^oR
T_{pc}		Phase change paint temperature
T_t	TT	Freestream total temperature - ^oR
T_{w_i}	TWI	Model wall temperature for given T/C location at initial time - ^oR
T/C	T/C	Thermocouple
t		time - sec
t_i	TIME	Initial time (before model insertion into flow)
Ve		Velocity at edge of boundary layer
α		Model angle of attack, deg
β		Model angle of sideslip, deg
u		Velocity
ρ		Density of air
ρ_m		Density of model material - lb$_m$/ft^3

NOMENCLATURE (Concluded)

Symbol	Computer Symbol	
μ		Viscosity of air-lb_m-sec/ft^2
γ		Ratio of specific heats $\frac{c_p}{c_v}$

Subscripts

aw	Adiabatic wall
i	Initial value before model insertion into tunnel flow
PG	Perfect gas (calorically and thermally perfect gas)
s	Reference sphere
t	Freestream total condition
w	Wall
∞	Freestream

The coordinate system used for this test is defined by Figure 2. The definition of the coordinate system symbols is given as follows:

b	Span, wing tip to wing tip
c	Chord, wing or vertical tail
l	Orbiter length
x	Distance from nose or leading edge
y	B.P. distance from centerline
z	Water plane distance from reference plane (FRL @ Z = 400 inches)
ϕ	Orbiter angular measurement 0.0 deg bottom centerline

Subscripts

N	Nozzle
O	Orbiter reference system
V	Vertical tail reference system
ET	External tank reference system
X_S	Solid rocket motors reference system

REMARKS

The installation of Model 56-OTS began on April 26, 1976. The first run was attempted on the night of April 27, 1976. However, during this run a severe vibration was observed. This vibration was due primarily to the 3 + G's of insertion deceleration and normal running loads.

The orbiter-tank attach structures (approximately 50 percent of the forward and aft protuberances) and the aft SRB-tank attach structures were blown off and destroyed. The severe shaking of the orbiter, tank, and SRB's crushed and fractured these parts which, like the rest of the model, were made from Novamide. The damaged Novamide protuberances were replaced with stainless steel and the model support hardware was braced to minimize model dynamics.

A combined total of 57 runs were made in approximately 218 occupancy hours. Two out of the 57 runs were repeats, although all runs yielded valid data.

CONFIGURATIONS INVESTIGATED

The model used during Test IH-42 was a 0.0175-scale replica of the Space Shuttle integrated vehicle-5 configuration, designated Model 56-OTS. This model is a phase-change paint model and is described by the VC70-000002 configuration control drawings modified in July 1975 for support of Test IH-42. The external tank (spike-nosed) was built to VC78-000002D lines, and the solid rocket boosters were built to VC77-000002F lines.

The orbiter model was originally fabricated by Lockheed Aircraft Company and was cast in one piece from their proprietary material "LH". The external tank and the SRB's were cast in single pieces around a steel sting using Novamide 700-55 material and machined to contour. Three complete model assemblies were available for this test: Model 56-OTS-1 (a paint-stripe model), and Models 56-OTS-2 and 56-OTS-3 (test models).

TEST FACILITY DESCRIPTION

The NASA/Ames 3.5-foot Hypersonic Wind Tunnel is a closed-circuit blow-down-type tunnel capable of operating at nominal Mach numbers of 5, 7, and 10 at pressures to 1800 psia and temperatures to 3400°R for run times to four minutes. The major components of the facility include a gas storage system where the test gas is stored at 3000 psi, a storage heater filled with aluminum-oxide pebbles capable of heating the test gas to 3400°R, axisymmetric contoured nozzles with exit diameters of 42 inches for generating the desired Mach number, and a 900,000 ft^3 vacuum storage system which operates to pressures of 0.3 psia. The test section itself is an open-jet type enclosed within a chamber approximately 12-feet in diameter and 40-feet in length, arranged transversely to the flow direction.

A model support system is provided that can pitch models through an angle-of-attack range of -20 to +18 degrees, in a vertical plane, about a fixed point of rotation on the tunnel centerline. This rotation point is adjustable from 1 to 5 feet from the nozzle exit plane. The model normally is out of the test stream (strut centerline 37-inches from tunnel centerline) until the tunnel test conditions are established after which it is inserted. Insertion time is adjustable to as little as 1/2 second and models may be inserted at any strut angle.

TEST PROCEDURES

The 56-OTS model was mounted, at various α and β combinations, to the tunnel quick-insert support mechanism. This mechansim injected the model into the airstream when steady-state test conditions had been established, and retracted the model at the completion of data recording. The model injection time, time on tunnel centerline, and retraction time were set to give a total exposure time of approximately five seconds, of which three seconds were on tunnel centerline. The 56-OTS Model (with protuberances) was used to obtain Orbiter ascent aerodynamic heating rates, utilizing phase-change paint techniques to determine isotherms of melt lines for different temperatures. The type of paint used for this test was Tempelac® paint. The specific paint melt temperatures used were 250, 300, 350, 400, 450, 500, and 550°F. However, the majority of the test was conducted using paint melt temperatures of 300 and 400°F.

Before the testing began, photographs of the grid model were taken for each attitude to be investigated. The model was then mounted in the test section and painted with the appropriate phase-change paint. The test section was closed and the wind tunnel started with the model out of the airstream. The model's initial temperature was recorded and the model was inserted into the airstream. After each run was completed, the model was retracted and separated, and the melt lines between the orbiter and external tank were photographed. The model was then washed with solvent and repainted for the next run.

Figures 3a through 3e are photographs of the Model 56-OTS installation in the NASA/ARC 3.5-ft HWT. These photographs are typical of post run conditions showing the phase-change paint melt lines and the oil-flow characteristics for each configuration.

PHASE-CHANGE PAINT DATA REDUCTION PROCEDURE

A special program was developed for use in conjunction with the photographic instrumentation to automatically reduce heating rate data. The three 35mm cameras were synchronized with the time the model came to centerline. The resulting data output linked the tunnel h/h reference with the isotherm lines visible on each photographic frame taken. This program was used on the ARC IBM-360 facility computer.

This data reduction procedure was developed for use in the NASA/ARC 3.5-ft HWT for Test IH-42, as well as the orbiter phase-change paint Test OH-53B. However, after the initial run to obtain the heat transfer paint melt lines in the model interstage area for Test IH-42, it became obvious that the cameras could not adequately photograph the areas of interest to yield definitive data. Therefore, the model components were separated after each run and photographs of the melt lines were taken. It should also be noted that the automatic data reduction was used only for the last data point before model retraction to indicate the heat transfer coefficient.

DATA REDUCTION

All test data were reduced at the NASA/ARC using the data reduction technique outlined below:

Phase Change Paint Data Reduction

The aerodynamic heat transfer coefficient was calculated as outlined below for each motion picture frame.

$$\dot{q} = h(H_{aw} - H_w) \equiv hH_t\left(\frac{H_{aw}}{H_t} - \frac{H_w}{H_t}\right) \equiv h\,C_p\,(T_{aw}' - T_w)$$

$$\text{where: } H_t = C_p\,T_t\,\theta \equiv \left(\frac{\gamma R}{\gamma - 1}\right) T_t\,\theta$$

θ corrects for thermally perfect, calorically imperfect air.

θ is calculated as a function of T_t using a polynomial curve fit.

$$\text{where: } \theta \equiv \frac{(T_\infty / T_t)\,TPG}{(T_\infty / T_t)\,PG} \geq 1$$

TPG - Thermally perfect gas

PG - Calorically and thermally perfect

$$T_{aw}' \equiv \frac{H_{aw}}{C_p} \equiv \frac{H_{aw}}{H_t} \cdot \frac{H_t}{C_p} = \frac{H_{aw}}{H_t}\,T_t\,\theta$$

$\frac{H_{aw}}{H_t}$ = 1.0, 0.9 or .85 (NOTE: $\dot{q}$ is independent of the H_{aw}/H_t used for both h and $\dot{q}$ evaluations).

$$\frac{H_w}{H_t} = \frac{T_{pc} / T_t}{\theta}$$

Assuming a semi-infinite slab solution, $\bar{T}$ is calculated from

$$\bar{T} = \frac{T_{pc} - T_{in}}{T_{aw'} \quad T_{in}}$$

β is then determined using $\bar{T}$ and iterating

$$1 - \bar{T} = e^{\beta^2} (1 - \text{erf } \beta)$$

The heat transfer coefficient is then derived by solving:

$$h = \frac{\beta \sqrt{k \rho C}\Big|_{AVG}}{\sqrt{t} \quad cp}$$

where:

$$\sqrt{k \rho C}\Big|_{AVG} = \frac{\left[\sqrt{k \rho C}\Big|_{T_{in}} + \sqrt{k \rho C}\Big|_{T_{pc}}\right]}{2}$$

using h,

$$\dot{q} = h \, H_t \left(\frac{H_{aw}}{H_t} - \frac{H_w}{H_t}\right)$$

To determine h at H_{aw}/H_t = 0.9 and 0.85 the value of $\dot{q}$ for H_{aw}/H_t = 1.0 was used in the following:

$$h = \frac{\dot{q}}{H_t \left(\frac{H_{aw}}{H_t} - \frac{H_w}{H_t}\right)}$$

For h/h_s comparison, the value of h_s, the stagnation heat transfer coefficient was determined as follows:

$$\dot{q}_s = h_s\,(H_t - H_w)$$

$$h = 0.768\,(P_r^{-0.6})\,(\rho_w\,\mu_w)^{.1}(\rho_s\,\mu_s)^{.4}\sqrt{\left.\frac{dVe}{dx}\right|_s}$$

$$\text{where } \left.\frac{dVe}{dx}\right|_s = \frac{1}{\sqrt{Nr}}\sqrt{2\,R\,T_t\left(1 - \frac{P_\infty}{P_s}\right)}$$

$$P_\infty/P_s = \frac{P_\infty/P_t}{P_s/P_t}$$

$$P_s/P_t = \left.\frac{P_{t_2}}{P_{t_1}}\right|_{Perfect} \cdot PSRC \qquad \text{where } PSRC \equiv \frac{(P_{t_2}/P_{t_1})\ TPG}{(P_{t_2}/P_{t_1})\ PG}$$

PSRC corrects for thermally perfect air and was obtained from a polynomial curve fit using T_t.

$$\left.\frac{P_{t_2}}{P_{t_1}}\right|_{Perfect} = \left[\frac{\frac{\gamma+1}{2}M_\infty^2}{1+\frac{\gamma-1}{2}M_\infty^2}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{\frac{\gamma+1}{2}}{\gamma M_\infty^2 - \frac{\gamma-1}{2}}\right]^{\frac{1}{\gamma-1}}$$

$$P_\infty/P_t = \left.\frac{P_\infty}{P_t}\right|_{Perfect} \cdot PRC \qquad \text{where } PRC = \frac{(P_\infty/P_t)\ TPG}{(P_\infty/P_t)\ PG}$$

(PRC corrects for thermally perfect air and is also derived using a polynomial curve fit of T_t.)

$$\left.\frac{P_\infty}{P_t}\right|_{Perfect} = \left[1 + \frac{\gamma-1}{2}M_\infty^2\right]^{\frac{-\gamma}{\gamma-1}}$$

REFERENCES

1. "Pretest Information for Testing the 0.0175-Scale Phase Change Paint Model 56-OTS in the ARC 3.5-ft Hypersonic Wind Tunnel Test IH-42" (January 27, 1976)

Table I

TEST : IH-42

DATE : 5-26-76

TEST CONDITIONS

MACH NUMBER	Freestream Static Pressure (PSIA)	Freestream Static Temperature (°F)	Reynolds Number per foot
5.3	405	1300	5.00×10^6

BALANCE UTILIZED: NA

	CAPACITY:	ACCURACY:	COEFFICIENT TOLERANCE:
NF			
SF			
AF			
PM			
RM			
YM			

COMMENTS:

TABLE II

TEST: IH-42 — **DATA SET/RUN NUMBER COLLATION SUMMARY** — **DATE:** 4-27-76

DATE	CONFIGURATION	SCHD. α	SCHD. β	PARAMETERS/VALUES Po PSIA	To °R		Re/ft ×10⁻⁶	MACH No.	PAINT TEMP. ~ Vs RUN No. 250°	300°	350°	400°	450°	500°	550°		OIL FLOW
4-27-76	OTS	0	0	405	1300		5.0	5.3	1*								
5-12-76		0	0						2								
		0	0												3*		
		0	0										4*				
5-13-76		0	0									5					
		0	0								6						
		0	0							7							
		-5	0									8					
		-5	0							9							
		0	0											10			
5-14-76		+5	0									11					
		+5	0							12							
		+5	+5									13					
		+5	+5							14							
		0	+5									15					
		0	+5							16							

TEST RUN NUMBERS

TYPE OF DATA — COEFFICIENT SCHEDULES — IDVAR (1) — IDVAR (2) — NDV

α OR β SCHEDULES

NOTE: * N.G.

RUN #1 – ET/ORB STRUTS CAME OFF (MODEL REMOVED FOR REPAIR)

RUN #2 – CONDUITS ON SRB AND ET NEEDS REPAIRING

RUN #3 — NO MELT LINES

RUN #4 — MELT LINES ON OMS & L.E. ONLY

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TABLE II

TEST: IH-42	DATA SET/RUN NUMBER COLLATION SUMMARY	DATE: 5-17-76

DATE	CONFIGURATION	SCHD. α	SCHD. β	PARAMETERS/VALUES Po psia	To °R		Re/ft ×10^6	MACH No.	PAINT TEMP. ~ VS RUN No. 250°	300°	350°	400	450°	500°	550°		OIL FLOW
5-17-76	OTS	-5	+5	905	1300		5.0	5.3				17					
		-5	+5							18							
		0	+5											19			
		+5	+5											20			
		0	-5									21					
5-18-76		0	-5							22							
		+5	-5									23					
		+5	-5							24							
		-5	-5									25					
		-5	-5							26							
		+5	0											27			
5-19-76	OT	0	0											28			
		0	0							29							
		-5	0											30			
		-5	+5											31			
		0	+5											32			

TEST RUN NUMBERS

TYPE OF DATA — COEFFICIENT SCHEDULES — IDVAR (1) — IDVAR (2) — NDV

α OR β SCHEDULES

NASA-MSFC-MAF

TABLE II

TEST: IH-42 **DATA SET/RUN NUMBER COLLATION SUMMARY** **DATE:** 5-20-76

DATE	CONFIGURATION	SCHD. α	SCHD. β	PARAMETERS/VALUES Po PSIA	To °R		Re/ft ×10⁶	MACH No.	PAINT TEMP. ~ VS RUN No. 250°	300°	350°	400°	450°	500°	550°		OIL FLOW
5-20-76	OT	0	+5	405	1300		5.0	5.3				33					
		0	+5							34/35							
		-5	+5									36					
		-5	+5							37							
		+5	+5									38					
		+5	+5							39							
		0	0									40					
		-5	0									41					
5-21-76		-5	0							42							
		+5	0									43					
		+5	0							44							
		0	-5									45					
		0	-5							46							
		-5	-5									47					
		-5	-5							48							
		+5	-5									49					
5-24-76		+5	-5							50							

TEST RUN NUMBERS

TYPE OF DATA α OR β SCHEDULES — COEFFICIENT SCHEDULES — IDVAR (1) IDVAR (2) NDV

NASA-MSFC-MAF

TABLE II

TEST: IH-42 — DATA SET/RUN NUMBER COLLATION SUMMARY — DATE: 5-24-76

DATE	CONFIGURATION	SCHD. α	SCHD. β	PARAMETERS/VALUES P0 PSIA	T0 °R		RN/ft ×10⁶	MACH No.	PAINT TEMP. ~ VS RUN No. 250°	300°	350°	400°	450°	500°	550°		OIL FLOW	
5-24-76	OTS	-5	+5	405	1300		5.0	5.3				51						
5-25-76		-5	+5														52	53
	↓	0	0														54	
↓	OT	0	0														55	
5-26-76		0	+5														56	
↓	↓	-5	+5	↓	↓		↓	↓									57	

TEST RUN NUMBERS

TYPE OF DATA — COEFFICIENT SCHEDULES — IDVAR (1) — IDVAR (2) — NDV

α OR β SCHEDULES

NASA-MSFC-MAF

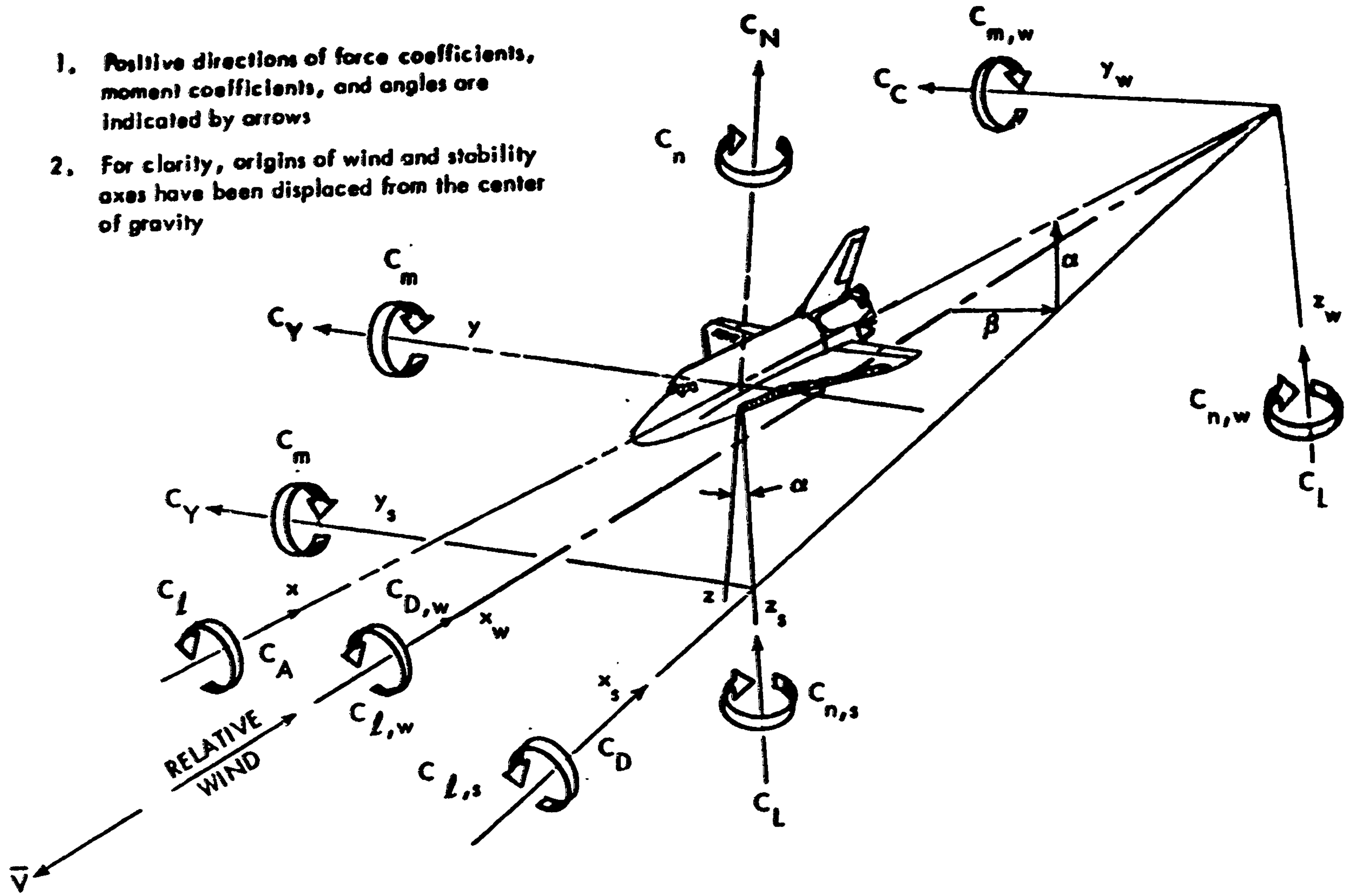
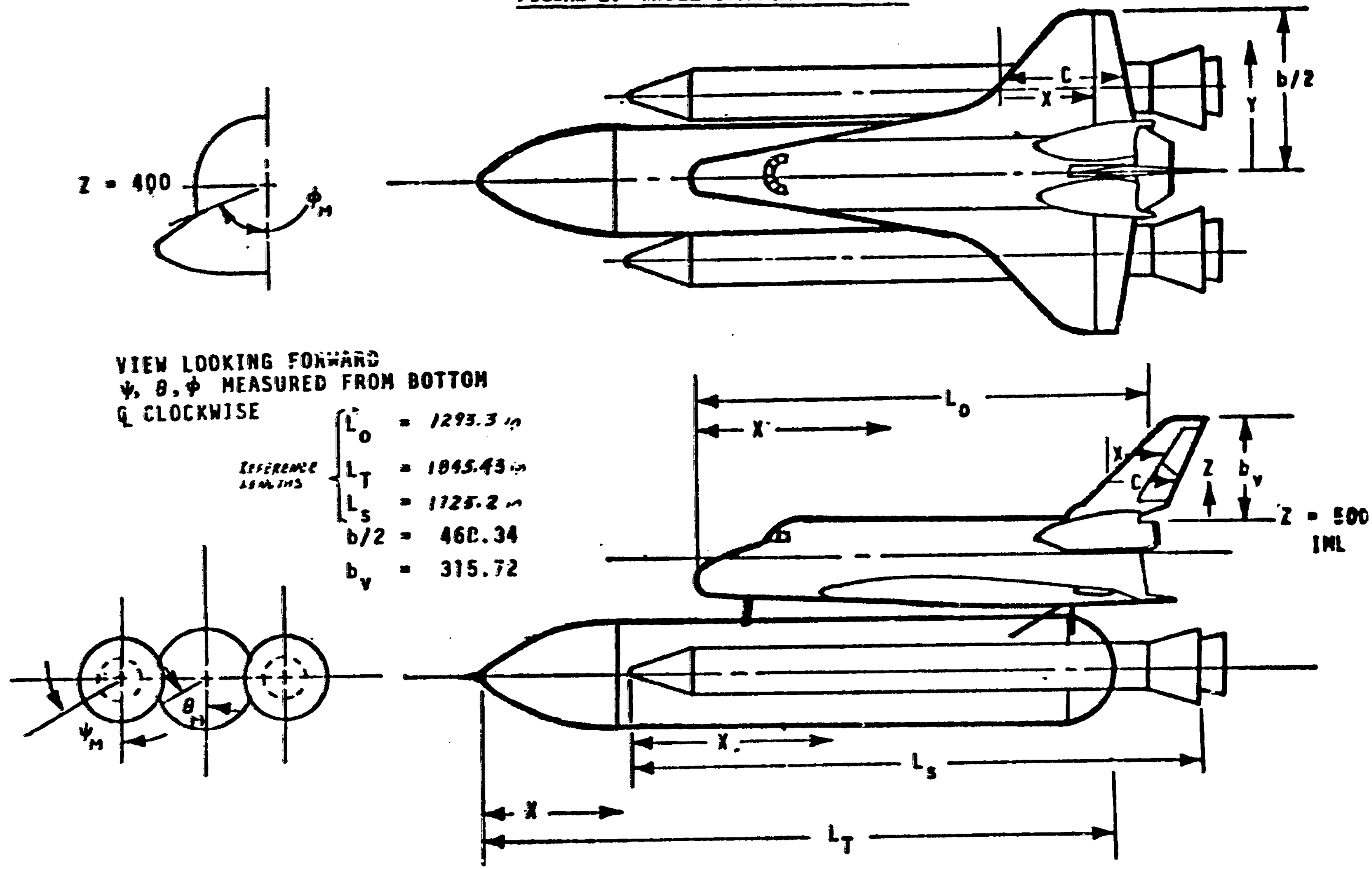


Figure 1. Axis systems.

FIGURE 2. MODEL COORDINATE SYSTEM



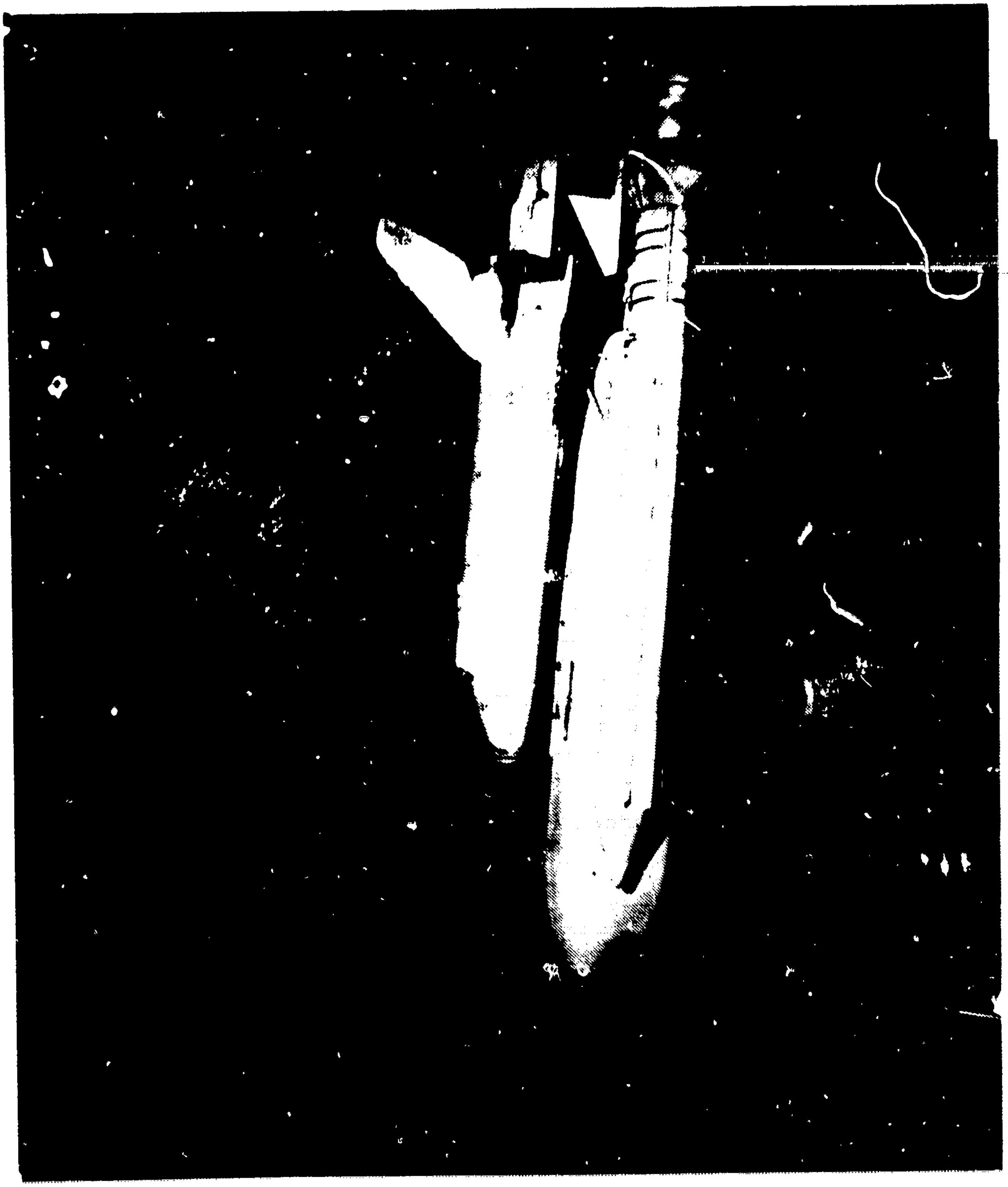


FIGURE 3a. OTS-SIDE VIEW, POST RUN # 20, $\alpha = 5^\circ$, $\beta = 5^\circ$
PAINT TEMP 500° MACH 5.3

ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 3.6. ORBITER BOTTOM VIEW, POST RUN # 22, $\alpha=0°$, $\beta=-5°$
PAINT TEMP. 300° MACH 5.3

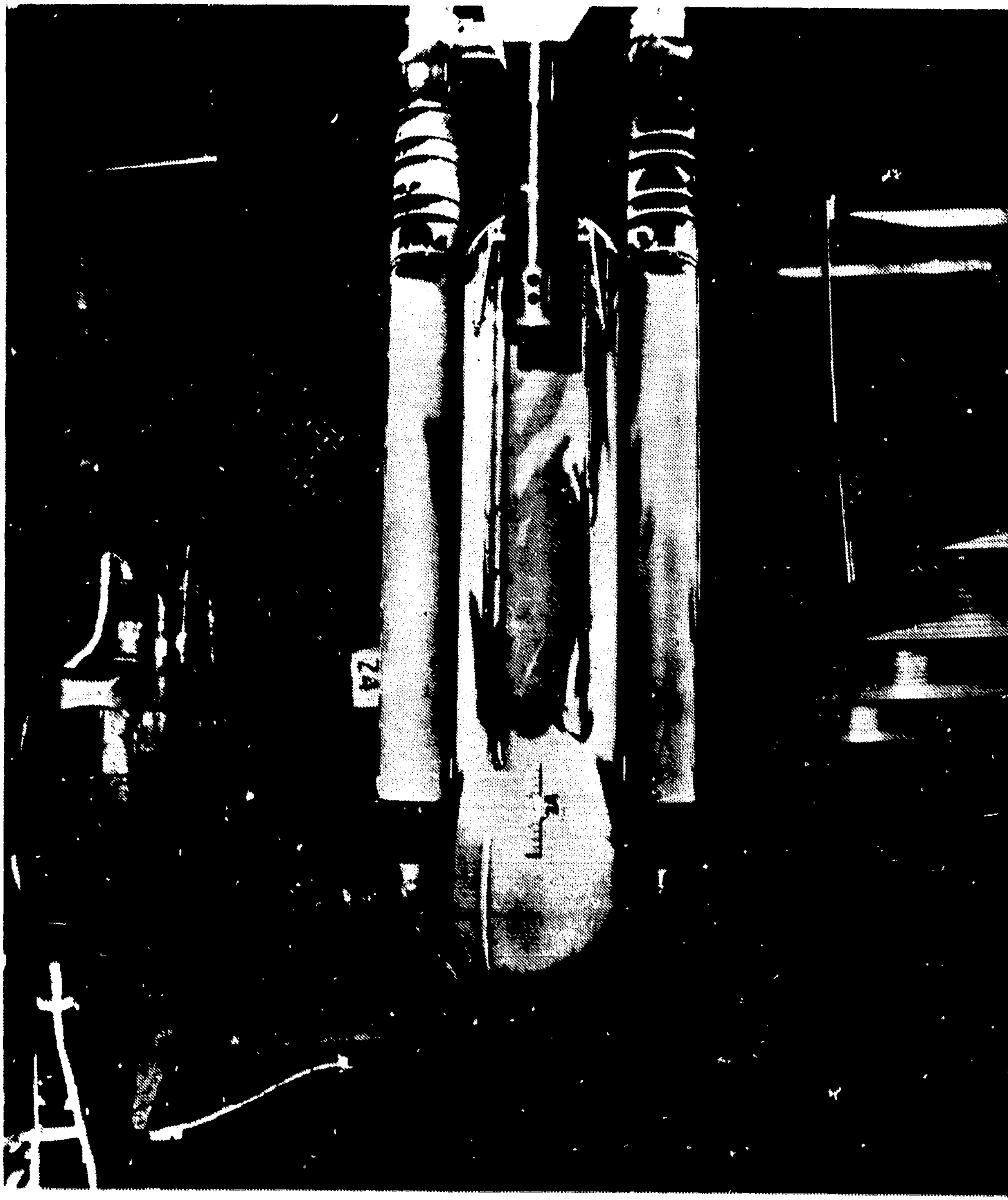


FIGURE 3C. TANK/SRB – TOP VIEW, POST RUN #28, α=+5°, β=−5°
PAINT TEMP. 300° MACH 5.3.

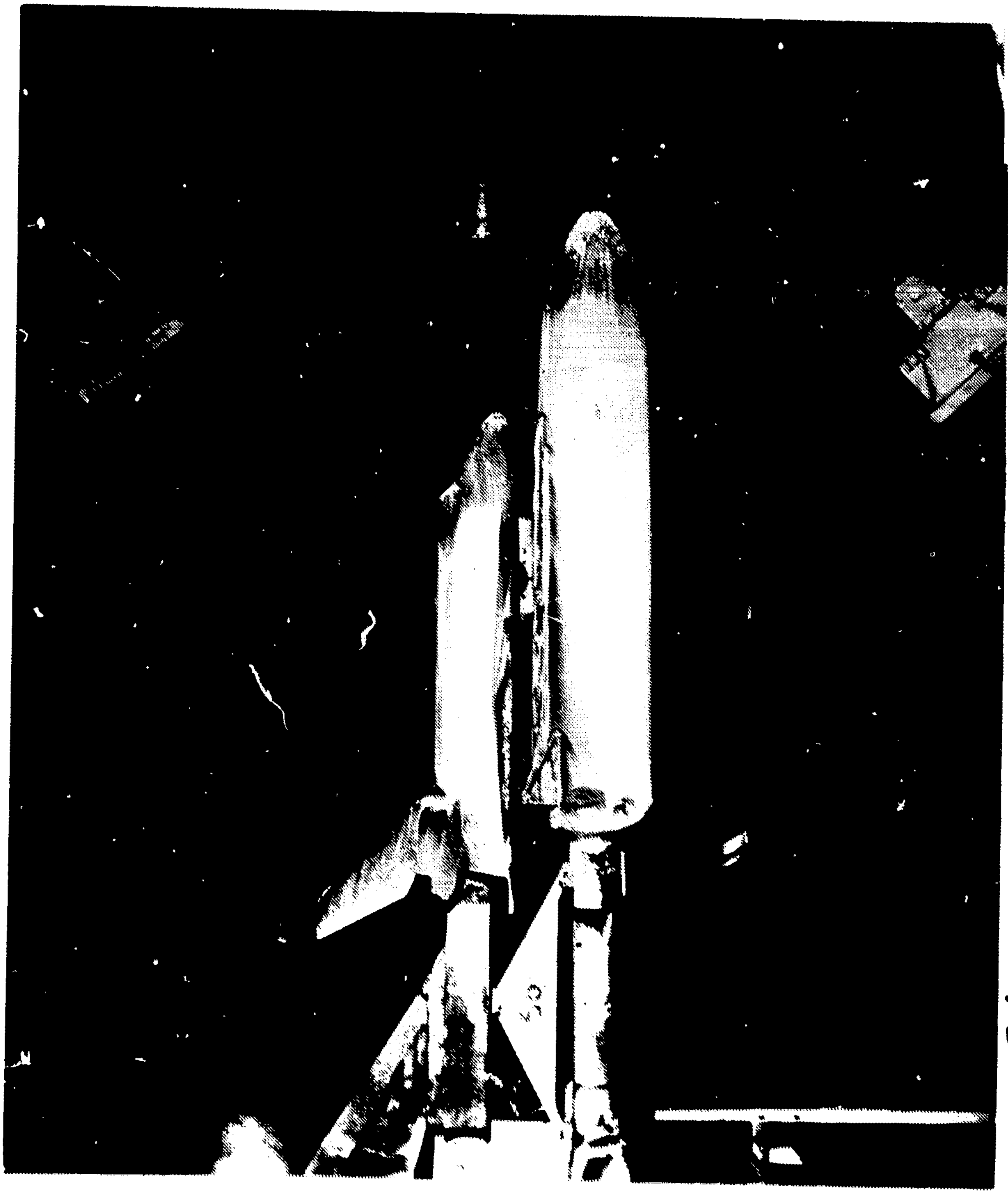


FIGURE 3d. ORBITER/TANK- SIDE VIEW, POST RUN # 56
$\alpha = 0°$, $\beta = +5°$ MACH 5.3 (OIL FLOW)

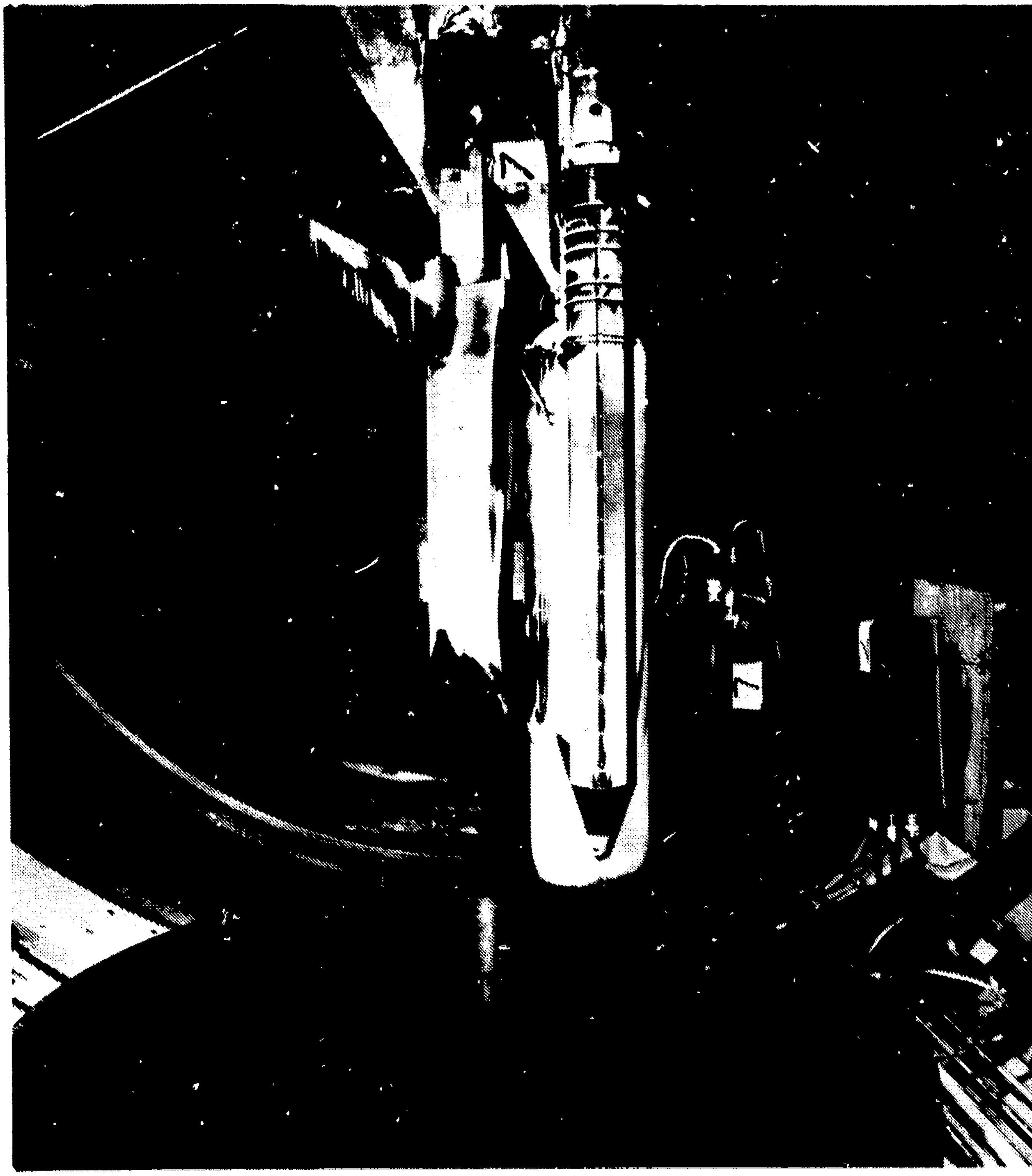


FIGURE 3e. OTS-SIDE VIEW, POST RUN #7, $\alpha = 0°$, $\beta = 0°$
PAINT TEMP. 300° MACH 5.3