NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

(NASA-CR-144618) RESULTS OF PHASE CHANGE PAINT TESTS OF 0.040 SCALE 50% FOREBODY MODELS (82-0) OF THE SPACE SHUTTLE ORBITER IN THE AEDC VKF B HYPERSONIC WIND TUNNEL (OH75) (Chrysler Corp.) 32 p HC $4.00

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SPACE SHUTTLE

AEROTHERMODYNAMIC DATA REPORT

JOHNSON SPACE CENTER

HOUSTON, TEXAS

DATA MANagement services

SPACE DIVISION CHRYSLER CORPORATION

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RESULTS OF PHASE CHANGE PAINT TESTS OF 0.040 SCALE 50% FOREBODY MODELS (82-0) OF THE SPACE SHUTTLE ORBITER IN THE AEDC VKF B HYPERSONIC WIND TUNNEL (OH75)

by

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Prepared Under Contract No. NAS9-13247

by

Data Management Services
Chrysler Corporation Space Division
New Orleans, La. 70189

for

Engineering Analysis Division

Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

WIND TUNNEL TEST SPECIFICS:

Test Number:	AEDC V41B - E3A
NASA Series Number:	OH75
Model Number:	82-0
Test Date:	September 1, 1975
Occupancy Hours:	8

FACILITY COORDINATOR:

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ABSTRACT

This report presents post-test information and data from phase change paint, aerodynamic heating wind tunnel tests of a Rockwell International Space Shuttle Orbiter forebody model. These tests were conducted in the Arnold Engineering and Development Center von Karman Facility Tunnel B Hypersonic Wind Tunnel.

The purpose of these tests was to determine the effect of simulated orbiter protuberances and penetrations (including RCS nozzles) on aerodynamic heating rates during simulated entry conditions.

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NOMENCLATURE

SYMBOL	PLOT SYMBOL	DEFINITION
C_p	C	specific heat of the model material - BTU/lb-°F
g		acceleration due to gravity, 32.17 ft/sec^2
h	H(TO)	heat transfer coefficient based on $T_{AW} = T_o$
	H(.9TO)	heat transfer coefficient based on $T_{AW} = 0.9\ T_o$
	H(r_{low}TO)	heat transfer coefficient based on $T_{AW} = r_{low} \times T_o$
h_s	HREF	reference heat-transfer coefficient based on Fay-Riddell Theory, BTU/ft^2-sec.-°R
M_∞	MACH NO.	free stream Mach no.
N_r	R	reference sphere radius used to calculate h_s (0.04 ft)
P_∞	P-INF	free stream static pressure, psia
P_r		Prandtl number
P_o	PO	tunnel stilling chamber pressure, psia
P_1,P_2		defined in context
q_o	Q-INF	free-stream dynamic pressure, psia
R		universal gas constant, ft-lb$_f$/lb$_m$-°R
Re/ft	RE/FT	free stream unit Reynolds number, ft^{-1}
	ROLL-MODEL	model roll angle-deg.
ST	ST(TO)	Stanton number based on T_o: $ST(TO) = \frac{H(TO)}{p_\infty V_\infty[.2235 + 1.35 \times 10^{-4}(T_o + 560)] \times 32.17}$
r_{low}		minimum recovery factor used in data reduction; function of angle of attack; r is non-dimensional

NOMENCLATURE (Continued)

SYMBOL	PLOT SYMBOL	DEFINITION
	STREF	reference Stanton number: $ST(TO) = \frac{HREF}{\rho_\infty V_\infty [.2235 + 1.35x10^{-4}(T_o + 560)]x32.17}$
T_{aw}		adiabatic wall temperature, °F
$\bar{T}$	TBAR	$\frac{T_{pc} - T_{IN}}{T_{aw} - T_{IN}}$
T_{IN}		initial model temperature, °F
T_∞	T-INF	free stream static temperature-°R
T_{pc}	TPC	paint melt temperature, °F
T_o	TO	tunnel stilling chamber temperature, °R
t	TIME	time from start of model injection, sec.
Δt	DEL TIME	time model exposed to airstream, sec.
V_e		velocity at edge of the boundary layer, ft/sec.
V_∞	V-INF	free stream velocity, ft/sec.
α	ALPHA-MODEL	model angle of attack, deg.
	ALPHA-PREBEND	sting prebend angle, deg.
	ALPHA-SECTOR	tunnel sector pitch angle-deg.
	YAW	model yaw angle
γ		ratio of specific heats of air
k	K	model thermoconductivity, BTU/ft-sec-°F
β		negative model yaw (positive sideslip)

NOMENCLATURE (Concluded)

SYMBOL	PLOT SYMBOL	DEFINITION
μ_∞	MU-INF	free stream viscosity, lb-sec/ft^2
μ_s		stagnation air viscosity, lb-sec/ft^2
μ_w		air viscosity along model wall (lb$_m$/ft-sec)
ρ	RHO	model material density-lb$_m$/ft^3
ρ_w		air density along model wall-lb$_m$/ft^3
ρ_s		stagnation air density lb$_m$/ft^3
ρ_∞	RHO-INF	free stream air density, slug/ft^3

INTRODUCTION

Aerodynamic heating phase change paint tests were conducted on a .040 scale Rockwell International Space Shuttle Orbiter for [illegible]. These tests were conducted in the AEDC VKF B Hypersonic Wi[illegible] Sept. 1, 1975.

The purpose of these tests was to determine the effects of simulated RCS nozzles, protuberances, and penetrations on aerodynamic heating rates during simulated entry conditions. The model was tested from 20° through 45° angle of attack at 0° and -1° angle of sideslip. All the above attitudes were tested at a nominal Mach number of 8. Reynolds number was varied from 0.5×10^6/ft through 2.0×10^6/ft.

CONFIGURATIONS INVESTIGATED

The models were 0.040 scale representations of the forward 50% of the Rockwell International Space Shuttle Orbiter as defined by Rockwell lines VL70-000140C. The Rockwell model designation was 82-0. The models were cast in one piece using Lockheed proprietary material "LH" on a steel sting. There were no movable or removable model parts. Models used for this test were the 82-1 (paint stripe model) and 82-4 (protuberance model). The "smooth" model was the 82-4 with filled RCS nozzles and penetrations. Figures 2a and 2b illustrate the protuberances and penetrations simulated on the model.

TEST FACILITY DESCRIPTION

The Arnold Engineering Development Center (AEDC) is an Air Force Facility located in Tullahoma, Tennessee. The tunnel used, Tunnel B, is located in the von Karman Facility portion of this center. Engineering and other technical operations in this tunnel are performed by contractor personnel of ARO, Inc.

Tunnel B is a continuous, closed circuit, variable density wind tunnel with an axisymmetric contoured nozzle and a 50-inch diameter test section. The tunnel can be operated at a nominal Mach number of 6 or 8 at stagnation pressures from 20 to 300 and 50 to 900 psia, respectively, and at a stagnation temperature of up to 1350°R. The model may be injected into the tunnel for a test run and then retracted for model cooling or model changes without interrupting the tunnel flow.

TEST PROCEDURE

Tempilaq®, a fusible coating that changes phase from an opaque solid to a transparent liquid at temperatures specified by the manufacturer, was used to indicate the location of isc herms on the model surface. The paints used had melting temperatures of 113, 125, 131, 150, and 175 °F.

Beattie-Coleman Varitron® 70 mm sequence cameras were used to record the progression of isotherms on the windward surfaces, as a function of time, during each test run. The cameras were located on the top and side of the wind tunnel and photographed the left side and bottom surfaces of the orbiter models. The cameras were operated at a nominal rate of 1 frame/sec. Kodak TRI-X Pan® black-and-white film was used.

Dual television monitors were used throughout the test to facilitate on-line cross-referencing.

Prior to each test run, the model was cleaned with a solvent, spray-painted with the phase-change coating, and allowed to reach isothermal conditions. The model was then injected into the wind tunnel for about 30 seconds, during which time the progression of the isotherms, indicated by the demarcation between melted and unmelted coating, was continuously photographed. The model was then retracted from the wind tunnel and the cycle repeated for the next run. The model temperature was measured prior to each run using a thermocouple probe.

TEST PROCEDURE (Continued)

The tests were conducted at the following nominal conditions:

M_∞	P_o, psia	T_o, °R	$h_s \left[\frac{BTU}{ft^2\text{-}sec\text{-}^oR}\right]$	Re/ft x 10^{-6}
7.90	110	1,270	0.0116	0.5
7.94	210	1,270	0.0162	1.0
7.98	430	1,300	0.0230	2.0

DATA REDUCTION

Thin film heat transfer coefficients were calculated for each melt line at which photographs were taken. The coefficients were calculated assuming three different recovery factors.

$$\frac{T_{aw}}{T_o} = r_{low},\ 0.90,\ \text{and}\ 1.0$$

The following calculations were then performed to obtain thin film coefficients:

$$\bar{T} = \frac{T_{pc} - T_{IN}}{T_{aw} - T_{IN}}$$

$$T_{aw} = \left(\frac{T_{aw}}{T_o}\right) \times T_o$$

$$h = \frac{\beta \sqrt{k\rho C_p}}{\sqrt{t}}\Bigg|_{AVG}$$

NOTE:

$$\sqrt{k\rho C_p}\Big|_{AVG} = \frac{\sqrt{k\rho C_p}\Big|_{T_{IN}} + \sqrt{k\rho C_p}\Big|_{T_{pc}}}{2}$$

where the flow parameter β results from iterative solution of:

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

Theoretical thin film heat transfer coefficients and stagnation point heating rates were calculated using the equations given below:

$$h_s = (.768)(C_p)(P_r)^{-.6}(\rho_w \mu_w)^{.1}(\rho_s \mu_s)^{.4}\sqrt{\frac{dVe}{dx}}$$

where

$$P_r = \frac{\mu C_p}{k}$$ (μ, C_p and k for air)

$\frac{dVe}{dx}$ = The streamwise velocity gradient along the model surface

and

$$\frac{dVe}{dx} = \frac{1}{N_r}\sqrt{2\ Rg\ T_o\left(1 - \frac{1}{P_1 P_2}\right)}$$

N_r = Nose radius, 0.0175 foot radius (1 foot full scale)

DATA REDUCTION (Concluded)

$$P_1 = \left[\frac{\gamma + 1}{2} \quad M_\infty^2\right]^{\frac{\gamma}{\gamma-1}}$$

$$P_2 = \left[\left(\frac{\gamma + 1}{2\gamma M_\infty - (\gamma - 1)}\right)\right]^{\frac{\gamma}{\gamma-1}}$$

Melt lines are shown on selected photographs taken during the test and are presented at the back of this report. The melt line on each photograph shows isotherms. Thin film coefficients and free stream data corresponding to the isotherms are presented in Table IV. The photographs are presented to provide qualitative data showing effects of the protuberances and depressions.

RESULTS AND DISCUSSION

Uncertainties of the basic tunnel parameters were estimated from repeat calibrations of the PO and TO instruments and from the repeatability and uniformity of the tunnel flow during calibrations. The parameters PO, TO, and MACH NO. with their uncertainties were then used to compute the uncertainties in the other parameters dependent on these by means of the Taylor series method of error propagation.

Uncertainty, percent				
MACH NO.	PO	TO	RE/FT	HREF
± 0.4	± 0.1	± 0.4	± 1.2	0.8

An estimate of the data precision of phase change paint data is hampered by the fact that an observer must determine the location of the melt line. For this analysis, only uncertainties attributable to the measured parameters are considered. The parameters needed for the solution of the equation for the heat-transfer coefficient, h, are T_{pc}, T_{IN}, T_{aw}, $\sqrt{\rho k C_p}$, and Δt. The table below summarizes the nominal uncertainties in these specific parameters.

Parameter	Uncertainty (+)
Δt	± 1.0
$\sqrt{\rho k C_p}$	±10.0
T_{IN}	± 0.5
T_o (T_{aw})	± 0.5
T_{pc}	± 0.5

RESULTS AND DISCUSSION (Concluded)

It should be remembered that the above uncertainties in T_{aw} and T_{pc} only reflect nominal measurement uncertainties. As previously mentioned, the interpretation of when phase change occurs (i.e., T_{pc}) is a matter of observer experience, and the "correct" assumption of what should be used for T_{aw} also requires engineering judgment. However, combining the above measurement uncertainties with the corresponding error sensitivity factor (derived by using the equation for the heat-transfer coefficient, h, and taking the square root of the sum of the squares) yields the following:

for $T_{pc} \leq 200^{\circ}F$, h uncertainty $\approx \pm 13$ percent

for $T_{pc} > 200^{\circ}F$, h uncertainty $\approx \pm 11$ percent.

REFERENCES

1) Test Data from the NASA/Rockwell International Space Shuttle Test (OH-75) conducted in the AEDC VKF Tunnel B, by L. Carter and C. Kaul.

2) Test Facilities Handbook (Tenth Edition). "von Karman Gas Dynamics Facility, Vol. 3." Arnold Engineering Development Center, May, 1974.

3) "Pretest Information for Phase Change Paint Tests on the 82-Ø .040 Scale 50% Forebody Models of the Rockwell International Space Shuttle Orbiter in the AEDC VKF 'B' Hypersonic Wind Tunnel (OH-75)," SD-SH-0203, By W. H. Dye, dated August, 1975.

TABLE I

MODEL MATERIAL PROPERTIES

T_{pc}, °F	TEMPERATURE AT WHICH PROPERTIES WERE EVALUATED, °F	$\sqrt{\rho C_p k}$, Btu/ft^2-°R-sec$^{1/2}$
113	95.5	0.0478
125	101.5	0.0481
131	104.5	0.0483
150	114.0	0.0487
175	125.5	0.0493

The model material properties were evaluated at a temperature equal to the average of the initial and phase-change paint temperatures.

TABLE II

TEST SUMMARY

Re/ft x 10^{-6} (ft^{-1})	MODEL ALPHA (deg)	YAW (deg)	PAINT MELT TEMP (°F)	SMOOTH MODEL GROUP NO.	PROTUBERANCE MODEL GROUP NO.
0.5	30	0	113	42	39
	35	0	125	43	40
	35	1.0	125	44	41
	40	0	113	11	8
	40	1.0	113	10	9
1.0	20	0	131	34	27
	25	0	113	33	28
	30	0	113	32	29
	30	1.0	125	35	38
	35	0	113	31	30
	35	1.0	125	36	37
	40	0	113	12	4
	40	0	125	--	6
	45	0	113	13	5
	45	0	125	--	7
2.0	20	0	131	16	--
	20	0	175	18	25
	25	0	131	19	22
	25	0	175	17	--
	30	0	131	20	23
	35	0	131	21	26
	40	0	131	14	1
	45	0	131	15	2
	45	0	150	--	3

Data Group 24 had no computer data. This group number was then voided.

TABLE III

MODEL DIMENSIONAL DATA

MODEL COMPONENT: BODY - B_{60}

GENERAL DESCRIPTION: 50% orbiter forebody, vehicle 140C.

NOTE: This body includes a small portion of the wing glove.

MODEL SCALE: 0.040

DRAWING NUMBER: VL70-000140C

DIMENSIONS:	FULL SCALE	MODEL SCALE
Length	645.15	25.80
Max Width	330.00	13.20

MODEL COMPONENT: CANOPY - C_{10}

GENERAL DESCRIPTION: Configuration 4 canopy and windshield as used with B_{25}, six glass panes in windshield

MODEL SCALE: 0.040

DRAWING NUMBER: VL70-000140B, 140C, 202B

DIMENSIONS:	FULL SCALE	MODEL SCALE
Length (X_o = 434.643 to 670) In.	235.357	9.414
Max Width		
Max Depth Glass - In.	28.00	1.12
Nose/windshield intersection, X_o =	434.643	17.386

TABLE IV DATA FOR MELT LINES PRESENTED IN FIGURES 3 THROUGH 8

Figure	Group	α	Mach No.	Re/ft $x10^{-6}$	P_o (Psia)	T_o (°R)	h_s (N_T=0.04ft)	h/h_s (T_o)	h/h_s (.9T_o)	h/h_s r_{low}TO*	ST (T_o)
3a	34	19.99	7.94	1.029	212.5	1269	0.01624	0.0498	0.0610	0.0688	0.001308
3b	27	19.98	7.94	1.020	212.3	1275	0.01625	0.0503	0.0616	0.0694	0.001326
3c	18	20.00	7.98	1.989	431.2	1299	0.0298	0.0856	0.1057	0.1199	0.001617
3d	25	19.99	7.98	1.995	432.0	1298	0.0230	0.0864	0.1068	0.1210	0.001630
4a	33	24.97	7.94	1.027	212.7	1271	0.01626	0.0239	0.0292	0.0329	0.000631
4b	28	24.97	7.94	1.018	211.8	1275	0.01623	0.0239	0.0292	0.0328	0.000631
4c	19	24.98	7.98	1.985	430.9	1300	0.02297	0.0474	0.0579	0.0650	0.000893
4d	22	24.99	7.98	1.982	431.2	1302	0.02299	0.0493	0.0602	0.0676	0.000935
5a	32	29.98	7.94	1.024	2125	1273	0.01625	0.0256	0.0312	0.0351	0.000675
5b	29	29.99	7.94	1.011	210.6	1276	0.01619	0.0257	0.0312	0.0351	0.000680
5c	20	30.00	7.98	1.986	431.3	1300	0.02298	0.0273	0.0333	0.0374	0.000517
5d	23	30.01	7.98	1.987	431.9	1301	0.02300	0.0277	0.0339	0.0380	0.000526
6a	31	35.00	7.94	1.020	211.6	1273	0.01622	0.0246	0.0301	0.0338	0.000650
6b	30	35.00	7.94	1.017	210.9	1272	0.01619	0.0252	0.0308	0.0345	0.000667
6c	21	35.01	7.98	1.998	431.9	1297	0.02299	0.0260	0.0318	0.0358	0.000492
6d	26	35.00	7.98	1.995	432.8	1300	0.02302	0.0259	0.0316	0.0355	0.000490
7a	12	40.07	7.94	1.009	212.1	[illegible]	0.01626	0.0197	0.0240	0.0270	0.000524
7b	4	40.01	7.94	1.022	211.5	[illegible]	0.01621	0.0197	0.0241	0.0270	0.000521
7c	14	39.98	7.98	1.993	430.5	[illegible]	0.02295	0.0232	0.0284	0.0319	0.000440
7d	1	39.99	7.98	1.975	431.2	1305	0.02300	0.0241	0.0294	0.0331	0.000458
8a	13	45.00	7.94	1.020	210.9	1270	0.01619	0.0450	0.0549	0.0616	0.001139
8b	5	45.01	7.94	1.024	212.0	1271	0.01623	0.0461	0.0563	0.0632	0.001217
8c	15	45.00	7.98	1.994	431.6	1297	0.02298	0.0438	0.0535	0.0602	0.000829
8d	2	45.02	7.98	1.987	431.4	1300	0.0299	0.0467	0.0570	0.0641	0.000847

*

α	r_{low}
20	0.892
25	0.902
30	0.912
35	0.923
40	0.934
45	0.945

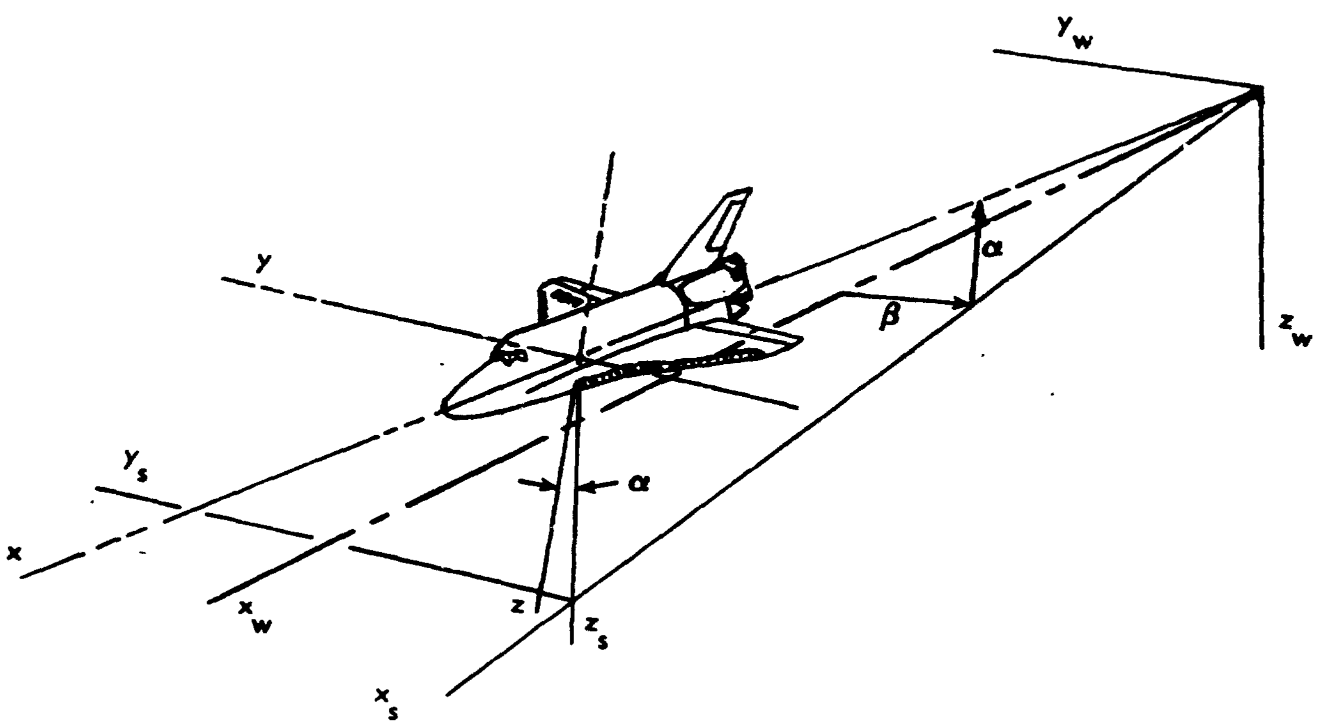
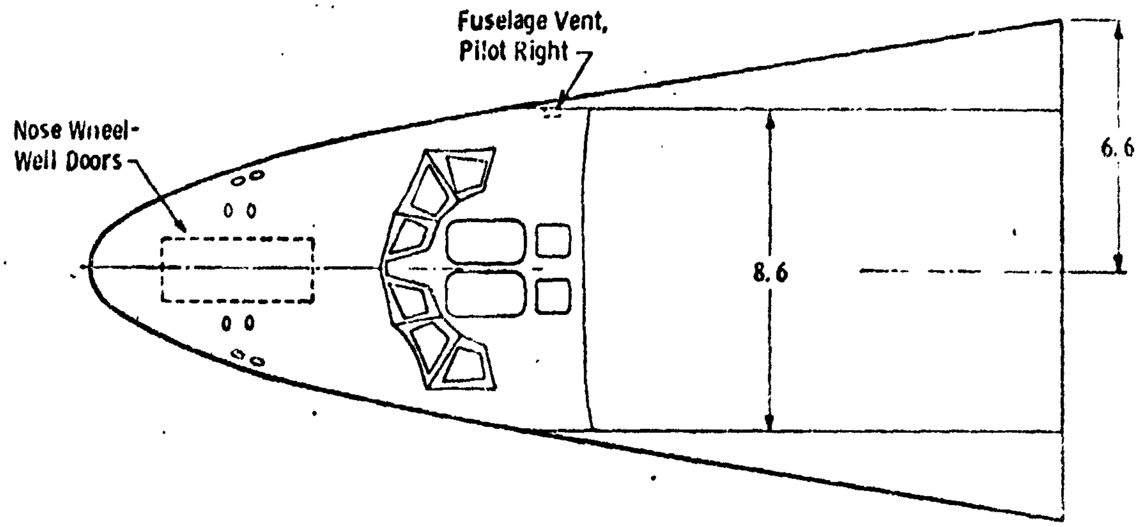
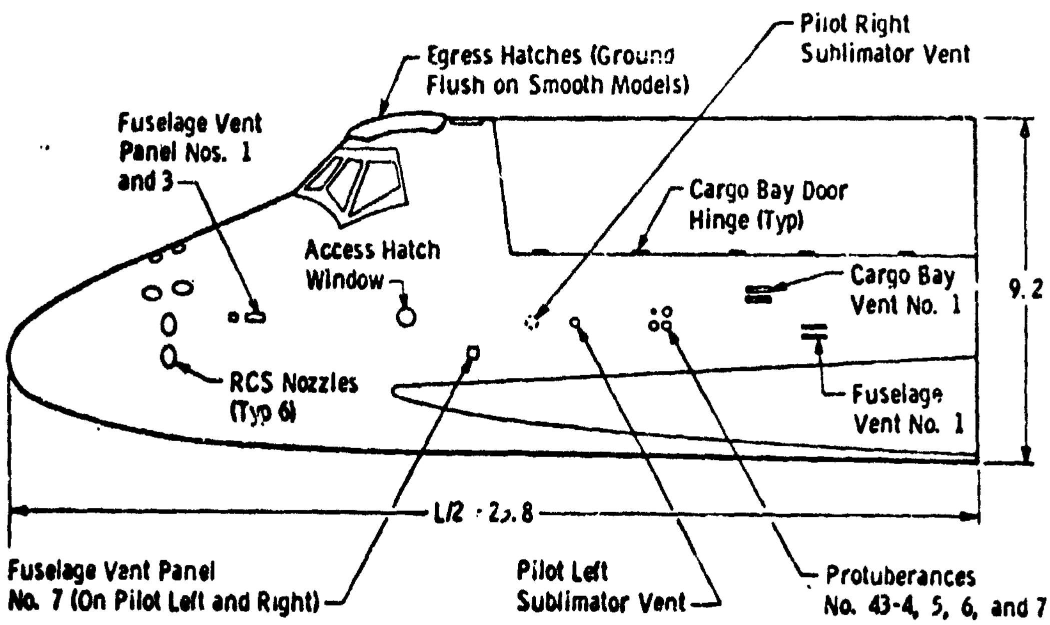


Figure 1. - Axis Systems.

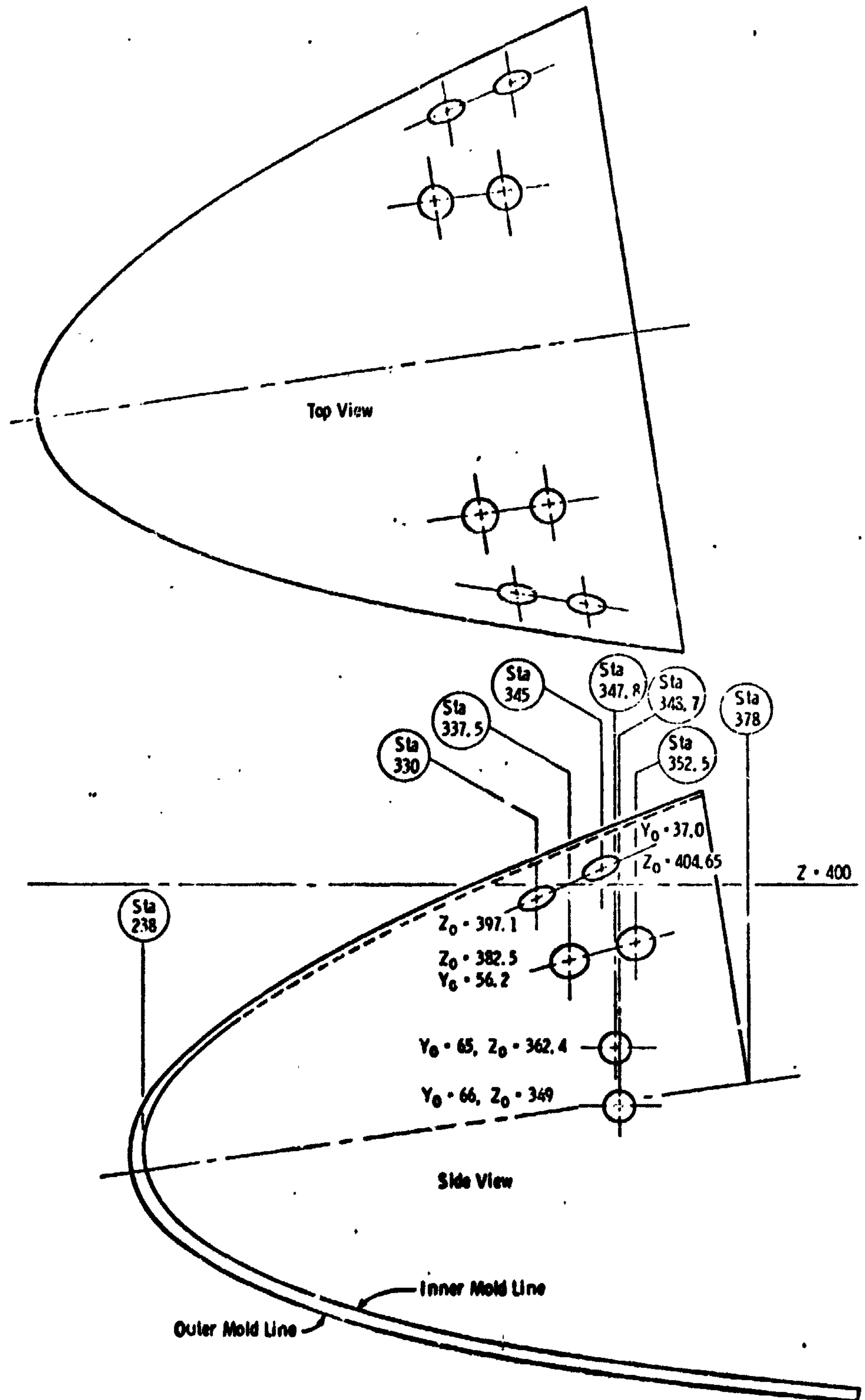


Note: The smooth paint models had the same basic dimensions as are shown here but did not have the protuberances.

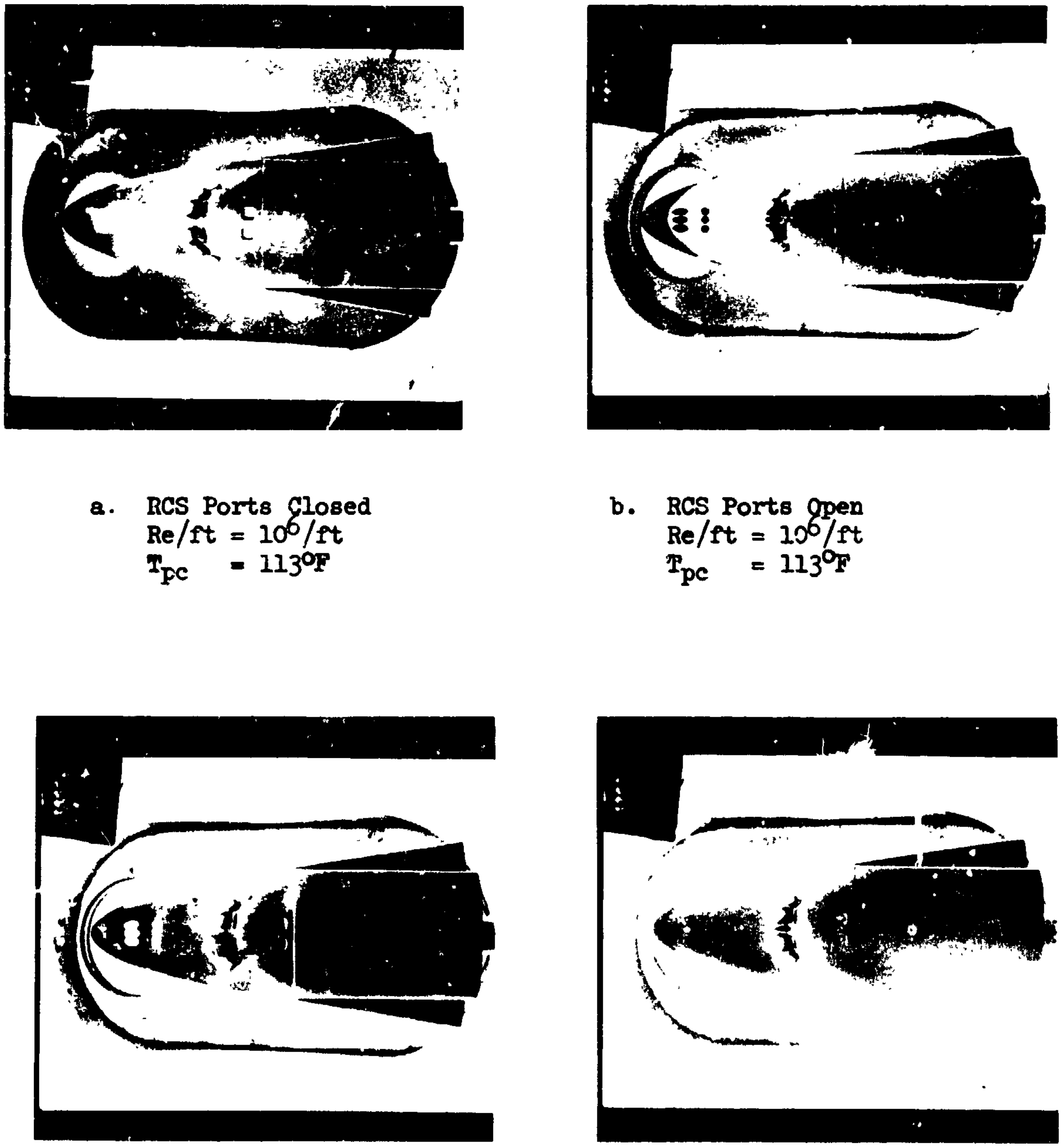
All dimensions are in inches.



a. Protuberance Model
Figure 2. Model Sketches



b. Nozzle Locations
Figure 2. (Continued)



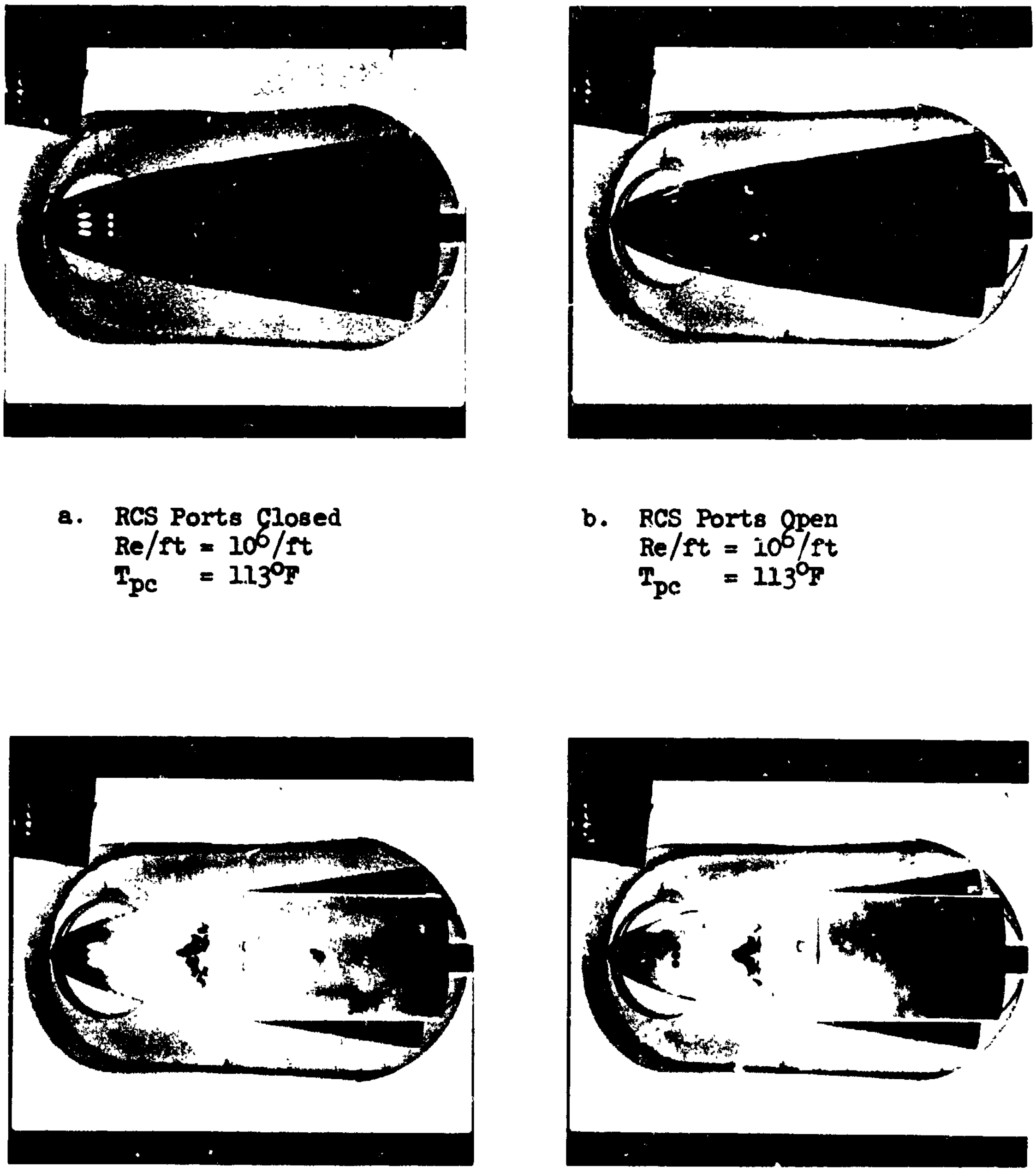
a. RCS Ports Closed
$Re/ft = 10^6/ft$
$T_{pc} = 113^oF$

b. RCS Ports Open
$Re/ft = 10^6/ft$
$T_{pc} = 113^oF$

c. RCS Ports Closed
$Re/ft = 2x10^6/ft$
$T_{pc} = 113^oF$

d. RCS Ports Open
$Re/ft = 2x10^6/ft$
$T_{pc} = 113^oF$

Figure 3. Melt Lines at 20 Degrees Angle of Attack



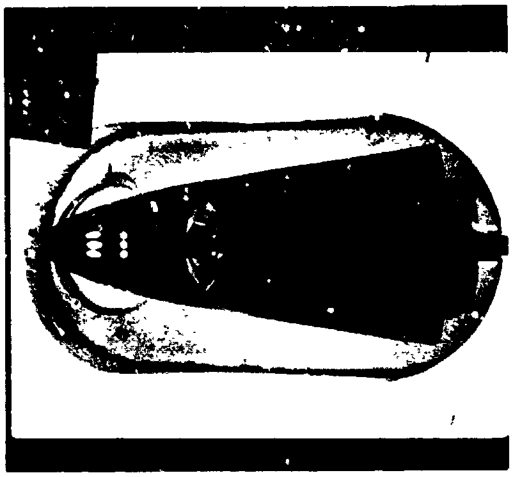
a. RCS Ports Closed
Re/ft = 10^6/ft
T_{pc} = 113°F

b. RCS Ports Open
Re/ft = 10^6/ft
T_{pc} = 113°F

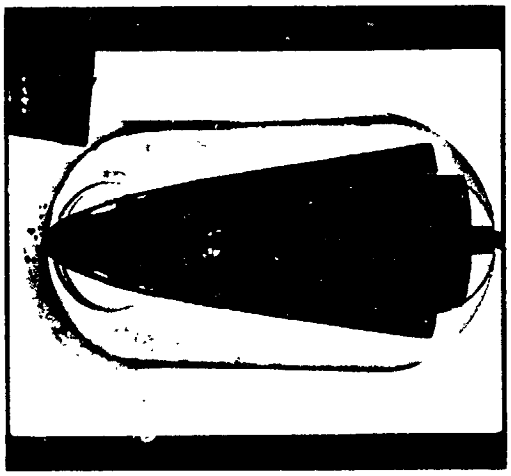
c. RCS Ports Closed
Re/ft = $2x10^6$/ft
T_{pc} = 131°F

d. RCS Ports Open
Re/ft = $2x10^6$/ft
T_{pc} = 131°F

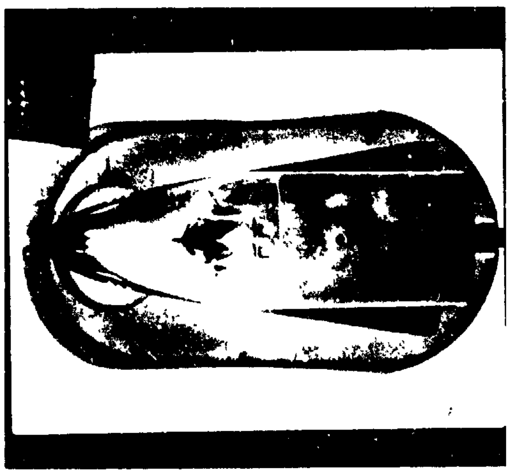
Figure 4. Melt Lines at 25 Degrees Angle of Attack



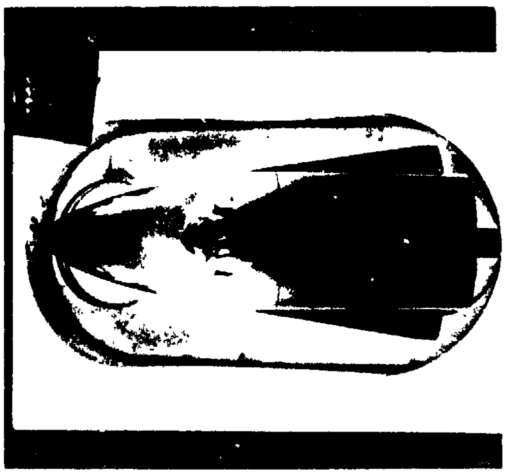
a. RCS Ports Closed
$Re/ft = 10^6/ft$
$T_{pc} = 113^{\circ}F$



b. RCS Ports Open
$Re/ft = 10^6/ft$
$T_{pc} = 113^{\circ}F$

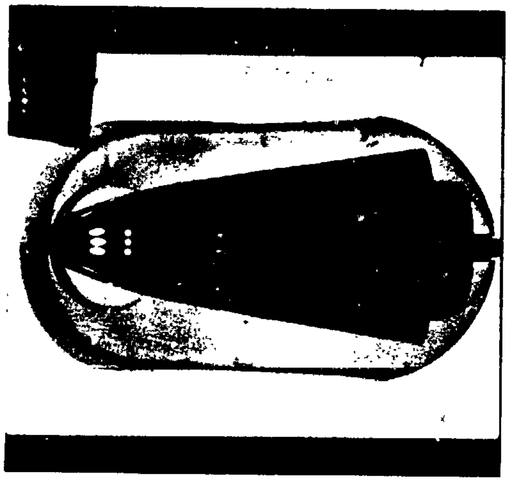


c. RCS Ports Closed
$Re/ft = 2x10^6/ft$
$T_{pc} = 131^{\circ}F$

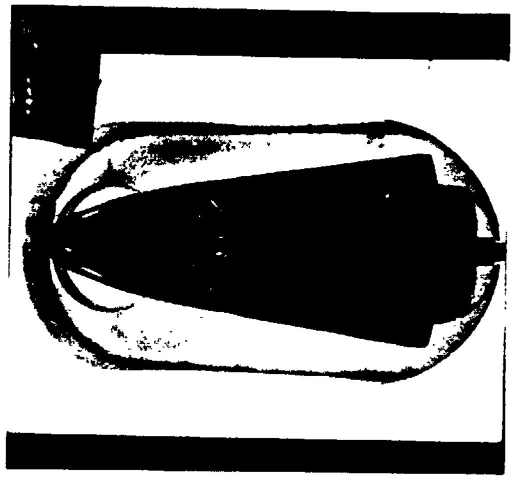


d. RCS Ports Open
$Re/ft = 2x10^6/ft$
$T_{pc} = 131^{\circ}F$

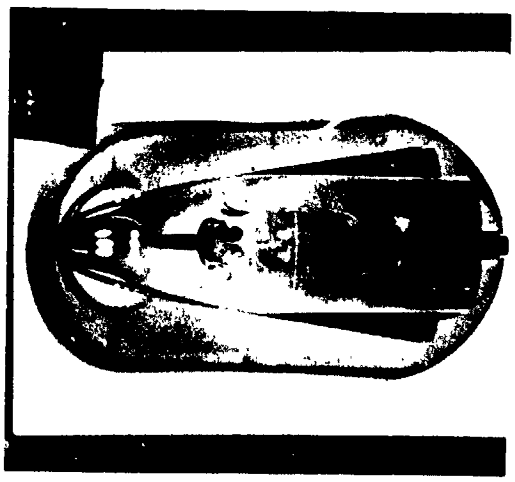
Figure 5. Melt Lines at 30 Degrees Angle of Attack



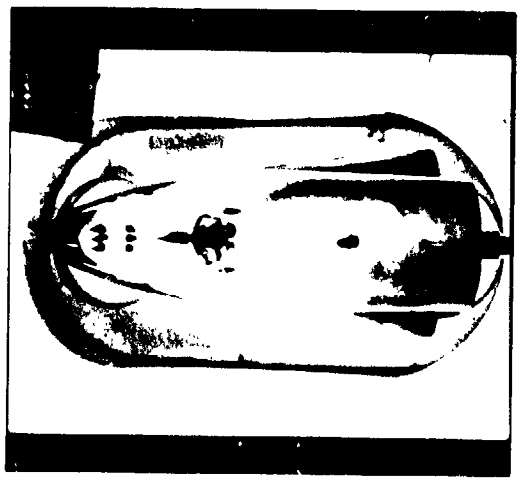
a. RCS Ports Closed
Re/ft = 10^6/ft
T_{pc} = 113°F



b. RCS Ports Open
Re/ft = 10^6/ft
T_{pc} = 113°F

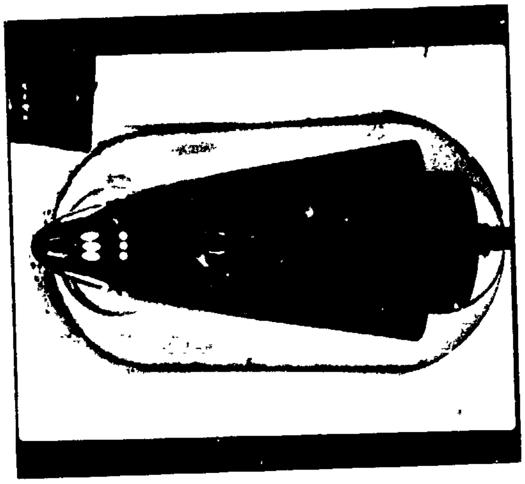


c. RCS Ports Closed
Re/ft = 2×10^6/ft
T_{pc} = 131°F

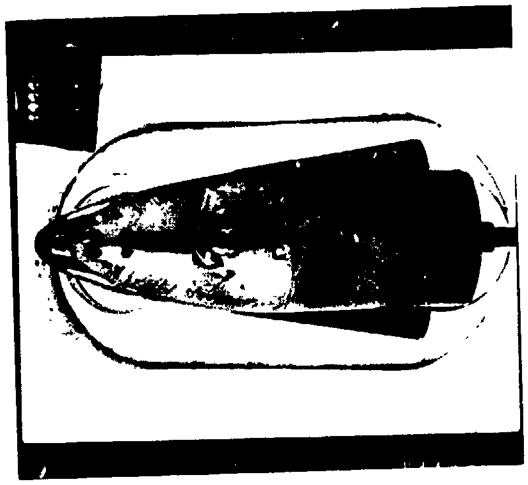


d. RCS Ports Open
Re/ft = 2×10^6/ft
T_{pc} = 131°F

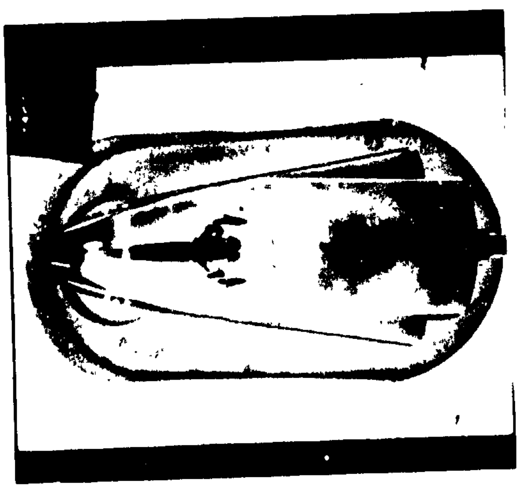
Figure 6. Melt Lines at 35 Degrees Angle of Attack



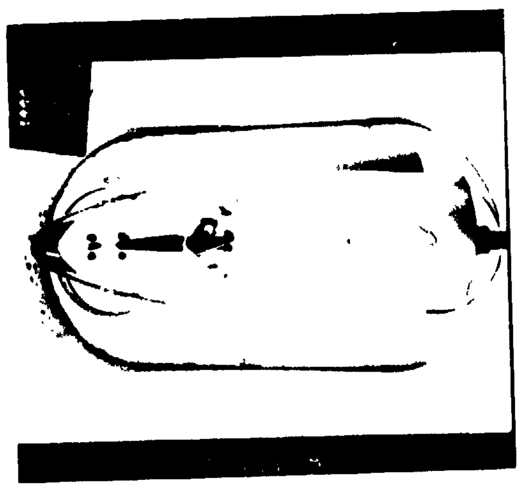
a. RCS Ports Closed
Re/ft = 10^6/ft
T_{pc} = 113°F



b. RCS Ports Open
Re/ft = 10^6/ft
T_{pc} = 113°F

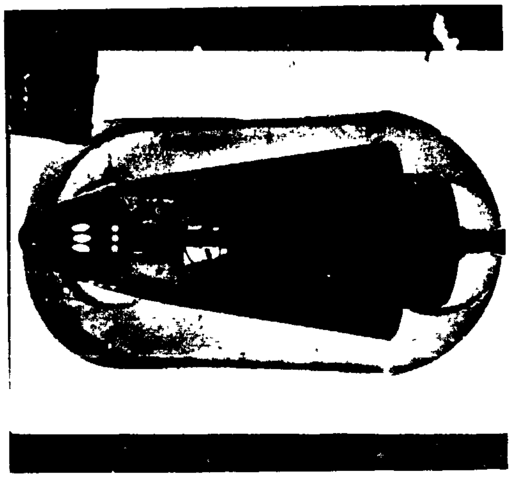


c. RCS Ports Closed
Re/ft = 2×10^6/ft
T_{pc} = 131°F

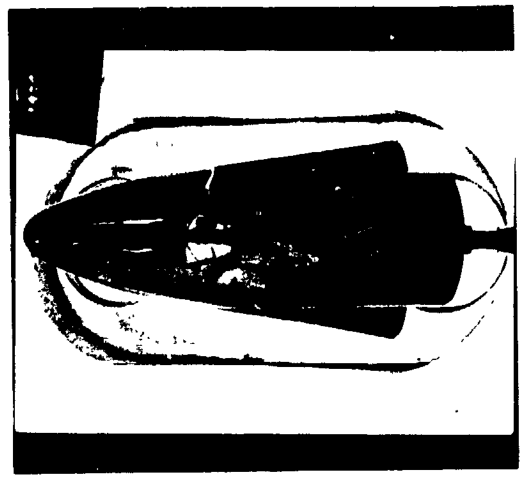


d. RCS Ports Open
Re/ft = 2×10^6/ft
T_{pc} = 131°F

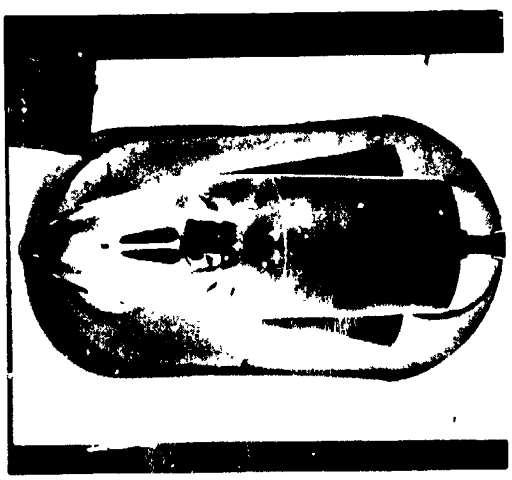
Figure 7. Melt Lines at 40 Degrees Angle of Attack



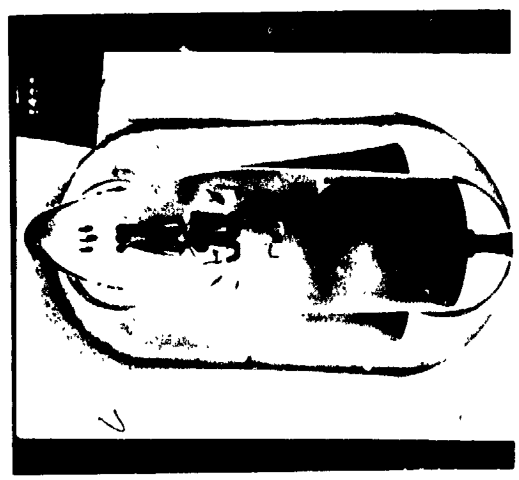
a. RCS Ports Closed
$Re/ft = 10^6/ft$
$T_{pc} = 113^\circ F$



b. RCS Ports Open
$Re/ft = 10^6/ft$
$T_{pc} = 113^\circ F$



c. RCS Ports Closed
$Re/ft = 2x10^6/ft$
$T_{pc} = 131^\circ F$



d. RCS Ports Open
$Re/ft = 2x10^6/ft$
$T_{pc} = 131^\circ F$

Figure 8. Melt Lines at 45 Degrees Angle of Attack