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RESULTS OF FLOW VISUALIZATION STUDIES IN THE NASA/MSFC 14 x 14 INCH TRISONIC WIND TUNNEL ON A .004 SCALE MODEL (34-0) SPACE SHUTTLE ORBITER AND INTEGRATED VEHICLE

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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: MSFC 584
NASA Series No.: IA-52
Date: 12-17 Oct, 1973 (28 Occ. Hrs.)

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RESULTS OF FLOW VISUALIZATION STUDIES IN THE NASA/MSFC 14 x 14 INCH TRISONIC WIND TUNNEL ON A .004 SCALE MODEL (34-0) SPACE SHUTTLE ORBITER AND INTEGRATED VEHICLE

By

W. P. Garton*

SUMMARY

This report presents details of flow visualization techniques developed during wind tunnel test IA-52 conducted in the NASA/MSFC 14 x 14 inch Trisonic Wind Tunnel. Testing was conducted from Mach = 0.9 to 5.0 on the orbiter alone and integrated vehicle configurations. Thin film oil paint and ultraviolet light sensitive oil applications were used on a .004 scale model vehicle. Test results presented herein are in the form of black and white photographs taken after the completion of a test run.

* Rockwell International

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TEST FACILITY DESCRIPTION

The Marshall Space Flight Center 14" x 14" Trisonic Wind Tunnel is an intermittent blowdown tunnel which operates by high pressure air flowing from storage to either vacuum or atmospheric conditions. A Mach number range from .2 to 5.85 is covered by using two interchangeable test sections. The transonic section permits testing at Mach 0.20 through 2.50 and the supersonic section permits testing at Mach 2.74 through 5.85. Mach numbers between .2 and .9 are obtained by using a controllable diffuser. The range from .95 to 1.3 is achieved through the use of plenum suction and perforated walls. Mach numbers of 1.44, 1.93 and 2.50 are produced by interchangeable sets of fixed contour nozzle blocks. Above Mach 2.50 a set of fixed contour nozzle blocks are tilted and translated automatically to produce any desired Mach number in .25 increments.

Air is supplied to a 6000 cubic foot storage tank at approximately -40°F dew point and 500 psi. The compressor is a three-stage reciprocating unit driven by a 1500 hp motor.

Tunnel flow is established and controlled with a servo-actuated gate valve. The controlled air flows through the valve diffuser into the stilling chamber and heat exchanger where the air temperature can be controlled from ambient to approximately 180°F. The air then passes through the test section which contains the nozzle blocks and test region.

Downstream of the test section is a hydraulically controlled pitch sector that provides a total angle of attack range of 20° (±10°). Sting offsets are available for obtaining various maximum angles of attack up to 90°.

CONFIGURATIONS INVESTIGATED

The 0.004-scale orbiter model general arrangement is shown in figure 1. The model has an aluminum wing and stainless steel body, vertical fin, and movable (interchangeable) surfaces. Data were taken with speed brake settings of:

δ_{SB} (deg) = 0, 24, 55.

The orbiter model was fabricated in conformance with the lines drawings listed below:

Nose	VL70-000143A
Mid-body and wing	VL70-000200
Aft body	VL70-000145
Vertical tail	VL70-000146A

The launch vehicle models (MSFC Model No. 453) were fabricated to 0.004-scale in conformance with the following configuration control drawings:

External Tank	VL78-000041B (except nose radius 30° vice 16.5" FS)
Solid Rocket Booster	VL77-000036A

The mated vehicle was assembled in accordance with the Shuttle Configuration Control Drawing VL72-000088D. Exact duplication of attached hardware and protuberances could not be maintained at 0.004-scale. Model fidelity, or lack thereof, in attachments and protuberances is indicated below:

Component	Description	Model Fidelity
AT_5	Front Orb/ET Attach.	No: single vertical mounting post (.099" diam.) at same body station.
AT_6, AT_7	Left and Right Rear Orb/ET Attach.	Yes
AT_8, AT_9	Front and Rear SRB/ET Attach.	No: single stand-off post mount .182" in diam. at approximately same body stations on ET ℄.
FL_1, FL_2	LOX and LH_2 Feedlines	Yes: represented by aft model orbiter/ET mounting posts (0.187" diam.) at correct body station.
FR_1	Umbilical Door Fairing	Absent.
FR_2	Splash Shield (LOX and LH_2)	Absent.
PS_1	SRB Electrical Tunnel	Absent.
PS_2	SRB Aft Attach Ring	Yes.
PS_3	Separation Rocket Fairing	Yes.
PT_1	LOX Vent Line Fairing	Yes.
PT_2	LOX Feedline	Yes.
PT_3	LH_2 Vent Line	Yes.

Model dimensional data sheets defining the various configuration designators are provided in Table III. The model components tested were:

B26	orbiter body
C9	canopy
R5	rudder
V8	vertical tail
W116	wing, basic

F7	body flap
E26	elevon
M7	OMS pods
S12	Solid Rocket Booster with Attach ring (PS2) and Separation Rocket Fairing (PS3)
T14	External Tank with LOX and LH_2 vent lines and LOX feed line (PT1,2,3)

TEST PROCEDURE

Model Preparation

The model parts were cleaned of oil and grease before assembly and then again after assembly to aid adhesion of the filler. All gaps, nicks, and screw slots were filled with polyester resin (auto body) filler so that no pockets for pigment or solvent remained. Final contouring was accomplished with #600 wet aluminum oxide paper.

The model was lightly degreased and then sprayed with white lacquer in several medium coats. Imperfections then evident were touched up with filler and # 600 paper. The model was then resprayed with lacquer and allowed to dry at least one hour following achievement of an acceptable finish. The color coat was then sealed with several coats of clear lacquer, as it has been found that the oil paint pigments tend to adhere to the color coat. The model should be allowed to dry overnight if possible; hardware and facility schedules did not permit this long a drying period for this test. The effects of surface imperfections may be noted in many of the photographs; Figure 11 shows these effects very clearly.

Medium Pr[illegible]aration

Red, yellow, and prussian blue oil paints were mixed with artist's linseed oil in the approximate proportions (by volume) shown below. It is believed that best results with black and white photography will be obtained with black or prussian blue oil paints.

Pigment	Linseed Oil	Mach No.	P_o
1	1	1.0	22
1	1.5 to 2.0	2.0	28
1	2.5 to 3.0	3.0	30
1	2.5 to 4.5 (?)	5.0	90

A medium composed of a mixture of silicone oil, silicone stopcock grease, and phosphor powder mixed to the consistence of thin pancake batter was found to be effective at $0.9 \leq M \leq 1.2$. It is believed th[illegible] it would be necessary to thin the mixture as Mach number increases. Enough phosphor should be used to provide ample pigmentation. Ultraviolet illumination of the model during the run to observe flow pattern development (and decide when to terminate the run) is required using either the phosphor or a "Zyglo" solution medium. Ultraviolet lighting is also required for black and white post-run photography of the model. The longer exposure times were found to permit puddling or running of the flow pattern on the model with the thin medium used at the higher Mach numbers. Figures 3 and 11 are examples of the results obtained with the phosphor/oil/silicone grease and the Zyglo solution, respectively.

Application

Oil Film - There was a tendency to apply too much pigment, with puddling and subsequent running during the post-run photography of the model. Better results were obtained with a thin coat of paint applied with an artist's brush (# 5 or # 6 is good) and then wiped off evenly with a facial tissue so that a thin film of pigment remained (Figure 31). The wipe pattern may be removed if desired by lightly spraying (from a distance of approximately 12") with an aerosol can of machine tool oil; an atomizer and linseed oil would also work. This produces a dappled appearance (Figure 32).

Phosphor - This was also brushed on thinly, but not wiped down. The same technique was used with the Zyglo solution.

Data Runs

Runs should be long enough to develop a pattern and blow away excess medium if possible. The appearance of the model during the run was monitored through glass walls and the run terminated on visual cues. Typical blows were 20-25 seconds in the transonic range, but as brief as 10 seconds at $M > 3.0$.

Photography

Black and white photography was employed to record the run results. Motion pictures are feasible with the oil paint technique. It may be desirable to open the tunnel immediately after the blow and roll the model to minimize running of the thin medium at higher Mach numbers. As previously mentioned, this problem is compounded with the fluorescing medium because of the longer exposure times required.

Model Clean-Up

The chosen cleaning method was to paint the model with liquid soap and rinse with hot water. Mineral spirits may also be used.

DATA INTERPRETATION

The data (Figures 2 through 30) obtained in this test have been (and are to be) used only for qualitative evaluation of flow characteristics in the selected flight conditions. Quantitative results will require more rigorous control of camera look angles than was provided in this study.

TABLE I. TEST CONDITIONS

TEST: MSFC TWT 584

DATE: 10/8/73

TEST CONDITIONS

MACH NUMBER	REYNOLDS NUMBER (per unit length)	DYNAMIC PRESSURE (pounds/sq.inch)	STAGNATION TEMPERATURE (degrees Fahrenheit)	STAGNATION PRESSURE (pounds/sq inch)
0.9	6.2×10^6/ft.	7.36	100	22
1.2	6.7	10.68	100	22
1.96	7.0	10.20	100	28
2.99	4.0	5.19	140	30
4.96	4.8	3.07	140	90

BALANCE UTILIZED: None

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

COMMENTS: Flow Visualization Only

MSFC - Form 263-1 (Rev. April 1973)

TABLE II.

TEST: TWT 584 (IA-52) — **DATA SET/RUN NUMBER COLLATION SUMMARY** — **DATE:**

DATA SET IDENTIFIER	CONFIGURATION	SCHD. α	SCHD. β	φ	λo	Zo	δsB	MACH 0.9	MACH 1.2	MACH 1.96	MACH 2.99	MACH 4.96
	Φ34 T14 S12	5	5	270	0	34"	0	1	2			
	↓	8	0	0	0	34"	0	3				
	↓	10	3	270	0	34"	0					4
	Φ34	0	0	0	—	—	24	5				
	↓	10	5	270	—	—	24	6				
	↓	10	0	0	—	—	-55			7	8	9

ΦRBITER-MODEL 34-0 (Φ34) = (B26 C9 F7 M7)(W116 E26)(V8 R5)

TANKS- MSFC MODEL 453

ET = T14 = T9 plus LOX and LH2 vent lines and LH2 feed line protuberances

SRB = S12

TEST RUN NUMBERS

COEFFICENTS — α OR β SCHEDULES — IDVAR (1) — IDVAR (2) — NDV

TABLE III. MODEL DIMENSIONAL DATA

MODEL COMPONENT: BODY - B[illegible]

GENERAL DESCRIPTION: Orbiter Fuselage Configuration 140 A/B

NOTE: B[illegible] identical to B[illegible] except underside of fuselage refaired to accept [illegible]$_{116}$.

Model Scale = .004

DRAWING NUMBER: VL70-000193, VL70-000140A

DIMENSIONS:	FULL-SCALE	MODEL SCALE
Length (Body Fwd Sta X_o = 238) - in.	1290.3	5.16120
Max. Width (at X_o = 1520) - in.	262.0	1.04800
Max. Depth (at X_o = 1464) - in.	250.0	1.000
Fineness Ratio	4.92481	4.92481
Area - ft^2		
Max. Cross-Sectional	340.88462	0.00545
Planform		
Wetted		
Base		

TABLE III. (Continued)

MODEL COMPONENT: Canopy-C9

GENERAL DESCRIPTION: Configuration 3A

Model Scale = .004

DRAWING NUMBER VL70-000140A
VL70-000143A

DIMENSION:	FULL SCALE	MODEL SCALE
Length (X_o=434.643 to 670)	235.357	0.94143
Max Width (@ X_o=513.127)	152.412	0.60965
Max Depth (@ X_o=485.0)	25.000	0.10000
Fineness Ratio		
Area		
Max Cross-Sectional		
Planform		
Wetted		
Base		

TABLE III. (Continued)

MODEL COMPONENT: R5 - Rudder

GENERAL DESCRIPTION: 2A and 3 configuration per Rockwell lines VL70-000095 and VL70-000139

Scale Model = .004

DRAWING NUMBER: VL70-000139
VL70-000095

DIMENSIONS:	FULL-SCALE	MODEL SCALE
Area ~ Ft^2	106.38	0.00170
Span (equivalent) ~ IN.	201.0	0.8040
Inb'd equivalent chord	91.585	0.36634
Outb'd equivalent chord	50.833	0.20333
Ratio movable surface chord/ total surface chord		
At Inb'd equiv. chord	0.400	0.400
At Outb'd equiv. chord	0.400	0.400
Sweep Back Angles, degrees		
Leading Edge	34.83	34.83
Tailing Edge	26.25	26.25
Hingeline	34.83	34.83
Area Moment (Normal to hinge line) Ft^3	526.13	0.00003

Product of area and mean chord

TABLE III. (Continued)

MODEL COMPONENT: WING-W[illegible]16

GENERAL DESCRIPTION: Configuration 4

NOTE: Identical to W[illegible] except [illegible]. Dihedral angle is along trailing edge of wing.

Model Scale = .004

TEST NO.

DWG. NO. VL70-000[illegible] VL70-000[illegible]

DIMENSIONS:	FULL-SCALE	MODEL SCALE
TOTAL DATA		
Area (Theo.) Ft^2		
Planform	2690.00	0.4304
Span (Theo In.	936.6816	3.74672
Aspect Ratio	2.265	2.265
Rate of Taper	1.177	1.177
Taper Ratio	0.200	0.200
Dihedral Angle, degrees(at X_o=1506.623, Y_o=	3.500	3.500
Incidence Angle, degrees 105, Z_o= 282.75)	0.500	0.500
Aerodynamic Twist, degrees	+3.000	+3.000
Sweep Back Angles, degrees		
Leading Edge	45.00	45.00
Trailing Edge	-10.056	-10.056
0.25 Element Line	35.209	35.209
Chords:		
Root (Theo) B.P.O.O.	689.2429	2.75697
Tip, (Theo) B.P.	137.8486	0.551[illegible]
MAC	474.8117	1.[illegible]
Fus. Sta. of .25 MAC	1126.721	4.5[illegible]
W.P. of .25 MAC	291.00	1.16[illegible]
B.L. of .25 MAC	187.35401	0.74[illegible]
EXPOSED DATA		
Area (Theo) Ft^2	1812.2205	0.02899
Span, (Theo) In. BP108	736.6816	2.[illegible]
Aspect Ratio	2.058	2.058
Taper Ratio	0.2451	0.2451
Chords		
Root BP108	570.6230	2.28249
Tip 1.00 $\frac{b}{2}$	137.8512	0.55140
MAC	354.2376	1.41695
Fus. Sta. of .25 MAC	1164.237	4.65695
W.P. of .25 MAC	292.00	1.16800
B.L. of .25 MAC	239.67786	0.95671
Airfoil Section (Rockwell Mod NASA) XXXX-64		
Root $\frac{b}{2}$ = 0.425	0.113	0.113
Tip $\frac{b}{2}$ = 1.00	0.12	0.12
Data for (1) of (2) Sides		
Leading Edge Cuff		
Planform Area Ft^2	118.333	0.00189
Leading Edge Intersects Fus M. L. @ Sta	505.0	2.02000
Leading Edge Intersects Wing @ Sta	1003.5	4.01400

TABLE III. (Continued)

MODEL COMPONENT: Body Flap - F_7

GENERAL DESCRIPTION: Configuration 3A

NOTE: Body flap has variable centerline deflection of +13.75° and -11.25° from null position. Hinge line located at X_o =1522.3.

Z_o = 284.3

Model Scale = .004

DRAWING NUMBER VL70-000140A, VL70-000145

DIMENSION:	FULL SCALE	MODEL SCALE
Length (X_o=1520 to X_o=1613) - IN.	93.000	0.372
Max Width - IN.	262.000	1.048
Max Depth (X_o = 1520) - IN.	23.000	0.092
Fineness Ratio		
Area - Ft^2		
Max Cross-Sectional		
Planform	150.5250	0.00241
Wetted		
Base	41.84722	0.00067

TABLE III. (Continued)

MODEL COMPONENT: ELEVON - E_{26}

GENERAL DESCRIPTION: Configuration 4

NOTE: VL70-000400 data for (1) of (2) sides. Identical to E_{25} except airfoil thickness

Model Scale = .004

DRAWING NUMBER: VL70-000200
VL70-000140 B

DIMENSIONS:	FULL-SCALE	MODEL SCALE
Area ft.	223.5814	0.00358
Span (equivalent) in.	368.34	1.47336
Inb'd equivalent chord in.	119.623	0.47849
Outb'd equivalent chord in.	55.1922	0.22077
Ratio movable surface chord/ total surface chord		
At Inb'd equiv. chord	0.2096	0.2096
At Outb'd equiv. chord	0.4004	0.4004
Sweep Back Angles, degrees		
Leading Edge	0.00	0.00
Tailing Edge	-10.056	-10.056
Hingeline	0.00	0.00
Area Moment (Normal to hinge line)	851.1502	0.00005

TABLE III. (Continued)

MODEL COMPONENT: OMS POD - M7

GENERAL DESCRIPTION: Configuration 3A

Model Scale = .004

DRAWING NUMBER VL70-000140A
VL70-000145

DIMENSION:	FULL SCALE	MODEL SCALE
Length (OMS Fwd Sta X_o=1233.0) - IN.	327.000	1.30800
Max Width (@ X_o=1450.0) - IN.	94.5	0.37800
Max Depth (@ X_o=1493.0) - IN.	109.000	0.43600
Fineness Ratio		
Area		
Max Cross-Sectional		
Planform		
Wetted		
Base		

TABLE III. (Continued)

MODEL COMPONENT: VERTICAL - V[illegible]

GENERAL DESCRIPTION: Configuration 3[illegible]

NOTE: Similar to V5 with radius on TE upper corner and LE lower corner where vertical meets fuselage.

Model Scale = .004

DRAWING NUMBER: VL70-00014[illegible]
VL70-00014[illegible]

DIMENSIONS:	FULL-SCALE	MODEL SCALE
TOTAL DATA		
Area (Theo) Ft^2	413.253	0.00661
Planform		
Span (Theo) In	315.7[illegible]	1.26[illegible]
Aspect Ratio	1.[illegible]5	1.[illegible]
Rate of Taper	0.5[illegible]	0.5[illegible]7
Taper Ratio	0.40399	0.4[illegible]3[illegible]
Sweep Back Angles, degrees		
Leading Edge	45.00	45.00
Trailing Edge	25.947	25.9[illegible]
0.25 Element Line	41.130	[illegible]
Chords:		
Root (Theo) WP	268.500	1.07400
Tip (Theo) WP	10[illegible].470	[illegible]
MAC	190.[illegible]	[illegible]
Fus. Sta. of .25 MAC	1463.50	[illegible]
W. P. of .25 MAC	635.5[illegible]	[illegible]
B. L. of .25 MAC	0.00	0.00
Airfoil Section		
Leading Wedge Angle Deg	10.00	10.00
Trailing Wedge Angle Deg	14.9[illegible]	14.9[illegible]
Leading Edge Radius (Min) - IN.	2.00	0.008[illegible]
Void Area	13.17	0.000[illegible]
Blanketed Area	0.00	0.00

TABLE III. (Continued)

MODEL COMPONENT: BOOSTER SOLID ROCKET MOTOR - [illegible]

GENERAL DESCRIPTION: Configuration 3A, Data for (1) of (2) sides, per Rockwell Lines VL77-000036A

Model Scale = 0.004

DRAWING NUMBER: VL72-000088A
VL77-000036A

DIMENSIONS:

	FULL-SCALE	MODEL SCALE
Length (Includes Nozzle) - IN.	1741.0	6.9640
Max. Width (Tank Dia) - IN.	142.3	0.5692
Max. Depth (Aft Shroud) - IN.	192.0	0.7680
Fineness Ratio	9.06771	9.06771
Area - FT^2		
Max. Cross-Sectional	201.06193	0.00322
Planform		
Wetted		
Base		
WP of BSRM Centerline (Z_T) - IN.	400	1.6000
FS of BSRM Nose (X_T) - IN.	200	0.8000

Table III. (Concluded)

MODEL COMPONENT: EXTERNAL TANK - T_{14}

GENERAL DESCRIPTION:

NOTE: T_{14} identical to T_9 but with external fuel lines added.

Model Scale = 0.004

DRAWING NUMBER: VL78-000018

DIMENSIONS:	FULL-SCALE	MODEL SCALE
Length - IN.	1858	7.432
Max. Width (Dia) - IN.	324.0	1.296
Max. Depth		
Fineness Ratio - L/D	5.73457	5.73457
Area - FT^2		
Max. Cross-Sectional	572.56	0.009161
Planform		
Wetted		
Base		

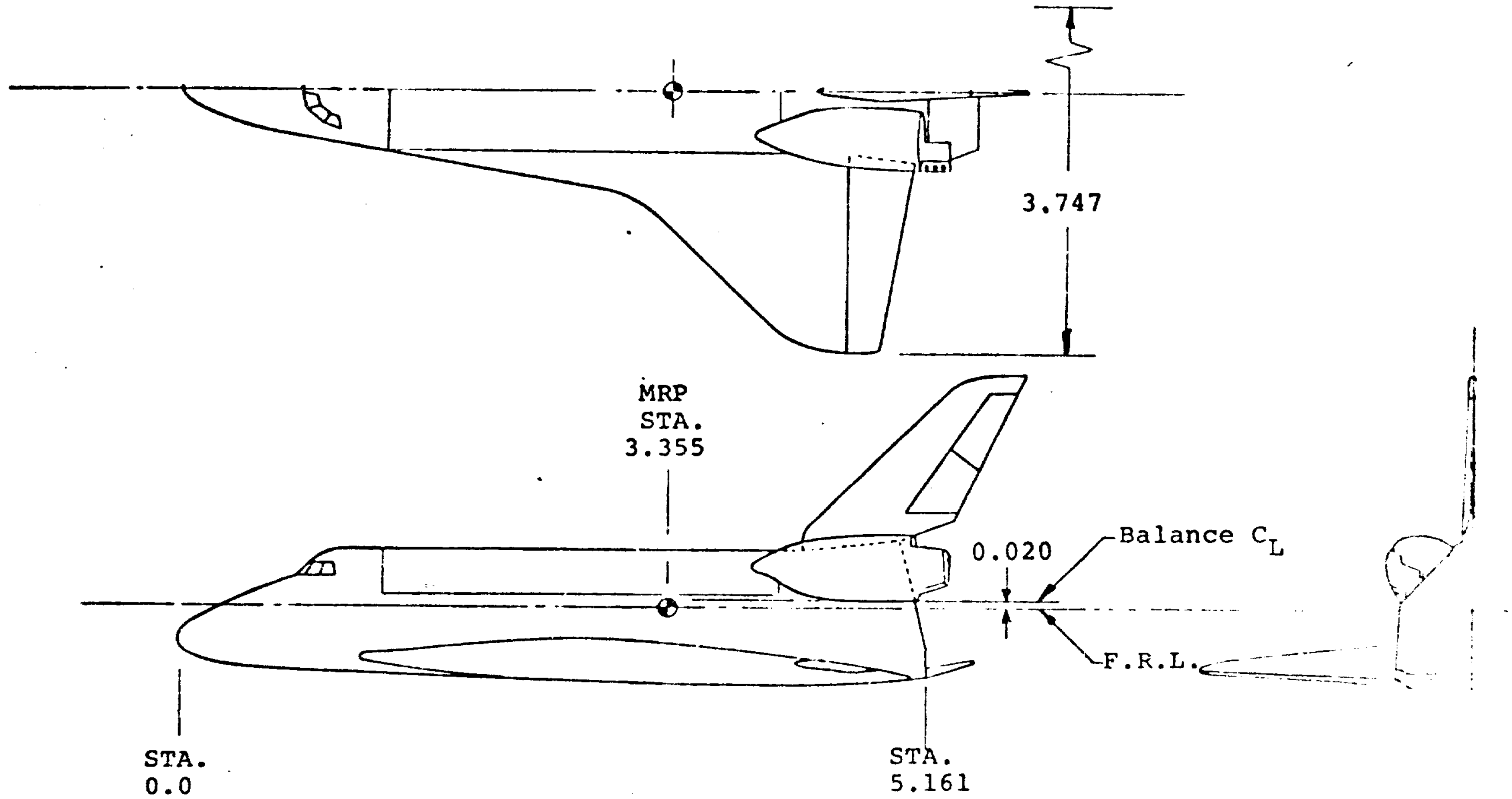

FIGURE 1. - General Arrangement of Orbiter Model

FIGURE 7. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE; $\alpha = \beta = 5°$, $M = 0.9$, BLUE OIL PAINT (TOP VIEW)

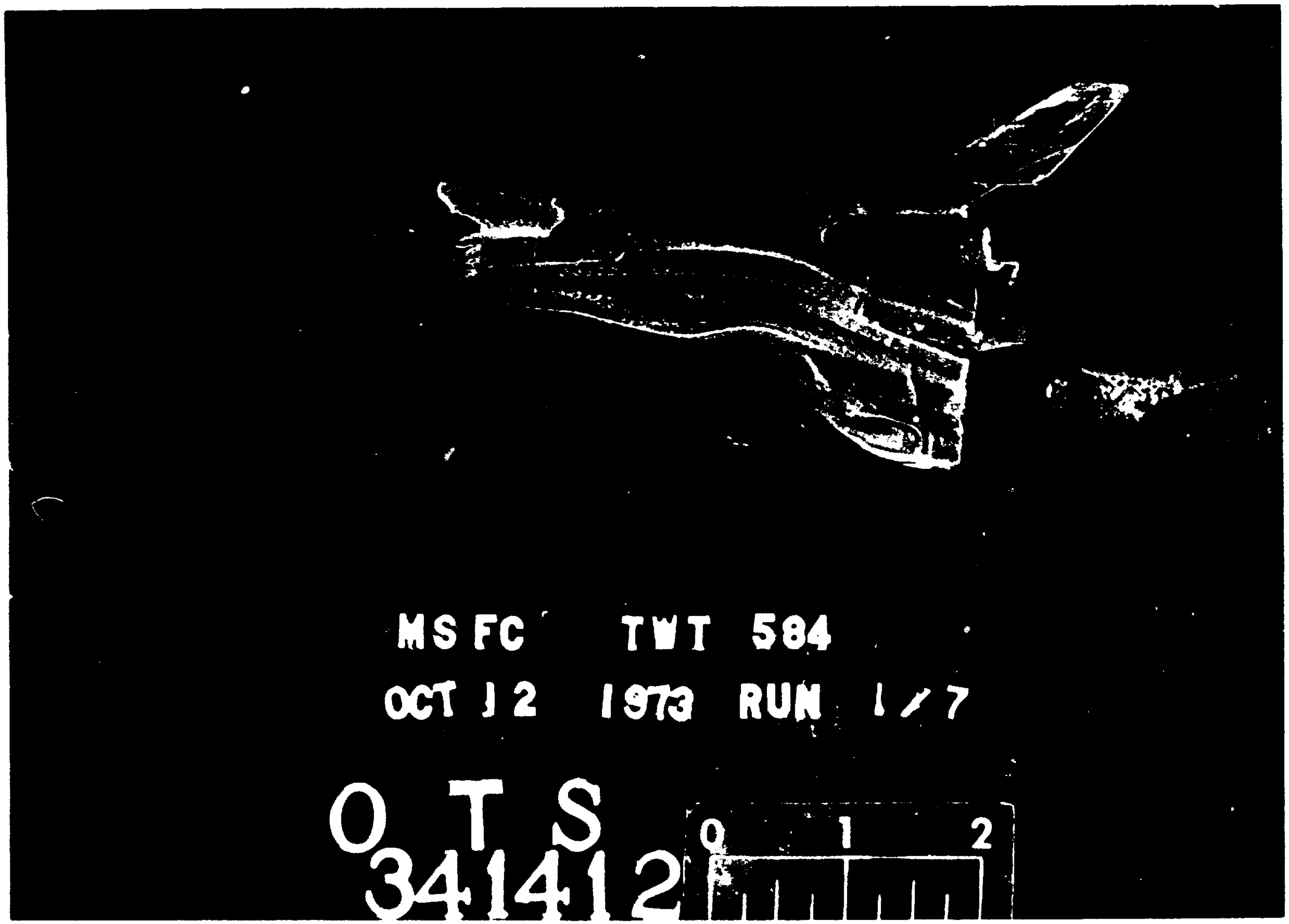

FIGURE 3. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = \beta = 5°$, $M = 0.9$, PHOSPHOR AND SILICONE OIL (LEFT OBLIQUE)

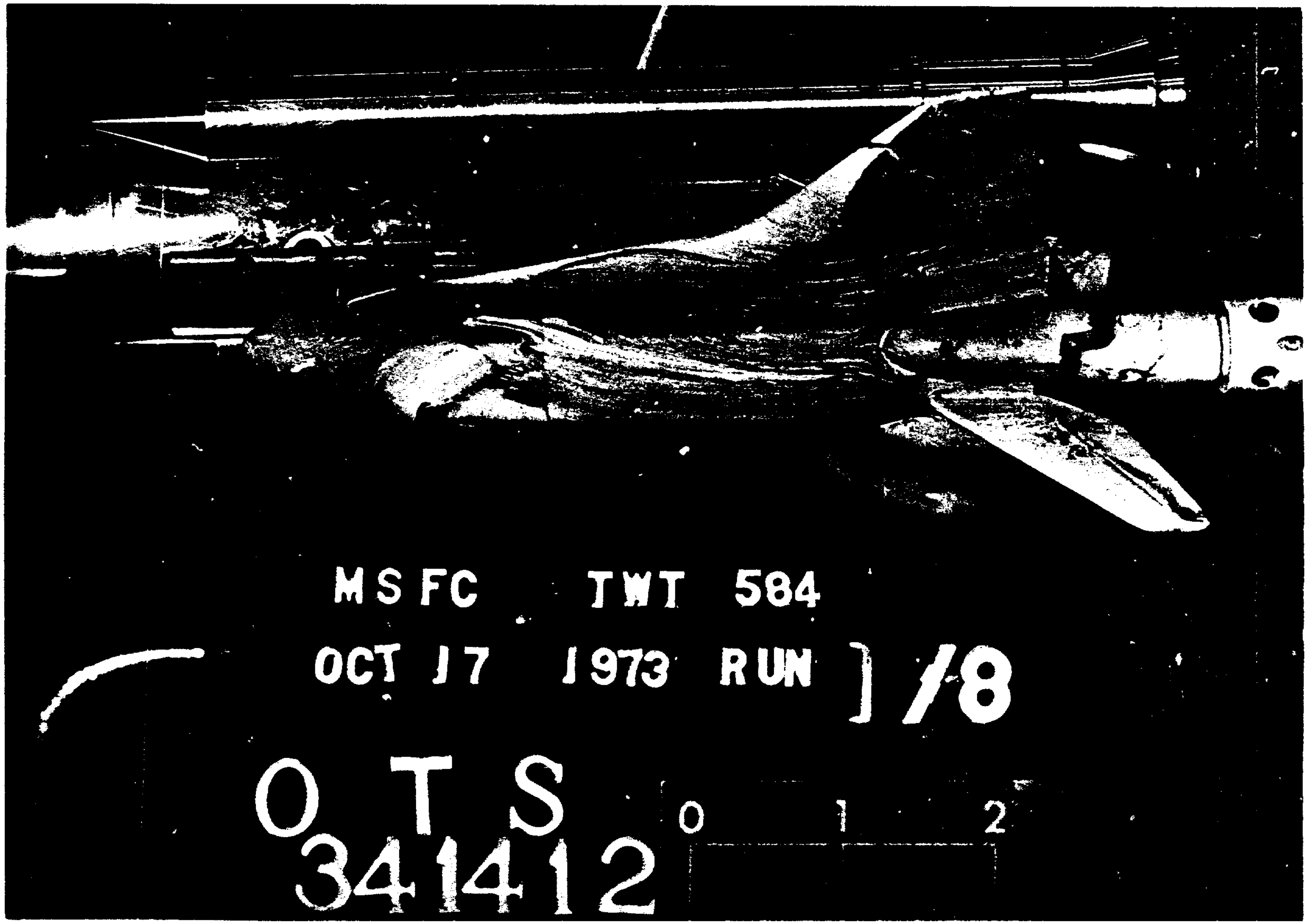

FIGURE 4. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = \beta = 5°$, $M = 0.9$, BLUE OIL PAINT (RIGHT OBLIQUE)

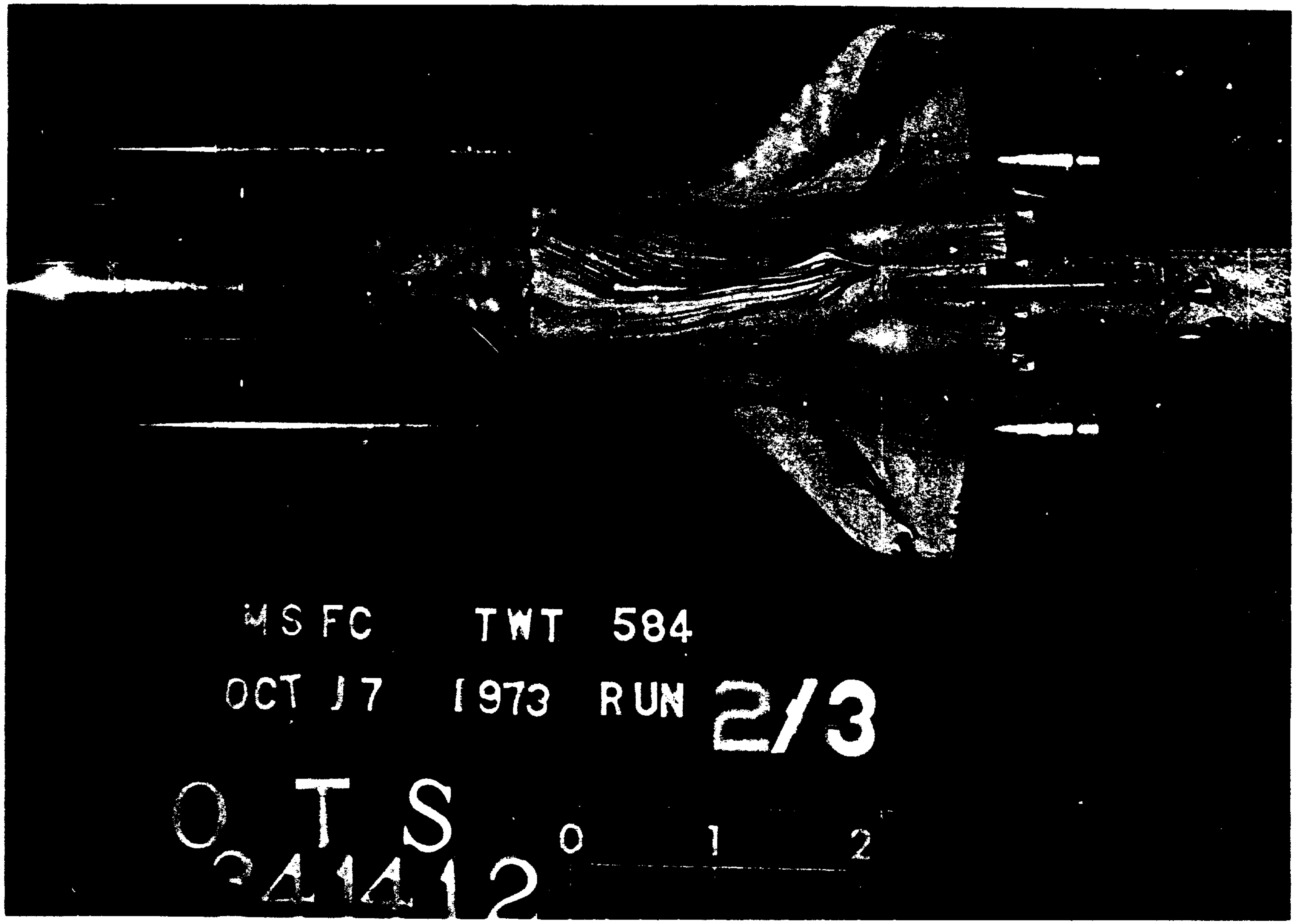

FIGURE 5. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = \beta = 5°$, $M = 1.2$, BLUE OIL PAINT (TOP VIEW)

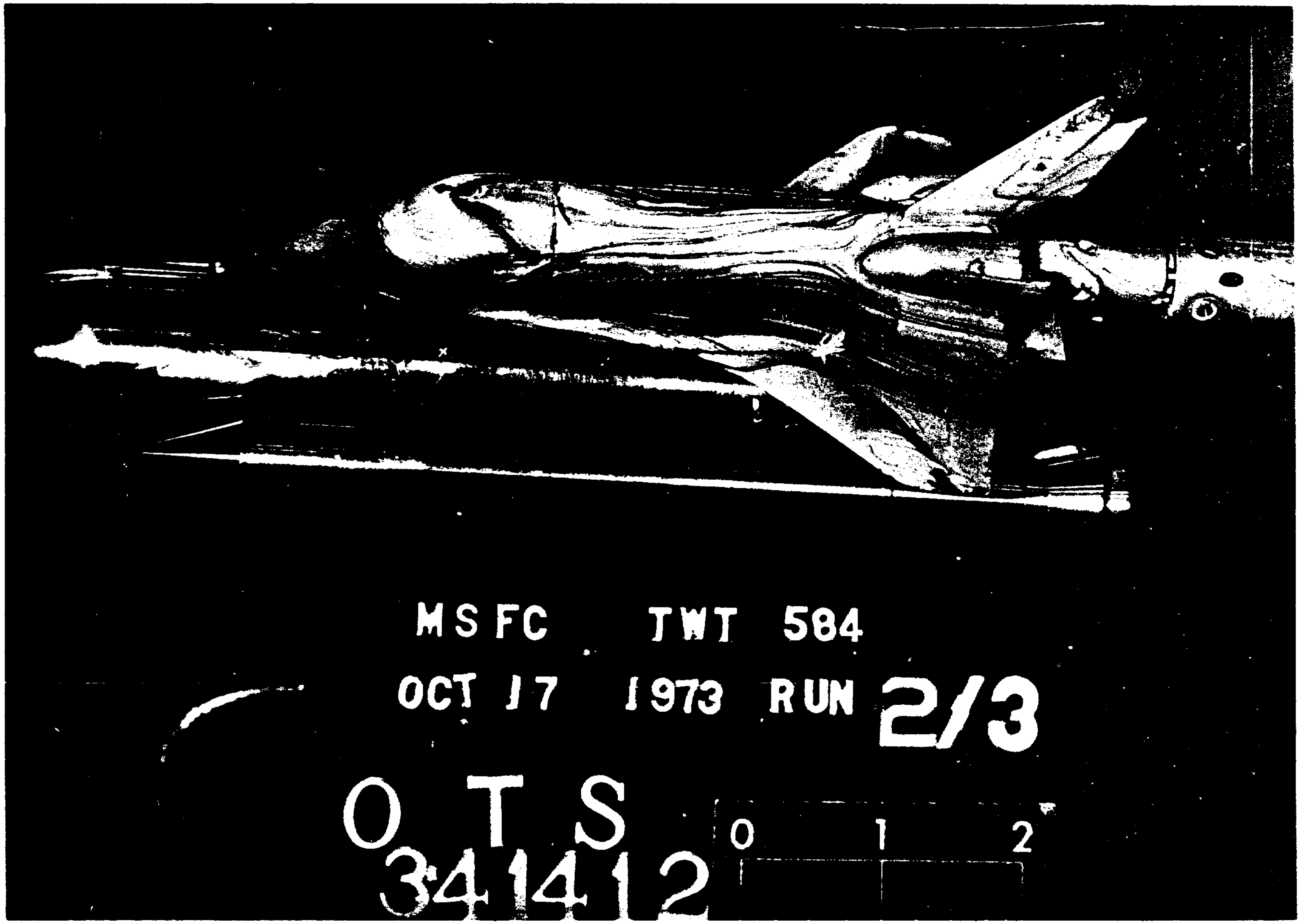

FIGURE 6. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = \beta = 5°$, $M = 1.2$, BLUE OIL PAINT (LEFT OBLIQUE)

FIGURE 7. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = \beta = 5°$, M = 1.2, BLUE OIL PAINT (RIGHT OBLIQUE)

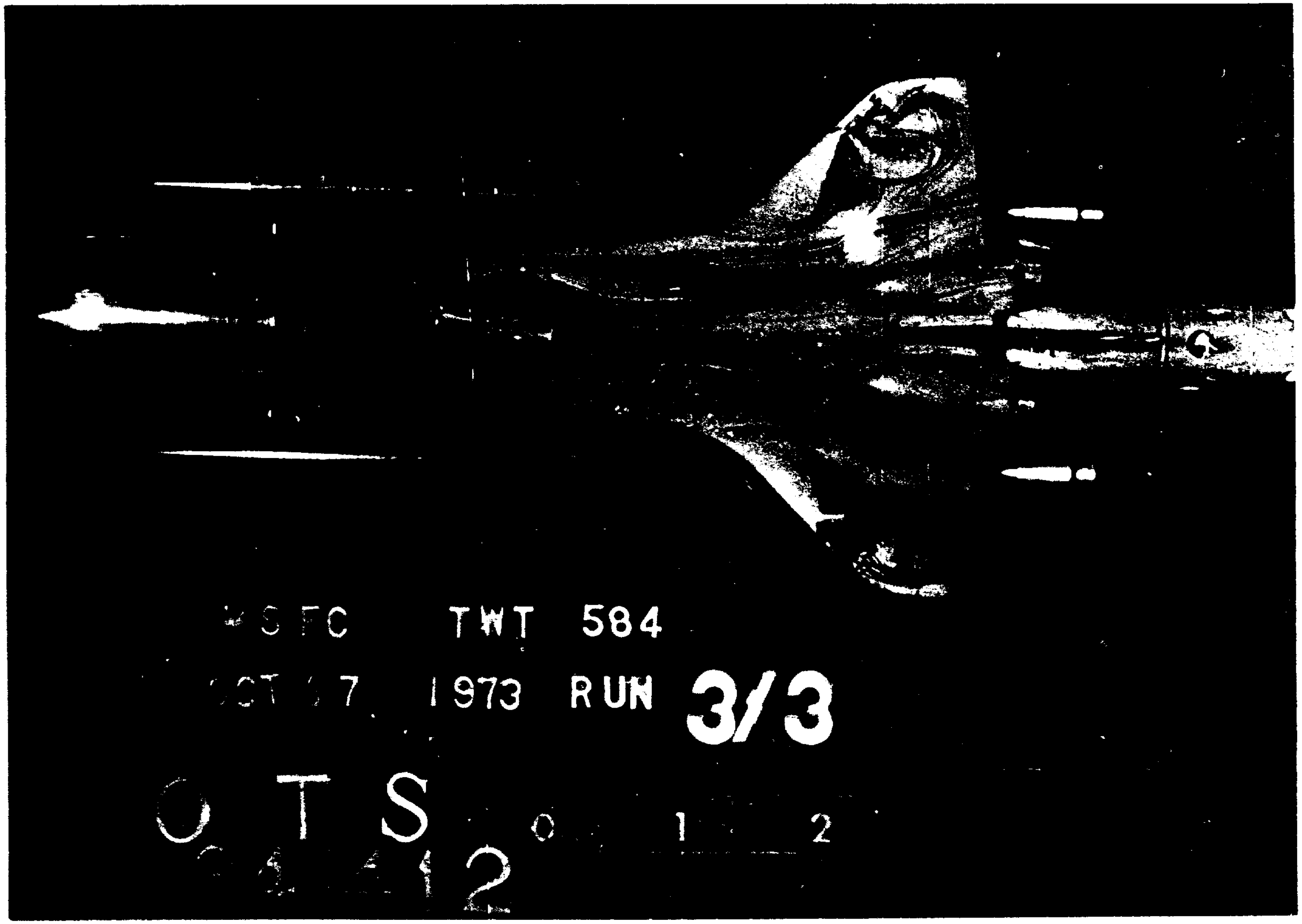

FIGURE 8. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, α = 8°, β = 0°, M = 0.9, BLUE OIL PAINT (TOP VIEW)

FIGURE 9. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = 8°$, $\beta = 0°$, M = 0.9, BLUE OIL PAINT (LEFT OBLIQUE)

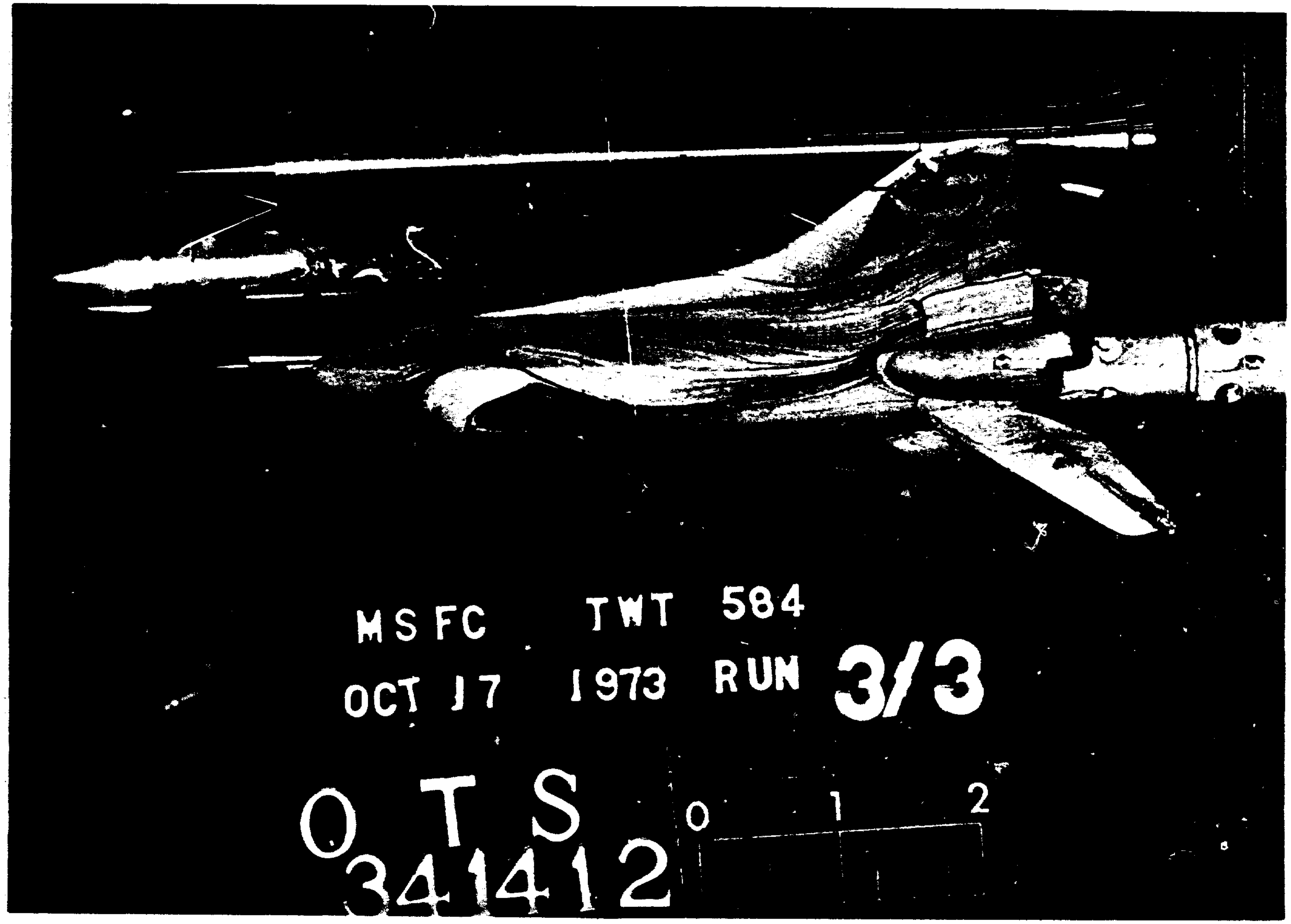

FIGURE 10. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = 8°$, $\beta = 0°$, $M = 0.9$, BLUE OIL PAINT (RIGHT OBLIQUE)

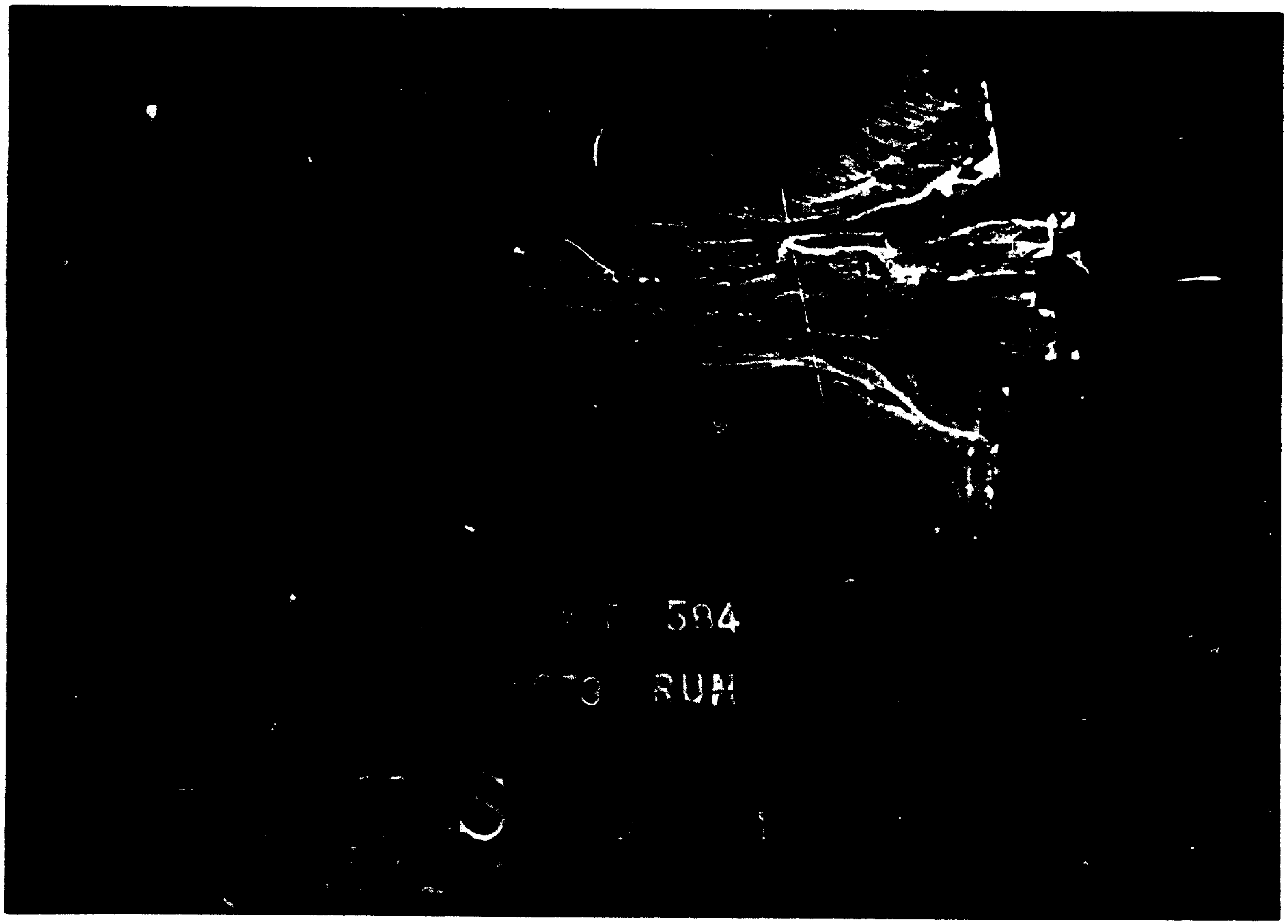

FIGURE 11. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = 10°$, $\beta = 3°$, $M = 4.96$, ZYGLO SOLUTION (TOP VIEW)

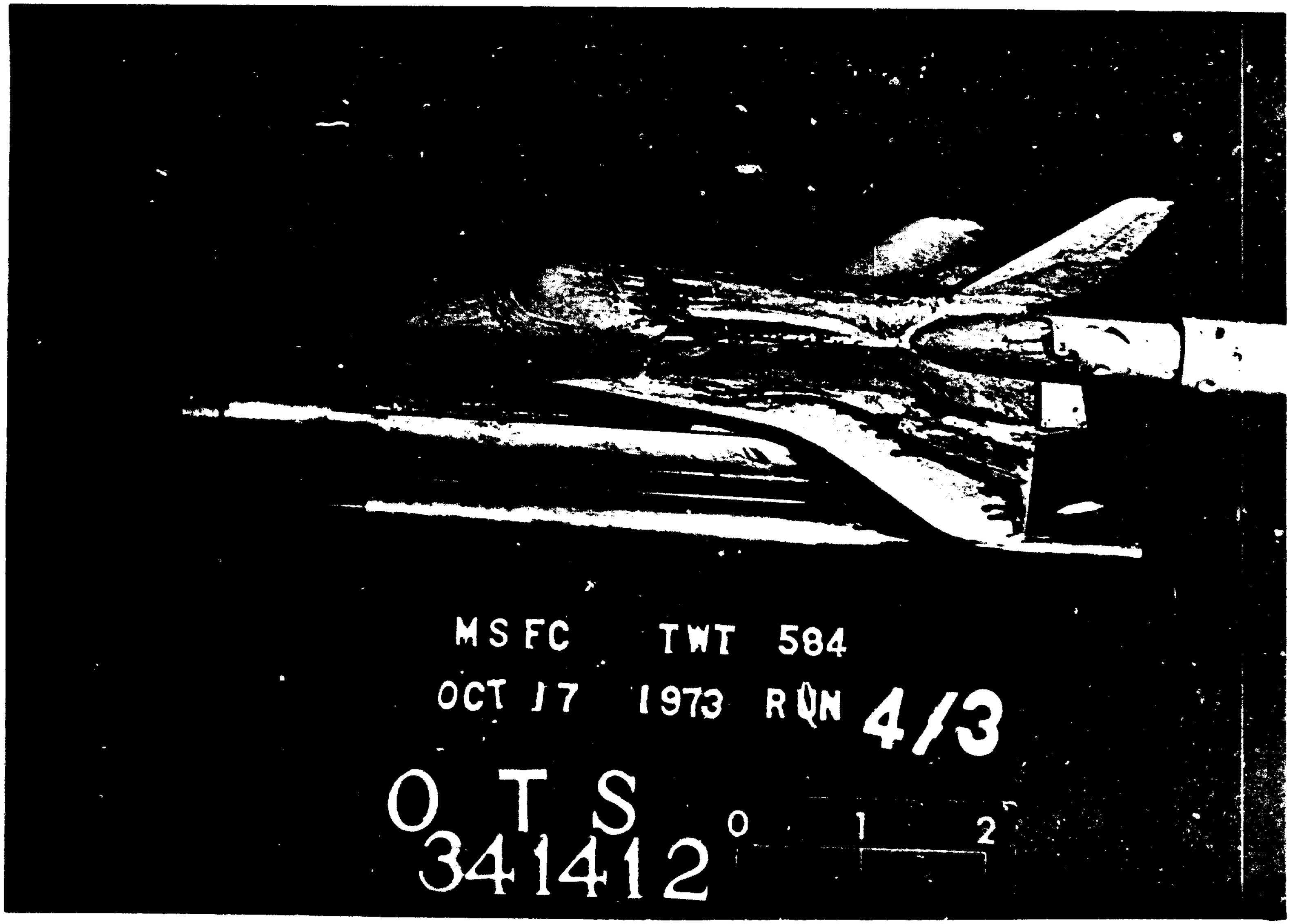

FIGURE 12. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = 10°$, $\beta = 3°$, $M = 4.96$, RED AND YELLOW OIL PAINT (LEFT OBLIQUE)

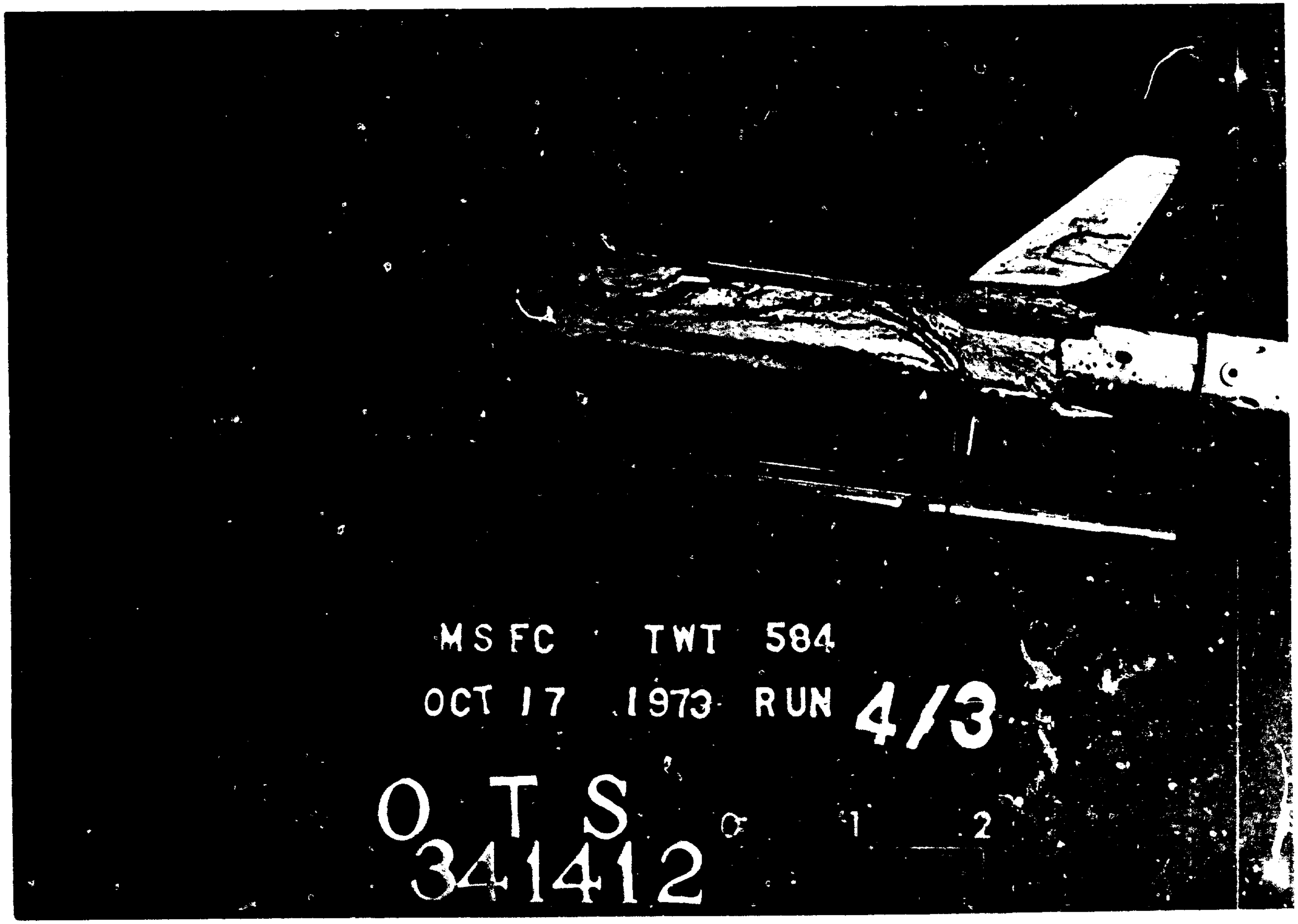

FIGURE 13. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = 10°$, $\beta = 3°$, M = 4.96, RED AND YELLOW OIL PAINT (LEFT SIDE)

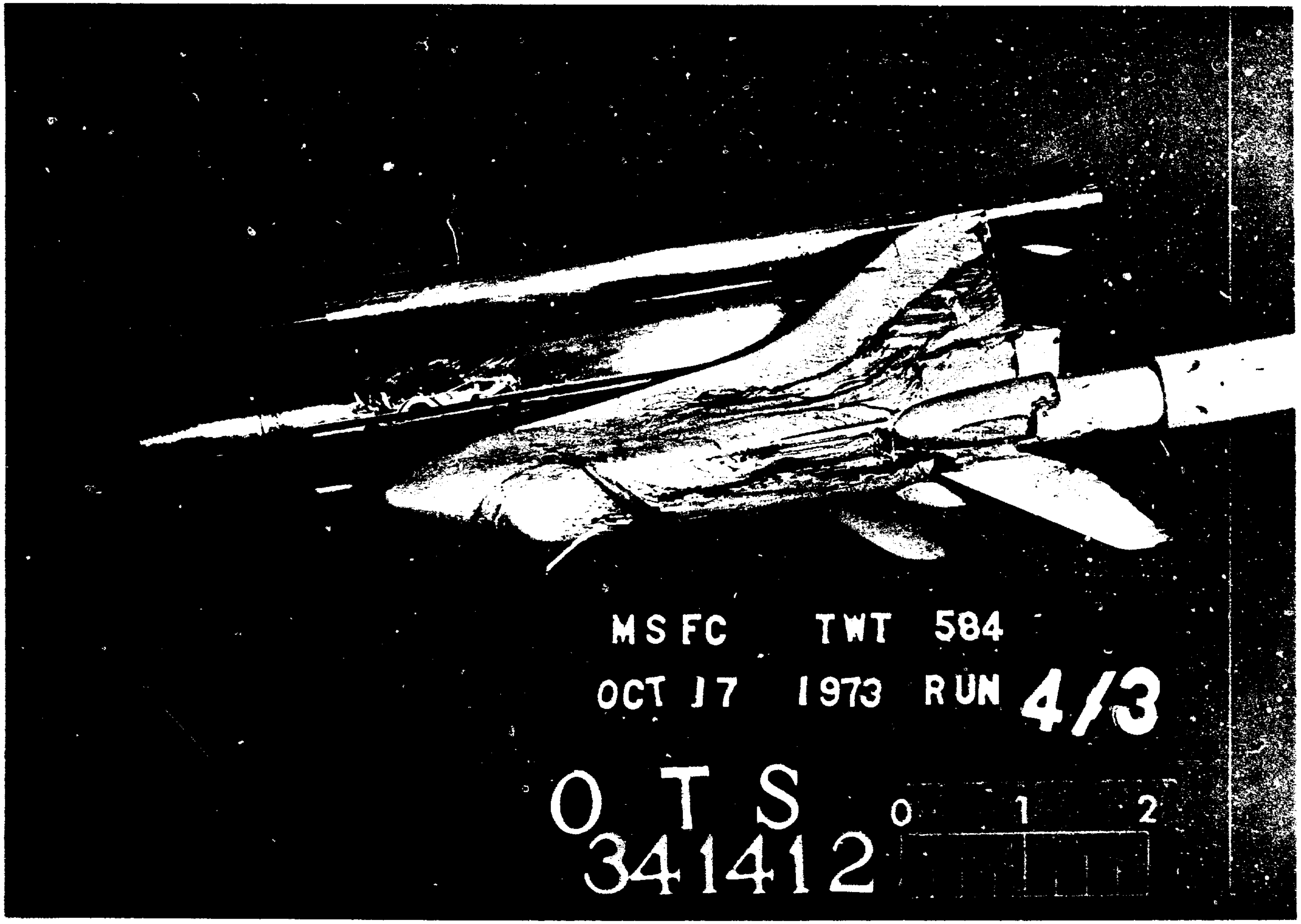

FIGURE 14. OIL FLOW PHOTOGRAPH OF INTEGRATED VEHICLE, $\alpha = 10°$, $\beta = 3°$, $M = 4.96$, RED AND YELLOW OIL PAINT (RIGHT OBLIQUE)

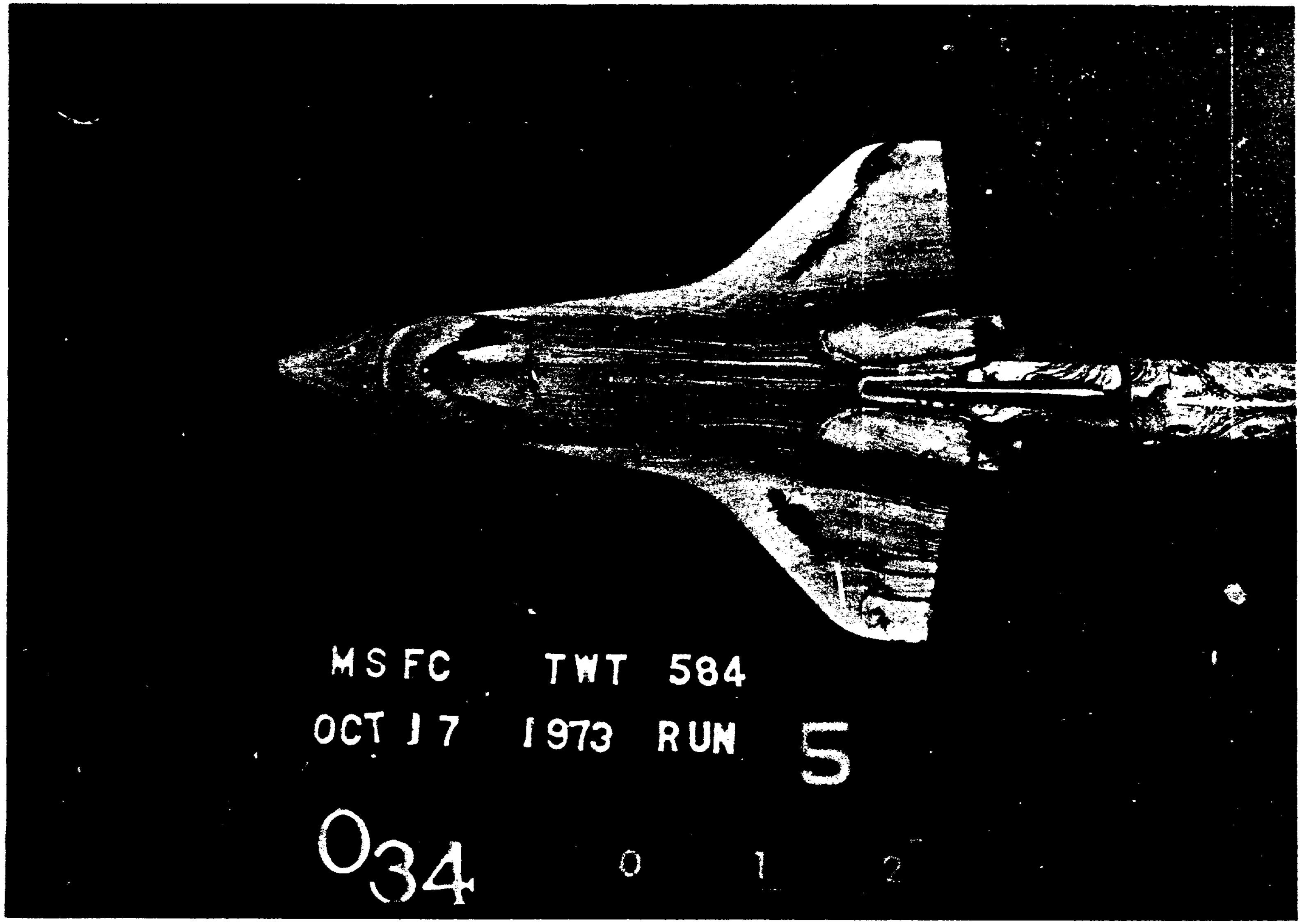

FIGURE 15. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = \beta = 0°$, $M = 0.9$, BLUE OIL PAINT (TOP VIEW)

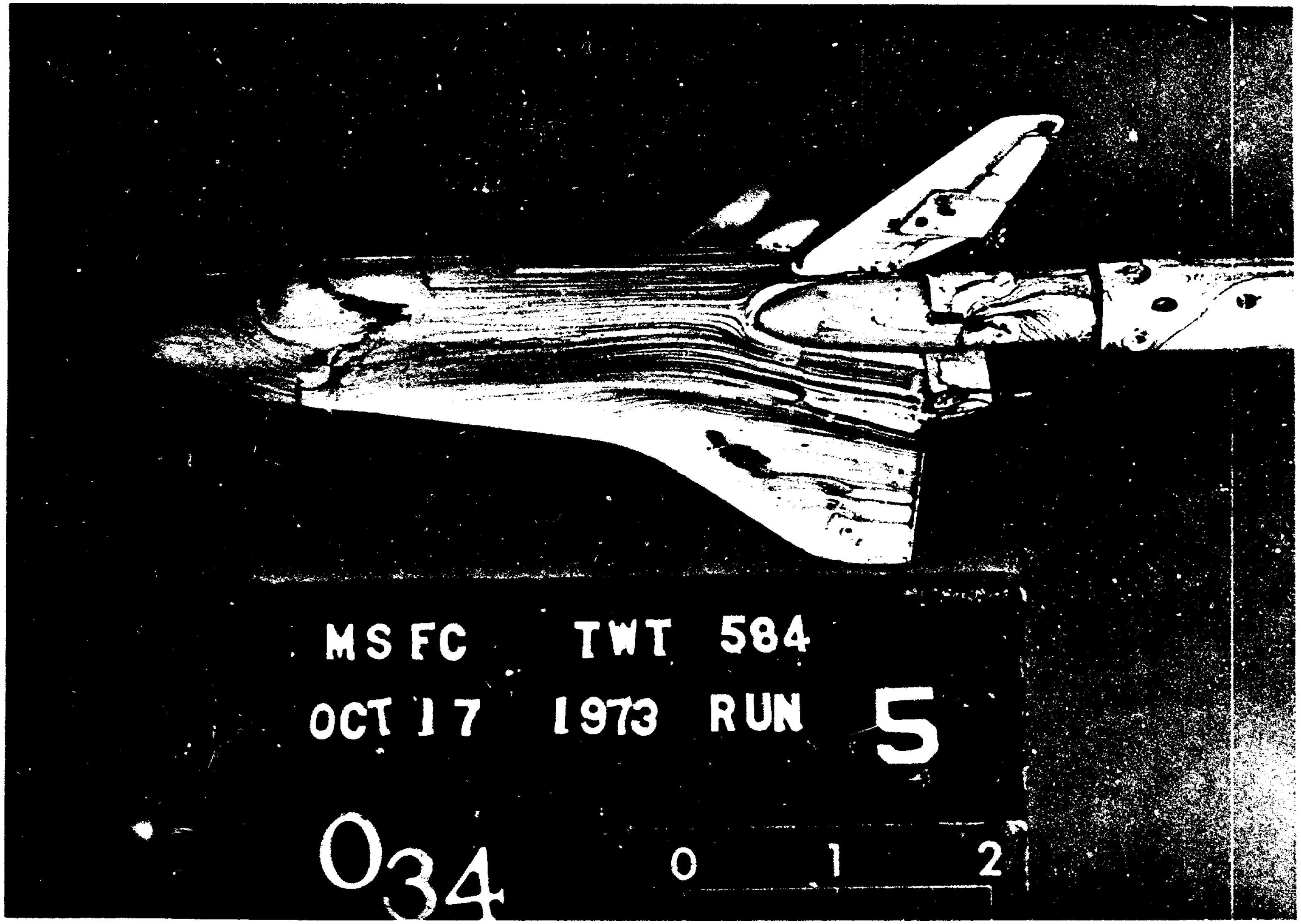

FIGURE 16. OIL FLOW PHOTOGRAPH ORBITER, $\alpha = \beta = 0°$, M = 0.9, BLUE OIL PAINT (LEFT OBLIQUE)

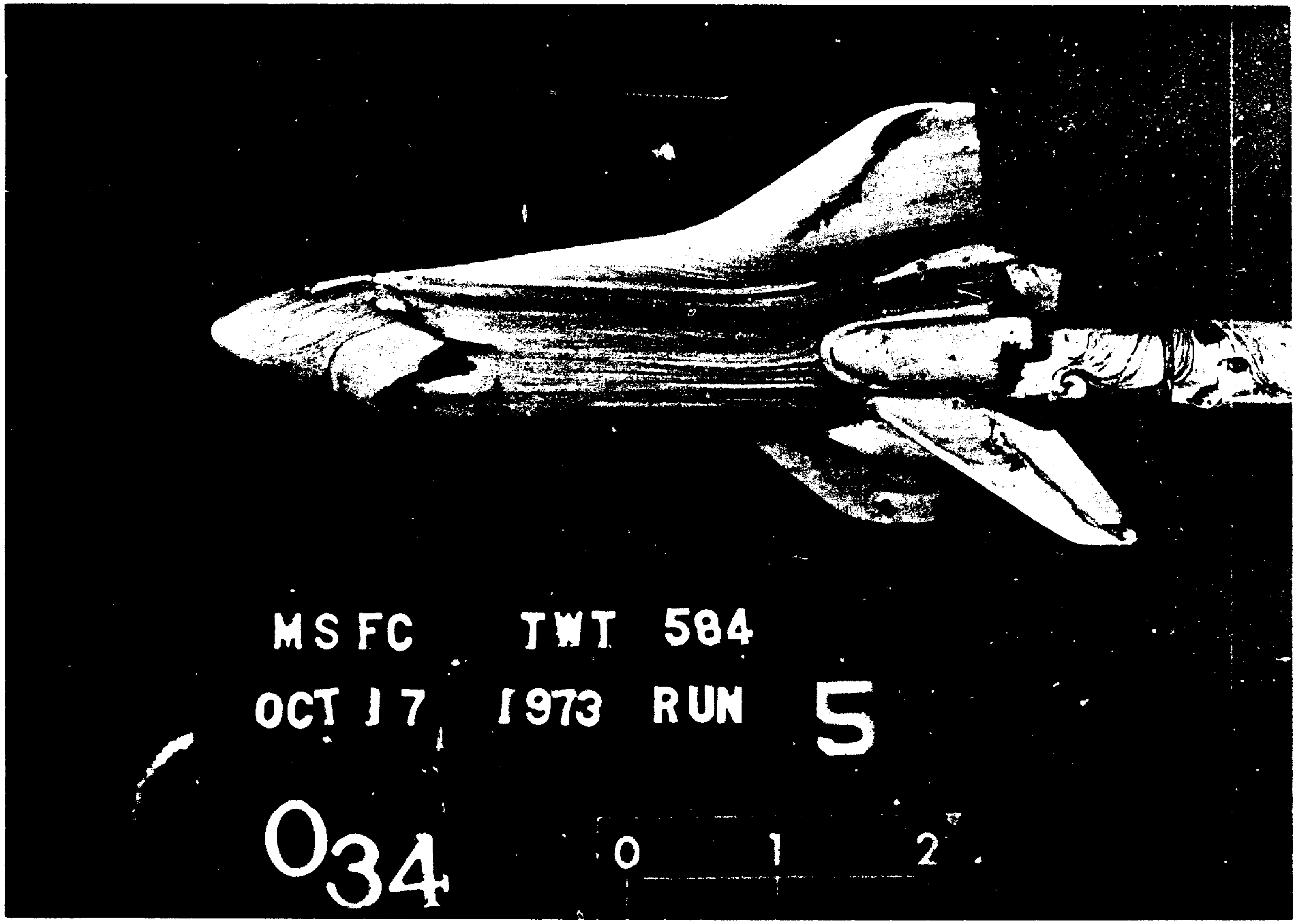

FIGURE 17. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = \beta = 0°$, $M = 0.9$, BLUE OIL PAINT (RIGHT OBLIQUE)

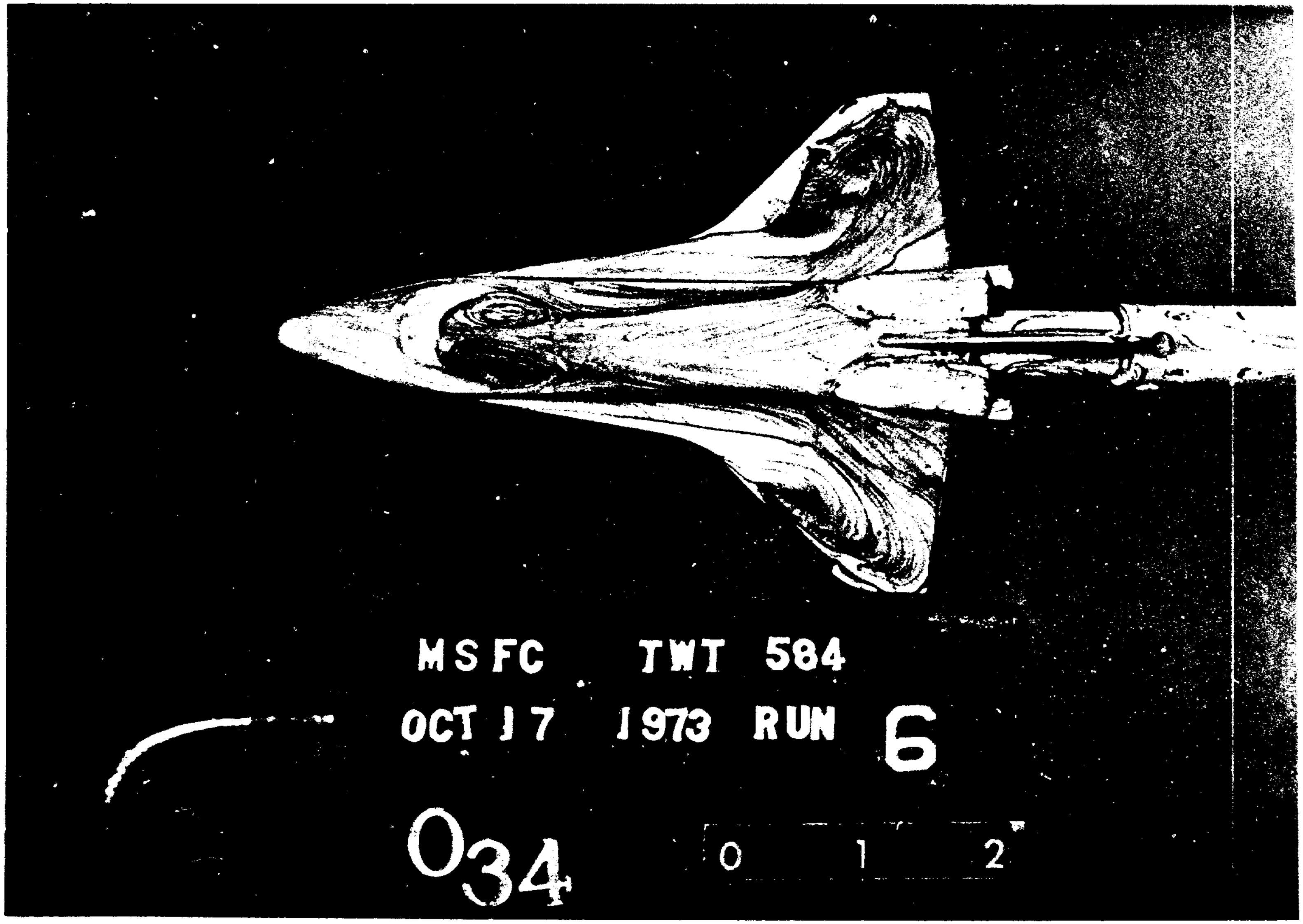

FIGURE 18. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 5°$, $M = 0.9$, BLUE OIL PAINT (TOP VIEW)

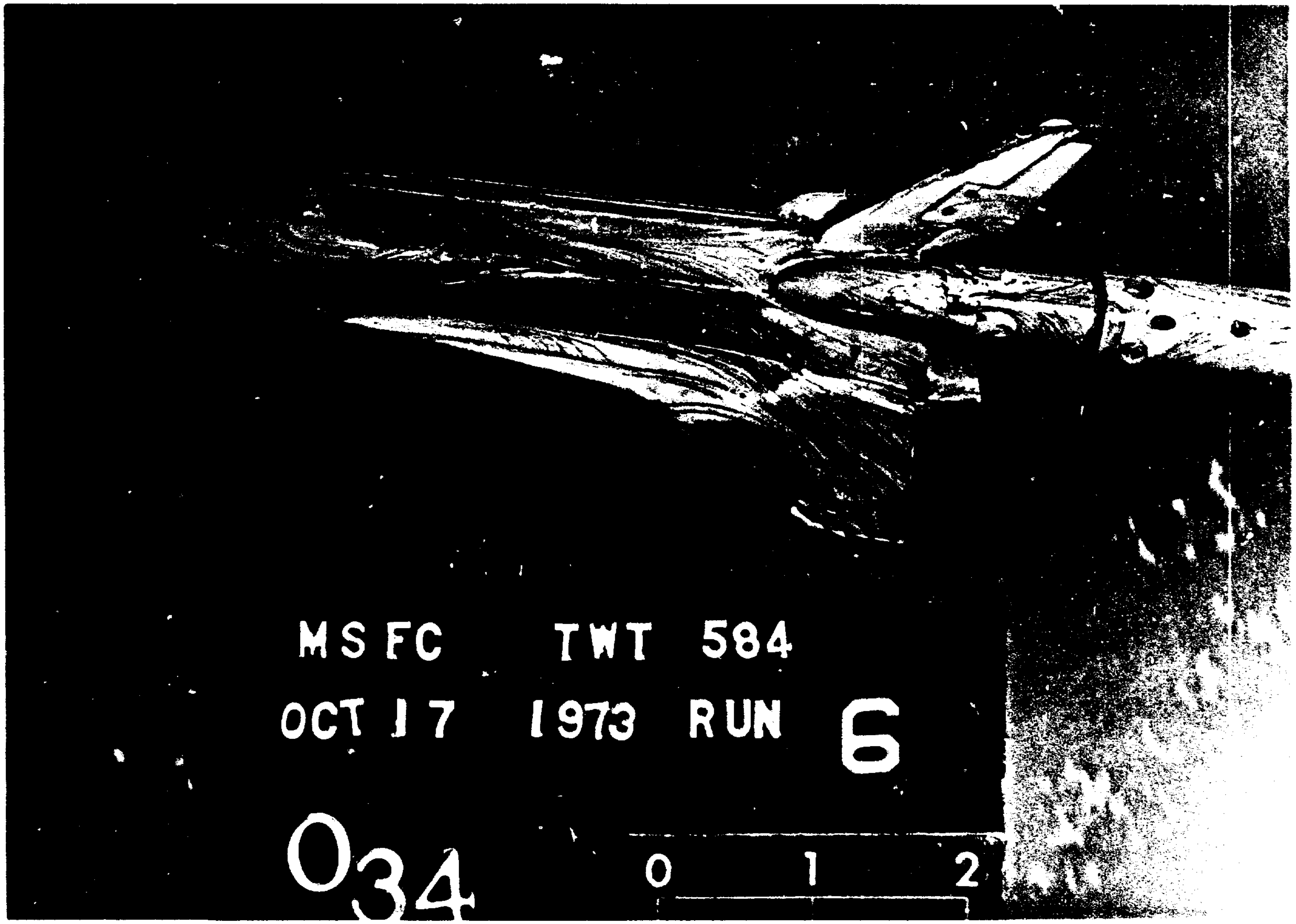

FIGURE 19. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 5°$, $M = 0.9$, BLUE OIL PAINT (LEFT OBLIQUE)

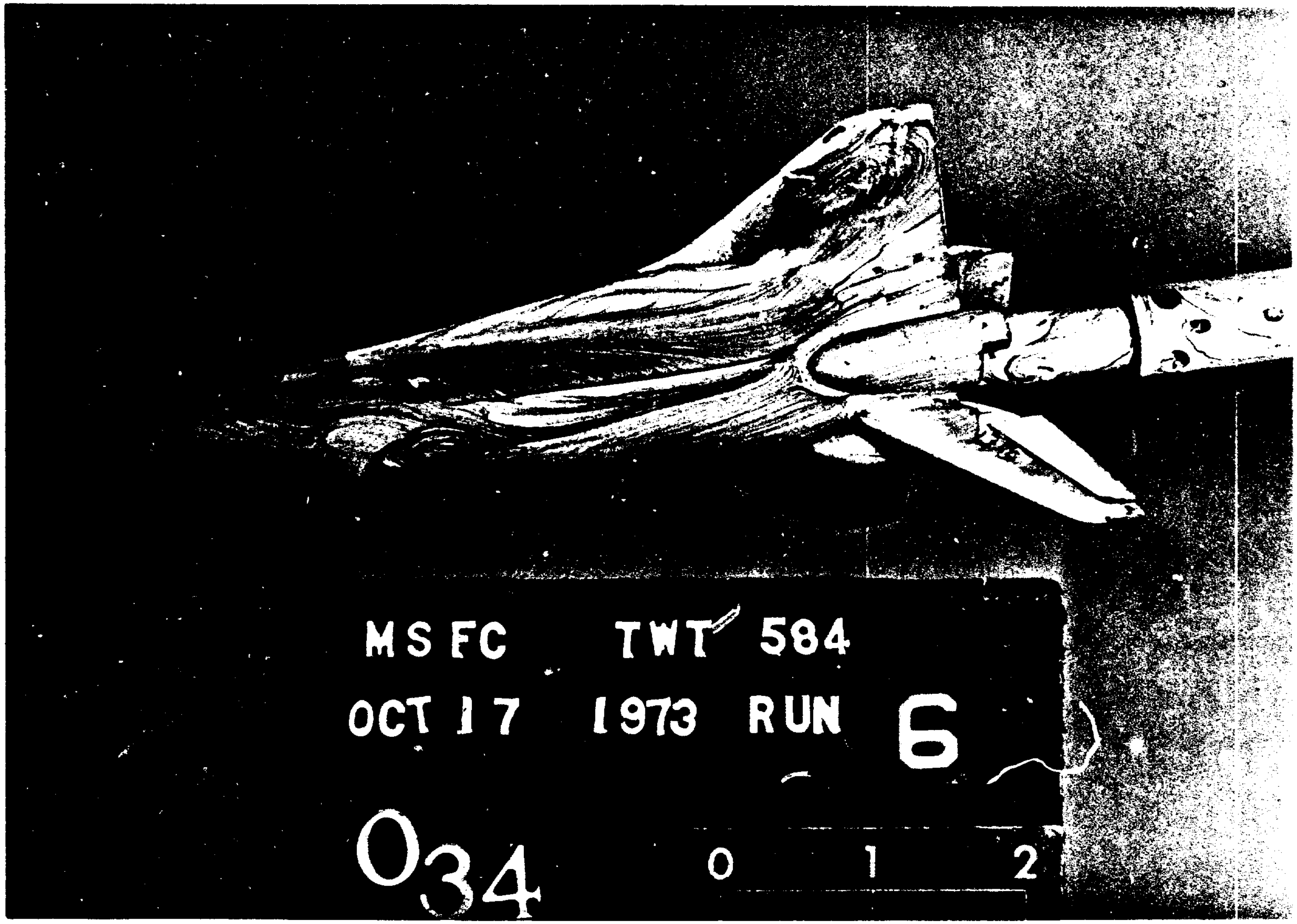

FIGURE 20. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 5°$, $M = 0.9$, BLUE OIL PAINT (RIGHT OBLIQUE)

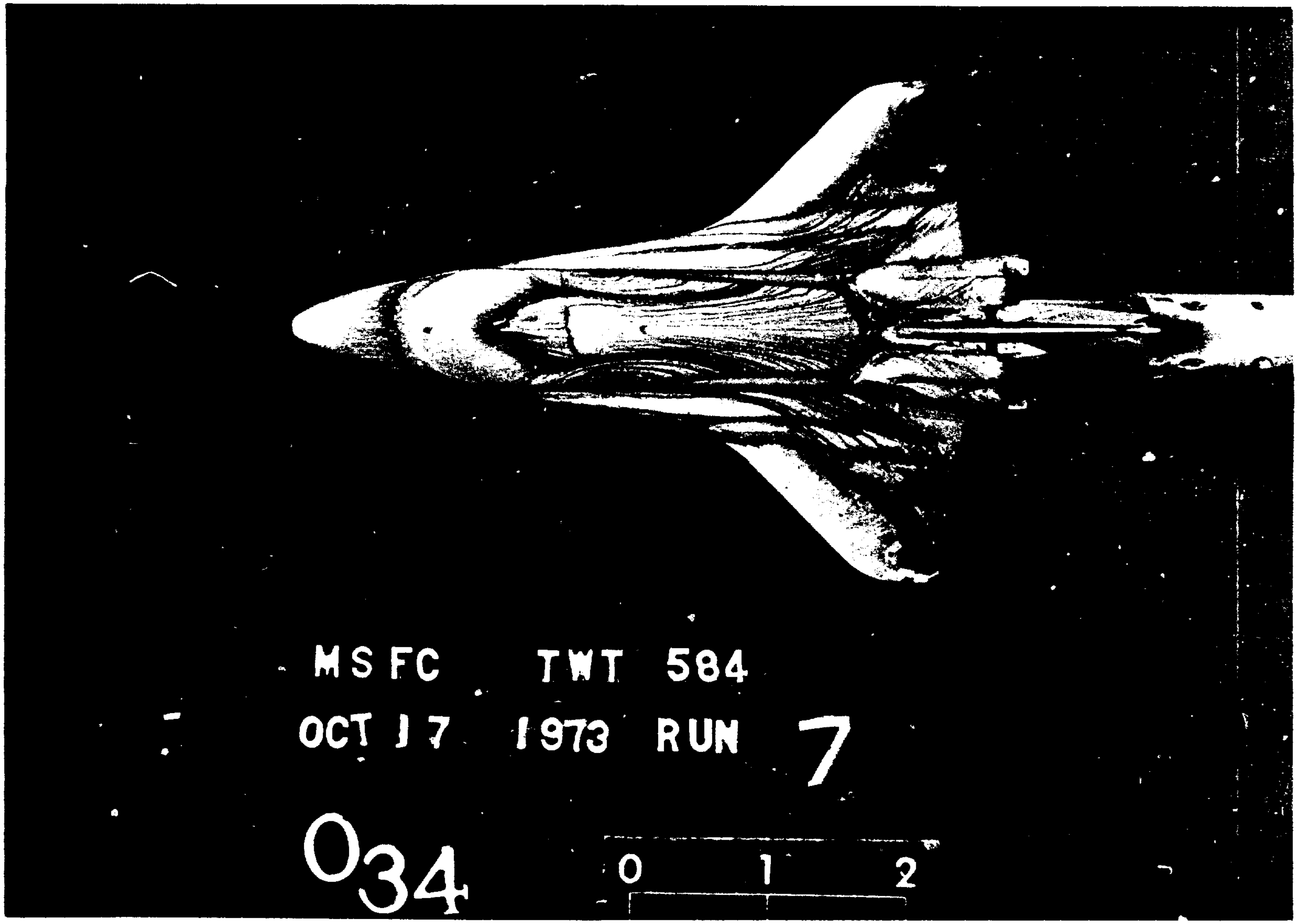

FIGURE 21. OIL FLOW PHOTOGRAPH OF ORBITER, α = 10°, β = 5°, M = 1.96, BLUE OIL PAINT (TOP VIEW)

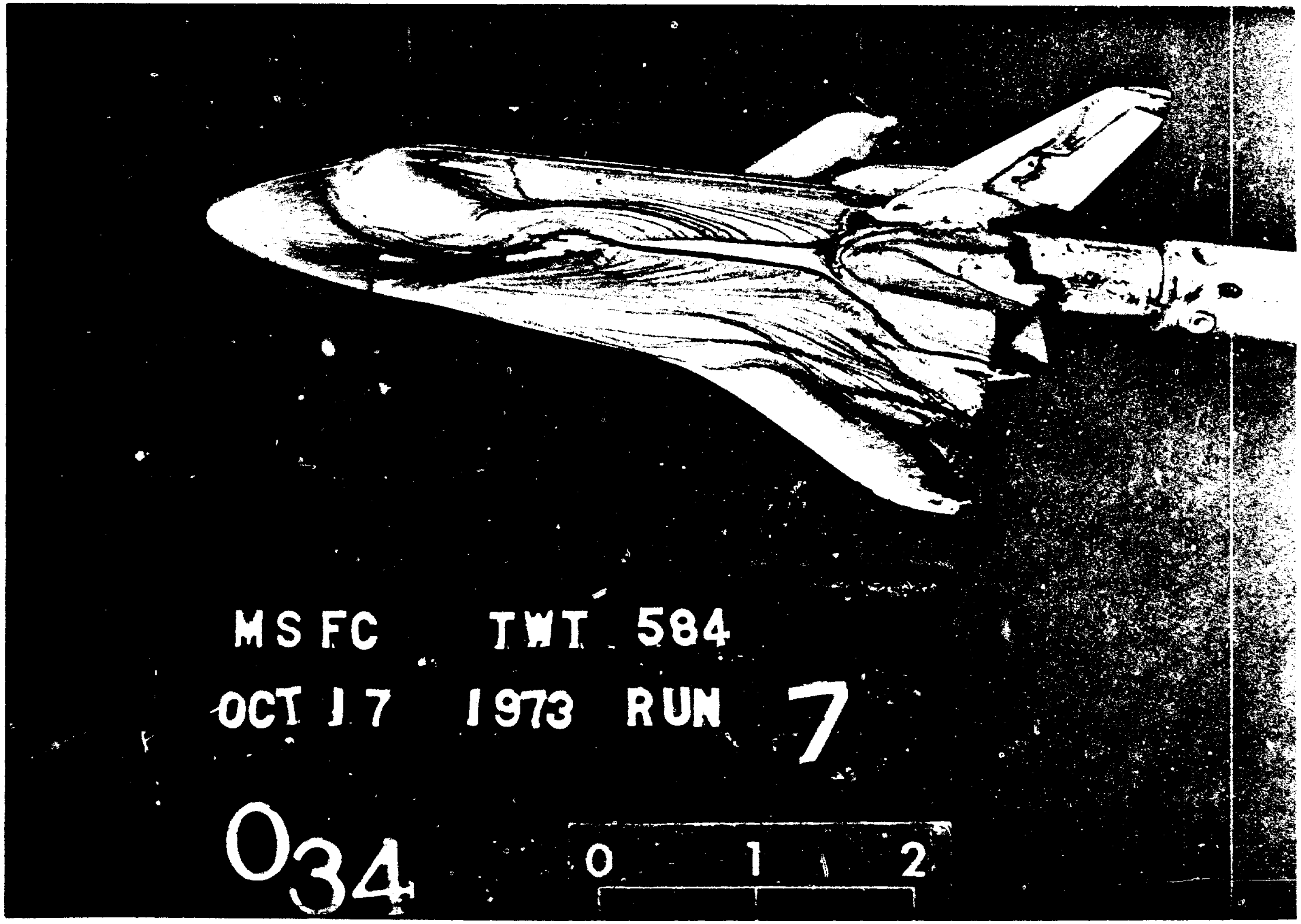

FIGURE 22. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 1.96$, BLUE OIL PAINT (LEFT OBLIQUE)

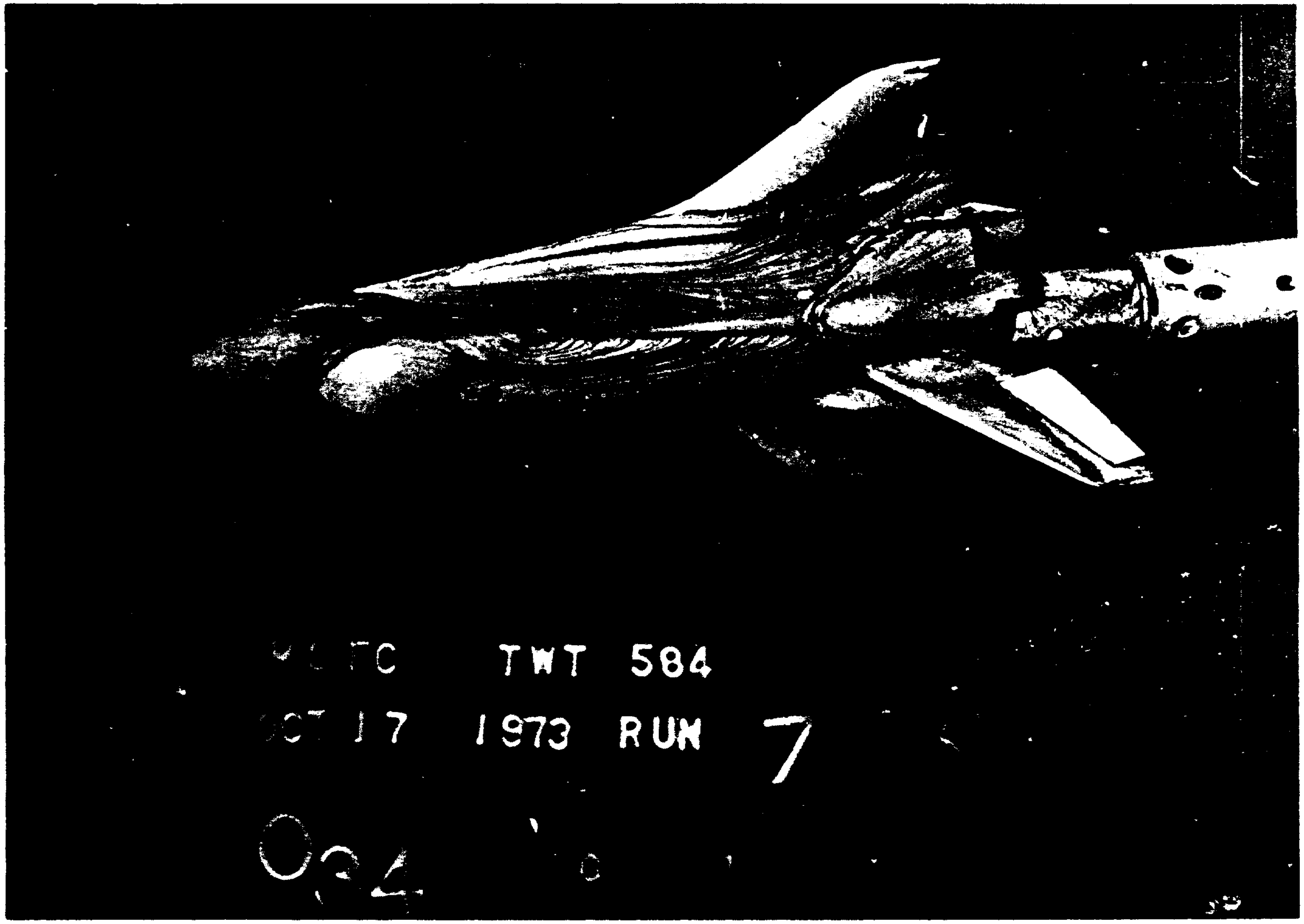

FIGURE 23. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 1.96$, BLUE OIL PAINT (RIGHT OBLIQUE)

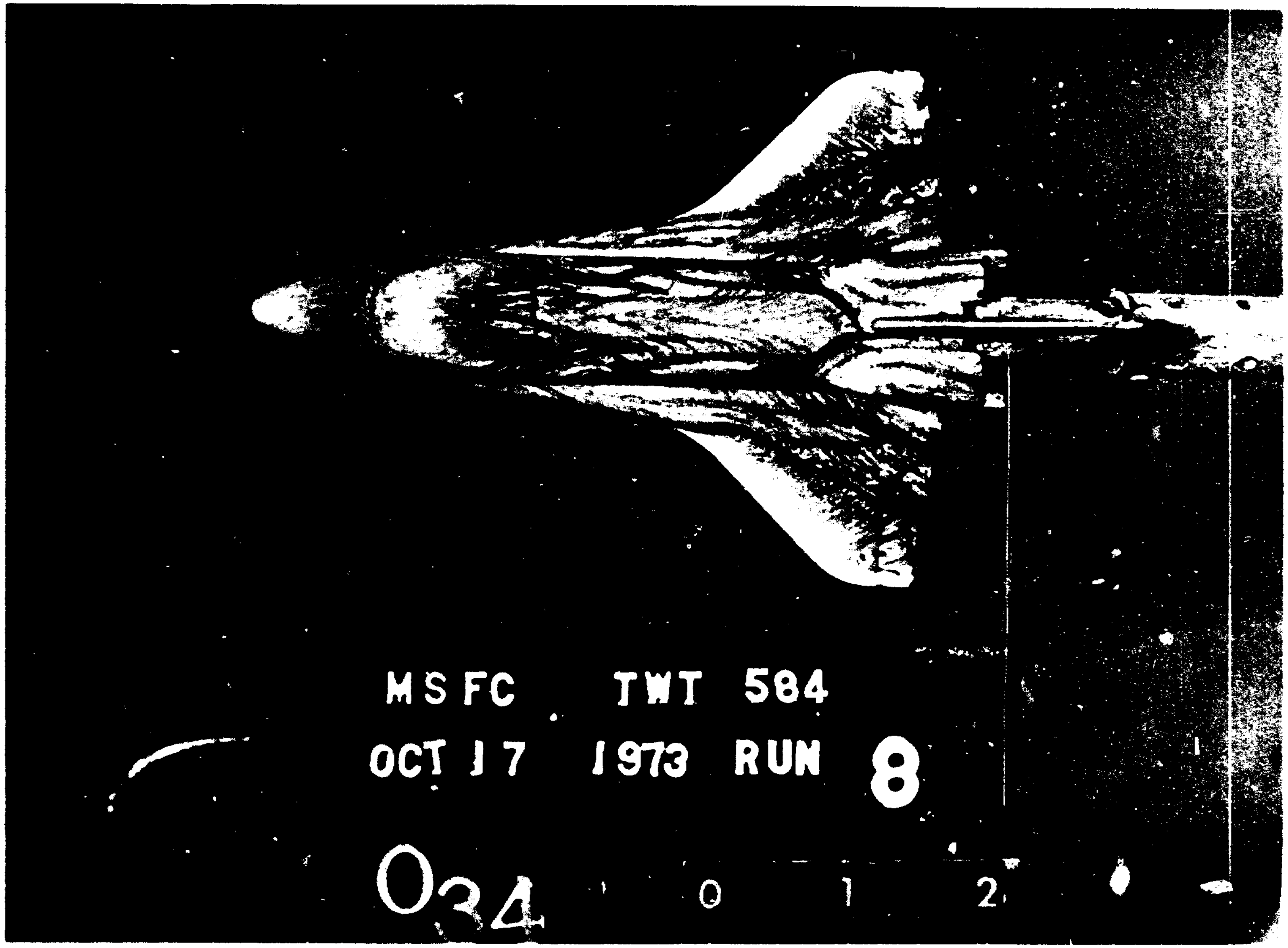

FIGURE 24. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 2.99$, BLUE OIL PAINT (TOP VIEW)

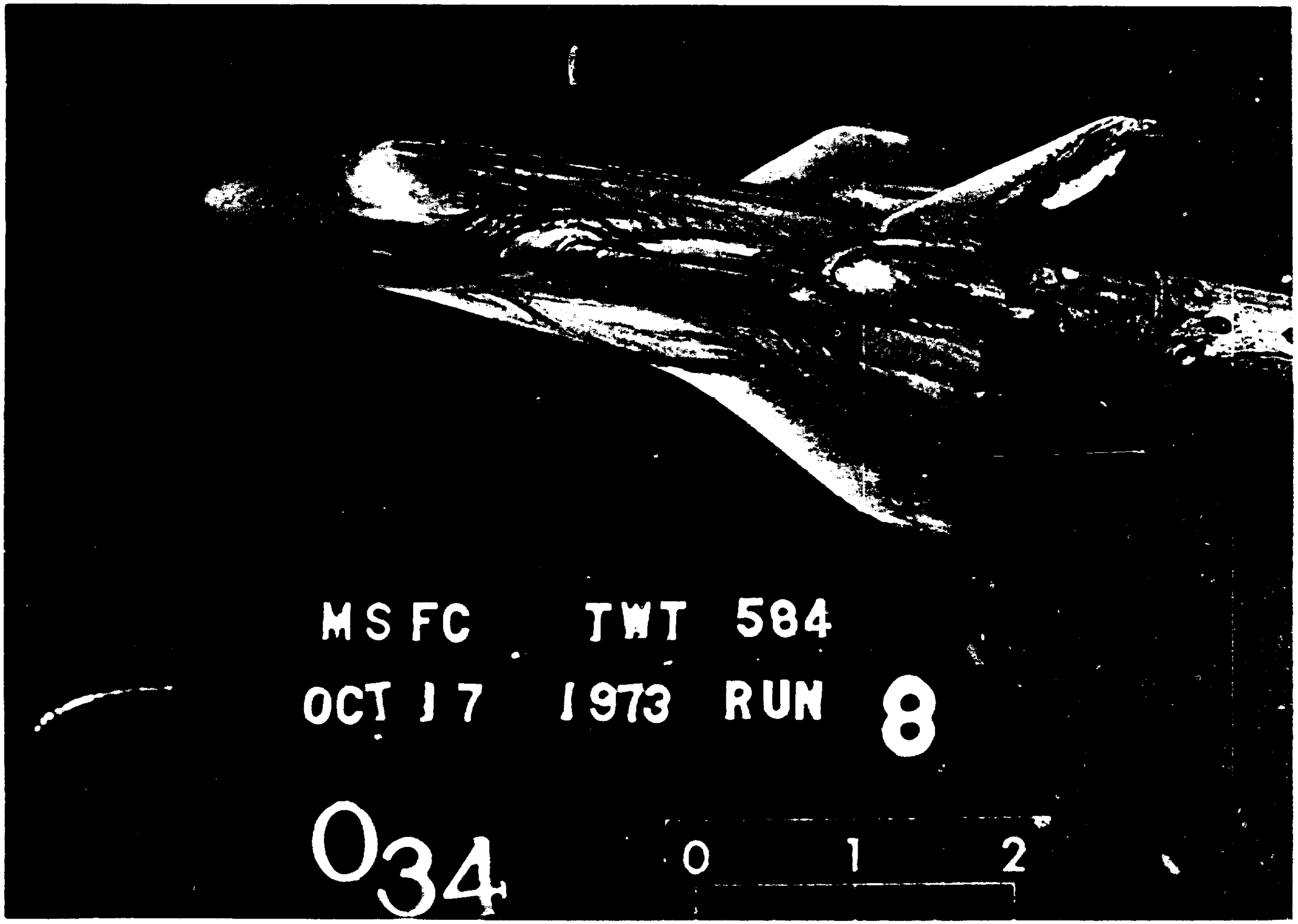

FIGURE 25. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, M = 2.99, BLUE OIL PAINT (LEFT OBLIQUE)

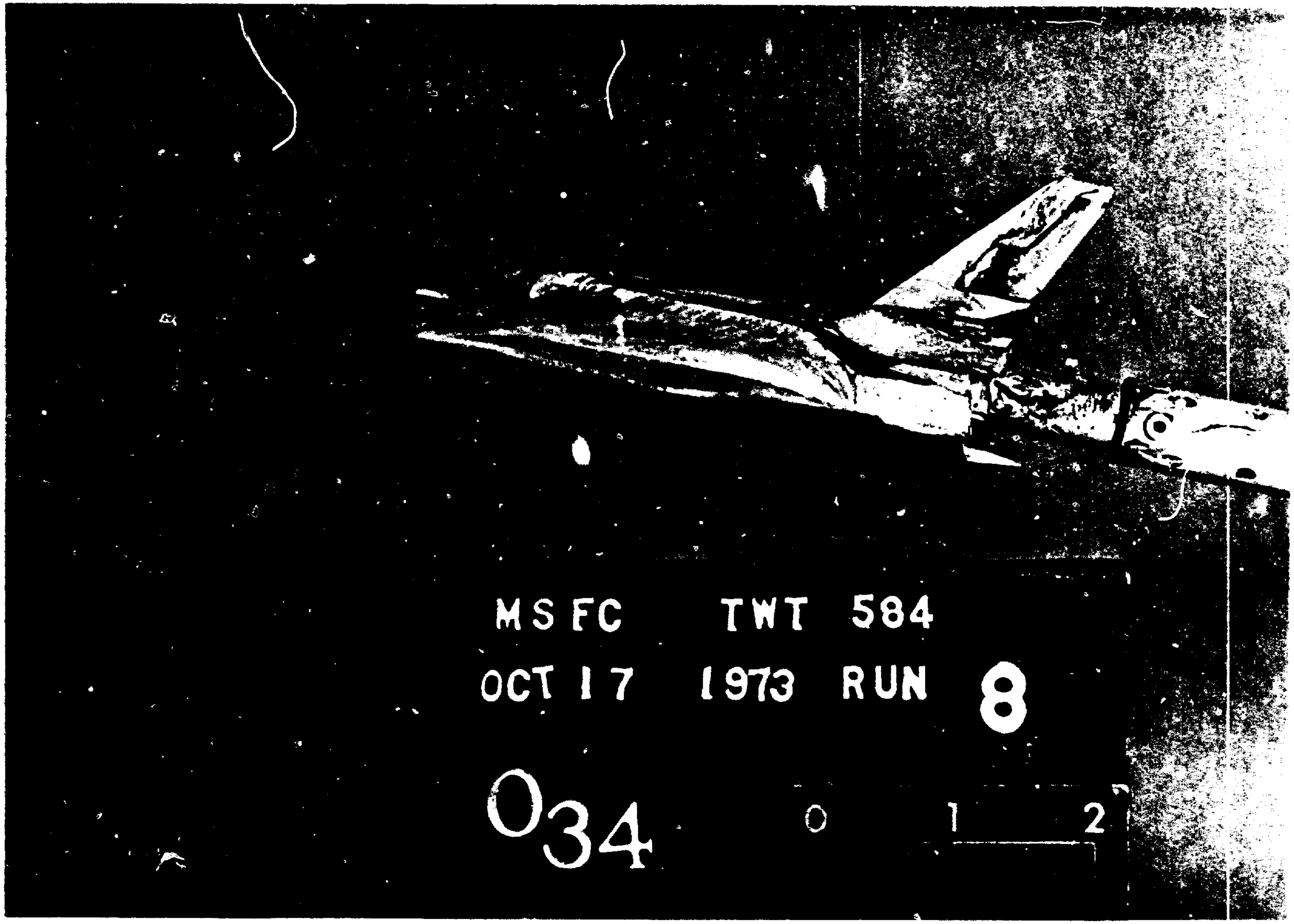

FIGURE 26. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 2.99$, BLUE OIL PAINT (LEFT SIDE)

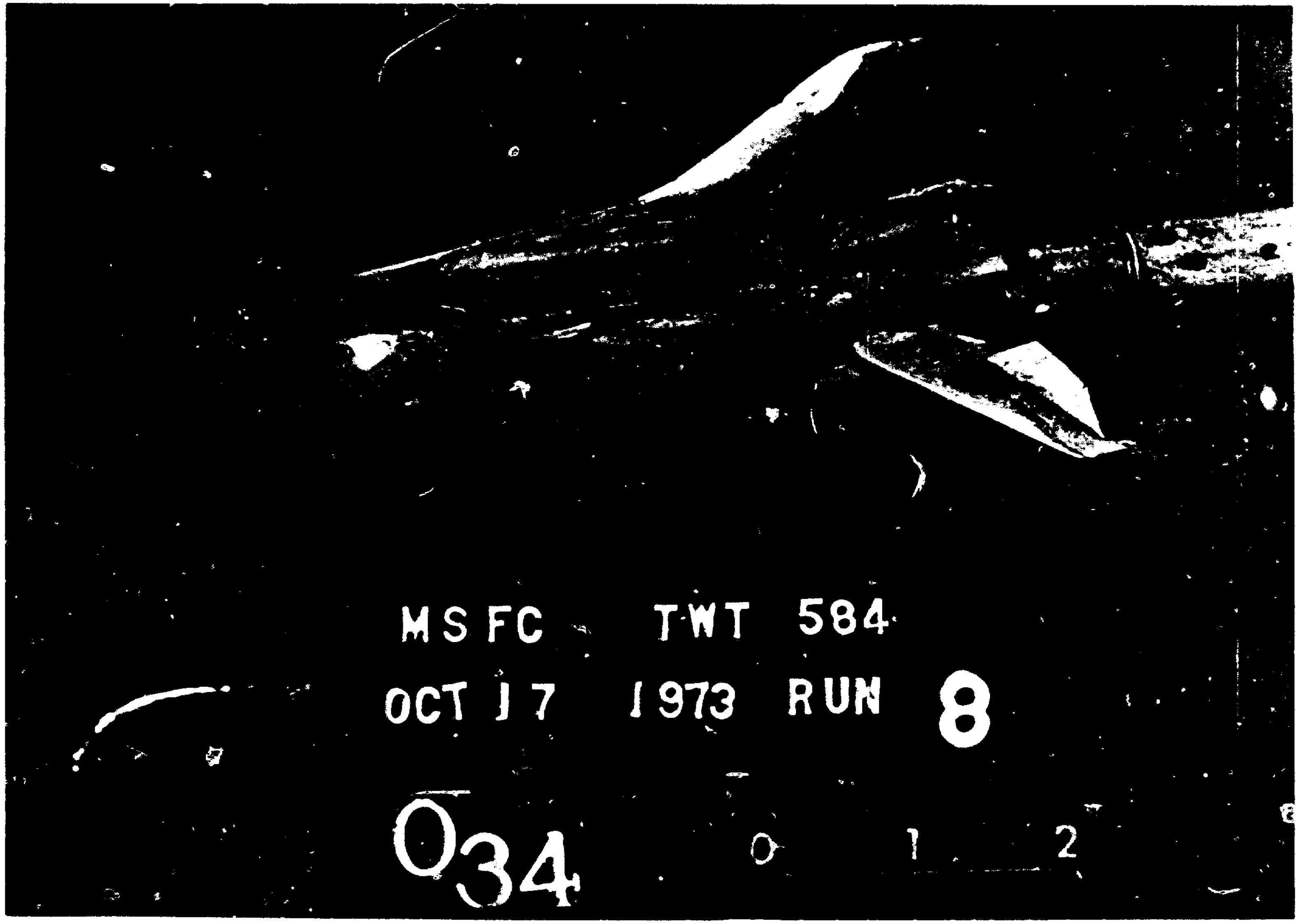

FIGURE 27. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 2.99$, BLUE OIL PAINT (RIGHT OBLIQUE)

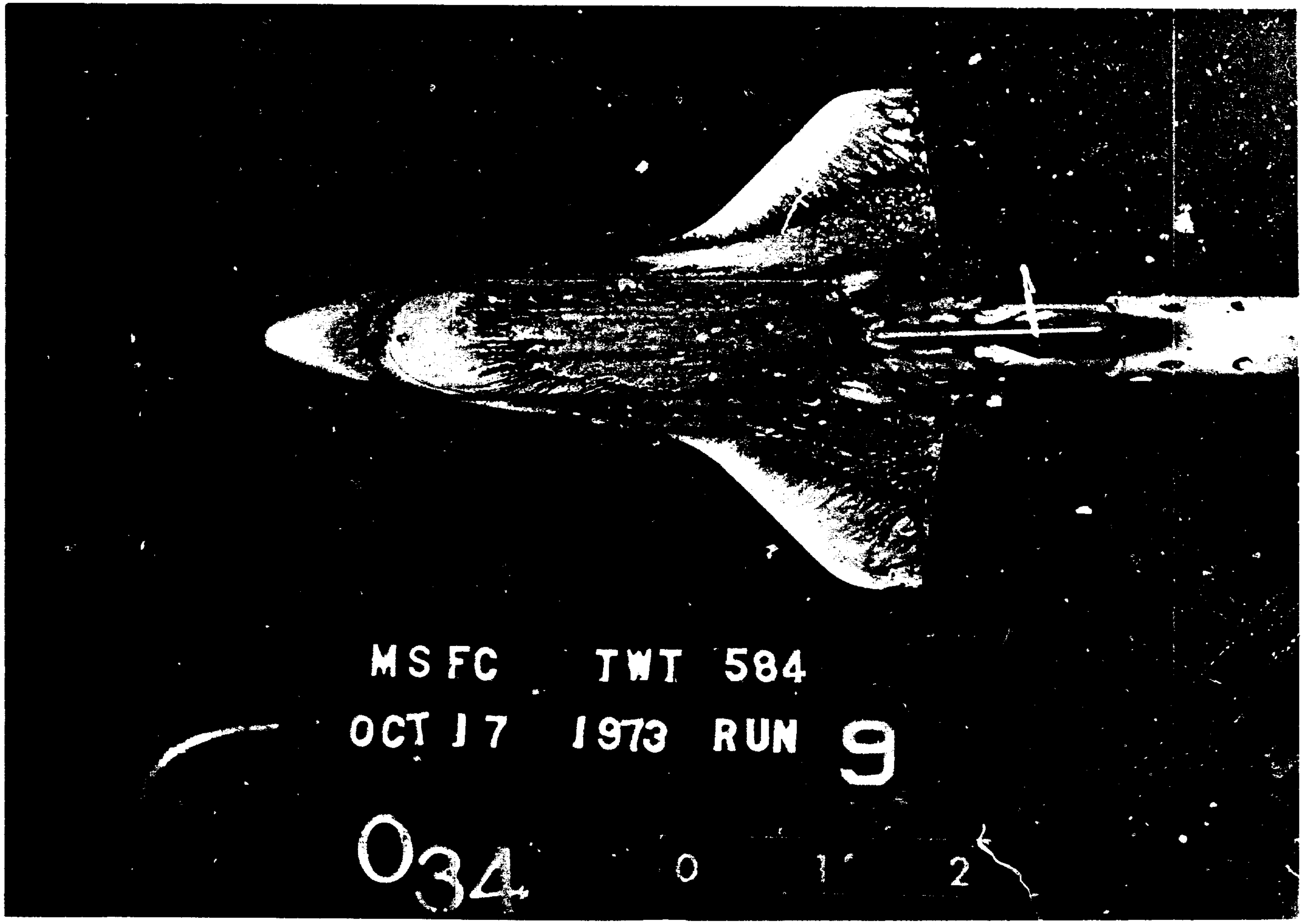

FIGURE 28. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 4.96$, BLUE OIL PAINT (TOP VIEW)

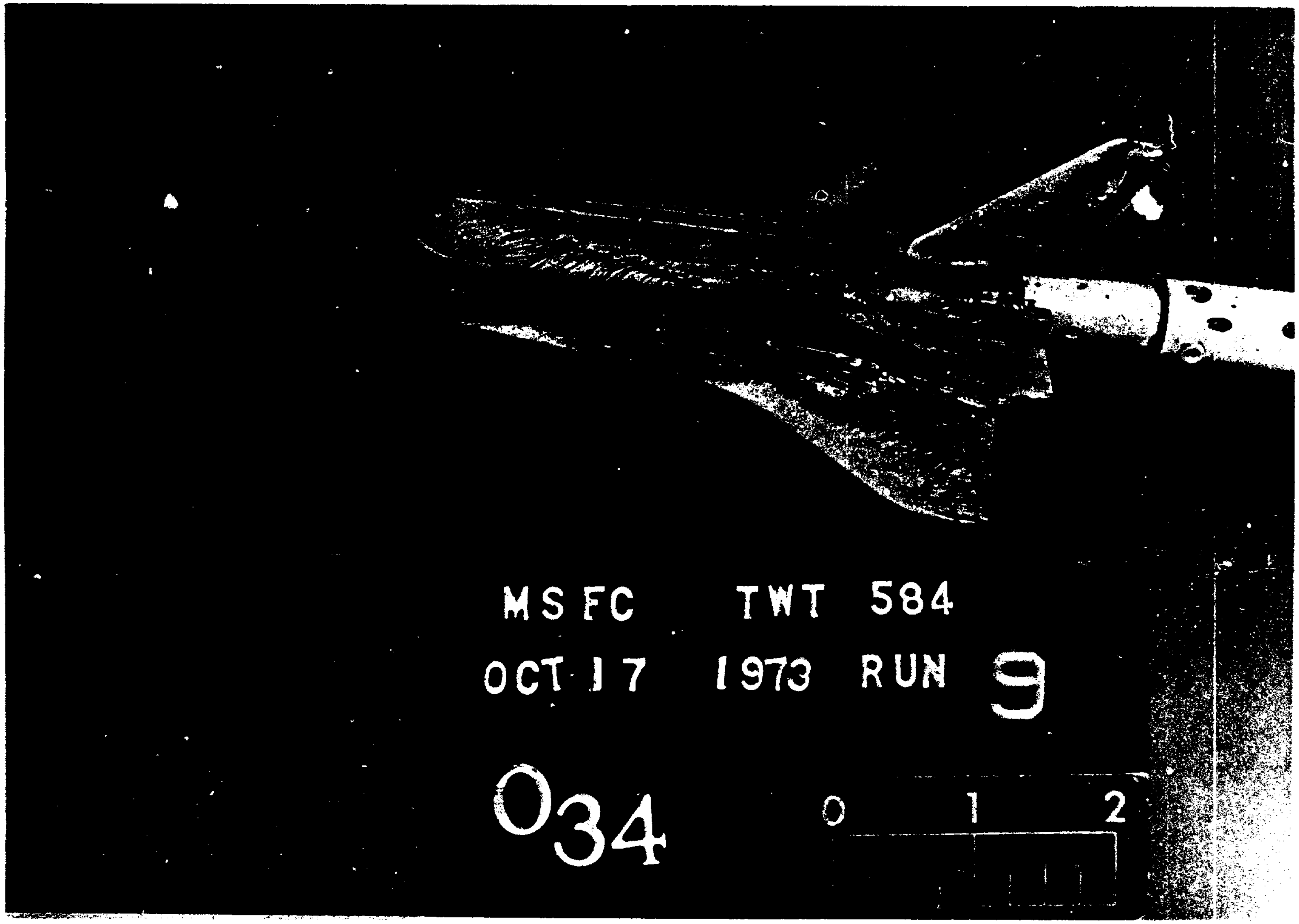

FIGURE 29. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 4.96$, BLUE OIL PAINT (LEFT OBLIQUE)

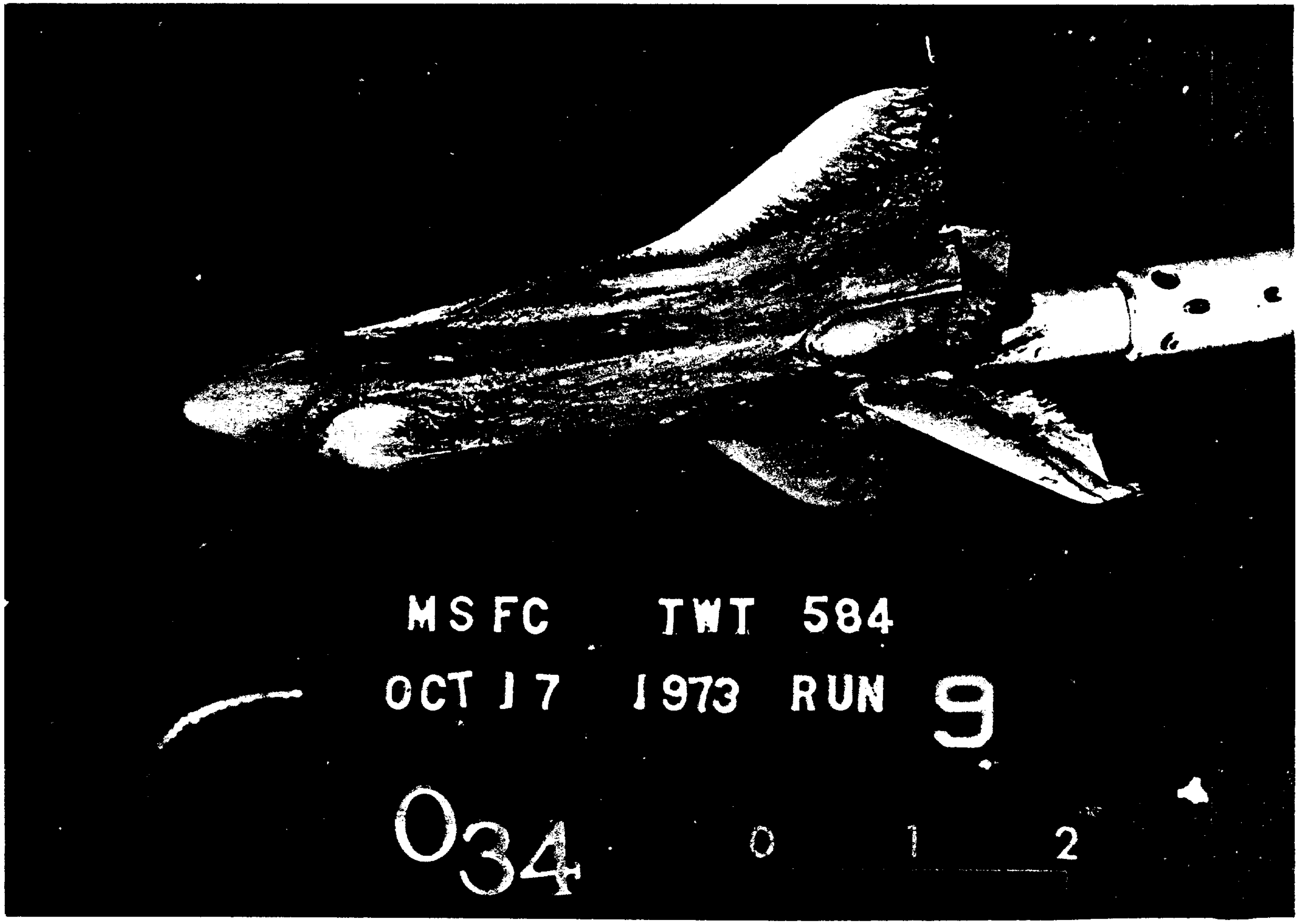

FIGURE 30. OIL FLOW PHOTOGRAPH OF ORBITER, $\alpha = 10°$, $\beta = 0°$, $M = 4.96$, BLUE OIL PAINT (RIGHT OBLIQUE)

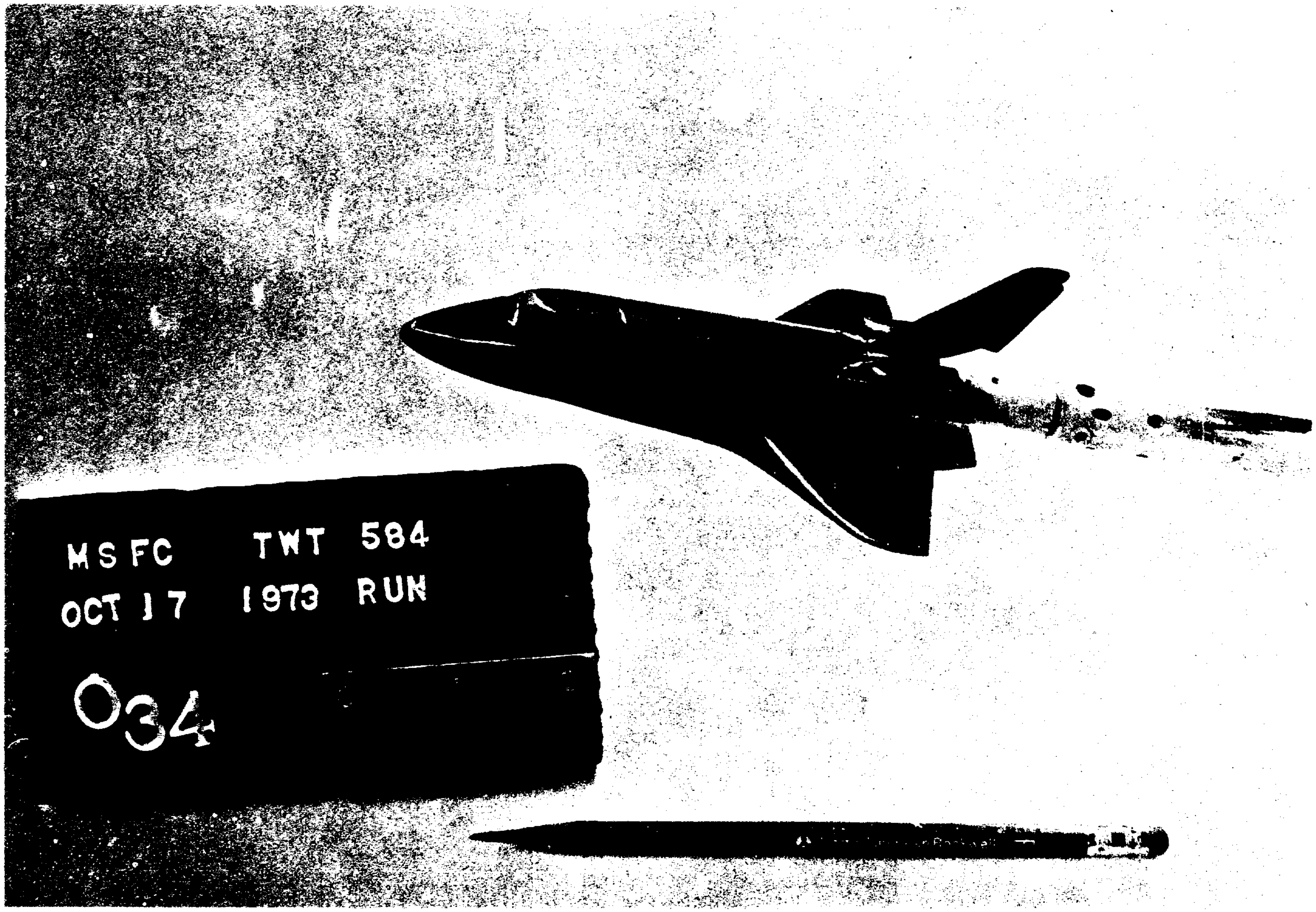

FIGURE 31. OIL FLOW PHOTOGRAPH OF MODEL PREPARATION: BLUE OIL PAINT BRUSHED ON AND WIPED DOWN

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FIGURE 32. OIL FLOW PHOTOGRAPH OF MODEL PREPARATION: APPEARANCE AFTER SPRAYING WITH MACHINE TOOL OIL